FIRE PROTECTION HANDBOOK®

Twentieth Edition

VOLUME I

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Dedication

In recognition of his extraordinary service as founder and professor of the fire protection engineering program at the University of Maryland, as chairman of the NFPA Board of Directors, as chairman of the NFPA Standards Council, as leader and mentor, this handbook is dedicated to Dr. John L. Bryan.

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Preface

The *Fire Protection Handbook*®—there is no other fire protection reference quite like it. For more than a century, the *FPH*™ has been *the* compilation of fire protection data and best practices. This 20th edition honors the traditions of thoroughness and accuracy that make this handbook so central to any fire protection library. At the same time, this edition includes new and expanded information throughout. For example, there are 25 new chapters and more than 500 new figures and tables. The pool of authors grew from 247 in the 19th edition to our current 260.

FPH users face a unique challenge: navigating quickly though such a wealth of information. This edition includes several new features to make it easier for readers to find the information they need. The most obvious change is the use of a second color to highlight important information such as subheads and expanded cross references to related chapters.

Other changes include the following:

- The addition of new features such as "Key Terms" and "Chapter Contents"—tools to help make the information easier to find
- The reorganization of the sections, so that each section contains fewer chapters

Clearly, a big team participated in creating the *FPH*. The authors are at the center of that team—and I'm particularly grateful for the evening and weekend time they devoted to their chapters. The authors were unfailingly cheerful and were marvelous at fitting the *FPH* into their busy lives and careers.

The section editors recruited authors, reviewed draft material, and resolved technical differences. They were simultaneously diplomats and technical taskmasters responsible for as many as 24 chapters. Their job was far from simple. The three associate editors completed a particularly important job in reviewing new chapters.

Special places in heaven are reserved for my colleagues, Robine Andrau (who timed her retirement to accommodate the *FPH* schedule), Betsey Henkels, and Michael Gammell. They faced a huge manuscript—a stack of paper and electronic files equivalent to 12,000 pages and 2,500 illustrations—and tamed it, one page at a time.

Many other people contributed to this handbook in large and small ways. We all share a simple goal of making our world a bit safer. I tip my hat to you all.

Pam Powell
Managing Editor and Senior Product Manager

Introduction

This is the 20th edition of the *Fire Protection Handbook*®. It has changed significantly since its inception in 1896 as the *Handbook of the Underwriter's Bureau of New England.*

The original author, Everett U. Crosby, was manager of the Underwriter's Bureau and one of the stock fire insurance company executives who came together to develop a consistent set of sprinkler rules in 1895 that led to the formation of NFPA. He also became the first secretary of NFPA, serving from 1896 to 1903, and was chairman of the executive committee from 1903 to 1907. Henry A. Fiske, who later succeeded Crosby as manager of the Underwriter's Bureau, joined Crosby as co-editor of the second edition in 1901. The third edition in 1904 was called the *Handbook of Fire Protection for Improved Risks,* and the fourth edition in 1909 became known as the *Crosby-Fiske Handbook of Fire Protection,* the title used until the 10th edition in 1948. H. Walter Forster, chair of NFPA's Safety to Life Committee, joined the editorial team in 1918 and became an editor for the sixth edition in 1921.

In 1935, Crosby, Fiske, and Forster donated all rights to their handbook to NFPA, which published the eighth and all subsequent editions. By the 11th edition, in 1954, the work was entitled the *NFPA Handbook of Fire Protection.* From the 12th edition in 1962 to this 20th edition, the handbook has been known simply as the *Fire Protection Handbook.*

The explosion of fire-related technology and fire protection knowledge during the last quarter of the twentieth century and into the beginning of the twenty-first century has driven exhaustive changes in the format and content of the *FPH*™. The original 5" × 7" pocket handbook is now a two-volume 8½" × 11" set.

As the most pressing concerns of fire protection have evolved—from property protection concerns of the late 1800s, through life safety concerns for public occupancies in the beginning of the 1900s, to the computer-modeled, risk assessment–based systems approach in use today—the number of subjects covered by the *FPH* has increased greatly.

Creation of the *Fire Protection Handbook* through 20 editions and 111 years has involved literally thousands of fire protection experts from within and without NFPA. It is their expertise that has established the *Fire Protection Handbook* as *the* reference source for fire protection practitioners worldwide.

Every effort has been made to make the content consistent with the best available information on current fire protection practices. If readers discover errors or omissions, the editors would appreciate those shortcomings being called to their attention. In offering this edition of the *Fire Protection Handbook,* the editors solicit suggestions for improvements to make future editions increasingly useful.

Arthur E. Cote, P.E., FSPE
Editor-in-Chief
NFPA Executive Vice-President and Chief Engineer (retired)

SECTION 1

Safety in the Built Environment

Robert E. Solomon

1.1 Challenges to Safety in the Built Environment
1.2 Fundamentals of Structurally Safe Building Design
1.3 Codes and Standards for the Built Environment
1.4 Legal Issues for the Designer and Enforcer
1.5 Fire Prevention and Code Enforcement
1.6 Premises Security
1.7 Protecting Against Extreme Events
1.8 Emergency Management and Business Continuity
1.9 Systems Approach to Fire-Safe Building Design

The term *built environment* has come into widespread use to describe all human-made structures, systems, components, and features that surround us. With the exception of one chapter on wildland fire management, the entire *Fire Protection Handbook*® focuses on the built environment. However, building encroachment into the wildland/urban interface can affect certain wildland mitigation strategies and tactics as they relate to the built environment.

The built environment includes more than simply land-based buildings, and safety in the built environment addresses much more than fire safety. The built environment includes all human-made structures, whether or not they are intended for human habitation. Furthermore, the structures are not limited to fixed structures, nor are structures limited to relatively conventional structures. Structures, in fact, can range from submarines to luxury passenger ships to aircraft, and from underground mines to nuclear facilities and transportation infrastructure such as bridges and tunnels.

Regardless of their configuration, these structures face an astonishing array of challenges to make them perform efficiently as well as safely. The purpose of this section is to introduce a wide ranging array of safety issues related to the built environment. Some of these subjects are more traditional, such as the ever-present subject of fire safety; some are newer, such as consideration for extreme or extraordinary design events; and some are a newer and more formalized way of looking at existing issues, such as business continuity.

Chapter 1, "Challenges to Safety in the Built Environment," provides statistical information on the long-term trends in building performance and safety-related problems as well as short-term trends and patterns that help to show the relative importance of various mitigation strategies. Among other topics, Chapter 1 addresses natural disasters and the importance of all-hazard education.

Chapter 2, "Fundamentals of Structurally Safe Building Design," focuses on current building design theories and concepts, concentrating on safety issues within the context of building design. In addition to defining building terms, the chapter introduces design loads and forces, basic building systems and components, fundamental design concepts, and basic design methodology.

Chapter 3, "Codes and Standards for the Built Environment," provides an overview of building codes and standards from their origins nearly 4000 years ago to the documents in use today. The chapter explains the differences between codes, standards, and other regulatory documents, and how these documents differ around the world.

The next two chapters explore the legal and administrative context in which codes and standards for the built environment operate. Chapter 4, "Legal Issues for the Designer and Enforcer," is new to this handbook and covers topics such as the legal implication and adoption of codes, key legal concepts for the engineer and enforcer, the engineer and negligence, and liability concerns associated with building design. Chapter 5, "Fire Prevention and Code Enforcement," introduces the functions of various fire prevention personnel before discussing inspection, enforcement, and plan review activities.

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The section's next three chapters are all new and focus on the emerging concerns of security, extreme events, and emergency management. Chapter 6, "Premises Security," explains types of security threats and various building configuration, layout, design, system, and program strategies to mitigate those threats. The aim of Chapter 7, "Protecting Against Extreme Events," is to outline a variety of measures available to help protect buildings and their occupants against the impacts of extreme hazard events. These design events are beyond the realm of the normal or expected hazards that a building is expected to encounter during its life cycle. Chapter 8, "Emergency Management and Business Continuity," defines the essential elements of an emergency management and business continuity program and a process for developing and implementing such programs. Business interruption can come in many forms—fire, earthquake, cyber, and pandemic, among others—and strategies for dealing with each one are considered.

The section concludes with a return to what, for many readers, will be more familiar territory: an exploration of a "Systems Approach to Fire-Safe Building Design" (Chapter 9). The chapter covers the Fire Safety Concepts Tree and its fire protection mitigation strategies.

SECTION 1

Chapter 1

Challenges to Safety in the Built Environment

John R. Hall, Jr. ❑ Erin R. Twomey

Chapter Contents

Defining the Challenges to Safety
Relevant Major Societal Trends
Major Databases
Overview of Types of Peril Causing Harm
Fire, Burns, and Electric Shock
Falls
Natural Disasters
Fatalities Involving Hazardous Environments

Key Terms

all-hazard education, built environment, Consumer Product Safety Commission (CPSC), hazard, International Classification of Diseases (ICD), *Remembering When,* risk, *Risk Watch*®

We expect a great deal of our built environments. We expect that they protect us from hazards arising from objects we bring into the environments and from the components of the structure itself. We expect that our built environment itself will not be harmful and will provide a protective envelope to shield us from harm arising outside the built environment. We expect it to keep us secure and comfortable and to provide conveniences for the time we spend in it. We expect a lot from our built environments in addition to functionality, usability, attractive appearance, affordability of construction and operation, and a host of other nonsafety goals and objectives.

The first step in evaluating the challenges to safety in the built environment is to classify the types of harm encountered. This chapter examines several perils causing harm to people and property in the built environment.

See also, Section 1, Chapter 7, "Protecting Against Extreme Events"; and Section 3, Chapter 1, "An Overview of the Fire Problem and Fire Protection."

DEFINING THE CHALLENGES TO SAFETY

Any harm that occurs inside a built environment could theoretically have been prevented or mitigated, at least in some very small way, by some feasible modification to the built environment. However, that definition of challenges to safety is far too sweeping to be useful. A built-in visual and motion building monitoring system might provide enough surveillance to reduce the fraction of heart attacks or strokes that prove fatal by detecting collapse or other actions indicating a person in distress, but if our purpose is to track the effectiveness of our current typical code and design choices, it would not be helpful to have tracking statistics dominated by the large number of heart attacks simply because it is technically feasible to build a structure that would help on some of them.

Any harm that occurs as a direct result of some failure in the built environment under conditions anticipated by the code is the type of event that should be tallied as an indicator of performance. However, that definition of challenges to safety is far too narrow to capture what good design can accomplish in the way of preventing or reducing harm. The narrow definition is more appropriate for assigning legal liability than for evaluating overall effectiveness and impact.

Also of concern is any harm that occurs as a result of conditions that were not anticipated by the code but that should have been, and would have been, anticipated with better information or better understanding of the factors driving perilous events and the performance of the built environment to challenges those events represent. The sometimes delicate and emotional debate if the codes should consider and provide design criterion for hostile acts or terrorism is a relatively new and highly complex subject. These events are neither predictable nor quantifiable. Although databases of such events exist, there is no return interval or probabilistic data to support a hard and fast design approach that could realistically be included in our design codes and standards to address these events. See also Section 1, Chapter 7, "Protecting Against Extreme Events."

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General crime deterrence and security measures, such as those covered by NFPA 730, *Guide for Premises Security,* do have a place in the types of harmful hazards that our codes and standards should address.

Options for Data

Natural disasters—including major wildfires but excluding other major fires—involve probabilistically occurring natural hazard–event triggers, whose probabilities vary by location (e.g., coastal location) and by characteristics (e.g., soil conditions) that themselves vary by location. Therefore, risk assessment for the hazards can be set up using risk maps for the triggering events, and codes can control design choices by specifying building performance in response to specified severities of these triggering events (analogous to fire scenarios used in performance-based design). The actual data on these natural disasters—and the losses they cause, which reflect both the event of severity and the building performance in resisting damage from the event—are what we track in order to gain insight into both the challenges to buildings and the performance of different building materials and designs in response to those challenges.

In the area of fire safety, the instances of harm occur in well-defined incidents, most of which lead to an encounter with an official body (e.g., a fire department) and the creation of an official record (e.g., incident report). These reported incidents are represented by the large or small samples of incidents captured by one or another international database. At least in the United States, these databases provide a baseline for surveillance of the magnitude of the harm proper design is intended to prevent or reduce. These databases provide information on the size of the problem, answering many, but far from all, of the questions we have about the effect of design choices and code language on resulting harm.

It is true that the database encompasses instances in which other parties are far more responsible than the builders and managers of built environments for the harm, instances that could not have been prevented or mitigated by even the most expansive, and often times expensive, of design standards. Nevertheless, the overall database can be used to identify candidate areas for targeted safety improvement, to estimate the magnitude of improved safety achievable by proposed design changes, and to monitor the changes in loss magnitudes associated with the implementation of design changes.

The databases available for monitoring, tracking, and surveillance of other types of harm within the built environment are not so well developed, except for major natural disasters, which are sufficiently few in number that they can be individually documented in great detail. For other instances of harm that do not involve fire or a natural disaster, there is less ability to develop statistics by type of harm and physical object creating the hazard (and thereby distinguishing between those that are part of the built environment and those that are not).

A notable exception may be criminal activity for which there are police crime and arrest databases. Deterrent systems comprised of metal detectors, screening processes, limited access doors, and overall procedural policies are examples of design changes to a built environment that could address this type of challenge.

Data are needed that can support a comprehensive analysis of all forms of harm associated with built environments, leading to a more focused analysis of options for action to address that harm and supported after actions are taken by follow-up monitoring of the impact of those actions in practice. This sequence corresponds to what is sometimes called program analysis and, after actions have been taken, program evaluation. Engineers and economists both apply risk assessment, which includes these steps as well, even though risk has different meanings to both.

Questions Involved in Safety Decisions

Conducting analysis in support of safety decisions requires detailed answers to a series of questions pertaining to the overall risk. Discussion of the following questions is the starting point for analysis.

- *Is this a significant risk?* Use readily available data to conduct a primary risk estimate. In this first triage phase, risks are identified and justifications are made as to whether or not the risk needs further examination.
- *What are the risk details?* Describe the circumstances of all probable scenarios of the risk, so an understanding of an overall developmental process of the risk can be created. During this process of risk factor identification, the potential impact of candidate strategies is determined. In this second triage phase, risks are deemed to be significant or not.
- *What are the best ways for dealing with this risk?* Identify candidate strategies, considering one or more options within each of several general approaches, such as prevention, mitigation, and separation. The options may be interventions, programs, or risk control techniques. In this treatment selection phase, a risk is considered and one or more ways are selected to address it. The risk is judged to be significant enough to focus on and conventional enough to change.
- *What is the best way to implement the strategy?* In this service delivery strategy phase, the cost-effectiveness of implementing one or more strategies that show promise is addressed.

The goal of this chapter is to provide readily available information that bears on the first question of establishing whether a risk is significant but not much on the subsequent questions. This chapter represents more of a starting point than a full overview of the challenges to safety in the built environment. A structure will be provided, and details will be filled in to the extent possible. It is the authors' intention that this starting point will be a first step in the development of more complete databases, providing answers to a wider range of safety questions about the built environment.

RELEVANT MAJOR SOCIETAL TRENDS

Growth in Older Population

For every form of fatal injury in a built environment, except for poisonings by solids or liquids and unintentional firearms injuries, older adults are at higher risk.[1] This part of the population is also the fastest-growing segment of the population, not only in the United States but also throughout the economically developed world.[2]

The United States has a death rate (8.3 per 1000 population) that is lower than its birthrate (14.1 per 1000 population). Annual population growth from 2000 to 2005 was 1.03 percent, and older adults defined as age 65 and older represent 12.4 percent of the total population. The United States must deal with both a need for more buildings to house a growing population and a need to remake the building stock to address the special needs of a rapidly growing older population.

Growth in High-Risk Areas

The U.S. population has been growing specifically in those regions where the likelihood of certain natural disasters is higher. Although population growth in coastal communities nationwide has actually been slower than in the rest of the country,[2] the state of Florida ranked third highest in number of people added in the 1990s, and Florida has by far the highest frequency of hurricane incidence of any state.[2,3] The geography of Florida is such that even population increases away from the coast can add to the people likely to be affected by hurricane-force winds and rain. The state that added the largest number of people was California, which also has by far the most people living in areas of frequent seismic activity.[2,3]

Whether growth in high-risk areas is disproportionately large or only proportional to growth elsewhere, it means the same perilous event will cause more deaths and damage more value in property, unless the increased exposure has been offset by improvements in protection.

MAJOR DATABASES

Even though 90 to 95 percent of all unwanted fires are unreported to fire departments, the ones that are reported number nearly 2 million a year, and they represent most of the deaths and property damage.[4] For every other type of harm, there is no analogous database with comparable breadth of scope and detail.

Major individual incidents, involving multiple deaths or millions of dollars of loss, are more likely to be extensively documented, and the more severe the harm caused by an incident, the more likely it is that a case study report on the incident will be published. It is, therefore, possible to develop lists and pattern analyses of these incidents. However, these large incidents generally account for only a small fraction of total harm to people, either by deaths or by nonfatal injuries. Such large incidents may account for a large share of damage to property, but for many forms of harm, like fire, they do not.

Database of Death Certificates

The national database of death certificates provides useful details on deaths due to injury.[5] The International Classification of Diseases (ICD) is designed for the classification of morbidity and mortality information for statistical purposes and for indexing of hospital records by disease and operations for data storage and retrieval.[5] The ICD has been revised approximately every 10 years since 1900 in order to reflect changes in understanding of disease mechanisms and in disease terminology.[5]

ICD-9 and ICD-10 were used to compile data tables for this chapter. However, although the traditional ICD structure has been retained, an alphanumeric coding scheme (ICD-10) replaces the previous numeric one (ICD-9).[5] This does provide a larger coding frame to leave room for future revision, but some categories of the previous edition have been left out of the latest revision. The data tables in the chapter will represent those changes.

Illnesses are generally not coded to indicate the involvement of or relevance of components of the built environment. This is an important gap, because it means we cannot really isolate and identify relevant illnesses, such as waterborne illness due to backflow or cross-connections in a plumbing system, Legionnaire's disease due to cultivating of bacteria or viruses in poorly designed or poorly operating air-circulation systems, and the kind of airborne illnesses associated with indoor air pollution. However, the statistics presented in this chapter will focus on fatal and nonfatal injuries, not illnesses.

The database of death certificates codes unintentional injuries as V01–X89, Y85–Y86. Deaths in which the injury was intentional (e.g., homicide, suicide) or where it the intent was unknown (codes X60–Y89) are largely excluded from the chapter. Deaths involving transportation or vehicles (codes V01–V99, Y85) are excluded from this chapter as being outside the definition of the built environment. Also excluded are injuries arising from medical problems (e.g., poisonings by drugs, medical malpractice), as these (codes X40–X49, Y4–Y84, Y88.0–Y88.3) are also deemed to be outside the definition of the built environment. Finally, statistics presented in the chapter exclude unintentional firearm injuries (codes X93–X95), radiation (codes W88–W91), and overexertion (codes X50–X57).

Databases on Injuries and Property Damage

Nonfatal injuries are not routinely captured, but there are three exceptions (in addition to the injury component of the fire incident databases). Occupational injuries are captured by the U.S. Department of Labor if they meet a severity threshold.[6] Injuries involving a trip to the hospital emergency room and associated with a consumer product are reported in a U.S. Consumer Product Safety Commission database.[7] (Recent changes mean that all emergency room injuries will be captured in the near future.) And the injuries people suffer that go unreported to any medical or other entity are tracked through an in-home sample survey as part of the National Health Interview Survey.[8] The database on occupational injuries uses approximately the same structure as the death certificate codes with additional detail in some places.

Apart from any natural disasters and fires, property damage is tracked only by the insurance industry and, for storms, by the National Weather Service.[9,10] Their published information has some useful detail, and it is possible that their unpublished coded data will in time permit more detailed analysis.

Influence of Major Incidents

Many issues in building codes and other codes for the built environment have historically been addressed not on the basis of number, rates, or percentages of fires or statistically derived indicators such as risk values, but rather on the basis of individual major incidents that indicate a specific type of hazard or

type of built-environment performance problem not previously encountered. For example, the Northridge earthquake of 1994 showed some problems with brittle fracture of structural steel that, although not necessarily significant in the loss in that incident, were nevertheless unexpected, leading to new research and code-change proposals. For this reason, this chapter includes not only statistics but also lists of deadliest or costliest incidents, where such lists are meaningful and potentially useful. There is an extended discussion in Section 2, Chapter 1, "Physics and Chemistry of Fire," of the past century of progress in fire safety, by major occupancy type, in which trigger events were often individual fires but progress could be measured statistically.

OVERVIEW OF TYPES OF PERIL CAUSING HARM

Table 1.1.1 provides a first-level classification of types of peril causing harm to people (deaths, injuries, and illnesses) and to property (including potential business interruption or other interference with mission continuity), cultural or historical value damage, and environmental damage. Direct and indirect perils causing harm are both of interest. Fire, burns, and electric shock; falls; natural disasters; water or storms; and harmful environments are the main types of peril causing harm in the built environment.

Fire is as a rapid, persistent, chemical reaction that releases heat and light.[11] In the built environment, fire is combined with explosions, electric shock, scalds, and other types of burns. The majority of harm to property by fire is from thermal or corrosive effects.

Falls are the most common type of peril causing harm in the built environment and include injuries caused by the fall and injuries due to objects falling on other people. Types of falls in the built environment include the following:

- Falls from or on stairs and steps
- Falls from or on ladders or scaffolding
- Falls out of structures
- Falls from one level to another
- Falling objects

Falling objects may be a direct result of structural collapse caused by another type of peril harming the built environment.

TABLE 1.1.1 Typology of Types of Peril Causing Harm to People and Property in the Built Environment

Peril Causing Harm	*Harm to People*	*Harm to Property**
Fire, burns, and electrical shock	Burns from fire, hot surfaces, steam, or other hot objects Electrical shock Injury from structural failure resulting from fire Explosions Injury from inhaled toxic products Injury from oxygen deprivation resulting from fire	Direct harm from thermal or corrosive effects of fire Damage from structural failure resulting from fire
Falls	Injuries due to fall Injuries due to objects falling on people	Structural collapse
Natural disasters (e.g., earthquakes, landslides, hurricanes, tornadoes)	Injury from structural failure resulting from natural disaster Fire injuries Injuries due to falling objects or objects in motion Fall injuries Postevent harmful environment (e.g., disease, exposure) Postevent electrical shock	Damage from structural failure resulting from natural disaster Fire Wind and water damage
Water (e.g., floods, storms)	Injuries due to falling objects or objects in motion Drowning Postevent electrical shock Postevent harmful environment	Damage due to wind, water, or storm loads (e.g., snow or hail) Flooding Water damage
Harmful environment	Poisoning by solid, liquid, or gas Mechanical suffocation Water-borne or airborne disease Adverse health effects of excessive heat or cold, insufficient or poor lighting, excessive noise or vibration, or radiation exposure (e.g., radon)	Corrosive or other damaging effects of moisture Damage due to heat or cold Damage due to noise or vibration Radiation damage

Note: The categories in this table are not taken from any published source and are not in general use. They are proposed only as a basis for organizing the material in this chapter. Some performance issues for the built environment are excluded from this typology, including all issues of amenities and issues of access, such as those addressed by the Americans with Disabilities Act (ADA). Vehicles and outdoor settings not involving structures are excluded from consideration here, even though most of those environments can be regarded as built.

*Includes business interruption, other functionality damage, and damage to heritage.

Natural disasters are created by natural processes and as disasters effect society and the built environment. Earthquakes, hurricanes, and tornadoes all contribute to structural damage and may produce serious types of harm such as fire, electric shock, and fall injuries, all of which can be fatal.

Water from storms and floods has the potential to create major property losses, although most of the deaths in this category are not associated with catastrophic events.

A harmful environment refers to an environment in which people are exposed to harmful substances, such as airborne disease and poisonous gases. The built environment serves as a barrier to protect people from harm. Like people, it is susceptible to any type of peril causing harm. Harmful environments can exist alone or as the result of another type of peril. Sick building syndrome, which can result from mold or release of volatile organic compounds (VOCs) from synthetic materials, may cause illness in some occupants.

The degree of harm depends on exposure and the relative vulnerability of the built environment to a particular peril. Both exposure and vulnerability depend considerably on the location chosen for the structure. Soil type, rainfall, geography, and wind speed are examples of factors contributing to the degree of harm on the built environment.

FIRE, BURNS, AND ELECTRIC SHOCK

This chapter will provide a few fire statistics in context with other hazards, with nonfire-thermal-related injuries addressed at greater length, because the fire loss experience including magnitudes, trends, and patterns is extensively discussed in Section 3, Chapter 1, "An Overview of the Fire Problem and Fire Protection."

Fire Losses and Injuries

Tables 1.1.2 and 1.1.3 provide overviews of U.S. fire deaths and related property damage, respectively. Table 1.1.2 compares fire deaths as estimated by the NFPA survey with those recorded by the primary fire-related X-codes in the national death certificate database. Table 1.1.3 excludes transportation and vehicle-related fires, which is why those statistics track more closely with NFPA survey data on structure fires alone and are also provided in Table 1.1.2. Death certificate counts from these X-codes can also exclude some incendiary fire deaths but should do so only if the fatal injury was itself known to have been intended, in which case it qualifies as a homicide or suicide and is classified there for primary categorization. It appears that few such fire deaths are so classified.

The NFPA survey can miss deaths occurring outside a reported fire. Clothing ignitions are the classic example, but the death certificate database tracks clothing ignition deaths separately, and such deaths total less than 200 per year, some of which will be reported to fire departments. The NFPA survey is also subject to some sampling variation. The estimate of total fire deaths, for example, is subject to a 95 percent confidence interval of plus or minus just under 400 deaths, which is a more typical difference between the structure fire death estimate and the death certificate tally.

TABLE 1.1.2 Tracking U.S. Fire Deaths Based on NFPA Survey

Year	*Total*	*Structure Fire Only*	*Based on Death Certificate Coding X00–X09 Only*
1993	4,635	3,980	3,914
1994	4,275	3,590	3,999
1995	4,585	3,985	3,768
1996	4,990	4,220	3,748
1997	4,050	3,510	3,502
1998	4,035	3,420	3,263
1999	3,570	3,040	3,348
2000	4,045	3,535	3,377
2001*	6,196	5,671	3,309
2002	3,380	2,775	3,159

*2,451 of these deaths occurred due to the events of 9/11/01.

Source: NFPA survey, National Safety Council (NSC), and National Center for Health Statistics (NCHS) Vital Statistics System provided data for the number of deaths.

TABLE 1.1.3 Tracking U.S. Property Loss to Fire

Year	*Based on NFPA Survey (in Billions of Dollars)*	*Estimated by Insurance Services Office (in Billions of Dollars)*
1993	8.546	11.331
1994	8.151	12.778
1995	8.918	11.887
1996	9.406	12.544
1997	8.525	12.940
1998	8.629	11.510
1999	10.024	12.428
2000	11.207	13.457
2001	44.023	17.118
2002	10.337	17.586

Note: NFPA survey figures are estimates by fire officers, sometimes with the benefit of information on insurance estimates. ISO estimates include actual home insurance claims and estimates and losses in uninsured or underinsured properties.

Sources: NFPA survey; Insurance Information Institute, *The I.I.I. Insurance Fact Book 2006,* New York: Insurance Information Institute, 2006.

Similarly, there are a number of possible reasons for the modest but growing gap between the NFPA estimates of direct property damage and the Insurance Services Office estimates of fire loss, as shown in Table 1.1.3. The insurance industry estimate may include indirect losses (e.g., reimbursement for temporary housing or business interruption) and may overadjust for losses in uninsured or underinsured properties. The fire department–based NFPA estimate will miss losses in unreported fires even if they result in insurance claims. The insurance industry estimate is a mix of detailed observations by highly trained loss appraisers and self-reported losses as adjusted in response

to comments from appraisers who have not personally observed the fire scene. It is hard to say whether such estimates will be higher or lower, more or less accurate, than estimates by fire officers, who lack the same loss-estimation training but sometimes have access to insurance appraisals of the same fires and experience in other occupations, which give them the insight into what things cost.

Although the NFPA survey estimates are the best measures of fire loss, when fire is considered by itself, the available statistics on other hazards and types of harm are most comparable to the death certificate data and the insurance industry estimates for fire.

Burns and Electric Shock

Table 1.1.4 provides available information on total U.S. burn injuries, based on in-home surveys conducted by the U.S. Department of Health and Human Services. The samples are sufficiently small that the estimates of burn injuries are subject to considerable uncertainty. (For example, the estimate of a quarter million bed-disabling burn injuries per year in or during 1980 to 1981 is subject to relative error of more than 30%.) This uncertainty is also the reason why published analyses of the survey data do not always address burns and, when they do, use 2- or 3-year averages to reduce error to an acceptable level. The principal finding of Table 1.1.4 is that total U.S. burn injuries declined from roughly 2 million in 1980 to 1981 (and for at least two decades) to roughly 1 million in 1991 to 1993.

Table 1.1.5 provides a 10-year trend on pressure vessel explosions. Explosions involving pressurized tires, pipes, or hoses make up the largest share of fatal injuries, whereas boiler injuries make up the smallest share. Note that gas cylinders are a category under pressure vessels. This can point to a rough separation of natural gas (excluding pressure vessels) and LP-gas (gas cylinder explosion), although each of these is part of a category that can include other various situations and gases. Within the "explosion of other specified pressurized device" there is a roughly even split that tilts somewhat toward the unknowns.

Table 1.1.6 provides a 10-year trend on deaths due to injuries from hot objects. Figure 1.1.1 indicates 67 percent of those fatal injuries involve hot tap water, drinks, food, fats, or cooking oil, whereas 22 percent of those fatal injuries are caused by steam or other hot liquid or vapor. Figure 1.1.2 provides an overview of the death rates per million population by age-group for deaths due to injury by steam or other hot liquid or vapor. These rates are a measure of the differences in risk of death from this type of harm for different age-groups. As with fire deaths, the very young and older adults are the two high-risk age-groups, but unlike fire, the very young are not that much more at risk

TABLE 1.1.4 U.S. Burn Injuries Based on Responses to National Health Interview (In-Home) Survey

Measure	*1980–1981*	*1985–1987*	*1991–1993*
Burn injuries (per year)	2,130,000	1,735,000	1,129,000
Burn injuries per 100 population (per year)	1.0	0.7	0.4
Medically attended burn injuries	1,615,000	1,614,000	1,073,000
Restricted-activity burn injuries	1,213,000	810,000	445,000
Bed-disability burn injuries	244,000*	399,000	124,000
Average number of days of restricted activity per restricted-activity burn injury	6.1	8.8	NA
Average number of days of bed disability per bed-disability burn injury	5.7	8.1	NA

*Relative standard error of estimate exceeds 30 percent.
NA = Not available or not yet available.

Sources: *Types of Injuries and Impairments Due to Injuries—United States,* Series 10, No. 159, 1986; *Types of Injuries by Selected Characteristics, 1985–87,* Series 10, No. 175, 1990; and advance data from John Gary Collins, U.S. Department of Health and Human Services, author of all analyses shown here.

TABLE 1.1.5 Unintentional Injury Deaths Due to Explosion of Pressure Vessel, Deaths Coded on U.S. Death Certificates

Year	*Total Explosion of Pressure Vessels*	*Explosion of Boiler*	*Explosion of Gas Cylinder*	*Explosion of Pressurized Tire, Pipe, or Hose*	*Explosion of Other Specified Pressurized Device*
1994	30	2	10	15	3
1995	36	2	11	16	7
1996	27	3	6	16	2
1997	33	5	11	15	2
1998	31	2	5	22	2
1999	33	6	6	14	7
2000	30	3	8	12	7
2001	38	1	14	12	11
2002	27	5	9	10	3

Source: CDC/NCHS website, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm.

TABLE 1.1.6 Unintentional Injury Deaths Involving Contact with Hot Objects or Substances, 1993–2002

Year	*Total*
1993	130
1994	107
1995	97
1996	104
1997	111
1998	108
1999	123
2000	110
2001	114
2002	102

Note: Involved corrosive substances and steam. Data prior to 1999 listed as Death Certificate Code E924. Post-1999 data listed as Death Certificate Codes X10–X19.

Sources: National Safety Council, *Accident Facts* and *Injury Facts,* Itasca, IL: National Safety Council, 1992–2006; 2002 data from CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

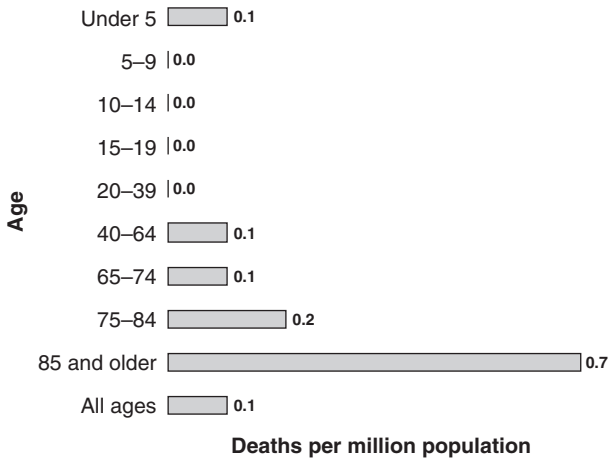

FIGURE 1.1.2 Deaths Due to Steam or Other Hot Liquid or Vapor, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

than the all-ages average, and the older adults have risks much higher than those for the very young.

Table 1.1.7 provides a 10-year trend for the available components of deaths due to unintentional injury by electrical current. The largest share of fatal injuries due to electrical current falls into the "other or unknown" category. This table reflects the revision of the ICD. Home equipment, industrial equipment, and generating plants or distribution categories were discontinued in the tenth revision. However, data from 1999 to 2002 also demonstrate that the largest share of fatal injuries falls into the "other specified" category.

According to data prior to 1999, injuries involving home or industrial equipment have been declining substantially. Those involving generating plants or distribution equipment have not. As a result, deaths from electric current associated with generating plants or distribution now routinely outnumber those associated with home equipment by a large margin.

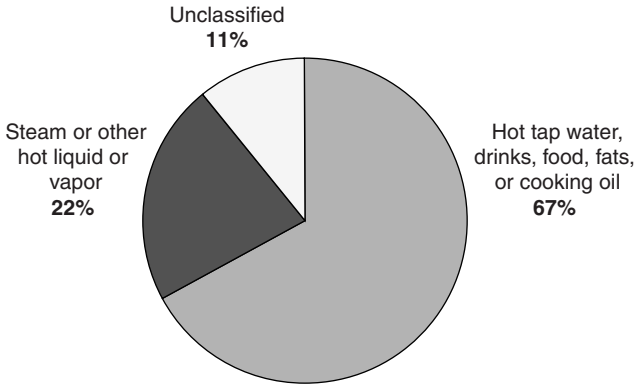

FIGURE 1.1.1 Deaths Due to Hot Object, by Type of Object, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

FALLS

Falling People

Falls account for by far the largest number of fatal injuries among all the types of injuries that can occur in the built environment. Table 1.1.8 provides 10 years of data pertaining to deaths due to falls for the major types of falls. The "other or unknown-type" category contains the largest share of deaths, whereas the category for falls on the same level from collision, pushing, or shoving has the smallest share of deaths. Nearly half of these types of falls occur in sports and the rest involve other or unknown-type activities.

Falls from or on Stairs or Steps. Note that deaths due to falls from or on stairs or steps—the major category of falls most clearly linked to the design of the built environment—have been increasing over the period analyzed and are up by about 20 percent in the most recent decade analyzed. This is a larger increase than can be explained by the growth in total population, but it might be better explained by an age-adjusted analysis, which would factor in not only the growth in the total population but also the growth in the older-adult share of the population.

Figure 1.1.3 provides an overview of deaths per million population, by age, for fatal falls from or on stairs or steps. The risk is negligible for children, even children under age 5, but rises rapidly among older adults. Half of all deaths from falls from or on stairs or steps are people age 75 and older. This risk for adults age 85 or older is roughly 14 times the all-ages risk and 65 times the risk for younger adults.

Falls from or on Ladders or Scaffolding. Table 1.1.9 shows the total number of falls on or from ladders or scaffolding, as

TABLE 1.1.7 Unintentional Injury Deaths by Electrical Current, Deaths Coded on U.S. Death Certificates

Year	Lightning*	Total Electric Current	Home Equipment	Industrial Equipment	Generating Plants or Distribution	Other or Unknown
1993	57	548	82	46	142	278
1994	84	561	84	42	144	291
1995	76	559	88	26	158	287
1996	63	482	66	15	135	266
1997	68	488	53	27	139	269
1998	63	548	59	27	144	318

Year	Lightning*	Total Electric Current	Electric Transmission Lines	Other Specified
1999	64	437	127	310
2000	50	395	99	296
2001	44	405	83	326
2002	66	431	109	322

*Not included in total.

Source: John R. Hall, Jr., *Burns and Toxic Gases in Non-Fire Situations,* National Fire Protection Association, 2005; National Safety Council, *Injury Facts,* 2005–2006 edition, Itasca, IL: National Safety Council, 2006.

TABLE 1.1.8 Unintentional Injury Deaths Due to Falls, Deaths Coded on U.S. Death Certificates

Year	Total	Falls on or from Stairs or Steps	Falls on or from Ladders and Scaffolding	Falls from out of Building or Structure	Falls into Holes or Other Openings in Surface	Other Falls from One Level to Another	Falls on Same Level from Slipping, Tripping, or Stumbling	Falls on Same Level from Collision, Pushing, or Shoving	Other Unknown-Type Falls
1993	13,141	1,087	301	509	107	1,156	520	9	9,452
1994	13,450	1,163	327	477	93	1,066	600	4	9,920
1995	13,986	1,241	352	467	94	1,145	491	8	10,188
1996	14,986	1,239	369	444	88	1,129	688	3	11,026
1997	15,447	1,295	368	549	70	1,106	726	4	11,329
1998	16,274	1,389	352	550	95	1,187	740	6	11,955
1999	11,331	1,421	375	550	NA	552	611	15	7,807
2000	10,419	1,307	412	506	NA	476	565	7	7,146
2001	11,322	1,462	439	580	NA	595	564	22	7,660
2002	11,382	1,598	406	557	NA	509	646	12	7,654

Source: National Safety Council, *Injury Facts* and *Accident Facts,* Itasca, IL: National Safety Council, 1992–2002; 2002 statistics from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

well as both components. Falls on or from ladders contains the largest share of fatal injuries. Falls involving ladders dominate by 4 to 1. Figure 1.1.4 provides an overview of deaths per million population for fatal falls from or onto ladders, by age of victim. The risk is highest by far for older adults. A majority (55%) of the deaths are adults age 65 or older.

Falls out of Structures. Figure 1.1.5 provides an overview of deaths per million population for fatal falls out of a building or structure, by age of victim. There has been considerable publicity surrounding preschool children falling out of buildings, resulting in a recent push for bars on windows, which, if installed incorrectly, can become a deadly barrier preventing safe escape from a fire in the building. However, as with every type of fatal fall examined so far, the higher risks are faced by older adults. The risk for adults age 85 and over is five times the all-ages risk.

Falls from One Level to Another. Table 1.1.10 provides a breakdown of the different types of fatal falls from one level to another. Falls from playground equipment are a negligible share of the total. Falls from cliffs are an important component

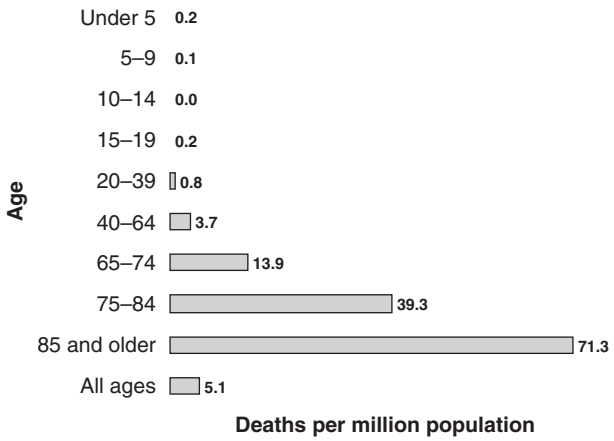

FIGURE 1.1.3 Deaths Due to Falls on or from Stairs or Steps, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

but one that has been declining sharply. Falls from chairs or beds compose the largest share of fatal falls from one level to another, and those deaths have not been declining.

Figure 1.1.6 shows that differences in this risk by age are the largest yet seen in this chapter. Adults age 85 or older have more than 30 times the all-ages risk of suffering a fatal fall from a chair or bed. This age group accounted for roughly half (49%) of all deaths from this type of fall. Young children have a higher risk than older children but much less risk than older adults.

The category of "other" falls from one level to another shows a very different profile than that for falls from chairs and beds. The age profile more closely resembles that for deaths due to falls involving cliffs, which means it would be inappropriate and possibly misleading to treat these underspecified falls as if

TABLE 1.1.9 Unintentional Injury Deaths Due to Falls from Ladders Versus Scaffolding, Deaths Coded on U.S. Death Certificates

Year	*Total Falls on or from Ladders or Scaffolding*	*Falls on or from Ladders*	*Falls on or from Scaffolding*
1994	327	268	59
1995	352	294	58
1996	369	299	70
1997	368	301	67
1998	352	284	68
1999	375	320	55
2000	412	355	57
2001	439	376	63
2002	406	360	46

Sources: National Safety Council, *Accident Facts* and *Injury Facts,* 1992–2004 editions, Itasca, IL: National Safety Council, 1992–2004; 2002 data from CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

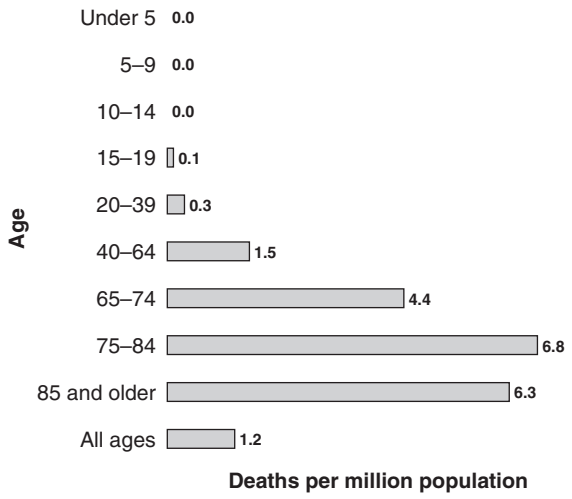

FIGURE 1.1.4 Deaths Due to Falls on or from Ladders, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

they were similar to falls from chairs and beds. The age profile for these falls looks more like one might expect from falls off roofs, but it seems unlikely that this specific scenario would account for such a large death toll.

Nonfatal Falls. Table 1.1.11 illustrates the number of nonfatal falls based on responses to the government's in-home survey of health problems. The nonfatal fall injuries in Table 1.1.11 outnumber the fatal fall injuries in Table 1.1.8 by nearly a thousand to one. The relative importance of various types of falls is different, reflecting in part the fact that some types of falls—for example, from stairs or steps, or out of a building structure—are more likely to be fatal than some other types of falls.

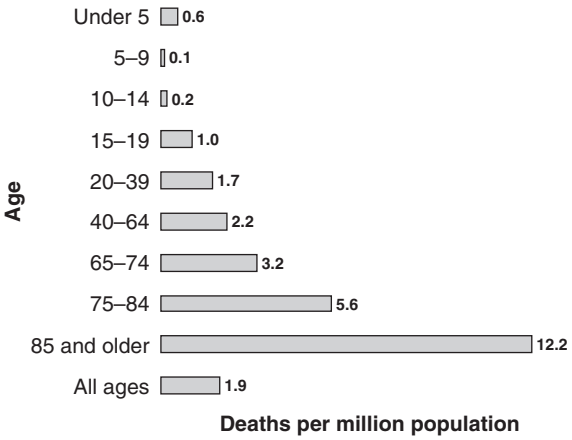

FIGURE 1.1.5 Deaths Due to Falls out of Building or Structure, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

TABLE 1.1.10 Unintentional Injury Deaths Due to Fall from One Level to Another, Deaths Coded on U.S. Death Certificates

Year	*Total Other Falls from One Level to Another*	*Falls from Playground Equipment*	*Falls from Cliffs*	*Falls from Chairs or Beds*	*Other Falls from One Level to Another*
1994	1066	4	107	429	526
1995	1145	2	113	516	514
1996	1129	3	91	485	550
1997	1106	6	64	501	535
1998	887	2	63	208	614
1999	1617	4	83	978	552
2000	1170	0	82	612	476
2001	1358	4	62	697	595
2002	1344	3	80	752	509

Sources: National Safety Council, *Accident Facts* and *Injury Facts,* 1992–2004 editions, Itasca, IL: National Safety Council, 1992–2004; 2002 data from CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

International Perspective on Falls. Table 1.1.12 illustrates the unintentional injury death rates due to falls at the international level. The table shows the averages of available 2000–2002 fatal fall rates for different countries. Unlike the case with fire deaths, the U.S. rate of fall deaths per million population is one of the lowest; Argentina has the lowest rate among all the countries listed.

An analysis of the international differences would need to begin with an examination of differences in age distributions, which could make a large difference in light of the enormous differences in risk of death from falls among age groups. Also, it would be useful to know how much variation in heights of surfaces normally encountered by people exists from place to place. Certainly, high-rise buildings are more common in some countries than others, but it is unlikely that this is a major factor in the overall statistics. Other differences, such as the average heights of beds or sleeping surfaces (e.g., futons), might exist, however, and might be important. Differences in contributing risk factors, such as the use of alcohol, could be important. And the possibility of differences in definitions used in practice or in data collection should also be considered.

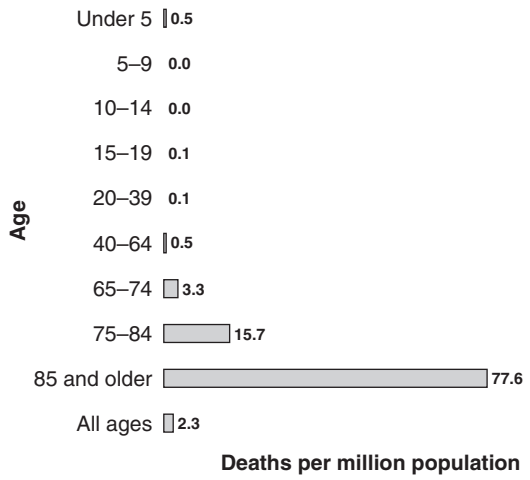

FIGURE 1.1.6 Deaths from Falls from Chairs or Beds, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

Falling Objects

Deaths due to falling objects are the kinds of deaths that might include a significant share that can be related to the design and operating decisions of the built environment. Unfortunately, the coding provides no details on the kinds of falling objects involved. Whatever the objects may be, the toll from objects has

TABLE 1.1.11 U.S. Nonfatal Fall Injuries Based on Responses to National Health Interview (In-Home) Survey

Type of Fall	*Estimated 1997 Injuries*
Total fall episodes	11,306,000
Total types of falls mentioned*	12,285,000
Onto floor or level ground	4,158,000
From or onto stairs or steps	1,296,000
From or onto curb or sidewalk	1,162,000
From or onto chair, bed, sofa, or other furniture	807,000
From or onto playground equipment	493,000
From ladder or scaffolding	447,000
Into hole or other opening	382,000
From or onto escalator, building or other structure, tree, toilet, bathtub, or pool	610,000
Unreported type	2,793,000
Refused to give type or did not know	135,000

Note: Sum may not equal total because of rounding error.
*More fall types are mentioned than there were fall episodes because respondents could specify up to two types.
Source: Centers for Disease Control and Prevention report, *Injury and Poisoning Episodes and Conditions: National Health Survey, 1997,* Series 10, No. 202, Table 3, p. 19, July 2000.

TABLE 1.1.12 Rates per Thousand Population of Unintentional Injury Deaths Due to Falls (Average of Latest Available 2000–2002 Rates)

Country	*Average Death Rate Due to Falls*
North America	
Canada	51
United States	47
Mexico	23
South America	
Chile	19
Argentina	8
Asia/Pacific	
New Zealand	65
Japan	50
Australia	32
Europe	
Hungary	312
Finland	216
Norway	195
Italy	183
Czech Republic	178
Slovenia	149
Croatia	139
Austria	121
Russia	104
Ireland	98
Poland	97
France	90
Sweden	61
Portugal	60
Netherlands	55
United Kingdom	55
Greece	53
Spain	37
Bulgaria	36

Note: Listings are limited to countries with the latest rates available (2000–2002).

Source: National Safety Council, *Injury Facts,* 2005–2006 edition, Itasca, IL: National Safety Council, 2006.

shown little decline. Table 1.1.13 illustrates the number of fatal injuries caused by falling objects.

Striking or Being Struck by Falling Objects

Within the category of people striking against or being struck by objects, it is possible to distinguish deaths due to people striking other people in a crowd, as in a hurried or rushed evacuation or when a crowd presses someone against a stationary barrier. Instances that might fit within this category might also be coded somewhere else. A good example would be a crowd-crushing situation that would be considered not to fit the "struck by" label.

Table 1.1.14 provides a breakdown of 2004 occupational injuries and illnesses by event or exposure, overall and for each of three groups of objects that are entirely or mostly recognizable as components of the built environment—floors, walkways, and ground surfaces; furniture and fixtures; and machinery.

TABLE 1.1.13 Other Deaths Due to Objects in Motion, Deaths Coded on U.S. Death Certificates

Year	*Due to Cataclysmic Earth Movement or Eruption*	*Struck by Falling Object*	*Struck by People or Against Object*
1993	17	714	187
1994	46	739	207
1995	25	656	198
1996	42	732	171
1997	20	727	247
1998	24	723	336
1999	46	701	131
2000	36	712	146
2001	28	707	135
2002	31	721	127

Sources: National Safety Council, *Injury Facts* and *Accident Facts,* 1992–2004 editions, Itasca, IL: National Safety Council, 1992–2004; 2002 data from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

NATURAL DISASTERS

Earthquakes

An earthquake is the vibration of the Earth's surface by the rapid release of energy. Most earthquakes are caused by slippage along a geologic fault in the Earth's crust.[12] The energy released during an earthquake is measured by the Richter scale (Table 1.1.15). Each unit of Richter magnitude equates to roughly a 32-fold energy increase. With each increase in magnitude comes the increased probability for loss of life and property damage. Earthquakes include many of the deadliest and costliest incidents in history.[13] Approximately 6200 earthquakes detectable by human beings occur every year.

Deadliest U.S. Earthquakes. Table 1.1.16 lists the 10 deadliest U.S. earthquakes of all time, leading with the 1906 San Francisco earthquake, which caused the costliest U.S. fire of all time. Six out of the 10 earthquakes occurred in California, and two others were offshore earthquakes near Alaska that produced tsunamis that resulted in the deaths of many. Since earthquakes have the ability to produce major postevent disasters such as fire, tsunamis, flooding, and landslides, these events could be listed as a multiperil incident. Reliable death tolls are hard to come by for older events, and property loss totals are even rarer, regardless of reliability. Therefore, it is possible that some of these incidents do not belong on the lists and other events, no longer even cited in general references, do belong.

Table 1.1.17 lists the 10 deadliest world earthquakes of all time, with the top earthquake occurring in China. This earthquake resulted in 830,000 estimated deaths and is possibly the greatest natural disaster of all time. The following earthquakes are estimated to have resulted in over 100,000 deaths each.

TABLE 1.1.14 Nonfatal Private-Industry Occupational Injuries or Illnesses Involving Days Away from Work, by Event or Exposure, and by Selected Objects Providing Source of Injury or Illness

	2004 Injuries and Illness per 10,000 Full-Time Workers			
Event or Exposure	*Total*	*Floors, Walkways, or Ground Surfaces*	*Furniture or Fixtures*	*Machinery*
Contact with objects or equipment	**37.6**	**0.8**	**2.2**	**6.2**
Struck against object	9.4	0.6	1.0	1.5
Falling object	6.9	0	0.7	0.4
Flying object	2.1	0	0	0.1
Swinging or slipping object	6.4	—	0.1	0.3
Rolling or sliding object	0.6	0	0	0.2
Unclassified or unknown type	0.8	—	—	0.1
Caught in or compressed by equipment or objects	6.2	0	0.2	3.1
Caught in or crushed in collapsing materials	0	0	—	—
Excavation or cave-in	0	0	—	—
Collapsing structure	0	—	—	—
Unclassified or unknown type	0.4	—	0	0.1
Rubbed or abraded by friction or pressure	1.7	0.1	0	0
Rubbed, abraded, or jarred by vibration	0.2	0	0	0.1
Unclassified or unknown type	0	—	—	—
Falls	**28.7**	**24.8**	**0.5**	**0.3**
Fall to lower level	9.0	7.9	0	0
Down stairs or steps	2.1	2.0	—	—
From floor, deck, or ground level	0.5	0.4	—	—
Through existing floor opening	0.1	0.1	—	—
Through floor surface	0.1	0.1	—	—
From loading dock	0.1	0.1	—	—
From ground level to lower level	0.1	0.1	—	—
Unclassified or unknown type	0.3	0.2	0	—
From ladder	2.5	2.1	—	0
From piled or stacked material	0.1	0.1	—	—
From roof	0.3	0.2	—	—
Through existing roof opening	0	0	—	—
Through roof surface	0	0	—	—
Through skylight	0	—	—	—
From roof edge	0.1	0.1	—	—
Unclassified or unknown type	0.1	0.1	—	—
From scaffold or staging	0.4	0.3	—	—
From building girders or other structural steel	0	0	—	—
From nonmoving vehicle	1.7	1.5	0	0
Jump to lower level	0.6	0.5	0	0
Fall on same level	18.7	16.2	0.4	0.3
To floor, walkway, or other surface	15.8	15.8	—	—
Onto or against objects	2.4	0	0.4	0.3
Unspecified or unknown type	0.3	0.2	0	0
Bodily reaction or exertion	**57.4**	**0.6**	**2.2**	**2.1**
Bodily reaction—slip, trip, or loss of balance without fall	4.2	0.3	0	0
Exposure to harmful substances or environments	**5.9**	**—**	**0**	**0.4**
Contact with electrical current	0.3	—	0	0.1
Of appliance, tool, or other equipment	0.1	—	0	0.1
Of wiring transformer or other electrical distribution equipment	0.1	—	—	—
Of overhead power lines	0	—	—	—
Of underground or buried power lines	—	—	—	—
From lightning	0	—	—	—
Unspecified or unknown type	0	—	—	—
Contact with temperature extremes	2.1	—	0	0.3
Hot objects	1.9	—	0	0.3

TABLE 1.1.14 Continued

Event or Exposure	2004 Injuries and Illness per 10,000 Full-Time Workers			
	Total	*Floors, Walkways, or Ground Surfaces*	*Furniture or Fixtures*	*Machinery*
Exposure to air pressure changes	0	—	—	—
Exposure to caustic, noxious, or allergenic substances	3.0	—	0	0
Exposure to noise	0	—	—	—
Exposure to radiation	0.2	—	—	0
Welding light	0.2	—	—	0
Unclassified or unknown type	—	—	—	—
Exposure to traumatic or stressful event	0.2	—	—	—
Unclassified or unknown type	—	—	—	—
Transportation incidents	**7.1**	**0**	**—**	**0.2**
Fires or explosions	**0.3**	**—**	**0**	**0**
Assault or violent act	**2.8**	**0**	**0**	**—**
Unclassified or unknown type	**1.5**	**0**	**0**	**0**

Note: Sums may not equal totals due to rounding error.
Source: Table R36, Case and Demographic Resources Tables, from http://www.osha.gov/oshstats.

TABLE 1.1.15 Richter Scale Magnitude

Richter Magnitudes	*Effects*	*Estimated Number per Year*
<2.0	Generally felt but not recorded	600,000
2.0–2.9	Potentially perceptible	300,000
3.0–3.9	Felt by some	49,000
4.0–4.9	Felt by most	6,200
5.0–5.9	Damaging shocks	800
6.0–6.9	Destructive in populous regions	266
7.0–7.9	Major earthquakes; inflict serious damage	18
8.0 and above	Great earthquakes; destroy entire communities	1.4

Source: Edward J. Tarbuck and Frederick K. Lutgens, *Earth Science,* eleventh edition. Upper Saddle River, NJ: Pearson Education Inc., 2006.

Costliest U.S. Earthquakes. Table 1.1.18 lists the 10 costliest U.S. earthquakes of all time, based on adjustment to 2004 dollars. The 1994 Northridge, California, earthquake and the 1989 Loma Prieta earthquake lead the list by a substantial margin, with the 1964 Anchorage, Alaska, earthquake ranking third. All but one of the costliest earthquakes occurred in California.

Landslides

Landslides are the downslope movement of rock and soil under the influence of gravity.[12] All material resting on a slope is considered to have an angle of repose, that is, an angle at which the material will remain stable.[13] Gravity is the controlling force of landslides, but several factors play an important role in creating downslope movement.

Factors Triggering Landslides. Landslides are sometimes triggered when periods of heavy rains or periods of snowmelt saturate surface materials. Oversteepening of slopes is another important trigger of landslides, whereas removal of vegetation allows for the enhancement of landslides. If the slopes are steep and water is plentiful, a landslide can easily occur.[12] Landslides commonly occur in connection with other major natural disasters such as earthquakes, wildfires, and floods.[14]

Landslides constitute a major geologic hazard because they cause $1–$2 billion in damages and more than 25 fatalities each year.[14] Landslides pose serious threats to the built environment in many parts of the country. Expansion of urban and recreational developments into hillside areas results in increasing numbers of residential and commercial properties in danger of landslides.

Deadliest Landslides Worldwide. Table 1.1.19 lists the 10 deadliest landslides of all time, six of which were caused by an earthquake. The most recent major landslide occurred in 1990 in Iran. A magnitude 7.7 earthquake shook the nation, triggering major landslides that claimed the lives of over 40,000 people. Two of the landslides making the list were triggered by consecutive days of torrential rains.

Hurricanes, Cyclones, and Tornadoes

A hurricane is a tropical cyclonic storm having winds in excess of 74 miles per hour. Hurricanes most often develop in late summer when water temperatures have reached 80°F or higher and, thus, are able to provide the necessary heat and moisture to the air. Based on the study of past hurricanes, the Saffir-Simpson

TABLE 1.1.16 Deadliest U.S. Earthquakes of All Time

Location	Richter Scale Magnitude	Year	Estimated Deaths	Comments
1. San Francisco, CA	7.7	1906	~3000	Fires caused extensive damage and deaths
2. Unimak Island, AK	8.1	1946	165	Tsunami: 159 Hawaii, 5 Alaska, 1 California
3. Prince William Sound, AK	9.2	1964	131	Tsunami: 98 Alaska, 11 California, 1 Oregon
4. Long Beach, CA	6.2	1933	115	Property damage estimated at $40 million
5. Ka'u District, Island of Hawaii	7.9	1868	77	Tsunami, landslide; largest earthquake in HI
6. San Fernando, CA	6.6	1971	65	Property damage estimated at $505 million
7. Loma Prieta, CA	6.9	1989	63	Estimated $6 billion in property damage
8. Northridge, CA	6.8	1994	61	Damages in excess of $40 billion
9. Charleston, SC	6.6	1886	60	Greatest historical earthquake in eastern United States
10. San Juan Capistrano, CA	7.5	1812	40	Damage estimate unknown

Sources: United States Geological Survey, Earthquake Hazards Program, http://www.usgs.gov; Frederick K. Lutgens and E. J. Tarbuck, *Earth Science,* eleventh edition, Upper Saddle River, NJ: Pearson Prentice Hall, 2006; "Earthquakes," *The 2006 World Almanac and Book of Facts,* New York: World Almanac Education Group, Inc., 2006.

TABLE 1.1.17 World's Deadliest Earthquakes on Record

Location	Richter Scale Magnitude	Year	Estimated Deaths	Comments
1. Shensi, China	~8.0	1556	830,000	Possibly the greatest natural disaster
2. Sumatra, Indonesia	9.0	2004	283,106	Deaths from earthquake and tsunami
3. Tangshan, China	7.5	1976	255,000	Deaths estimated as high as 655,000
4. Aleppo, Syria	NA	1138	230,000	
5. Damghan, Iran	NA	856	200,000	
6. Nan-shan, China	7.9	1927	200,000	Large fractures in the Earth's surface
7. Gansu, China	8.6	1920	200,000	Major fractures in surface; mudslides
8. Ardabil, Iran	NA	893	150,000	
9. Kanto, Japan	8.3	1923	143,000	Fire caused extensive destruction
10. USSR	7.3	1948	110,000	

NA = Not available.

Sources: United States Geological Survey, Earthquake Hazards Program, http://www.usgs.gov; Frederick K. Lutgens and E. J. Tarbuck, *Earth Science,* eleventh edition, Upper Saddle River, NJ: Pearson Prentice Hall, 2006; "Earthquakes," *The 2006 World Almanac and Book of Facts,* New York: World Almanac Education Group, Inc., 2006.

scale (Table 1.1.20) was established to rank the relative intensities of hurricanes. Predictions of hurricane severity and damage are expressed in terms of this scale.[12]

Deadliest U.S. Hurricanes. Table 1.1.21 lists the 10 deadliest U.S. hurricanes of all time. Eight of the deadliest hurricanes occurred before the convention of assigning names to hurricanes that began after World War II. Poor record keeping prior to the twentieth century and the fact that some hurricanes wiped out all life on isolated or island communities may mean that some hurricanes with true death tolls high enough to justify inclusion are not recognized as such. This also explains the considerable variation in estimated death tolls for some of these storms from one source to another.

The most recent hurricane to appear on the list of the 10 deadliest is Hurricane Katrina in 2005. Hurricane Katrina struck the Gulf Coast as a strong category 3 hurricane, resulting in severe storm surge damage along the Louisiana, Mississippi, and Alabama coasts and extensive wind damage. Secondary events, including severe urban flooding as a result of failure of parts of the levee system in New Orleans, resulted in over 1300 deaths.[15]

Deadliest Cyclones Worldwide. A *cyclone* (the term includes hurricanes and typhoons) is a low-pressure center characterized by a counterclockwise flow of air in the Northern Hemisphere (and a clockwise flow in the Southern Hemisphere). The terms *hurricane* and *typhoon* are regional names, with hurricane being the common choice for cyclones east of North and Central America.[12] Table 1.1.22 lists the five deadliest cyclones of all time. Four of the five occurred on the Indian subcontinent, and the deadliest one of all—the 1970 cyclone in what was then

TABLE 1.1.18 Costliest U.S. Earthquakes of All Time

	Location	Magnitude	Year	Estimated Total Property Damage (in Billions of Dollars)	
				Year of Occurrence	In 2004
1.	Northridge, CA	6.7	1994	13.00–20.00	17.00–25.00
2.	Loma Prieta, CA (San Francisco Bay Area)	6.9	1989	7.00	10.70
3.	Anchorage, AK (tsunami damage)	9.2	1964	0.50	3.10
4.	San Fernando, CA	6.5	1971	0.60	3.10
5.	Southern California (primarily in Los Angeles)	5.9	1987	0.40	0.60
6.	Southern California (Landers, Big Bear)	7.6	1992	0.09	0.10
7.	Northern California coast	7.1	1992	0.07	0.09
8.	Kern County, CA	7.5	1952	0.06	0.43
9.	Long Beach, CA	6.3	1993	0.04	0.58
10.	Central California (Coalinga)	6.4	1983	0.03	0.06

Source: Insurance Information Institute, *The I.I.I. Insurance Fact Book 2006,* New York: Insurance Information Institute, 2006.

TABLE 1.1.19 World's Deadliest Landslides

Rank	Location	Year	Estimated Number of Deaths	Precipitating Event
1	Kansu, China	1920	180,000	Earthquake
2	Western Iran	1990	45,000–50,000	Earthquake
3	Khait, Tadzhikistan	1949	12,000	Earthquake
4	Minatitlan, Mexico	1959	5,000	Earthquake
5	Belluno, Italy	1963	4,000	Earthquake
6	Huascaran, Peru	1962	3,500	
7	Chiavenna, Italy	1618	2,420	
8	Bihar, India	1968	1,000	Heavy rains
9	Chungar, Peru	1971	400–600	Earthquake
10	Rio de Janeiro, Brazil	1966	550	Heavy rains

Sources: James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979; Lee Davis, *Natural Disasters,* New York: Facts on File, 1992; United States Geological Survey Natural Hazards Support System, http://nhss.cr.usgs.gov.

TABLE 1.1.20 Saffir-Simpson Hurricane Scale

Category	Central Pressure (millibars)	Winds (mph)	Storm Surge (ft)	Damage
1	≥980	74–95	4–5	Minimal
2	965–979	96–110	6–8	Moderate
3	945–964	111–130	9–12	Extensive
4	920–944	131–155	13–18	Extreme
5	<920	>155	>18	Catastrophic

Sources: Edward J. Tarbuck and Frederick K. Lutgens, *Earth Science,* eleventh edition, Upper Saddle River, NJ: Pearson Education Inc., 2006; U.S. National Weather Service website, http://www.nhc.noaa.gov/aboutsshs.shtml.

TABLE 1.1.21 Deadliest U.S. Hurricanes of All Time

Rank	*Hurricane*	*Year*	*Category*	*Estimated Deaths*
1	Texas (Galveston)	1900	4	8000
2	Florida (Lake Okeechobee)	1928	4	2500
3	St. Jo, Florida	1841	NA	4000
4	Katrina	2005	3	1300+*
5	Louisiana (Cheniere Caminanda)	1893	4	1000–1400
6	South Carolina/Georgia (Sea Islands)	1893	3	1000–2000
7	Georgia/South Carolina	1881	2	700
8	Florida Keys	1935	5	408
9	Louisiana, Last Island	1856	4	400
10	Audrey	1957	4	390

*Estimated deaths as of 10/05.
NA = Not available.

Sources:
1. James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979.
2. Eric S. Blake et al., 2005, "The Deadliest, Costliest, and Most Intense United States Tropical Cyclones From 1851 to 2004 (and Other Frequently Requested Facts)," NOAA, Technical Memorandum, NWS TPC-4, 48 pp.
3. Lee Davis, *Natural Disasters,* New York: Facts on File, 1992.
4. Tom Ross and Neal Lott, *Billion Dollar U.S. Weather Disasters, 1980–2005,* NOAA, National Climatic Data Center Fact Sheet, 2006, http://www.ncdc.noaa.gov/oa/reports/billionz.html.
5. "Hurricanes," *The 2006 World Almanac and Book of Facts,* New York: World Almanac Education Group, Inc., 2006.

TABLE 1.1.22 World's Deadliest Cyclones of All Time (Includes Hurricanes and Typhoons)

Rank	*Storm*	*Year*	*Estimated Deaths*
1	East Pakistan*	1970	200,000–1,000,000
2A	Bengal, India	1737	300,000
2B	Haiphong, Vietnam	1881	300,000
4	Bangladesh	1991	139,000
5A	Bengal, India	1876	100,000+
5B	Bombay, India	1882	100,000+

*The lack of timely, substantial relief from the government led to the breakaway creation of Bangladesh.

Sources: National Safety Council, *Injury Facts 2000,* Itasca, IL: National Safety Council, 2000; *World Almanac 2006,* New York: World Almanac Education Group, Inc., 2006; James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979; Lee Davis, *Natural Disasters,* New York: Facts on File, 1992.

East Pakistan—triggered the most extreme response to ineffective emergency response in world history, namely, the creation of the breakaway nation of Bangladesh.

Costliest U.S. Hurricanes. Table 1.1.23 lists the 10 costliest U.S. hurricanes of all time. The list is comprised mainly of hurricanes from 2004 and 2005. The 2004 Atlantic hurricane season caused an estimated $22.9 billion in insured losses according to ISO's Property Claim Services unit, the highest amount ever recorded in a single year up to the 2005 season.[9] The 2005 hurricane season was the worst on record, with 26 named storms, 14 of which became hurricanes and more than $46 billion in insured losses, resulting in a record high.[9] The season produced Katrina in August, the most costly hurricane in U.S. history. The losses from Hurricane Katrina doubled the losses of Hurricane Andrew in 1992.

Tornadoes. A tornado is a small, very intensive cyclonic storm with exceedingly high winds. Tornadoes form in association with severe thunderstorms that produce high winds, heavy rainfall, and hail. Their sporadic nature and violent winds cause many deaths each year. One commonly used guide to measure tornado intensity is the Fujita intensity scale (Table 1.1.24). Because tornado winds cannot be directly measured, a rating on the Fujita scale is determined by assessing the worst damage produced by a storm.[12]

Table 1.1.25 lists the number of tornadoes and associated deaths for the past 10 years. Table 1.1.26 lists the 10 deadliest U.S. tornado incidents of all time and in a contiguous region. The three single-tornado incidents on the list all occurred in the nineteenth century.

Tornado incidents rarely produce combined property losses in excess of $1 billion and, possibly for that reason, there were not enough tornado incidents with documented high property losses to justify preparing a list of the 10 costliest tornado incidents.

Water or Storms

Deaths in the water certainly occur as a consequence of a natural disaster. However, most of the deaths in the water or storms group do not involve catastrophic events. They involve drownings or submersions in more everyday situations, typically associated with swimming or diving. Table 1.1.27 provides an overview of these water- and storm-related fatal injuries.

Drownings in bathtubs come closest to involving design options for the built environment. Figure 1.1.7 shows that this

TABLE 1.1.23 Costliest U.S. Hurricanes of All Time

Rank	Hurricane	Category	Location	Year	Estimated Loss (in Billions of Dollars)	
					In Year of Occurrence	*In 2004*
1	Katrina	3	AL, FL, GA, LA, MS, TN	2005	34.40	34.40*
2	Andrew	4	FL, LA, MS	1992	15.50	20.87
3	Charley	4	FL, NC, SC	2004	7.48	7.48
4	Ivan	3	AL, FL, GA, +12 other states	2004	7.11	7.11
5	Hugo	4	U.S Virgin Islands, PR, 4 states	1989	4.20	6.40
6	Wilma	3	FL	2005	6.10	6.10*
7	Rita	3	Gulf Coast	2005	4.70	4.70*
8	Frances	2	FL, GA, SC, NC, NY	2004	4.60	4.60
9	Jeanne	3	PR, FL, PA, GA, SC, NY	2004	3.66	3.66
10	Georges	2	U.S Virgin Islands, PR, 4 states	1998	2.90	3.36

*Expressed in 2005 dollars.

Sources:

1. Insurance Information Institute, *The I.I.I. Insurance Fact Book 2006,* New York: Insurance Information Institute, 2006.
2. Eric S. Blake et al., 2005, "The Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2004 (And Other Frequently Requested Facts)," NOAA, *Technical Memorandum,* NWS TPC-4, 48 pp.
3. Tom Ross and Neal Lott, *Billion Dollar U.S. Weather Disasters, 1980–2005,* NOAA, National Climatic Data Center Fact Sheet, 2006, http://www.ncdc.noaa.gov/oa/reports/billionz.html.

risk targets the very young and very old, much as fire does. Children under age 5 have roughly three times the all-ages risk, a higher relative risk than the same age children have for death from fire. Older adults show a lower relative risk for drowning in bathtubs than they do for death from fire.

Storms

Types of Storms. Storm data collected by the National Weather Service[10] show significant annual averages of damage (including both property and crop damage) in 2000 to 2004 from three types of storms:

- *Hail storms* average $0.97 billion per year
- *Thunderstorms (including wind)* average $0.33 billion per year
- *Winter storms* average $0.52 billion per year

Four other types of storms or storm effects—lightning, coastal storms, tsunamis, and ice storms—are not shown in the preceding list because each type averages much less damage per year in 2000 to 2004 than do the listed types. Clearly, this will not be true of 2005, when losses from the December Asian tsunami are included.

TABLE 1.1.24 Fujita Intensity Scale

Scale	Wind Speed (mph)	Damage
F0	<72	Light damage
F1	72–112	Moderate damage
F2	113–157	Considerable damage
F3	158–206	Severe damage
F4	207–260	Devastating damage
F5	>260	Incredible damage

Source: Edward J. Tarbuck and Frederick K. Lutgens, *Earth Science,* eleventh edition, Upper Saddle River, NJ: Pearson Education Inc., 2006.

TABLE 1.1.25 Tornadoes and Deaths Due to Tornadoes in the United States

Year	Number of Tornadoes	Deaths
1989	856	50
1990	1133	53
1991	1132	39
1992	1297	39
1993	1173	33
1994	1082	69
1995	1234	30
1996	1173	25
1997	1148	67
1998	1424	130
1999	1345	94
2000	1071	40
2001	1216	40
2002	941	55
2003	1376	54
2004	1819	36

Source: U.S. National Weather Service, as cited in Insurance Information Institute, *The I.I.I. Insurance Fact Book 2006,* New York: Insurance Information Institute, 2006.

TABLE 1.1.26 Deadliest Tornado Incidents of All Time

Rank	*Location*	*Number of Tornadoes*	*Dates*	*Estimated Deaths*
1	Southeastern United States	60+	February 19, 1884	800+
2	Illinois, Indiana, and Missouri	8	March 18, 1925	606
3	South Carolina	1	September 10, 1811	500+
4	Alabama, Arkansas, Georgia, Mississippi, North Carolina, and Tennessee	3+	April 4–7, 1936	402
5	Mississippi	1	May 7, 1840	317
6	Alabama, Georgia, Kentucky, Ohio, and Tennessee	148	April 3–4, 1974	307
7	Missouri	1	May 27, 1896	306
8	Illinois, Indiana, Michigan, Ohio, and Wisconsin	37–40	April 11, 1965	272
9	Alabama	20	March 21, 1932	268
10	Arkansas, Missouri, and Tennessee	31	March 21–22, 1952	229

Sources: National Safety Council, *Injury Facts 2000,* Itasca, IL: National Safety Council, 2000; *World Almanac Book of Facts 2006,* New York: World Almanac Education Group, Inc., 2006; James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979; Lee Davis, *Natural Disasters,* New York: Facts on File, 1992; National Oceanic and Atmospheric Administration, Storm Prediction Center, "The 25 Deadliest U.S. Tornadoes," http://www.spc.noaa.gov/faq/tornado/killers.html.

Winter Storms. Available references do not cite a sufficient number of very costly individual winter storms, ice storms, hail, storms, or freezes to generate comparable lists. It also is not clear how much of the reported loss for such storms is relevant to such an assessments of impact on the built environment. For example, crop damage and snow removal costs would not be relevant to such an assessment. Damage due to snow loading is not separately tabulated in any published data, which would be the most relevant form of damage.

It can be noted that the highest U.S. property loss discovered for a winter storm was the 1993 blizzard dubbed the "Storm of the Century," with losses estimated at $3 to $6 billion, including $1.75 billion in insured loss. In the 1990s, however, at least three European winter storms, code named Daria, Lothar, and Vivian, each accounted for at least $4 billion in insured losses. The Storm of the Century also would rank second on a list of the 10 deadliest U.S. winter storms, accounting for an estimated 200 to 270 deaths, second only to an 1888 storm in the Northeast, in which 400 to 800 people were estimated to have died. A 1956 winter storm in Europe had the highest worldwide death toll identified at 1000 killed.

TABLE 1.1.27 Deaths Due to Drownings, Submersions, Storms, or Floods, Deaths Coded on U.S. Death Certificates

Year	*Cataclysmic Storms or Floods**	*Total Drownings and Submersions*	*Drownings in Bathtubs*	*Other or Unknown Type Drowning During Sport or Recreation*	*Drowning or Submersion Including Swimming or Diving Not for Sport or Recreation*
1993	96	3807	306	858	2643
1994	107	3404	301	694	2409
1995	74	3790	281	822	2687
1996	93	3488	330	645	2513
1997	136	3561	329	648	2584
1998	204	3964	337	685	2942
1999	144	3499	290	1467	1742
2000	54	3458	317	1439	1702
2001	89	3250	291	1309	1650
2002	72	3416	321	1134	1961

Note: Excluded from the table are water transport accidents, suicides, homicides, and incidents where it could not be determined whether injury was intentional or unintentional.
*Not included in total drownings and submersions.

Sources: National Safety Council, *Injury Facts and Accident Facts,* Itasca, IL: National Safety Council, 2004; 2002 data from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

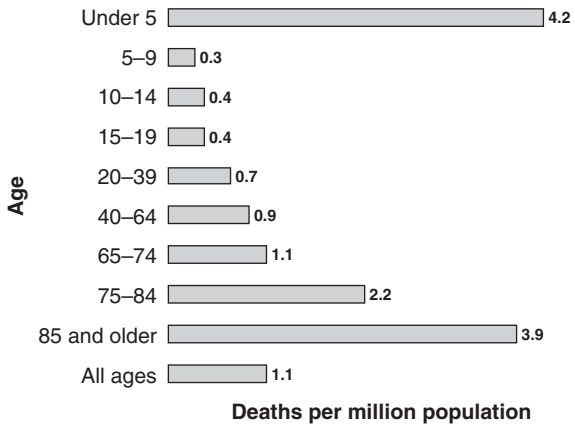

FIGURE 1.1.7 Deaths Due to Drowning in Bathtub, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

Estimating Property Loss from Natural Disasters

Table 1.1.28 represents an attempt to estimate property loss not limited to catastrophes for major sources of such loss. The table is limited to insured loss and to loss covered under homeowner policies. The table combines published data on shares of premium dollars that go toward compensation for losses with published data on the share of losses accounted for by each of several major hazard groups.

The fire and lightning losses in Table 1.1.28 should be comparable to NFPA statistics on property damage to in-home fires, and, in fact, the figures are reasonably close. This encourages optimism that the figures on wind and hail and on water damage and freezing are also comparable.

TABLE 1.1.28 Estimated Insured Property Damage Under Homeowners Multiple-Peril Policies

	Estimated Loss (in Billions of Dollars)		
Year	*Fire, Lightning, and Debris Removal*	*Wind and Hail*	*Water Damage and Freezing*
1994	5.2	2.0	4.7
1995	5.9	4.0	2.9
1996	5.4	5.0	3.6
1997	6.7	3.2	3.1
1998	6.5	6.3	3.3
1999	7.2	5.6	4.4
2000	9.1	4.5	4.9
2001	8.3	5.8	5.9
2002	8.4	5.3	5.6
2003	8.3	6.6	5.7
2004	6.2	13.4	4.6

Source: *The I.I.I. Insurance Fact Book 2003–2006,* New York: Insurance Information Institute, 2003–2006.

It has already been noted that fire losses in individual large loss fires do not dominate total property losses due to fire. In the majority of the years shown in Table 1.1.28, losses due to hurricanes—the large-loss windstorms—would dominate total property damage due to wind and hail. However, losses due to major flood events do not appear to dominate the total water damage and freezing values. In any event, most home insurance policies exclude damage due to major floods from coverage, which is why the Federal Emergency Management Agency's National Flood Insurance Program (NFIP) was created. The plumbing failures and ordinary rainstorms that probably account for most or all of the loss under water damage and freezing should constitute challenges that design for the built environment is meant to address.

Floods

Deadliest U.S. Floods. Table 1.1.29 lists the 10 deadliest U.S. floods of all time. The well-known Johnstown, Pennsylvania, flood of 1889 has by far the highest death toll on the list. The most recent flood to appear on the list was the 1972 Rapid City, South Dakota, flash flood. Like the classic Johnstown flood, a dam collapse was a critical event in the large loss. The other floods primarily involved rising waters swollen by rain and are more in keeping with the use of flood plain maps as a device for quantifying risk by location. Half of the floods on this list involved locations in the Mississippi River valley.

Deadliest Floods Worldwide. Table 1.1.30 lists the five deadliest floods of all time worldwide. All of them occurred in China. Two of the incidents, occurring three centuries apart, were initiated or worsened by deliberate acts in a wartime setting. One involved the destruction of river dikes by rebels, and the other involved flooding crops already ravaged by destruction by troops. In general, lists in this handbook of deadliest or costliest incidents exclude wartime incidents, which would account for many of the deadliest fires and avalanches* of all time, to name just two examples. The exception is made here only because there are so few incidents known to involve death tolls on the scale of incidents in Table 1.1.26 that the alternative to including these incidents would have been to shorten or exclude this list.

Costliest U.S. Floods. Table 1.1.31 lists the 10 costliest U.S. floods of all time. Even though all loss figures have been adjusted for inflation, half of the listed floods are from the last decade of the twentieth century. The costliest incident of all resulted in as much loss as the next two costliest floods combined. Four of the 10 floods involved the Mississippi River valley. The last three floods on the list were due in whole or in part to rivers swollen by melting snow, a scenario that did not contribute to any of the 10 deadliest floods.

Table 1.1.32 provides an overview of death tolls and losses from U.S. floods for the five most recent years available based on the storm data tracking done by the National Weather Service of the U.S. National Oceanic and Atmospheric Administration.

*An avalanche is a type of landslide distinguished by usually rapid movement of a newly detached segment of earth.[12] This definition is useful for *Fire Protection Handbook* Section 3, Chapter 1, "An Overview of the Fire Problem and Fire Protection."

TABLE 1.1.29 Deadliest U.S. Floods of All Time

Rank	*Flood*	*Year*	*Estimated Deaths*
1	Johnstown, PA South Fork dam collapsed	1889	2209
2	Scioto, Mad, Miami, and Muskingum River Valleys, OH, IN, and IL Rain-swollen waters bridged levees	1913	732
3	San Fransicquito Canyon, CA St. Francis dam collapsed	1928	450
4	Ohio and Mississippi River Valleys Rain-swollen waters bridged levees	1937	380
5	Willow Creek, OR Flash flood due to fast, heavy storm	1903	325
6	Mississippi River Valley Rain-swollen waters bridged levees	1927	313
7	Rapid City, SD Flash flood due to heavy rain and dam collapse	1972	236
8	Mississippi River Valley Rain- and snow-melt-swollen waters flooded banks	1874	200–300
9	Mississippi River Valley Snow-melt-swollen waters bridged levees	1912	200–250
10	Kansas City, MO, and Lower Mississippi, Missouri, Kansas and Des Moines River Valleys Rain-swollen waters flooded banks	1903	200

Sources: National Safety Council, *Injury Facts 2000,* Itasca, IL: National Safety Council, 2000; *World Almanac Book of Facts 2006,* New York: World Almanac Education Group, Inc., 2006; James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979; Lee Davis, *Natural Disasters,* New York: Facts on File, 1992.

Flash floods always dominate river floods as causes of death and in most years also dominate as causes of property loss, but the damage caused by river floods in the exceptional years is more than enough to dominate multiyear statistics.

FATALITIES INVOLVING HAZARDOUS ENVIRONMENTS

The broader notion of a hazardous environment is that, as people move about within the built environment, they are exposed in some manner to hazards with the potential to cause harm. An atmosphere contaminated by deadly carbon monoxide is an obvious example. Most other examples of hazardous environments involve hazards that are less pervasive and more avoidable.

Carbon Monoxide and Other Poisonings by Gases and Vapors

Table 1.1.33 gives a 10-year overview of trends in poisonings by gases and vapors. The two major components are motor vehicle exhaust gas and other utility gas or carbon monoxide.

TABLE 1.1.30 World's Deadliest Floods of All Time

Rank	*Flood*	*Year*	*Estimated Deaths*
1	Huang He (Yellow) River, China	1931	3,700,000
2	Huang He (Yellow) River, China	1887	900,000
3	Kaifeng, China Dikes were destroyed by rebels	1642	300,000
4	Northern China Crops flooded and also destroyed by government, causing famine	1939	200,000
5	Chang Jiang (Yangtze) River	1911	100,000–200,000

Sources: National Safety Council, *Injury Facts 2000,* Itasca, IL: National Safety Council, 2000; *World Almanac Book of Facts 2006,* New York: World Almanac Education Group, Inc., 2006; James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979; Lee Davis, *Natural Disasters,* New York: Facts on File, 1992.

TABLE 1.1.31 Costliest U.S. Floods of All Time

Rank	Flood	Year	Estimated Loss (in Billions of Dollars)	
			In Year of Occurrence	*In 2005*
1	Mississippi River Valley Rain-swollen waters bridged levees	1993	15.0–20.0	20.3–27.0
2	Connecticut River Valley Rain-swollen waters were due to Hurricanes Connie and Rita, but without storm surge or wind factors	1955	1.8	13.1
3	Kansas River Basin Rain-swollen waters bridged levees	1951	1.0+	7.5
4	Mississippi and Missouri River Valleys	1947	0.85	7.4
5	Texas, Oklahoma, Louisiana, and Mississippi Flooding with hail and tornadoes caused damage	1995	5.0–6.0	6.4–7.7
6	Willow Creek, OR Flash flood due to fast, heavy storm	1903	0.25–0.33	1.8–2.3
7	Mississippi River Valley Rain-swollen waters flooded banks	1937	0.30+	4.1
8	California Flooding was due to snow melt after blizzard	1996	3.0	3.1
9	Northeast to Mid-Atlantic United States Flooding was due to snow melt after blizzard	1996	3.0	3.1
10	Northwestern United States Snow melt and heavy rain led to flooding	1996–1997	2.0–3.0	2.43–3.65

Sources: National Safety Council, *Injury Facts 2000,* Itasca, IL: National Safety Council, 2000; *World Almanac Book of Facts 2006,* New York: World Almanac Education Group, Inc., 2006; James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979; Lee Davis, *Natural Disasters,* New York: Facts on File, 1992.

Table 1.1.34 provides a five-year trend overview of the latter, for which half the deaths are attributed to carbon monoxide with no other details reported. The two largest components with details known are LP-gas from portable containers, for which deaths appear to be declining, and carbon monoxide from incomplete combustion of domestic fuels, for which no clear trend is apparent.

Tables 1.1.35 and 1.1.36 provide eight-year trends of deaths from carbon monoxide associated with unvented releases from heating and cooking equipment, respectively. Gas-fueled heating equipment dominates these figures, particularly in recent years. Deaths from carbon monoxide from charcoal grills include, and are probably dominated by, deaths from improper indoor use of these grills.

TABLE 1.1.32 Losses Due to Floods According to Storm Data Compiled by U.S. National Weather Service

Year	Deaths				Property Damage (in Billions of Dollars)				
	Total	*Flash Floods*	*River Floods*	*Small Stream or Urban Flood*	*Total*	*Flash Floods*	*River Floods*	*Small Stream or Urban Flood*	*Combined Crop Damage*
1996	131	94	31	6	3.5	1.1	1.0	0.0	0.4
1997	118	86	29	3	7.0	0.9	6.0	0.0	0.1
1998	136	118	14	4	2.6	0.9	1.4	0.0	0.3
1999	68	60	5	3	1.8	1.2	0.2	0.0	0.4
2000	38	30	3	5	1.5	0.8	0.5	0.0	0.2
2001	48	35	11	12	2.6	0.9	0.4	0.0	1.3
2002	49	38	7	4	1.3	0.3	0.3	0.0	0.7
2003	86	67	18	1	5.2	2.1	0.4	0.0	2.7
2004	82	58	24	0	3.7	0.9	0.8	0.0	2.0

Note: Sums may not equal totals because of rounding error.

Source: U.S. National Weather Service Summary of Natural Hazard Statistics for 2000–2004 in the United States.

TABLE 1.1.33 Non-Fire Unintentional Injury Deaths Due to Poisoning by Gases and Vapors, Coded on U.S. Death Certificates

Year	Total	Gas from Pipeline	Motor Vehicle Exhaust Gas	Other Utility Gas or Carbon Monoxide	Other
1993	660	14	245	290	111
1994	685	24	246	307	108
1995	611	27	234	272	78
1996	638	23	219	283	113
1997	576	13	208	251	104
1998	546	15	190	254	87
1999	597 (63)*	—	—	—	—
2000	631 (38)*	—	—	—	—
2001	656 (63)*	—	—	—	—
2002	691 (51)*	—	—	—	—

*Only deaths due to organic solvents and hydrocarbons and their vapors are reported separately after 1998. Their totals are shown in parentheses.

Sources: National Safety Council, *Injury Facts* and *Accident Facts,* Itasca, IL: National Safety Council, 2005–2006; 2002 data from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm; John R. Hall, Jr., *Burns and Toxic Gases in Non-Fire Situations,* National Fire Protection Association, 2005.

TABLE 1.1.34 Non-Fire Unintentional Injury Deaths Due to Utility Gas or Carbon Monoxide, Excluding Motor Vehicle Exhaust Gas and Gas from Pipeline, Deaths Coded on U.S. Death Certificates

Year	Total	LP-Gas from Mobile Container	Carbon Other and Unspecified Utility Gas	Monoxide from Incomplete Combustion of Domestic Fuels	Other Carbon Monoxide	Unknown Type Carbon Monoxide
1994	307	59	11	59	25	153
1995	272	57	13	44	18	140
1996	283	57	18	52	10	146
1997	251	39	25	50	14	123
1998	254	37	11	60	18	128

Source: Statistics from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

TABLE 1.1.35 Unintentional Injury Non-Fire Deaths Due to Carbon Monoxide, by Type of Heating Device, 1993–2002

Year	Central Heating Unit (Furnace) Natural-Gas-Fueled	Water Heater Gas-Fueled	Space Heater or Furnace LP-Gas-Fueled	Any Device Liquid-Fueled[a]	Any Device Solid-Fueled[b]
1993	43	11	83	15	10
1994	64	7	93	12	8
1995	55	5	90	7	8
1996	35	8	99	21	10
1997	61	8	55	12	6
1998	63	8	54	5	5
1999	21	1	25	2	0
2000	41	3	32	6	2
2001	32	0	29	6	6
2002	22	1	50	4	5

Notes: Statistics shown here include proportional allocation of deaths and injuries involving gas-fueled heating equipment with unknown type of equipment for 1993–1997. These allocations do not appear in the source reports.

[a]Principally oil-fueled furnaces and portable kerosene heaters.

[b]Includes coal-fueled furnaces, wood stoves, and fireplaces.

Sources: John R. Hall, Jr., *Burns and Toxic Gases in Non-Fire Situations,* National Fire Protection Association, 2005; 2002 data taken from Debra S. Ascone and Natalie Marcy, *Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products, 2002 Annual Estimates,* July 2005, Table 1. Statistics no longer reported separately for liquid-fueled or solid-fueled heating devices.

TABLE 1.1.36 Unintentional Injury Non-Fire Deaths Due to Carbon Monoxide, by Type of Cooking Device, 1993–2002

Year	Range, Stove, or Oven Gas-Fueled	Grill Charcoal
1993	6	27
1994	9	15
1995	5	14
1996	15	19
1997	5	23
1998	3	16
1999	6	17
2000	11	8
2001	10	12
2002	3	10

Sources: John R. Hall, Jr., *Burns and Toxic Gases in Non-Fire Situations,* National Fire Protection Association, 2005; 2002 data taken from Debra S. Ascone and Natalie Marcy, *Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products, 2002 Annual Estimates,* July 2005, Table 1.

Carbon Monoxide Detectors. In 2002, 29 percent of households had at least one carbon monoxide detector. As had happened at this point per home smoke alarms, usage is higher for affluent households (34% of households with annual incomes of at least $50,000). Unlike smoke alarms, carbon monoxide detectors have been adopted in single-family dwellings (35%) far more than in apartments (17%), modular or manufactured homes (16%), and duplexes and townhouses (21%). Interestingly, carbon monoxide detectors are far more common in houses that use some type of fuel for central heating (38% for gas, 29% for fuel oil) than in homes that use electric power for central heating (13%). It appears that homes with significant potential sources of unvented carbon monoxide are understandably more motivated to obtain carbon monoxide detectors.[16]

For context, Table 1.1.37 provides statistics on suicide deaths due to gas or vapor and on related deaths when it was not determined whether the death was intentional or not. Suicides are far more numerous than unintentional injury deaths by the same mechanism of gas or vapor. Note that all these death tolls have been declining significantly with the possible exception of suicide by gas or vapor other than motor vehicle exhaust.

Poisonings

Table 1.1.38 provides a 10-year overview of other hazardous environment deaths involving specific objects. The first three columns are for poisonings by various solids or liquids. Cleaners and paints are shown separately because that category includes substances that might be encountered in components of the built environment. Fumes from cleaners and flaked-off lead paint are examples. Corrosives and caustics are shown separately because they also have the potential, although probably less than with cleaners and paints, to be encountered after application of substances to components of the built environment.

More often, these substances cause fatal poisonings because they are accessed in stored form and then ingested. The

TABLE 1.1.37 Deaths Due to Poisoning by Gases and Vapors, 1993–2002

Year	Unintentional Injury*	Intentional Injury (Homicide or Suicide)*	Undetermined Whether Unintentional or Deliberate*
1993	660	2092	107
1994	685	2044	84
1995	611	2095	107
1996	638	2007	118
1997	576	1918	77
1998	546	1726	82
1999	597 (63)	1618 (64)	89 (9)
2000	631 (38)	1521 (65)	87 (12)
2001	656 (63)	1519 (61)	89 (10)
2002	691 (51)	1485 (51)	85 (14)

Notes: Prior to 1999, suicides were distinguished by motor vehicle exhaust versus other gas. In the early 1980s, motor vehicle exhaust suicides outnumbered suicides by other gases by nearly 5 to 1. In the late 1990s, the ratio had declined to only 3 to 1.

*Beginning in 1999, only organic solvents and halogenated hydrocarbons and their vapors are distinguishable, and their totals are shown in parentheses.

Sources: John R. Hall, Jr., *Burns and Toxic Gases in Non-Fire Situations,* National Fire Protection Association, 2005; National Safety Council, *Injury Facts and Accident Facts,* Itasca, IL: National Safety Council, 2005–2006; 2002 data from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

separately listed cleaners, paints, corrosives, and caustics are a very small part of the overall category of poisonings by solids and liquids, as the third column demonstrates. Most of this category consists of alcohol products.

Machinery and Instruments

The fourth column of Table 1.1.38 tabulates deaths occurring when someone is caught in or between two objects. The fifth tabulates deaths involving machinery, more than half of which involve agricultural machinery, pointing to the high risks involved in farming. The sixth column tabulates deaths caused by cutting or piercing instruments and objects.

Almost none of the deaths shown in Table 1.1.38 can be said to arise from hazards of the built environment. However, there may be significant indirect effects. Specifically, the design of the built environment may make access to hazardous products, by small children or other people with reduced capacity to make sound risk judgments, more or less difficult. The design, through ergonomics or a lack thereof, may make interaction with machinery or other large objects more or less likely to cause injury. More likely, Table 1.1.38 is relevant in setting priorities and tracking progress for more general safety programs as opposed to choices involving the built environment.

Suffocation

The same is true of Table 1.1.39, which provides a 10-year overview of deaths due to suffocation or inhaling foreign objects.

TABLE 1.1.38 Other Hazardous Environment Deaths, Deaths Coded on U.S. Death Certificates

Year	Poisoning by Cleaner or Paint	Poisoning by Corrosive or Caustic	Other and Unknown-Type Poisoning by Solids or Liquids[a]	Caught in or Between Objects	Caused by Machinery[b]	Caused by Cutting or Piercing Instrument or Object
1993	21	13	461	91	999	108
1994	13	14	454	83	970	103
1995	10	10	441	90	986	118
1996	10	9	422	71	926	97
1997	14	8	466	85	1055	104
1998	10	5	402	118	1018	121
1999[c]	—	—	—	74	622	93
2000	—	—	—	85	676	84
2001	—	—	—	85	648	116
2002	—	—	—	109	652	115

Note: The ICD is revised periodically, and these revisions can affect the classifications of death certificate code categories. The tenth revision completely revised the categories effective with 1999 data.
[a]Includes alcohol or petroleum products, agricultural products, chemical or pharmaceutical products, and foods or plants. Alcohol products dominate.
[b]Majority of deaths caused by machinery are specifically caused by agricultural machinery.
[c]Categories with dashes were discontinued after 1998.
Source: National Safety Council, *Injury Facts,* Itasca, IL: National Safety Council, 2002–2006; 1999–2002 data from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

Only mechanical suffocation has identified components that could relate to the built environment, and they are shown in detail in the 4-year overview of Table 1.1.40.

Suffocation in a bed or cradle accounts for hundreds of deaths annually, and a bed is a sufficiently large piece of furniture that it can be treated as part of the specification of a built environment, even though codes for the built environment rarely set requirements for contents and furnishings, particularly in private homes, which is where most of the suffocation deaths in beds and cradles probably occur. Nevertheless, Figure 1.1.8 provides an overview of differences in risk of such suffocation by age of victim. Crib deaths of very young children clearly dominate.

Excessive Temperatures

Deaths due to excessive heat and cold vary considerably from year to year. Death certificate data from 1993 to 2002 in Table 1.1.41 show that, in most years, cold is the dominant killer. Storm data for 2000 to 2004, collected by the National Weather Service, shows just the opposite, with excessive heat the leading killer in four of the five years, usually by a wide margin. When

TABLE 1.1.39 Deaths Due to Suffocation or Foreign Objects, Deaths Coded on U.S. Death Certificates

Year	Total Suffocation or Foreign Object	Suffocation or Respiratory Tract Obstruction Due to Food	Suffocation or Respiratory Tract Obstruction Due to Object Other Than Food	Mechanical and Other Types of Suffocation	Foreign Body Entering Other Bodily Orifice
1994	4161	1110	1955	1078	18
1995	4274	1088	2097	1062	27
1996	4338	1126	2080	1114	18
1997	4437	1095	2180	1145	17
1998	4608	1147	2368	1070	23
1999	4572	640	2828	1085	19
2000	4896	744	3187	934	31
2001	4813	742	3021	1021	29
2002	4863	819	2940	1085	19

Source: CDC/NCHS website, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm.

TABLE 1.1.40 Deaths Due to Mechanical Suffocation, Deaths Coded on U.S. Death Certificates

Year	*Mechanical and Other Types of Suffocation*	*Accidental Suffocation and Strangulation in Bed*	*Confined or Trapped in a Low-Oxygen Environment*	*Due to Cave-In, Falling Earth, and Other Substances*	*Other Specified Threats to Breathing*	*Unknown Threats to Breathing*
1994	1078	227	9	58	375	359
1995	1062	207	14	59	406	339
1996	1114	219	15	57	436	347
1997	1145	236	21	54	451	339
1998	1070	247	13	55	400	328
1999	1552	509	19	57	203	764
2000	1002	327	15	64	195	401
2001	1091	456	20	56	210	349
2002	1092	509	19	57	203	304

Sources: National Safety Council, *Injury Facts* and *Accident Facts,* Itasca, IL: National Safety Council, 1992–2000; 1999–2002 data from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

detailed circumstances are known and reported, most of the death certificate excessive temperature deaths are specifically attributed to weather as the cause of the extreme temperatures.

Excessive heat or cold, as a cause of death that can be essentially eliminated by a properly designed and operated building, provides the connection to the built environment, although mostly indirectly. Homelessness creates exposure to these potentially lethal conditions, as does the absence of effective and affordable climate control, principally heat for the winter. These problems are not really problems in the design of the building—although the cost of heating and the extent of natural cooling can vary considerably as a function of design—but are always problems arising from our efforts to live in environments of our own making.

Figure 1.1.9 provides a breakdown of deaths due to hunger, thirst, exposure, or neglect. Nearly half involve exposure to harsh weather, so they belong with the deaths shown on Table 1.1.41 as due to excessive heat or excessive cold.

SUMMARY

If we are guided by the relative magnitude of real harm done to real people—either direct harm to people or damage to their property—then the statistics presented here would appear to give us five priority areas for future attention, aimed at improved safety:

- Fire, burns, or shock because of harm to both people and property
- Falls because of harm to people

FIGURE 1.1.8 Deaths Due to Suffocation in Bed or Cradle, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

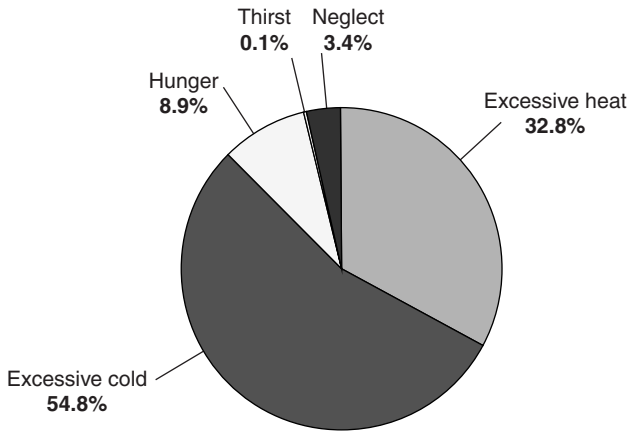

FIGURE 1.1.9 Deaths Due to Hunger, Thirst, Excessive Heat or Cold, or Neglect, by Cause, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

TABLE 1.1.41 Deaths Due to Natural or Environmental Factors, Excluding Lightning, Storms, Floods, Earth Movement, or Eruption, Deaths Coded on U.S. Death Certificates

Year	*Excessive Heat*	*Excessive Cold*	*Hunger, Thirst, Exposure, or Neglect*	*Animal or Plant*	*Other Natural Environmental Factor**
1993	299	641	243	176	13
1994	221	633	221	152	10
1995	716	553	203	159	15
1996	249	685	224	175	19
1997	182	501	224	170	25
1998	375	420	252	157	26
1999	594	598	170	223	22
2000	301	742	172	223	12
2001	300	599	128	176	13
2002	350	646	117	194	13

*Specifically, these were due to high, low, or changing air pressure; travel; or motion.

Source: National Safety Council, *Injury Facts and Accident Facts,* Itasca, IL: National Safety Council, 1992–2002; 2002 statistics from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

- Natural disasters because of harm to both people and property
- Water or storms because of harm to property more than people
- Harmful environment because of harm to people

Except for natural disasters, these priority areas primarily center around harm occurring in homes—dwellings, duplexes, manufactured homes, and apartments—which are traditionally the places where strict control by codes stops. Even if you allow for the fact that more time is spent at home than anywhere else, the risks from falls, fires, and water are higher at home than elsewhere. In terms of the first triage question—is this a big enough problem to worry about?—the answer for these four is yes. The next question asked how much of a difference can be made through changes in your built environments. To answer that question, it helps to distinguish among the five types in terms of the relative safety focus each has received in recent decades.

Fire has been the primary focus of NFPA for more than a century. Natural disasters are the focus of emergency managers at all levels of government and have been a focus of much of the insurance industry for some time. Water damage due to plumbing problems has been a focus of plumbing codes for some time.

Falls are the odd group in that they so clearly dominate any characterization of deaths in the built environment but have never been the primary focus of any major national organization or governmental agency.

Fatal falls can be made less likely through three distinct elements of design in the built environment. First, a variety of design decisions can make footing either more or less precarious. The dimensions of steps and stairs have long been controlled through codes, but there are other design elements, such as flooring angles, that may not have received much attention. Illumination levels at walking surfaces can also influence the safe use of the stairs. Also, the "slipperiness" or slip resistance of various surfaces, ranging from the aptly named "throw rug" or highly polished wood floor at one extreme to thick carpet or grooved concrete at the other extreme, has a bearing on the probability that a fall will occur.

Second, there is the effect of the surface's ability to absorb the impact of a fall without causing harm, or at least not fatal harm. Different flooring products certainly vary in this regard, but there is also a potential influence from lower walls, hard corners, protruding sharp or hard edges, and so forth.

Finally, there is the presence or absence, effectiveness or ineffectiveness, of physical aids to stabilization, such as handrails. These are all the design elements that compensate for the dangers created by walking surfaces or that permit an incipient fall to be interrupted or minimized on impact.

With so many opportunities to intervene via design in the number one cause of unintentional injury and deaths in the built environment, it is remarkable that falls have not emerged previously as a point of focus. The broad interception of the goals of NFPA *101®*, *Life Safety Code®,* has provided a limited basis for focus on falls by some of the technical committee volunteers working with NFPA. More recently, the U.S. Centers for Disease Control and Prevention has identified falls by older adults as a priority focus for its work, and NFPA's Center for High Risk Outreach has given preventative education regarding falls in the *Remembering When* program. Falls among children age 14 and under are one of the risk areas addressed in NFPA's school-based injury prevention program, *Risk Watch®*. Notwithstanding these serious and worthwhile programs, there is still a niche to be filled in focusing on code provisions to shape design of the built environment to reduce fatal falls.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on safety challenges in the built environment discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following document.)*

NFPA 730, *Guide for Premises Security*

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Chapter 2

Fundamentals of Structurally Safe Building Design

Revised by
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Chapter Contents

Challenges to the Built Environment
Design Loads and Forces
Basic Building Systems and Components
Fundamental Design Concepts
Basic Design Methodology

Key Terms

building code, building envelope, built environment, dead load, design load, earthquake force, horizontal load, live load, load and resistance factor design, load-path concept, occupancy type, overstress, performance level, performance-based design, snow and ice load, stress design, structural integrity, structural system, vertical load, wind force

Engineers sometimes joke that structural design is "the art of molding materials we do not wholly understand, into shapes we cannot precisely analyze, to withstand forces we cannot really assess, in such a way that the community at large has no reason to suspect the extent of our ignorance." Although overstated, this saying contains truth. The structure design and construction process contains many inherent uncertainties.

Despite these uncertainties, it is possible to provide relatively uniform levels of safety and reliability by starting with a design that meets the basic requirements of the adopted building code and then ensuring that, as it is built, the structure conforms to the approved design documents—the plans and specifications. For help, owners, architects, engineers, building officials, and contractors turn to the building code, not only to help define their roles, but also to provide the minimum standards for design and construction quality.

From a structural standpoint, today's model building codes scope the general building requirements for given occupancies, including such items as height and area limitations, construction types, basic building configurations, and construction techniques. Additionally, the building codes adopt, by reference, design load standards that define the minimum permissible strengths to resist floor loads and other unique environmental forces due to wind, snow, water, and earthquakes. Material design standards, which also tend to be adopted by reference in the building codes, define material strengths, properties, and specific design methods that can be used by engineers with reasonable safety. Some minimum standards for construction quality are also specified in the building codes. For the purposes of this chapter, the many codes and standards that affect the structural design and construction of buildings are collectively referred to as "building codes." This collection of codes and myriad referenced standards work to provide a safe, functional, and appealing structure at the end of the design and construction process.

Operating within this environment of codes and standards, the structural engineer must optimize the design in such a manner that the building provides acceptable levels of safety and serviceability while being economical to construct. One approach to "optimum" building design says that if a structure is loaded to the slightest fraction beyond its strength limit, all elements should simultaneously fail and the entire structure collapse. This approach is seldom used. Instead, most structures are designed such that if they are overloaded, they are able to deform and give some warning to occupants prior to failure, so that evacuation and perhaps shoring can occur.

See also Section 1, Chapter 1, "Challenges to Safety in the Built Environment"; Section 1, Chapter 3, "Codes and Standards for the Built Environment"; and Section 1, Chapter 4, "Legal Issues for the Designer and Enforcer."

CHALLENGES TO THE BUILT ENVIRONMENT

The total complex of houses, factories, offices, schools, and so on in which we live and work is referred to as the "built environment." Each year, lives and property are lost due to building

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failures. Mostly, hurricanes or other high winds, earthquakes, floods, and other dramatic events precipitate these building failures. Much less often, failures are precipitated by minor events or even ordinary loads and conditions due to inadequate design and construction, lack of proper code enforcement, simple neglect, or decay. Although building codes are intended to protect lives, clearly there are instances where they have not done so. Problems occur for both existing buildings and new construction.

Existing Buildings

Modern construction materials are very different from those used in the past. In some respects they are better, and in others, worse. However, the methods and details that are used to combine these materials into finished buildings have improved significantly with time. Building codes and construction methods change with time, incorporating new materials and methods of construction and "lessons learned" from various failures induced by disasters such as fires, earthquakes, and hurricanes. Because of continual improvements in building codes, most buildings designed and constructed today are considered safer and more reliable than buildings that were designed using older building codes. Building loss investigations, the ability to do more analysis, and widespread use of various hazard simulation models—all benefit the design and construction process.

In most communities, new building construction in any year represents less than 2 percent of the total number of buildings.* There are two exceptions to this general rule. The first is a new, fast growth/development community. The second involves massive rebuilding efforts following a natural disaster or postwar period. Consider the status of many communities in Louisiana, Mississippi, and Alabama that had a high percentage of their commercial and residential structures destroyed beyond repair as a result of Hurricane Katrina in August 2005. Jurisdictions that had little or no significant construction since the 1970s are now undergoing a tremendous rebuilding effort.

However, given the general 2 percent rate of new buildings, at any one time at least 50 percent of the building population is likely to be more than 30 years in age. For many communities, this percentage is actually much greater. Because of continual improvements in building codes and building technology, older buildings designed to the standards and codes of 30 or more years ago are by some measures considered unsafe in comparison to current standards. Therefore, it is likely that every community contains a significant number of buildings that could be unsafe if exposed to major events that newly constructed buildings could better survive.

Existing buildings are typically replaced only when either a better financial use is found for the property or because the physical condition of the building becomes so poor as to preclude further use. Once a building is constructed, and an occupancy permit issued, building codes contain few restrictions on the building's continued use. In general, the following apply:

- The owner is required to meet certain zoning restrictions in terms of types of use or contents.
- Major additions, alterations, or changes in use may trigger improvements to meet newer building codes. However, these requirements may be circumvented by physical separation of the new and existing construction or by other negotiated means.
- If the local building official becomes aware of an obviously unsafe condition, the official has the power to condemn a building. However, such actions are quite rare and typically occur only after a damaging event or failure.
- Some codes, like NFPA *101*®, *Life Safety Code*®, and some regulations, like the Americans with Disabilities Act, impose requirements on existing buildings, and some of these provide for enforcement of retroactive requirements, regardless of whether any other work efforts are undertaken.

As a result, many existing buildings contain latent risks due to deterioration, owner-initiated changes that were not done in accordance with the permitting process, deferred maintenance, or basic details of construction that would not be found in newer construction.

New Buildings

Every building is unique in some ways and without prototype. To be safe and serviceable, it is vital that the construction be in accordance with the approved design documents. This requires that all parties involved in the construction process—code developers, owners, architects, the insurance community, engineers, code officials, and contractors—each exercise the skill and responsibility necessary to make certain that their part of the project is done in conformance with the intended requirements, while still meeting the limitations of project schedules and budgets.

A common challenge to this process is communication—for contractors and building officials to be able to correctly interpret the architect's and engineer's intent from their drawings and specifications, and for the architects and engineers to be able to interpret the intent of code developers from the building codes.

Another challenge of new construction is for engineers and code developers to predict the types and magnitudes of forces and events that a building may experience during its existence, and to define design loading conditions within building codes that are sufficient to withstand those conditions, without undue financial penalties. Ongoing debate—since 2001—involves the need to carefully analyze the design assumptions as they may relate to certain extreme events, most notably terrorism and hostile acts. The cadre of codes and standards simply cannot strive for "more" safety or "ultimate" safety, but rather they need to provide an "appropriate" level of safety.

DESIGN LOADS AND FORCES

Basic Types of Loads and Forces

Building codes define the following basic types of loads and forces as a basis for structural design. These loads and forces include the following:

*The conservative estimate of 2 percent is based on assessor's data for the county of Orange, California, an area of high growth. The annual development in Orange County between 1972 and 1994 added an average of 3 percent annually to the cumulative number of developed parcels.

- Dead load
- Live load
- Snow and ice loads
- Wind forces
- Earthquake forces

Dead Load. Dead load is the weight of the building itself. It includes the weight of all permanent fixed items, such as floor framing, walls, ceilings, roofing, and major fixed service equipment, but excludes loads from variable items, such as furnishings, people, traffic, and equipment, that change constantly throughout the building's life. Dead load is the easiest to predict and can be known with the most certainty, although there can still be some variation between dead load estimated by the engineer and the actual as-constructed weight.

Live Load. Live load is the weight of items such as furnishings, people, traffic, and equipment related to the use or occupancy of the building. This weight is generally known with little certainty, as it can vary over time. Building codes include tables of minimum required design live loads for various occupancy types, which are sometimes posted on signs within buildings. These design live loads represent reasonable maximum bounds on the amount of weight from these variable items that may be placed on a floor or roof during its life. It is extremely unlikely, except in certain types of occupancies such as warehouses, that all areas of floors and roofs would simultaneously be loaded to the design levels at the same time. Hence, building codes include "live load reduction factors" that account for the low likelihood of simultaneous heavy loading of large portions of the building and allow the design load to be reduced for building elements that support larger areas. Thus, an individual floor beam might be designed to support a larger floor load (on a pounds per square foot basis) than a column that supports many beams.

Snow and Ice Loads. Snow and ice loads are the design weights required by building codes to be considered for accumulation of snow and ice. Building codes define snow load in terms of "ground snow loads" that represent a weight of snow having a 2 percent annual probability of being exceeded (50 year mean recurrence)[1]—that is, such heavy loads are anticipated to occur only every 50 years or so. The building codes include maps that specify minimum design snow loads for various regions of the country. However, snow depths can be highly variable, particularly within mountainous regions, where local building officials often specify "standard" ground snow loads within their jurisdictions that are different from those indicated in the maps.

The ground snow load, contained on building code maps and enforced by building officials, is not the same load that is actually used to design buildings. Design snow loads are calculated based on the ground snow load, but require modifications to account for the effects of roof slope, thermal conditions (heated versus unheated), wind conditions that can cause snow to drift across roofs, and building shape or geometry conditions, which may cause drifts or snowfalls from adjacent higher roofs to accumulate. Design load standards are used to translate the basic ground snow loads into specific design weights that vary over the roof surface.

Wind Forces. Design wind forces are determined using horizontal wind pressures associated with a design wind velocity that is specified for a location. Just as with snow loads, building codes include maps of design wind velocity values for most areas (Figures 1.2.1 through 1.2.4). However, these maps exclude some "special wind regions" in which local terrain conditions produce occasional high wind conditions. In those areas, the building official is required to specify the design wind velocity.

Prior to 1998, the commonly accepted definition of design wind velocity was based on the "fastest-mile" wind speed, which was the wind speed based on the time required for a mile-long sample of air to pass a fixed point. Around 1998, U.S. building codes redefined the design wind velocity as the mean wind speed averaged over 3 seconds, measured at 33 feet above grade, over relatively open terrain.[2] The resulting wind velocity maps are generally based on a 50-year wind speed.[2] However, in hurricane-prone regions, wind velocity maps have been modified to include an adjusted value based on both hurricane simulation techniques and 500-year wind speed records. This "3 second gust" method is an improvement over the earlier method in that the fastest mile did not account as well for the effect of short duration gusts. Also, the older codes did not include the more severe winds anticipated in hurricane-prone regions.

The mapped wind velocity is not directly used to design buildings. Instead, the mapped wind values are modified depending on terrain conditions, elevation, and topographic effects such as hills or ridges that can cause local high-velocity conditions to occur. The design forces are calculated from these site-modified wind velocities, considering the building's shape, its flexibility, the quantity of openings that can allow fluctuating wind pressures to enter the building, and the total building area that may be subjected to locally varying wind gust pressures. Design load standards provide guidance to engineers on how to determine the appropriate pressures to design building components for relatively regular and normal looking buildings. Buildings that are very tall, flexible, or unusual in shape sometimes require special wind-tunnel testing using scale models in order to determine appropriate design wind pressures. In fact, more extensive use of, and reference to, wind tunnel testing techniques are the subject of one of the 30 recommendations of the NIST study of the World Trade Center disaster.[3]

Earthquake Forces. Earthquakes do not directly exert forces on buildings. Rather, they produce ground accelerations and deformations that vary with time. The response of the building to these ground movements results in stresses and deformations throughout the building. The severity of these effects depends on the event magnitude, its distance from the structure, local soil conditions, and the weight and stiffness characteristics of the building structure itself. Building codes provide procedures that allow engineers to determine the design forces. These are calculated as pseudo-inertial forces equal to the building mass times specified design accelerations. These design accelerations are determined from mapped values of design ground accelerations found in building codes, modified to account for the building's structural characteristics (Figure 1.2.5).

As with wind loads, the definition of the design ground acceleration used in building codes has evolved. Until 1991, building codes included maps that presented design ground motions

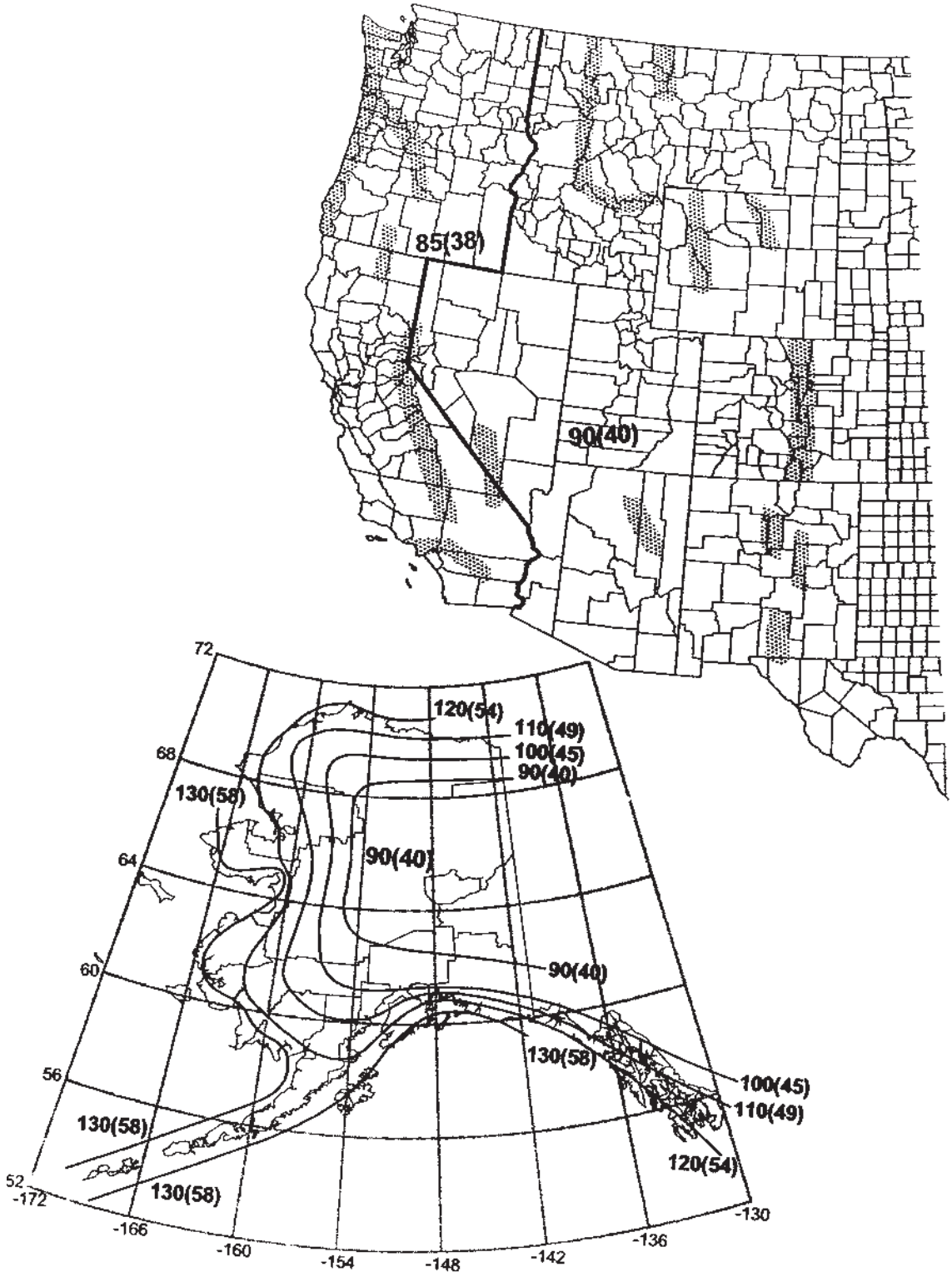
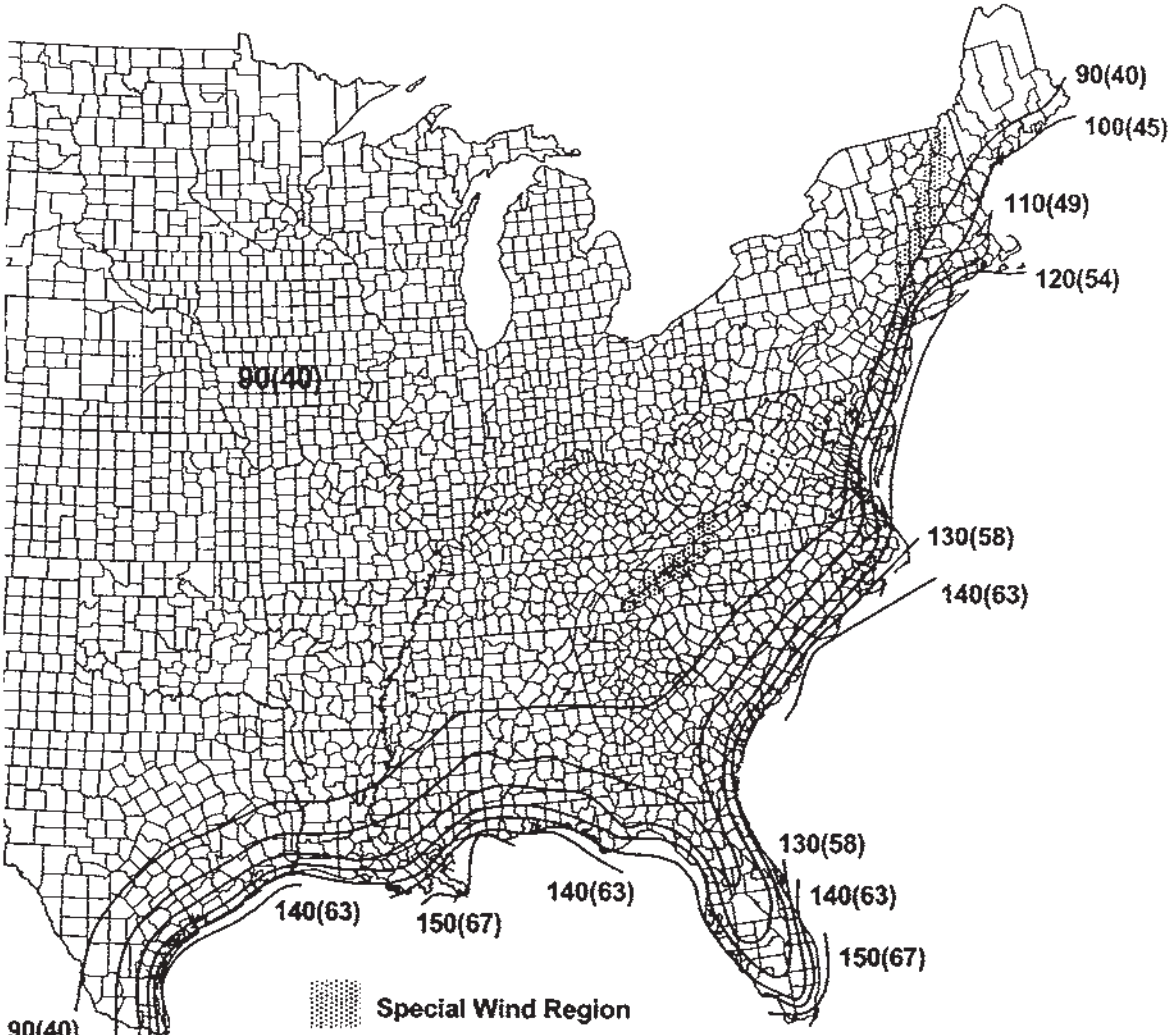


FIGURE 1.2.1 Basic Wind Speed (Source: Reprinted with permission from ASCE/SEI 7)

in the form of seismic zones. The seismic zones covered broad geographic regions, often encompassing several states. Within each seismic zone, the building codes specified earthquake acceleration values that approximately represented the most severe shaking likely to occur in any 500 year period—in statistical terms, having a 10 percent chance of being exceeded in 50 years. The use of broad geographic seismic "zones" resulted in these accelerations being very approximate.



Notes:
1. Values are nominal design 3-second gust wind speeds in miles per hour (m/sec) at 33 ft (10 m) above ground for Exposure C category.
2. Linear interpolation between wind contours is permitted.
3. Islands and coastal areas outside the last contour shall use the last wind speed contour of the coastal area.
4. Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.

FIGURE 1.2.1 Continued

Starting in 1991, codes began to abandon seismic zones and present design ground motions on maps in the form of ground motion "contours" that more precisely presented the likely levels of ground motion at any given site. Using these maps, each site location has a unique value of design ground acceleration depending on its location relative to known faults and seismic source zones. The newer mapped earthquake acceleration contours also represent a more unlikely event, corresponding to

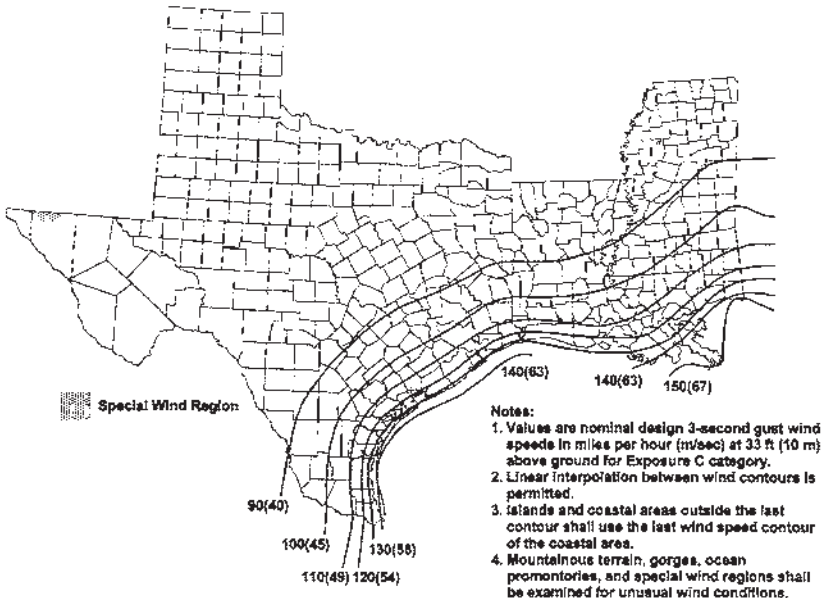


FIGURE 1.2.2 Basic Wind Speed: Western Gulf of Mexico Hurricane Coastline (Source: Reprinted with permission from ASCE/SEI 7)

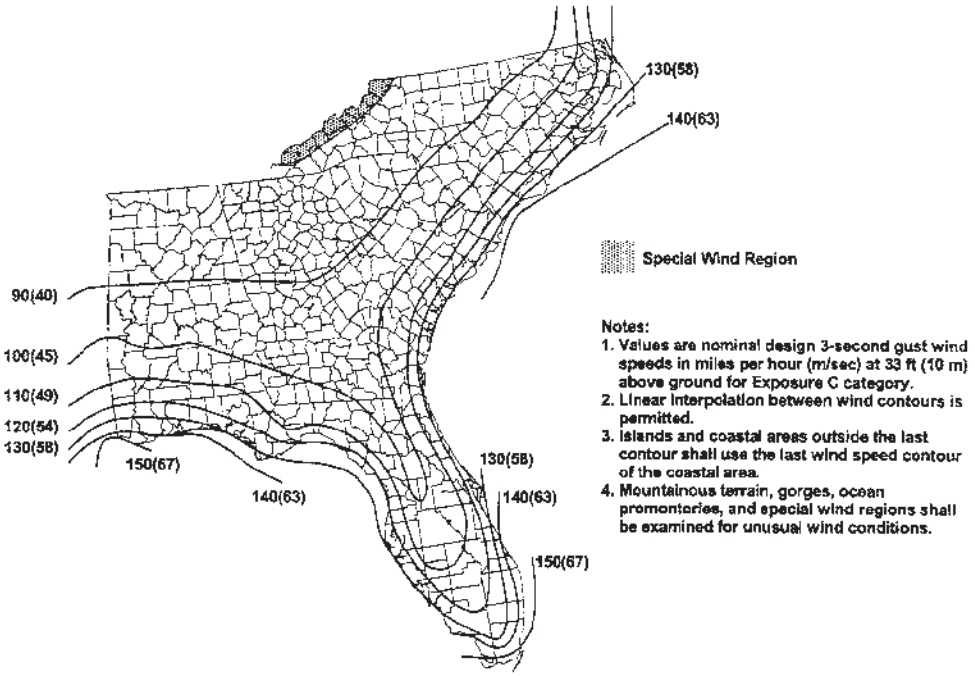


FIGURE 1.2.3 Basic Wind Speed: Eastern Gulf of Mexico Southeastern U.S. Hurricane Coastline (Source: Reprinted with permission from ASCE/SEI 7)

a 2500 year event, or one having a 2 percent chance of being exceeded in 50 years. This rather rare event is more appropriate for sites in the eastern United States, for example, where large earthquakes occur infrequently, and does not significantly increase the hazard in the western United States, where destructive ground shaking occurs more often. The intent of the newer building code regulations is to prevent structural collapse for these 2500 year events. However, actual design is based on providing a less severe level of damage for design ground accelerations taken as two-thirds of the mapped values.

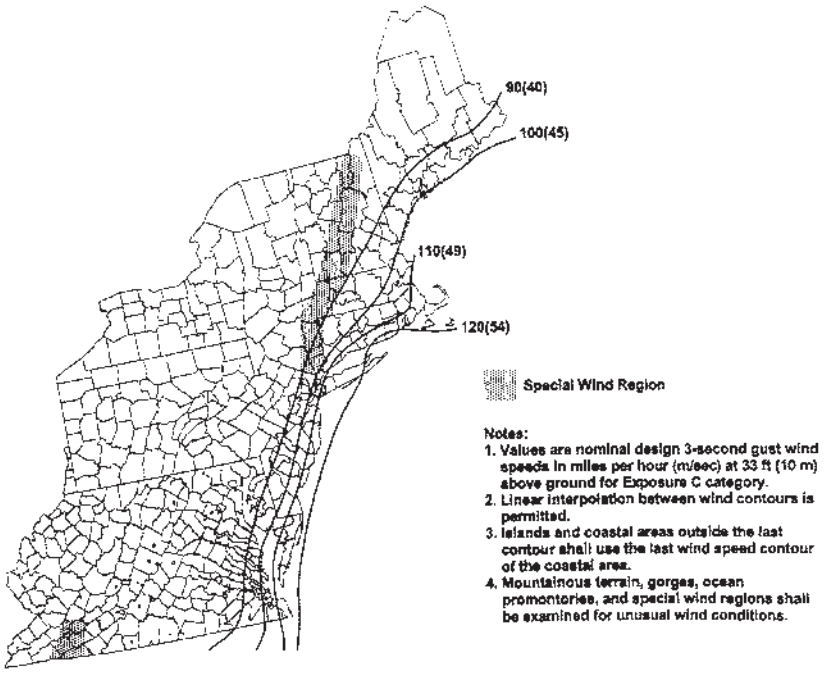


FIGURE 1.2.4 Basic Wind Speed: Mid- and Northern Atlantic Hurricane Coastline (Source: Reprinted with permission from ASCE/SEI 7)

In regions with moderate or strong earthquake potential, design ground acceleration values are so large that engineers cannot economically design ordinary buildings to resist the full acceleration values without also permitting some degree of damage. In fact, most buildings are designed to crack and yield when affected by design level shaking, ultimately holding together and not collapsing. The intent of the earthquake code provisions for ordinary buildings is to perform for and protect "life safety," but not protect property investments. In order to accomplish this, design forces are calculated using special reduction factors R that reduce the predicted ground accelerations into artificial design values. These R values are specified in the building codes, based on the type of structural system used and the historical performance of various systems.

In addition to specification of minimum design forces, building code provisions for earthquake resistance also include prescriptive detailing requirements intended to provide sufficient toughness to hold buildings together as they deform. The prescriptive provisions regulate the types of connections and reinforcements that are used in different types of construction and also the configuration (geometric shape) of the building and its elements. In addition, in locations where stronger accelerations may occur, some types of construction, such as unreinforced masonry, are not permitted.

Other Loads. Building codes and design load standards also include provisions for other common types of loading, including flood loads, soil loads, hydrostatic pressure, impact, and forces caused by thermal expansion and contraction or impact. However, building codes have either very limited provisions or no provisions at all for some very unusual types of loads such as those induced by tornadoes, blasts, or explosions. Industry-specific design standards, such as those developed by the military, the U.S. General Services Administration, the Department of State, or the Department of Energy, are typically used for the design methods of structures that must resist such load conditions.

Combining Design Loads. Once the individual design forces have been determined, they must be combined to consider the effects of simultaneous application; for example, the occurrence of high wind loads and occupancy-related loads such as furnishings and equipment. When combining loads of different types, the probability that loads occur concurrently is considered and loads that occur infrequently are typically not combined together. For instance, a full design snow load would not be combined with a full design wind or earthquake event, although some portion of the design snow might be considered. Building codes include equations for required combinations of loading that must be considered in building design. Some special types of structures also use load combinations defined in industry-specific standards. As an example, tanks are designed for earthquake inertial forces in conjunction with forces caused by earthquake-induced sloshing of tank contents.

Actual Versus Design Loads

Building codes deal with the uncertainties associated with predicting design loads through the use of probability and statistics. For example, building codes define a 50 year wind, or a 2500 year earthquake event. However, the resulting design maps correspond only to a statistical representation of the

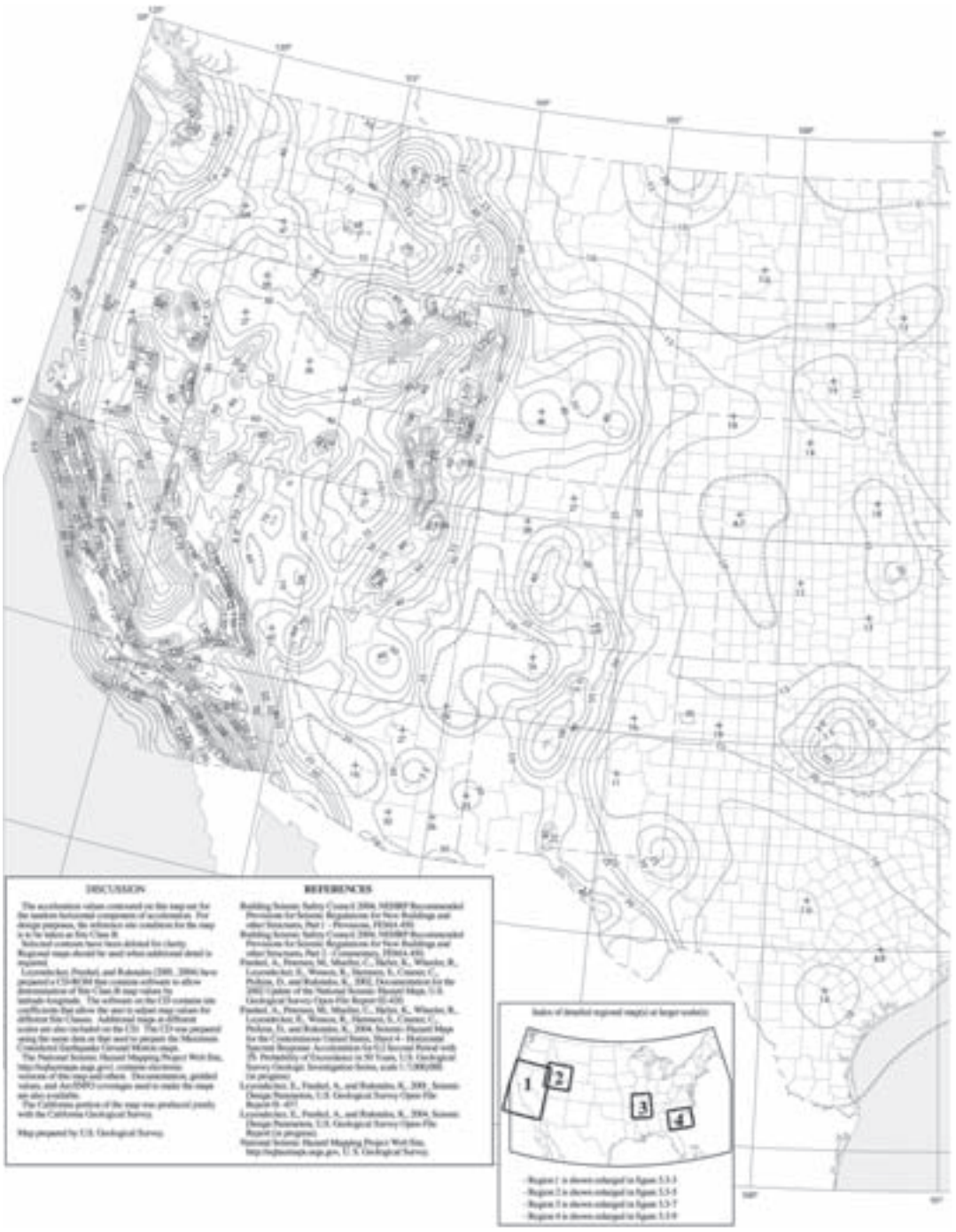


FIGURE 1.2.5 Maximum Considered Earthquake Ground Motion for the Conterminous United States of 0.2 Second Spectral Response Acceleration (5% of Critical Damping), Site Class B (Source: National Earthquake Hazards Reduction Program Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, FEMA 450, 2003, Figure 3.3-1)

probabilities, based in part on the historical record and also in part on the experience and judgment of the code developers. Because neither can completely predict the future, it is possible that code-specified design loads will be exceeded. For example, earthquakes sometimes occur on previously undiscovered fault lines, or changes in global climatic patterns can result in increased wind or snow hazards that are not accounted for by the building codes.

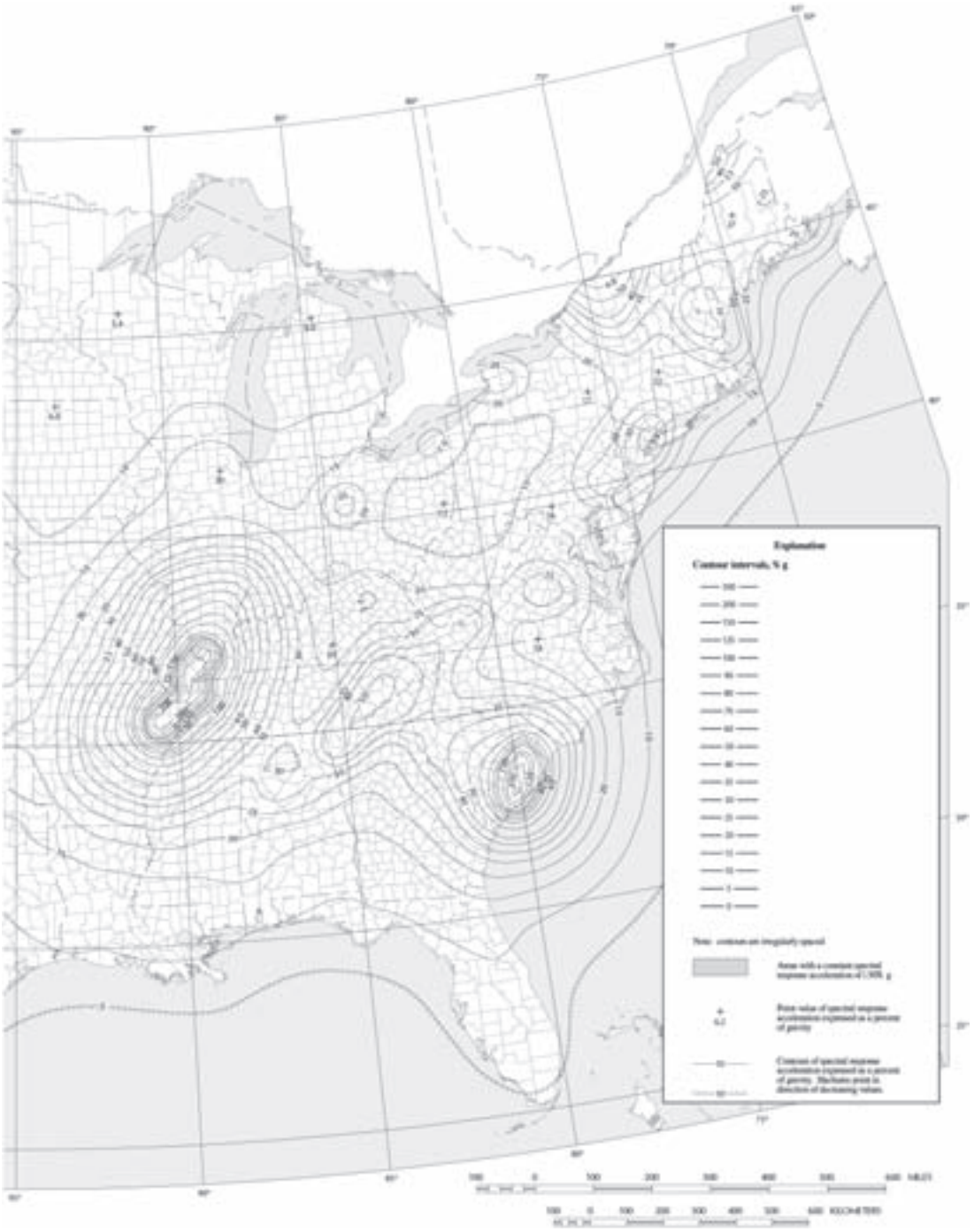


FIGURE 1.2.5 Continued

External Versus Internal Forces

Building codes define loads and forces such as dead, live, and snow loads, and wind or earthquake forces that are considered externally applied, in that they act upon the structure. When these forces and loads are applied on a structure, they result in movement (deflection) of the structure and also the development of internal forces or stresses within the individual structural elements. The building's structural elements, such as floors, beams, columns, or walls, are designed to control the magnitude of these deflections and stresses. Engineers must therefore use the external forces specified by the building code to calculate the distribution of internal forces and deflections in each building element. Although such calculations can be performed using manual methods, today elaborate computer programs are commonly used to assist the engineer in this task.

Internal forces calculated in individual elements include tension, compression, shearing, and bending forces (or bending "moments"). After the engineer determines these forces, they are compared against maximum permitted material strengths that are defined in building codes to verify the adequacy of each proposed design.

BASIC BUILDING SYSTEMS AND COMPONENTS

Basic Building Systems

Basic building systems include the building envelope system, the structural system, the foundation system, the plumbing system, mechanical systems (such as heating, ventilating, and air-conditioning systems), and the electrical system. Other critical building systems include the fire protection system and the security system, for example.

This chapter focuses primarily on the building envelope system and the structural system and briefly addresses the foundation system. The building envelope and structural systems enable a building to withstand the loads and forces placed on it. Stated another way, the building envelope and structural systems keep the building intact and standing; the skin and skeleton fulfill similar functions in human anatomy.

Building Envelope System

The building envelope has been described as being composed of "several building components that work together to protect the building's structure and its contents from the elements."[4] The building envelope consists of building elements such as windows, precast or similar nonstructural wall panels, and like elements that enclose and protect the building and create the finished appearance.

Basic Structural Systems

To resist both vertical loads such as dead weight and snow, and lateral forces such as those produced by winds or seismic effects, any stable building or structure requires two distinct structural systems: a vertical support system and a lateral force-resisting system. Each system consists of a series of structural components (beams, columns, walls, etc.) that combine to provide resistance against either vertical or lateral loading. These structural components can consist of individual elements, such as columns, or they may consist of combinations of elements that connect to produce subsystems, such as shear walls, moment-frames, braced frames, and so on.

Vertical Support System. Basic structural components that combine to form the vertical support system include roof and floor framing systems, columns, bearing walls, and foundations. All structures must have complete and sound vertical load-supporting systems or they would collapse under their own weight and that of their contents. This is in contrast to structures with missing or inadequate lateral force-resisting systems that could conceivably stand indefinitely, because extreme lateral loading events (high winds and earthquakes, for example) are quite rare.

Lateral Force-Resisting System. Basic structural components that provide lateral force-resistance include shear walls, braced frames, and moment-resisting frames, as well as diaphragms (such as roof decks, floor slabs, or horizontal bracing systems) and foundations. Depending on the type, use, and geometry of the structure in each application, these components can be combined to form a structural system.

Comparison of Vertical Support and Lateral-Force Resisting Systems. Frequently, there is little visible difference between the frames, bearing walls, and so on, used to provide vertical support, and the similar frames, shear walls, and so on, used to resist lateral forces. The basic distinction that exists between vertical support and lateral-force-resisting systems arises from the following factors:

- All loads applied to a structure tend to be resisted first by the structural components that have the greatest rigidity (relative to other components) in the direction of load. Thus, vertical loads supported by an elevated floor slab tend to be borne by the closest adjacent columns. On the other hand, lateral forces applied against a floor diaphragm may span entirely past interior support columns (which provide little or no lateral rigidity) and be resisted by more distant (but very rigid) walls or braced frames.
- The connections used to fasten components must provide adequate strength to resist the imposed forces and deflections. In addition, the various components that form a structure must be designed considering the likely deflection and rigidity of adjacent elements. Where the design assumptions require a rigid or inflexible link between lateral load resisting components, the connection must impart rigidity; however, where independent motion is more appropriate, the connection must provide adequate flexibility to accommodate structure deformations without impact or binding.

Structures must be able to resist forces that are imposed from any direction. Most structures are therefore designed with two separate lateral-force-resisting systems, one for each of two orthogonal axes of the building. When forces are applied about either orthogonal axis of the structure, some of the resisting elements are aligned parallel to the forces. Wall and bracing elements have high relative rigidity in-plane and thus provide substantial lateral support. However, walls or bracing systems have low relative strength and rigidity when aligned perpendicular to the direction of load, and thus must be properly attached to and supported by structural components that are parallel to the forces.

Types of Basic Structural Systems. Building codes define certain standard structural systems, called basic structural systems. In essence, basic structural systems are those that resist vertical and lateral loads. These basic structural systems are the following:

- *Bearing wall system.* Any structure in which vertical walls and/or diagonally braced frames simultaneously support both the weight of the structure and resist lateral loads.

- *Building frame system.* System in which the weight of the structure is completely supported by beams and columns. Resistance to lateral loads is independently provided either by walls, termed shear walls, and/or diagonally braced frames.
- *Moment-resisting frame system.* This structure is composed of beams and columns that are rigidly interconnected into moment-resisting frames to provide resistance to both vertical loads and lateral forces, without assistance from walls or diagonal braces.
- *Dual system.* System that provides two independent lateral-force-resisting systems, each capable of resisting all or part of the total lateral design forces. One system must always be a moment-frame system; the other can consist of either reinforced shear walls or braced frames that are added at selected locations.
- *Special systems.* Special systems include base-isolated systems or guyed systems, which do not fit the previous descriptions. A base-isolated system is a special type of seismic-resistant construction in which the structure is mounted on rubber bearing or sliding steel plates. A guyed system is a structure that is braced by guy wires, such as a radio-transmission tower.

Diaphragm Systems. Diaphragms are horizontal-spanning systems that tie vertical walls and columns together, provide stability to walls and other vertical elements, prevent excessive torsional (plane) deformations, and transfer forces to shear walls or frames below. Lateral forces resisted by diaphragms originate from wind forces applied against exterior walls, from seismic inertial forces, or from forces transmitted from shear walls or frames above.

The use of building floor and roof systems as diaphragm systems can be very efficient, because most of the structural elements required for diaphragm action are also required for these systems. Horizontal bracing systems provide diaphragm-like performance for applications where solid-surface construction cannot be used or is not required.

Building Foundation Systems

Foundation systems are used to transfer vertical and horizontal loads from the aboveground structure into the underlying soils. Common foundation types include piles, piers, caissons, spread footings, and mats. Piles, piers, and caissons are deep foundation systems designed to support heavy buildings on soft, compressible surface soils. Spread footings and mats are shallow foundation systems designed to support light buildings or heavier buildings on stiffer, stronger surface soils (Figure 1.2.6)

Basic Building Components

Basic structural components that collect loads from roof and floor levels and transfer them to foundations include moment-resisting frames, vertical walls, diagonally braced frames, and diaphragms and horizontal bracing. These underlying structures are surrounded and protected from the environment by the building envelope. Critical structural design considerations for the building envelope include resistance to lateral pressure or impact, accommodation of transient building movements, and accommodation of long-term building movement.

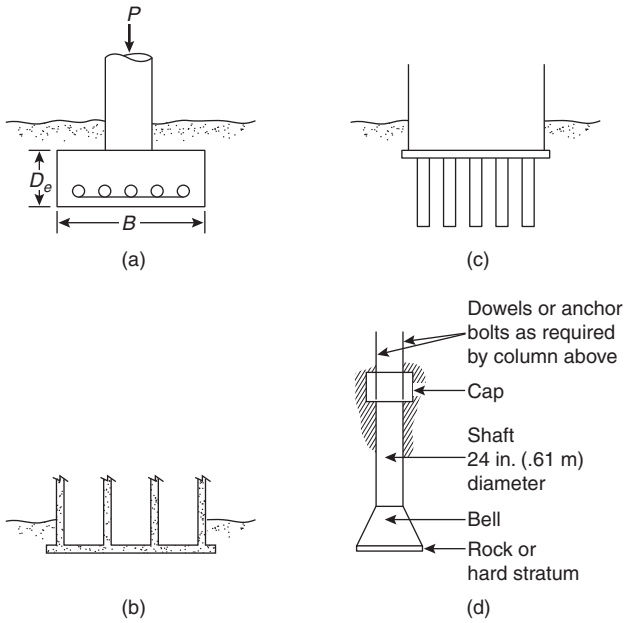


FIGURE 1.2.6 Common Types of Foundation Systems: (a) Spread Footing, (b) Mat, (c) Pile, and (d) Pier or Caisson

Resistance to Lateral Pressure or Impact. Exterior walls, windows, and doors provide the primary protection against wind pressures and small stones and missiles thrown up by wind. Windows must be designed to resist design wind pressures while still maintaining moisture protection at surrounding gaskets. In special hurricane-prone areas, impact protection may be required as well. Near grade and around entrances, missile or impact resistance may also be required for protection against small stones thrown up by lawnmowers or attempted forced entries. Walls must have adequate shear and bending strengths and strong enough connections to resist code-defined wind pressures and earthquake inertial forces.

Accommodation of Building Movements. The structure that supports the building sways and drifts during windstorms or earthquakes. The attached building components must be designed to accommodate these movements without damage. Frequently, by adding jointing and special connection details that allow structural movements without binding against cladding or window elements, these movements can be accommodated. In relatively flexible buildings, glass panels may need to be able to rock within their frames to accommodate building sway without binding. These sway or drift limits are part of the serviceability of performance and must remain within a certain tolerance level to prevent occupants from feeling motion sickness under "usual" conditions.

Accommodation of Long-Term Building Movements. After completion of construction, all buildings experience some

degree of long-term movements as the building adjusts to its environment. Building components can experience some shrinkage or expansion. Foundations can slightly settle. Over the long term, some of this movement may continue in the form of thermal cycling or perhaps continuing foundation movements due to moisture-related expansive soil conditions. These movements often cause slight cracking and distress that can be observed in many buildings. Although not specifically a code-regulated issue, the details of building construction used should attempt to minimize both the amount of such movement that occurs and the damage sustained as a result of such movements.

Moment-Resisting Frames. Moment frames rely on bending forces developed at the connections of the beams to the columns to resist lateral forces. Because moment frames tend to be much more flexible than either shear walls or braced frames, lateral deflections of moment-frame structures tend to be much greater. The ratio between relative story deflection and story height is called the story drift ratio. Moment frames that permit too much story drift during windstorms or earthquakes may permit an excessive amount of damage to nonstructural components, such as siding, partitions, and contents.

Critical design elements of moment-resisting frames include beams and columns and the beam-column connection.

- *Beams and columns.* Frame elements must be designed to resist internal bending and shear forces. Optimum performance is gained when the members selected are stronger in shear than in bending and when the building's columns are stronger in bending than its beams. This provides a controlled damage mode under very large loads and forces and, in multistory frames, increases the total energy dissipation capability of the frame.
- *Beam-column connection.* The stability of the frame is dependent on the rigidity and strength of the beam-column connection. Adequate strength and toughness must be provided in the connection to permit repeated cycling of stresses without a loss of integrity. Connections can be made of bolted or welded components, or a combination of bolted and welded elements. Since the toughness of welded joints is highly dependent on the workmanship, special quality control measures are often required in the most critical welds.

Shear Walls. The shear wall is designed as a vertical beam element. As shown in Figure 1.2.7, critical design considerations for shear walls include in-plane shear, in-plane bending, and bending from forces perpendicular to the wall:

- *In-plane shear.* The wall acts as a web, or shear membrane, to resist in-plane shear forces. Adequate anchorage must be provided along the top and bottom edges of the web to transfer the shearing forces into and out of the web.
- *In-plane bending.* To resist bending stresses due to overturning moments, structural elements, called chords or boundary elements, are concentrated at the vertical edges of the wall. Chords are tension-only elements, which resist the tension component of bending forces. Boundary elements are tension-compression elements, which resist tension forces as well as extremely large compression strains (large enough to cause crushing of unconfined concrete) due to bending and vertical loads. Boundary elements are required by building codes only in high-seismic zones. Both chord and boundary elements must be anchored into a foundation that is capable of transferring the vertical components of overturning forces into the ground.
- *Bending from forces perpendicular to wall.* Adequate bending strength and anchorage must be provided to resist in-

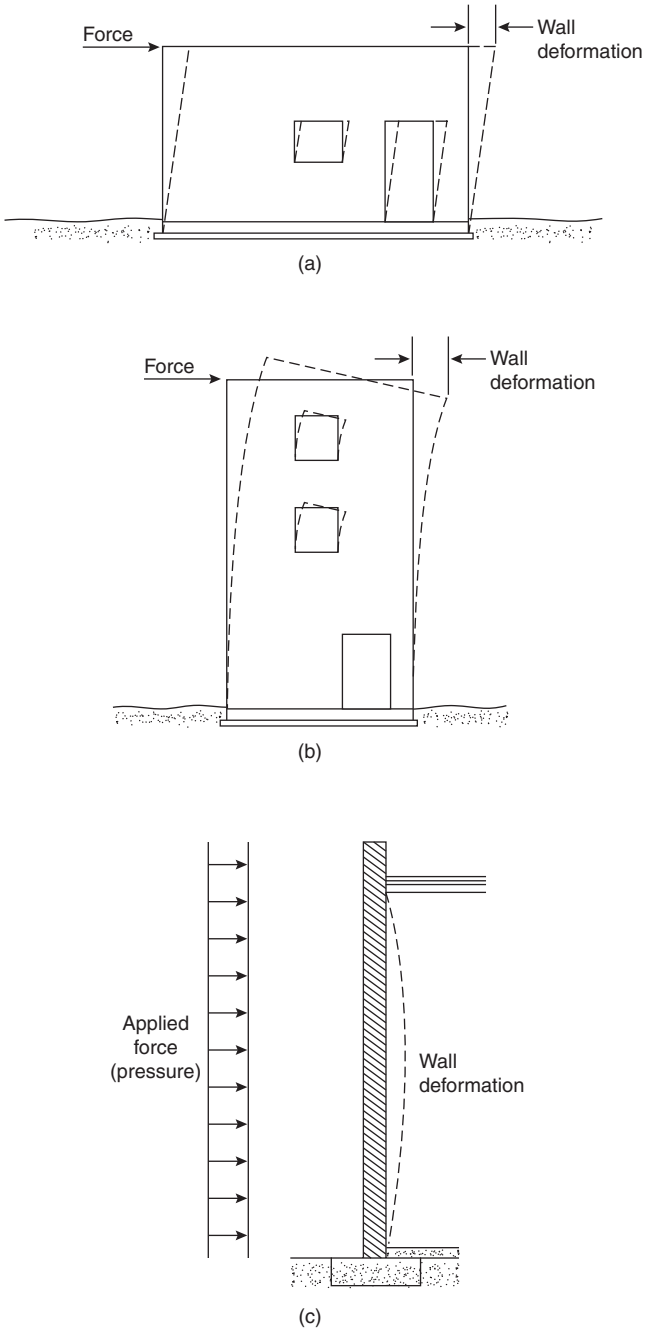


FIGURE 1.2.7 Types of Wall Deformation: (a) In-Plane Shear Deformation, (b) In-Plane Bending Deformation, (c) Bending from Forces Perpendicular to Wall

ertia loads and wind pressures applied perpendicular to the plane of the wall.

Diagonally Braced Frames. Braced systems rely on the axial rigidity of vertical and diagonal elements to resist lateral forces. The configuration of diagonal elements within the bracing can vary, and some configurations have better seismic performance than others. Commonly encountered types of bracing systems, in order of relative performance (best to worst) when subjected to overload or damaging conditions, include the following:

1. *Eccentrically braced frame (EBF).* A special type of bracing system that is designed to provide a high degree of overload resistance by permitting controlled overstresses within a short, ductile beam segment, called a "link." Figure 1.2.8 shows examples of eccentrically braced frames.
2. *Concentrically braced frame (CBF).* A type of bracing system that provides overload resistance by permitting controlled overstresses in the bracing members. Buckling-restrained braced frames (BRBF) are considered a special class of concentrically braced frames, with a high degree of seismic resistance. Figure 1.2.9 shows examples of other concentrically braced frames:
   - *Tension-compression bracing.* Diagonal elements are provided either singly or paired in an "X" pattern to resist forces both in tension and compression.
   - *Chevron bracing.* Arranged in either a "V" or inverted "V" configuration, the diagonal elements resist lateral forces by sharing the load between tension and compression elements. Bracing in this configuration also resists vertical loads applied to the beam, although building codes require that the beam be designed to resist vertical loads as if the bracing did not exist. This configuration can experience problems when overstressed because buckling of the diagonal undergoing compression creates a force imbalance that increases bending forces on the beam.
   - *Tension-only bracing.* Similar to tension-compression bracing, except that the diagonal elements, by being very slender, are assumed to buckle at very low compression forces. This configuration can experience a loss of strength under repeated tension-compression cycles. In regions subject to significant ground shaking, tension-only bracing is limited to structures of less than two stories in height.
   - *K-bracing.* This system provides the poorest overload performance. Overstresses in the diagonal elements can lead to buckling of the diagonal undergoing compression. The resulting force imbalance creates a lateral force on the column, which could possibly lead to a general collapse of the system. Building codes include several restrictions on the use of this type of bracing.

As shown in Figure 1.2.10, critical design elements of bracing systems include diagonal elements, vertical elements, and horizontal elements:

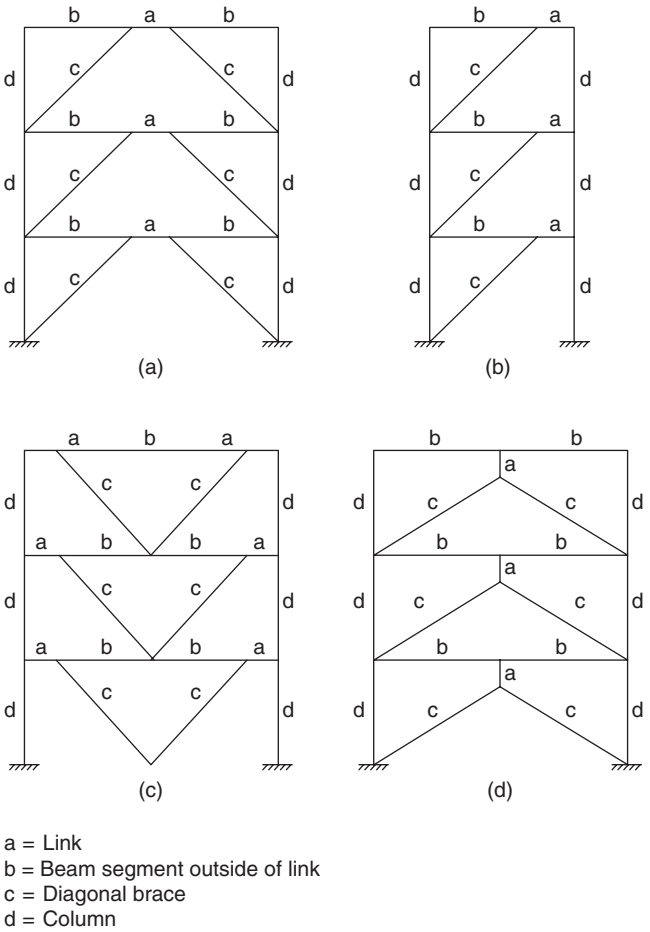


FIGURE 1.2.8 Examples of Eccentrically Braced Frames (Source: Copyright © American Institute of Steel Construction, Inc. Reprinted with permission. All rights reserved.)

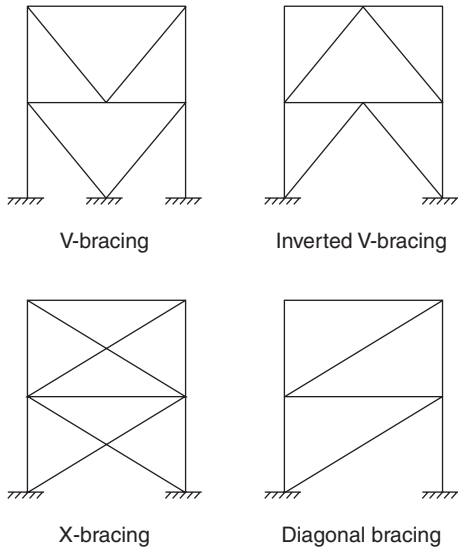


FIGURE 1.2.9 Examples of Concentric Bracing Configurations (Source: Copyright © American Institute of Steel Construction, Inc. Reprinted with permission. All rights reserved.)

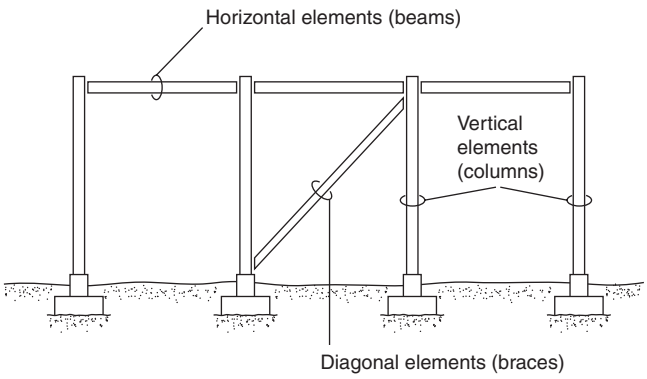


FIGURE 1.2.10 Diagonal Elements, Vertical Elements, and Horizontal Elements

- *Diagonal elements.* Designed to resist lateral (story shear) forces. Because bracing connections often tend to have brittle modes of failure, for some loading conditions the connections must be designed to be stronger than the braces themselves.
- *Vertical elements.* Designed to resist overturning forces.
- *Horizontal elements.* Designed as axial struts to collect and transfer tension and compression forces into the diagonal elements. The strut system can be sloped, such as when pitched roof elements are used as struts.

Diaphragms and Horizontal Bracing Components. Diaphragms are generally designed as beams that span between the vertical-resisting elements (frames, walls, braced frames, etc.). Critical design elements of diaphragm systems include the following:

- *Shear membrane.* The floor or roof acts as a web, or shear membrane, to resist shear forces. The web is assumed to resist shear forces only (no tension or compression).
- *Chords and boundary elements.* Located at the extreme edges of the diaphragm, the chords resist tension forces caused by bending in the diaphragm, in a manner similar to the flanges of an I-beam. When compressive stresses warrant, boundary elements may also be required to resist the compressive forces caused by bending.
- *Collectors.* Also called drag struts, collectors are used to resist axial tension and compression forces within the diaphragm by:
  - Collecting shear forces from the diaphragm and transferring them to the vertical resisting elements (walls, braces, or frames)
  - Redistributing chord forces at diaphragm offsets and gathering loads and distributing them to intersecting walls, braces, or frames
  - Redistributing diaphragm shear forces and local chord forces around openings within the diaphragm
  - Distributing points of concentrated force into the diaphragm, such as from heavy rooftop equipment

Foundation Components. Critical design issues for foundation systems include bearing strength, overturning resistance, sliding resistance, bending and shearing strength, and ground hazards:

- *Bearing strength.* The foundation system must have sufficient strength to transfer the weight of the structure to the surrounding soils without adverse settlements.
- *Overturning resistance.* Piles must have sufficient compressive and tensile capacity to resist overturning loads; spread footings must be massive enough and/or support adequate soil surcharge to counteract uplift.
- *Sliding resistance.* Either passive soil pressure, friction, or a factored combination of both may be used, depending on the soil type and foundation geometry.
- *Bending and shearing strength.* The foundation system must have adequate strength to transmit loads without failure or excessive deflections.
- *Ground hazards.* Some sites are susceptible to special hazards that can occur within the site itself, such as excessive settlement, potential slope failures, water-induced scour or shaking-induced-liquefaction. In some instances, the risk of these hazards can be reduced by conducting site improvements prior to construction, such as by soil densification or by removal of unsuitable materials. In other instances, the site itself may not be suitable for the structure.

FUNDAMENTAL DESIGN CONCEPTS

General Structural Integrity

Building codes and their referenced design load standards require structures to be designed so that, when damage is sustained locally, the damage does not spread to an area disproportionate to the original area of local damage. This is most often accomplished by providing designs that have a robust load path, stable geometry, and structural systems that are designed specifically for overstress.

Load-Path Concept

The load-path concept requires a continuous system of interconnected elements throughout the structure, adequately connected to transfer applied loads and forces from the points of origin or application to the final points of resistance. As an example, columns are used to transfer loads from roof beams to foundations. While providing a continuous load path is an obvious design requirement for vertical loads, a continuous load path is sometimes overlooked or not completely developed when designing for lateral force resistance. The failure to review all members and connections for each combination of load can lead to weak links in the load path.

Important aspects of developing, designing, and detailing the lateral load path include the following:

- Considering all likely conditions of load. In addition to the basic design loads such as gravity forces, forces caused by thermal expansion or contraction, and outside events such

as wind or earthquakes, the possible directions of application of these forces must be considered.
- Providing means of collecting load or force from one element (such as roof sheathing) and transferring it to another (such as a wall).
- Ensuring stiffness compatibility of load-resisting elements acting in parallel (before and after yield). For example, welding cannot be used to "increase" the strength of a connection using bolts, because slight movement or slip within the bolted connection may cause the more rigid weld to bear all of the force and fail.
- Considering eccentric loading or attachment conditions. It is often not physically possible to attach parts together in a concentric manner and some eccentricity must be permitted in order to make the attachment. This eccentricity causes additional bending and deformation forces in the local area around the connection that the structure must be designed to resist. These local forces are often referred to as secondary. However, they can be very large and often cause failures if not adequately considered in the design.
- Considering transfer of design loads through the foundation system into the surrounding soil. Inadequate consideration may result in portions of a structure sliding in the soil or in local foundation settlements due to high bearing pressures.

Structural Geometry

Although it is typically the structural engineer's responsibility to determine the actual details of structural resistance, the architect and other design team members can also greatly affect the ultimate resistance of the structure by controlling the configuration of the structure and the distribution of weight. The configuration of a structure can have significant impact on the way it behaves when subjected to extreme loads.

Although architectural design impacts the overall structural configuration, local geographic, cultural, and climatologic conditions can also dictate many aspects of building geometry. In coastal flood zones, for example, structures may need to be elevated on columns or piers above potential storm surge or flood heights. In inner-city areas, local planners often promote street-level plazas or parking into the design of tall buildings, which redefines the building geometry in lower levels.

A simple, symmetrical, and regular structural geometry tends to result in better performance of structures subjected to extreme loads such as earthquakes or blasts. Buildings with significant irregularities in geometry, mass, or stiffness tend to twist or deform unevenly as the building is overloaded, resulting in local areas of high stress concentration. Although irregular features often create pleasing aesthetic effects, such areas can also become early damage initiation points that can rapidly degrade structural integrity and result in poor performance unless additional attention is given to them during design and construction.

It is the mutual responsibility of the architect and structural engineer to identify and resolve geometry problems early in the design process. The challenge to the design team is to create a building with a structural system that is reasonably regular and yet still retains the intended form and function. Poor geometry can result in poor performance unless special attention is given during the design process (often at increased design and construction cost).

Designing Structures to Resist Overstress

Traditionally, the possibility of overload or overstress has not often been considered in structural design, except in areas of active seismicity or buildings subject to possible blast pressures. Structures designed without such consideration of inadvertent overload could collapse when subjected to moderate overloads or an inadvertent failure of a single member. Structures specifically designed to resist strong earthquakes or large blast pressures, however, are typically detailed with toughness and redundancy. Tough and redundant structures may have the same strength and general appearance as other structures, but contain a reliable method of resisting possible overloads without collapse.

Although buildings are designed to resist most load conditions without damage, unpredicted overload conditions can occur, and for some design load conditions, overstress and damage can result. When these unpredicted conditions happen, structures may experience undesirable failure modes. Undesirable failure modes include those resulting in total collapse of the structure, such as caused by progressive column failures, and those involving sudden failure, such as a buckling or brittle (e.g., shear) failure.

During overload conditions, structural materials that are overstressed may crack, buckle, or yield. Once such behavior, often termed *nonlinear behavior,* occurs, the load-deformation characteristics of the element—that is, its ability to resist loading without adverse deflection—changes substantially. When nonlinearity occurs, the structural elements either behave in a brittle manner, in which rapid loss of load carrying capacity occurs, or in a ductile manner, in which the element can continue to carry load, but may have substantially increased deformation and deflection. The difference between brittle and ductile behavior can be demonstrated by the following example. If a piece of chalk is bent, the chalk quickly breaks, as the bending stress exceeds the tensile strength of the chalk. On the other hand, if a metal paper clip is bent, the metal deforms and refuses to break unless bent back and forth many times. The chalk is brittle; the metal paper clip is ductile.

Ductility is a material property that exists only for nonbrittle materials such as steel. It is a measure of the material's ability to undergo nonlinear deformation without fracture (breaking). Nonlinear behavior can be safely accommodated in structures that use ductile materials (such as steel) either as the primary structural element or as reinforcing for more brittle materials. For example, plain concrete and masonry are brittle materials, but properly reinforced concrete and masonry can behave in a ductile manner and produce structures that exhibit satisfactory seismic performance. Conversely, although steel is an inherently ductile material, proper proportioning of members and design and detailing of connections is necessary to assure ductile behavior of the overall structural system. A structure can be designed to resist overstresses in a ductile

manner. Important features of ductile design include (1) selecting ductile materials and member configurations, (2) assuring that connections are stronger than the elements they connect, (3) providing redundancy or backup systems, and (4) controlling damage modes.

Redundancy in a structural system allows for redistribution of internal loads around local areas of overstress or failure. Redundancy effectively provides a backup system for protection against collapse when localized failures occur. As an example, a cantilever is a nonredundant structural system and collapses when yielding occurs at the base of the cantilever.

Some elements behave in a ductile manner if subjected to one type of loading and in a brittle manner if subjected to other types of loading. For example, reinforced concrete or masonry beams generally behave in a ductile manner when overloaded in bending, but behave in a brittle manner when overloaded in shear. Careful design practice can control the actual failure mechanism by proportioning the beam to be stronger in shear than it is in bending, so that the more ductile mode then controls the behavior.

BASIC DESIGN METHODOLOGY

In building design, there are three basic approaches: allowable stress design, load and resistance factor design (LRFD), and performance-based design.

Allowable Stress Design

Allowable stress design is the simplest and most common method used for building design. Fundamentally, it requires that the applied forces or stresses on any element not exceed the strength of that element divided by a factor of safety. The factor of safety used generally varies from 1.5 to 3.0, depending on the reliability or variability of the data on which the value of strength is determined and also the consequences of failure. Forces in individual elements are calculated using the various design loads and forces prescribed by the building code. Element strengths are calculated in accordance with procedures specified by material design standards published by different organizations supported by the materials industries.

EXAMPLE: A steel beam is made from material with a specified minimum yield strength of 36,000 lb/in.^{2} (248,000 kPA). Building codes require a minimum factor of safety of 1.5 for simple gravity (dead plus live) loads. Thus, the beam must be designed for this condition using a maximum "allowable stress" of 36,000/1.5 = 24,000 lb/in.^{2} (248,000/1.5 ≈ 165,000 kPa).

One drawback associated with the allowable stress design method is that the factors of safety used are generally independent of the certainty inherent in the definition of the applied loading. Structures that support basically nothing other than self-weight are designed using the same factor of safety as structures that support highly variable and unpredictable types of loading, such as vehicular traffic, although it would be more appropriate to provide a greater margin of safety when the loading is uncertain.

Load and Resistance Factor Design (LRFD)

The load and resistance factor design method is an alternative procedure that provides several improvements over the allowable stress design method. These include the following:

- Load and resistance factor design separates the factor of safety into components that are separately applied to the types of loading experienced and the types of elements used. Hence, the factor of safety in any structure or element varies, based on the uncertainty in both the expected loading and the predictability of the element strength.
- The procedures for calculating the strength of structural sections more realistically estimate the likely value than those used in allowable stress design procedures. This provides the opportunity to compare the strengths of any element relative to another, so that the path of failure due to overload becomes more transparent. By calculating the expected strength of each component, the engineer gains the opportunity to proportion the structure in a manner so that overload conditions are less likely to result in catastrophic failures.

Although the load and resistance factor design method offers many improvements over the allowable stress design method, many engineers regard the method as more complex and confusing. Hence, both methods are still commonly used. Although load and resistance factor design is common for concrete elements, allowable stress design has been common for the design of steel, timber, and masonry elements. The design profession is slowly moving toward universal adoption of LRFD procedures.

A Third Approach

Although both the allowable stress and load and resistance factor design methods incorporate a finite probability of structural failure, this may be misunderstood by the public, who may believe that there is no possibility of failure of a code-conforming structure. For example, owners of relatively new buildings may be upset to learn, following relatively moderate earthquakes, that their damaged building had performed within the intent of the building code. The expected response after a hurricane may be similar.

Ordinary occupancy buildings designed in accordance with building codes are intended to provide good and serviceable performance for load conditions commonly encountered, resist relatively rare load conditions with moderate but repairable damage, and provide protection against collapse for very rare extreme events (see Section 1, Chapter 7, "Protecting Against Extreme Events"). For some hazards such as tornadoes, very little protection is provided. Essential facilities such as hospitals and fire stations are designed with expectations of somewhat better performance. Specifically, the minimum permissible design loads for such structures are increased relative to those for ordinary occupancy structures. However, the extent that the actual performance of these essential facilities is improved is not quantifiable. Although very special structures such as nuclear power plants can be and have been designed to resist all kinds of extreme events without damage, the added cost of design and

construction and the required limitations on architectural freedom have limited building codes to providing lower levels of protection.

Sophisticated owners of very valuable or important facilities have sought better quantification of the risks associated with extreme events, to permit them to make better business decisions and tradeoffs between paying added initial costs for better building construction and avoiding the future costs of insurance protection, damage repair, and potential business interruption. This has led to the development of a third design methodology—*performance-based design.*

Performance-Based Design

Rather than following prescriptive requirements contained in the building codes, the design professional using performance-based design procedures directly develops a design capable of achieving specific performance goals and objectives. Performance-based procedures intended to ensure adequate fire/life safety protective features in buildings have been under development for a number of years. Recently, structural engineers have also begun to develop performance-based design procedures, primarily for application to earthquake-resistant design.

The structural engineer using performance-based design applies a procedure to predict and estimate damage or behavior anticipated of a structure's design to design events, compared against preselected objectives. The design is revised until the predictive methodology indicates that acceptable performance can be obtained. Predictive methods can include calculation procedures as well as construction and laboratory testing of prototype designs. Performance-based design benefits owners who want to understand how their buildings may be expected to perform if they are subjected to various design events. It also helps them determine levels of acceptable performance based on the costs of different levels of performance.

Building owners have the three following basic interests in relation to building performance:

- Preservation of safety
- Preservation of capital
- Preservation of function

Some building owners may not be particularly interested in either preservation of the capital invested in a building or in maintaining its function, feeling that the probability of a damaging event is low and that insurance is available and sufficiently inexpensive to provide protection against these rare unexpected events. For other building owners, performance-based structural design is an attractive alternative approach that provides financial justification for providing the same or better performance than that defined in the building code.

Building Importance Defined in Building Codes. The basic reason that municipalities adopt building codes is to protect the public safety; the primary goal of building codes is, therefore, to protect life safety for the most severe events (fire, wind, earthquake, etc.) likely to affect the structure during its life. In effect, codes deem some buildings more important than others. For some types of buildings, structural failure could result in greater loss of life than other types or could result in the loss of vital disaster recovery services. Greater protection is warranted for such buildings. To assist with the assignment of appropriate levels of safety to buildings with different intended occupancies and uses, the American Society of Civil Engineers' *Minimum Design Loads for Buildings and Other Structures*[5] defines several standard occupancy categories. An abbreviated summary of these occupancy categories follows:

- *Occupancy type I.* This category includes structures such as sheds or agricultural buildings that are normally unoccupied. The failure of such buildings is unlikely to result in significant probability of life loss. Therefore, relatively little protection is required for such structures, and it is considered acceptable if they collapse during a rare event.
- *Occupancy type II.* This category includes most types of buildings, including most commercial, residential, and institutional structures. It is literally defined in the building codes as all buildings except those specifically included in other categories. Under extreme loading these structures are expected to be heavily damaged but not collapse.
- *Occupancy type III.* This category includes important buildings that accommodate a large number of people, that provide important public services (such as utilities), or that house occupants with limited mobility such as schools or detention facilities. It also includes facilities that house moderately hazardous substances, such as certain chemicals or petroleum products, and facilities with potential to cause a substantial economic impact or mass disruption of life in the event of failure. Greater protection against collapse is warranted for these structures for rare events, and less damage is acceptable for more moderate events.
- *Occupancy type IV.* This category includes buildings that are deemed to be essential to the public welfare such as hospitals; fire, rescue, and police stations; and essential communication, transportation, and water storage facilities. It is highly desirable that these facilities be capable of functioning following even a rare event.

Benchmark Damage Levels. In recent years, a series of standard definitions of tolerable damage levels, termed *performance levels,* have been developed. Standard definitions are found in *NFPA 5000®, Building Construction and Safety Code®*:

- *Serviceability performance.* The serviceability level of performance is a state in which structural elements and nonstructural components have not sustained detrimental cracking or yielding, or degradation in strength, stiffness, or fire resistance requiring repair that is troubling to occupants or disruptive of building function. Nonstructural components and permanent fixtures and features have also not become displaced or dislodged.
- *Immediate occupancy performance.* The immediate occupancy level of performance is a state in which minor, repairable cracking, yielding, and permanent deformation of the structure and nonstructural elements may have occurred. Although repair may be required, the structure would not be considered unsafe for continued occupancy.

- *Collapse prevention performance.* Under this level of performance, the building may experience substantial damage to structural and nonstructural elements, with some failures occurring. However, collapse is avoided and emergency responders can effect occupant rescue and building evacuation.

Quantification of Risk. The fundamental improvement that the performance-based design method offers is a quantification of the degree of risk of damage associated with load events that are likely to occur, might possibly occur, and could conceivably occur during the existence of a structure. Benefits of this approach are a structure unlikely to experience unwanted damage, and quantification of risk that can be directly used in financial analysis by evaluating the cost/benefit of increased performance versus future insurance payments and risk of loss (Figure 1.2.11). For the basic occupancy types defined in building codes, risk levels for various types of transient loading are defined to be consistent with the performance objectives outlined in Figure 1.2.11.

Criteria to Confirm Compliance. To assess the damage level associated with any risk level of loading, design procedures must present criteria for determining the strength or deformation resistance of each building element at each damage level. ASCE/FEMA 356 "Prestandard for the Seismic Rehabilitation of Buildings"[6] and Appendix G of the SEAOC "Recommended Lateral Force Criteria and Commentary"[7] provide criteria that may be used to determine these values.

SUMMARY

The combination of building codes, design load standards, material design standards, and the engineering process provides a reasonably uniform factor of safety to building design. Design load standards provide a statistically derived method to define the vertical loads and lateral forces to which buildings may be subjected, as well as uniform margins of safety in design. Material design standards define the means to determine the usable strengths of building components. The engineering process provides a rational method to determine the minimum levels of strength and toughness in individual building components and also a measure of warning to permit occupants to evacuate if overload conditions occur. Various methodologies used to design building components in the engineering process include the allowable stress, load-and-resistance factor, and performance-based design methods.

There are many challenges to safe building design. Each building is unique in location, geometry, use, construction, and condition. Because building codes, materials, and methods of construction change with time, and uncorrected deterioration may reduce the strength or safety of buildings with time, many buildings exist that would be considered substandard relative to current building codes. Even in new construction, mistakes or misunderstandings during either the design or construction process can result in building defects. In addition, design load standards referenced in building codes cannot define with certainty the actual ranges of loading or exposure to snow, wind, or other extreme events to which any building may be subjected throughout its existence.

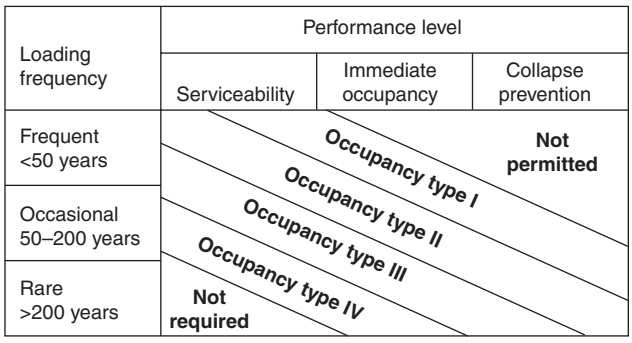


FIGURE 1.2.11 Performance Objectives for Building Occupancy Types

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fundamentals of safe building design discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA *101®, Life Safety Code®*
NFPA 5000®, Building Construction and Safety Code®

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Chapter 3

Codes and Standards for the Built Environment

Arthur E. Cote ■ Casey C. Grant

Throughout history there have been regulations for the built environment that are intended to prevent fire and restrict its spread. Over the years, these regulations have evolved into the codes and standards developed by organizations concerned with safety. In many cases, a particular code dealing with a hazard of paramount importance may be enacted into law.

See also Section 1, Chapter 2, "Fundamentals of Structurally Safe Building Design"; Section 1, Chapter 5, "Fire Prevention and Code Enforcement"; and Section 11, "Fire Prevention Practices."

HISTORY OF REGULATIONS FOR THE BUILT ENVIRONMENT

Rules and Regulations from the Ancient World

King Hammurabi, the famous lawmaking Babylonian ruler who reigned from approximately 1795 to 1750 B.C., is probably best remembered for the *Code of Hammurabi,* a statute primarily based on retaliation.[1]

The *Code of Hammurabi* is arguably the most well-known and best preserved of the regulatory codes serving the ancient world. It was carved on an 8-foot-high black stone monument (Figure 1.3.1) and was clearly intended to be on display in public view for the citizens of the day. In the year 1901 the stone was discovered, not in Babylon, but in a city of the Persian mountains to which some later conqueror is assumed to have carried it in triumph.

This noted code organizes and displays a legal system that appears to be well established and, thus, it provides testament to the earlier societal regulatory doctrines that surely predate it. Extensive in nature and covering many topics, including property, mercantile exchange, and family responsibilities, the following decree from the *Code of Hammurabi* is among those more closely related to what might be considered the inchoate roots of modern building codes:[2]

> 229: If a builder build a house for some one, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death.

Today, society no longer endorses Hammurabi's ancient law of retaliation but rather seeks to prevent accidents and loss of life and property. The current legal system serves as the retaliatory arm when negligence is found to be the cause of harm to an individual. After close to four millennia, rules and regulations have evolved that represent today's codes and standards for the built environment.

The earliest recorded building laws appear to be more concerned with the prevention of collapse. Although fire was still a threat, collapse due to poor construction and the inability to adequately address large-scale destructive events due to naturally occurring hazards such as wind and earthquake seemed to be more prominent in the minds of policy makers of the day.

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Concepts of Safety Versus Risk
Role of Codes in the Built Environment
International Considerations
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Enforcement of Codes and Standards
Codes for the Built Environment

Key Terms

building code, code, conflagration, consensus code, fire prevention code, performance-based approach, prescriptive-based code, standard, standards-developing organization

FIGURE 1.3.1 The *Code of Hammurabi* (Source: Babylonian Plaque from Chaldea with Cuneiform Writing Sculpture/Relief, Musée de Louvre, Paris; © Superstock, Inc./Superstock)

When the cities of the ancient world burned, it was typically due to the incursion of a hostile neighbor, and the likely policy response was military power rather than fire prevention measures incorporated into the built environment. Regardless, the scattered historical records of the ancient world provide brief mention of citywide conflagrations not caused by warfare, most notably the conflagrations said to have occurred in the ancient cities of Knossos, Crete (Greece), in 1450 B.C., Babylon, Mesopotamia, in 538 B.C., Carthage in 146 B.C., and Rome in A.D. 64. However, record keeping and statistical loss data for these early conflagrations are admittedly inconsistent and riddled with exaggerations that at times are striking. As a result many of these incidents exist today more as folklore than verifiable recorded events.

As civilization grew, so did the recognition that fire was a threat that needed to be addressed. Among the earlier legal rules taking a regulatory stand specific to fire, one well-preserved doctrine is traced to the Roman Empire in what is known as *The Law of the Twelve Tables*.[3] Established circa 450 B.C., Table VIII, Part 10 of this set of regulations indicates:

> 10. Any person who destroys by burning any building or heap of corn deposited alongside a house shall be bound, scourged, and put to death by burning at the stake provided that he has committed the said misdeed with malice aforethought; but if he shall have committed it by accident, that is, by negligence, it is ordained that he repair the damage or, if he be too poor to be competent for such punishment, he shall receive a lighter punishment.

As with earlier regulatory codes, retaliation after an incident had occurred remained the primary enforcement vehicle, and preventative design concepts still eluded the primary policy makers. Nevertheless, we see here a focus on fire rather than structural collapse and similar nonfire occurrences, and this focus distinguishes *The Law of the Twelve Tables* of the Roman Empire from other early regulatory codes for the built environment.[4]

Perhaps most notable and best documented among the nonwarfare-initiated conflagrations of premodern civilization is the burning of Rome in A.D. 64. The legacy of this fire is based on the sheer magnitude of the event, as the fire was devastating and Rome was by far the largest city the ancient world had ever seen. The fire began during the night of July 18 in the merchant section of the city, and after burning for six days and seven nights in this city with a population estimated at close to 1 million inhabitants, it left 70 percent of the city destroyed. Only 4 of the city's 14 wards remained intact. In addition to the unparalleled magnitude of the fire, it also gained further lasting historical significance due to the political outfall and subsequent religious persecution of the Christians who became the focus of blame for the fire.[5]

Early Building and Fire Laws

Throughout the Middle Ages, Europe bore witness to numerous citywide conflagrations; however, these were most often the result of raids, attacks, or warfare rather than natural or more conventional accidental occurrence. But the roots of modern fire regulations were slowly evolving. In England, Alfred the Great instituted fire prevention regulations in 871 that mandated the covering of cooking fires at night. Existing fire prevention regulations were reportedly further strengthened by William the Conqueror in 1000. In 1189, the mayor of London promoted the "Assize of Buildings," which regulated all methods of building and among other details recommended use of party walls made of stone to mitigate fire spread. The "Assize of Buildings" is considered one of the earliest of the European building codes, but it is unclear how widely it was used or enforced since large fires still occurred, such as the great fire of 1212 that partially destroyed the city of London.[6]

Later, there evolved many building regulations for preventing fire and restricting its spread. In London, during the fourteenth century, an ordinance was issued requiring that chimneys be built of tile, stone, or plaster; the ordinance prohibited the use of wood for this purpose. All of these measures, however, were relatively primitive and resulted in marginal or nonexistent positive impact. In the meantime, the populations of European cities were increasing at striking rates and the features of many cities were radically changing as they attempted to keep up with the population growth.

Another European citywide fire of historic proportions was the great fire of London in 1666. Burning over a period of five

days, this fire destroyed some 13,000 buildings and left an estimated 100,000 inhabitants homeless. As a result, the English Parliament introduced legislation known as the London Building Act. Yet in the years subsequent to the fire, the noble efforts of the policy makers to rewrite the basic design approach met with only partial success, as there was apparently little or no enforcement mechanism, and they met with questionable success in the years that followed.[7]

Another noteworthy milestone that resulted from the great London fire of 1666 was the spawning of the fire insurance industry. The modern contractual concept of insurance predates the event and may have occurred as early as 1347, based on activities recorded in Genoa, Italy. This contractual insurance arrangement, as well as others, provided the right circumstances to evolve into a viable business model immediately after the fire. Following the disaster, Dr. Nicholas Barton founded the Phoenix Fire Insurance Company and implemented the first use of "fire marks," which were metal or ceramic plaques affixed to the exterior of insured buildings to identify them to the insurance company's private fire brigades that they were to be protected. The Phoenix Fire Insurance Company began underwriting in 1680 and ceased trading in 1712, but the concept prospered and over the next 250 years over 200 different companies used about 80 different design plaques across the United Kingdom. The concept was imported to the United States but developed in reverse, since insurance ultimately evolved from the fire brigades rather than the fire brigades evolving from the insurance companies.[8] Today the insurance industry continues to have a major influence on the collective conscience of society when it comes to fire-safe buildings. Its influence on shaping fire safety policies, including prevention and mitigation, has been significant, since its collective approach to loss is less tolerant than society tends to be on an individual basis. In other words, someone else's losses are no longer someone else's, since we all ultimately pay for those losses through shared increases in our own insurance premiums. Insurance makes us collectively more responsible and, thus, the insurance industry continues to play an important role in shaping today's fire protection safety infrastructure for the built environment.

A conflagration is generally recognized as a large destructive fire, and in the insurance industry it is understood to be a fire that causes substantial destruction. A review of the historical record indicates a seemingly countless list of incidents when cities from the earliest civilizations have been either partially or totally destroyed by fire. Warfare is an obvious factor in some of these incidents, but even when removing those that are the result of embattled people, fire has still been a scourge throughout the millennia. Admittedly, the historical records from ancient times are lacking specificity, but nevertheless a review of various sources on file in the NFPA Library has resulted in mention of the incidents listed in Table 1.3.1.

Although the Industrial Revolution had a dramatic effect on the growth of the populations and overcrowding in urban cities across the globe and the resulting increase in the occurrence of devastating large-scale fires, it also marked a historical turning point for technological innovations that became part of the arsenal for protecting the built environment. The nineteenth century saw a plethora of new devices and technological innovation for fire protection. The proverbial parade of advancements is noteworthy: in 1800 Englishman John Carrey invented a crude automatic sprinkler; in 1821 Joseph Boyd patented the first rubber-lined cotton fire hose; in 1845 William Channing was credited with the invention of the first fire alarm telegraph; in 1852 a patent was issued for the first sprinkler perforated pipe system; also in 1852 the first Central Office (i.e., central station) and fire alarm boxes were installed in Boston; in 1853 the first practical motorized fire pumper was tested in Cincinnati; in 1860 Philip Pratt produced the first practical automatic sprinkler system; in 1863 Alanson Crane patented the first portable fire extinguisher; in 1864 Stewart Harrison produced the first practical sprinkler, significantly improved in 1874 by Henry Parmelee and again in 1880 by Frederick Grinnell. These inventions continued into the twentieth century with important technological innovations, such as the invention in 1940 of soy protein aerofoam by Percy Julian, the introduction of high-pressure water mist fog nozzles in 1942 by the U.S. Navy, and the invention in 1969 of the first battery-powered smoke detector by Randolph Smith and Ken House.[9]

Yet aside from these built-in fire protection devices, tools, and agents, the age-old natural commodity of water still remained the primary tool in the fire protection arsenal. Delivering water to control a fire was viewed as critical in the ancient world, and it remains so today. The earliest fire pump is generally credited to Ctesibius of Alexandria in the second century B.C. During medieval times, the fire pump was reinvented in Europe and is reported to have been used in several German cities, including Augsburg in 1518 and Nuremberg in 1655. Various reports exist throughout the next several hundred years of fire apparatus used in cities such as Boston, London, and Philadelphia, with the eventual development of steam-powered, horse-drawn pumpers replacing more primitive hand pumps, which

TABLE 1.3.1 Various Notable Citywide Nonwarfare Conflagrations Through History

City	*Year*
Knossos, Crete (Greece)	1450 B.C.
Babylon, Mesopotamia	538 B.C.
Carthage	146 B.C.
Rome	64
London	1212
Moscow	1570
London	1666
Constantinople	1729
Lisbon	1755
Bombay	1803
Moscow	1812
Cairo	1824
Hamburg	1842
Constantinople	1922
Managua, Nicaragua	1931
Hakodate, Japan	1934
Chungking	1949
Guatemala City	1960

in turn were replaced by motorized apparatus of similar basic design to what is used today. In the late 1800s, as "tall" buildings (i.e., 15 stories) started to become a part of the cityscape, water towers and aerial ladders made their appearance in European and U.S. cities.[10]

In colonial America, the need for laws that offered protection from the ravages of fire developed simultaneously with the growth of the colonies. The laws outlined the fire protection responsibilities of both homeowners and authorities. Some of these new laws were planned to punish people who put themselves and others at risk of fire.

Among the first legislative acts in colonial America were those of New York City and Boston requiring that dwellings be constructed of brick or stone and roofed with slate or tile, rather than built of wood with thatched roofs and wood chimneys covered with mud and clay. The intention of these building ordinances was to restrict the spread of fire from building to building in order to prevent conflagrations. As an incentive for helping to prevent fires in Boston, a fine of 10 shillings, equivalent to about $100 in 2007, was imposed on any householders who had chimney fires. This fine encouraged citizens to keep their chimneys free from soot and creosote. This ordinance was among the first fire code requirements in America to be established and enforced.

As further examples, in colonial Boston no person was allowed to build a fire within "3 rods" (about 49.5 ft or about 15.5 m) of any building or in ships that were docked in Boston Harbor. It was illegal to carry "burning brands" for lighting fires except in covered containers, and arson was punishable by death. Regardless of such precautions, in Boston and in other emerging communities, fires were everyday occurrences. Therefore, it became necessary to enact more laws with which to govern building construction and to make further provisions for public fire protection. There emerged a growing body of rules and regulations concerning fire prevention, protection, and control. From these small beginnings, various codes have evolved in the United States, ranging from the most meager of ordinances to comprehensive handbooks and volumes of codes and standards on building construction, systems, processes, and general fire safety.[11]

Development of Modern Building and Fire Regulations

The rapid growth of early North American cities inspired much speculative building, and the structures usually were built close to one another. Construction often was started before adequate building codes had been enacted. For example, the year before the great Chicago fire of 1871, Lloyd's of London stopped writing policies in Chicago because of the haphazard manner in which construction was proceeding. Other insurance companies had difficulty selling policies at the high rates they had to charge. Despite these excessively high rates, many insurance companies suffered great losses when fire spread out of control.

With the widespread immigration and rapid growth of North American cities, the nineteenth century witnessed fire after fire sweep through large urban centers. The ability to quickly rebuild and the boundless resources available in the new frontier, along with the laissez-faire attitude of North America settlers, created a societal character of relative indifference to these large-scale fires. A fair question was, when would the plague of destruction reach a point when society would no longer tolerate these events? Some will argue that the turning point occurred with the great Chicago fire of 1871.

The summer and early autumn of 1871 had been particularly dry in the Northern Lakes region of the midwestern United States, and on October 8, 1871, fire visited the city of Chicago. Starting around 9:00 p.m., the incident originated in a cow barn on Chicago's west side and by midnight the fire had spread furiously and jumped the nearby river. When the flames finally were confined two days later, approximately 250 citizens had lost their lives, some 18,000 buildings were destroyed, and approximately 100,000 people were homeless.[12] As a historical footnote, in northern Wisconsin a forest fire unrelated to the Chicago fire occurred on the same evening and virtually erased the town of Peshtigo, Wisconsin, and surrounding villages, resulting in a death toll estimated at over 1500 and ranking among the worst life-loss fire events in North American history. Since 1922, based on a presidential proclamation, Fire Prevention Week is celebrated during the first week of October each year in remembrance of the Chicago and Peshtigo disasters.[13]

Following the Chicago fire, the so-called "great rebuilding" took place with rapid replacement of the structures in the burned districts. Unfortunately, the freewheeling construction and nonexistent enforcement replicated many of the inherent design mistakes that allowed the fire of 1871 to spread with such rapidity, and just three years later in 1874, another fire occurred that destroyed 800 buildings. Finally, more definitive action occurred to strengthen the local building and fire regulations.

Following the great Chicago fire of 1871, various professionals seeking to learn from the disaster visited the city. Boston Fire Chief John S. Damrell learned much from the Chicago fire, but his warnings to his own city were ignored by the city fathers who held the somewhat condescending view that their style of masonry and granite construction was superior to the heavily wooden construction of the Midwest and elsewhere. Damrell thought otherwise and was significantly concerned with the wood mansard roofs atop the granite and masonry structures as well as the poor water supplies in the heavily congested downtown area. His fears would manifest themselves on Saturday, November 9, 1872, sometime after 7:00 p.m., when fire struck a five-story mercantile building in the high-value business district. A delayed alarm, along with an equine epidemic that crippled all the fire horses throughout the city, resulted in the fire gaining significant headway and soon it was jumping from rooftop to rooftop. By the time it was brought under control the following day, 14 people had died and 776 buildings were destroyed in the heart of the city.[14]

It is worth pausing to reflect on the significant influence of Chief Damrell in advancing the cause of fire safety after the great Boston fire. Damrell was chief of the Boston Fire Department from 1866 to 1877 (which includes the great Boston fire of 1872). He then became chief of the City Department of Inspection in Boston from 1877 to 1903. He was one of the founders of the National Association of Fire Engineers (NAFE) in 1873, which today is the International Association of Fire

Chiefs (IAFC), and was its first president. He also was one of the founders of the National Association of Commissioners and Inspectors of Public Buildings (NACIPB) in 1891 and likewise served as its first president. Among his accolades relating to the built environment, he was an outspoken proponent of the need for national building and fire codes, and he directly contributed to a draft developed by the NAFE in the mid-1870s. This document was among the earlier comprehensive draft building codes of that era, which subsequently had an influence on the development in 1896 of the "National Board's Model Building Law," compiled by the National Board of Fire Underwriters (NBFU) for an unsuccessful initiative to have a building code adopted in New York State.[15] This eventually led to the publication in 1905 (after his death) of the *Building Code Recommended by the National Board of Fire Underwriters,* published by the NBFU, which was operating at that time in conjunction with the National Fire Protection Association (NFPA).[16]

The National Board of Fire Underwriters, which was later renamed the American Insurance Association (AIA) and now is the American Insurance Services Group (AISG), organized in 1866, realized that the adjustment and standardization of rates were merely temporary solutions to a serious technical problem. This group began to emphasize safe building construction, control of fire hazards, and improvements in both water supplies and fire departments. As a result, the new tall buildings constructed of concrete and steel conformed to specifications that helped limit the risk of fire. These buildings were called Class A buildings. The 1905 *NBFU Building Code,* which would later become the *National Building Code* (NBC), was a first and very useful attempt to show the way to uniformity. As reported at the 19th Annual Meeting of the NFPA (in 1914) that included a symposium on state and local building codes, North Carolina was the first state to adopt a state building code (about 1905), Wisconsin had also adopted a code, and Ohio, Illinois, and Pennsylvania were in the process of doing so.[17]

In San Francisco in early 1906, although there were some new Class A concrete and steel buildings in the downtown section, most of the city consisted of fire-prone wood shacks. Concerned with such conditions, the National Board of Fire Underwriters wrote that "San Francisco has violated all underwriting traditions and precedents by not burning up."[18]

On April 18 of that same year, the city of San Francisco experienced a conflagration—started by an earthquake—that killed 452 people and destroyed some 28,000 buildings. Total financial loss was $350 million, which is over $6.7 billion in estimated 2000 dollars.[19] Although the contents of many of the new Class A buildings were destroyed in the San Francisco fire, most of the walls, frames, and floors remained intact and could be renovated.

Cities across North America have experienced significant destruction throughout the years by large destructive fires. Even after eliminating consideration of fires caused by warfare, there is a significant number of these incidents. A review of various sources on file in the NFPA Library has resulted in mention of the incidents listed in Table 1.3.2.

The burning of the city of San Francisco in 1906 was daunting by its sheer magnitude of loss, as illustrated by Figure 1.3.2. Yet of the many individual stories of survival, one particularly worthy of further mention from a historical context is the successful defense of the San Francisco Mint, also known by the nickname of the "Granite Lady." Built in 1874, by 1880 it was producing 60 percent of U.S. gold and silver coins, and until the Fort Knox depository opened in 1937 it would hold roughly a third of the nation's gold reserves in its vaults. With a group of mint employees and soldiers, mint Superintendent Frank Leach used a specially designed internal water-well and hose system to defend the building while everything around it was totally consumed by fire. The direct loss of the facility would have been catastrophic, but some have estimated that the indirect loss would have been worse and might have included the collapse of the U.S. economy. After the fire, the mint was the focal point of the financial regrowth, and today the landmark building is the San Francisco History Museum.[20]

Following analysis of the fire damage caused by the San Francisco disaster and other major fires, the National Board of Fire Underwriters became convinced of the need for more comprehensive standards and codes relating to the design, construction, and maintenance of buildings. With this increasing recognition of the importance of fire protection came more knowledge about the subject. Engineers started to accumulate information about fire hazards in building construction and in manufacturing processes, and much of this information became the basis for the early codes and standards.

TABLE 1.3.2 Various Notable Citywide Nonwarfare Conflagrations in North America

City	*Year*	*Estimated Buildings Destroyed*
Charleston	1740	300
New York City	1835	674
Charleston	1838	1,158
Philadelphia	1839	52
Pittsburgh	1845	1,115
Quebec	May 1845	1,500
Quebec	June 1845	1,300
San Francisco	1851	500
Sacramento	1852	2,600
Troy, NY	1862	507
Philadelphia	1865	50
Portland, ME	1866	1,500
Chicago	1871	15,000
Boston	1872	776
Galveston, TX	1885	568
Seattle	1889	640
Minneapolis	1893	200
Atlantic City	1902	12
Baltimore	1904	1,600
San Francisco	1906	28,188
Chelsea, MA	1908	3,500
New Bern, NC	1922	600
Chelsea, MA	1973	1,400

Note: For sake of comparison, the great fire of London in 1666 consumed 13,000 buildings.

FIGURE 1.3.2 The Great Earthquake and Ensuing Conflagration That Devastated San Francisco in 1906

At the dawn of the twentieth century the cities of North America were experiencing rapid growth, and the scourge of uncontrolled fires destroying portions or even entire cities was the primary focus of the building professionals of the day. But as the built environment began a fundamental shift in the early 1900s to superior building techniques that limited the building-to-building affliction of fire, attention also began to constrict inward with an additional focus on fires occurring within a single building and, in particular, fires that caused a large loss of life. A string of large life-loss fires began to catch the attention of the general public and reached an apogee with the Iroquois Theater Fire in Chicago, Illinois, that occurred on December 30, 1903, killing 602 and injuring more than 250 people.[21]

The public was becoming less tolerant of these large life-loss fires during the early years of the 1900s. The turning point came in 1911, when on March 25 a fire struck the top three floors of the 10-story Asch Building in New York City. These floors were occupied by the Triangle Shirtwaist Company, which employed garment workers (mostly young women and girls) in so-called "sweatshops." By the time this fast-moving fire was out, 146 workers had either burned to death on the upper floors or plunged to their deaths in front of tens of thousands of onlookers.

The impact of the Triangle Shirtwaist fire on the public conscience was profound. This was due in large part to the growing labor movement that was occurring at the same time, and the fire became a rallying cry for the rights of workers as exemplified by the funeral parade that followed, with an estimated crowd of 400,000 people. The event was likewise a milestone from the standpoint of codes for the built environment. One direct result of this fire of paramount historical importance was the establishment of the NFPA *Building Exits Code* two years later at the 1913 NFPA Annual Meeting. Through the years this essential model code came to be retitled as NFPA *101*®, *Life Safety Code*®, and today provides the backbone of the building exit requirements in building codes used throughout North America and in other parts of the world.[22]

CONCEPTS OF SAFETY VERSUS RISK

There are two broad categories of voluntary codes and standards: (1) safety codes and standards and (2) product standards. These documents are not solely a matter of science, especially safety codes and standards.[23] Codes and standards embody value judgments as well as facts and sometimes must use empirical evidence on judgment to compensate for gaps or limits in the relevant science (also see the *SFPE Handbook of Fire Protection Engineering*[24]). Codes and standards oriented toward safety tend to be more complicated and extensive than product standards. Furthermore, safety codes and standards are often adopted with the power of law and, thus, require more extensive technical advisory support and enforcement.

Safety is the inverse or opposite of risk, so greater safety means the reduction or elimination of some risk to people or property or some other vulnerable entity of concern. Risk can never be entirely eliminated, and so safety is never absolute. Even short of absolute safety, any relative increase in safety will not have unlimited value. Individual, organizational, or societal decision makers must decide whether a particular increase in safety (i.e., reduction in risk) is worth more to them than what they must pay in order to achieve that safety increase.

Because financial resources are the most obvious sacrifice required to decrease risk, the trade-off involved is often called "willingness to pay." The lower the risk becomes, the more it typically costs to achieve each additional constant or incremental increase in safety. In addition, part of the cost of risk elimination can be the reduction of some freedoms. Many aspects of safety systems or materials standards have this effect, as they come to bear on the establishment of an "acceptable level" of

risk.[25] In addition, the standard of care provided by the code may either eliminate certain materials or processes or set demanding performance criteria for such elements.

Assessments of levels of risk are also needed with respect to cost of use of the codes and standards themselves, including complex calculations or other costs of information. If tolerance limits are exceeded, codes and standards will be modified in practice or ignored. Also, the more onerous and costly compliance becomes, the more carefully critics will examine the "degree of contribution to a safe environment" that the code or standard will bring about. In other words, attempts at applying cost–benefit models may be used as a part of the justification for an increased level of performance or, conversely, to show why the suggested performance is impractical from an economic standpoint.

The many effects of codes and standards on what people value bring various complex factors into play—social, economic, political, legal, business-competitive, and others—that affect how much people value safety and how much they value what may be sacrificed for safety. No solely economic, engineering, or public health approach can do justice to all these factors, many of them unavoidably or even intrinsically subjective, in establishing a cost–benefit analysis.

One of the strengths of the voluntary consensus codes and standards-development system in the United States is that the deliberative committee structure, which comprises a balanced representation of all affected interests, including users, consumers, manufacturers, suppliers, distributors, labor, testing laboratories, enforcers, and federal, state, and local government officials, can consider all of the diverse factors at hand and develop a consensus on an acceptable level of standardization. It has been observed that "this may be one of the greatest strengths of the present private standards-writing system, insofar as it truly represents variety, and one of the greatest insufficiencies of a governmental system."[26] So-called government consensus simply seeks agreement from one segment of like-minded thinkers—hardly a model for consensus.

ROLE OF CODES IN THE BUILT ENVIRONMENT

Understanding the Built Environment

A *code* is a law or regulation that sets forth minimum requirements and, in particular, a *building code* is a law or regulation that sets forth minimum requirements for the design and construction of buildings and structures. These minimum requirements, established to protect the health, well-being, and safety of society, attempt to represent society's compromise between optimum safety and economic feasibility.[27]

Although builders and building owners often establish their own requirements, the minimum code requirements of a jurisdiction must be met. Features covered include, for example, structural design, fire protection, means of egress, light, sanitation, and interior finish. Inasmuch as a model building code is actually a law once adopted, various state and local jurisdictions write their own codes. Because of the complexities of modern building code development, several organizations develop model building codes for use by jurisdictions, which can then adopt the model codes into law either in total or with amendments deemed to be necessary for that jurisdiction.

In a stylistic sense, there are two broad, general approaches used to write codes for the built environment: specification or prescriptive codes and performance-based codes.[28]

Prescriptive-Based Codes

Prescriptive or specification-based codes spell out in detail what materials can be used, the building geometry (heights and areas), and how the various building components should be assembled. The traditional codes that have evolved through history tend to be prescriptive or specification oriented.

The requirements contained in the traditional building codes are generally based on the known properties of materials, the hazards and risks presented by various occupancies, and the lessons learned from previous experiences, such as fire and natural disasters. As mentioned earlier, the promulgation of modern building codes in North America began with the disastrous conflagrations that occurred in the late nineteenth and early twentieth centuries. Early building codes have grown into documents prescribing or specifying minimum requirements for structural stability, fire resistance, means of egress, sanitation, lighting, ventilation, and built-in safety equipment. Typically, more than half of a modern building code usually refers in some way to fire protection.

The establishment of height and area criteria, which is a common feature in today's building codes, provides a good example of the impact of prescriptive or specification-oriented building codes on fire protection and prevention. The criteria establish the maximum height and area of a particular building on the basis of its intended use. These requirements have typically varied considerably from one type of occupancy to the next. Requirements such as those based on height and area criteria establish inherent fire limits or fire districts for buildings or groups of buildings in certain areas of a municipality.

The prescriptive evolution of height and area requirements has a historical orientation. In 1913, Professor Ira Woolson of the National Board of Fire Underwriters presented a paper before the American Society of Mechanical Engineers, and this document provided one of the first recorded attempts to clearly articulate a set of allowable heights and areas for factory buildings. This paper was published in the January 1914 issue of the NFPA *Quarterly*.[29]

From a prescriptive or specification perspective, the types of building construction are important factors in establishing height and area limitations, and only specific types of construction are allowed within the fire limits. Such a restriction is intended to reduce the conflagration potential of the more densely populated areas. Other requirements found in prescriptive or specification-oriented building codes that directly relate to fire protection include (1) enclosure of vertical openings such as stair shafts, elevator shafts, and pipe chases; (2) provision of exits for evacuation of occupants; (3) requirements for flame spread of interior finish; and (4) provisions for automatic fire suppression systems. Exit requirements found in most building codes are based on requirements found in NFPA *101*®, *Life Safety Code*®.

Prescriptive or specification-oriented building and fire codes have historically served us well, but they also have limitations. Because of their well-defined yet rigid nature, they tend to lack flexibility for unusual or alternative designs, and they don't necessarily take advantage of the most cost-effective design solution or a clearly desirable specific level of safety. Further, they generally do not make direct use of new and useful design tools, such as state-of-the-art computerized fire models.[30]

Performance-Based Codes

Performance-oriented building and fire codes detail the goals and objectives to be met and establish criteria for determining if the objective has been reached. Performance-oriented building and fire codes are a relatively new and evolving concept, which is only in recent years enjoying widespread acceptance.

Unlike prescriptive and specification-based codes, which may or may not explicitly state their goals and objectives, a performance-based code is fundamentally grounded on the goals and objectives it contains. Its entire focus is to clarify these goals and objectives and provide an implementation method for achieving them. In contrast, prescriptive and specification-based codes are like a recipe of items that are to be followed absent of any meaningful interpretability beyond what the code states.

Building and fire codes that are performance oriented allow more flexibility for state-of-the-art designs and help identify the most cost-effective design solutions without compromising levels of safety. Performance-based codes may still embody a fair number of specification-type requirements, but provisions exist for widespread substitution of alternate methods and materials ("construction modifications"), if they can be proven adequate in the regulatory framework that accompanies the performance-based code. Thus, the designer and builder gain added freedoms to select construction methods and materials that may be viewed as nontraditional as long as it can be shown that the performance criteria can be met. Performance-based approaches have been and are being utilized today through the "equivalency" provision found in most codes and standards for a limited number of applications. In other cases, building configurations or designs may be so unusual that the only way to design them is to apply performance-based design principles to the entire structure. Examples include developing fire safety for unique architectural designs not anticipated by current codes and standards, developing equivalent means of protection to existing prescriptive requirements, and preparing fire reconstructions.[31]

Performance-based approaches today generally require a major interactive undertaking by both the designer and the authority having jurisdiction (AHJ). As performance-based approaches and their supporting pieces further mature, they can be expected to enjoy greater acceptance overall.

INTERNATIONAL CONSIDERATIONS

Basics of International Standards Development

In the common lexicon of codes and standards development, and especially in the various international arenas, the term *standards* is most generally used to characterize all the various types of standardizing documents (i.e., codes, standards, guides, policies, norms, etc.). Further clarification of the term *standard,* however, is helpful for this discussion.

This is especially true since the Agreement on Technical Barriers to Trade (TBT) under the World Trade Organization (WTO), which is further discussed later, defines the term "Technical Regulation" and "Standard." These definitions are noteworthy because of the influence of the WTO. These terms are (1) Technical Regulation: documents which lay down product characteristics or their related processes and production methods, including the applicable administrative provisions, with which compliance is mandatory; and (2) Standard: documents approved by a recognized body, that provide, for common and repeated use, rules, guidelines or characteristics for products or related processes and production methods, with which compliance is not mandatory.[32]

As a further clarification of the lexicon of international standards writing, the entities that administer various "standardizing activities" are generally known throughout the world as "standards-developing organizations" and are commonly referred to by the acronym SDO, which has been expanded in the last few years to include those SDOs that have activities or a basis in more than one country. These are now being recognized as international SDOs, or ISDOs.[33]

It is estimated that there are approximately three-quarters of a million standards in the world, based on information last compiled in 1997.[34] The number of reported documents is between one-half and three-quarters of a million documents, and the higher estimate reflects anticipated underreporting of the data and countries not included in the analysis. For purposes of comparison, Figure 1.3.3 provides general estimates of certain larger collections of national standards for selected countries around the world.

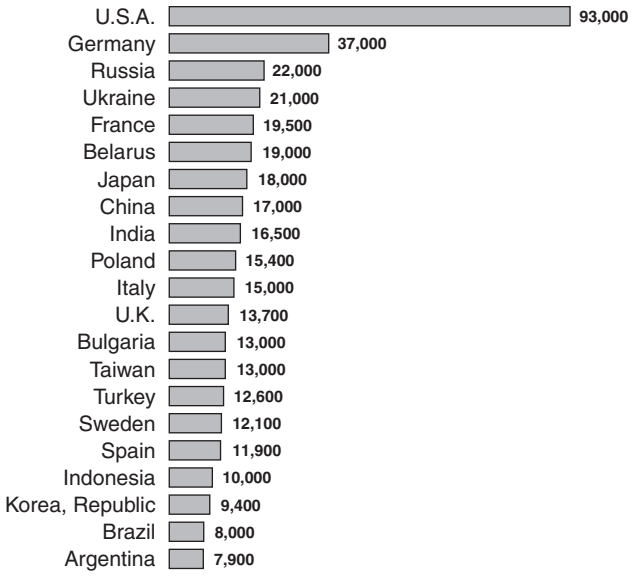

FIGURE 1.3.3 Estimates of Various Collections of National Standards Throughout the World (as of 1997)

"One-Country/One-Vote" Model. Arguably the most widely recognized ISDOs today are those of the "one-country/one-vote" design based in Geneva, Switzerland. Perhaps most notable among these are the ISO (International Organization on Standardization), IEC (International Electrotechnical Commission), and ITU (International Telecommunication Union). These organizations enjoy a casual bureaucratic recognition by various world political organizations that is not readily available to other ISDOs. They are referred to herein as "one-country/one-vote" organizations because the prime mechanism for establishing a final position on any particular subject is by a single vote from each participating country.

These organizations claim to achieve both "technical" consensus and "political" consensus. They do so by obtaining agreement of those participating on their various technical committees, first by establishing technical consensus, and then having the technical agreements ratified by a majority of member countries, which effectively establishes political consensus.

Perhaps the most noteworthy contrast to the "one-country/one-vote" processes are those based on principles involving "full consensus." This process is characteristic of the methods used by the ISDOs of North America. Each individual person, regardless of his or her particular nationality, has the ability to participate directly in the issues under consideration. "Full-consensus" organizations are more democratic in their design in comparison to those organizations based on "one-country/one-vote" and do not require a ratification of their technical consensus on a country-by-country basis.

"Full-Consensus" Model. In the realm of codes and standards development, the ISDOs located in North America have certain characteristics that make them relatively unique.[35] The significant private-sector standards-development system in the United States is largely self-regulated, with certain oversight and coordination efforts provided by ANSI (American National Standards Institute), a federation of U.S. codes and standards developers, and corporate and government users of those standards. Unlike most areas of the world, nongovernment organizations (NGOs) are responsible for the establishment, development, and ongoing maintenance and updating of these private-sector documents.

ANSI provides accreditation for the development of documents that meet its fundamental principles for full consensus. Organizations that meet these requirements typically have elaborate processes involving volunteer committees and utilizing extensive public input and decision-making authority. Although federal, state, and local governments usually participate, they do so as would any other participant. The resulting documents are referred to as "model documents," and it is then up to any particular authority to subsequently implement the issued document as it sees fit (i.e., into law, as a specification, etc.).

Of all the attributes of the North American ISDOs, of special note is the fact that they are oriented around a particular subject matter and based on individual participant involvement. A trademark of North American processes is that they are blind to the geographic roots of their input and, thus, they allow anyone, anywhere, to participate on an equal basis.

In Search of Alternative ISDO Approaches. The developers of codes and standards based in North America are characterized as either an SDO or an ISDO. These organizations typically exist with a dual personality, providing for the domestic needs of their constituents, while at the same time not being exclusively dedicated to any particular collection of those constituents (i.e., serving the needs of constituents in multiple countries).

It is admittedly a virtue to have participants involved in any process that provides wide representation rather than simply a narrow or limited focus. But is there an outward boundary to such representation, and at what point does the representation become misleading? When does it become "involvement without representation"?

At the root of these questions is the effectiveness of processes based on the collective representation of very large entities such as entire nations (i.e., the "one-country/one-vote" design). This model lends itself well to consideration of universal issues of sweeping impact, in which the singular voice of each country is able to speak clearly and contribute decisively to a common good.

But is this same model the most appropriate approach, or more importantly, to be considered the *only* approach, to myriad technical details on which civilization is built? Although it can be argued that the "one-country/one-vote" model may perhaps lend itself well to certain topics and certain types of standards-development activities, it should not be expected to be the *only* approach for all standards activities. Clearly, alternative approaches exist, and one of these approaches is the "full-consensus" approach.

The "one-country/one-vote" model does not have the flexibility to equitably address detailed technical issues in the same manner as the "full-consensus" approach. It is convenient, of course, when a particular technical topic is used in the same manner in all of the countries of the world, but the many blends of society make such a convenience a rarity.

For example, consider the common scenario in which a technical standard addresses a focused topic. In particular, consider a case study that has a relatively extreme focus, such as a hypothetical standard addressing harness gear for reindeer. Does it make sense for all the nations of the world to vote equally on this standard? Why should the nations at the equator have an equal vote with the Nordic nations that are clearly more familiar with—and affected by—the topic? The casual assumption that all topics exist equally in all nations, and that the "one-country/one-vote" model is the *only* approach needed, is not well founded.

Regional Nature of ISDOs. When discussing SDOs and ISDOs, a topic of related interest is regional organizations. These exist today both in a formal sense and in a less than formal or de facto sense.[36]

Although many jurisdictions have country-specific SDOs, there is a tendency for them to cluster regionally to assert their collective presence. The boundaries of such regions are not always geographically clear. More commonly, they are generally based on the culture and influence of the primary participants or at least those participants with the primary control.

Various examples exist of formalized regional standards bodies. Fitting this description are organizations such as CEN

(European Committee for Standardization) for Europe, COPANT (Pan American Standards Commission) for the Americas, and PASC (Pacific Area Standards Congress) for the Pacific Rim nations. Although organizations such as these are easily distinguished, it is the nonformalized regional developers that are of interest in this discussion.

In a unified sense, all the various codes and standards developers of the United States comprise a de facto regional standards body, which is particularly the case based on the coordinating role played by American National Standards Institute (ANSI). Thus, we can observe that the standards-developing organizations of the United States exist independently as SDOs, in a collective sense as a regional organization, and in a practical sense as ISDOs.

As a contrast to the North American situation, the organizations of the "one-country/one-vote" design based in Geneva, Switzerland, and in particular ISO and IEC, enjoy an informal recognition by various world political organizations that is not readily available to other ISDOs. Despite their international stature, however, are implications that they are a European-based regional organization based on their operating characteristics. For example, in late 2000 it was reported that CEN and CEN-affiliated countries (33 in all) have 50 percent or more voting members on 80 percent of all ISO committees.[37]

Today, as an observation, ISO and IEC are typically considered as ISDOs, while gaining recognition as European regional SDOs. Meanwhile, the standards organizations based in the United States are typically considered as North American regional SDOs, while gaining recognition as ISDOs.

World Trade Organization (WTO) and the Technical Barriers to Trade (TBT) Agreement. The World Trade Organization (WTO) is today generally considered the foremost-recognized global organization dealing with the rules of trade between nations.[38] Its main function is to ensure that trade flows smoothly, predictably, and freely. The goal is to help producers of goods and services, exporters, and importers conduct their business.

The WTO is headquartered in Geneva, Switzerland, with a staff of approximately 500, and is represented by 140 member countries and customs territories (as of November 30, 2000) that account for over 90 percent of world trade. Over 30 other countries are negotiating membership. At its heart are the WTO agreements, negotiated and signed by the bulk of the world's trading nations and ratified in their parliaments.

Technical Barriers to Trade. The WTO's top-level decision-making body is the Ministerial Conference, and reporting to the Ministerial Conference and considered the prime operational entity is the General Council. Three other councils and various committees, working groups, and working parties report to the General Council, but of particular note is the Council for Trade in Goods. The Council for Trade in Goods likewise has various committees reporting to it, one of which is the Committee on Technical Barriers to Trade.

This committee is responsible for the Agreement on Technical Barriers to Trade (TBT), which tries to ensure that regulations, standards, testing, and certification procedures do not create any unnecessary obstacles to free trade. Technical regulations and industrial standards may vary from country to country, and having too many different standards makes life difficult for producers and exporters. If the standards were set arbitrarily, they could be used as an excuse for protectionism.

However, the TBT Agreement recognizes that countries have the right to establish protection at levels that they consider appropriate, and they should not be prevented from taking measures necessary to ensure that those levels of protection are met based on the need to fulfill certain legitimate objectives. These legitimate objectives include protection of human health and safety, national security, prevention of deceptive practices, protection of animal or plant life or health, and the environment.

International Standards. The TBT Agreement encourages the countries to use international standards when these are appropriate, although it does not require them to change their levels of protection as a result of standardization. As guidance for member countries, Annex 3 to the TBT Agreement provides the *Code of Good Practice for the Preparation, Adoption, and Application of Standards,* which attempts to ensure that standards do not present an obstacle to international trade.

An obvious question that comes into play when attempting to implement the TBT Agreement is "What is an international standard?" This matter was first addressed in the Report (2000) of the Committee on Technical Barriers to Trade.[39] Included in this particular report is Annex 4, entitled "Decision of the Committee on Principles for the Development of International Standards, Guides and Recommendations with Relation to Articles 2,5 and Annex 3 of the Agreement." This annex outlines the principles and procedures that should be observed for the preparation of international standards and attempts to ensure the following essential characteristics:

- Transparency
- Openness
- Impartiality and consensus
- Effectiveness and relevance
- Coherence
- Ability to address the concerns of developing countries

The elements outlined here can be found as inherent traits in the various organizations that exist today to develop codes and standards in the international arena. For example, these elements fit the more commonly recognized international developers like ISO and IEC, but clearly others also meet or exceed these requirements, such as many of the North American codes and standards developers (e.g., ASME, ASTM, IEEE, NFPA, and others). For certain aspects such as openness, impartiality, and consensus, the "full-consensus" approach and the "one-country/one-vote" approach are arguably equivalent in the way they meet these characteristics. No directly interested party is disenfranchised.

ROLE OF STANDARDS IN THE BUILT ENVIRONMENT IN THE UNITED STATES

While the term *standards* is often used to describe all standardizing documents, including codes for the built environment (es-

pecially in North America), a distinction exists between codes versus standards. As previously noted, a code is a law or regulation that sets forth minimum requirements where something must be done. A standard typically spells out the methods for achieving the desired result; that is, "how" something must be done. However, the distinction is not precise and it is not always easy to differentiate between a code and a standard.

Many requirements found in building codes are excerpts from, or based on, the standards published by nationally recognized organizations. The most extensive use of the standards is their adoption into building codes by reference, thus keeping the building codes to a workable size and eliminating much duplication of effort. Such standards are also used by specification writers in the design stage of a building to provide guidelines for the bidders and contractors.

Numerous NFPA standards are referenced by model building codes and, thus, obtain legal status where these model codes are adopted. Notable examples of such referenced NFPA standards are those that deal with extinguishing systems, flammable liquids, hazardous processes, combustible dusts, liquefied petroleum gas, electrical systems, and fire tests.

The model building codes contain entire chapters or appendices that list standards published by many organizations, including standards-making organizations, professional engineering societies, building materials trade associations, federal agencies, and testing agencies. The sections are prefaced with a statement indicating that the standards are to be used where required by the provisions of the code or where referenced by the code.

Fundamentals of Voluntary Consensus

The voluntary standards development system in the United States is efficient, cost-effective, and highly productive and results in the promulgation of thousands of quality standards each year. A diverse, decentralized network of private-sector entities develops the U.S. voluntary standards. Many different organizations are involved, and this feature is one of the great strengths of the system.

Based on information compiled in 1996 and not updated since that time, the U.S. standardization community currently maintains approximately 93,000 standards in active status.[40] The number of U.S. standards at any given moment in time, however, is difficult to identify. Today, it is assumed that the number 93,000 is still a relatively valid estimate, since various newly created standards tend to offset a trend of the largest U.S. producer of standards, the U.S. Department of Defense, to retire more standards each year than it generates.

Standards exist for virtually all industries and product sectors. The oldest standards-developing organization in the United States is the U.S. Pharmacopeia, which published standards for 219 drugs in 1820. Today, the U.S. federal government supports the overall approach used in the United States through Public Law 104-113, which indicates that the federal government will support and (as needed) participate in the development of private, voluntary consensus documents, or if not, then to justify otherwise. This is further discussed later in the section entitled "National Technology Transfer and Advancement Act."

For a variety of reasons, data on the number of standards must be treated with caution. These reasons include (1) uncertainty on whether to consider as a standard a product description, specification, definition of a term, or description of a procedure; (2) the distinction between a single standard with many sections and a series of separate but related standards may be arbitrary; (3) the influence and impact of various standards on the economy can vary dramatically; (4) many documents become technologically obsolete but remain in a technically active status; (5) information on the number of state and local government standards is extremely limited and fragmented; and (6) statistical information typically does not include de facto standards (i.e., unsponsored and unwritten yet widely accepted standards, such as the configuration of typewriter and computer keyboards).

The 93,000 standards in the United States generally comprise 49,000 (53%) private-sector standards and approximately 44,000 (47%) federal government standards. Furthermore, private-sector standards (i.e., developed by NGOs) can be further subdivided based on the type of sponsoring organization: standards-developing organizations, scientific and professional societies, and industry associations. Table 1.3.3 provides a summary of this information.[41]

In comparison to most systems, the institutional structure of the U.S. voluntary consensus standards system is highly decentralized. Approximately 700 standards developers exist in the United States, with approximately 620 engaged in ongoing standards-setting activities that are mostly organized around an academic discipline, profession, or a given industry. The

TABLE 1.3.3 U.S. Standards and Their Developers

	Number of Standards	*Percentage*
Private Sector		
Standards-developing organizations	17,000	18
Trade associations	16,000	17
Scientific and professional societies	14,000	15
Developers of informal standards	3,000	3
Subtotal of private sector	49,000	53
Federal Government		
Department of Defense (DOD)	34,000	37
General Services Administration (GSA)	2,000	2
Other	8,000	8
Subtotal of federal government	44,000	47
Overall total	93,000	100

Source: Toth, R. B., "Standards Activities of Organizations in the United States," NIST Special Publication 806, National Institute of Standards and Technology, Gaithersburg, MD, 1996.

remainder of the aforementioned 620 organizations typically have a small number of standards that were developed in the past, which may or may not be occasionally updated.

It is interesting to note that, of the 620 private-sector standards developers in the United States, the 20 largest developers account for a little more than 70 percent of all private-sector development. Table 1.3.4 indicates the number of standards organizations by sector for the U.S. standards-development community.[42]

American National Standards Institute (ANSI)

The significant private-sector standards-development system in the United States is largely self-administered, with oversight and coordination provided by ANSI, a federation of U.S. codes and standards developers, company organizations, and government users of those standards.

Originally known as the American Engineering Standards Committee, its first meeting was held on January 17, 1917, by the following founding organizations: American Institute of Electrical Engineers, American Institute of Mining Engineers, American Society of Civil Engineers, American Society of Mechanical Engineers, and the American Society of Testing and Materials. The government Departments of War, Navy, and Commerce were soon involved, along with NFPA and other organizations. One of the first documents that was accepted and registered under the established rules as an "American Standard" was the 1920 edition of NFPA 70, *National Electrical Code®*.

TABLE 1.3.4 Number of U.S. Standards-Developing Organizations

	Number of Standards	*Percentage*
Private Sector		
Standards-developing organizations	40	6
Scientific and professional societies	130	19
Trade associations	300	43
Developers of informal standards	150	21
Subtotal of private sector	620	89
Federal Government		
Department of Defense (DOD)	4	1
General Services Administration (GSA)	1	1
Other	75	10
Subtotal of federal government	80	11
Overall total	700	100

Note: Numbers are rounded to the nearest 10, except for components of the federal government.

Source: Toth, R. B., "Standards Activities of Organizations in the United States," NIST Special Publication 806, National Institute of Standards and Technology, Gaithersburg, MD, 1996.

In 1928 the name of the American Engineering Standards Committee was changed to the American Standards Association. This organizational title was used until 1968 when the organization became known briefly as the United States of America Standards Institute (USASI) before adopting the current title of American National Standards Institute.

Organizational membership in ANSI fluctuates, but as of 2006 it is comprised of approximately 265 U.S. professional organizations, technical societies, and trade associations, along with 1100 U.S. companies. ANSI is able to fulfill its coordinating role for the voluntary standards system in the United States because of the support it receives from those actively involved in standards work. NFPA is an ANSI-accredited codes and standards organization, with "audited-designator status," resulting in ANSI accreditation for virtually all NFPA codes and standards. Approximately 11,180 standards approved by ANSI were designated as "American National Standards."

ANSI coordinates and harmonizes private-sector standards activity in the United States. In order for a document to be designated an American National Standard, the principles of openness and due process must have been followed in its development, and consensus among those directly and materially affected by the standard must have been achieved. ANSI also represents the interests of the United States in the international standardization activities of the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO).

The ANSI arrangement is unique in the ISO/IEC arena, since most countries are represented by a single organization that is either fully or partially funded by that country's national government. The United States, however, is represented by a single private organization (ANSI) that further represents the interests of numerous organizations, including private standards-development organizations (e.g., ASTM, IEEE, NFPA, etc.). This results in a complex legal and business environment involving international copyright.

Further complicating this situation is that U.S. standards developers (SDOs) do not limit their activities to only U.S. constituents and typically have members involved from other countries. It is not unusual for the U.S. representation or secretariats in IEC and ISO standards-developing activities to be true international standards developers (ISDOs) in their own right.

Under ANSI procedures, all American National Standards must be reviewed and reaffirmed, modified, or withdrawn no less frequently than every five years—a requirement that ensures that voluntary standards in the United States keep pace with developing technology and innovations. Thus, the voluntary system produces quality standards that do not become outdated.

United States Standards Strategy. A "National Standards Strategy for the United States" was first approved by the ANSI board of directors on August 31, 2000, and it was superseded by a second edition, now renamed as the "United States Standards Strategy" (USSS), which was approved by the ANSI board of directors on December 8, 2005.[43]

Work on this latest edition of the USSS began in 2004 as the result of a collaborative process when ANSI convened a committee to review and revise the previously published National Standards Strategy for the United States (2000). The updated and renamed U.S. Standards Strategy reflects the input of hundreds of representatives of industry; small, medium and large enterprises; standards developers and consortia; consumer groups; and federal and state governments that contributed to the revision process.

The USSS establishes a framework that will be used by U.S. stakeholders to improve trade issues in the global marketplace, enhance consumer health and safety, meet the needs of diverse industries, and advance U.S. viewpoints in the regional and international standardization arenas. The U.S. standardization system functions under the belief that standards should meet societal and market needs and should not be developed to act as technical barriers to trade. The USSS promotes standards that are technically suitable, applied globally, and developed in accordance with the principles of openness, transparency, consensus, and due process within the World Trade Organization's Technical Barriers to Trade Agreement.

The document is built on 12 initiatives that address the role of government; health, safety, and environmental responsibilities; consumer interests; prevention of standards as trade barriers; responsiveness to cross-cutting technologies; efficiency in standards development; the priority of standards education; and other crucial considerations. Key updates to the strategy relate to intellectual property rights, funding models for the standards system, national priorities, and global trade issues.

National Technology Transfer and Advancement Act

Of particular interest to anyone involved with the development of codes and standards in the United States is the National Technology Transfer and Advancement Act of 1995 (NTTAA). The NTAA, also referred to as Public Law 104-113, was signed into law on March 7, 1996, and requires that all federal agencies use standards developed by voluntary consensus standards bodies instead of government-unique standards whenever possible. Perhaps even more importantly, the act includes provisions that encourage federal agencies to partner with the private sector in the development of standards that not only help improve the efficiency and effectiveness of government but also strengthen the U.S. position in the global marketplace.

A similar government document that preceded the NTTAA and also still referenced is the OMB (Office of Management and Budget) Circular A119, *Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities.* The enactment of the NTTAA and the OMB Circular A119 that guides federal agencies in their implementation of NTTAA has prompted federal, state, and local agencies to increasingly turn to voluntary consensus standards as alternatives to requirements and specifications developed by government agencies

The adoption of voluntary consensus standards developed in the private sector by agencies at all levels of government makes good sense. As stated in OMB Circular A119, "the use of [voluntary consensus] standards, whenever practicable and appropriate, is intended to achieve the following goals:

- Eliminate the cost to the Government of developing its own standards and decrease the cost of goods procured and the burden of complying with agency regulation;
- Provide incentives and opportunities to establish standards that serve national needs;
- Encourage long-term growth for U.S. enterprises and promote efficiency and economic competition through harmonization of standards; and
- Further the policy of reliance upon the private sector to supply Government needs for goods and services."[44]

The NTTAA compelled federal agencies to decisively turn to consensus-based, voluntary standards as alternatives to specifications that had previously been developed only for government use. The streamlined approach to standards development and implementation central to the NTTAA has saved millions of U.S. dollars by using consensus standards for procurement purposes and mitigating overlap and conflict in regulations. Since the passage of NTTAA in 1996, tremendous progress has been made in the cooperative standardization efforts of industry and government. Significant accomplishments have been realized in critical areas such as health and safety, security and defense, protection of the environment, and technological advancements.

Standards-Developing Organizations (SDOs) in the United States

Authority and technical expertise in the U.S. standards-developing system are highly decentralized and linked to specific industry sectors. This system has evolved based on the development of a wide range of consensus standards processes in many different standards-developing organizations (SDOs). The basic common principles of consensus codes and standards development are, thus, applied in different ways, with procedures and objectives specific to the needs of a particular industry or professional community. The following three types of organizations generally develop standards handled and administered by the private sector.[45]

Standards-Developing Organizations. These organizations typically have the development of codes and standards as one of their central activities or missions. Membership-oriented codes and standards-developing organizations are the most prominent of these organizations, and they tend to have the most diverse membership among all SDOs, since they are not limited to a particular industry or profession. These membership organizations have a notable number of international members, which is a feature of many U.S. SDOs in general, and makes the U.S. codes and standards-developing system somewhat distinct from the rest of the world. Because of their diverse membership, codes and standards-developing membership organizations tend to have the strictest due-process requirements. Aside from membership organizations, standards development is also a key activity of certain testing and certification organizations, such as Underwriters Laboratories Inc. or the American Gas Association.

Two examples of standards-developing organizations are ASTM and NFPA, both of which are membership based. ASTM has a membership of approximately 30,000. The 132 ASTM technical committees are responsible for more than 12,000 standards, and approximately one-third of ASTM's sales of standards are to international users. NFPA, for sake of comparison, has about 80,000 members. The approximate 250 consensus technical committees of NFPA are responsible for about 300 safety-oriented documents, which are dramatically fewer than ASTM. This difference in committee structure provides some indication of the distinction between product standards handled by ASTM and safety codes and standards handled by NFPA.

Furthermore, despite NFPA having substantially fewer documents than ASTM and some other standards developers, the total number of pages generated by NFPA (because they are mostly safety-oriented documents rather than product oriented) is often comparable and, in some cases, clearly more. As noted earlier, safety standards tend to be more complex, which leads to greater length.

The number of published standards is not necessarily an absolute indicator of overall activity level or significance, and a vivid example of this concept is the *Boiler and Pressure Vessel Code* administered by ASME. Although it is considered a single standard, it is approximately 12,000 pages in content and far exceeds the size of almost all other standards that are more commonly only several pages in length. In a similar fashion, any of the model building codes and similar safety-related documents for the built environment far exceed most other standards in terms of page count. In fact, neither numbers nor page counts are as valid indicators of impact as would be numbers of users by document and numbers of lives and dollars affected, but both of these measures are very hard to develop.

Scientific and Professional Societies. These societies are a refined form of membership organizations that support the practice and advancement of a particular profession. The most recognized of these societies involve the engineering disciplines. A unique characteristic of these societies is that the participants, as part of their standards-development processes, typically function as individual professionals and not as specific representatives of their sponsoring organization or industry.

Prominent examples of scientific and professional societies include the American Society of Mechanical Engineers (ASME) and the Institute of Electrical and Electronics Engineers (IEEE). ASME has an international membership of more than 120,000. The ASME standards process has more than 700 committees responsible for 600 codes and standards. ASME has responsibility for the previously mentioned *Boiler and Pressure Vessel Code* and is one of the most prominent single documents in the U.S. standards-development arena and in the world. IEEE has a worldwide membership of more than 365,000 engineering professionals. The approximately 900 standards published by IEEE focus specifically on areas of electrotechnology.

Another example involving a relatively new developer is the Society of Fire Protection Engineers (SFPE). The SFPE was established in 1950 and incorporated as in independent organization in 1971, but only in the last few years has it pursued the development of standards and guides on various technical topics. The SFPE is the professional society representing those practicing in the field of fire protection engineering. With approximately 4500 members and 57 regional chapters, the society's purpose is to advance the science and practice of fire protection engineering and its allied fields, to maintain a high ethical standard among its members, and to foster fire protection engineering education. Several volunteer committees and task groups work under the society's auspices on technical projects to further advance the state of the art.

Industry Associations. Industry or trade associations are organizations of manufacturers, service providers, customers, suppliers, and others that are active in a given industry. The development of technical standards is specifically intended to further the interests of their particular industry sector.

The Association for the Advancement of Medical Instrumentation (AAMI) is an example of a trade organization that develops standards. Approximately 2000 health care professionals support its activities and include representatives from industry, health care facilities, academia, research centers, and government agencies, such as the Food and Drug Administration (FDA). Industry association SDOs are likely to be more openly responsive to commercial market concerns than other types of SDOs. Other examples of industry associations include the American Petroleum Institute (API) and the National Electrical Manufacturers Association (NEMA).

ENFORCEMENT OF CODES AND STANDARDS

The types of government and the characteristics of governing authorities around the world vary considerably, yet despite the differences, there are some aspects that are common with relation to legislative adoption of codes and standards. For the sake of illustration, the following discussion focuses on this topic, based on a form of government similar to that used in the United States.

Today the life and property of every citizen are safeguarded to at least some extent by safety legislation enacted by the Congress of the United States, state legislatures, city councils, town meetings, and many other jurisdictions and levels of government. The implementation and enforcement of this legislation are in the hands of administrative agencies of government, such as federal departments and agencies, state fire marshal offices and other appropriate state agencies, local fire departments, building departments, electrical inspectors, and so on.

In the earlier days of the United States, the protection of citizens from fire was solely the concern of the local community. Present-day fire fighting is carried on by local fire departments. Although most communities have had some type of building code since the beginning of the twentieth century, they have not had fire prevention or life safety codes until more recently.

With the need for more detailed, comprehensive standards and codes relating to the construction, design, and maintenance of buildings came the knowledge that regulations based on such codes certainly could prevent most incidents of damage to the building, its contents, and the activities therein, as well as reduce losses in the incidents that did occur.

Regulations relating to safety are determined and enforced by different levels of government. Although some functions overlap, federal and state laws generally govern those areas that cannot be regulated at the local level.

Nationally Based Safety Regulations

There is a substantial amount of federal regulation pertaining to safety. Under the U.S. Constitution, Congress has the power to regulate interstate commerce. This power has been interpreted to permit Congress to pass laws authorizing various federal departments and agencies to adopt and enforce regulations to protect the public from hazards.

Any federal department or agency in the United States can promulgate safety regulations only if authority to do so is granted by a specific act of Congress. These regulations have the force of law, and violations can result in legal action. In general, such federal laws can be enacted to provide (1) that all state laws on the same subject are superseded by the federal law, (2) that state laws not conflicting with the federal law remain valid, or (3) that any state law will prevail if it is more stringent than the federal law. Among the federal agencies that have the authority to promulgate fire safety regulations are the Consumer Product Safety Commission (CPSC), the Department of Health and Human Services (HHS), the Occupational Safety and Health Administration (OSHA), and the Department of Homeland Security (DHS). Fire safety regulations are compiled for effective use in documents like NFPA 1, *Uniform Fire Code*™, which provides us with an important tool for mitigating unwanted fire. Figure 1.3.4 illustrates the level of adoption of NFPA 1.

It must be recognized that model codes are only representations of possible regulations, and they do not actually become law until enacted by state and municipal legislatures.[46] In addition, local or special geographical circumstances may dictate additional criteria that are deemed to be unnecessary for inclusion in the model document. The general areas of model code adoption and use in the United States can be seen in the examples provided in Figures 1.3.4 and 1.3.5. Although these illustrations are representative of code adoption activities in the United States, a similar approach of using model codes exists in numerous other countries. The world's most widely adopted code, NFPA 70, is adopted in virtually every state in the United States, Mexico, and several other countries in Central and South America and elsewhere around the world.

Regulations of State and Local Government

Within the scope of the police power of state government in the United States is the regulation of building construction for the health and safety of the public—a power usually delegated to local government jurisdictions of the state.

Building code requirements usually apply to new construction or to major alterations to existing buildings. Retroactive application of code requirements is very rare. Building code applicability usually ends with the issuance of an occupancy permit or certificate of occupancy. The basic premise that legislation should regulate for the safety of current occupants and for current risk is not generally the province of building codes once a structure is occupied. Then, after-occupancy codes or safety maintenance codes apply. Also, at this point the authority of the building official usually ends and the fire official begins. A notable exception is NFPA *101, Life Safety Code*®. NFPA *101* does impose retroactive criteria on existing buildings even when no work or renovation is planned. This approach recognizes that changes in the state of the art do occur over the life of the building. Previously unknown or misunderstood hazards or threats may demand changes to some level of the life safety features in the building. Thus, the retroactive imposition of certain requirements is mandated by NFPA *101*.

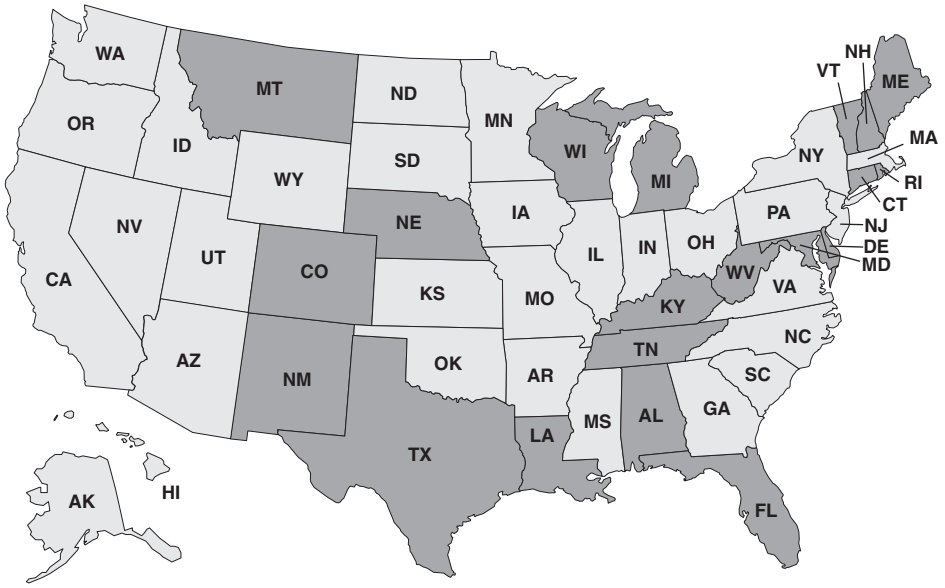

FIGURE 1.3.4 Adoption of NFPA 1, *Uniform Fire Code*™ (as of 2006)

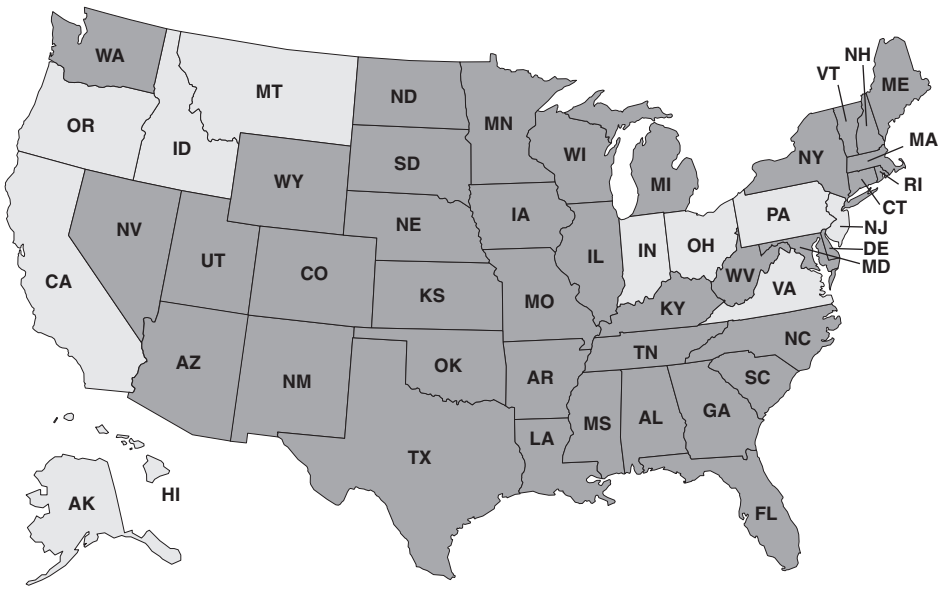

FIGURE 1.3.5 Adoption of NFPA *101*®, *Life Safety Code*® (as of 2006)

This division of authority, however, does not preclude interaction between the two officials during both a building's development and its subsequent use. In practice, many jurisdictions assign responsibilities to officials in various departments for codes whose natural "homes" are or are not in their departments. This division of authority varies considerably among communities.

In most states in the United States, the principal fire official is the state fire marshal. For the most part, the state fire marshal is the statutory official charged by law with responsibility for the administration and enforcement of state laws relating to safety of life and property from fire. Usually the state fire marshal also has the power to investigate fires and to conduct arson investigations.

The manner in which each state handles the promulgation of building and fire regulations varies widely. In some states, each local government may have its own code, whereas in others the local authority has the option of adopting the state codes. In still others, the state codes establish the minimum requirements below which the local regulations cannot go. Finally, in some states the local government has no choice and must adopt the state code. Another variation of this is the Mini-Max (for minimum-maximum) code that asserts that a community may not require less than, or more than, the state-specified regulation.

These situations have resulted in a plethora of different local codes. Some of the local governments adopt one or more of the model codes. In many instances, these adoptions include some form of local amendments that remove or add various requirements. Others draft their own local codes. This lack of uniformity has been criticized by materials producers, building designers, builders, and others and some years ago prompted the appointment of federal commissions to study the situation and make recommendations to the administration.[47–49]

The legal procedure for adopting codes and standards into law can also vary from one enforcing jurisdiction to another. Usually, the simplest and best way is to adopt by reference. This method, applicable to public authorities as well as to private entities, requires that the text of the law or rule cite the code or standard by its title and give adequate publishing information to permit its exact identification. The code or standard itself is not reprinted in the law. All deletions, additions, or changes made by the adopting authority are noted separately in the text of the law. Adoption of a current edition of a code or standard obviates outdated editions maintained as law until a new law referencing a new edition is adopted.

CODES FOR THE BUILT ENVIRONMENT

Although building codes provide much focus, a variety of other related codes also readily serve the built environment. Specifically, these codes address distinct interrelated topics that are essential components in structures of all kinds.

Topics that are typically addressed include electrical, plumbing, mechanical, fuel gas, energy, and fire prevention. Yet this is not an all-inclusive list, and any particular subject that lends itself to specific and detailed criteria is eligible and, thus, "electrical codes," "plumbing codes," "mechanical codes," and so on have also evolved. Often the reference to "building codes" is intended to include, in a general sense, a reference to all of these related codes for the built environment.

Of these different related topics, fire prevention codes are somewhat unique (e.g., construction versus ongoing operation and maintenance). It often is difficult to differentiate between items that should go into a fire prevention code and those best included in a building or other related code, or in some cases, identical requirements that need to appear in two or more codes. Generally, those requirements that deal specifically with construction of a building are part of a building or similar code administered by the building department. A fire prevention

code, on the other hand, includes information on fire hazards in a building and is usually regulated by the fire official.

Requirements for exits and fire-extinguishing equipment are generally found in building codes, whereas the maintenance of such items is covered in fire prevention codes. More simply stated, building and other related codes address the original design or major renovation of a building, whereas a fire prevention code usually addresses the building during its useful life after the initial construction or renovation is complete.

U.S. Codes for the Built Environment

With the exception of the independent operations of some of the largest cities, the business of code development for the built community in the United States is primarily in the hands of the model code organizations. The primary objectives of these organizations are to provide standardization of construction regulations and/or support of the enforcement of these regulations. In the United States, the following provides further discussion on the two prominent organizations that currently have code sets for the built environment.

NFPA. In December 1999, NFPA embarked on a project to establish a complete set of consensus codes and standards for the built environment. NFPA already had at its disposal a number of major codes such as NFPA 1, *Uniform Fire Code*™, NFPA 54, *National Fuel Gas Code,* NFPA 70®, *National Electrical Code*®, and NFPA *101*®, *Life Safety Code*®, among others that could serve as a strong foundation for the basis of this collection, as well as the balance of the 300 NFPA codes and standards that directly support these leading documents.

NFPA has historically been involved with the development of a model building code as early as 1905 through the collaborative efforts of the National Board of Fire Underwriters, but a current up-to-date version was needed to cover structural design issues and other items normally found in a building code. Although major NFPA codes like NFPA *101* covered the most salient building code issues as they relate to fire protection, other items such as general structural design, foundation and building envelope issues, energy conservation, and accessibility were not as well addressed as they could and should have been in the existing NFPA codes and standards. The result was the development of *NFPA 5000*®, *Building Construction and Safety Code*®, with the 2002 edition being the first edition. Other important codes, such as a plumbing code, mechanical code, and energy code, were contributed to the set by partnering organizations.

In the setting of this coalition, model codes and standards are developed through a full, open, ANSI-accredited, consensus-based process allowing full participation and decision making by all interested groups. This process has long been the hallmark of the U.S. system of codes and standards development under the auspices of ANSI and its predecessor organizations. This unique system relies on the energies and expertise of private citizens brought together by nongovernment organizations like NFPA and its partners to forge consensus over important issues of technology and public safety. The building and construction fields have greatly benefited from this type of codes- and standards-development process. Consensus codes and standards exist today that address almost every aspect of the built environment, from life safety to electrical safety, from fuel gas to energy efficiency.

The codes and standards processes of NFPA and its partners are accredited by the American National Standards Institute (ANSI), and the features that earned that accreditation make them considerably more accessible to the general public than the processes used by other code organizations. This coalition is the only one that is based on truly national and international organizations and is not an amalgamation of regional (partial U.S.) organizations, each of which has an independent and arguably narrow geographic focus.

ICC (International Code Council). In 1995 the International Code Council (ICC) was established. The purpose of the ICC was to combine the codes of the three traditional regional model-building code organizations into a single national model. In a sense, the ICC is coming of age as a national organization and is striving to overcome the challenges of combining three distinctly different regional organizations, each of which has uniquely inherent geographic characteristics.

The three regional organizations that joined forces to create ICC are the Building Officials and Code Administrators (BOCA), the International Conference of Building Officials (ICBO), and the Southern Building Code Congress International (SBCCI). BOCA was originally known as the Building Officials Conference of America and published its first regional building code in 1950. It has traditionally had a regional focus on the Northeast and Great Lakes portions of the United States. ICBO first published its regional building code in 1927. The ICBO codes have traditionally been used in the western United States but have also been utilized in municipalities as far east as Indiana. Organized in 1940, SBCCI first published its building code in 1945, which has traditionally been used throughout the southern United States.

The current documents of the ICC, as well as its three founding regional organizations (BOCA, ICBO, and SBCCI), are developed in a process that has traditionally been by and for building officials, which restricts involvement and final voting to the building official community. This is in contrast to the codes and standards developed and maintained in an open, full-consensus process that allows widespread involvement, such as those accredited by the American National Standards Institute and used by NFPA. In particular, the documents of NFPA and its partners are developed and maintained in an open, full-consensus process that allows widespread involvement, inclusive of decision-making authority, and, thus, provides documents that are more technically balanced and economically fair.

Other Organizations Related to Codes for the Built Environment

Wide ranges of organizations provide support, input, or involvement for the codes and standards infrastructure in North America. The following paragraphs provide additional information on certain applicable groups.

AISG (American Insurance Services Group). As previously noted, the National Board of Fire Underwriters (NBFU), renamed the American Insurance Association (AIA), and now known as the American Insurance Services Group (AISG), first published the *National Building Code* in 1905. This early building code initiative occurred as part of the close collaborative relationship through the years between the NBFU and NFPA technical committees, which began soon after NFPA was created in 1896 and continued until the early 1960s, when NBFU evolved into the AIA. The building code was used as a model for adoption by cities, as well as a basis to evaluate the building regulations of towns and cities for town grading purposes. The code was periodically reviewed by the NBFU staff, revised as necessary, and republished. The last code revision was the 1976 edition. Since then, the AISG has discontinued updating and publishing the *National Building Code,* and Building Officials and Code Administrators (BOCA) acquired the right to use the name *National Building Code* on its regional building code, although this code was discontinued with the formation of ICC. The AISG also developed a fire prevention code, most recently published in 1976, but has also discontinued the updating and publishing of this document.

ANSI (American National Standards Institute). The significant private-sector standards-development system in the United States is largely self-regulated, with oversight and coordination provided by ANSI, a federation of U.S. codes and standards developers, company organizations, and government users of those standards.

ANSI coordinates and harmonizes private-sector standards activity in the United States. In order for a document to be designated an American National Standard, the principles of openness and due process must have been followed in its development, and consensus among those directly and materially affected by the document must have been achieved. ANSI also represents U.S. interests in the international standardization activities of the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) and serves as the primary gateway for voicing the U.S. position in these arenas.

ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers). ASHRAE was formed by the merger of two societies, American Society of Heating and Ventilating Engineers (ASHVE)—which was originally established in 1895 and known after 1954 as the American Society of Heating and Air-Conditioning Engineers (ASHAE)—and the American Society of Refrigerating Engineers (ASRE), which was founded in 1905. The two societies merged in 1959 to form the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE).

The mission of ASHRAE is to advance the arts and sciences of heating, ventilation, air conditioning, refrigeration, and related human factors to serve the evolving needs of the public and ASHRAE members. The standards and guidelines generated by ASHRAE are administered by almost 90 active standards and guideline project committees, addressing such broad areas as indoor air quality, thermal comfort, energy conservation in buildings, reduction of refrigerant emissions, and the designation and safety classification of refrigerants.

Association of Major City Building Officials (AMCBO). The Association of Major City Building Officials (AMCBO) was formed in 1972 by the Building Commissioners of 20 of the nation's largest cities to serve as a national forum in which major cities could come together to identify common problems and seek common solutions. This group focuses on issues of building codes, administrative techniques, and public safety in buildings. The association has approximately three dozen members and is focused on providing a national forum of city and county building officials united to discuss topics of mutual interest.

AMCBO is affiliated with the National Conference of States on Building Codes and Standards (NCSBCS). The activities of AMCBO include encouraging the development of comprehensive training and educational programs for building code enforcement personnel, providing scientific and technical resources for the improvement of building codes, and enhancing building technology and products to reduce the cost of construction and maintain safety levels.

CFPA-I (Confederation of Fire Protection Associations–International). CFPA-I is a body of leading fire protection organizations from around the world that have joined forces to collectively direct their resources at reducing the global fire problem and increasing life safety. By sharing experience, research, technical know-how, and fire statistics, the group aims to maximize the effectiveness of fire prevention and protection and foster improved international fire safety codes and standards. The CFPA-I typically meets in full session every three years at which time some of the more challenging global fire problems are debated. These sessions provide an opportunity to share advanced research and developments that have taken place in specific problem areas. Significant advances have been made in recent years in fire safety and CFPA-I has provided an exceptional forum to disseminate this knowledge. At this time, two suborganizations that exist within CFPA-I are the Confederation of Fire Protection Associations-Europe (CFPA-E), which is comprised of European fire protection associations, and the CFPA-Asia (CFPA-A), which includes the fire protection associations in the Asian region.

Council on Tall Buildings and Urban Habitat (CTBUH). The Council on Tall Buildings and Urban Habitat was initially formed in 1969 and at that time was known as the Joint Committee on Tall Buildings. The original membership and support were from the International Association of Bridge and Structural Engineers and the American Society of Civil Engineers. In 1973, as a result of the increased emphasis on planning and environmental criteria, other prominent organizations became sponsoring societies of the council, and in 1976 it was renamed to its current title as the Council on Tall Buildings and Urban Habitat. In 1974 the council was admitted as a consulting nongovernmental organization to the United Nations' UNESCO under Category C, and in 1979 it was admitted as a Category B organization.

The CTBUH is sponsored by architectural, engineering, planning, and construction professionals, and as an international

nonprofit organization was established to facilitate professional exchanges among those involved in all aspects of the planning, design, construction, and operation of tall buildings and the urban habitat. The council's primary goal is to promote better urban environments by maximizing the international interaction of professionals and by making the latest knowledge available to its members and to the public at large in useful form.

Inter-Jurisdictional Regulatory Collaboration Committee (IRCC). The purpose of the Inter-Jurisdictional Regulatory Collaboration Committee, which has evolved into a more identifiable existence during the 1990s, is to work internationally, producing documents on the development, implementation, and support of construction-related, performance-based regulatory systems. The current membership of approximately a dozen key government and private organizations from around the world supports the IRCC focus to identify public policies, regulatory infrastructure, and education and technology issues for implementing and managing these systems, where necessary in conjunction with international bodies having compatible interests.

IAPMO (International Association of Plumbing and Mechanical Officials). The International Association of Plumbing and Mechanical Officials began in 1926 as the Plumbing Inspectors Association of Los Angeles, to bring about an improvement in the application of commonsense codification and application of ordinances based on scientific knowledge.

In 1928, additional cities joined and it became known as the Plumbing Inspectors Association of Southern California, and the following year it became the California Plumbing Inspectors Association because of statewide interest. In 1935 the name was changed to Pacific Coast Plumbing Inspectors Association because of interest from other states, which at that time included the 11 western states. In 1945, the name was changed to Western Plumbing Officials Association, and in 1967, due to interest in the association and its goals beyond the borders of the United States, the name was again changed to its current tile of the International Association of Plumbing and Mechanical Officials (IAPMO).

Today, IAPMO is responsible for administering the development of the Uniform Plumbing Code and the Uniform Mechanical Code. Recent editions of these documents are ANSI-accredited, consensus-based codes. They are the most widely adopted plumbing and mechanical codes in the United States and are also used in various jurisdictions around the world.

National Conference of States on Building Codes and Standards (NCSBCS). NCSBCS is a nonprofit corporation founded in 1967 as a result of congressional interest in the reform of building codes. It attempts to foster increased interstate cooperation in the area of building codes and standards and coordinates intergovernmental code administration reforms. NCSBCS is an executive branch organization of the National Governors Association and includes as members governor-appointed representatives of each state and territorial government. It has a working relationship with the National Conference of State Legislatures and the Council of State Community Affairs Agencies.

National Institute of Building Sciences (NIBS). NIBS was authorized by Congress in 1974, under Public Law 93-383, as a nongovernmental, nonprofit organization governed by a 21-member board of directors. Fifteen of the board members are elected and six are appointed by the president of the United States, with the advice and consent of the U.S. Senate. The institute is a core organization that serves primarily as an investigative body, offering its findings and recommendations to government and to responsible private-sector organizations for voluntary implementation. It carries out its mandated mission essentially by identifying and investigating national problems confronting the building community and proposing courses of action to bring about solutions to the problems. NIBS's activities are broad based and center around regulatory concerns, technology for the built environment, and distribution of technical and other useful information.

Working under its very broad mandate, NIBS has established a Consultative Council, with membership available to representatives of all appropriate private trade, professional, and labor organizations; private and public standards, codes, and testing bodies; public regulatory agencies; and consumer groups. The council's purpose is to ensure a direct line of communication between such groups and the institute and to serve as a vehicle for representative hearings on matters before the institute.

World Organization of Building Officials (WOBO). WOBO was founded in 1984, with the primary objective of advancing education through worldwide dissemination of knowledge in building science, technology, and construction. WOBO was established because of increased participation of nations in the global marketplace, the rapid development of new international building technologies and products, and development of international standards that now make it impossible for building officials to confine their concern to activities within their own national boundaries. It currently has consultative status with the United Nations under the nongovernment organization classification.

SUMMARY

Codes and standards serve many purposes, but foremost is their contribution to the overall betterment of civilization. Their role is particularly important as we work toward the challenges of a safer and more cost-effective built environment. In today's complex world, codes and standards provide a point of measurement to simplify our lives. In this sense, codes and standards provide the practical foundation for a better tomorrow.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on building and fire codes and standards discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code*™
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 54, *National Fuel Gas Code*
NFPA 70, *National Electrical Code*®
NFPA 70A, *National Electrical Code Requirements for One- and Two-Family Dwellings*
NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*
NFPA 88A, *Standard for Parking Structures*
NFPA 88B, *Standard for Repair Garages*
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 90B, *Standard for the Installation of Warm Air Heating and Air-Conditioning Systems*

NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*
NFPA 99, *Standard for Health Care Facilities*
NFPA *101*®, *Life Safety Code*®
NFPA 105, *Standard for the Installation of Smoke Door Assemblies and Other Opening Protectives*
NFPA 204, *Standard for Smoke and Heat Venting*
NFPA 220, *Standard on Types of Building Construction*
NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations*
NFPA 703, *Standard for Fire Retardant–Treated Wood and Fire-Retardant Coatings for Building Materials*

Integrated Consensus Code Set for the Built Environment (NFPA and partners)

NFPA 1, *Uniform Fire Code*™
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*
NFPA 54, *National Fuel Gas Code*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 70, *National Electrical Code*®
NFPA *101*®, *Life Safety Code*®
NFPA 5000®, *Building Construction and Safety Code*®
Uniform Plumbing Code—IAPMO (NCA/NAPHCC)
Uniform Mechanical Code—IAPMO
ASHRAE 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*
ASHRAE 90.2, *Energy Code for New Low-Rise Residential Buildings*

Chapter 4

Legal Issues for the Designer and Enforcer

Arthur E. Schwartz

Chapter Contents

General Land Use and Building Regulation
Key Legal Concepts for the Engineer and Enforcer
The Engineer and Negligence
The Engineer and the Americans with Disabilities Act
Engineer and Enforcer Inspections
Liability of Code Enforcement Officials

Key Terms

Americans with Disabilities Act, building code, fire code, inspection, intentional tort, negligence, quality assurance, quality assurance plan, quality assurance program, strict liability, tort

The collection of codes and standards that regulate the built environment represent a compilation of methods, systems, and uses that society deems as providing an acceptable level of safety and performance. These documents can be legislatively implemented or adopted and are normally considered to be part of statutory law. This type of law prescribes, among other things, the basic requirements of matters of design and construction for that particular government jurisdiction.

Codes and standards such as those developed by NFPA, the International Code Council, the International Association of Plumbing and Mechanical Officials, and numerous other private sector organizations are voluntary documents that are developed under some set of procedures established by the organization. The voluntary nature of such documents means they are not legally binding until adopted by a government entity at the federal, state, or local level. Once adopted, they can be legally imposed, enforced, and established as the standard of care—a statutory law for that particular jurisdiction. In simple terms, they do become *the* law for design and construction issues in that community or state.

The collection typically represents minimum levels of performance or *de minimus* care rather than optimum or maximum levels of performance. One of the ways in which a code or standard stops short of requiring maximum performance is through limits to conditions under which the required standard of care can be expected to produce specified outcomes, such as the following:

- Applies to occupants not intimate with ignition
- Assumes a single ignition point
- Assumes the maximum considered earthquake (MCE)

These statements define challenges that may otherwise be too great to assure the desired level of performance. This is perhaps for economic reasons (cost is too much), for technological reasons (no existing system or feature addresses the problem), or for reasons of physics (no imaginable system or feature could address the problem). In most cases, it is a combination of two or all three of these reasons. With that said, the designers and owners have an obligation to maintain a standard of care for their project. That standard is to protect the general population from harm in most cases, and the most commonly applied measure of that protection will be in the prevailing code.

In building design and construction, an orchestra of owners (money), architects and engineers (design talent), and code officials or authorities having jurisdiction (AHJ) (enforcement talent) work to develop a clear plan and picture for a usable and safe building or structure. The contract documents, normally comprising the plans and specifications, must not only be prepared to meet the requirements of the prevailing codes and standards; they must also be clearly understood by the general contractor and their subcontractors, component or supplier vendors, fabrication shops, and third party inspection agencies.

Adopted codes and standards become the starting point for the designer and the code official to ensure that minimum standards of care for that community are met. In this context, codes are not providing just good ideas or suggestions, they provide a baseline of performance and legally binding obligations on the parties to a building project. Designers may choose to do more, but they may not

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choose to do less without penalty. Likewise, those who review the plans and specifications, or who conduct on-site inspections must be acutely aware of the provisions of the code, and they must verify that what has been specified has been provided.

Code-based regulations that may be available but not yet adopted, forensic studies that may have identified a previous problem or issue but have yet to be codified in some consensus-based document, or current research that may indicate potential solutions to emerging problems or existing issues, may cloud the *standard of care* criteria for that jurisdiction should a failure occur that results in death or injury to building occupants or even to first responders. Such documents may serve a role when a negligence claim is filed. Short of negligence resulting in personal injury in the duty of care, however, are other circumstances where a designer may have failed to meet certain contract obligations that required compliance with the prevailing code documents. Improper specification and selection of wall coverings, incorrect selection of sprinkler system types and designs, failing to address concerns based on the Americans with Disabilities Act (ADA), or failing to provide a useable building to the client fall short of causing injury to occupants, but are a type of harm according to the law.

See also Section 1, Chapter 3, "Codes and Standards for the Built Environment"; Section 1, Chapter 5, "Fire Prevention and Code Enforcement"; and Section 12, Chapter 6, "Liability of Fire Service Organizations for Negligent Fire Fighting."

GENERAL LAND USE AND BUILDING REGULATION

The Tenth Amendment to the U.S. Constitution states, "The powers not delegated to the United States by the Constitution, nor prohibited by it to the States, are reserved for the States respectively, or to the people." It is deemed to be the defining statement that defers matters such as public safety in certain circumstances away from the federal government and gives it to each state. Such matters include building restrictions, which have been accomplished through such public means as municipal ordinances, zoning laws, covenants, height restrictions, and smart growth laws.

Prior to establishing building regulations, issues of land use were among the early topics to be considered. Prior to the 1850s the owner of a *fee simple absolute* had the maximum extent of rights possible in and under the law. Under U.S. jurisprudence, few forms of private and public land use controls existed prior to 1850. In the mid-nineteenth century, the courts accepted the creation of subdivisions by developers, which contained restrictions on all lots. For example, a developer may have provided that only single-family dwellings could be constructed on the lots. Minimum lot sizes, property line setbacks, and access to such areas are typical follow-on rules for such subdivided spaces. Such general land use and building restrictions set the stage for the development and implementation of building and fire codes.

Zoning Ordinances

In the twentieth century, zoning ordinances became widespread. Under such ordinances, municipalities are permitted to divide an area into various uses. These may include residential uses (single-family, manufactured housing, town-home, multifamily), industrial, commercial, or agricultural uses among others.

Private restrictions such as easements and restrictive covenants are also often enforced. Whereas these restrictions may encompass the use of the building (multifamily residential occupancy versus a residential board and care occupancy) or the allowable number of occupants in certain assembly occupancies, there are certain other regulations that may affect the use of the building, the business it houses, or a combination of the two. Liquor licenses or health code and sanitary code criteria are examples of such broad-use provisions. The courts may issue an injunction barring a violation and may even order a noncomplying business to shut down until corrections are made, or in a worst-case scenario, a nonconforming structure to be demolished—for example, see *Stewart v. Finklestone,* 206 Mass.28, 92 N.E. 37 (1910). The unsafe structures provision in building codes gives code officials extraordinary power to take drastic action when a building is deemed an imminent threat to health, life, or property. However, general restrictions may not be enforced where the neighborhood has changed (e.g., from residential to commercial), where numerous violations of general restrictions have occurred (e.g., failure of administrative enforcement), where there has been a delay in enforcing restrictions (e.g., lack of staffing or funding), where the party who seeks to enforce the restrictions has committed violations, or where the restrictions may have expired because of the passage of time (regulatory sunsetting of restriction). These circumstances may be further compounded in the event of "adverse possession," whereby real property is held in a manner that conflicts with the true owner's rights. In these cases, a long-term violation concerning a land use or right-of-way access may have simply existed for so long that it is has come to be treated as acceptable because of the passage of time.

Under a zoning ordinance, a municipality is divided into residential, commercial, industrial, or manufacturing districts. Generally residents may be permitted to live in residential sections. Stores and residences may be permitted in commercial districts, and virtually any use may be permitted in a manufacturing zone. In addition, residential districts may be classified according to more specific uses. As an example, some zoning ordinances provide for single-family and multiple-family dwelling zones. Some zoning ordinances are even more restrictive and keep residences out of zones that are classified as commercial or industrial. Many municipalities also have ordinances that determine everything from minimum lot size requirements for particular buildings to curb cuts to the number of entrances.

The Role of Building Codes

Building codes are enacted and enforced under a state's police powers, that is, the general power to enact laws that promote the health, safety, and general welfare of its citizens, and that authority, including the authority to supplement the building code, is sometimes delegated to local government. Building code provisions must be reasonably related to the purpose or objective of the state's obligation to protect the welfare of its citizens. However, the government agency often enacts its code provisions while

granting broad power and discretion to the enforcing body or entity. The governmental agency's judgment will generally not be reversed by a court unless the judgment is clearly erroneous or unreasonable. For this reason, building and fire codes establish a formalized appeals process to provide a method for resolving a dispute over an application or interpretation of the code or other regulation. This appeals process is directed at the local level and is used by exception for situations in which the owner/developer and the AHJ reach an impasse that may delay progress on the project. Court involvement is possible, but is normally reserved as a measure of last resort.

Building codes sometimes apply to buildings and structures constructed prior to the adoption of the codes. The courts have permitted retroactive application of building codes because of their importance in protecting the public health and safety. More typical, however, is the concept of "grandfathering," whereby buildings constructed before the establishment of applicable codes are allowed to remain in use provided there are no imminent hazards.

The duty to comply with building codes is generally placed on the owner of the building or structure. The building codes typically assess fines for noncompliance. Inadequate design, improper application of code provisions, or outright disregard for the code-specified criteria are examples of noncompliance. Deviation from approved plans by the contractor without the benefit of a supplemental review by the code official may also result in noncompliance. Corrections of such violations are often disputed between the responsible parties and not easily resolved in some cases. In addition, some states and municipalities permit criminal prosecution of persons who knowingly violate building codes.

Most communities have adopted building codes. Some states have statewide building codes. Usually, before a building or structure can be built, the owner must apply for a building permit. A reviewing authority will analyze the plans and specifications to determine whether the proposed building complies with the appropriate zoning ordinance and the relevant requirements from the applicable building code. Most zoning and building ordinances provide that a new building may not be occupied until a code official has inspected it and issued a certificate of occupancy.

The Role of Fire Codes

Fire codes are a critical subset of general building codes and are key to protecting the public health and safety under a state's police powers. Fire codes may vary in their applicability but in many cases, they contain requirements that influence not only the construction of new buildings, but also criteria for ongoing protection for the life of the building. Probably the most well-known example of the importance of both the establishment and enforcement of rigorous building and fire safety codes is illustrated by the 1911 Triangle Factory fire in New York City. This fire triggered a review of not only existing rules and regulations in effect at the time of the fire, but also of the need to consider additional safety precautions. The trial included arguments on the factory owners' compliance and adherence, or lack thereof, to certain provisions of New York state labor laws and fire codes. Table 1.4.1 explores some of the code and compliance issues.

TABLE 1.4.1 1911 Triangle Factory Fire

Fire Protection Feature	*1911 New York State Law*	*Triangle Shirtwaist Company Compliance*
Doors	"All doors leading in or to any such factory shall be constructed as to open outwardly, where practicable, and shall not be locked, bolted, or fastened during working hours."	Door direction was fiercely debated at trial.
Staircases	Buildings with more than 2500 square feet per floor, but less than 5000 square feet per floor, require two staircases.	The Triangle Shirtwaist Company floors had 10,000 square feet of space. Any additional floor space would have required a third staircase.
Fire escapes	Required at the discretion of building inspectors. The building inspector insisted that the fire escape proposed for the building "must lead down to something more substantial than a skylight" (as specified by the architect).	The building architect promised "the fire escape will lead to the yard and an additional balcony will be put in." In the final construction, however, the fire escape ended at a second floor skylight. During the fire, the fire escape collapsed under the weight of the fleeing workers.
Non-wood surfaces	Metal trim, metal window frames, and stone or concrete floors required for buildings more than 150 ft high	The ten-story building was 135 ft high.
Sprinklers	Not required	Not installed
Fire drills	Not required	Not conducted

Source: Adapted from University of Missouri/Kansas City Law School website.

As with many building tragedies, the reaction of the professional design community was to attempt to address the underlying factors and remedy problems. Improvements to codes, including both incremental and sweeping changes, oftentimes follow such events. Even with improved codes, failure to design per the code or failure to properly enforce the provisions of the code may result in a catastrophe. Subsequent investigations to determine how and why a failure occurred may result in negligence claims against a building owner/operator, designer, contractor, or in rare instances, the entity responsible for enforcement and oversight of the code.

KEY LEGAL CONCEPTS FOR THE ENGINEER AND ENFORCER

The concepts of tort law, negligence, intentional tort, and strict liability are central to the engineer's and enforcer's understanding of their legal responsibility and exposure.

Tort Law

Tort is a generally defined and understood term in all jurisdictions and occurs when a person interferes with another person or his property. *Tort* is a legal term that is applied to a civil wrong that occurs and that may lead to a civil lawsuit. Basically, a tort is a "civil wrong, other than breach of contract for which the court will provide a remedy in the form of an action for damages," according to *Blacks Law Dictionary* (6th ed., 1990). Torts fall into one of three broad categories: (1) negligence, (2) intentional tort, and (3) strict liability.

Negligence

Negligence involves an unreasonable breach of duty by one person to another. The most common and likely tort encountered in the design and construction of a building involves negligence; thus, it will be discussed in more detail.

Intentional Torts and Strict Liability

Intentional torts are conditions reasonably foreseeable to cause harm to an individual and that do so. *Strict liability* is generally used to hold an individual responsible for errors, omissions, or other acts that cause damage or loss to another person. Intentional tort and strict liability will usually emanate from the action of, for example, a building owner who locks the exit doors (intentional tort) or installs a faulty product in a building (strict liability), rather than the engineer or enforcer. This chapter will not offer further discussion on intentional tort and strict liability.

THE ENGINEER AND NEGLIGENCE

As a result of performing professional services, the engineer may become liable for injuries or damages caused by negligence. A consulting engineer working in the construction industry may make an error in a plan that could result in a building failure. For example, the error could relate to the design of a structural system or component, fire protection system, fire wall, or any number of related systems like stairs, means of egress, or electrical systems. Likewise, an engineer working for a fire protection system component manufacturer could make a design error, resulting in a defective product. Lack of a rigorous quality control program at the manufacturing site may also contribute to a product that does not perform as intended. In either case, property may be damaged or someone may be injured, causing a claim to be made or a lawsuit to be filed against the engineer, the designer, the contractor, or the manufacturer.

The law draws a clear distinction between the rules applying to the engineer working in construction and other consulting areas (professional negligence) and the engineer working in manufacturing (strict product liability). The law places significantly different burdens on a plaintiff suing an engineer working as a consultant than on a plaintiff suing the manufacturer of a defective product.

A consulting engineer may be liable for negligence to clients or even to third parties. Similarly, a manufacturer may be liable for negligence to customers and subsequent users for damages caused by defects in the design or manufacture of its products. Suits for negligence fall under tort law. A suit for a tort must be distinguished from a suit for breach of contract. In a breach of contract lawsuit, the plaintiff seeks to recover damages for a breach of an agreement the defendant made with, or for the benefit of, the plaintiff. As an example, consider a designer who fails to deliver contract documents in the agreed-upon time. This may cause construction financing to be impacted, critical phasing or scheduling timelines to be missed, or start of construction permits to be invalidated. Tort law, on the other hand, has created an independent concept of a duty which one person owes another person, a duty not to injure or damage him, and is unrelated to the law of contracts.

Negligent Actions

English common law initially held that a person could be liable for injuries or damages they may have caused to another person, even though they were not at fault. However, by the early nineteenth century, the doctrine of negligence had become accepted. Accordingly, a person could be held liable for causing injury or damage to another person only if the person was negligent. At first, this concept was applied to certain tradespeople or professionals, such as blacksmiths or surgeons. The courts reasoned that such persons represented themselves as having certain skills in which the public could place their confidence. Accordingly, the courts determined that they owed the public a certain degree of expected service, and that if any of them breached this concept of expected service by being negligent, the service provider could be held liable for damages. Negligence could take the form not only of a positive act, such as a careless surgical procedure, but also of an omission (e.g., failure to meet the standard of conduct or performance).

Eventually, courts in England and the United States developed numerous rules governing negligence suits or actions. Among those rules are the following four elements that the plaintiff must show in an action to prove a negligence case against the defendant:

1. A duty that the defendant owed to the plaintiff to conform to a certain standard of conduct as established by the law
2. A breach of a legal duty by the defendant
3. The breach of duty must have a causal connection to the injury sustained by the plaintiff; the law requires that the breach of duty (the defendant's actions or failure to act) must be the "proximate cause" of the harm suffered by the plaintiff
4. Damage suffered by the plaintiff, since clearly, if the plaintiff has not sustained any personal injury or damage to his property, he is not entitled to recover any money from the defendant

These four elements can be connected to the work product expected to be provided by the architect or engineer. Was the conduct of the designer consistent with accepted practice? Did the project specification meet the prevailing requirements of the codes in effect in the jurisdiction? Did the design provide a safe and functional building that would not cause bodily injury or property damage? At the end of the project, did the designer deliver a useable, functional, and safe building suitable for the intended purpose?

Code Compliance

Frequently, professional service agreements provide that the design professional will prepare the design and specifications in compliance with "all applicable codes, regulations, and laws." Those codes, regulations, and laws include building codes, fire codes, zoning laws and ordinances, and federal and state statutes. Such "all applicable codes" contract provisions can be problematic. With the ever-expanding number of construction regulations and laws, the typical engineer may not be an expert in all applicable rules and may therefore not want to agree to broad statements of legal compliance. Thousands of laws, codes and regulations that relate to construction are on the books; all are subject to change, and some are open to interpretation. During both the design and construction phases of a project, an engineer is often called on to interpret codes and regulations, and the engineer's interpretation may differ from those of government officials. Government officials may insist that certain aspects of the design or construction be performed in a certain way, although this is not clearly called for by the applicable law.

In other instances, codes and ordinances may seem to be in conflict. In more cases than not, such conflicts may be nothing more than differing objectives. For example, property distances in the zoning law may have to more to do with encroachment and privacy issues whereas in the building code, such separation distances may have more to do with fire spread. These competing regulations may place the engineer in the untenable position of having to comply with two differing contractual obligations. A commonly encountered example of this provision involves the installation of sprinklers in electrical equipment rooms. Nationally recognized model standards and codes include stipulations that sprinklers are to be installed throughout the building unless a specific exception is granted. These standards and codes recognize the need to provide sprinkler protection in electrical equipment rooms. A local or state rule may explicitly state that sprinklers are not permitted to be installed in such rooms. In this case, the designer must choose between two provisions that cannot be met simultaneously.

In addition, there are additional issues to consider. Who will pay for design changes required to reflect a new code or regulation put in force during the course of a project? Although most permitting processes preclude the imposition of revised code-based requirements once the project is under way, there may be extraordinary circumstances when such changes must be made midstream in the construction process. Framed initially as an issue of who pays, this changes into an issue of what happens when the rules change in midcourse. If the change is at the request of the customer, they would be expected to modify the contract and allow for amendments to contract dollar amounts and an adjustment to the design and construction completion schedule. Also, if a project is suspended at any stage of development for an extended time, who will pay for design changes necessitated by new regulations when the project is resumed? If a professional service agreement does not provide for such circumstances, the engineer may need to provide extensive redesign services without compensation to bring the project up to code.

Accordingly, the engineer may want to meet with the client and the client's attorney prior to executing the agreement in order to reach an understanding on which legal statutes, ordinances, and regulations of law will apply to the project. If possible, the engineer should attempt to limit the language of the agreement to a statement that the engineer will comply with those codes, ordinances, regulations, and laws to which the parties have specifically agreed. In this conversation, it is important for the agreement between the engineer and the client to contain an appropriate cutoff date that states when the engineer's responsibility to adhere to new codes and/or regulations terminates. A reasonable cutoff date might be on submission of the plans and specifications to the appropriate code authorities. Any additional design changes deemed necessary after that date should be considered an additional service. In the written agreement, the engineer should make clear, if possible, that any conflicting interpretations by government agencies with which the engineer or the owner must comply may result in additional costs to the owner for which the owner should be responsible.

Standard of Care

What is the standard of care? Was it met? These are the first questions asked when an engineer is accused of professional negligence. As stated, the elements of professional negligence include (1) the owing of a duty, (2) a breach of that duty (e.g., failure to meet the professional standard of care), (3) causation (e.g., proximate cause) and (4) damages or harm. All four elements must be demonstrated in order to prove professional negligence. For example, although an injured party may suffer damages or harm resulting from the actions of an engineer, there may not be negligence because the engineer did not breach a duty (e.g., the engineer did not fail to meet the professional standard of care). Also, the legal interpretation of the professional

standard of care may vary from the public perception and the client's perception.

As a general rule, what is expected or required of the engineer is that the engineer render services with an ordinary degree of skill and care that would be used by other reasonably competent practitioners of the same discipline under the same circumstances, taking into consideration the contemporary state of the art and geographic considerations: It may be stated as follows: "The standard of care for all professional engineering and related services performed or furnished by Engineer will be the care and skill ordinarily used by members of the subject profession practicing under similar circumstances at the same time and in the same locality."

The standard of care has also been referred to as the "reasonable person" approach. What is reasonable and what is ideal or optimal may be two different things. It is reasonable to provide two exit stairs in a 20-story office building if that is all that the code requires. Compliance with codes, if those codes are accepted in the profession as the standard of care, is strong evidence that the designer is acting reasonably. This evidence is especially strong if the codes are nationally accepted, such as those published by the NFPA.

The "reasonable person" concept dates from the English common law doctrine that held that the public had the right to expect those providing services to so do in a reasonably careful and prudent manner as established by the actions of their own peers under like circumstances. This doctrine does not contemplate perfection or flawlessness. Performing to perfection is not the standard to which professional engineers or other professional service providers are held under the U.S. system of jurisprudence. Instead, the standard is whether the engineer's actions are reasonable, normal, appropriate, and prudent under the specific facts and circumstances. An engineer or designer cannot be expected to design for an unknown or unforeseeable hazard. The delicate issue and debate of what, if anything, codes and standards should do to address hostile or malevolent acts is a prime example of this. Events such as terrorist attacks are neither predictable nor symmetrical and are difficult to design for.

As noted earlier, it is not uncommon for some clients and members of the public unfamiliar with the standard of care to view professional engineering as an exact science rather than a licensed profession whose practitioners use ordinary skill, care, professional judgment, and discretion to address the needs of the client and the public. Sometimes these expectations are generated and are a result of unfortunate statements in the professional engineer's promotional materials or exaggerated comments included in proposals submitted to the client. For example, some clients will attempt, through the professional services contract, to augment the tort-based duty of reasonable care with a standard of care that requires the professional engineer to "perform to the highest standard of practice," to "warrant" or "guarantee" a result, or to "certify" that a result will be or has been achieved. Acceptance of these or similar provisions sets a far higher standard of care and subjects the professional engineer to a far greater liability exposure. Such provisions will also void most professional liability insurance, which is written based on the customary standard of care.

THE ENGINEER AND THE AMERICANS WITH DISABILITIES ACT

Accessibility Provisions for Newly Constructed and Altered Buildings and Facilities

The Americans with Disabilities Act of 1990 (ADA), also known as Public Law 101–336, became effective in 1990 after being signed by President George H. W. Bush. In general terms, the ADA is a wide-ranging civil rights law that prohibits, under certain circumstances, discrimination based on disability. Designers and owners/operators of buildings have, under ADA provisions, an obligation to provide reasonable accommodation for persons with disabilities. These provisions are now mainstreamed into the code requirements and criteria. The provisions are a mix of somewhat subjective measures (such as what constitutes reasonable accommodation) and technically specific and prescriptive rules that give precise performance measures (dimensions, numbers, etc.). The ADA provisions are also somewhat unique in that they must oftentimes be applied to the stock of existing buildings in certain circumstances. Voluntary compliance is an important component of an effective strategy for implementing Title III of the ADA. Private businesses that voluntarily comply with ADA accessibility requirements help to promote the broader objectives of the ADA by increasing access for persons with disabilities to the goods, services, and facilities available in communities.

Title III of the ADA authorizes the Department of Justice to certify that state laws, local building codes, or similar ordinances meet or exceed the ADA Standards for Accessible Design for new construction and alterations. Title III applies to public accommodations and commercial facilities, which include most private businesses and nonprofit service providers. Examples of covered businesses are restaurants, banks, commercial lending institutions, movie theaters, stadiums, groceries, convenience stores, health care facilities, and professional medical offices, to name a few. Congress, by authorizing the certification of state and local accessibility requirements under Title III, recognized the important role that state and local building codes and standards may play in achieving compliance with the building-related aspects of accessibility. State and local building officials who are involved in plan approval and construction inspection processes may provide important assistance to construction and design professionals through their oversight of the accessibility requirements of a certified state or local code. In any legal challenge that might be brought under the ADA to facilities constructed in compliance with an ADA-certified code, compliance with the certified code constitutes evidence, albeit refutable, of compliance with Title III of the ADA.

Importance of ADA Certification

The benefits of certification are not limited to potential ADA lawsuits. Certification facilitates ADA compliance by ensuring that certified state and local accessibility requirements meet or exceed ADA requirements. In this regard, business owners, builders, developers, architects, engineers and others in the de-

sign and construction industry are benefited because, once a code is certified, they can refer to certified code requirements and rely on them for equivalency with the ADA.

Certification of a state or local accessibility code also allows business owners, builders, developers, and architects to rely on their state or local plan approval and building inspection processes for assistance with ADA compliance through the implementation of certified accessibility requirements. Should a mistake occur in the design or initial construction phase of a project, the mistake can be identified early through the plan approval and inspection processes and corrected at a time when adjustments can easily be made and the costs for doing so remain low. In this manner, state and local building code officials in jurisdictions with an ADA-certified code can play an important role in checking to determine whether accessibility requirements have been met. Finally, jurisdictions that provide accessibility "checkpoints" such as those described above through the implementation of a certified code provide a significant benefit to private industry and an incentive for growth and development.

Engineer Responsibility Under ADA

Engineers are expected to use reasonable professional efforts and judgment to interpret applicable ADA requirements and other federal, state, and local laws, rules, codes, ordinances, and regulations as they apply to the project. However, as noted earlier, engineers should not be expected to warrant or guarantee that the client's project will comply with all interpretations of the ADA.

ENGINEER AND ENFORCER INSPECTIONS

Engineer's Role in Inspection

An *inspection* can be any kind of activity involving a visual or physical examination of work in progress or the results of work. It is important that the engineer, the client, and other involved parties have the same understanding of what observations and evaluations the engineer will perform and what scope and degree of error detection and quality assurance such activities can be expected to deliver. For example, unless an engineer is being retained specifically for the purpose of construction management services that entail inspection, the engineer will more typically agree only to "observe" or "review" a contractor's construction work for "general conformance" with the contract documents. It is not uncommon, however, to see contract language for general design services which transfer to the design professional significant responsibility and risk for inspection even though that is not within the scope of services for which the design professional is being paid. One example of how this responsibility may get formally transferred to the designer is contained in *NFPA 5000®*, *Building Construction and Safety Code®*, Chapter 40, "Quality Assurance during Construction."

The term *inspection* is sometimes used in contracts generated by owners when "monitoring," "reviewing," or "observing" might be more appropriate. When used to describe monitoring of the contractor's work, *inspection* may imply a greater responsibility than the engineer intends to provide. The client may think that the engineer is committing to police the project and through the inspection ascertain all instances where the contractor's personnel did not comply with the detailed plans and specifications and other contract documents. Some clients may even state in the contract that the purpose of the inspection is to assure the client that all problems are discovered and promptly reported to the client. The engineer is not inspecting the contractor's work to guarantee that it has no defects. The engineer can only "observe" the work and exercise reasonable care to determine that the work generally conforms with the contract documents. This is the industry standard and should be understood by the client. After all, the engineer is not being compensated for the man-hours it would take to watch everything done by the contractor to ensure no defects or deficiencies exist. Moreover, the contractor should be held accountable for those defects and deficiencies rather than the engineer.

The Role of Quality Assurance

If the intent of the owner was to raise the level of scrutiny or involvement of the engineer or architect of record, (also known as the registered design professional, or RDP) on daily progress and oversight of the project, then a much higher level of inspection, referred to as a quality assurance (QA) plan or program, may be called for. By their nature, QA programs establish another level of review. This supplemental compliance is not a substitute for, and does not in any way usurp the powers of, the AHJ. It does work to ensure that both routine as well as complex construction features are completed in accordance with the contract documents as well as with the specified code provisions. Quality assurance plans and programs do raise the level of surveillance and involvement of the engineer—specifically the RDP. In the realm of *NFPA 5000,* the following terms apply:

- *Quality assurance.* The procedures conducted by the RDPs responsible for design and the RDPs responsible for inspection that provide evidence and documentation to the RDPs, the owner, and the AHJ that the work is being constructed in accordance with the approved construction documents.
- *Quality assurance plan.* Written documentation of the tests, special inspections, and observations to be performed in the quality assurance program.
- *Quality assurance program.* A predefined set of observations, special inspections, tests, and other procedures that provide an independent record to the owner, AHJ, and RDP responsible for design that the construction is in general conformance with the approved construction documents.
- *Quality control program.* The operational procedures provided by the contractor to control the quality of the work and ensure compliance with the approved construction documents.

Agreeing to observe whether the contractor's work is in "general conformance" with the design concept is realistic. This is a manageable risk, whereas "inspecting" whether the work meets the details of the plans and specifications creates much greater

risk. The latter type of inspection needs to be clearly established as to the span of control, level of detail, and additional costs that would be involved.

LIABILITY OF CODE ENFORCEMENT OFFICIALS

Under the U.S. system of civil jurisprudence, it is generally recognized that any individual may sue any other individual in a court of law. Most state constitutions contain an "open courts" provision that seeks to limit any encroachment on an individual's right to sue another individual or entity. Having said that, the U.S. system of civil jurisprudence also recognizes the doctrine of sovereign immunity, a fundamental principle of English common law. Based on the divine right of kings ("the King can do no wrong"), today sovereign immunity remains as a means of protecting the public official as well as those who are employed or work on behalf of the government. The scope of protection includes building and fire code enforcement officials and other government employees involved in the code enforcement process. In some jurisdictions, the scope of protection may extend to consultants or contractors retained to perform a governmental function.

In recent decades, the sovereign immunity doctrine has been somewhat eroded as a result of court decisions and legislation waiving the application of sovereign immunity to certain governmental functions and activities. For example, under the Federal Tort Claims Act (and similar state laws), so-called "discretionary functions" (policy-making activities) of government continue to have sovereign immunity protection whereas so-called "ministerial functions" (day-to-day operational activities) of government do not have sovereign immunity protection. Since each state law may vary, depending on statutory language and court interpretation, it is critical for code enforcement officials to be familiar with the scope of sovereign immunity in the jurisdiction in which the official is employed.

SUMMARY

Professional engineers and code enforcement officials play a critical role in protecting the public health, safety, and welfare. Both groups must have a full understanding and appreciation of their respective roles in the design and construction process, recognizing general land use and building regulations, risk management considerations, ethical obligations and liability exposure that may arise in connection with the rendering of services to clients, members of the public, and others involved in the design and construction process.

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NFPA *101®, Life Safety Code®*
NFPA 5000®, Building Construction and Safety Code®

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Chapter 5

Fire Prevention and Code Enforcement

Ronald R. Farr ■ Steven F. Sawyer

Chapter Contents

Fire Prevention Personnel
Fire Prevention Inspections
Code Enforcement
Record Keeping
Plan Review Practices
Consultation
Fire Investigation
Public Fire and Life Safety Education
Other Enforcement Agencies

Key Terms

dwelling fire safety survey, enforcement, fire inspector, fire investigator, fire marshal, fire prevention, inspection, plans examiner, public fire and life safety educator

Fire prevention includes any fire service activity that decreases the incidence and severity of uncontrolled fire. Usually fire prevention methods used by the fire service focus on inspection, which includes engineering, code enforcement, public fire safety education, and fire investigation. Similar methods and activities may also be provided by the private sector in large industrial or storage type occupancies, airports, and large assembly venues.

Inspection, including enforcement, is the legal means of discovering and eliminating or correcting deficiencies that pose a threat to life and property from fire. Education informs and instructs the general public about the dangers of fire and about fire-safe behavior. Fire investigation aids in fire prevention efforts by indicating problem areas that may require corrective educational efforts, inspection emphasis, or legislation. Good engineering practices, including plans review—another fire prevention method—can ensure compliance with codes and standards before construction or installation of built-in safeguards begins.

Historically, fire prevention was encouraged only after a large disaster. As an example, in the early years of the development of U.S. cities, following fires where a portion of a city burned down, laws were enacted prohibiting thatch roofs, thus preventing fire spread. Even though the fire service has attempted to be more proactive, major fire prevention efforts, in many cases, don't take precedence today until after a large event. This is supported by looking at past fire and life safety codes as they relate to postevent reviews and subsequent changes in codes, standards, and inspection methods or through redirection of code-enforcement priorities.

The full value of fire prevention was not realized until fire departments and agencies began to compile meaningful information concerning the causes and circumstances of fires. Such information highlighted problem areas and led progressive departments to initiate more effective fire prevention efforts. The results of such efforts are borne out statistically every year, confirming the effectiveness of fire prevention programs. Fire prevention, as the most important priority in cutting fire losses, received an endorsement in 1973, when the United States National Commission on Fire Prevention and Control published the results of its in-depth study on U.S. fires. In its report *America Burning,* the commission emphasized that increasing efforts toward fire prevention would measurably affect the U.S. fire loss picture. Statistics validate this position for areas in which fire prevention activities have been implemented.

See also Section 1, Chapter 3, "Codes and Standards for the Built Environment"; and Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety."

FIRE PREVENTION PERSONNEL

Effective fire prevention depends on the adoption and use of up-to-date codes and standards and a personnel network to support the enforcement of these codes and standards. Adoption of model codes and standards with modifications for local conditions provides the basis for fire prevention

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programs. The personnel assigned to fire prevention should be technically capable and motivated to enforce fire codes, educate the general public, and investigate fire causes. Those who manage these responsibilities must be proactive and must be backed up with the appropriate resources—financial, training and staffing. This network of people is usually organized at the state, county, and/or local level. Some industries, such as colleges and universities, hospitals, and chemical and large manufacturing facilities may also have on-site fire prevention personnel.

Because of the importance and diversity of fire prevention activities, when possible, certain members of the fire prevention department should specialize in specific fire prevention functions. Staff size of a fire prevention division, bureau, or fire marshal's office will depend on the needs of the jurisdiction and the department size. In many cases the fire marshal must perform all duties of the fire prevention division and is the only member of the fire prevention staff. This office may be divided into specialized subsections addressing administration, fire prevention, code inspections, code enforcement, engineering, public fire and life safety education, data collection, and fire investigation. Other areas of expertise may be provided by specialists in a particular type of occupancy such as health care. These subsections may be headed by subordinate officers or specialists.

The fire prevention division personnel should consist of those department members best qualified for this work. In addition, qualified technical specialists should be available when possible. The department's overall effectiveness depends on the technical skills that the fire prevention personnel possess. It is also important that such personnel be able to properly communicate technical requirements to building owners, architects, engineers, other code-enforcement personnel, and other professionals involved in the construction industry as well as the general public.

State, county, municipality, or fire district laws or administrative regulations often delegate responsibility and authority for fire prevention to the fire chief or fire department head, who may then delegate this authority to an individual or division. In some states, the local fire marshal's authority and area of enforcement responsibility is derived from state laws, independent of or in addition to the powers and duties of the fire department chief. Personnel assigned to the fire prevention division should be knowledgeable about their authority. For example, the span of oversight for new versus existing buildings and the ability to make on-site inspection visits may vary from jurisdiction to jurisdiction

State and Provincial Fire Marshal/Commissioner

Most states have offices to oversee certain phases of fire prevention. The state's chief fire prevention administrator is usually called the state fire marshal. The organizational structure of state fire marshal offices differs from state to state. Most state fire marshals receive their authority from the state legislature and are answerable to the governor, a high state officer, or a fire commission. In some states, the state fire marshal's office may be a division of the state insurance department, state police, department of public safety, commerce department, or other state regulatory agency. Some offices are organized as independent state agencies.

State fire marshals' offices normally function in areas beyond the scope of municipal, county, or fire district organizations. Depending on the authority outlined in enabling legislation or administrative regulations, state fire marshal offices may have combined responsibilities in the following areas: code enforcement, fire prevention inspections, plans review, product approval, fire and arson investigation, fire data collection and analysis, fire service training, public fire and life safety education, fire legislation development, explosives and other hazardous materials regulation, manufactured housing regulations, electrical inspections, and state agency and public fire protection consulting.

State fire marshals may share responsibility with local fire officials, or each may have specifically defined areas of concern. Local fire protection officials are sometimes delegated the authority to act as agents for the state in stipulated areas of inspection, enforcement, and investigation.

At the national level in Canada, Human Resources and Social Development Canada (HRSDC) is responsible for fire safety enforcement in all nonmilitary federal government properties and for gathering national fire statistics. The Canadian Forces Fire Marshal (CFFM) oversees properties of the Department of National Defence, where fire protection facilities include a number of operating fire departments.

In Canada, each of the provinces has a provincial fire commissioner or fire marshal, whereas the three territories have territorial fire marshals. The provincial/territorial fire officer's responsibilities vary with each jurisdiction but may include code enforcement, fire service training, operation of fire-reporting systems, and fire investigation, as well as support of local fire departments. The Canadian Council of Fire Marshals and Fire Commissioners consists of the previously mentioned HRSDC and the CFFM, plus each provincial and territorial fire commissioner or fire marshal. The association exerts a major influence on fire safety policy in Canada.

County or Local Fire Marshal

In each county or community there is usually an individual assigned the duties of fire marshal. In smaller communities this individual may be the fire chief or another fire line officer with additional duties. In larger departments this may be a staff position or line position with only fire prevention duties. The chief officer for fire prevention activities may be called fire marshal, chief of the fire prevention division, or chief fire inspector.

The fire marshal should be well versed and knowledgeable in all aspects of the department's responsibility. He or she should also have knowledge of management, public relations, budget preparation, human resources, and other administrative functions.

Fire Inspector or Fire Prevention Officer

Fire inspectors or fire prevention officers should be selected for these tasks based on their technical training, expertise, and their ability to motivate people. Individuals in this position are

responsible for conducting fire inspections and also may be responsible for other division duties, including fire investigations, public education, or plans review, among others. An inspector conducting an inspection should be able to convince property owners or occupants to maintain or improve fire-safe conditions. The inspector who relies only on police power cannot accomplish as much as the inspector who relies on a proactive approach by showing the benefits and advantages for the employees and the business when fire safety elements are maintained. Strict enforcement of the fire law of the jurisdiction is necessary to achieve compliance and to ensure fire-safe conditions in the community are maintained.

Plans Examiner

The review of plans and specifications is a code-enforcement process intended to ensure compliance with the fire protection and life safety provisions of the building code, as well as the fire code prior to installation or construction. Individuals in plan examination must be technically proficient in both the intent and the letter of the applicable codes. The fire plan examiner reviews site plans, building and fire protection system plans, means of egress, and other fire and life safety plans and specifications and may prepare recommendations or consult with individuals involved in building construction, remodeling, or renovations. The plan examiner must regularly interact with other public safety officials and agencies at the local, state, and federal levels, including building, public works, zoning, health, and others, to ensure the construction of fire-safe, code-conforming buildings.

Fire Protection Engineer

Due to the complexity and magnitude of some fire protection problems, the services of fire protection engineers (FPEs) can be beneficial. Fire protection engineers may be employed by fire departments on a consulting or contractual basis or as full-time staff. The staff fire protection engineer contributes a high level of technical ability to the plans review process, interpretations, consultations, and the preparation of recommendations for a broad range of fire protection problems. Due to increasing interest in performance-based building and fire codes, the fire protection engineer is often in the best position to evaluate such proposals and assess the equivalent level of fire and life safety. The fire protection engineer's credentials, based on professional training, licensure, and registration as a professional engineer (PE), are recognized by architects, builders, and other professionals involved in the building process.

Public Fire and Life Safety Educator

The public fire and life safety educator creates public awareness of fire as a personal, family, business, and community concern and then strives to motivate the general public to do something about fire risks, based on proper fire-safe behavior. Today, many communities have expanded the role of the public fire and safety educator to other risks such as water, bike, firearms, motor vehicle, poison, fall, choking, natural disaster, and weather safety. Personnel selected for this function should be knowledgeable in a wide area of fire technology and other risks and be able to develop and present effective fire prevention, fire safety and other hazard prevention programs. This job requires someone with the imagination, creativity, motivation, communication skills, and adaptability needed to develop and convey fire and safety programs to all segments of the community. Program outreach may start at the kindergarten level and extend to the older adults community.

All levels of fire department personnel should participate in presenting the fire safety, fire prevention and other risk message to the community. Nonuniformed personnel, advocacy groups, older adults, teachers, and others with education backgrounds are also being used successfully by fire departments in this area of fire and risk prevention.

Fire Investigators

Fire cause determination and subsequent investigation can be the responsibility of the fire department alone or in cooperation with other agencies such as the police department. When a fire department is responsible, fire cause determination and investigation may be assigned to the fire chief, fire marshal, battalion chiefs, company officers, fire inspectors, or other personnel specially trained as fire investigators.

Investigative personnel should be perceptive, inquisitive, and thorough in determining facts and conducting an investigation. Investigation experience should be supported by training in areas such as chemistry, criminal law, forensics, and criminal investigation. An increasing number of progressive departments have fire investigation personnel trained in appropriate fields of criminal justice and provided with police powers. NFPA 921, *Guide for Fire and Explosion Investigations,* provides a guide to assist individuals who are charged with the responsibility of investigating and analyzing fire and explosion incidents and rendering opinions as to the origin, cause, responsibility, or prevention of such incidents. Although origin and cause are crucial to understanding how the fire started, an investigation can also analyze other factors such as performance of built-in fire protection systems and building construction assemblies, egress systems, and when appropriate, response by building staff for certain types of occupancies such as health care.

National Professional Qualifications

Professional qualifications standards for fire service career positions are the responsibility of the NFPA Professional Qualifications Correlating Committee. Four of the 15 standards are of particular interest to the fire prevention community: NFPA 1031, *Standard for Professional Qualifications for Fire Inspector and Plan Examiner;* NFPA 1033, *Standard for Professional Qualifications for Fire Investigator;* NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator* and, NFPA 1037, *Standard for Professional Qualifications for Fire Marshals.*

Certification to the career levels defined in these standards is accomplished by agencies based on third-party accreditation. Accreditation for the fire service is currently available through the National Professional Qualifications Board of the National

Board on Fire Service Professional Qualifications (NBFSPQ) and the International Fire Service Accreditation Congress of Oklahoma State University.

Programs such as the NFPA Certification Program for Fire Inspector Certification to Level I and II and Fire Plan Examiner Level I are available on a national level. Many states also have their own certification program, require a national certification, or certify individuals to nationally recognized standard.

FIRE PREVENTION INSPECTIONS

Fire inspections can be classified into three types: installation and new construction, ongoing compliance, and re-inspection. These inspections are usually conducted by state or local fire prevention or fire department personnel. The type of inspections, frequency, occupancy types, and other factors that fire prevention personnel are permitted to make are based on state or local regulations. In addition to mandatory inspections, the fire department may also conduct voluntary fire inspections, such as home fire safety surveys.

Installation and new construction inspections ensure compliance with adopted codes and standards and help to eliminate problems before the building is occupied, a new process or hazard is introduced, or a new fire protection system is placed in service. These inspections also benefit the fire service by helping them to become familiar with the building before it is occupied and with the fire protection systems that have been installed.

Ongoing compliance inspections are needed to ensure that the occupancy, fire protection systems, and hazards protection are intact. These inspections ensure compliance with prior approvals, ordinances, and adopted codes and standards. Ongoing inspections should be performed at regular intervals based on legal requirements, hazards presented, and life safety issues. These inspections are often carried out yearly, based on licensing requirements. The frequency of other inspections is based on state or local laws.

One of the most important inspections is the re-inspection. If during an inspection, fire and life safety violations have been found and notices sent, a re-inspection is mandatory to ensure compliance. Violations that go unchecked place a liability on the inspecting agency for not following up on the original violation. It is also imperative that re-inspections be performed to ensure that unsafe conditions are corrected. Adequate time should be made available to inspection personnel to perform re-inspections.

The organization and operation of fire prevention inspection programs vary. Inspections required under the fire prevention code traditionally have been conducted by personnel from the fire prevention division. However, this responsibility is being shared increasingly with fire company personnel. The department's training program must train all its members in fire prevention.

Fire Prevention Inspection Objectives

Inspections conducted as part of code enforcement help to ensure compliance with mandated life safety conditions within a structure. The condition of and usability of means of egress, interior finish, emergency lighting, exit signs, and all fire doors should be inspected. Inspection of means of egress should include inspection of the exit discharge area.

Inspections, which are intended to prevent fires from occurring, are effective because the inspector identifies potential hazards that could cause a fire, allow a fire to develop, or allow a fire to spread. In addition to locating and correcting potential fire causes, the fire inspector should check any accumulation of combustible trash and debris, storage practices, maintenance procedures, and safe operation of building utilities.

Inspections determine that processes, high-hazard contents, hazardous materials, and flammable and combustible liquid installations and operations are installed correctly and hazards are properly protected. Inspections also determine the proper installation, operation, and maintenance of fire protection features, systems, and appliances within the building. The inspection process should ascertain whether each fire protection system is tested and maintained regularly and that records are kept for inspection and maintenance by the building owner or others.

Fire detection equipment, alarms, annunciation and notification systems, sprinkler-valve operation, supervisory switches, and fire pumps all should be tested and maintained regularly as part of the overall inspection process. Other fire protection features, including standpipes and fire escapes, should be tested and maintained or closely examined to detect possible malfunctions due to deterioration from weather, corrosion, or overall lack of preventive maintenance. Portable fire extinguishers should be checked as to proper type, placement, maintenance, testing, and distribution in the structure.

Technical information on a building and its processes should be recorded during the inspection. When used in prefire planning, such information can be valuable to the fire department in case of a fire at the property. The type of construction, vertical openings, utility type and placement, fire protection systems, fire department access, occupancy, hazardous materials, or special life-hazard conditions are the kinds of information that should also be noted during inspections and used to develop fire-fighting plans. This information also helps to ensure that the proper system or system component has been selected for the hazard. For example, a warehouse commodity may not be permitted to be stored over a certain height or in a certain configuration because of the type of sprinkler system that was installed.

In addition, the fire inspector should review written fire safety emergency procedures to ensure they are adequate and up-to-date with respect to the type of occupancy involved and the various types of fire protection features available. In many cases, it may be necessary to witness an actual drill or planned exercise of the emergency plan to properly evaluate its effectiveness. This should be coordinated closely with the facility manager.

Inspections provide an opportunity to educate the owners or occupants of a building about fire-safe behavior and the need for adequate fire and life safety conditions in the areas under their control. "Selling" fire prevention is the key to success in obtaining code compliance, and how fire prevention is "sold" should be an important consideration in training programs for inspection personnel. When inspection programs are properly

designed and put into practice, inspectors may achieve more through public education and persuasion than through exercising their enforcement authority. A bonus is that many of the concepts discussed at the workplace can be translated to fire-safe practices at home. The persuasive effect of the inspector's presence, coupled with the inspector's ability to spot and see that hazards are corrected, enhances the effectiveness of the inspection program.

Fire Company Inspections

In many communities, in-service fire suppression personnel conduct most or all regular or routine inspections. Company fire inspection procedures may include conducting building surveys, recognizing common problems concerning life safety conditions, locating fire hazards, and determining the operability of fire protection systems. Inspections also may include checking use and storage of hazardous materials, which may require issuing a hazardous-use permit. The inspection process helps familiarize fire company personnel with individual buildings and locations in their jurisdiction at which they may have to fight fires or perform other emergency duties. This information can be used in formulating prefire plans.

Company inspections are usually conducted in the fire company's first-due response area. Inspections and re-inspections may be scheduled by the company officer, by the battalion or district officer, or by the fire prevention bureau, according to requirements of the department. Before fire fighters perform inspections, they should receive proper training and be qualified and authorized to conduct inspections as fire prevention officers.

The inspection may uncover some situations that are easy to correct or others that require more technical skill. In either case, follow-up responsibilities should be assigned to the fire companies, fire company officers, and district chiefs according to the department's resources. The fire prevention division may help to obtain compliance by building owners after violations are located by fire companies, so it is essential for fire prevention personnel to coordinate their activities closely with those of fire company personnel.

Fire Prevention Division Inspections

In some departments, inspection personnel from the fire prevention division are solely responsible for conducting fire prevention inspections. The objectives of their inspections, like those of the general inspections performed by in-service fire suppression personnel, are to ensure compliance with applicable fire and life codes and to locate conditions that can cause a fire, cause a fire to spread, or endanger life and property. Each inspection must be thorough. The owner or occupants of the property being inspected must be notified when unsafe conditions are found. Inspections usually are required by law in order to locate any violations and to see that they are corrected. Legal direction by the municipal attorney or state attorney's office is available when a building owner does not cooperate. To perform such work competently, the inspector should have appropriate technical education, specialized training, and experience.

Even when in-service fire suppression personnel perform some or all regular or routine inspections, fire prevention division personnel may be concerned with the initial inspection, follow-up inspections, or enforcement actions necessary to correct fire code violations. Fire prevention division personnel may perform inspections associated with the issuance of permits as required by the fire code and may be concerned with buildings and premises that require a high level of code application. The inspector may need to confer with the property management or with fire department officers to prepare comprehensive reports, recommendations, or orders.

Both in-service fire suppression personnel and fire prevention division inspections may reveal conditions hazardous to the health and safety of owners, occupants, and the general public. Even when these hazardous situations are not specifically covered in the fire code or laws, such conditions must be brought to the attention of the owners or occupants; when necessary, other inspection authorities should be notified for the record. This mutual assistance in the inspection of buildings or premises can greatly enhance the level of life safety for the general public. Close cooperation among responsible inspection authorities should be encouraged and, where possible, recognized in municipal ordinances or interdepartmental administrative agreements.

The time of day and the actual day an inspection is conducted should be taken into account in an effort to identify conditions that may not be found during normal working hours. For example, night inspections of public assembly and mercantile occupancies should be part of routine inspection procedures to ensure compliance with occupancy load requirements and to demonstrate that the means of egress are in good operating order. Evaluation and knowledge of staff in a health care occupancy should account for the three shifts that provide care to patients on a 24-hour basis. Inspections based on citizen complaints should be conducted by the fire prevention division in a timely manner. An informed and interested public can be an important asset in uncovering unsafe conditions that might develop between routine inspections.

Dwelling Inspection Process

Nearly 85 percent of loss of life occurs in residential occupancies; approximately 75 percent occurs in one- and two-family dwellings. Residential inspections traditionally have not been mandatory because of unfounded concerns associated with the rights of citizens to ensure the sanctity of their homes or dwelling units. For years, however, many fire departments have inspected dwellings on a voluntary, by invitation, or planned basis and have been successful in reducing residential fire loss. Some departments test smoke alarms at homes where they have responded to medical calls. Inspections of this nature, whether conducted by career or volunteer fire department personnel, should be supported by a strong publicity program. Adequate training must be provided for all personnel involved. Voluntary inspections can be conducted either as a separate part of the fire inspection program or as part of fire prevention programs that include occupant fire escape planning and such practices as Operation EDITH (exit drills in the home), smoke alarm or

residential sprinkler drives, spring cleanup, burn prevention programs, heating fire safety, and so on. In some cases, banks or mortgage companies may require a dwelling inspection to verify the presence of smoke and carbon monoxide alarms when existing homes are sold and even when homeowners refinance their property.

For further information on dwelling inspections, see NFPA 1452, *Guide for Training Fire Service Personnel to Conduct Dwelling Fire Safety Surveys.* The Annex of NFPA 1452 includes sample materials for use during a dwelling fire safety survey (Figures 1.5.1 and 1.5.2).

CODE ENFORCEMENT

Fire Prevention Codes

The fire laws of the state, county, fire district, or community delegate general responsibility and authority to the fire officials involved in fire prevention activities. A fire code adopted into law that outlines specific fire prevention requirements and enforcement procedures is essential for an effective fire prevention program.

State law or local ordinances may outline how a fire code is written or adopted. The fire prevention official may have authority to write a local fire code or to adopt a nationally developed model code by reference. Using a model fire code is preferable to using one that has been developed locally. Nationally developed consensus codes are based on a broad spectrum of accepted fire prevention experience and may prevent a fire prevention official from being accused of developing a fire code that is biased, ultra-conservative or unreasonable.

There are additional advantages to adopting a model fire code. A model code provides a document that may be recognized as authoritative by architects, engineers, and builders who already are familiar with code requirements; provides an interpretation process by which the local official may determine the intent of the code-developing body should a question arise; and allows for periodic revision to reflect new technology and current thinking.

Several organizations publish model fire codes that jurisdictions may adopt by reference for enforcement use. NFPA publishes NFPA 1, *Uniform Fire Code*™, which incorporates many NFPA standards by reference. The International Code Council has developed its own model fire code, the International Fire Code. This code references codes, standards, and other NFPA documents. NFPA 1, *Uniform Fire Code*, and referenced NFPA codes and standards are found in the volumes of the NFPA *National Fire Codes,* published yearly and considered to be the most authoritative set of fire and life safety regulations in the world. Highly specialized topics, hazards, and occupancies are governed by the NFPA *National Fire Codes*.

Code Administration

Most fire codes specify similar enforcement procedures and contain similar requirements. A typical fire code contains an administrative section that establishes the legal framework and organization for the fire prevention program. This section usually

Fire Safety Survey
ANYTOWN Fire Department Fire Safety Education Program

YES	NO	
		General
❑	❑	Home has smoke detector.
❑	❑	Smoke detector is in working order.
❑	❑	Family has and practices an exit plan.
❑	❑	House numbers are visible from street.
		All Household Areas
❑	❑	Extension cords are used appropriately.
❑	❑	Electrical cords are in good shape.
❑	❑	There are no overloaded outlets.
❑	❑	Windows can be easily opened.
❑	❑	Wastepaper is properly disposed of.
❑	❑	Household chemicals are stored away from children.
❑	❑	Matches are out of reach of minors.
❑	❑	Large ashtrays are in every room where smoking may occur.
		Basement
❑	❑	Combustibles are removed from heating areas.
❑	❑	Furnace filters are clean and in good shape.
❑	❑	Fuse box does not have pennies.
❑	❑	Washer and dryer are properly grounded.
❑	❑	Clothes dryer lint collector is clean.
❑	❑	Basement door is closed.
		Kitchen
❑	❑	Combustibles are removed from cooking areas.
❑	❑	Small appliances are unplugged when not in use.
❑	❑	Kitchen hood vent is clean and maintained.
		Living Area
❑	❑	Fireplace has proper screen and hearth.
❑	❑	Chimney is clean, and ashes properly disposed of.
		Attic
❑	❑	Area is clear of all combustible materials.
❑	❑	Heating ducts are properly maintained.
		Garage
❑	❑	There is a solid core door between garage and residence.
❑	❑	Power mower is properly stored.
❑	❑	Flammable liquids are properly stored.

Remarks: _____

With your consent, the Fire Safety Survey Team has made a Fire Safety Survey of your home. The items checked "No" may cause a fire or be hazardous to you and your family. You are urged to correct these at once for your own safety. If all items have been checked "Yes," you are to be complimented on your personal fire prevention effort.
If you wish to discuss any hazard, or have any questions, please call the ANYTOWN Fire Department, Fire Safety Education Center at ###-####. You should know what to do in case of emergency.
For All Emergencies Call 911

FIGURE 1.5.1 Sample Home Safety Survey Sheet to Be Completed by Fire Department Surveyor and Given to Homeowner (Source: Figure A.10.2(b), NFPA 1452, *Guide for Training Fire Service Personnel to Conduct Dwelling Fire Safety Surveys,* 2005 edition)

ANYTOWN FIRE DEPARTMENT

Home Inspection of number _____ St., Rd., Pl., Ave.

Dear Occupant:
With your consent, the undersigned fire department inspector has made a fire safety inspection of your home. The inspector has checked below those conditions that could start a fire and has left instructions on how to correct these fire hazards. YOU ARE URGED TO CORRECT THEM AT ONCE – please do not put it off. If you wish to discuss any hazard, please call the Fire Department – 555-5555.

(signed)

John Doe, Fire Chief.

_____ , 20 ____

Basement
1st Floor
2nd Floor
Attic
Garage
Yard

1. Rubbish and trash accumulations.
2. Ashes improperly handled.
3. Flammable liquids improperly stored.
4. Painting materials, oily rags, unsafe.
5. Storage or work areas congested, not fire safe.
6. Combustibles too near heating devices.
7. Smokepipes and flues unsafely arranged.
8. Masonry chimneys unsafe.
9. Gas-fueled devices improperly arranged.
10. Electrical circuit overloading, improper fuses.
11. Electric cords and motors unsafe.
12. TV & radio sets poorly arranged.
13. Outbuilding and yard, cleanup needed.
14. Building maintenance fire safety.
15. Babysitter information.
16. Home fire extinguisher information.
17. NO DEFECTS NOTED. CONGRATULATIONS!

Type of heat used in home _____

Number of home occupants ____ ; number of invalids ____ on ____ floor.

_____
Fire department inspector

FIGURE 1.5.2 Sample Follow-Up Correspondence from Fire Department to Homeowner (Source: Figure A.10.2(c), NFPA 1452, *Guide for Training Fire Service Personnel to Conduct Dwelling Fire Safety Surveys,* 2005 edition)

outlines the code's applicability to occupancy types and specifies whether it applies to new or existing buildings, or both.

The code may define the enforcement authority of the fire prevention official and assistants, including lawful right of entry for inspections, the right to issue orders to correct hazardous conditions, and the right to order evacuation of an unsafe building or premises. The code may further assign duties that require the investigation of fires and the maintenance of fire records. Permit requirements, conditions, and procedures to issue notices of violation may be included.

The administrative section should be written in such a way as to provide the fire prevention official with as broad a scope of authority as possible. This facilitates enforcement of the fire code, other county or city ordinances, and state laws that pertain to the fire safety of buildings and premises, as well as to the control of hazardous materials within the jurisdiction. This section also may outline the owner's or occupant's responsibility for properly maintaining a structure, premises, permitted use and its fire protection features.

Subsequent code sections may define important code-related terminology, outline general fire precautions, and establish the proper installation, operation, testing, and maintenance procedures for fire protection systems and appliances within a building. Final sections of the code may outline the use and maintenance of specific types of equipment, processes, hazards, and occupancies, or they may describe handling requirements for various types of hazardous or explosive materials. Annexes may reference supplemental standards or other helpful data in the administration or application of the fire code.

Enforcement Procedures

The fire prevention process includes a number of enforcement procedures used to establish compliance with the fire code. They are described in the following paragraphs.

Permits. The permit is an official document issued by the fire prevention division to authorize the performance of a specific activity or event. Permits are issued in accordance with applicable codes by the fire official for the use, handling, storage, manufacturing, occupancy, or control of specific hazardous operations and conditions, installation of fire protection systems, special events, and other fire-related activities. The permit should be issued only if the condition of the approval meets code requirements.

The permit process provides the fire prevention official with information on what, where, how, or when specific hazards or fire protection systems are being installed, stored, or used within the jurisdiction or when special events will take place. The process allows cross-checking with building, zoning, public health, or other departmental requirements for the use outlined on the permit. Furthermore, it allows the fire official to review and approve devices, safeguards, and procedures that may be needed to ensure the safe use of hazardous materials, operations, special events, and fire protection systems. The lack of a required permit or failure to meet permit requirements constitutes a violation and is grounds for stopping an event, installation, operation, or use of a structure or operation.

The permit is the property of the issuing agency, not the permit holder. A license or permit authorizes, by law, the right of entry for inspection purposes to ensure compliance with the permit requirements. If an inspector operating under a fire code permit is refused entrance to perform a regulatory inspection, this refusal constitutes grounds to halt operation in, or use of,

the structure involved. Permits are usually issued for the place, process, and operator and are nontransferable so that the notification function of the permit process is maintained.

Certificates. A certificate, which is a written document issued by the authority of the fire official to any person or business, grants permission to conduct or engage in any operation or act for which certification is required. Depending on the needs of a jurisdiction, certificates of approval may be required before smoke or heat detectors, fire extinguishers, fireproofing materials, or other fire protection devices are offered for sale to the general public. This procedure is designed to ensure that only those fire protection appliances that will function in a satisfactory manner are offered for sale to the public.

Certificates of fitness are issued to individuals or businesses with demonstrated proficiency in skills, training, and testing in areas that affect fire safety. This includes pyrotechnics and persons who handle explosives; persons who install fire protection equipment and systems, including sprinklers; and persons who maintain fire extinguishers and fire detection systems. Certification requirements may include a financial bond or liability insurance if conduct of the regulated activity is inherently hazardous.

Licenses. A license is a permission granted by a competent authority to individuals about to engage in a business, occupation, or other lawful activity. Licenses are issued to provide knowledge of specific business locations, ensure compliance with particular standards, and add a source of revenue to the community. The fire prevention division may issue some licenses directly and may be involved in the checkoff process for licenses issued by other regulatory authorities.

Enforcement Notices

When violations of the fire code or ordinances are discovered during inspections, the violations must be called to the attention of the owner or occupants. When the situation is not corrected during the inspection or is a recurring uncorrected violation, several types of enforcement procedures may be available to the fire inspection officer.

Warnings or Notices of Violation. The inspection official may issue these notices to the owner or occupant, stating that a specific violation of the fire code or ordinances has been identified during the inspection. Depending on the legal requirements of the jurisdiction, a notice of violation will be sent to the building owner or, much like receiving a traffic ticket, the owner may be required to sign a form and keep a copy of the document. The specific violation and recommendations for correction of the violation should also be noted in the violation notice. A reasonable period of time should be permitted for correction of some violations based on their severity; all imminent life safety violations, however, should be corrected immediately. Re-inspection after the allotted time is essential to ensure that the correction has been made. If it has not, further legal action should be taken. All violations noted during the inspection, even those corrected during the inspection, should be noted on the notice of violation for future inspections.

Red Tag or Condemnation Notices. These notices are usually attached to appliances, systems, or equipment that would be unsafe and dangerous if allowed to remain in operation. The red-tag process requires that a competent service technician repair or replace the item before the tag can be removed and the equipment returned to operation. This process also may require that the fire official inspect the completed work before granting approval to resume the operation of the equipment in question.

Citations or Summonses. Violations of the fire code requirements or other fire regulations are considered either misdemeanors or civil infractions. An authorized fire official may issue a citation or summons to an individual who is in violation of the fire code. These documents constitute a notice for the violator to appear before the appropriate court to respond to the violations.

Warrants. A warrant is an order issued by a magistrate or agent of the court that directs a law officer to arrest a violator of the law and bring the violator before the court to respond to the charges specified in the document. The person requesting the warrant must provide factual information to the magistrate or court officer issuing the warrant, showing sufficient "probable cause" of a violation.

When authorized by state law or local ordinances, fire marshals, fire investigators, and other fire officials may be empowered to issue summonses, serve warrants, and make arrests. Police or peace officer training, in accordance with the standards of the state, is required by most states before a fire official may serve warrants and make arrests.

Where violations represent a clear and imminent hazard to life or property, it may be necessary for the fire official to take immediate action to correct unsafe conditions. Entrance into private property, shutdown of an operation, evacuation of a building, and withdrawal of permits are actions that the fire official may find necessary to ensure the safety of the public. These powers may be explicitly stated or implied in discretionary powers and "duty to act" requirements of appointing laws or ordinances. In all cases, actions must be based on clearly demonstrable threats to public safety, showing that delay would provide an unreasonable danger to residents, occupants, guests, or the public and that this judgment is based on accepted standards or concepts of safety.

In some states local fire officials can apply for and obtain an administrative search warrant. An administrative search warrant permits the fire official or other regulatory official the right to enter a premise to perform duties required by law.

RECORD KEEPING

Keeping records and files on all actions taken by the in-service fire suppression personnel, fire prevention division, or the fire marshal's office is an essential part of code enforcement and administration. All records of code enforcement, all documents relating to inspections, violation notices, summonses, plans review comments and approvals, fire reports, investigations, permits issued, certificates issued, variances or modifications that

were allowed, and so on are to be handled as legal documents. Well-organized and well-maintained inspection files and building records are essential foundations for enforcement actions. Complete and accurate records also are needed to measure fire department effectiveness in accomplishing fire prevention goals and to provide department management with information for budgetary and administrative purposes.

Types of Records

For each inspected property, a file should be maintained that summarizes information about the inspected premises and contains copies of all inspection reports. Records and reports of fire prevention activities should be clear, concise, and complete. Every time an inspector or fire prevention officer inspects a location, information about that location should be included in a record or a report. The occupancy file of each building visited should include a complete history of the building site; building plans and specifications, if available; fire protection system plans; information on and permits issued for the use, storage, and handling of hazardous materials; a summary of the types of operations or transactions carried out on the property; correspondence; inspection reports; and records of fires at that location. These files should also be reviewed by inspection personnel before they perform an inspection. This gives the inspector information on past violations and newly installed equipment or permits.

Files are needed for properties where a certificate of occupancy, a license, or a permit has been issued. Files also should be maintained on properties with automatic sprinklers, standpipe systems, private hydrants, or other private means of fire protection. A special notation or key should identify any system or equipment that is legally required. With a well-maintained system of files, established data need not be recompiled for each inspection. Inspection work planning is expedited, and time is used more effectively in the field for the inspection itself.

Computer Applications

In recent years, the use of computer technology has helped fire prevention officials handle record keeping and manage fire prevention programs. The number of programs, devices, and options available has grown sharply. The use of computers installed in vehicles, personal digital assistants (PDAs), and other devices has made the job of inspecting and reporting much easier. Many communities have found their records are more accurate and complete when computers are used for processing, organizing, or managing a great deal of the information associated with the overall fire prevention activity. Fire prevention reporting systems should be designed to collect, store, and process data and to schedule periodic activities according to local policy. For example, all information, including occupancy description, activity, and violations, is collected on a standard form during an inspection. After the inspection, forms are completed and processed according to local needs. These data, to be useful, must be collected and maintained in a uniform and consistent manner.

Computers can produce management reports related to inspection activity and to fire prevention personnel resource allocation. In addition, separate master file listings can be provided of occupancies currently under inspection and all occupancies to be inspected. Inspection forms or schedule sheets can be printed to show when periodic inspections are required and indicate violations to be checked for correction during follow-up inspections. These management reports should document the following:

1. The occupancy inspected, the location, the time of day, the date, and the name of the inspector
2. The code violations that have been corrected, filed by type, number, and kind of occupancy
3. The manner in which the fire department used its resources to accomplish fire prevention program objectives

These systems save the inspector time and provide data in a form useful for decision making by operational management. Because they contain a current inventory of occupancies, the systems can provide information for fire protection fiscal and long-range master planning.

PLAN REVIEW PRACTICES

Traditionally, the building department has been active in the design, construction, and final occupancy inspection of buildings. The fire prevention division's role traditionally began when the building was occupied, and it was concerned with the maintenance of life safety conditions and fire protection systems, as well as fire-safe storage and handling of contents.

Today, a progressive fire prevention division's role in the building construction process is changing. An increasingly important and practical fire prevention function involves the participation of the fire marshal or a designated representative in the review of building plans and specifications and in the construction process. In most cases, plans review is conducted in cooperation with the local building, zoning, and public works departments or with state agencies that may have this review authority.

The review of building plans and specifications provides the fire service with its best opportunity to see that fire protection standards are met before construction is completed and the building is occupied. The type and depth of the review process depend on the community's needs and the functions of other local departments or state agencies with review authority.

The fire official should participate in preconstruction conferences; address questions relating to fire protection features in the planned building, to the building code, or to fire code requirements; and comment during the plans review process. If questions and issues concerning the effect of construction on fire safety are discussed at this time with the architect, engineers, contractors, and other code officials, misunderstandings and conflicts that could arise during or after construction can be prevented. The fire official can emphasize fire safety code requirements and coordinate responsibilities with other code enforcement officials. Design professionals and contractors benefit from this procedure as well, because problems that otherwise would cost them time and money are identified and eliminated before construction begins.

Site Plan Reviews

The site plan review provides the fire official with the first look at new construction and at additions or modifications to existing buildings. The site plan provides an overview of the intended construction in relation to existing conditions and includes information such as building placement, exposures, size, type of construction, occupancy, water supply from both public and private sources, hydrant placement, and access. The site plan also may provide information about existing conditions that must be modified, such as abandoned underground flammable liquid tanks or pipelines in the area. The contour of the land may be significant. The current and projected uses of adjoining properties, including zoning, also should be reviewed at this time.

Preliminary Building Plans

The review of preliminary building plans gives the fire official an opportunity to comment on those features of the building that significantly affect life safety and protection of the building from fire. The depth and scope of the review and comments will depend on local conditions.

The provision for required fire protection systems is a primary concern in plans review. Because an estimated 75 percent of the building code may relate directly to fire protection and life safety within the building, the review may include, among other items, the type of occupancy, allowable areas and heights, fire separations, fire resistance of construction, interior finish, occupant load, number, location and arrangement of means of egress, protection of vertical openings, fire protection system, and special hazards.

Final Building Plans and Specifications

When the final building plans are submitted, they should include modifications required by the review official and agreed to by the design professional submitting the plans. Plans may be approved if they agree with the applicable code requirements. A building permit can then be issued, and construction may begin.

Plans review and approval must be followed by on-site inspections to ensure that the fire protection features and systems are constructed and installed as planned and approved. All deviations from the approved plans should be documented and, in certain cases, approvals must be obtained for the deviations. All agreements reached on-site or by telephone should be documented for all parties in follow-up correspondence or file memos. This correspondence and a copy of the approved plans should be retained in an organized filing system, so a permanent record of building construction is available for future reference.

When practical, building construction information should be provided to the fire companies responsible for that location. Information provided in all of the plans discussed in this section can aid in fire department prefire planning. Walk-throughs of the building by first-due fire companies should be conducted at various times during construction to familiarize them with the building.

Certificates of Occupancy

If the fire marshal's office is not the primary issuing agency for occupancy certificates, then either the fire marshal's office or the fire prevention division should be involved in the final inspection process. Each agency should certify the building before the certificate of occupancy is issued. This certificate indicates that all requirements under the building, fire and other applicable codes have been met and that the building is safe and habitable. All fire protection systems should be tested and placed in service before occupancy is allowed. The building should not be occupied until inspection agencies have approved it. This final review helps to ensure the life safety of the occupants and to verify that any required corrections have been made before occupancy.

CONSULTATION

The public looks to the fire service for answers and advice concerning fire problems. Due to its unique ability to provide this information, the fire department should offer consulting services to the community. Fire prevention officers must be able to explain fire codes, fire-related sections of building codes, and the application of specific standards to design professionals, contractors, and members of the building trades. Consultation also should be available directly to property owners, managers, occupants, and members of the general public, who may not be as familiar with fire problems and their solutions.

To maximize this service, the fire department should inform and instruct citizens about the best ways to deal with fire hazards. When the fire prevention division receives frequent calls about the same problem, it may wish to develop standard recommendations for that problem. If an issue relates to a specific group or business, they may wish to have a meeting with those affected to explain or clarify the issue. The fire department should maintain a library of up-to-date reference materials. In addition, the chief and other officers should be acquainted with individuals outside the fire department who have specialized knowledge or experience and who could act as resource persons. These and other consulting services are usually based in the fire prevention division or the fire marshal's office. State, city, or town webpages might also include FAQ sections on such everyday items as the requirements for location and placement of smoke alarms in the home or the permit, plan review, and inspection procedure required by the jurisdiction.

FIRE INVESTIGATION

The thorough investigation of fires is an integral part of the fire department's commitment to public safety and fire reduction. Fire investigation includes two areas: (1) fire cause determination and (2) investigation of criminal actions that may have contributed to a fire.

Fire cause determination is of major importance to a fire prevention program. Analysis of the causes of fires in a community is the basis for establishing fire prevention program priorities and providing fire safety information to the public.

Maximum utilization of resources must be based on firm information about the local fire problem. As information is accumulated from fire investigations, data become available on which to base corrective programs. Over time, this data will indicate trends in the area's fire problem, and a fire prevention program designed to tackle priority areas can be implemented.

If it is determined that a fire is caused by arson or other unlawful burning of property, a full criminal investigation should be conducted. Other fires for which a cause cannot be readily determined, including those classified as suspicious or undetermined, should also be investigated. Assertive fire investigations by skilled, trained specialists can deter arsonists.

In communities and states where fire service investigators have police powers, personnel may conduct an investigation to the point of arrest and incarceration of perpetrators. Where fire department personnel do not have police powers, fire cause determination must be made by the fire department and the follow-up investigation conducted by the police, sheriff, state police, or investigators from the state fire marshal's office. In some instances, cooperation with federal agencies such as the Bureau of Alcohol, Tobacco and Firearms (BATF) brings additional investigative and law enforcement resources to the local investigation units.

NFPA 921, *Guide for Fire and Explosion Investigations,* provides guidance in performing fire and explosion investigations. For additional information on fire investigations, see Section 3, Chapter 2, "Fire Loss Investigation."

PUBLIC FIRE AND LIFE SAFETY EDUCATION

Public fire and life safety education is an increasingly valuable area of public fire protection. This function has undergone rapid change and growth, focusing increasingly on the importance of prevention in public fire protection management. In recent years the focus of these programs has expanded to include other risks such as water, bike, firearms, motor vehicle, poison, fall, choking, natural disaster, and weather safety.

Public fire and life safety education includes three facets: (1) fire prevention education, (2) fire reaction education, and (3) other risk hazards. All three areas are necessary to change fundamentally the way the general public views fire as well as other hazards and to encourage people to act in a safe manner. The public needs to be motivated and instructed in actions that minimize the dangerous effects of a fire, should one occur. The basic method of instruction is changing from "preaching" to "teaching." Information is best presented in short, interesting, even humorous messages that require thought and that place responsibility for action on the recipients. In addition to the preventive aspect, the all-hazards approach to public education can also include a preparation aspect. For weather-related hazards that may result in long-duration power outages, having a supply of nonperishable foods on hand or a means to provide alternative light and heat sources should be considered. Recipients relate most effectively to the fire and life safety message when it is presented in a dramatic context. Cultural and language factors should be considered when fire and life safety messages are prepared for communication throughout the community.

National fire safety campaigns can be matched to local efforts. NFPA's *Learn Not to Burn*® effort is one such national campaign with messages designed to supplement, but not supplant, local fire prevention education programs. NFPA also offers other risk prevention programs such as *Risk Watch*® and *Remembering When.* NFPA has many public fire safety materials and programs designed for general public use and for specific groups and fire safety concerns. Community programs can be developed using the *Learn Not to Burn* theme and applying it to priority local fire problems (see Figure 1.5.3).

Community awareness and participation at the grassroots level are the keys to encouraging people to adopt fire and life safety behaviors. Civic and service clubs, youth and fraternal organizations, neighborhood action groups, the business community, schools, and other groups are contributing to the growth of fire and life safety education. Highly effective programs in such areas as escape planning, smoke alarm installation, fire hazard inspections, burn prevention, juvenile fire-setting problems, fire safety for babysitters, and fire safety for the elderly have been conducted by community groups in conjunction with local fire prevention personnel.

Many fire departments and fire prevention divisions have appointed full-time fire and life safety education officers. As their numbers have increased, the level of talent and professionalism of fire and life safety educators has also increased. Many fire departments no longer require that fire and life safety education officers be trained fire fighters; rather, these departments recognize the value of hiring educators with teaching experience

FIGURE 1.5.3 *Risk Watch* Program Being Used in a School (Source: Cote, Arthur E., *Fundamentals of Fire Protection,* 2004, Figure 7.5. Reproduced courtesy of Jones and Bartlett Publishers.)

and skills to develop and present educational programs geared to all ages and groups.

For additional information on fire and life safety education see Section 5.

Groups with Special Information Needs

Groups with information needs similar to those of the general public but different enough to require specialized programs include, among others, educational, industrial, institutional, high-rise, civic, service, elderly, professional, disabled, and commercial groups. Many innovative ways are used to reach such groups with fire and life safety information. See Section 5, Chapter 5, "Reaching High-Risk Groups."

Seasonal Activities

Informative educational programs of interest to the general public often are built around the four seasons of the year. Public education programs include National Fire Prevention Week, which is always the week that includes October 9, and Operation EDITH. Many topical and effective materials are available from NFPA for use in public education programs, including some featuring Sparky® the fire dog, the symbol of personal and property fire safety.

OTHER ENFORCEMENT AGENCIES

Building Department

Building departments are usually responsible for a variety of items related to building construction, structural integrity, protection, and occupancy features necessary to minimize danger to life and property. They provide oversight of design regulations to safeguard life, health, property, and public welfare and to minimize injuries by regulating and controlling the permitting, design, construction, quality of materials, use and occupancy, location, and maintenance of all buildings and structures within the jurisdiction, as well as certain equipment.

Effective building safety depends on the adoption of up-to-date codes and standards and a personnel network to use and enforce them. Adoption of codes and standards with modifications for local conditions provides the basis for building safety programs. The personnel assigned to the building department should be technically capable and motivated to enforce the building codes. This network of people can be organized at the state, county, and/or local level.

Because of the importance and diversity of building safety activities, whenever possible, certain members of the building department should specialize in specific functions. Staff size will depend on the community's needs and the department size and level of involvement. This office may be divided into specialized subsections addressing administration, inspections, enforcement, engineering, plumbing systems, mechanical systems, electrical systems, and planning and zoning. Other specialties may include members with structural expertise or flood plain management. Often these subsections are headed by subordinate officers.

In addition, qualified technical specialists should be available when possible—the department's overall effectiveness depends on the technical skills that the building department personnel possess. It is also important that such personnel be able to properly communicate technical requirements to building owners, architects, engineers, and other professionals involved in the construction industry as well as the general public.

State, county, municipal, or district laws or administrative regulations often delegate responsibility and authority for building safety to a specific individual, who may then delegate this authority to an individual or division. In some states, the local building official's authority and area of enforcement responsibility is derived from or stipulated by state laws. Personnel assigned to the building department should be knowledgeable about what authority they have.

The resources may vary depending on the size of the community, the type and pace of construction projects and the complexity of the projects. Quality assurance programs, such as those found in Chapter 40 of *NFPA 5000®*, *Building Construction and Safety Code®*, provide another tool for the code enforcement officer to ensure that the proper materials, designs, and techniques are being applied. All inspection or enforcement authorities from building departments, fire departments, or other offices still have most of the same legal obligations for inspection and enforcement issues as discussed previously.

Planning and Zoning Departments

Planning and zoning departments and inspectors have responsibility for the use and community planning of structures, buildings, and lands. They are responsible for such things as building and land maintenance, land use, building use, and community development.

Plumbing Department

Plumbing departments and inspectors are responsible for the erection, installation, alteration, repair, relocation, replacement, addition to, use, or maintenance of plumbing systems. Plumbing systems typically include all potable water, building supply, distribution pipes, and all plumbing fixtures and traps. Systems also include all drainage and vent pipes as well as all building drains and building sewers, including their respective joints and connection, devices, receptors, and appurtenances within the property lines of the premises. Plumbing departments will also be responsible for medical gas and medical vacuum systems, liquid and fuel gas piping, and water heaters and vents.

Mechanical Department

Mechanical departments and inspectors are responsible for the design, construction, and installation of mechanical systems. They will review the quality of materials, location, operation, and maintenance or use of heating, ventilating, cooling, and refrigeration systems; incinerators; and other miscellaneous heat-producing appliances. This includes the addition to or erection, installation, alteration, repair, relocation, replacement, use, or maintenance of any heating, ventilating, cooling, and refrigeration systems; incinerators; or other miscellaneous heat-producing appliances.

Electrical Department

Electrical departments and inspectors are responsible for the safeguarding of persons and property from hazards arising from the use of electricity. Their duties include plan review, inspection and enforcement of the installation of electrical conductors, equipment, and raceways; signaling and communications conductors, equipment, and raceways; and optical fiber cables and raceways for public and private premises. This includes buildings, structures, manufactured homes, recreational vehicles, floating buildings, yards, lots, parking lots, and carnivals. Also addressed are industrial substations, installations of conductors and equipment that connect to the supply of electricity, and the installations used by the electric utility, such as office buildings, warehouses, garages, machine shops, and recreational buildings that are not an integral part of a generating plant, substation, or control center.

SUMMARY

Fire prevention and code enforcement on the municipal, county, and state/provincial levels encompasses a variety of functions that include code inspections and enforcement, plans reviews, public fire and life safety education, and fire investigation. The successful implementation of fire prevention functions relies on the adoption of up-to-date codes and standards and the presence of technically capable and motivated personnel. This chapter has examined the functions and personnel needed for effective fire prevention and control of related hazards, that is, fire service activities that decrease the incidence and severity of uncontrolled fire.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire prevention and code enforcement. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code*™
NFPA 921, *Guide for Fire and Explosion Investigations*
NFPA 1031, *Standard for Professional Qualifications for Fire Inspector and Plan Examiner*
NFPA 1033, *Standard for Professional Qualifications for Fire Investigators*
NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*
NFPA 1037, *Standard for Professional Qualifications for Fire Marshals*
NFPA 5000®, Building Construction and Safety Code®

Organization/Agency Information and Program Sources

International Association of Fire Chiefs (IAFC), Washington, DC
International Code Council (ICC), Washington, DC
International Fire Marshals Association (IFMA), Quincy, MA
International Fire Service Training Association (IFSTA), Oklahoma State University, Stillwater, OK
National Association of State Fire Marshals (NASFM), Washington, DC
National Conference of States on Building Codes and Standards, Herndon, VA
National Fire Academy (NFA), Emmitsburg, MD
National Fire Protection Association (NFPA), Quincy, MA
National Institute of Standards and Technology (NIST), Center for Fire Research, BFRL, Gaithersburg, MD
United States Fire Administration (USFA), Emmitsburg, MD
Western Fire Chiefs Association (WFCA), Fallbrook, CA

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NFPA Checklists for Inspecting Detection and Suppression Systems
NFPA Fire and Life Safety Inspection Manual
NFPA 1, *Uniform Fire Code*™

Chapter 6

Premises Security

Lauris V. Freidenfelds

Chapter Contents

Security Threats
Department of Homeland Security
Security Program Development
Security Vulnerability Assessment (SVA)
Guidelines, Standards, and Codes
Architectural Security Elements
Technology Security Elements
Operational Security Elements

Key Terms

access control, crime prevention through environmental design (CPTED), Department of Homeland Security (DHS), intrusion detection system, mass notification system, operational security, risk management, security program, security vulnerability assessment (SVA), terrorist activity

Security is "an intangible quality" that is most easily quantified or defined when it is breached or lost. The dictionary defines *security* as the quality or state of being secure—that is, free from danger, fear, or anxiety, or free from risk of loss.[1] Security has as much to do with perception as with reality. It can involve many components, from prevention through detection to apprehension. Finally, it can be said that security does not mean the same thing to everyone.

Crime has the fundamental components of motive and opportunity. The motive can be deep seated and, if that is the case, difficult to eliminate. Some people are deeply motivated by need—whether financial, habitual, spiritual, or simply for power. In some extreme circumstances, this need may be elevated enough for persons to sacrifice their own lives for their cause, often resulting in an act we call terrorism. A political motivation normally accompanies this level of commitment.

The other component of crime is opportunity. This aspect of crime is easier to manage. A great deal of crime targeting is based on opportunity. Most police and security professionals will agree that the elimination of opportunity is the single most effective means for preventing someone from becoming the victim. Making it difficult to perpetrate a crime is, therefore, the most effective deterrent.

The elimination of opportunity requires its identification through methods discussed in the security vulnerability assessment (SVA) section of this chapter. Although the focus of business and corporate security programs may be limited to their specific sites, the section on the Department of Homeland Security discusses the role of these programs in identifying and eliminating the actions of terrorists and criminals on a global scale. Once the opportunities are identified, the security program should address their mitigation or elimination. The security program can include architectural, technology, and operational security elements.

For related topics, see Section 1, Chapter 7, "Protecting Against Extreme Events"; Section 1, Chapter 8, "Emergency Management and Business Continuity"; and Section 14, Chapter 10, "Security and Intrusion Detection Systems."

SECURITY THREATS

Eliminating all security threats is difficult, if not impossible, because security threats are varied and dynamic. As one security threat is eliminated, another may develop. Thus, security programs look at establishing priorities, estimating probabilities, and dealing in reasonable measures.

The targets of security threats can be either people or assets. Clearly, most people would feel that eliminating the threats against individuals or groups of individuals should have the higher priority. Assets can be prioritized based on their criticalness to the organization.

Role of Motive

As stated earlier, motive plays a key role in criminal activity. Individuals can unknowingly create motives for criminal activity against them. Conflicts at work or at home can motivate criminal activity—for example, denying a promotion or providing a negative performance evaluation can

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motivate criminal activity. The criminal activity may result in attacks on the individual or on assets under the control of the individual or organization.

Security Tools

One of the core tenets of providing security for individuals, as well as for assets, is to deny unauthorized or unwanted access to them. Access control systems play an important role in this. Another security tool is surveillance. Most criminals do not wish to be identified so that they can avoid prosecution and continue their activity. Many will avoid areas where it is known that security has a surveillance program in place.

Jurisdiction of Responsibility

The scale of criminal activity usually determines the jurisdiction of responsibility. If planned criminal activity targets just one or a few individuals or assets in a private organization, then that organization's security entity is usually the lead in mitigating the threat. The organization's security department can request assistance from public law enforcement if it cannot handle the incident on its own. If the threat is large in scale and has the potential to impact the public outside the domain of the private enterprise, then the public law enforcement agencies usually take over. This type of threat is considered terrorism.

The United States government (both individuals and assets) are frequently viewed as targets of terrorism. For that reason, it is on the forefront of establishing standards and guidelines for the protection of government individuals and assets. The establishment of the Department of Homeland Security (DHS) indicates that there is a growing shift in priorities from programs addressing apprehension to those focusing on prevention activities.

DEPARTMENT OF HOMELAND SECURITY

Establishment of the Department of Homeland Security (DHS)

In the past, acts of terrorism and large-scale incidents (e.g., bombings and biochemical attacks) involving major office buildings, transportation systems, and the like were considered not likely to occur on U.S. soil. The 1993 bombing at the World Trade Center, the 1995 Oklahoma City bombing, and the September 11, 2001, terrorist attacks have, however, created a new paradigm that is at best difficult to quantify and at worst challenging to predict. The threat and reality of international and domestic terrorism has had a negative impact on the sense of security of our society. This has led to the establishment of the Department of Homeland Security (DHS), which is a large organization of 22 previously disparate domestic agencies coordinated into one department to protect the nation against threats to the homeland.

DHS's Vision, Mission, and Strategic Goals

DHS's vision, mission, and strategic goals are as follows[2]:

Vision
Preserving our freedoms, protecting America . . . we secure our homeland.

Mission
We will lead the unified national effort to secure America. We will prevent and deter terrorist attacks and protect against and respond to threats and hazards to the nation. We will ensure safe and secure borders, welcome lawful immigrants and visitors, and promote the free-flow of commerce.

Strategic Goals
Awareness: Identify and understand threats, assess vulnerabilities, determine potential impacts and disseminate timely information to our homeland security partners and the American public.

Prevention: Detect, deter and mitigate threats to our homeland.

Protection: Safeguard our people and their freedoms, critical infrastructure, property and the economy of our Nation from acts of terrorism, natural disasters, or other emergencies.

Response: Lead, manage and coordinate the national response to acts of terrorism, natural disasters, or other emergencies.

Recovery: Lead national, state, local and private sector efforts to restore services and rebuild communities after acts of terrorism, natural disasters, or other emergencies.

Service: Serve the public effectively by facilitating lawful trade, travel and immigration.

Organizational Excellence: Value our most important resource, our people. Create a culture that promotes a common identity, innovation, mutual respect, accountability and teamwork to achieve efficiencies, effectiveness, and operational synergies.

The DHS and local public law enforcement agencies are getting more involved in assisting the private sector with security. However, this involvement consists of activities primarily focused on sharing information about threats and activities that become known to the intelligence agencies of the United States government. Some of this information is provided as sensitive information to the security community at local, regional, or national levels as appropriate, whereas other information impacts the DHS "Threat Advisory" level (Figure 1.6.1).

An interesting phenomenon that has developed is that public police departments are becoming more sophisticated in the implementation and use of detection capabilities. Many cities are installing video surveillance cameras to assist police officers in the field. It is likely that this concept will continue to grow, at least in the public areas. The determination of what and how much security is necessary on private property is still in the hands of private business managers.

SECURITY PROGRAM DEVELOPMENT

Risk Management Approach

The concept of developing an appropriate security program can be daunting to even the most experienced security professional.

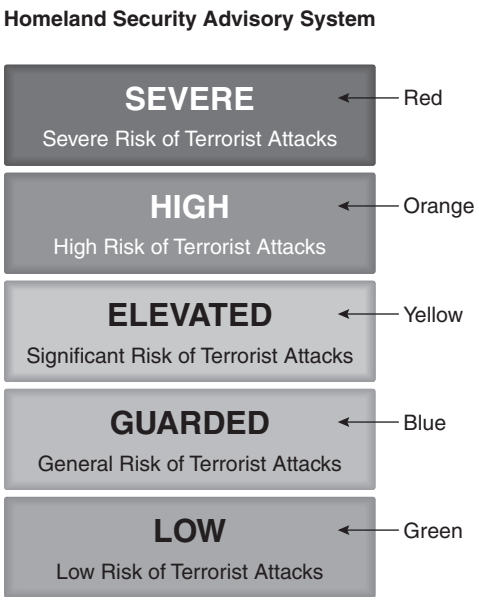

FIGURE 1.6.1 Department of Homeland Security's Threat Advisory Levels

Some people make the mistake of implementing security solutions without understanding the threats or vulnerabilities. This can lead to ineffective security programs, implementing programs that are too restrictive or, in the worst case, will not protect against a foreseeable threat. Alternatively, well-intentioned security programs can have the unintended consequence of inhibiting free and unencumbered egress for occupants. Security should be applied in a risk management approach that considers other factors such as fire safety and also maintaining a usable facility. The goal is a balance between security and other considerations in which every restriction is a minimally disruptive but effective response to a realistic threat. Implementing a program that is considered too restrictive can lead people to deride and resist the program. Implementing a program that does not address the foreseeable risks and vulnerabilities can be a waste of resources and lead to its failure.

How much security is needed can be driven by tort law—"reasonable measures" standard—that is, the foreseeability of crime. The security program should be able to address foreseeable incidents. The plan for implementing a security program should be based on performing a security vulnerability assessment (SVA); researching applicable guidelines, standards, or codes; and developing the appropriate strategy for the mitigation of security vulnerabilities. This process should be continually updated and modified because risks and vulnerabilities are dynamic and can often change. In addition, physical changes to buildings (e.g., tenant improvements, building renovations) will cause the plan to be evaluated and revised in many cases.

Security Program Elements

The security program should comprise architectural, operational, and technical elements (Figure 1.6.2). The appropriate interaction of these elements will be discussed in greater detail later, but the foundation of this concept is the coordination of technological and architectural elements to support operations. The technology aspects of security are but one element of effective security programs. Technology must be integrated with architecture and operations to form an effective security program. The appropriate use of each of the elements depends on the culture, style, and capabilities of the corporation. Overemphasis on only one or ignoring one of the other components can lead to a program that may be both inefficient and ineffective.

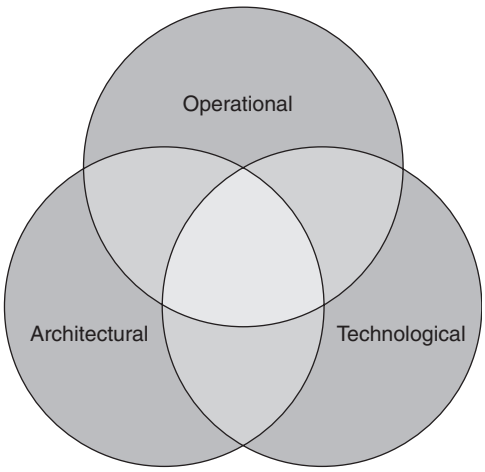

FIGURE 1.6.2 Security Program Elements

Technology is the tool that can make security operations more efficient. There are systems such as access control, video surveillance, intrusion detection, communications, contraband and weapon detection, asset monitoring, and others. It may not be economically possible to provide staff at each door to screen people entering and leaving the building. Security systems can execute that assignment with devices such as a biometric identity verification reader and other door controls. The effective security programs include technology systems that can adjust to the level of the known or potential threat.

Security can be considered more of an art than a science. Because the industry has evolved largely without standards until very recently, the methodology for achieving security can have many designs and options.

SECURITY VULNERABILITY ASSESSMENT (SVA)

Quantifying Types of Threats

There are many theories regarding the methodology of how to execute a security vulnerability assessment (SVA). Many are good, such as the FEMA 426, *Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings.*[3]

Some threats to security are sufficiently common (e.g., fires or break-ins) that probability and severity estimates can be developed directly from historic data. Some threats to security are rare events (e.g., earthquakes or hurricanes) that can be characterized in terms of return frequencies using historic data, extreme-value statistical methods, and possibly scientific

understanding of the underlying physical phenomena that generate such occurrences.

Some threats to security, however, are so rare—or even unprecedented—that no predictions can be developed from experience. Expert judgment may have to suffice, and experts are often no better than anyone else at anticipating the truly unexpected (such as the September 11, 2001, attacks). Also, if the threats are the result of deliberate hostile acts—as they often will be in the security realm—it may be appropriate to base predictions on the attractiveness and vulnerability of the target. Military planning, which is based less on past frequency or current intent and more on current or future capability, may be relevant.

Prior to September 11, 2001, very few people in the United States would have believed that adversaries would commandeer commercial aircraft and sacrifice their own lives to commit an act of terror. Acts of terrorism on U.S. soil were not considered probable enough to justify a mitigation strategy to prevent them nor to determine building construction strategies to manage such hazards. Although the World Trade Center (1993) and Oklahoma City (1995) incidents might have elevated the notion of terrorist attacks, establishing criteria to deal with them simply did not occur. U.S. Department of State embassies located throughout the world have typically applied some very sophisticated security and deterrent strategies. The extent to which these elements could or should be applied to buildings on U.S. soil is now a topic of debate in all areas relating to the built environment.

Assessment Objective

The best approach is to develop a tool that will address the issues and factors important to the organization. The SVA should be organized to take into consideration the following factors:

- Foreseeable likelihood of the threat or incident
- Impact of the threat or incident
- Mitigation strategies

The objective of the assessment should be to answer questions such as the following and others that are more specific to the type of business:

- Does my building represent a potential target?
- Are we located near a target?
- Do tenants in my building elevate the risk by attracting an attack?
- Are we capable of dispersing critical operations or staff to backup locations?
- Can we separate screened from nonscreened people routinely or as part of response to an attack in progress?
- Do we have backup programs in place?
- Is my staff properly trained?
- Can we reasonably detect weapons, explosive devices, and biological or chemical agents at entries?
- Can we reasonably detect biological or chemical agents in air returns/intakes?
- Can we mitigate their effects?
- Is our voice-data infrastructure protected?
- Is our HVAC and electrical infrastructure protected?

The following impact questions should also be addressed:

- What would be the impact on operations if we were the target of an explosive, biological, or chemical attack?
- How long can we operate in this manner?
- What are the costs of operating in this manner?
- Can our operations be relocated efficiently?
- What would happen if a nearby facility were targeted?

SVA Process

As described in NFPA 730, *Guide for Premises Security,* Chapter 5, the SVA is a seven-step process.

Step 1: Formation of Team. The process should begin with the formation of a team of personnel from all organizational areas. Commonly, the individual responsible for an organization's security serves as team leader.

Step 2: Organization/Facility Characterization. Step 2 involves a characterization of an organization and the facilities to be protected. It includes identification of assets (i.e., people, property, information, and products); physical features and operations; laws, regulations, and corporate policies; social and political environment and internal activity (i.e., community resources, crime statistics, internal activities, and loss experience); and review of "current layers of protection" (including both site security features and safety measures).

Step 3: Threat Assessment. Step 3 is the conducting of a threat assessment. The process includes a classification of critical assets, identification of potential targets, consequence analysis (effect of loss, including any potential off-site consequence), and the definition of potential threats (by identifying potential adversaries and what is known about them).

Step 4: Threat Vulnerability Analysis. Step 4 is the conducting of a threat vulnerability analysis that identifies actual and potential threat scenarios and estimates a relative security risk level. The relative security risk level is a function of determining the severity of the consequences of an adversarial event, the potential for such an attack, and the likelihood of adversary success in carrying out the anticipated event or activity.

Step 5: Define Specific Security Countermeasures. Step 5 involves defining specific security countermeasures. All information from the previous four steps, including characterization, threat, and vulnerability analysis, is considered. An effective countermeasure is one that drives improvements in mitigating the defined threats and results in a reduction in the security risk level.

Step 6: Assess Risk Reduction. Step 6 involves taking into account the countermeasures defined in Step 5, reassessing the relative security risk levels developed in Step 4, and considering additional security risk reduction measures (security countermeasures) where appropriate.

Step 7: Document Findings and Track Implementation. Step 7 involves documenting findings and recommendations

in a report and tracking the implementation of accepted recommendations.

The process should be repeated as often as deemed necessary, but annually is usually a good minimum frequency.

GUIDELINES, STANDARDS, AND CODES

Governmental Guidelines

As stated before, the security industry has largely grown without the benefit of guidelines, standards, or codes. The earliest guidelines and standards evolved from the U.S. Department of Defense's mandating of security for defense contractor facilities as early as World War II. Terrorists have typically focused on federal government buildings or structures or objects that represent iconic or highly symbolic targets. This has prompted the federal government to establish guidelines that can be applied to certain federal facilities. Some organizations consider these guidelines applicable for their high-profile private corporate facilities.

On June 28, 1995, the U.S. Department of Justice published the *Vulnerability Assessment of Federal Facilities.*[4] The report recommended the formation of an Interagency Security Committee (ISC), which was formed by Executive Order 12977 on October 19, 1995, to establish long-term construction standards for federal buildings. The result was the publication of the *ISC Security Design Criteria for the New Federal Office Buildings and Major Modernization Projects.*[5] Additionally, there are many specific guidelines and requirements for specific federal agency facilities.

Commercial/Nongovernmental Guidelines

In the commercial, nongovernment sector there are fewer guidelines. The insurance industry has prompted the Underwriters Laboratories (UL) to establish some of the guidelines. Insurance companies noted that with respect to assets they insured there were no established standards for the prevention of loss. UL is one organization that developed standards and guidelines insurance companies found acceptable. To encourage implementation of these guidelines, insurance companies provided financial incentives for those who implemented and maintained these systems. Included are central station requirements, jewelry store protected property requirements, and others. Many industry associations provide standards or guidelines for specific components of a security program, such as glazing material, bank vault construction, and door hardware.

NFPA 730, *Guide for Premises Security*

On August 18, 2005, the NFPA approved NFPA 730 as an American National Standard. This guide provides construction, protection, and occupancy features and practices intended to reduce security vulnerabilities to life and property. Similarly, on the same date, the NFPA approved NFPA 731, *Standard for the Installation of Electronic Premises Security Systems.* NFPA 731 covers the application, location, installation, performance, testing, and maintenance of electronic premises security systems and their components. Using NFPA 730 as a guideline for establishing a security program, NFPA 731 can provide a minimum standard for applying security technology.

Concentric Circles or Layered Approach

No single feature or attribute can provide the total security package. Rather, the synergy of multiple features, systems, and policies work to provide an appropriate level of protection. Good physical security is built using a layered approach, with the perimeter being the first physical line of defense against a general threat level for any facility. Security is then applied in layers that are targeted to address specific threats. With respect to the development of security countermeasures, and in consideration of the defined threats, the SVA team's efforts should be to develop or strengthen the security by applying layers of protection beginning with a focus on the concentric circles of protection design methodology (Figure 1.6.3).

As described in NFPA 730, the concentric circles methodology provides for protection of defined critical assets by considering four primary protection elements. The primary elements of an effective protection plan design follow:

- *Deter.* Discourage an adversary from attempting an assault by reducing the likelihood of a successful attack or offense.
- *Detect.* Determine that an undesirable event has occurred or is occurring. Detection includes sensing the event, communicating the alarm to an attended location, and assessing the alarm.
- *Delay.* Impede adversary penetration into a protected area.
- *Respond*. Counteract adversary activity and interrupt the undesirable event.

Theft, sabotage, or other malevolent acts can be prevented in two ways: by either deterring or defeating the adversary. In the development of security countermeasures, it is important to

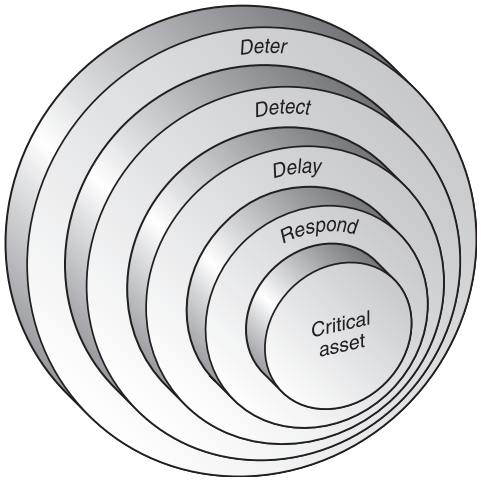

FIGURE 1.6.3 Concentric Circles of Protection (Source: NFPA 730, *Guide for Premises Security,* 2006, Figure A.5.2.5.)

understand that a properly designed and implemented security program integrates people, procedures, and technologies for the protection of assets. The use of technologies alone is not the solution.

The "new world" we live in poses a new challenge: the increased presence and threat of adversarial attack. Our journey now involves an important dual approach, the combination of today's security methodologies with traditional safety and risk management practices to strengthen security layers of protection. An effective security program, resulting from the completion and implementation of a comprehensive SVA, provides measurable benefits in the workplace for personnel (staff, guests, and visitors), in the protection of property, and in operations, resulting in enhanced business performance.

The security professional has the benefit of a plethora of available tools. The challenge is to select the correct ones and apply them appropriately. A growing popular concept is crime prevention through environmental design (CPTED). It is based on the premise that "the proper design and effective use of the built environment can lead to a reduction in the incidence and fear of crime, thereby improving the quality of life."[6] The goal of CPTED is to reduce opportunities for crime that may be inherent in the design of structures or of neighborhoods.

ARCHITECTURAL SECURITY ELEMENTS

Architectural security elements are elements that provide physical deterrence and prevention of intrusion/crime. In addition to the hard physical elements, architecture can play a role in creating segregation of buildings, staff, and traffic flow—a particularly important concept in the design of hospitals, where the people are unable to defend themselves against crime because of their physical condition, and in the design of courthouses, where the people are opposing each other in legal and criminal cases. These architectural elements, designed in conjunction with the appropriate technology elements, can provide a major contribution to an effective security program.

Lighting

Protective lighting is a valuable and inexpensive deterrent to crime. It provides visibility for checking badges and people at entrances, inspecting vehicles, preventing illegal entry, and detecting intruders both on grounds and outside and inside buildings. The recommendations for minimum lighting can be found in NFPA 730 paragraph 6.4.6.1 (Table 1.6.1). More information on recommended lighting levels for outdoor protective lighting is also provided in the *Lighting Handbook,* 9th edition, published by the Illuminating Engineering Society of North America (IESNA).

TABLE 1.6.1 Recommended Minimum Intensities for Outdoor Protective Lighting

Location	*Footcandles (on horizontal plane at ground level)*
Perimeter of outer area	0.15
Perimeter of restricted area	0.4
Vehicular entrances	1.0
Pedestrian entrances	2.0
Sensitive inner areas	0.15
Sensitive inner structures	1.0
Entrances (inactive)	0.1
Open yards	0.2
Docks/piers	1.0

Source: U.S. Army Field Manual 19–30, 1979; reproduced in NFPA 730, *Guide for Premises Security,* 2006, as Table 6.5.2.1.

Fences

Fences serve multiple roles in a security program. First, a fence line can be a barrier to prevent or minimize the chances for intrusion. The fencing material should be commensurate with the intended barrier protection required. Second, it can clearly indicate the outermost perimeter of an area that has access restrictions. This indication may require additional specific signage (to assist in prosecution) at designated locations to ensure proper warning. Checking with local ordinances to obtain proper installation and any related restrictions is advisable. It is also a good idea to see whether the local jurisdiction has recommendations or requirements for signage. The fence should be as straight as possible to provide for ease of observation. Clear zones should be provided on both sides of the fence to provide an unobstructed view. Utility poles in close proximity to the fence should be provided with a "security collar," a device that prevents climbing the pole to a height greater than that of the fence.

Gates and Barriers

The number of entrances should be kept to a minimum, consistent with safe and efficient operation of the facility. Entrances can be designed for vehicular traffic or for pedestrians and are usually closed by a gate or turnstile. Gates can be single- or double-swing for walkways, multifold for wide entrances, double-swing and overhead single- and double-sliding for driveways, cantilever single- and double-sliding for driveways where an overhead track would be in the way, or vertical-lift for special purposes such as loading docks. Any of these gates can be motor operated. When entrances are not staffed, they can be securely locked, illuminated during the hours of darkness, and periodically inspected. Semi-active entrances, such as railroad siding gates or gates used only during peak traffic flow periods, can be kept locked except when actually in use.

When the SVA dictates that the threat may be in the form of a vehicle attempting to gain access through force, vehicle arrest barriers or pop-up bollards may be recommended. These devices are designed to stop vehicles at the specified speed and mass (Figure 1.6.4).

Berms and Natural Elements

Within the perimeter fence and gates are several architectural elements that can add to the security program. Consistent with CPTED principles, natural features such as mature trees and

FIGURE 1.6.4 High-Security Road Block Barrier (Source: Courtesy of Delta Scientific)

FIGURE 1.6.5 Concrete Bollards (Source: Wausau Tile, Inc., http://www.wausautile.com)

elevation changes with berms and valleys can be used to prevent vehicles from gaining enough speed on the site to do damage. Drives and close proximity access roads should be designed with a serpentine-type route to again limit the speed that can be achieved.

Standoff Distance

When the threat or risk scenarios developed in the SVA indicate a need to consider vehicle-borne explosives, an effective means of providing security against this threat is to create a standoff distance from the building to a point where a threat vehicle is allowed to approach the building. The greater the distance, the less impact the explosion would have. The distance can be achieved by placing bollards (Figure 1.6.5), planters, or barriers at the distance where the explosion effect can be sufficiently dissipated. When designing for an explosives attack, an assumed explosives size (TNT equivalent) must be agreed on. The standoff distance is valid for that design assumption, but may not be as effective for a scenario that is greater than the design point. The same holds true for other interventions that address the explosives design scenario.

Walls/Glazing

Building perimeter construction should be sufficient to address the potential threats identified in the SVA. The threats may include explosives or intrusion attacks. When the standoff distance required to address the described potential explosive device cannot be achieved, the structural components of the building need to be reinforced to handle and mitigate the threat. The three types of materials presently listed by UL for use as burglary-resisting glazing materials are laminated glass, polycarbonate, and acrylic. Glazing materials that meet the UL requirements are listed under the category "Burglary-Resisting Glazing Material (CVYU)" in the *UL Security Equipment Directory.*

Component and cladding systems that are more robust when a proximate explosive is discharged can minimize the amount of airborne debris. Specially designed glazing systems actually restrain or retain glass panels in exterior windows.

Doors

As with gates, the number of doors into a building should be limited to only that which is necessary. In most commercial burglaries, the point of attack is a door, window, or other accessible opening. On doors with glass lites (i.e., glazing within a door) or doors adjacent to glazed panels, there is the concern of an intruder breaking the glass and reaching in to unlock the door. To protect against this type of attack, a double cylinder lock (i.e., a lock that requires a key to lock and unlock the door from either side) can be used under limited circumstances; however, this application can be in conflict with *life safety requirements.* (See NFPA *101*®, *Life Safety Code*®, 7.2.1.5.)

An alternative is to use a conventional single-cylinder deadbolt and either to replace the glass with burglary-resisting glazing material or to install a polycarbonate sheet behind the glass lite. When used to provide backup protection to a glass lite, the polycarbonate sheet is attached to the door with wood screws and countersunk washers. To allow for the expansion and contraction of the polycarbonate, the holes drilled in the polycarbonate sheet must be of a slightly larger diameter than that of the wood screw. This technique can basically be applied to any type of window.

Locks/Door Hardware

Door hardware is traditionally an architectural feature. Mechanical locks and door hardware should take into account the risks identified in the SVA and consideration should be given to security-type cylinders on the required doors. Nonduplicatable keys are typically a good idea. Higher-security keys are available from many manufacturers. Antipry devices can be applied where necessary, especially if door position monitoring is not provided at the door. The electronic door hardware needs

to be well coordinated with the security technology systems. Where building and life safety codes allow the use of electronic security door hardware, it should be *fail secure* as opposed to *fail safe,* with a mechanical or manual means of releasing the door to allow for egress. (Fail secure hardware remains engaged when there is no power, requiring power to unlock or disengage. Fail safe electronic hardware requires power to stay engaged; when power is removed, the hardware disengages.) In most cases, close coordination of the various failure mechanisms and scenarios and the manual releasing methods must be laid out to make it absolutely positive that the door can always be released via mechanical or manual means.

Signage

Utilize signage and site flow to prevent visitor frustration and anger. Focus on communicating with the unfamiliar visitor. Anticipate the questions unfamiliar visitors would have as they enter the facility to accomplish a common goal, such as paying taxes or visiting a clinic with two children in tow. Clearly communicate answers to those questions via coordinated signage. Design the signage based on the reality of how people prefer to access and use the facilities. Important components include consistent terminology, clear and consistent signage, multilanguage handouts, customer service or information centers in lobbies, and self-help kiosks. If handmade signs are necessary, make sure they are coordinated and consistent in production to ensure size and message constancy. Periodically review posted signs to verify their accuracy.

Signage should be posted from the entrance to the property all the way inward. Due to the number of functions at many of the facilities, signs may need to include the practical reason for visiting an office as well as the office name. This is sometimes the case, but frequently existing signs list the "official" name of an office, which is not the same as the colloquial name for it and does not indicate the functions performed there. Consideration should be given to having both listed.

Consider the use of "authorized entry only" signs or way-finding signage to prevent "wandering" or use of unauthorized or nonpublic areas. Color-coded strips on the floor are one example of a way-finding method.

Mailrooms

One vulnerability that may be identified in the SVA is the daily flow of mail and packages into the facilities. By their very nature, mailrooms, loading docks, and any areas that receive shipments are among the most vulnerable areas. Risks include improvised explosive devices (IEDs) (e.g., parcel bombs or vehicle bombs) and chemical or biological agents (e.g., anthrax). Because a criminal can remotely reach deep into a facility through mail and packages, an added level of precaution may be warranted. Typical detection provisions include using technology (X-ray machines and magnetometers) to screen mail and packages. Technology to monitor the air quality is much less mature. Attempts to mitigate the risk (reaction) through physical modifications, such as building separate mail handling areas with dedicated, separate ventilation systems, should be considered. Some federal government facilities actually process incoming mail at isolated, physically remote locations that are geographically separate from the primary facility or office.

TECHNOLOGY SECURITY ELEMENTS

Design Concepts

Today's design concepts involve multiple levels of integration and utilization of networks and sophisticated interfaces that result in simple and easy-to-use access control systems. The challenge that designers face is having a good understanding of specific system capabilities, interface options, and limitations. Too many video systems attempt to handle the access control requirements, and some access control systems attempt to become video switchers and controllers. Multitasking of this technology is now on the brink of utilizing video smoke detection apparatus. Although multifunctionality of this type of equipment may be desired, it may not be ideal. Specifiers of these systems and equipment must be aware of the intended use of the products, of the compatibility with other systems, and of the intended goal or objective the overall system is striving for.

Currently no standard can be considered a commonality conduit for system communication. In other words, no one system or communications protocol is the de facto standard. This "open architecture" term (a concept describing the capability of communicating universally with all system components on the market) has been a catchphrase picked up by the security industry based on a concept that has been effective in the building automation industry.

Although simple open or closed circuit devices can provide inputs to any and all systems, the concept of data communications is still a proprietary function. Security companies have developed their systems with proprietary concepts to protect their investments. Manufacturers do not build field panels that will communicate with their competitors and vice versa. Although there have been companies that built systems that could communicate with some third-party field panels, these are becoming few and far between. Some manufacturers of card readers sell their product to anyone, and these communicate via an industry standard output (defined as Wiegand) for use by all of those systems that desire to use their devices.

Many access control system manufacturers work with selected video surveillance systems to enhance their marketability. They share communication codes and work to provide as much feature compatibility as possible. When one system is required to communicate data to another, one of the systems must share its code and allow the other to write to it.

The effective security technology design for a door requires more than just an access control card reader. The typical configuration of security technology at a door can consist of the card reader to provide authorization screening into the protected space, the electronic door hardware, a door magnetic contact switch to monitor the position of the door (making sure that the door is closed after a legal opening), and a request-to-exit motion detector or other device to use to leave the protected space (Figure 1.6.6).

In large institutions and organizations, such as universities and multisite organizations, the implementation of security sys-

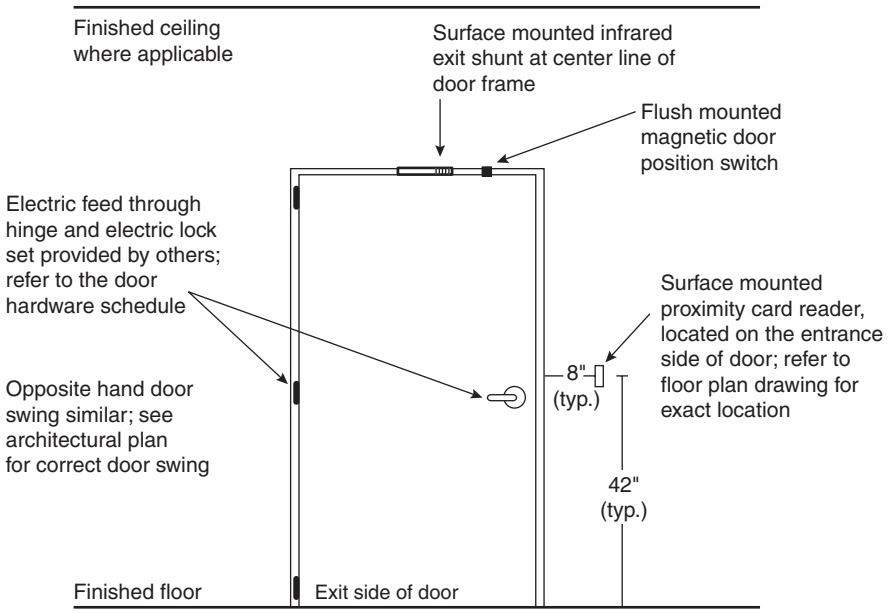

FIGURE 1.6.6 Single-Door Security Device Details

tems can be decentralized leading to multiple security systems and concepts. When possible, develop, publish, and support a security section to the organization's building standards document to codify the security standards applicable by category of facility.

Access Control

The backbone of most security systems is the access control system, which consists of a central processor or server with a graphical user interface (GUI) on one end and a microprocessor-based field panel controlling the card or identity readers at doors or portals. These systems have evolved into being able to process thousands of simultaneous access requests and allowing authorized people access through a door in under a second. The systems have the capability to matrix access authority levels and time/day zones to the level that each cardholder can have different access authority at every door dependent on the time/day and location of the reader.

The field panels provide most of the processing. These field-installed multiplex panels serve to multiplex data generated by multiple card readers and/or intrusion alarm devices for transmission to the file server and energize or de-energize power circuits to electric door locking devices.

The process that occurs can be described as follows. When entering an access-controlled door, the reader is designed such that on presentation of an access card, unique card identification data are transmitted to an associated multiplex field panel where the cardholder attributes contained within the cardholder database are analyzed, and access is allowed or denied accordingly. On authorization of access, the multiplex field panel temporarily unlocks the associated locking mechanism and shunts the associated door position switch or switches.

Identification

Cardholder Database. Most access control systems incorporate a database of information on the cardholder. The cardholder database includes some identification information, information about the unique card issued to that person, and usually a digitalized photo that is captured in the enrollment process. The photo can be printed onto the card for manual identity verification.

Access control has been performed by reader devices that would read the information on a card and base the go/no-go decision on the information about the cardholder stored in the database. The assumption has always been that possession of a card is restricted to the authorized user. Card readers have utilized technologies such as magnetic stripes, barium ferrite, Wiegand wires, and proximity (i.e., technology that utilizes radio frequency). Some of these technologies are no longer commonly used, such as barium ferrite and Wiegand wire; but all are still available.

Smart Cards. There has been some talk about the use of "smart cards" in security systems. These smart cards are small storage chips on a card, yet they are not processors. The cards may have a future in the security world in carrying the biometric characteristics for use by these systems. Smart cards have been used in the debit card market. These systems are capable of rewriting data onto the chip and thus lend themselves to systems that alter the information based on usage.

Biometric Devices. Recently a huge groundswell of interest has developed in biometric devices, which compare a unique physical characteristic, such as a fingerprint, hand geometry, iris, retina, facial features, or voice pattern, to a known characteristic in the database. These characteristics are presumed

to be unique to the individual, and any alteration or duplication attempt should be both difficult to reproduce as well as detectable.

The concept that is driving the biometric growth is the need to identify positively the individual attempting to gain access into an area. Security directors are no longer satisfied with the "possession of an authorized card" concept as the only means to allow access into secure areas. In the strictest of security environments, the access and identity verification process involves multiple tests: a valid card (what I have), a password or PIN code (what I know), and a biometric characteristic (what I am). This is commonly referred to as multifactorial identification.

The disadvantage of biometric readers is that until recently they have been stand-alone devices. Such a device requires that a stored template be called up for comparison to the presented characteristic. The device determines whether there is a match between the two of them, a decision that is not made by the access control system. The biometric device manufacturers have been independently developing these devices and have just recently started working with the access control system manufacturers to incorporate the biometric characteristics into the access control system databases.

Contrary to popular belief, the biometric readers are not tied into any national databases for identification purposes. Work is being done to develop biometric devices that will compare a presented biometric characteristic and identify that person, but as of now the only devices that can do that are limited to small databases (200 templates). The major obstacle is the processing speed; the comparison needs to be executed in a reasonable time frame, which typically is defined as under 2 seconds.

Intrusion Detection System (IDS)

Intrusion detection systems (IDS) are a fairly mature concept with few new developments. The systems have been designed to utilize field-installed devices, such as magnetic door position switches (door contacts), motion detectors, such as microwave or passive infrared (PIR), and other event initiating devices; process these inputs; and transmit the appropriate signal to a graphical user interface (GUI), central station, or other annunciating device.

Many access control systems incorporate the application software to handle intrusion detection processing as a subroutine. This capability allows the flexibility to manage these inputs and relate them to other inputs, information, or actions and create more intelligent responses. Intrusion detection systems are more frequently being integrated with video systems to provide visual information and confirmation of the event that occurred in the area of the initiating device.

Emergency and Duress Notification

Emergency and duress notification provide the ability to place security devices, known as duress or panic alarms, in critical areas such as cashier areas, emergency departments, psychiatric units, parking areas, executive suites, and so on, to notify the security department covertly of a security incident.

Video Surveillance

The major innovations in the video world have resulted from the digitalization of video signals, video recording capabilities, and the storage of these data in arrays of hard drive storage vehicles. Digital technology has been a part of video camera devices for some time, and the benefits of this technology are evident. One benefit of digital video cameras has been the reduction in the size of the actual video camera device and another is improved functionality. Color video cameras now are capable of operation at low light levels.

Digital video signals can be manipulated at the pixel level and hence the advent of digital video motion detection. The concept involves the ability to monitor the digital image and look for a pixel change in a designated area. If there is a change in signal, ostensibly due to movement, an output or alarm condition can be transmitted. This is a similar technology that can be applied in the previously mentioned video detection technology.

The video signals can be stored on digital video recorders (DVRs) and retrieved and viewed on PC graphical user interfaces (GUIs) as compared to the analog method of recording video signals onto VCRs, the digital methodology allows better management and manipulation of data (such as date and time) to be associated with the video image. This allows users to retrieve the desired video image based on the date and time stamp data. We no longer have to view the entire tape to find the recorded activity. The innovative systems can also provide for retrieval based on activity recorded with other parameters. The processing of video signals has seen much advancement due to digitalization.

A major new advantage of the digital video systems is the development of what some people call video analytics capabilities of these devices. Fairly sophisticated new capabilities are being designed into these systems, including the ability to discern motion in a particular direction, to detect packages left stationary for a prescribed length of time, to detect when the video image has been blocked, and to count the number of people or vehicles in the video scene. Some systems can read license plates on vehicles. With these capabilities, video systems can perform more than just security functions for the owner.

Communications

Incorporating emergency communication devices in parking garages and on university campuses is common. One of the newest critical security technology requirements is being driven by the DOD for facilities that house its staff. The DOD has developed a requirement for mass notification systems (MNS). This concept (at the request of the U.S. Air Force) has also been codified into the 2007 edition of *NFPA 72®*, *National Fire Alarm Code®*. A broad description of MNS is that it is both a communications and an emergency management tool that provides real-time instructions and information to building occupants or nearby personnel during an emergency event or situation. The unified facilities criteria (UFC), which superseded the Interim DOD Antiterrorism/Force Protection Construction Standards for Buildings, was issued on July 31, 2002. The UFC requires that antiterrorism features be included in all force protection

plans and that mass notification systems be installed in all DOD facilities worldwide by 2007. Commercial applications are beginning to appear as well. A mass notification system (MNS) is defined in the 2007 edition of *NFPA 72* as "a system used to provide information and instructions to people, in a building, area site, or other space."

Weapons/Contraband Screening

Depending on the results of the SVA, there may be a need for package screening and weapons detection devices at the entrance to a facility. Significant research and development is being done in this area. The devices are cumbersome, unattractive, expensive, and not very specific in terms of information they provide. Nevertheless, a good design should incorporate the physical space for these systems should the threats in the SVA warrant them. The number of devices should be coordinated with the expected throughput at the entrance. As detection devices, these devices cannot resolve problems without the intervention of security staff.

Asset Tracking

Some of the more sophisticated access control systems incorporate asset tracking or management subsystems. These systems utilize radio frequency or infrared technology-based transponders, which are typically attached to the asset, such as expensive merchandise or a laptop. This transponder is an active device that sends signals to a hardwired receiver, typically mounted in the ceiling. The reception of a unique code, transmitted by a transponder, is analyzed and can result in an alarm depending on the location of the receiver.

The newer asset tracking systems are active systems, in that they are constantly polling for known devices. When the transponder signal is lost, that event results in an alarm condition. The older retail-type asset tracking systems relied on a passive design, in which the transponder was required to send a signal to a receiver that was located at an illegal point and thus the signal would be interpreted as an alarm condition once received. If no signal were received, it was assumed the asset was in a legal location.

Infant Monitoring

It is becoming standard and customary in a hospital to have a computerized security system design to prevent infant/mother mismatching and deter abduction of newborn infants from protected nurseries and hospitals.

OPERATIONAL SECURITY ELEMENTS

Operational security refers to security practices and procedures as well as the security awareness of personnel (employees, faculty, administration, staff, residents, students, etc.). This component of the security program is the most effective and least expensive to pursue, but it is also the most difficult to quantify and implement. It may involve changing long-standing habits as well as changing the mind-set of the personnel involved. The security awareness of the general population in the facility can be just as important as the presence of a professional security force. The security for a facility can be supported by as few as a part-time security staff person with other responsibilities to as many as hundreds of dedicated security professionals. The appropriate application and quantity depends on the findings of the SVA and the services expected from them. The previously mentioned architectural and technology elements can provide the support for this operational element.

Security Plan/Policies

An effective asset protection program should include the development and implementation of a documented security plan and needs to have the cooperation and support of top management. This facility security plan needs to address the protection of all of an organization's defined critical assets, which can include people, property, information, and products. A security plan is a document that usually contains an organization's security-related measures and procedures, as well as information required to implement them. The objective of a security plan is to ensure that security measures and personnel respond in an integrated and effective way to mitigate the effects of an adversarial act in a manner that is appropriate for that particular organization or facility.

One of the security program elements that is often overlooked is physical key control. It is recommended that a designated person be responsible for centrally cataloging the keys in a database. Steps to establish key control include the following:

- Develop key control records.
- Designate a representative or representatives by name to be responsible for maintaining those records.
- Train these individuals on key control procedures and responsibilities.
- Centralize key duplication capabilities.
- Institute a method by which key controllers can request new keys.
- Institute limitations on who has the authority to request key duplication.
- Develop an audit schedule to monitor the system and compliance.

Traditional Security Staff

Security Staff Duties. In making a decision about whether to utilize a security force of any size, consider the following duties that security services can properly perform:

Entrance control. Operate and enforce a system of access control, including inspection of identification and packages.

Roving patrol. Patrol routes or designated areas, such as perimeters, buildings, vaults, and public areas.

Traffic control. Direct traffic (vehicular and pedestrian), conduct vehicle inspections, control parking, check permits, and issue citations.

Key control. Receive, issue, and account for certain keys to the building and its internal areas.

Security and fire systems. Monitor, operate, and respond to intrusion and fire alarm systems or protective devices. Do not assume it is a false or nuisance alarm.

Utility systems. Monitor, record data, or perform minor operations for building utility systems.

Lost and found. Receive, create a receipt for, and store found items.

Reports and records. Prepare reports on accidents, fires, thefts, and other building incidents.

Response to emergencies. In case of any emergency, such as fire, bomb threat, assault, or civil disturbance, respond, summon assistance, administer first aid, and assist public safety personnel.

Law and order. Maintain law and order within the area of assignment.

Hazardous conditions. Report potentially hazardous conditions and items in need of repair.

Other services. Handle service requests such as escorts and support of the business operations.

Proprietary Versus Contracted Security Services. The decision to hire employees versus contracting an agency depends on the organization's goals. Some basic elements should be considered when comparing the two services, as shown in Table 1.6.2.

Generally, organizations have chosen contracted security services over proprietary security services for economic reasons. This is particularly true for the nonspecialized security organizations, where tasks are not as complex as those found in health care, college campuses, museums, and so on. When the responsibilities and tasks are more specialized, a higher-quality security officer is required. This situation is particularly true in institutions or organizations that are standards driven, such as health care, which must adhere to the Joint Commission (JC) Environment of Care Standards. When those conditions exist, there is greater similarity in wages, making the decision less economical and more centered on quality of personnel and service to the organization.

Security personnel should be armed only when compelling reasons warrant this. Some security personnel are armed for a deterrent effect—that is, to prevent crime or other unauthorized activity—responsible officials must weigh that advantage against such disadvantages as the danger to innocent personnel if a firearm is used by a security person; the possibility of an accidental discharge; and the possibility, no matter how remote, of irrational behavior on the part of security personnel.

Most states require minimum training for nonproprietary security officers. Some states require training regardless of this statute. It is recommended that beyond the initial required training, continual education and specific topic training be conducted for security officers.

Nontraditional Staff

An often forgotten resource of security support is the nontraditional security staff. Utilizing receptionists and other observers

TABLE 1.6.2 Comparison of Proprietary Security Department Versus Contract Service Provider

Proprietary Security Department	*Contract Service Provider*
Higher quality, due to quality of institutional selection process and required training Higher rates for proprietary due to shift differential for second and third shift staff	Generally less expensive (especially true for the initial contract, as it is generally a competitive bidding process) Union dues, additional services, training, equipment, uniforms, etc. can mean additions to billing rate
More control Required adherence to institutional policies and procedures Direct supervision of proprietary supervisor	Flexibility in scheduling of replacements (i.e., sick time, vacations, terminations, etc.) Ability to provide special assignment personnel, usually not at premium rate
More loyalty as an employee of the institution, particularly in a largely proprietary institution	Impartiality when handling security incidents No perceived allegiance to employing institution
Perception among staff of higher prestige as an employee of a proprietary department/institution	Some loss of supervision of contract employee by institution (e.g., co-employment responsibilities)
Better institutional control over wages and benefits	Employed by "two masters" concept; similar to "co-employment" from the employee perspective Employees may have difficulty understanding who their boss is Many contract agencies are union employees
Trends indicate that attrition rate for proprietary employees is lower than for contracted services	May be some mitigation of negligent acts' liability on behalf of institution holding the contract Liability falls with contractor, depending on contract language, type of incident, etc.

Source: Sako & Associates, Inc., research.

provides a force multiplication concept. Simply put, doing so adds more resources to the security program, although these individuals may not constitute a dedicated security resource. They need to be trained to accept the responsibility for the security for their work areas as if they were at home. Security should not be a barrier; rather it should be appropriate to maintain accessibility and service.

Mandatory training should be provided for all employees on the goals of the security system and their role in it. Training should also become a mandatory part of employee in-processing for new hires. To meet the recommended requirement of annual updates, reinforcement training modules scheduled during annual milestones, such as employee performance reviews, benefits reviews, and so on, should be developed. To meet the recommended requirement, at least monthly security reminders should be included in the program, and articles (in industry publications, newsletters, pay stubs, etc.), email reminders, bulletin board entries, video vignettes, web-based quizzes, and so on should be developed.

Screening Employees

A policy to perform a criminal history background check on all new employees should be developed and implemented. It is in the best interest of the organization to ensure its employees have a demonstrated history of adhering to the law. Such policies have become industry norms in the corporate world for several reasons, such as security, liability, and risk management issues. Criteria for communicating, storing, and acting on the information should be developed. In-depth background checks (i.e., education verification, more comprehensive checks) on personnel in sensitive positions, such as managers, employees who handle contracts, employees who handle money, security personnel, should be conducted. The same concept should be required for all long-term contractors through the contracts with these vendors.

SUMMARY

A comprehensive security program incorporates architectural, technical, and operational security elements into an effective security plan. The appropriate application of each of the elements should be driven by the results of a well executed security vulnerability assessment (SVA). The security risks and vulnerabilities are dynamic and the SVA should be updated periodically. Security technology improvements and developments happen frequently, so consulting your security professional is recommended.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on premises security discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 72®, National Fire Alarm Code®
NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA *101®, Life Safety Code®*
NFPA 730, *Guide for Premises Security*
NFPA 731, *Standard for the Installation of Electronic Premises Security Systems*

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UL 608, *Burglary Resistant Vault Doors and Modular Panels,* 2004.
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SECTION 1

Chapter 7

Protecting Against Extreme Events

Brian J. Meacham ❑ Carl Galioto

Chapter Contents

Hazard Events
Establishing Protection and Performance Objectives
Performance-Based Analysis and Design
Mitigation Strategies

Key Terms

blast load, blast protection, continuity of business (COB), deliberate event, disproportionate damage, extreme event, extreme hazard event, mitigation, natural hazard, performance-based analysis, performance-based design, risk characterization, threat assessment

For centuries, the impact of significant fire and natural hazard events has driven changes to building design practice, technology, operations, and regulation. The Fire of London in 1666 was a driver for early building and zoning requirements, as well as fire-resistive construction. Conflagrations in U.S. cities in the late nineteenth and early twentieth centuries, as well as large industrial fire losses, led to the development of fire sprinklers, the beginnings of model fire and building codes, and the widespread construction of "fireproof" buildings.[1] Following the 1906 earthquake in San Francisco and the 1933 Long Beach earthquake, requirements for earthquake resistance began to be included in building codes.[2] Large life-loss events such as the 1911 Triangle Shirtwaist Company fire and the 1942 Cocoanut Grove nightclub fire were early drivers for emergency egress requirements.[3]

With each event, building and fire regulation, design practice, and building technology were reviewed, and if deemed appropriate, changes were made in an attempt to minimize the potential for repeat consequences of a similar nature. In determining what, if anything, needed to change, due consideration was given to the events, the response of the buildings, available technology, and societal risk tolerance. Over time, the need for significant regulatory changes lessened, and by the end of the twentieth century, the state of building and fire regulation, design practice, and available technology had combined to significantly reduce the loss of life from fire and natural hazard events as compared with the previous century. In fact, great effort in the latter part of the twentieth century was focused on finding ways to provide more flexibility in building design without compromising the safety record that had been achieved, much of which came under the general heading of risk-informed performance-based regulation and design.[4–8]

As the twenty-first century begins, attention is again focused on the impact of significant, or extreme hazard events. The consequences of the attacks on the World Trade Center Towers in 2001, the Station nightclub fire in 2003, and Hurricane Katrina in 2005 have been substantial enough to create considerable discussion as to whether or how building design may need to change to achieve more resilience against extreme events. The question of whether or not building regulation, design practice, or technology needs to change as a result of these events is beyond the scope of this chapter, as are emergency preparedness criteria, which are also crucial. However, there are a number of measures in regulation or in building-specific designs that can increase a building's resilience to extreme events.

Regarding mitigation of extreme events, some of the themes that recur throughout this chapter include redundancy, reliability, and tenability. In order to be highly reliable, most building systems require a degree of either redundancy or diversity of operation. The fundamental reason for having

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two exits from a floor, even if one will suffice based on calculation, is to ensure a measure of redundancy and subsequent reliability. The need for structural redundancy has long been understood and the cost of such redundancy accepted, as the consequences of failure could be disastrous. Many owner-occupied buildings include redundant systems due to the potential cost of system failure and its consequent business interruption. For such facilities and features, systems are described as being "code plus" or optimum design.

The aim of this chapter is to outline a variety of measures available to help protect buildings and their occupants against the impacts of extreme hazard events. The chapter is structured so as to broadly outline extreme events, their assessment, issues of concern, protection objectives, and how the protection objectives can be met. A much more detailed discussion can be found in *Extreme Event Mitigation in Buildings: Analysis and Design*.[8]

See also Section 1, Chapter 1, "Challenges to Safety in the Built Environment"; Section 1, Chapter 6, "Premises Security"; Section 1, Chapter 8, "Emergency Management and Business Continuity"; Section 2, Chapter 8, "Explosions"; Section 4, Chapter 5, "Strategies for Occupant Evacuation During Emergencies"; Section 6, Chapter 15, "Explosives and Blasting Agents"; Section 8, Chapter 1, "Air-Moving Equipment"; Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems"; and Section 14, Chapter 10, "Security and Intrusion Detection Systems."

HAZARD EVENTS

Hazard events are incidents that result in the possibility of physical harm or damage to buildings and their occupants. Section 1, Chapter 1, "Challenges to Safety in the Built Environment," provides an overview of losses that have occurred as a result of such events. In general, hazard events may be categorized as natural disasters, such as intense earthquakes, tsunamis, hurricanes, floods, and tornadoes, as well as human-caused or technological disasters, such as fires, explosions, and terrorist attacks. Extreme hazard events are incidents that make demands on a building, its systems, and its occupants that go beyond the usual design parameters imposed by codes, standards, and good professional practice.[9]

Natural Hazard Events*

Natural hazards are caused by geology, weather, and seismicity and are exacerbated by human behavior. Earthquakes, floods, and hurricanes are all examples of these types of events. Because many hazards are interrelated, they can occur as both isolated and combined events. Some of these types of extreme events are localized in nature, whereas others are regional. Natural hazards can impact structures and infrastructure, producing casualties and large financial losses.

*Much of this section is excerpted with permission from Thompson, A. C. T., Kammerer, A., Katzman, G., and Whittaker, A. S., "Natural Hazards," *Extreme Event Mitigation in Buildings: Analysis and Design,* B. J. Meacham and M. Johann (Eds.), National Fire Protection Asssociation, Quincy, MA, 2006.

Earthquakes. The earth's crust is composed of tectonic plates that move relative to one another, typically at tens of millimeters per year, accumulating strain energy. An earthquake occurs when the strength of the rock forming the crust is exceeded by the accumulated strain energy, which causes the rock to break. When the rock ruptures, seismic waves are propagated in all directions. In addition to the direct fault rupture and strong shaking that are typically associated with seismic events, other devastating secondary events are frequently triggered. Earthquakes can cause landslides, liquefactions, tsunamis, fires, and dam failures. Figure 1.7.1 illustrates a consequence of liquefaction.

Earthquakes are more prevalent at plate boundaries, although very large intraplate earthquakes also have occurred. Although earthquakes typically cause less annual economic loss than other hazards such as floods,[10] they have the potential to cause unanticipated regional devastation in just minutes, because there is currently no proven method for their short-term prediction. Earthquakes can affect all types of structures and infrastructures, including housing and commercial buildings, transportation elements (railroads, highways, tunnels, and bridges), utilities (water, gas, and sewer lines), industrial facilities, power plants, and dams. Globally, the risk of death and injuries from an earthquake varies greatly depending on local construction practices and the availability of emergency services. In addition to the short-term impacts, social, physical, and economic impacts result in long-term economic and social consequences.

Floods. Flooding produces extensive and costly damage to property. Floods are capable of damaging and undermining buildings and infrastructure, generating large-scale erosion, and causing loss of life and injury. Loss of life results principally from the sudden destruction of structures, washout of access routes, and motorists attempting to cross swollen streams. Flooding can be caused by a variety of events, particularly large weather systems that produce sustained and sometimes intense

FIGURE 1.7.1 Foundation Failure Due to Liquefaction in the 1999 Izmit, Turkey, Earthquake (Source: Photo by J. Stewart and J. Bray; courtesy of the Pacific Earthquake Engineering Research Center, University of California, Berkeley)

rainfall or storm surges. On a smaller scale, floods can be caused by local effects, such as intense thunderstorms and rapid snow melt. Seismically based hazards, such as tsunamis and dam failures, can also create flood conditions on rare occasions.

Riverine Flooding. River-based flooding is the most common form of flooding[11] and can occur in a wide variety of landscape types. Narrow channels may experience fast-moving, deep flooding, whereas flat areas may accumulate water and remain inundated with shallow water over long periods of time. In some cases, local heavy precipitation can produce flooding in areas other than known floodplains or drainage channels. Flash floods occur rapidly and without warning and are capable of significant damage due to high water velocities and large amounts of floating debris. Flash flooding is principally affected by the intensity and duration of rainfall and the topography of the affected area. Intense localized precipitation, dam brakes, ice-jam floods, and alluvial-fan floods can cause flash-flood conditions.

Coastal Flooding. In contrast to riverine flooding, storm surge typically occurs at a coastline due to large storms, such as tropical cyclones and severe winter storms. Storm-surge levels are strongly influenced by four factors: high wind speeds that drive large amounts of water onto the coastline; low barometric pressure that causes the water surface to rise; timing of landfall in relation to peak tides; and coastal shoreline configurations.[12] In addition to the storm-surge level, resulting damage is also influenced by the velocity of the storm center (with slow-moving storms doing the most damage); the nature of the coastal geology, vegetation, and slope; previous storm damage; and human activity. Storm surge can result in loss of life and in significant damage to structures, infrastructure, and the coastline.

Tsunamis. Tsunamis are large sea waves that usually are generated by underwater earthquakes that result in a rapid drop or uplift of the ocean floor. Tsunamis can also result from volcanic activity, submarine landslides, and, on very rare occasions, from a meteor or other space debris hitting the ocean. Tsunami waves can be more destructive than wind-developed surface waves, because they often have a pressure front that reaches deep into the water column. Most tsunami waves resulting from large seismic events have high speeds, long wavelengths, and low amplitudes as they travel across the ocean, making them difficult to detect. As a tsunami reaches coastal waters, the waves slow and pile up where the ocean bottom becomes shallower, causing the wave height to increase greatly. The damaging effect of the wave is increased significantly as waterborne debris is collected and forced to move with the water mass, battering objects in the path. Although damage from tsunami waves is often limited to the immediate vicinity of the affected coastline, large tsunami waves have damaged and flooded areas up to a mile inland.[13] Tsunami waves can travel very long distances with little energy dissipation. As a result, tsunamis can have significant impact on regions far from the source of the tsunami, as was the case with the 2004 Indian Ocean tsunami (See Figure 1.7.2).

Tropical Cyclones. Hurricanes, tropical storms, and typhoons are all classifications of tropical cyclone. Hurricanes and typhoons describe the same phenomena, with the appropriate terminology depending on the location of the event. Tropical

FIGURE 1.7.2 Damage from the 2004 Indian Ocean Tsunami (Source: Photo by J. Borrero; courtesy of the University of Southern California Tsunami Research Center)

cyclones affect coastal areas worldwide, often with devastating effect. Tropical cyclones are regions of atmospheric low pressure that originate over warm tropical waters and are characterized by winds circulating around an eye. Generally, the number of tropical cyclones varies seasonally and peaks as sea and surface temperatures peak. Tropical cyclones are commonly associated with severe winds, storm-surge flooding, high waves, coastal erosion, extreme rainfall, thunderstorms, lightning, and tornadoes. Storm surge and extreme rainfall cause coastal, riverine, and flash flooding; contamination of land, groundwater, and water supplies; agricultural, structural, and utility damage; coastal erosion and landslides; and loss of life due to drowning. High winds also impact utilities and transportation, cause fatalities due to downbursts and tornadoes, create large volumes of debris, and result in agricultural losses and building damage.

Tornadoes. A tornado is a rapidly rotating funnel of air that is typically spawned by a severe thunderstorm. Tornadoes are almost always accompanied by heavy precipitation and may be associated with large hail and lightning in some cases. Large fires may also produce local (usually small) tornadoes. The central United States is often particularly susceptible to tornadoes and is known as Tornado Alley. Although most tornadoes remain aloft, they are capable of great destruction when they touch the ground. Tornadoes can lift and move very large objects, including homes and cars, and can generate a tremendous amount of debris, which becomes airborne, causing additional damage. Tornadoes have also been known to siphon large volumes of water from bodies of water. The path of a single tornado is generally very localized, though it can range up to dozens of kilometers.

Wildland Fires. Wildland fires may be caused by lightning as well as by intentional or unintentional ignition. In densely populated areas, wildland fires can have significant impacts on the built environment, such as the Oakland fires of October 1991, which resulted in more than $1.5 billion in damage,[14] and the fires in New Mexico in 2000, which ultimately consumed part of the Los Alamos National Laboratory.[15,16]

Extreme Natural Hazard Events. Protection against natural hazard events is included in model building codes in North America and in most countries worldwide. This includes provisions for earthquakes, flooding, high wind, snow loads, and other natural hazards as appropriate to geology and climate. However, the protection measures included within the building codes are not aimed at providing the maximum level of protection possible for the most significant natural hazards that are possible. Rather, the general approach is that prescriptive code requirements provide for a level of building performance and occupant safety that reflect a level of performance for the most frequent and likely events, with some requirements for higher levels of performance against larger magnitude events in some areas (e.g., seismic protection in California, hurricane protection in Florida, or snow loads in Minnesota) for specific buildings with high social or public importance (such as hospitals, schools, and shelters).

Extreme natural hazard events can be considered those natural events that exceed the magnitudes (deterministically expressed) typically considered by building codes, or are considered very rare (probabilistically expressed) by the codes, which means that not all buildings are required to withstand the associated loads (e.g., not all buildings are designed to remain fully operational following a 2500 year seismic event). If a building or facility serves a critical economic, social, or public service function, houses very large numbers of people, or has other attributes that may result in the desire for continued operation during and beyond the occurrence of extreme natural hazard events, protection measures beyond those required by the code may be deemed necessary.

Fire

Although fire can impact a building as an external exposure, such as from a wildland fire or other external fire hazard, building fires are typically internal hazard events. As in the case of protection against natural hazard events, building codes include numerous provisions against the development and spread of fire, which have been added to the codes over time. Sometimes, however, fires can still become extreme events. This can happen when a fire overwhelms the egress system or fire protection systems, or because these systems do not exist or have been deliberately compromised, inadequately designed, or simply failed. Two examples of fires that became extreme events are The Station nightclub fire and the Windsor Building fire.

The Station Nightclub Fire. On February 23, 2003, a large crowd was gathered at The Station nightclub in West Warwick, Rhode Island (USA), where a live band was scheduled to perform. The band took the stage and began with a flash of pyrotechnics. The pyrotechnics ignited sound dampening foam material, which was installed on portions of the interior walls and ceilings of the unsprinklered club. The foam was highly combustible, and within minutes the entire club was engulfed in flames, overtaking the crowd before everyone could escape. This disastrous incident ultimately claimed the lives of 100 building occupants.

Windsor Building Fire. The Windsor Building, located in the heart of the commercial and banking center in Madrid, Spain, was one of the tallest in the city. At about 2300 hours on the evening of Saturday, February 12, 2005, a fire broke out on the 21st floor of the unsprinklered building. Although the fire brigade was reportedly on site by about 2330, the fire spread rapidly to most of the floors above the 21st, and by 0100 hours, the fire brigade had to retreat.[17] Soon afterwards, large pieces of the facade started falling off, taking the perimeter bay of the reinforced concrete slab with it in places. Eventually, the fire spread downwards as well, ultimately leading to the collapse of virtually all the slab edge bay above the 17th floor, as well as one internal bay on the north side. Although no lives were lost, the magnitude of the fire necessitated the building's demolition.

Deliberate Events

Events that are consciously instigated against buildings and their occupants are referred to as deliberate events. In the current en-

vironment, acts of terrorism, such as the 2001 attacks on the World Trade Center and the Pentagon come readily to mind. A variety of components, materials, and common platforms can be combined to create both the weapon and the delivery system.

Explosives. Explosives can be easily and cheaply obtained or fabricated and deployed. As such, their use can result in spectacular and fatal consequences, making attacks using explosives a preferred tactic of terrorists.[9,18] This was tragically demonstrated by the attacks using vehicle-delivered explosives on the World Trade Center in 1993 and the Murrah Federal Building (Figure 1.7.3) in 1995.

Like natural hazard or fire events, an explosion can have a significant impact on buildings and their occupants, such as the following:

- Blasts occurring near primary structural members could lead to catastrophic collapse, proportionate to the load and building design and construction.
- Even when key structural members are protected or designed to sustain blast effects, casualties are still likely from overpressures and from flying debris—especially glass.
- Blasts which occur within a building are magnified by reflected and reinforced pressures, which means that smaller explosive charges, such as those carried in a satchel or backpack, can be lethal and cause massive damage.

Chemical, Biological, Radiological, and Nuclear Events. The potential for mass casualties from chemical, biological, radiological, or nuclear (CBRN) attack have been an area of concern since the anthrax episodes in 2001. Although CBRN agents can be delivered to a population in a number of different ways, such as by food, water, and "dirty" bombs, airborne chemical and biological agents are often given the most attention.

The ease or difficulty with which terrorists could cause mass casualties with an improvised chemical or biological weapon or device depends on the chemical or biological agent selected. For example, a terrorist does not need sophisticated knowledge or dissemination methods to use toxic industrial chemicals, but will likely face serious technical and operational challenges when working with other chemicals or with biological agents.

Chemical agents of concern fall into five broad categories: choking agents, blood agents, blister agents, nerve agents and nonlethal (riot-control) agents.[19] Choking or pulmonary agents include chlorine (CL) and phosgene (CG). In sufficient concentrations, their corrosive effect on the respiratory system results in pulmonary edema, filling the lungs with fluid and choking the victim. Blood agents, or cyanides, are absorbed into the body primarily by breathing, preventing the normal utilization of oxygen by the cells and causing rapid damage to body tissues. Agents such as hydrogen cyanide (AC) and cyanogen chloride (CK) are highly volatile and dissipate rapidly in the gaseous state. Blister agents, or vesicants, are used primarily to cause medical casualties. Blister agents affect the eyes and lungs and blister the skin. Sulphur mustard (HD), nitrogen mustard (HN-2, HN-3), and Lewisite (L, HL) are examples of blister agents. Nerve agents are perhaps the most feared of all chemical weapons. Essentially, nerve agents affect the transmission of nerve impulses. Most of the agents in this category were discovered shortly before or during World War II and are related chemically to organophosphorous insecticides. Similar in action to many pesticides, nerve agents are lethal in much lower quantities than

FIGURE 1.7.3 Damage to the North and East Sides of the Murrah Federal Building (Source: FEMA News Photo)

the classic agents in the choking, blood, and blister categories. Nerve gases are effective when inhaled or when absorbed by the skin, or both, although there are differences in effectiveness. The rapid action of nerve agents calls for immediate treatment. Nonlethal agents, such as tear gas and other riot-control agents, are generally not considered chemical weapons because they are not life threatening in all but the highest concentrations. Examples of these agents include orthochlorobenzylidene malononitrile (CS), chloroacetophenone (CN), chloropicrin (PS), and bromobenzyl cyanide (BBC).

The principal biological agents of concern can be classified into three broad groups: bacteria, viruses, and toxins.[19] Bacteria are small free-living organisms, most of which may be grown on solid or liquid culture media. They reproduce by simple division. The diseases they produce often respond to specific therapy with antibiotics. Possible agents include anthrax, brucellosis, and plague. Viruses are organisms that lack their own cell membranes and so require other living cells in which to replicate. They are therefore intimately dependent upon the cells of the host that they infect. They produce diseases that generally do not respond to antibiotics. However, they may be responsive to antiviral compounds, although the few antiviral compounds that are available are of limited use. Possible viral agents include smallpox and the various hemorrhagic fever viruses. Toxins are poisonous substances produced by and derived from living plants, animals, or microorganisms. Some toxins may also be produced or altered by chemical means. Toxins may be countered by specific antisera and selected pharmacologic agents. Possible agents include botulinum and ricin toxins.

Radiological and nuclear materials can come from a variety of sources, including from approved medical materials and treatments, from fuel or waste from power generation or weapons manufacturing, or directly from nuclear weapons. Perhaps of most concern is the use of radiological and nuclear material in a "dirty bomb," which may have sufficient quantities of radiological and nuclear waste material to pose a significant hazard within a building or a larger area within a community.

ESTABLISHING PROTECTION AND PERFORMANCE OBJECTIVES

Several factors come into play in determining whether a building is at risk for an extreme event. For natural hazard events, the geographic location of the building is a primary concern. In the case of technological events, such as fire or accidental explosion, building design, construction, contents, use, operations, and maintenance are significant factors. With respect to terrorist attack, symbolic importance, service or mission criticality, and the potential magnitude of consequences from a successful attack can be critical factors. Even if some level of extreme event risk exists, however, building owners, developers, and design teams face a difficult task in designing buildings that provide an appropriate level of protection while retaining features that make them desirable spaces for working and living, including comfort, openness, and aesthetics, and meeting other important objectives, such as sustainability, usability, energy efficiency, and cost effectiveness.

This is not a new challenge, however, and even prior to the extreme events of recent years, efforts were already under way to help designers and engineers balance openness, aesthetics, and other design goals with safety and security.[20] In addition, over the past several years, there has been a slow shift from prescriptive-based to performance-based regulations and design (see for example, NFPA *101®*, *Life Safety Code®*; *NFPA 5000®*, *Building Construction and Safety Code®*; and the *ICC Performance Code for Buildings and Facilities*).[21]

Taken together, the combination of risk assessment and performance-based regulation and design provides a powerful approach for addressing extreme event analysis and mitigation in buildings.[22] The resulting risk-informed performance-based approach brings together concepts of risk characterization, building performance objectives, and mitigation strategy assessment and selection into a process that helps inform the overall design process.

Risk Characterization*

Risk characterization is a process that brings together analytical data such as statistics, risk analysis, historical data, computational modeling, test results, and cost data with stakeholder concerns in a way that allows agreement to be reached through deliberation on levels of tolerable risk.[23] It is a decision-driven activity, directed toward informing choices and solving problems.

A fundamental premise of risk characterization is that to adequately address a risk problem, one must develop a broad understanding of relevant losses, harms, or consequences to interested or affected parties. For extreme event mitigation in buildings, the stakeholders can include the government, facility owners/operators, occupants, neighbors, emergency officials, insurers, and the public. If a key perspective is omitted, the risk problem may be formulated improperly and the ensuing analysis may omit key parameters, resulting in further costs at a later date.

Bringing the stakeholders together, or at least anticipating the diverse perspectives of the stakeholders, is critical to the success of risk characterization. A singularly-focused view of risk and its tolerability may inadvertently miss important considerations such as technical, social, economic, value, or perceptual impacts. In addition, if some stakeholder views are not represented in the process, certain stakeholder groups may disagree with various parts of the process, from the problem statement to the risk measure selected. It is not necessary, however, for every stakeholder to be fully accommodated in the risk characterization process, despite the difficulties caused by a diversity of views. Involving as many views as feasible from the outset will help minimize roadblocks to gaining agreement throughout the process.

In addition to representing the views of the stakeholders, the success of the risk characterization process also depends critically on conducting a systematic analysis that is appropriate to the problem and treats uncertainties of importance to the decision problem in a comprehensible and reasonable way. Success

*This section draws heavily from Meacham, B. J., "Risk-Informed Performance-Based Analysis and Design," *Extreme Event Mitigation in Buildings: Analysis and Design,* B. J. Meacham and M. Johann (Eds.), National Fire Protection Association, Quincy, MA, 2006.

also depends on a deliberative process to formulate the decision problem, guide analysis to improve decision participants' understanding, interpret analytic findings and uncertainties, and improve the ability of stakeholders to participate effectively in the risk decision process.[6] In other words, good risk characterization requires the following components:

- A risk problem definition that stakeholders accept
- A sound scientific base for assessing the risk and developing acceptable mitigation strategies
- The proper use of analytical techniques with appropriate consideration of uncertainties and unknowns
- A good understanding of criteria to indicate acceptability of results such as mitigation effectiveness and cost effectiveness
- Sufficient discussion and deliberation to ensure that all parties understand all of the issues

Ideally, the process requires several iterations as new information and data become available, and as participants gain a better understanding and raise more issues. The process needs to be interactive, equitable, and free of ill-informed, ungrounded solutions. The iterative nature of the process just described is illustrated in Figure 1.7.4. In each stage of deliberation, multiple stakeholders interact to integrate key issues at the outset of hazard mitigation planning.

Essential to any risk characterization effort is the need to diagnose the risk and state of knowledge. The aim is to identify and characterize who or what will be impacted, and by what (e.g., threats, vulnerabilities, and risks). To help, certain diagnostic questions should be asked about the hazards and the risks, including the following:

- Who or what is exposed (e.g., people, property, and/or operations)?
- If people, what groups are exposed (e.g., vulnerable populations, including mobility impaired and those with cognitive disorders)?
- What is posing the risk (e.g., hurricanes, high wind, floods, earthquake, fire, terrorism)?
- What is the nature of the harm (e.g., sudden injury or death, morbidity, delayed mortality, property loss, operational losses, threat to community welfare, loss of critical functions, or legal issues)?
- What qualities of the hazard might affect judgments about the risk (e.g., dread, individual control, vulnerability, familiarity, immediacy, and/or degree of technical knowledge available)?
- Where is the hazard experience (e.g., local, regional, or national and in similar facilities)?
- Where and how do hazards overlap (e.g., are some classes of people or facilities disproportionately exposed to one or multiple hazards? Is there a geographical component to overlapping hazards)?
- How adequate are the databases on the risks (e.g., solid data, limited data with some judgment, few data with considerable judgment, or speculation)?
- How much scientific consensus exists about how to analyze the risks (e.g., is there agreement on analytical methodology, theoretical basis for analysis, and harms not analyzed)?
- How much scientific consensus is there likely to be about risk estimates (e.g., is epistemic [knowledge] uncertainty a serious problem, and how significant is variability in population)?
- How much consensus is there among the affected parties about the nature of the risk?
- Are there omissions from the analysis that are important for decisions (e.g., are possible harms, management options, or effects left unassessed)?

To provide focus to the diagnostic phase, a threat, vulnerability, and risk assessment (TVRA) approach is often employed.

Threat, Vulnerability, and Risk Assessment. The intent of a threat, vulnerability, and risk assessment is to (1) identify potential threats or hazards to people, facilities, operations, and finances; (2) evaluate the likelihood of specific threat or hazard scenarios occurring; and (3) assess the consequences (severity) should a threat or hazard scenario occur.[22]

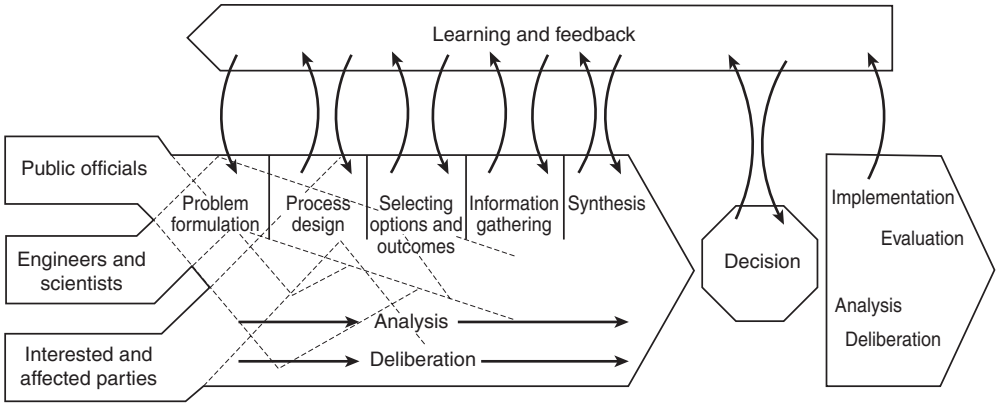

FIGURE 1.7.4 Risk Characterization Process (Source: Adapted from Stern, P. C., and Fineburg, H. V. (Eds.), *Understanding Risk: Informing Decisions in a Democratic Society,* National Research Council, National Academy Press, Washington, DC, 1996, p. 28)

Threat assessment focuses on identifying and understanding the potential sources of unwanted events. It should consider the full range of events pertinent to the building, from fire and natural hazard events to terrorist and other extreme events. *Vulnerability assessment* focuses on identifying potential weaknesses in a facility that could lead to impact from an event or aggressor (e.g., a potential weakness that might allow terrorists to access a building, such as a lack of building security, the ability to drive a vehicle close to a facility, and so forth). In some cases, vulnerability assessment is closely tied to consequence analysis in that it considers the response of a facility to an event of a certain magnitude, thus indicating the facility's vulnerability to that event (e.g., assessing the response of a facade to a certain size explosive load would both indicate the facade's vulnerability to a blast of that size as well as to identify potential consequences that may result should the blast occur). *Risk assessment* involves identifying events of concern, determining the likelihood of those events, and predicting the potential consequences should such events occur.

Although threat, vulnerability, and risk assessments can vary, a comprehensive TVRA should encompass the following components:*

- Asset identification and valuation
- Target potential
- Threat identification
- Threat scenarios
- Vulnerability assessment
- Consequence analysis
- Risk assessment
- Prevention and mitigation strategies
- Cost and effectiveness analyses
- Prevention and mitigation option selection

To help address these issues in a readily understandable and transparent manner, a variety of tools can be used, from simple spreadsheets to complex computer models. In many cases, a simple matrix may be sufficient to outline high-risk facilities, mitigation options, relative mitigation costs and effectiveness, and overall risk-cost-effectiveness assessment. A simple matrix of this type might include the following:

- Facility
- Location
- Event scenarios
- Life safety impact (relative impact on occupant life safety given an event)
- Damage potential (relative impact on the facility and systems given an event)
- Operational impact (relative impact on operations given an event)
- Relative risk (a relative measure of overall risk, incorporating the previous three factors)
- Mitigation options (a list of potential mitigation measures or strategies)
- Relative mitigation effectiveness (relative effectiveness of mitigation measures)
- Relative mitigation cost (relative cost of mitigation measures)
- Relative cost effectiveness (a relative measure of cost effectiveness given relative mitigation effectiveness and relative cost
- Relative risk/cost ranking (a relative measure of relative risk and relative cost effectiveness)

Such a matrix might take the form illustrated in Figure 1.7.5. From such a matrix, multiple mitigation options could be selected, based on their overall risk-cost-effectiveness ranking or other factors.

Establishing Target Building Performance Levels. Another key component in the process is establishing target building performance levels for the facility in question. In this context, a target building performance level reflects the expectation of how a building's systems will perform under the hazard scenarios of concern. The intent is to describe the target performance, using parameters that can be measured or calculated, as based on the tolerable limits of damage, injury, operational capacity, or other loss. The term "tolerable" is used to reflect the fact that absolute protection is not possible. Some possibility of damage, injury, or loss is currently accepted in structures. The exercise here is to determine how much additional risk (possibility of loss) is likely and tolerable from extreme events, as represented by the extreme event scenario chosen for evaluation. The term *impact* is used as a broad descriptor of loss.

An often-used approach to illustrate how events (design loads), impacts (consequences), and desired performance relate is through a matrix structure. For example, Table 1.7.1, from the *Department of Defense Minimum Antiterrorism Standards for Buildings*,[24] illustrates levels of performance for different building systems, as well as for occupants, under specific event conditions.

A similar approach is used within the building code environment as well.[21] In this case, four design performance levels are provided to bound the expected performance of facilities when subjected to various design loads (from hazard events). See Table 1.7.2.

The basis of this approach is the use of importance factors to assign buildings into performance groups, each of which will have its own target performance (tolerable risk) levels. This matrix display of target levels can be matched with a similarly configured matrix with predicted response of buildings for each performance group to a given severity of hazard as illustrated in Figure 1.7.6.

Regardless of the specific approach taken, key factors to consider include the following:

- What are the extreme event threat scenarios?
- Who and what are at risk?
- How are they at risk?
- What are the potential consequences?

*See Meacham, B. J., "Threat, Vulnerability and Risk Assessment," B. J. Meacham and M. Johann (Eds.), *Extreme Event Mitigation in Buildings: Analysis and Design,* National Fire Protection Association, Quincy, MA, 2006, for example, for a much more in-depth discussion on TVRA.

	Facility	Location	Event Scenarios	Life Safety Impact	Damage Potential	Operational Impact	Relative Risk	Mitigation Options	Basis of Mitigation Option	Relative Mitigation Effectiveness	Relative Mitigation Cost	Relative Cost Effectiveness	Relative Risk/ Cost Ranking
1													
2													

FIGURE 1.7.5 Example Risk-Cost-Mitigation Effectiveness Matrix

TABLE 1.7.1 Levels of Protection for New Buildings

Level of Protection	*Potential Structural Damage*	*Potential Door and Glazing Hazards*	*Potential Injury*
Below standards	Severe damage. Frame collapse, massive destruction, little left standing.	Doors and windows fail, resulting in lethal hazards.	Majority of personnel suffer fatalities.
Very low	Heavy damage. Damage results in onset of structural collapse. Major deformation of primary and secondary structural members, but progressive collapse is unlikely. Collapse of nonstructural elements.	Glazing will break and will likely be propelled into the building, resulting in serious glazing-fragment injuries, but fragments will be reduced. Doors may be propelled into rooms, presenting serious hazards.	Majority of personnel suffer serious injuries. There are likely to be a limited number of fatalities (10 to 25%).
Low	Damaged and unrepairable. Major deformation of nonstructural elements and secondary structural members and minor deformation of primary structural members, but progressive collapse is unlikely.	Glazing will break but will fall within 1 meter of the wall or will otherwise not present a significant fragment hazard. Doors may fail but they will rebound out of their frames, presenting minimal hazards.	Majority of personnel suffer significant injuries. There are likely to be a few fatalities (<10%).
Medium	Damaged and repairable. Minor deformation of nonstructural elements and secondary structural members and no permanent deformation in primary structural members.	Glazing will break, but will remain in window frame. Doors will stay in frames, but will not be reusable.	Some minor injuries, but fatalities unlikely.
High	Superficial damage. No permanent deformation in primary structural members, secondary structural members, or nonstructural elements.	Glazing will not break. Doors will be reusable.	Only superficial injuries are likely.

Source: Adapted from *Department of Defense Minimum Antiterrorism Standards for Buildings,* Unified Facilities Criteria, UFC 4-010-01, U.S. Department of Defense, Washington, DC, 2003.

TABLE 1.7.2 Performance Levels of Impact for Buildings and Facilities

Impact Levels	*Mild*	*Moderate*	*High*	*Severe*
Structural damage	There is no structural damage and the building or facility is safe to occupy.	There is moderate structural damage, which is repairable; some delay in re-occupancy can be expected.	There is significant damage to structural elements but no large falling debris; repair is possible. Significant delays in reoccupancy can be expected.	There is substantial structural damage, but all significant components continue to carry gravity load demands. Repair may not be technically possible. The building or facility is not safe for re-occupancy, as re-occupancy could cause collapse.
Nonstructural systems	Nonstructural systems needed for normal building or facility use and emergency operations are fully operational.	Nonstructural systems needed for normal building or facility use are fully operational, although some cleanup and repair may be needed. Emergency systems remain fully operational.	Nonstructural systems needed for normal building or facility use are significantly damaged and inoperable; egress routes may be impaired by light debris; emergency systems may be significantly damaged, but remain operational.	Nonstructural systems for normal building or facility use may be completely nonfunctional. Egress routes may be impaired; emergency systems may be substantially damaged and nonfunctional.
Occupant hazards	Injuries to building or facility occupants from hazard-related applied loads are minimal in numbers and minor in nature. There is a very low likelihood of single or multiple life loss. The nature of the applied load (i.e., fire hazard) may result in higher levels of expected injuries and damage in localized areas, whereas the balance of the areas may sustain fewer injuries and less damage.	Injuries to building or facility occupants from hazard-related applied loads may be locally significant. There is a low likelihood of single life loss and a very low likelihood of multiple life loss. The nature of the applied load (i.e., fire hazard) may result in higher levels of expected injuries and damage in localized areas, whereas the balance of the areas may sustain fewer injuries and less damage.	Injuries to building or facility occupants from hazard-related applied loads may be locally significant with a high risk to life, but are generally moderate in numbers and nature. There is a moderate likelihood of single life loss and a low probability of multiple life loss. The nature of the applied load (i.e., fire hazard) may result in higher levels of expected injuries and damage in localized areas, whereas the balance of the areas may sustain fewer injuries and less damage.	Injuries to building of facility occupants from hazard-related applied loads may be high in numbers and significant in nature. Significant risk to life may exist. There is a high likelihood of loss in higher levels of expected injuries and damage in localized areas, whereas the balance of the areas may sustain fewer injuries and less damage.
Overall extent of damage	Damage to building or facility contents from hazard-related applied loads is minimal in extent and minor in cost.	Damage to building or facility contents may be locally significant, but is generally moderate in extent and cost. The nature of the applied load (i.e., fire hazard) may result in higher levels of expected injuries and damage in localized areas, whereas the balance of the areas may sustain fewer injuries and less damage.	Damage to building or facility contents from hazard-related applied loads may be locally total and generally significant. The nature of the applied load (i.e., fire hazard) may result in higher levels of expected injuries and damage in localized areas, whereas the balance of the areas may sustain fewer injuries and less damage.	Damage to building or facility contents from hazard-related applied loads may be total. The nature of the applied load (i.e., fire hazard) may result in higher levels of expected injuries and damage in localized areas, whereas the balance of the areas may sustain fewer injuries and less damage.
Hazardous materials	Minimal hazardous materials are released to the environment.	Some hazardous materials may be released to the environment, but the risk to the community is minimal. No emergency relocation is necessary.	Hazardous materials may be released to the environment with localized relocation needed for buildings and facilities in the immediate vicinity.	Significant hazardous materials may be released to the environment, with relocation needed beyond the immediate vicinity.

Source: *Performance-Based Building Design Concepts,* © International Code Council, Inc., Washington, DC. Reproduced with permission. All rights reserved.

Magnitude of design event (Increasing magnitude of event →)	Increasing level of performance → Performance groups			
	PG I	PG II	PG III	PG IV
Very large (very rare)	Severe	Severe	High	Moderate
Large (rare)	Severe	High	Moderate	Mild
Medium (less frequent)	High	Moderate	Mild	Mild
Small (frequent)	Moderate	Mild	Mild	Mild

FIGURE 1.7.6 Relationships Among Magnitude of Design Events (Loads), Performance Groups, and Tolerable Impacts (Source: *Performance-Based Building Design Concepts,* © International Code Council, Inc., Washington, DC. Reproduced with permission. All rights reserved.)

- How likely is it for the consequences to be realized?
- What level of performance should be targeted for the facility?

Once this information is available, various mitigation options can be considered and assessed, on effectiveness in mitigating the events of concern, as well as on cost effectiveness. Such a process can be used for developing building code provisions for specific facility designs (Figure 1.7.7). To help in identifying potential mitigation options (solutions and verification methods) and their effectiveness, a performance-based approach can be quite helpful.

PERFORMANCE-BASED ANALYSIS AND DESIGN

In the broadest sense, performance-based analysis and design is a process of engineering a solution to meet specific levels of performance, where performance may be stated in terms of qualitative or quantitative objectives, criteria, or limiting states of damage or injury.[22] Performance-based analysis and design has gained momentum in recent years and is being used increasingly for structural engineering for natural hazards;[25] for fire protection engineering, as explained in the NFPA's *Introduction to Performance-Based Fire Safety,*[26] and the *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings;*[27] and for multihazard mitigation design, including extreme events.[28]

Performance-Based Structural Design

The basic process for performance-based structural design is shown in Figure 1.7.8. In brief, the process consists of the following steps:

- Select appropriate performance objectives.
- Develop a preliminary design constructed to meet the objectives.
- Verify that the design can achieve the objectives.
- Iteratively revise the design until an acceptable design is achieved.

Performance objectives are quantified statements of the severity of a design event, its probability of occurrence, and the permissible damage given that the event is experienced.[25] The design event or its probability of occurrence is often defined as the hazard. Probabilities of occurrence may be expressed as mean annual recurrence intervals (the average period of time, in years, between repeat occurrences of an event of a given or larger magnitude) or annual probabilities of exceedance (the likelihood in any year that a given event will be experienced, calculated as the inverse of the mean recurrence interval). Note that the two expressions of probabilities of occurrence describe the same event. For example, using the mean-annual-recurrence taxonomy, a 100 year flood would be the level of flooding expected to occur, on average, once every 100 years. Using the annual probability-of-exceedance taxonomy, a 100 year flood would have an annual probability of exceedance of 0.01. Use of a particular taxonomy is often a combination of personal preference and industry norm.

Associated with a design event is the amount of damage that is tolerable (performance level). As discussed previously, performance levels may be qualitative or quantitative. As used in structural design, a qualitative performance level might relate to the effect of the damage from a design event on the state (also may be described as stability or capacity) of the building after the event is experienced—for example, whether the building remains safe for continued occupancy, whether it is

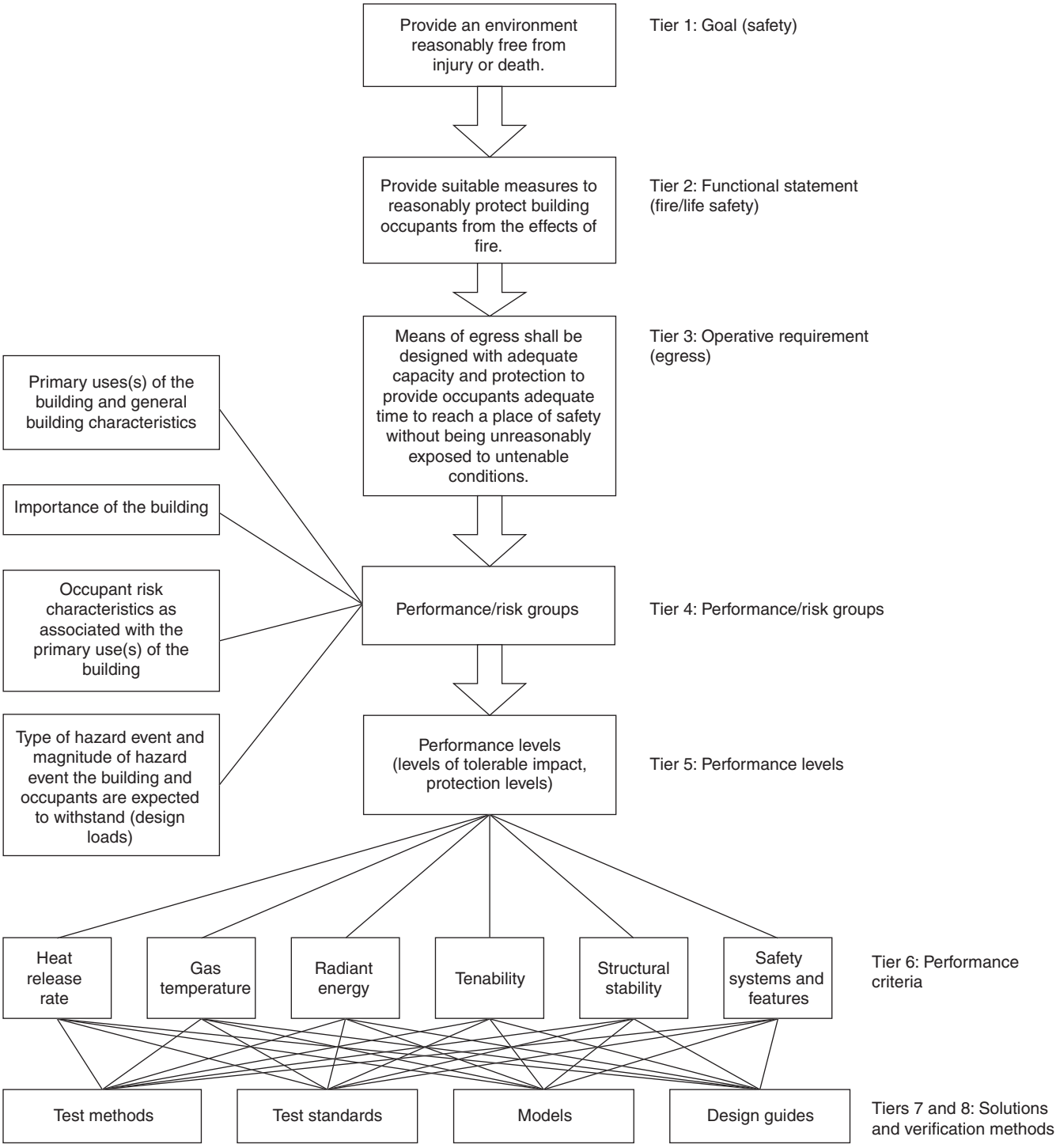

FIGURE 1.7.7 Going from Goals to Implementation in a Risk-Informed Performance-Based Environment (Source: Meacham, B. J., "Performance-Based Building Regulatory Systems: Structure, Hierarchy and Linkages," *Journal of the Structural Engineering Society of New Zealand,* Vol. 17, No. 1, 2004, pp. 37–51)

damaged but functional or operational in its intended service, or whether the safety of occupants is threatened. Quantitative expressions of performance levels, as used in structural analysis and design, relate to specific physical states, such as the extent of strength or stiffness loss, the amount of energy dissipated, and so on. Such expressions of performance are often meaningful only to structural engineers. Given that both qualitative and quantitative descriptions are used in practice, most authoritative

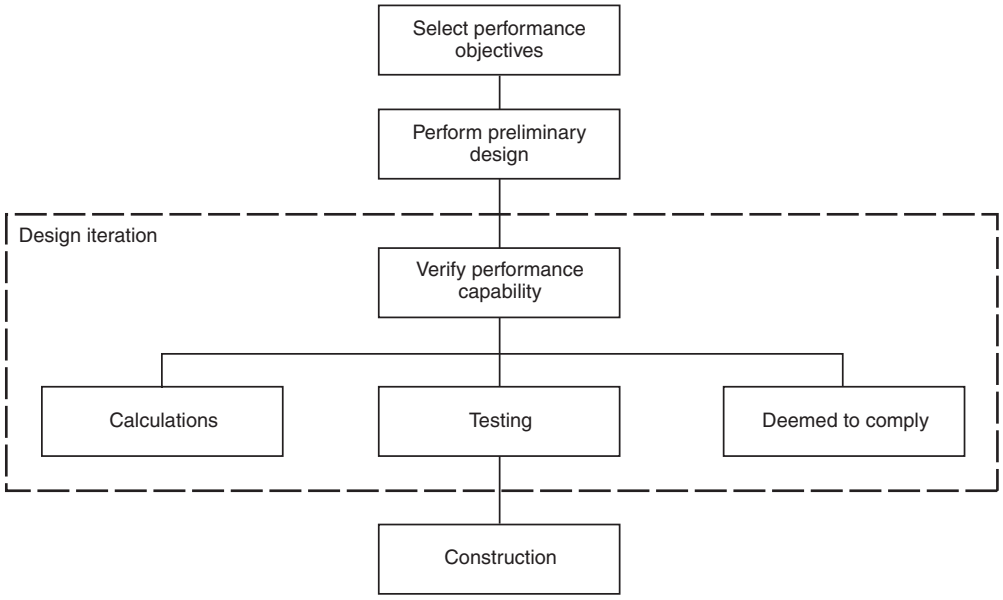

FIGURE 1.7.8 Performance-Based Structural Design Process (Source: *Performance-Based Building Design Concepts,* pp. 6-1–6-22 © International Code Council, Inc., Washington, DC. Reproduced with permission. All rights reserved.)

documents giving guidelines for performance-based structural design provide both qualitative and quantitative descriptions of performance levels to facilitate communication between structural engineers and others, such as the lay public.

Performance-Based Fire Safety Design

Following the structural engineering community, the performance-based concept has been adopted by the fire safety engineering community, where performance-based fire safety design has been defined in NFPA's *Introduction to Performance-Based Fire Safety* as follows:

> . . . an engineering approach to fire protection design based on (1) agreed upon fire safety goals, loss objectives, and design objectives; (2) deterministic and probabilistic evaluation of fire initiation, growth, and development; (3) the physical and chemical properties of fire and fire effluents; and (4) quantitative assessment of the effectiveness of design alternatives against loss objectives and performance objectives.

Although this definition is not universal, research conducted in the 1990s into the evolution of performance-based codes and performance-based fire safety analysis and design methods determined that the concepts are entrenched in more than a dozen performance-based fire safety analysis and design approaches under development or in use around the world.[4]

Development of performance-based design options has in some cases also resulted in a more clearly developed set of rules for prescriptive-based designs.[22] This is particularly true where performance-based design options require proposed solutions to be measured against the goals and objectives of the code. Codes such as NFPA *101* and *NFPA 5000* offer a detailed set of goals and objectives that apply to traditional prescriptive-based code regulations and the newer performance-based code regulations. The goals and objectives provide qualitative conditions to describe the level of performance, the intended perils considered by the code, and the expected outcome when the goals and objectives are met. This level of detailed performance goals and objectives did not exist in U.S.-based codes until performance-based design concepts were introduced into codes beginning in 2000.

Many of these performance-based design approaches, including the one described in the *SPFE Engineering Guide to Performance-Based Protection Analysis and Design of Buildings,* contain the following seven interrelated steps:[4,6,22,26,29]

1. Identify site or project information.
2. Identify goals and objectives.
3. Develop performance criteria.
4. Develop event scenarios, design scenarios, and design loads.
5. Develop candidate design options.
6. Evaluate candidate design options and select final design.
7. Develop final design documentation.

The basic flow of these steps is outlined in Figure 1.7.9 as a sequential process. In reality, however, it often involves several iterations, especially during the evaluation stage (step 6). The iterative nature of the evaluation, including the possibility of revisiting the performance criteria selected, is shown in Figure 1.7.10. (Figures 1.7.9 and 1.7.10 both illustrate the process without reference to fire, indicating its applicability to any engineering problem.)

The advantage of the performance-based analysis and design approach lies in the flexibility that can be achieved without

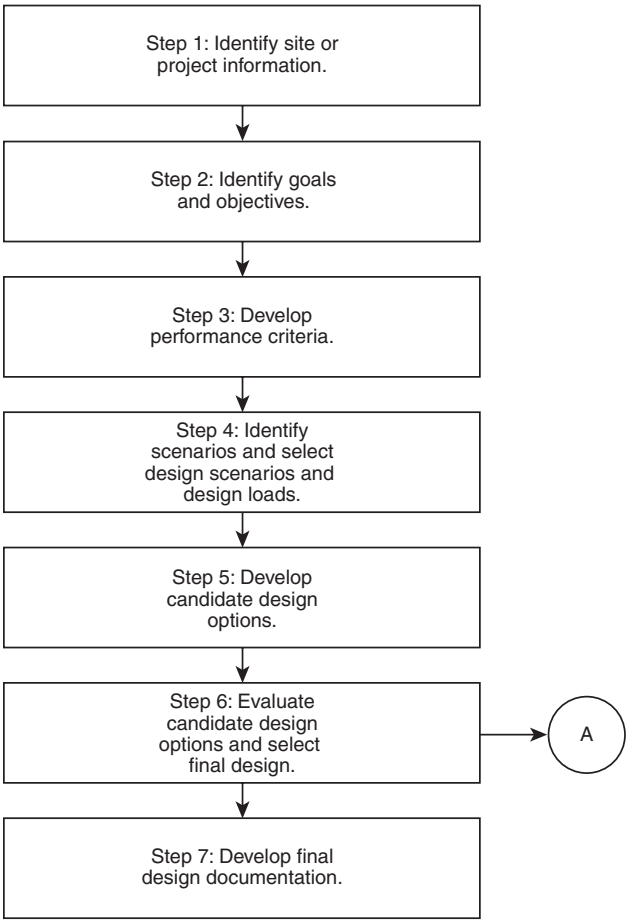

FIGURE 1.7.9 Seven Steps in the Performance-Based Analysis and Design Process (Source: Meacham, B. J., *Assessment of the Technological Requirements for the Realization of Performance-Based Fire Safety Design in the United States,* NIST GCR-98-763, National Institute of Standards and Technology, Gaithersburg, MD, 1998, p. 13)

compromising on safety, cost, or other important factors such as aesthetics, usability, and function.[22] The approach allows all parties involved to agree on the goals, objectives, criteria, and analysis and evaluation methods, resulting in a design that best fits all parameters—a performance-based design solution. A performance-based analysis and design approach can be used in conjunction with performance-based regulations or on its own. When performance-based regulations exist, issues such as goals, objectives, criteria, and performance requirements may already be identified and will not necessarily require development as part of the analysis.

MITIGATION STRATEGIES

There are a large variety of mitigation strategies available for addressing the potential impacts of extreme events in buildings. Detailed discussion can be found in NFPA's *Extreme Event Mitigation in Buildings, Analysis and Design,*[8] as well as other texts cited and listed under additional reading. For the purpose of this chapter, the focus will be on mitigating blast, CBRN, and extreme fire events.

Protection Against Blast Loads*

Implementing physical protection strategies against blast loads requires the active collaboration of engineers, architects, landscape architects, security specialists, and others to ensure the attractive integration of site and structure in a manner that minimizes the opportunity for attackers to approach or enter a building.[18] This protection includes such features as the following:

- Personnel involved in active site security and perimeter control
- Landscaping and earthworks that can function both as blast barriers and vehicle controls
- Appropriately designed street furniture and features such as planter boxes, bollards, and plinths that prevent vehicular access

It is also possible to design into a building itself a range of blast-resistant features, such as additional reinforcing details, composite fiber wraps to strengthen columns and slabs, and high-performance glazing materials. Figure 1.7.11 illustrates blast damage.

Based on experience with blast effects on buildings and people, several basic tenets of physical protection for buildings have evolved over time.[18] These basics are as follows:

- Prevent glazing and facade materials from shattering and entering occupied spaces.
- Keep the blast energy outside the building.
- Protect occupants from injury by fragments and larger objects, blast pressure, or physical translation.
- Prevent structural collapse—global, local, and progressive.

In support of these basic principles, the following should be considered when designing buildings to protect against terrorist attacks:[30]

- *Deflect* a terrorist attack by showing, through layout, security, and defenses, that the chances of success for the terrorist are small. Targets that are otherwise attractive to terrorists should be made anonymous.
- *Disguise* the valuable parts of a potential target so that the energy of attack is wasted on the wrong area, and the attack, although completed, fails to make the impact the terrorist seeks; the attack is reduced to an acceptable annoyance.
- *Disperse* a potential target so that an attack can never cover a large enough area to cause significant destruction, and thereby reduce impact. This protection strategy is suitable for a rural, industrial installation, but probably unachievable for an inner-city building.
- *Stop* an attack from reaching a potential target by erecting a physical barrier to the method of attack; this protective

*Much of this section is excerpted with permission from Hadden, J. D., Little, R. G., and McArthur, C., "Bomb Blast Hazard Mitigation," *Extreme Event Mitigation in Buildings: Analysis and Design,* B. J. Meacham and M. Johann (Eds.), National Fire Protection Association, Quincy, MA, 2006.

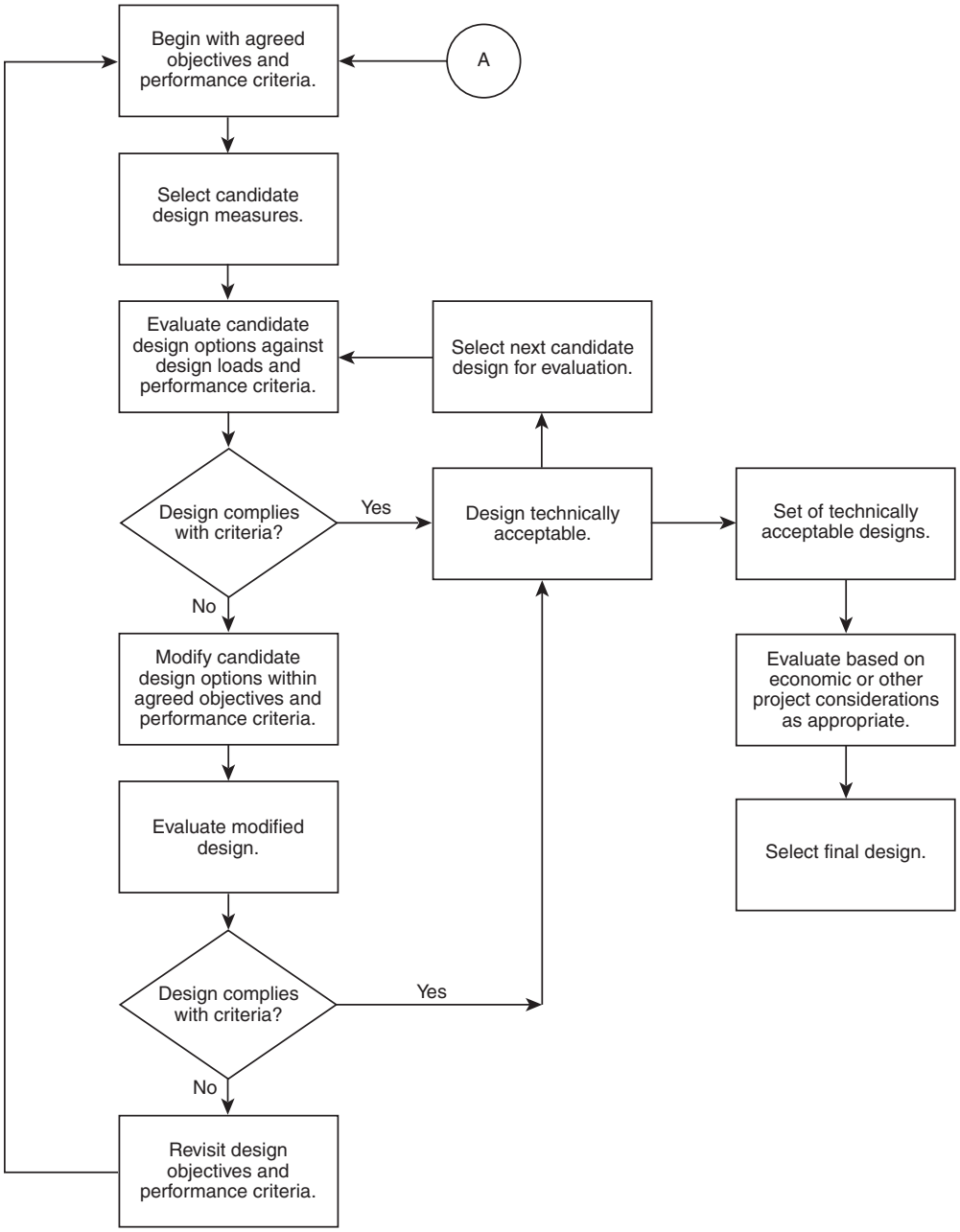

FIGURE 1.7.10 Iterative Nature of the Performance-Based Design Evaluation Process (Source: Meacham, B. J., *Assessment of the Technological Requirements for the Realization of Performance-Based Fire Safety Design in the United States,* NIST GCR-98-763, National Institute of Standards and Technology, Gaithersburg, MD, 1998, p. 14)

design approach covers a range of measures, from relatively large standoff distances to vehicle bollards and barriers to pedestrian entry controls. In particular, this is the only defense that will be successful against a large vehicle bomb.

- *Blunt* the attack once it reaches its target by hardening the structure to absorb the energy of the attack and protect valuable assets.

Despite the great strides that have been made in developing new materials and innovative techniques that will reduce building damage and occupant injury in the event of a bomb attack, the enormous amount of energy generated by even modest amounts of high explosives will still cause extensive building damage and personal injury if detonated at close range. If adequate standoff distance can be established and maintained, the other tenets of building protection become realistically achievable.

FIGURE 1.7.11 Blast Damage at the Chamber of Shipping, London, 1992 (Source: Arup)

The importance of standoff distance in the risk management equation cannot be overemphasized (Figure 1.7.12). If adequate standoff cannot be established, a combination of active site security, operational procedures, and building improvements must be provided.

Threat Assessment and Blast-Protection Objectives. As outlined above, the starting point in design against extreme events is for the designer and client (the developer, owner, or tenant) to agree on the level of threat to be considered and the objectives of any protection measures. This holds true for blast protection. Assessing the terrorist bomb threat to a particular building is not an exercise in precise mathematics or statistical analysis; the range of possible combinations of device type, size, and distance to which a building might be exposed is almost infinite. Despite the difficulties in carrying out such an assessment, however, it is an essential first step. Ultimately the objective of the bomb threat assessment is for the project participants to agree on one or more combinations of charge weight and location(s) to be protected against.

The blast-protection objectives must also be realistic. To expect any building, other than perhaps a hardened military facility, to withstand unscathed a large vehicle bomb immediately outside the front door is unrealistic. However, on a large facade it may be acceptable for the windows closest to the seat of the explosion to produce a certain level of hazard on grounds of economy, with the understanding that other windows, which are offset from the seat, remain intact. In other cases, fully protecting the exposed rooms at the closest range may be required. Building designers must decide whether to glaze the whole facade to the extent required for the most heavily loaded point at ground level or whether to adopt a graded approach to protection. Another consideration is whether the facade or other building components are expected to be reusable after the "design explosion" or whether a level of permanent damage and distortion is acceptable, necessitating replacement.

Conducting threat assessments and defining blast-protection objectives are part of a process of selecting a position on the scale of possible events from which to develop measures consistent with those objectives. This process should lead to the design of a building that offers greater protection—not only from the agreed-on threats, but also against a band of other possible scenarios—than would be the case if no added protection was provided. However, those involved in the process should never lose sight of the fact that the only certainty when designing counterterrorist measures for a building is that the event used for design will not be the attack to which the building is actually exposed. Some may view this caution as a reason not to design against a specific threat, because it will inevitably be the wrong one. A more appropriate reaction is to attempt an analysis that will (1) show that the design will achieve objectives and targets for a diverse range of extreme events and (2) identify the type and severity of events where objectives and targets will not be achieved and provide some insight into the performance expectations for those events.

Building Design and Layout. The threat assessment should be carried out before the design progresses too far, so that fundamental changes in the building can be implemented without substantial modifications. For example, as part of a threat, vulnerability, and risk assessment, one should ask if there is any way to increase the standoff distance, since as noted earlier, every meter added to the standoff distance contributes significantly to reduction in blast impact. At close proximity, and leaving aside local effects, the peak blast pressure is, broadly, inversely proportional to the square of the distance, so anything that can be done to maximize standoff, such as vehicle and pedestrian barriers, is of great value (see Figure 1.7.12).

Other features to be treated with caution and, if possible, designed out at an early stage are floors bridging over public roads, reentrant features such as partially enclosed courtyards, and even deep window recesses. All of these features exacerbate blast effects due to confinement and reflection of the blast wave. Another issue to consider during early planning is access and egress. Ideally, doors should be well dispersed around the perimeter to enable evacuation in the direction considered the safest, either before or after an explosion.

The most widespread cause of injuries and internal disruption from an external bomb blast is the fragmentation and inward projection of window glass. This has been observed in large explosions around the world, from London to Jakarta

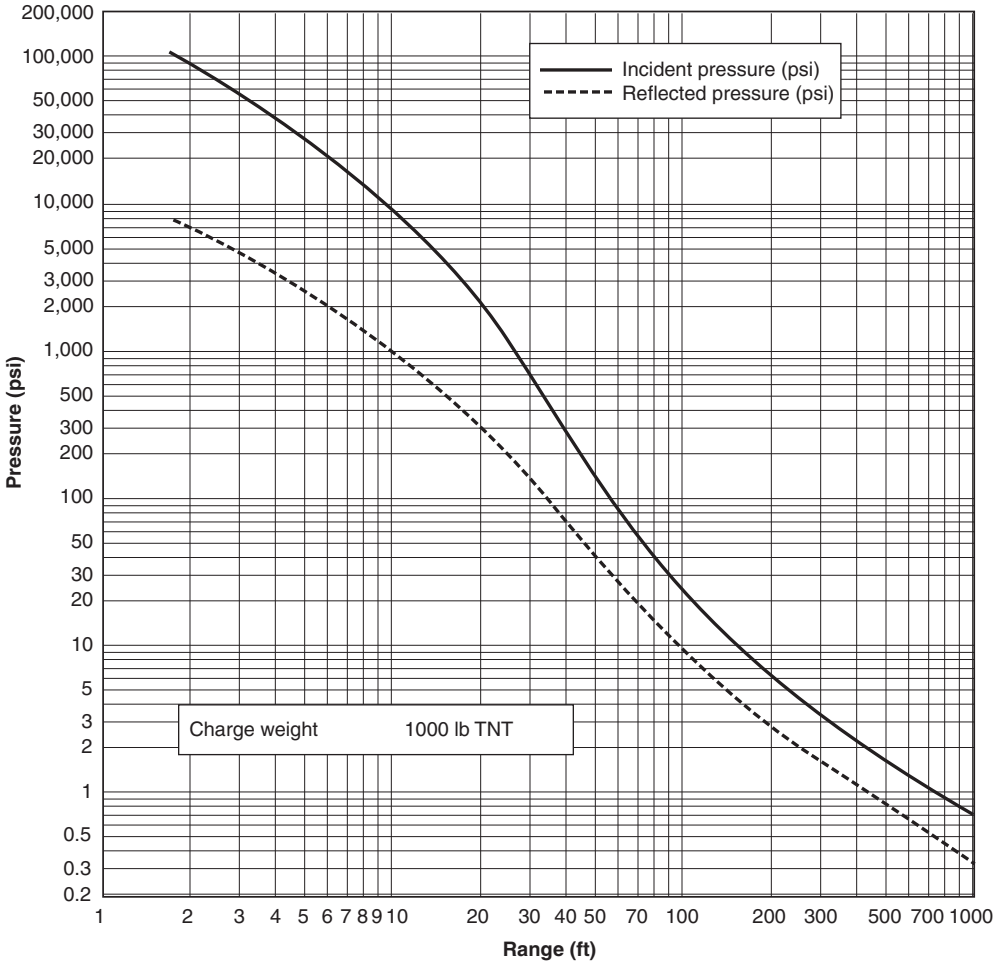

FIGURE 1.7.12 Comparison of Peak Blast Pressures on Surfaces with Incident and Reflected Orientations as a Function of Standoff Distance for a Given Charge (Source: Hyde, D. W., *ConWep Version 2.1.0.8,* USAE Engineer Research and Development Center, Vicksburg, MS, 2005)

to Oklahoma to Nairobi. Plain annealed glass, which is in the majority of homes, is the most hazardous type, because it breaks into dagger-like shards. During an explosion, these shards are thrown at high speed deep into the building, causing laceration injuries. Blast pressures entering through shattered windows can also cause potentially fatal lung damage or eardrum rupture and may throw people against walls and other solid objects. As noted above, standoff distance is a significant mitigation measure. In addition, there are a range of options available for reducing the hazard from glazing, from adding antishatter film to laminated glass, to means to better anchor windows and frames to resist the effects of explosions.[19] Figure 1.7.13 illustrates the relative effectiveness of various mitigation measures.

Bomb attacks on the Alfred P. Murrah Federal Building, Khobar Towers, and other buildings led to the introduction of measures to reduce vulnerability to disproportionate collapse in new U.S. federal facilities.[31] Investigation into this aspect of building design is continuing, and design guidelines are being developed by engineers and researchers around the world.

Most steel or in-situ concrete frames have the potential to perform well under blast loads from typical terrorist vehicle bombs. Local damage can be severe, with columns or slabs close to the explosion destroyed or badly distorted, but overall catastrophic collapse is relatively rare. Some simple modifications to normal construction practice[32] will improve the blast resilience of such structures, but even with these measures, repairs and member replacement may still be required. For all but the most mission-critical facilities, when striking a balance between expenditure and protection, the designer's aim should be to avoid disproportionate damage, not to eliminate damage completely.

In any framed structure, the beam-to-column connections are critical. In a concrete frame, reinforcing bars projecting from a beam can be anchored into the upper and lower sections of a column, rather than just into the concrete at the junction of the two structural elements, where damage may be severe. In steel frames, a simple low-cost "belt-and-braces" approach can be beneficial, with a bolted end plate backed up by a welded seating cleat below, each designed to support a full beam reaction on its own.

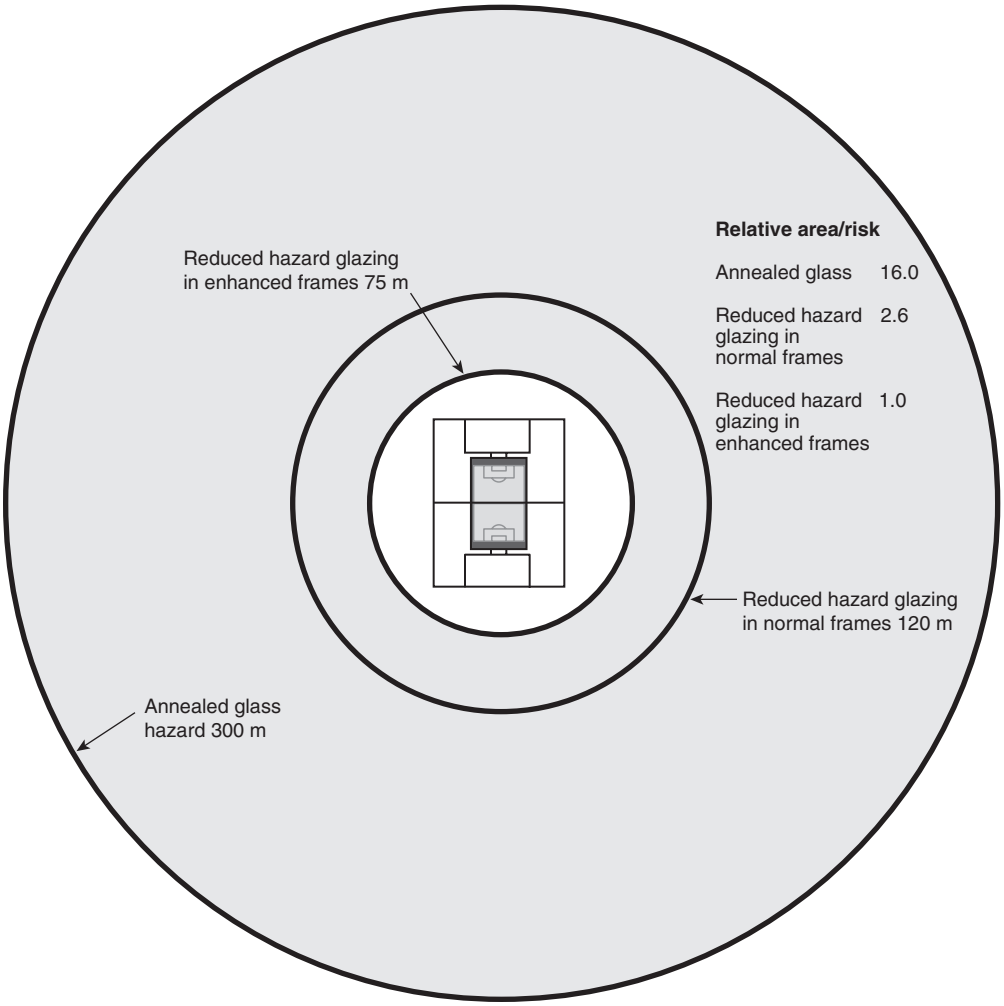

FIGURE 1.7.13 Effectiveness of Different Forms of Glazing After Large Vehicle Bomb (Soccer Stadium Shown for Scale) (Source: Hadden, D., "The Trade-Offs of Handling Risk and Resilience," *Proceedings of the Workshop on Lessons from the World Trade Center Terrorist Attack,* Technical Report, MCEER-02-SP08, Multidisciplinary Center for Earthquake Engineering Research, New York, 2002)

Structural designers may also need to consider the ability of floor slabs to resist upward loads from blast. Portions of a suspended floor slab may not actually need reinforcement on its top face to resist normal downward gravity loads. However, if blast pressures enter the ground level there may be uplift on the floor slab above, which could then fail in reverse bending if it has no top reinforcement and drop back down on the level below.

Computer Modeling and Other References. After settling on the threat, the protection objectives, and the building layout, more detailed engineering can follow. However, at this point opinions on how to proceed diverge. A topographical computer model of the building and its surroundings can be constructed. Sophisticated software can then be used to evaluate the blast pressures and impulses at points around the building for each of the agreed-on threats. However, the sheer complexity of modeling with confidence the influence of adjacent buildings, plus the uncertainties of bomb location and effective charge weight, may undermine the value of such an exercise. The response of the various building surfaces to the blast wave, which may include failure of some surfaces, can also affect the propagation of the blast wave. Merely representing these as rigid and unyielding surfaces may produce misleading results.

Alternative methods of deriving air blast pressures and impulses involve referencing published charts or tables,[33] using established, empirically based software, such as the Conventional Weapons Effects Program (ConWep),[34] or relying on advanced software, such as Air3d[35] or AutoDyne®[36] and the like, to model local conditions. In the end, however, designers should keep in mind that there are no exact answers when designing counterterrorist blast protection measures or universally established design codes to fall back on. In short, there is no substitute for a rational and realistic threat assessment backed by well-founded engineering principles and appropriate analysis.

Robustness and Protection Against Disproportionate Damage

Robustness is a fundamental concept in engineering design and is generally considered among the key public expectations for building performance. Simply, robustness implies a certain degree of "reserve" strength to deal with variations in loading that a building may see in its lifetime and that are not entirely predictable. Elements of robust design are built into codes and standards, but can also be addressed more explicitly in an engineered analysis and design approach, such as may be the case for design against extreme events.[37] The following are the simplest and most common principles of robustness:

- Allow for strength of materials to be variable, taking a statistically justified approach to the design strength.
- Enable imposed loads to be greater than codified values, adopting a margin for error based on experience/historical precedence.
- Allow for a limited amount of damage or failure of part of the structure and design for the subsequent redistribution of loads to the remaining structure.

When considering the robustness of a structure, consideration is given to the extent of damage that may occur from events of various sizes. As with robustness, many codes and standards contain some provisions aimed at assuring the level of damage from an event is proportional to the magnitude of the event (the building is robust against the expected events and associated loads), with the aim being to avoid disproportionate damage.

In brief, *disproportionate damage* occurs when the consequence of an event is far greater than expected. A key here is the link between the "expectations" and "realizations" of events and impacts. In general, "small" events are generally expected to have "small" consequences (i.e., "small" amounts of damage). Similarly, it is expected that for many buildings, "large" events can result in large amounts of damage, particularly if the event is rare or unforeseen. A "small" event resulting in "large" amounts of damage would be considered disproportionate.

In other words, many code-based design hazards will fit into the small event scenario. The resultant loss of structure or function is what may be expected or anticipated. Code-based designs that anticipate larger event scenarios resulting in larger losses may be deemed acceptable. Such a large event, which is considered highly unlikely, may impose such loading on the structure that mitigating factors are essentially impossible to apply.

If a certain class of buildings is expected to perform better under "large" events, additional protection may be mandated by code (e.g., building codes reflect higher performance requirements for critical facilities, such as hospitals as compared with garages associated with single-family dwellings, even for the same earthquake event) or developed as part of the design process. Where building codes do not already require mitigating measures against disproportionate damage, the topic should be considered by the design team based on building population, location, and other risk factors deemed important to the building or facility.

Protection Against the Spread of Airborne Contaminants*

The nature of mechanical systems is to use networks of pipes and ducts to connect various parts of the building. Even if the systems are off, these networks can provide routes through the building that allow the spread of fire, smoke, and biological or chemical compounds, causing the danger to spread beyond the hazard's origin. A number of building-design elements can limit the likelihood of such systems from spreading fire, smoke, or chemicals through a building:

- Smoke and fire spread can be addressed through the use of automatic dampers that seal ducts at certain points in their routes.
- The spread of chemical or biological agents, smoke, or fire can be limited by designing separate duct networks for different parts of the building.
- The risk of introducing smoke or chemicals into the systems can be reduced by careful location of the air intakes, monitoring of the air intakes, and stringent filtration.

Piping systems for heating, ventilation, and air-conditioning (HVAC) systems are generally closed loops; their contents do not come into contact with air, or people, at any point. The exceptions to this are domestic water systems and open-loop cooling tower systems. As such, most of the risks of spreading contaminants within a building are associated with duct systems. These systems are large and open to the air at many locations. However, many of the risks have been known for some time, and several mitigation measures related to ductwork are addressed within codes and standards of the National Fire Protection Association (NFPA) and of the International Code Council (ICC), including the following:

- *NFPA 5000*
- NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilation Systems*
- NFPA 90B, *Standard for the Installation of Warm Air Heating and Air-Conditioning Systems*
- International Building Code[22]

The American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) has developed guidance regarding HVAC design concepts to help mitigate and control spread of chem-bio agents by way of the ductwork.[38] is one such expert document on this topic.

Further details can be found in Section 8, Chapter 1, "Air-Moving Equipment," and Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems." In addition to circulating air within a building under normal conditions, HVAC systems can also be used for managing the impact of fire and other events. Considerable design guidance is available for the design of smoke control and management systems as well (see References).

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*Much of this section is excerpted with permission from Cousins, F., "HVAC System Design for Extreme Events," *Extreme Event Mitigation in Buildings: Analysis and Design,* B. J. Meacham and M. Johann (Eds.), National Fire Protection Association, Quincy, MA, 2006.

Chemical, Biological, Radiological, and Nuclear Sources. The potential for an extreme event involving chemical, biological, radiological, or nuclear (CBRN) substances exists whenever a CBRN substance is present in a building. Triggering of such an event could be the result of anything from an accidental release to someone coming to work sick to a deliberate attack. As with consideration of other extreme events, the assessment and mitigation decision process should begin with a threat, vulnerability, and risk assessment, from which suitable mitigation measures can developed.

Accidental releases could come from spills of common chemicals (such as chlorine) inside or outside of a building as a result of anything from breaking a small storage container (dropping or shaking off a shelf during an earthquake) to a large transportation vehicle crash (truck or train car) in close proximity to the building. In a deliberate attack, agents can be delivered to buildings as packages, by intruders, through vehicles, and by projectiles. There also exists the possibility of airborne transmission of viruses, such as severe acute respiratory syndrome (SARS), influenza and related infectious diseases. To provide protection against CBRN spread, it is important to understand properties of the contaminants as well as release/delivery mechanisms,[19] as different methods of delivery will require different means of hardening the HVAC system.

Protection Against CBRN Spread Initiating Inside of a Building.[39] One of the key issues with HVAC systems is that they link multiple parts of the building together through relatively large pathways (the size of the connection depends on the type of system selected and the way in which the building is normally operated). If an agent is released within a building, then the HVAC systems can provide a path for dispersion to all areas connected to that HVAC system. The most effective way to prevent spreading of the agent is to isolate the systems serving the room in which the agent is released from those serving the rest of the building.[38,40–42] In most buildings, it is not practical to do this for every room within the building, because this would mean providing multiple, extremely large equipment rooms and distribution shafts.

Two scenarios that apply to most buildings, and for which mitigation measures are both inexpensive and effective, are the release of an agent in a delivery area and the release of an agent in a mechanical space. If the agent is brought in through the delivery of a package, then the area where the package is most likely to be opened should be protected. In most commercial buildings, this means that independent HVAC systems should be provided in reception areas, the mailroom, and the loading dock and adjacent receiving areas. These systems should be independent of other areas of the building. They should recirculate air within those rooms only, and all air leaving those rooms should be exhausted from the building. The exhaust outlet should be located well away from any air intakes. These measures will help to control the spread of any agent that is released.

An example of an independent exhaust system used in a reception area is shown in Figure 1.7.14. The figure shows a chemical and biological material released from the outside into the reception area. All air is recirculated within the room, and the room's system does not interface with any other building systems. Of course, management procedures are also required to ensure that all packages are delivered and opened centrally.

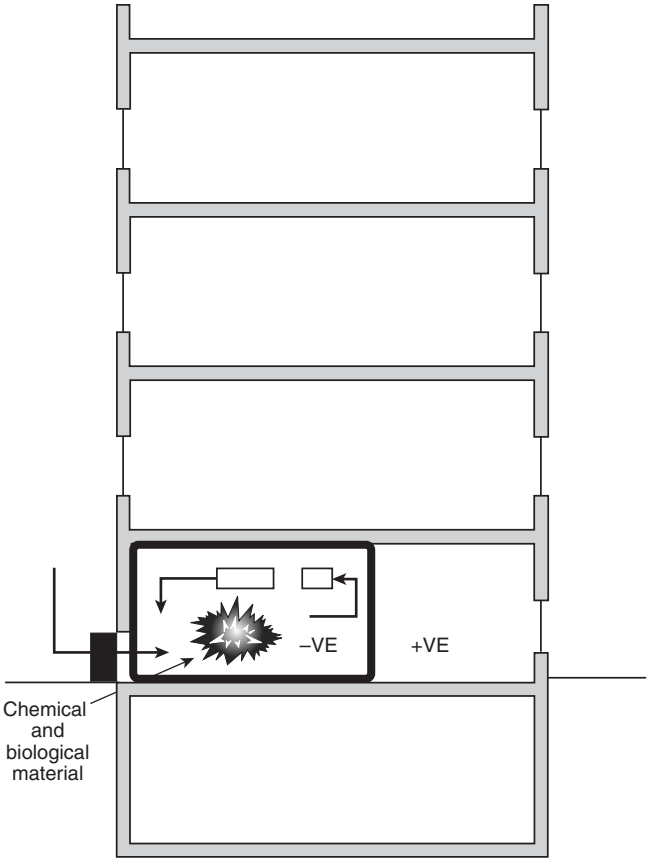

FIGURE 1.7.14 Example of an Independent Exhaust System (Source: Arup)

Another area of high vulnerability is the mechanical room. If an agent is introduced within an air-handling unit, it will be dispersed around the building very quickly. In this case, the risk can best be reduced by controlling access to the mechanical room. The level of access control required will depend on the use of the building.

Consideration should also be given to protection in main building lobbies and security screening areas, particularly if these locations serve as the point for detecting and controlling against introduction of agents into the building. Once access past these points is granted, then the spaces previously mentioned as well as exit stairs that connect the floors of the building can be entered to disperse any agent or substance.

Protection Against CBRN Spread Initiating Outside the Building. All buildings with mechanical ventilation have air intakes. In general, each air intake serves a large portion of the building. The air intake is more critical than the exhaust because it allows a contaminant to be drawn into the building. Air exhausts should also be protected, although to a lesser extent, because they provide weak points for contaminants to enter the building when the systems are off. Several strategies can be ad-

opted to minimize the risk of a containment being drawn into the building, depending on the level of risk associated with the building.

A number of mitigation measures can be provided at minimal cost as part of good-practice HVAC design.[38,40–42] These measures include the following:

- Restrict access to building system plans.
- Locate air intakes away from public access areas.
- Install air intakes at high levels.
- Require security clearance for maintenance personnel.
- Locate air intakes away from horizontal surfaces.
- Provide physical protection of mechanical rooms and air intakes.
- Control supply of air system components.
- Provide surveillance at air intakes.
- Provide multiple air intakes.
- Provide filtration at air intakes.
- Provide protection for incoming potable water supply.

Restrict Access to Building System Plans. Controlling who has access to HVAC system plans prevents an attacker from determining where the intake locations are. It also prevents a would-be attacker from understanding the interconnection of the various areas of the building and knowing the levels of protection that have been put in place. This lack of information makes planning an attack more complicated and increases the likelihood of failure. Information on the following should be restricted: mechanical and electrical systems; elevators; fire, life safety, and security systems; and emergency operations procedures.

Locate Air Intakes Away from Public Access Areas. Air intakes should be located in nonpublic areas. Placement in nonpublic areas prevents an attacker from easily releasing an agent adjacent to the air intake without entering a restricted area. Access management practices can be implemented to reduce the risk of attack.

Install Air Intakes at High Levels. Most chemical and biological agents are heavier than air. Locating the air intakes at high levels, even if they are on a publicly accessible street, reduces the risk of the agent actually entering the building. Figure 1.7.15(a) shows an example of a vulnerable system; Figure 1.7.15(b) shows an example of a more protected system. Figure 1.7.15(c) shows a best-case scenario.

Require Security Clearance for Maintenance Personnel. The mechanical systems of any building are highly vulnerable. All maintenance personnel should be security screened upon employment. Maintenance workers on external contracts should be supervised at all times or be subject to the same security clearances.

Locate Air Intakes Away from Horizontal Surfaces. If an intake is located at a high level, then the easiest way to release an agent into the system is to send a projectile up to the air intake. It is more difficult to do this if there is no horizontal surface on which the projectile can lodge and release the agent. Air intake and exhaust openings should therefore be sloped or vertical.

Provide Physical Protection of Air Intakes. Air intakes should be protected so that they cannot be penetrated by a projectile or other device. Air intakes are usually protected by steel louvers for weatherproofing and have a half-inch metal mesh to prevent birds and vermin from nesting within them. These physical barriers can be strengthened by using heavier gauge meshes and more protective louvers; however, these measures will also increase the required size of the air intake.

Control the Supply of Air System Components. Components that are to be introduced directly into the air system and that require frequent replacement, such as filters, should be bought from reputable manufacturers and inspected for tampering before being used within the system. Such supply management will prevent an agent from being introduced through system components.

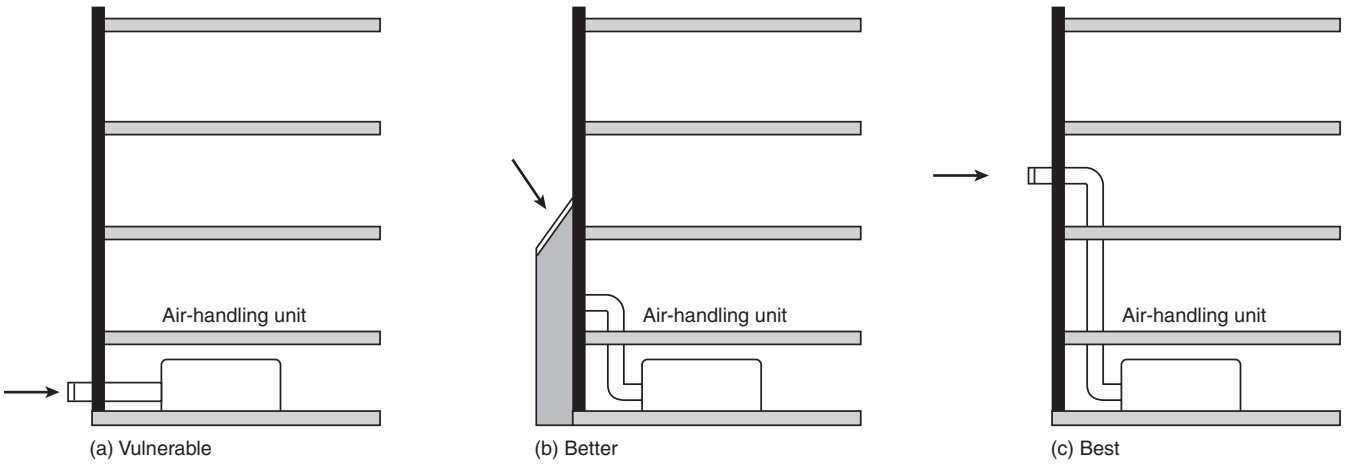

FIGURE 1.7.15 Protecting Air Intake from Airborne CBRN Agent (Source: Arup)

Provide Surveillance at Air Intakes. It is sometimes not possible to locate air intakes away from horizontal surfaces or to protect them from projectile attack. Many building intakes are located at high levels of the building, set back from the edge of the roof. This situation has the advantage of making them invisible to a casual street-level observer and meets the requirement to put them out of a publicly accessible area, but it does not meet the requirement to locate them away from horizontal surfaces. In these cases, the most practical approach may be to provide camera surveillance or motion detection at the air intake. This type of surveillance will shut down the system if suspicious activity is observed.

Provide More Air Intakes. Another strategy is to provide more air intakes, so that the portion of the building impacted by an event is reduced. However, this approach may lead to more complex HVAC systems and additional surveillance requirements, and thus it may not always be a practical solution.

Provide Filtration at Air Intakes. If a chemical or biological agent is released, then it may be possible to prevent the spread of the agent through filtration.[38,40–42] Such protection can be provided through physical filtration (using fibrous filters) or chemical filtration (using chemical reactions to eliminate gases), usually with activated carbon or through the use of UV light to denature bacteria and viruses. In general, a filtration-protection strategy should only be used for high-risk buildings or for high-risk areas within buildings, because it can lead to significant energy use increases and maintenance impacts. Energy consumption increases with the use of physical filters because the filters introduce a pressure drop that the fans within the mechanical systems must overcome. Filtration for chemical and biological agents should be suitable for particle sizes of 0.3 to 35 microns for bacteria and of 0.01 to 0.3 microns for viruses. These sizes are much smaller than the sizes usually filtered out using standard building filters. Filters are rated using the MERV system—a minimum efficiency reporting value. High efficiency particulate air (HEPA) filters are commonly used for this type of filtration.

Protection Against Extreme Fire Events

Protection against extreme fire events is not a new concept. In some respects, current building codes are a reflection of responses to past extreme events. In some cases, protection levels mandated by codes may be adequate for extreme fire events, whereas in other cases additional mitigation measures may be warranted. As with the assessment for disproportionate damage and other threats discussed previously, risk assessment will help inform the need for additional mitigation measures.

Regardless of whether code-based or a result of an engineering analysis and design, key factors for extreme fire event mitigation include redundancy, reliability, and tenability. Almost by definition, an extreme event will significantly stress building systems. As a result, consideration should be given to increased redundancy or diversity of operation, as appropriate given the outcome of a threat, vulnerability, and risk assessment.

Redundancy and diversity of operations are not new concepts in fire and life safety design. The fundamental reason for having two exits from a floor, even if one will suffice based on calculation, is to ensure a measure of redundancy and subsequent reliability. The need for structural redundancy for nonfire loads has long been understood and the cost of such redundancy accepted for essential facilities because the consequences of failure could be disastrous. Many owner-occupied buildings go even further, including redundant systems due to the potential cost of system failure with its consequent business interruption. This is one example of a facilities system that satisfies the "N+1" or even greater concept. For every building, however, building failure after people have escaped has been deemed tolerable for a wide range of hazards such as earthquake or hurricane.

An area that perhaps warrants more attention is fire detection, suppression, and control. The implementation of fire detection and suppression systems, in addition to having some level of structural fire resistance, is accepted for most building types because the benefits are widely understood. It is well known that fire alarm systems detect fire and smoke, that appropriately designed and installed sprinkler systems, coupled with appropriately designed, constructed, and monitored fire-rated systems (walls, doors, opening protection), are enormously successful in controlling fire with resultant savings to life and property. Currently, however, reliability and redundancy within or between these systems are not always required, and where provided, is not always well understood (i.e., sometimes the provision of different types of systems in a "defense-in-depth" approach is confused with redundancy of or within a particular system). Where questions exist, it would be wise to examine the potential implications of the failure of fire detection, suppression, and control systems in buildings, especially those whose occupancy and/or configuration, such as a very tall tower, could pose a greater impediment to successful evacuation and emergency response.

Protection Against Uncontrolled Fire Spread. As outlined in NFPA 550, *Guide to the Fire Safety Concepts Tree,* there are three primary approaches to manage the impact of fire: control the combustion process, contain through construction, or suppress by automatic or manual means (see Figure 1.7.16). Detailed discussion regarding these three approaches is provided elsewhere in this handbook. However, it is worth considering the issues of reliability and resilience of systems in the context of extreme events.

Because even small fires, if uncontrolled, can become extreme fires, it is preferable that fires be quickly detected and suppressed, thus minimizing threats to personal safety and to property. Most high-occupancy or otherwise important facilities are protected throughout by automatic sprinklers and standpipe systems. However, current codes permit the water supply for a sprinkler system to be carried by one sprinkler riser or combined sprinkler/standpipe riser. In an extreme event, it is possible that such a single riser can be compromised, cutting off all water supplies to the entire building sprinkler system, causing the building and its occupants to rely on fire barriers and fire-rated construction of the building structure and means of egress.

Having a backup for suppression systems in the form of redundant fire suppression systems, water feeds or storage, fire-rated construction, or other system is a good thing. However, it

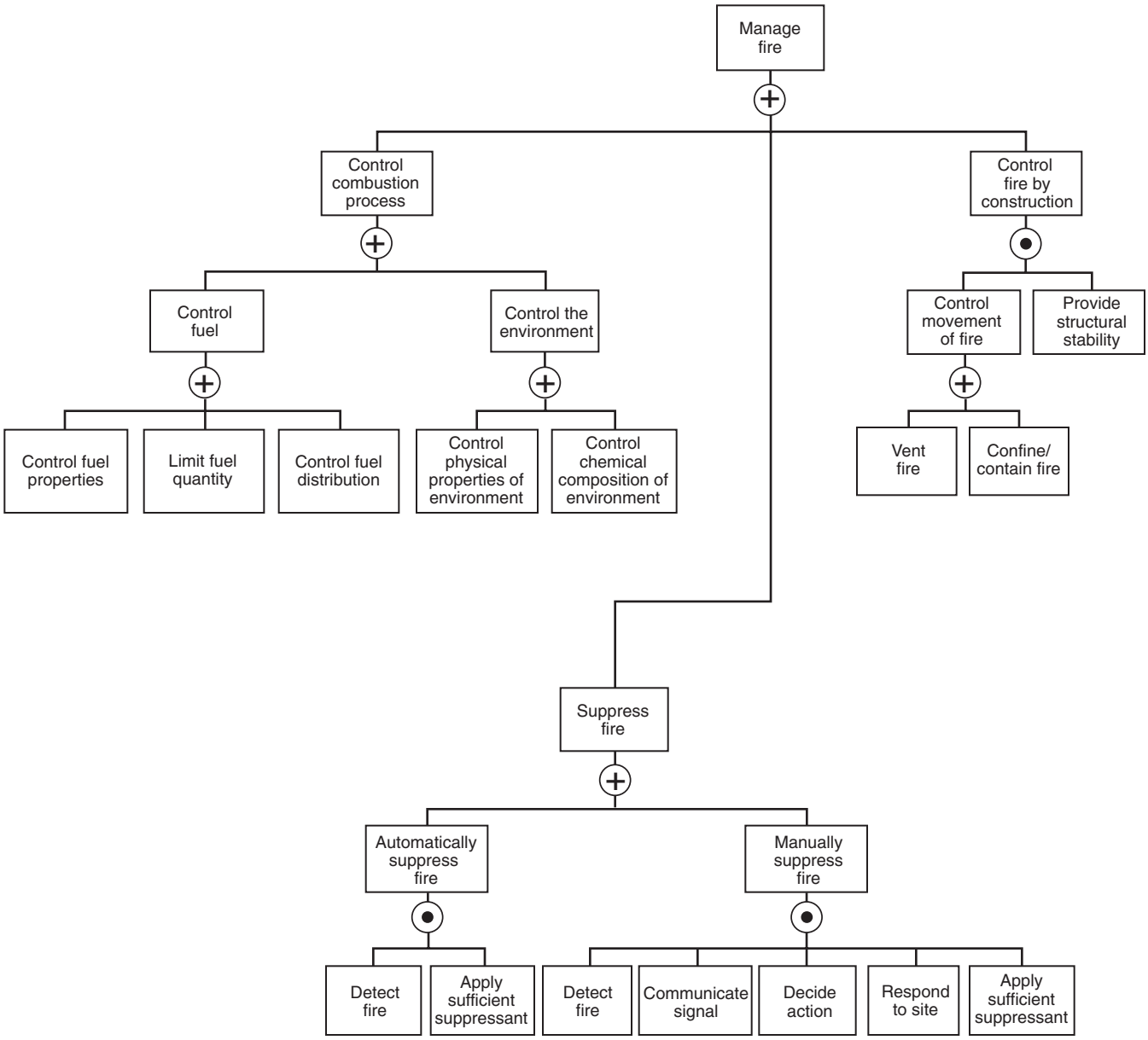

FIGURE 1.7.16 Manage Fire Branch of the Fire Safety Concepts Tree (Source: NFPA 550, *Guide to the Fire Safety Concepts Tree,* Figure 4.5.1)

is also worthwhile to consider increasing the reliability of the suppression system water supply as well, when warranted by a threat, vulnerability, and risk assessment. In buildings of significant concern, such as high-rise buildings, this can be achieved rather cost-effectively in many cases. For example, in most high-rise buildings, a minimum of two stairs are required for egress, and two fire standpipes are required to support fire-fighting operations. Although the stairwells and standpipe risers are already in place, it might be appropriate to increase the reliability and resilience of the sprinkler systems by changing both of the required standpipes into combined sprinkler/standpipe risers, thereby giving the sprinkler system two sources of water.

Protection of Occupants in Place. For many circumstances, especially in high-rise buildings, evacuating occupants on the floor where a hazardous event is occurring and on the floor above and below the event while isolating occupants elsewhere in the building from hazard is a recognized option. See Section 4, Chapter 5, "Strategies for Occupant Evacuation During Emergencies."

The design conditions in this scenario would be those occupants on the three affected floors and those on all other floors. The objective on the affected floors is rather obvious: to separate the occupants from the hazard as quickly as possible. This goal is achieved by maximizing flow through the doors to the vertical exits and down the vertical exits.

Many people who perished on September 11, 2001, in the South Tower of the World Trade Center were likely following directions to remain in place, and consequently it is possible that building occupants will now be less likely to follow directions to remain in place and will take initiative to evacuate a high-rise building in the event of a fire (or other) emergency anywhere in the building. Such a general self-initiated evacuation could impede the egress of people exiting affected floors, and occupants on nonaffected floors may need to be convinced that it is in their best interest, and in the general interest of those at risk, to remain in place. People may be much more likely to choose to remain in place if they are given enough information with which to make a decision and therefore believe that they have taken responsible initiative for their personal safety.[43]

Protection of Occupants by Partial or Full Building Evacuation. Protecting occupants during evacuation is an important role of the egress system, which may include corridors, stairs, and elevators.

Stairs. Quite obviously, one of the keys to a successful full building evacuation is the tenability and the efficacy of the stairs. To maintain tenability, the stair enclosures should remain intact and resistant to damage from fire and from fire-fighting operations in order to maintain fire resistance. The stairs should remain tenable so there is an environment that supports the vigorous physical activity of what can safely be assumed to be a sedentary population, who will require the opportunity to rest in the descent. Therefore, wide landings are advisable to provide such a rest stop.

The stairs also must remain smoke-free to maximize visibility. Visibility must be maintained by effective lighting so that the stairs are bright and remain illuminated under emergency conditions via generators and battery backup in the event of generator system failure. Optional installation of photoluminescent markings on handrails, stair nosing, and other prominent features can also aid in occupant descent.

From the standpoint of smooth flow, stairs should be of a sufficient width to accommodate two large adults walking side by side and therefore many experts believe that the minimum stair width should be increased from the current 44 to 66 in. (112 to 168 cm). At present, both NFPA *101* and *NFPA 5000* have addressed this issue in the interim by mandating stair widths of 56 in. (144 cm) when the cumulative number of occupants expected to utilize the stair is 2000. This moves toward the number previously noted. In addition, the 56 in. (144 cm) width is also expected to improve counterflow of first responders.

Fire Service Elevators. Dedicated elevators have been used for fire service access in the United Kingdom and other locations for decades and there is general interest in employing such elevators for certain classifications of high-rise buildings. Use of dedicated elevators for the fire service may warrant consideration when building-specific risk assessments indicate the need.

Occupant Evacuation Elevators. Unique building configurations could merit the use of occupant evacuation elevators. Such building configurations could be very tall structures with observation decks or other assembly occupancies at the building top. Some jurisdictions require refuge floors (such as Hong Kong) or refuge areas. These refuge areas can be served by occupant evacuation elevators to assist in their evacuation.

In the United States, an effort being coordinated by the American Society of Mechanical Engineers (ASME) is under way to make occupant use elevators a practical option in future tall building design. Task group efforts and work are expected to introduce basic provisions for hardened fire service elevators and occupant evacuation elevator concepts in the next editions of NFPA *101*, *NFPA 5000*, and the IBC.

Emergency Responder Considerations

When considering design for extreme events, discussions with the fire department and other emergency responders should be held early in the design process to assist in addressing their concerns and requirements as they may pertain to a building or facility, and to be able to incorporate these into the design early on. There are several building systems and features that can assist emergency responders in being able to conduct their work, including the following:*

- Fire department notification system
- Mass notification systems
- Site and building access
- Fire command center
- Internal communication systems
- Fire protection equipment
- Water supply
- Smoke purge systems
- Emergency response plans

Notification. Automatic fire department notification is helpful in giving the fire department and other emergency responders early and rapid notification of a fire or other event. Such a system will typically be triggered from an internal building system, such as fire detection or suppression system activation. In some cases, manual fire department notification may be used, particularly when internal alarms go to a central supervised location within the building (such as a security desk) or to a remote supervisory station.

Mass Notification Systems. These systems can be used to alert occupants in multiple buildings or campus-style compounds of a threat that may affect more than one building or area. The systems may direct the occupants to a safe area, such as an underground parking garage for an imminent hostile threat or to site-specific areas away from the threatened building or area.

Site and Building Access. Easy access onto the site, into the building, and to the area of fire origin should be provided for

*Much of this section is excerpted with permission from Marrion, C., and Custer, R., "Design to Manage Fire and Its Impact," *Extreme Event Mitigation in Buildings: Analysis and Design,* B. J. Meacham and M. Johann (Eds.), National Fire Protection Association, Quincy, MA, 2006.

the fire department and its equipment. Security gates, bollards, locked doors, and other security systems, which can help limit incidents, can delay response to the area of origin. Care should be taken to address these "competing objectives" during design, making sure security systems can be controlled as needed to facilitate emergency responder access into controlled areas.

Fire Command Center. A fire command center or area set aside as a control area is required in high-rise buildings. Depending on the building, its type of occupancy, susceptibility to various threats, and so on, it may also be beneficial to have a command center from which emergency responders can stage their operations. This area should contain appropriate equipment, including status indicators and controls for all appropriate fire protection equipment. The fire command center should be large enough to allow responders to undertake necessary operations.

Equipment. It may be necessary to provide equipment on site to assist fire fighters in their operations. This equipment may include standpipes and hose connections, internal communication systems, equipment storage cabinets, and so on. On-site access can assist emergency responders in reducing the time to get equipment to the area of origin, as well as assist them in undertaking their operations.

Water Supply. Adequate water supply should be provided on site. This includes not only a municipal supply but also may include on-site storage tanks. The equipment necessary to access the water supplies inside and outside of the building, including hydrants, siamese connections, and standpipes, should be accounted for in the design.

Smoke Purge Systems. In some buildings, it may be appropriate to provide means to clear the resultant smoke and heat generated during fire-fighting operations to facilitate fire fighting and search and rescue operations. Smoke purge systems may be appropriate in such cases.

Emergency Response Plans. Emergency response plans should be developed for the individual building. Planning and training internally, as well as with emergency responders, will help in managing an incident more effectively. This training may include pre-incident planning to assist emergency staff and building personnel in understanding the building, its fire and life safety systems, particular hazards, key structural elements, and events that could impact critical equipment.

A more comprehensive treatment of egress issues, including use of elevators for egress can be found in the text *Egress Design Solutions,*[44] the *Life Safety Code® Handbook,* the *SFPE Handbook of Fire Protection Engineering,*[45] and Section 4 of this handbook.

Protection Against Unauthorized Access

There are four primary strategies for protecting against unauthorized entry to a building: deter, delay, detect, and prevent.[23] Also see NFPA 730, *Guide for Premises Security,* NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs,* as well as Section 1, Chapter 6, "Premises Security," and Section 14, Chapter 10, "Security and Intrusion Detection Systems."

Deterrence focuses on providing a visible presence of security, with the aim of making a potential aggressor "think twice" about trying to gain entry. This presence can range from a security force to CCTV, bollards, lighting, or other measures that are visible to a potential aggressor. *Delay* reflects strategies that will slow an attack. Delay strategies include bollards or landscaping to hinder vehicle approach, access control, turnstiles, and similar measures aimed at slowing and restricting access. *Detection systems,* such as X-ray, gamma-ray and other screening tools, glass-break detectors, door contacts, smoke detectors, explosive detectors, and chemical detectors, are used to detect the presence of a threat within a facility. As a final measure, *prevention* means hardening; it is intended to mitigate consequences should a threat scenario be realized. Prevention can include a variety of physical measures, from structural hardening to fire protection systems to heating, ventilation, and air conditioning (HVAC) system filters, dampers, and controls, as described earlier in this chapter.

In many cases, it is appropriate to implement the concept of *concentric rings of protection* or *defense in depth,* with critical assets located in the core and layers of protection surrounding the asset, in concert with deter, delay, detect, and prevent strategies. This concept is illustrated in Figure 1.7.17. In all cases, the details of security design should be based in a comprehensive threat, vulnerability, and risk assessment focused on the building, its location, and its security needs. Section 14, Chapter 10, "Security and Intrusion Detection Systems" includes in-depth discussion of these concepts.

Providing for Business Continuity

In addition to considering the impacts from extreme events on buildings and their occupants, it is often important to consider the impacts to whatever business operations may be housed within a building as well. This is especially important for owner-occupied buildings and facilities, but should also be a consideration for those looking to lease space in a facility. It is important because building codes are typically focused on life safety issues, with some property protection components, but do not explicitly consider impacts to the businesses operating within the building.

For normal-hazard events, the protection afforded by meeting the code can usually provide some level of protection for the business operations as well. For extreme events, it may not be reasonable to assume protection is afforded at a related level. For example, in a severe earthquake, flood, or fire, the building may be designed to allow people to escape, but the building may verge on collapse and the contents totally lost. If this is unacceptable to the mission of a business, additional protection may be warranted.

For many organizations, the focus for business continuity is on the impact to the business in terms of loss of equipment and operations, loss of contents, and related factors associated

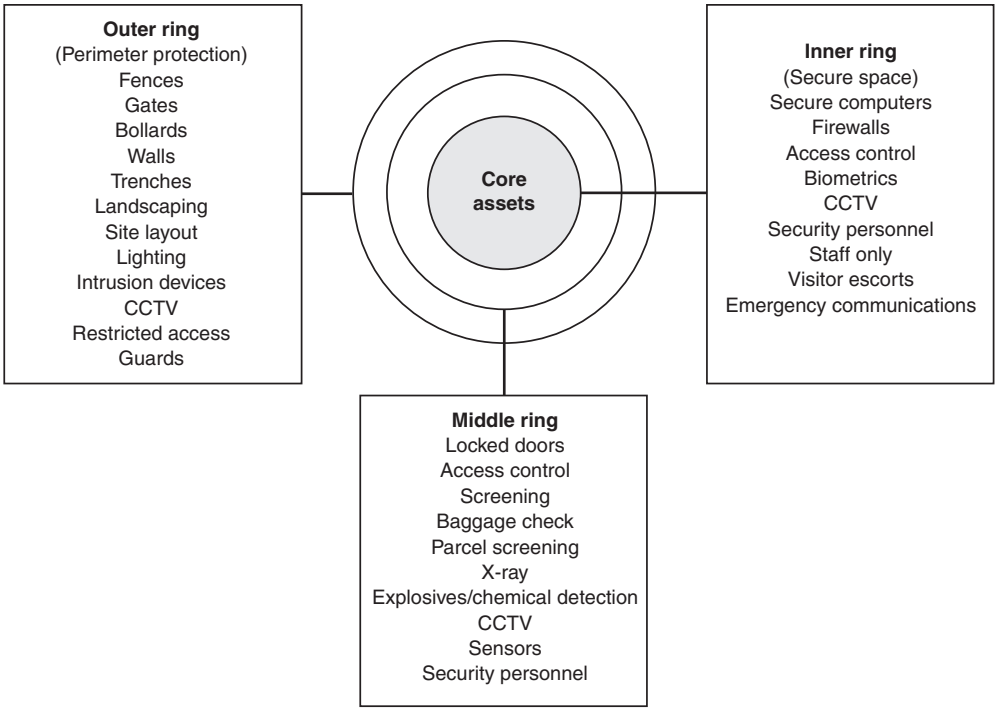

FIGURE 1.7.17 Rings of Protection/Defense in Depth (Source: Arup)

with total downtime and return to operations (in addition to life safety and property impact concerns). A core question for starting the process concerns how big a loss can be tolerated over what period of time. The answer will depend on the business and can be addressed in various ways, from interruption in activities, to loss of contents, to impact on the customer base. Some factors to consider include the following (these will vary by business type):

- Value of stored material (including how valued and by whom)
- Loss impact in terms of material worth (i.e., replacement cost)
- Impact of loss on supply chain (i.e., replacement time, end product cost)
- Loss impact of potential changes in market perception (i.e., reliability, continued service)
- Value of operations equipment (including how valued, replacement cost, and replacement time)

As part of establishing business continuity objectives for extreme event scenarios, decision makers should determine to what extent the organization understands and values the facility, its contents, and operations (i.e., where does the facility fit within the big picture of organizational goals and objectives), as well as how much impact the facility can have on the big picture if significantly damaged, which can then inform mitigation design and other risk management decisions. A more comprehensive treatment of assessment for business continuity can be found in NFPA 1600 and Section 1, Chapter 8, "Emergency Management and Business Continuity."

SUMMARY

This chapter has outlined a variety of measures available to help protect buildings and their occupants against the impacts of extreme hazard events. Given the nature of extreme events, issues have been raised for consideration and not necessarily for application in every situation. Societal expectations can further affect this process if an outcome of an extreme event is large life loss. Engineering methods, design approaches, and operational considerations are always under scrutiny to determine if the best and most appropriate measures are being considered.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on protecting against extreme events discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 90B, *Standard for the Installation of Warm Air Heating and Air-Conditioning Systems*

NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria and Large Spaces*
NFPA *101®*, *Life Safety Code®*
NFPA 550, *Guide to the Fire Safety Concepts Tree*
NFPA 551, *Guide for the Evaluation of Fire Risk Assessments*
NFPA 730, *Guide for Premises Security*
NFPA 731, *Standard for the Installation of Electronic Premises Security Systems*
NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs*
NFPA 5000®, *Building Construction and Safety Code®*

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Chapter 8

Emergency Management and Business Continuity

Donald L. Schmidt

Chapter Contents

Program Management
Risk Assessment
Prevention and Mitigation
Resources
Planning
Emergency Management
Business Continuity
Crisis Management
Training, Drills, and Exercises
Program Evaluation and Maintenance

Key Terms

business continuity, business continuity plan, business impact analysis, crisis, crisis management plan, critical infrastructure, disaster management, emergency action plan, emergency management, emergency response plan, incident command system (ICS), industrial fire brigade, 9/11 Commission, recovery time objective, risk assessment, strategic plan, vulnerability assessment

Emergency management and business continuity planning is necessary for all entities public and private. Emergency response is typically a site-level function, whereas business continuity may permeate multiple levels of an organization depending on the nature of the business and the arrangement of critical business functions. A crisis management team comprised of senior managers will command the organization's response to enterprisewide threats including those that threaten an organization's brand, image, or reputation.

An emergency management and business continuity program requires an assessment of hazards to people, property, business operations, and the environment. Knowledgeable people, systems, and equipment are needed to detect threats, warn occupants to take protective action, alert response teams, and stabilize the incident. Threat-specific response procedures must be implemented to protect occupants at risk, emergency responders, facilities, operations, and the environment. An incident management system is required to manage the response and recovery effort and coordinate the efforts of internal and external responders.

A program requires training all personnel on basic protective actions including evacuation, shelter-in-place, and lockdown. Those with a role in the program must be trained to discharge their duties. Leaders must have the highest level of training to enable them to assess a developing situation, direct resources to stabilize the incident, and recover the organization. A combination of training, drills, and exercises is necessary to build and maintain the competencies necessary to carry out the program. Periodic evaluation and updates are necessary to keep the program current.

This chapter defines the essential elements of an emergency management and business continuity program. It also describes a process for development and implementation of a program that incorporates the essential elements.

For additional information on related topics, see Section 1, Chapter 6, "Premises Security"; Section 1, Chapter 7, "Protecting Against Extreme Events"; Section 4, Chapter 5, "Strategies for Occupant Evacuation During Emergencies"; Section 10, Chapter 1, "Emergency and Standby Power Supplies"; Section 12, Chapter 12, "Disaster Planning and Response Services"; and Section 12, Chapter 17, "Pre-Incident Planning for Industrial and Municipal Emergency Response."

PROGRAM MANAGEMENT

Goals and Objectives

There are numerous goals and objectives for an emergency management and business continuity program. Many are interrelated. Some are optional, others are mandatory. At the very least, businesses must protect their employees and occupants within their buildings. Individual companies may decide that they cannot tolerate any downtime. As a result, they invest substantially to mitigate hazards and implement robust emergency response and business continuity plans.

Unfortunately, all hazards cannot be mitigated, and most companies cannot afford the redundancy necessary to prevent any possibility of business interruption. Choices must be made that are

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mindful of business goals and objectives, financial constraints, corporate culture, management support for the program, geopolitical events, economic conditions, regulatory requirements, and industry practices. The following are typical objectives for an emergency management and business continuity program:

- Protect the health and safety of people, including emergency responders and the community surrounding the facility
- Stabilize an incident, or at least prevent a bad situation from deteriorating
- Support public emergency services and others who stabilize the incident
- Understand hazards and the potential impacts of hazards
- Identify prevention and mitigation opportunities and pursue them, if economically feasible
- Prevent or minimize damage to property, including buildings and their contents
- Prevent any business interruption, or at least minimize the impact of hazards on business operations
- Prevent environmental contamination
- Protect market share
- Minimize financial loss
- Protect brand, image, and reputation
- Comply with contractual or customer requirements
- Comply with regulatory requirements
- Act as a responsible corporate citizen

As a minimum, goals should include protection of people, property, and the environment from foreseeable hazards. This includes safeguarding people, including employees, guests, contractors, visitors, and the community that surrounds the facility as well as emergency responders. Protection of physical assets could include facilities, machinery and equipment, raw materials and finished goods, and operations within the facilities. Environmental protection includes the prohibition of any discharge into the air, ground, or bodies of water. Protection of an organization's image, reputation, market share, and shareholder value may also be included. Whether stated or not, all organizations must comply with laws, rules, and regulations promulgated by local, county, state, or federal governments.

Administration

Management's Role. The foundation of an emergency management and business continuity program is management commitment, direction, and support. Management must set policy, appoint a program coordinator and advisory committee, and provide funding for prevention, mitigation, planning, training, equipment, supplies, and other resources. Managers must be held accountable for development of the program and for keeping it current.

Policy Statement. Development of an emergency management and business continuity program begins with senior management endorsing the program and outlining goals, objectives, and their support in a policy statement. The policy should define the vision of the organization and vest authority in those responsible for the program so they can develop the program and keep it current. This includes the authority to take immediate action to protect the health and safety of people.

Laws, Regulations, and Industry Codes of Practice

Many laws, rules, and regulations have been promulgated at the federal, state, and local levels of government for risk assessment, prevention/deterrence, mitigation, emergency response, business continuity, and recovery. Many of these statutory requirements focus on emergency response and include requirements for protection of people and protection of the environment. The Occupational Safety and Health Administration's (OSHA) "Emergency Action Plans" standard prescribes basic requirements for evacuation planning and accountability. Numerous other OSHA standards prescribe requirements for risk assessment, mitigation of hazards to employees, and emergency planning.

Fire prevention codes including NFPA 1, *Uniform Fire Code*™, and the *International Fire Code* have been adopted across the United States and include basic requirements for emergency response planning. Many states and some cities have amended model codes to include more stringent requirements. Some cities have also adopted local ordinances under the name of "homeland security," requiring enhanced planning, training, or drills to prepare for acts of terrorism or other extreme events.

The National Commission on Terrorist Attacks Upon the United States (the 9/11 Commission) recommended that NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs,* be recognized as the U.S. national preparedness standard.[1] The recommendation was adopted within the National Intelligence Reform Act of 2004.[2] The Canadian Standards Association has licensed NFPA 1600 for the development of a new voluntary Canadian National Standard. NFPA 1600 is also one of five international standards used as the source for the new International Standards Organization (ISO) Standard 223 "Societal Security—Guidelines for Incident Preparedness and Operational Continuity Management."

There are numerous standards, guidelines, and recommended practices published by industry groups for their members. Many industry groups have published standards for risk assessment and loss prevention/mitigation, including security, emergency response, and business continuity. For example, the chemical industry has published guidelines and best practices for emergency response for decades. Banking and financial services industries have an integrated, deep-layered plan to ensure that the U.S. banking system remains viable during any event—regardless of size and magnitude. Following the terrorist attacks of September 11, 2001, additional regulations were promulgated to protect privately owned and controlled critical infrastructure.*

*Critical infrastructure includes banking and financial services; energy (electrical power, oil, and gas production and storage); public health; information and telecommunications; water supplies; agriculture; and transportation (aviation, rail, mass transit, waterborne commerce, pipelines, and highways).

Emergency Management Codes, Standards, Recommended Practices, Laws, and Regulations. The following is a listing of various emergency management codes, standards, recommended practices, laws, and regulations:

- NFPA 1, *Uniform Fire Code*™, Chapter 10, "General Fire Safety"
- NFPA 99, *Standard for Health Care Facilities,* Chapter 12, "Health Care Emergency Management"
- NFPA *101*®, *Life Safety Code*®
- NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs*
- NFPA 1620, *Recommended Practice for Pre-Incident Planning*
- NFPA 600, *Standard on Industrial Fire Brigades*
- NFPA 1561, *Standard on Emergency Services Incident Management System*
- *International Fire Code,* Chapter 4, "Emergency Planning and Preparedness"[3]
- National Incident Management System/Incident Command System
- 28 CFR 36, Nondiscrimination on the Basis of Disability by Public Accommodations and in Commercial Facilities (Americans with Disabilities Act)
- 29 CFR 1910.156, Fire Brigades
- 29 CFR 1910.38, Emergency Action Plans
- 29 CFR 1910.119, Process Safety Management of Highly Hazardous Chemicals
- 29 CFR 1910.120, Hazardous Waste Operations and Emergency Response
- 29 CFR 1910.146, Permit-Required Confined Spaces
- 29 CFR 1910.151, Medical Services and First Aid
- 33 CFR 154, Facilities Transferring Oil or Hazardous Material in Bulk
- 40 CFR 68, Chemical Accident Prevention Provisions
- 40 CFR 112, Oil Pollution Prevention Regulation (SPCC and Facility Response Plans)
- 40 CFR 260-265, Hazardous Waste
- 40 CFR 355, Emergency Planning and Notification
- 40 CFR 370, Hazardous Chemical Reporting: Community Right-to-Know
- 49 CFR 190-195, Pipeline and Hazardous Materials Safety Administration, Department of Transportation

Business Continuity Best Practices and Standards. The following is a listing of various business continuity best practices and standards:

- *Good Practice Guidelines, A Framework for Business Continuity Management,* 2005, The Business Continuity Institute, http://www.thebci.org/gpgdownloadpage.htm
- *Professional Practices for Business Continuity Planner*s, 2004, Washington, DC, DRI International http://www.drii.org/displaycommon.cfm?an=2
- ANSI/ARMA 5-2003, Standard for Records and Information Management; ANSI/ARMA 5-2003, Vital Records Programs: Identifying, Managing, and Recovering Business-Critical Records, Lenexa, KS, ARMA International

Organization

Development, implementation, and maintenance of an emergency management and business continuity program require personnel with technical knowledge of the organization, its facilities, operations, resources, and hazards as well as persons knowledgeable in emergency management, business continuity, and crisis communications. The organization should reach out to public agencies, solicit their input on plan development, and coordinate operational procedures. Advance planning and coordination is essential for effective incident management. Table 1.8.1 provides a listing of potential internal and external participants in the development of an emergency management and business continuity program. Key to a well-organized program is the appointment of a program coordinator, the appointment of an advisory committee, and sufficient funding for the development and maintenance of the program.

Program Coordinator. The organization should appoint a program coordinator to develop the program under the direction of the advisory committee. Often multiple persons are assigned to develop components of the program including environmental, health, and safety (EHS), medical, risk management (RM), and security staff. Separate emergency response, business continuity, and crisis management teams organized within different levels of the organization are common. However, all teams, organizations, and plans must be carefully coordinated for effective response.

Advisory Committee. An advisory committee should be appointed to provide direction for, and assist with, development of

TABLE 1.8.1 Program Participants

Source	*Participant*
Internal	Management (executive, operations, supervisory)
	Legal
	Environmental, health, and safety
	Human resources
	Public relations or public affairs
	Regulatory affairs
	Risk management
	Operations
	Facilities or property management
	Engineering
	Security
	Medical
	Information technology
	Purchasing/supply chain/distribution
External	Law enforcement
	Fire (including rescue service)
	Emergency medical services
	Hazardous materials
	Emergency management
	Public works
	Contractors
	Vendors

the program. The committee should establish objectives for the program consistent with senior management's vision as written in the policy statement.

The advisory committee should identify resources from all functional areas of the organization that may be needed to develop the program, mitigate hazards, or respond to or recover from an incident. The committee can assist with the coordination of intradepartmental activities and should oversee the periodic evaluation and revision of the program.

Finance and Administration. Sufficient funding is necessary for the development and maintenance of the program. Senior management must appropriate funding to meet minimum statutory requirements. The program committee should also recommend appropriation of additional funds for prevention and mitigation of hazards and enhanced planning commensurate with the organization's financial situation, risk profile, risk management program, and tolerance for risk. Success of the program in the long term depends on continued funding. The program coordinator and advisory committee must continually assess funding needs to keep the program current and inform senior management to ensure sufficient funds are appropriated.

Procurement and accounting procedures should be established to support the program. This includes establishing a budget that does not penalize any department that bears responsibility for developing the plan. The program benefits all, and costs should be allocated to all departments. Authority levels and procedures for approval of monetary expenditures should be established to support the program and to expedite procurement during an incident. Procurement procedures should comply with governance standards even during emergencies.

RISK ASSESSMENT

Understanding the hazards that could injure people, damage facilities, interrupt business operations, contaminate the environment, or injure the brand, image, or reputation of the organization is a prerequisite for further planning. A thorough risk assessment should begin with the identification of hazards; quantification of their probability of occurrence; and estimation of their potential impact on people, property, the environment, and the organization itself.

Hazard Identification

There is a long list of potential hazards, including naturally occurring, human-caused, and technological events. For most hazards, there are varying probabilities of occurrence and severity of impacts. The challenge of risk assessment is to identify credible hazards and realistically assess potential impacts. An assessment of vulnerability is necessary to estimate the impact of a hazard (Table 1.8.2).

Vulnerability Assessment and Impact Analysis

Vulnerability assessment and impact analysis are the next steps in the risk assessment process. The vulnerability of an asset to a specific hazard and the magnitude of that hazard will determine its potential impact. Prevention and deterrence may reduce the probability of hazard occurrence but do not reduce the impact or severity of consequences. Mitigation efforts can reduce vulnerability or reduce the impacts.

An assessment of assets at risk (e.g., people, including emergency responders; property; operations; the environment; and the organization itself) will identify opportunities for prevention/deterrence and mitigation. The impact analysis will also identify assets that may be damaged, disrupted, or interrupted, requiring business continuity planning.

The vulnerability assessment requires technical expertise to understand the characteristics and variability of each hazard and how each hazard can injure people and or damage buildings, equipment, and critical infrastructure (Figure 1.8.1). The analysis should also evaluate the impact of each hazard on business operations, the ability to deliver services, and potential financial consequences. Environmental contamination resulting from overpressurization, explosion, ruptured piping or tanks, spillage or release of materials, fire protection water runoff, flooding, or other means must also be considered.

The impact analysis should evaluate the loss of single or sole source suppliers, damage to raw materials, the interruption of utility systems, damage to machinery and equipment essential to production, and the loss of people and their technical knowledge. The analysis should also consider critical timing when a loss would have the greatest impact on operations and financial results. Critical times may be seasonal (in preparation for or during the holiday shopping season), at the end of accounting periods, or as a new product or service is launched.

The organization must also assess the scenarios that could injure its brand, reputation, or image. Consider loss of customers, lost market share, failure to meet contractual obligations, or regulatory fines or penalties. Allegations of a product defect, whether substantiated or not, can scare away customers. Misconduct or impropriety of senior management could result in fines or penalties and jeopardize the future viability of a company.

Natural disasters such as Hurricane Katrina or a significant act of terrorism can wreak havoc in a widespread area and impact commerce nationwide. The hazard assessment and impact analysis must look beyond the property line to identify scenarios that could damage more than one facility owned or operated by the entity or prevent suppliers from shipping critical raw materials or subassemblies. Also important is an assessment of the impact resulting from interruption of critical infrastructure including transportation systems, energy supplies, telecommunications, and financial services.

PREVENTION AND MITIGATION

Emergency management and business continuity planning is not simply reactive. Prevention/deterrence and loss mitigation are important elements of a successful program. The risk assessment process provides an excellent opportunity to identify opportunities for prevention/deterrence and mitigation.

Site Selection and Code Compliance

Prevention and mitigation begin with the selection of a site for a new building. Building in an area that is less prone to natural

TABLE 1.8.2 Hazards

Medical emergencies
- Injury
- Illness
- Foodborne illnesses (mass)
- Disease pandemic

Fire or explosion
- Explosion
- Bomb explosion
- Fire
- Wildfire

Buildings and equipment
- Structural failure or collapse
- Entrapment
- Mechanical breakdown

Transportation incidents
- Motor vehicle
- Railroad
- Watercraft
- Aircraft
- Pipeline

Hazardous materials
- Hazardous material spill/release
- Radiological incident
- Hazmat incident off-site
- Nuclear power plant incident
- Natural gas leak

Meteorological
- Severe thunderstorm
- Tornado
- Lightning
- Flooding
- Dam/levee failure
- Windstorm
- Hurricanes and tropical storms
- Winter storm (snow/ice)
- Drought
- Climate change

Geological
- Earthquake
- Tsunami
- Landslide
- Subsidence/sinkhole
- Volcano

Security
- Labor strike
- Demonstrations
- Civil disturbance (riot)
- Bomb threat
- Lost/separated person
- Child abduction
- Kidnapping
- Extortion
- Hostage incident
- Workplace violence
- Robbery
- Sniper incident
- Terrorism
- Arson
- Crime or theft
- Sabotage or vandalism

Utility interruption or failure
- Communications
- Electrical power
- Water
- Gas
- Steam
- Heating/ventilation/air conditioning
- Pollution control system
- Sewage system
- Other critical infrastructure

Supplier failure to perform
- Loss of key supplier/customer
- Loss of shipping or transportation

Computer systems
- Hardware failure
- Data corruption
- Power surge
- Lightning
- Loss of or lack of capacity
- Host site interdependencies
- Direct physical loss
- Systems outages
- Firewall, ID check
- Water damage
- Cyberterrorism
- Passwords, access, data backup
- Computer fraud
- Loss of encryption
- Denial of service
- Improper system use by employee
- Telecommunications interruption or failure
- Loss of use of critical equipment
- Vendor failure (single or sole source provider)
- Internet service provider
- Inadequate supervision
- Electricity brownout or blackout

Employment practices
- Privacy
- Harassment

Financial
- Investments and financial instruments
- Financial transactions

Product, professional, contractual liability, and directors and officers liability
- Product liability or warranty
- Contractual liability
- Architect/engineering
- Directors and officers liability
- Libel or slander
- Fraud

Intellectual property
- Copyright/patent infringement
- Trademark infringement
- Theft of intellectual property
- Theft of information

Strategic risk
- Mergers and acquisitions

Regulatory, societal, and technological change
- Regulatory changes
- Societal change
- Technological change
- Economic change

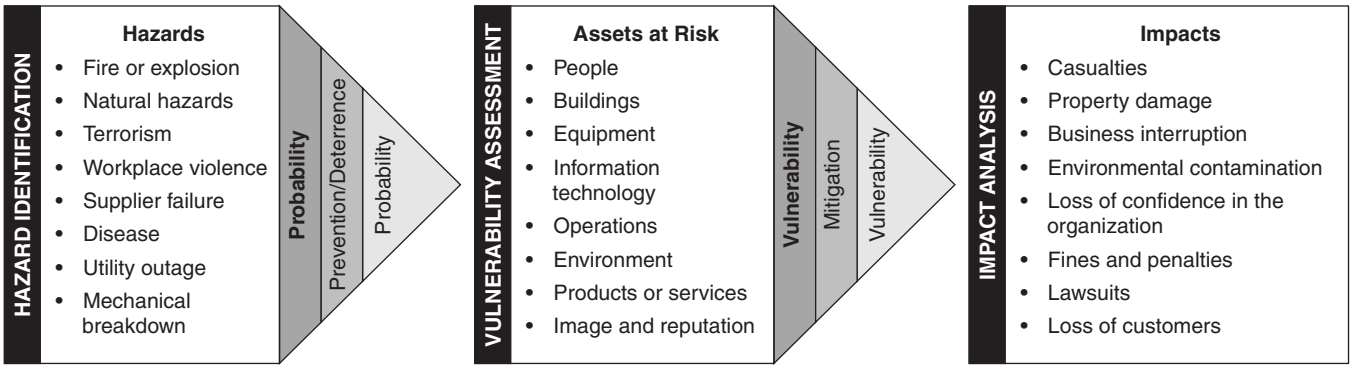

FIGURE 1.8.1 Risk Assessment Process (Source: Donald L. Schmidt, Preparedness, LLC)

hazards can reduce or eliminate damage from earthquake, hurricane, flooding, landslide, or wildfire. Constructing and operating buildings, systems, and equipment in accordance with applicable building codes, fire prevention codes, and environmental regulations will help protect people, property, and the environment. Replace hazardous materials such as flammable liquids and gases with less hazardous materials.

Physical, Operational, and Cyber Security Factors

Physical, operational, and cyber security should be addressed within a comprehensive program. Careful layout of buildings on the property and the arrangement of roadways, parking areas, landscaping, lighting, walls, and doors can reduce crime and limit exposure to some acts of terrorism. Concepts of Crime Prevention Through Environmental Design (CPTED) can be followed to reduce the incidence of crime. NFPA 730, *Guide for Premises Security,* provides general guidance for all types of facilities and specific guidance for individual occupancies. Section 1, Chapter 6, provides additional guidance on these subjects.

Surveillance of the perimeter of buildings and access points can detect potential problems allowing intervention. Surveillance technology can act as a deterrent and provide information to identify perpetrators and provide evidence for prosecution of criminals.

Buildings can be built with fire-rated walls to separate high-hazard operations from low-hazard operations, or high-hazard operations can be located in detached buildings. Hazards should be protected in accordance with the latest codes and standards. Protective systems should be installed to detect incipient problems, notify operators to respond, warn occupants to evacuate, suppress a fire or explosion, or contain runoff of hazardous materials.

Identify critical information sources including vital records and drawings as well as electronic data, and ensure backups are securely stored off site. Duplication or redundancy of essential personnel, critical systems, equipment, information, operations, or materials provides an immediate backup in the event of loss or damage.

RESOURCES

Resource Inventory and Constraints

Many resources are required to support the emergency management and business continuity program. These include people with expert knowledge; surveillance, detection, alarm, notification, warning, communications, suppression, and other systems; facilities including an emergency operations centers for managing an incident; information about hazards, systems, and equipment; and intelligence* about developing threats.

One of the most important resources is sufficient funding for all facets of the program. Senior management must be aware of resource needs and the cost to procure, prepare, maintain, and deploy resources.

Resource constraints must be understood and planning must be commensurate with the expected resource limitations. Will the resource be available when needed? Can a trained and certified medical team respond within 4 to 6 minutes with an automated external defibrillator (AED) to resuscitate a heart attack victim? How many trained medical responders and AEDs do you need to respond to all employees on all floors of all buildings? What is the cost for providing an AED and the annual training required to certify sufficient responders? Is the automatic sprinkler system properly designed to control a fire involving racked storage of flammable liquids? What liability could the organization accrue if personnel are injured in the performance of their emergency response duties?

Maintain an inventory of all resources and use the inventory when auditing the program to verify that all resources are available, immediately accessible, and reliable.

GAP Analysis

GAP analysis has become a common term to describe a review of a program or program element for the purpose of determining whether the program or an individual element is sufficient to meet the intended need. Applied to emergency management and business continuity program resources, a GAP analysis is used to identify any shortfalls in the quantity, response time, capability, limitations, cost, or liability associated with required resources. A strategy should be developed to acquire sufficient resources or adjust plans and procedures to overcome any limitations or shortfalls.

Mutual Aid

Mutual aid agreements with other organizations with similar facilities, systems, or equipment may be one means of responding to an emergency or restarting business operations while a facility is recovering from a loss. Neighboring facilities, businesses, or even an organization's competition may provide assistance by providing personnel, equipment, or supplies for response to fires and other emergencies. This is common with high-hazard industrial facilities located remotely from capable public fire suppression services. Mutual aid agreements can be used for continuity of critical functions by sharing facilities, use of machinery and equipment, or production of common products.

Mutual aid agreements should be in writing, reviewed by legal counsel, and signed by an authorized manager. Agreements should define liability and detail funding and cost arrangements. In addition, agreements should define authority, roles, responsibilities, procedures, communications, resources, and required qualifications.

PLANNING

Depth and Complexity of Planning

The depth and complexity of planning are dependent on the organization, the hazards and vulnerability of the organization's

*Information Sharing and Analysis Centers (ISAC) have been established to advance the physical and cyber security of the critical infrastructures of North America. ISACs provide and maintain a framework for valuable interaction within individual industries and with government. Information on the ISAC Council can be downloaded from http://www.isaccouncil.com/sites/index.php

facilities, the protection of facilities, the availability and capability of external resources, and the tolerance for interruption of business functions. The depth of planning also depends on regulations and the philosophy and culture of the organization. Planning is required at all levels, and coordination and connectivity of plans and organizations at each level are needed to ensure prompt, efficient, and effective response and recovery. There are four levels of planning: strategic, crisis management, emergency response, and business continuity.

Strategic Plan. A strategic plan is overarching and developed at the highest level of the entity. It includes the goals and objectives of the emergency management and business continuity program. It sets minimum performance standards for, and defines the role and responsibilities of, the corporate, business units, and individual facilities for prevention, mitigation, emergency response, business continuity, and crisis management.

Crisis Management Plan. A crisis management plan protects the entity from serious threats to brand, image, or reputation. A crisis may arise from a single event such as a serious fire, hurricane, act of terrorism, or widespread environmental contamination. It may arise from allegations of a product defect or product contamination. Acts of impropriety or allegations of systemic discrimination or harassment have been headline news for a number of major corporations. Financial and strategic risks, however, are often the leading cause of corporate crises. A crisis evolves when the scope of the event or series of events is widespread or the impact on the entity as a whole is significant.

Crisis communications is an important element of the crisis management plan designed for communications with internal and external audiences. Internal audiences include employees, and external audiences include the news media, stakeholders, customers, suppliers, and regulators. The crisis communications plan assigns responsibility to a spokesperson, includes scripts for potential scenarios, procedures for the release of information, and a system for tracking issues that develop over time.

Emergency Response Plan. Develop an emergency response plan for every facility. Since hazards vary by geography and facility, emergency response plans must be customized for each facility. The functions and level of response of the emergency organization should be commensurate with the magnitude of hazards, the availability and capability of internal and external resources, and the adequacy of funding. Every facility should have an emergency response plan with protective actions including evacuation and accountability of building occupants, shelter in place, and lockdown.

Business Continuity Plan. Business continuity plans include strategies, resources, and procedures for maintaining and restoring critical functions that enable the entity to fulfill its mission or achieve its business objectives. Information technology is central to many business continuity plans, but it is not the sole focus of business continuity plans. The impact analysis should identify critical functions and the time frame for restoration of functions before irreparable harm is done to the entity. Business continuity plans must define the alternate operating strategies, necessary resources, and procedures to overcome interruption or disruption of all critical functions.

Direction, Control, and Coordination

Incident Management System. Successful stabilization of, and recovery from, an incident requires effective management and direction of the organization's resources in coordination with external resources called to assist.

A small-scale incident can be managed by one person with the support of others. One person alerts the first aid team to respond to the location of the victim and dials 9-1-1 to request an ambulance. A first aid team responds to the victim and administers first aid and directs paramedics or EMTs to the scene. Larger-scale incidents require more resources, and management of additional resources becomes more difficult. A scalable incident management system is essential to effective management of the incident.

Within the United States, the National Incident Management System (NIMS) was developed following the terrorist attacks of September 11, 2001. NIMS is a national approach to incident management applicable at all jurisdictional levels and across functional disciplines. NIMS is applicable across a full spectrum of potential incidents and hazard scenarios, regardless of size or complexity, and it was designed to improve coordination and cooperation between public and private entities.

Small incidents may be handled solely by the business without any intervention from public agencies. Larger-scale incidents that overtax the resources of the business require the resources of local public agencies. Resources—public and private—will be managed by the public sector incident commander. Incidents involving or potentially involving mass casualties, widespread property damage, or widespread economic impact, such as natural disasters, acts of terrorism, and public health emergencies, most likely would be managed by a combination of state and federal agencies and resources. Responses to the terrorist attacks of September 11, 2001, and Hurricane Katrina are examples.

The incident command system (ICS) is a component of NIMS. ICS defines the operating characteristics, interactive management components, and structure of incident management engaged throughout the life cycle of an incident. ICS integrates a combination of facilities, equipment, personnel, procedures, and communications operating within a common organizational structure, designed to enable effective and efficient incident management.

The organizational structure necessary to carry out an incident action plan develops from the incident commander down, as the size and complexity of the incident increase and the need for additional resources expands (Figure 1.8.2). ICS's organizational structure includes five major functional areas: command, operations, planning, logistics, and finance/administration. The command function fulfilled by the incident commander is supported by staff, including public information officer, safety officer, and liaison officer.

Within these five functional areas, branches may be established. For example, the operations section can be expanded

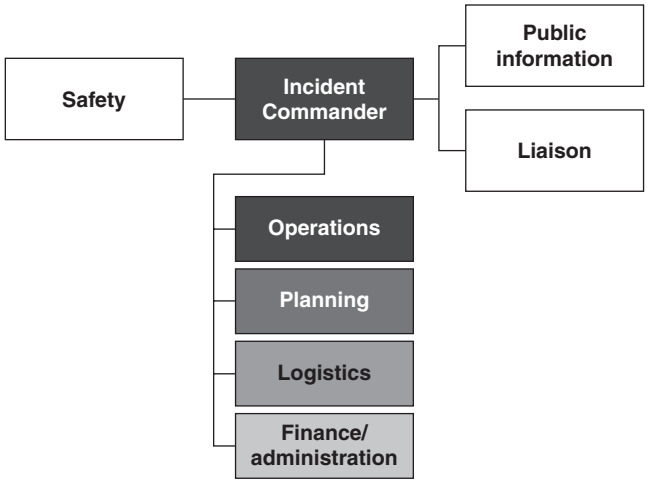

FIGURE 1.8.2 Incident Command Organization

into branches for protective actions for life safety, supervision of building systems and utilities, and site and building security. The expansion of the organization enables a manageable span of control. With the assignment of additional managers, one person is not overwhelmed with more responsibilities than can be effectively managed.

A defined command structure ensures there is an orderly line of authority for decision making. In the private sector, this is especially important since the traditional management structure may not work well during an emergency. Authorization to warn occupants to take protective action (e.g., evacuate a building) must be vested in the leader of the emergency response team who also serves as incident commander. Any delay in the order to evacuate a building at risk may endanger building occupants and first responders.

Transfer of command to the first arriving fire department or law enforcement officer and subsequently to the highest-ranking officer in charge continues this process and ensures there is a clear authority in charge who is properly briefed and able to command all resources. As additional resources from multiple departments, functional areas, or jurisdictions arrive on scene, unification of command authority becomes necessary. A unified command structure enables all to identify incident objectives, determine resource objectives, develop a consolidated incident action plan, and work jointly toward stabilization of the incident.

Management of an incident requires facilities where the leader and members of the emergency response, business continuity, and crisis management teams can assemble or confer to assess the situation, develop the incident action plan, and direct resources. Responses to site level emergencies require identification of an incident command post—the location in proximity to the incident where the incident commander will direct operations. Interior and exterior incident command post locations should be identified in advance, based on hazard scenarios and coordinate locations with the lead public agency that will respond to the incident.

Major emergencies, crises, and business continuity efforts are managed from an emergency operations center (EOC) that may be located on site or distant from the incident. "Virtual" EOCs can be created via conference call. Staff can collaborate and share information via the Internet or a private intranet and develop incident objectives and an incident action plan. The ability to communicate with all responders and resources is critical to effective incident management. Interoperable communications capabilities such as common radio frequencies or sharing of equipment to enable interdepartmental and multijurisdictional communications may be necessary for larger incidents.

Coordination with Public Agencies. The services of public agencies will be required for many incidents including medical emergencies, fires, hazardous materials spills, and acts of terrorism. Coordination of planning between the private entity and the public responders helps assure emergency responders arrive at the correct location or entrance, dispatch the appropriate complement of equipment, and seek out the person who has been designated as the facility's incident commander.

Incident management requires unification of command of all responding agencies. Working relationships should be established with internal department heads, emergency response and business continuity team leaders, and the leaders of public emergency response organizations. The leaders of the facility's emergency response and business continuity teams should be introduced to public emergency services. A clear understanding of who is in charge will help avoid delays and confusion and help assure a smoother response.

A cooperative private-public pre-incident planning effort begins with facility management compiling information about the site, facility, building construction, occupancy, hazards, protection systems, and emergency organization. This information should be reviewed by fire, law enforcement, hazardous materials, emergency medical responders, and others who may respond to the facility. Public emergency responders can then develop site- and facility-specific tactical response plans. NFPA 1620, *Recommended Practice for Pre-Incident Planning,* describes the information that should be compiled and provides example report forms to display information that should be immediately available to emergency responders.

Finance and Administration. Besides the financial support for response teams and plans, plans must address administrative and financial procedures for approval and procurement of resources needed during an incident. Procedures must assure that the approval process is compliant with the organization's fiduciary authorization levels and procedures. In addition, accounting procedures must be established to track all costs related to the emergency, business continuity, and recovery efforts. This includes setting up account numbers for time and costs, tracking work hours for nonexempt labor, and documenting claims for property damage, business interruption, liability, and other claims that may or may not be insurable. These procedures should be organized under the finance and administration section of the incident command system.

EMERGENCY MANAGEMENT

Functions and Level of Response

The size of a facility, the nature and severity of hazards, the availability and capability of external emergency services, regulations, and funding factor into the determination of the functions and level of response of the emergency organization. A large campus or facility with many lives at risk requires a more robust capability to protect occupants. A facility that manufactures, treats, or stores large quantities of highly hazardous materials warrants or may legally require a hazardous materials response team. If the facility is distant from public emergency services, response time is excessive, or the knowledge or capabilities of the public emergency responders is limited, then the facility will need to organize and train personnel to provide first aid, administer CPR, deploy an automated external defibrillator, fight incipient fires, or contain a spill of hazardous materials.

Functions of an emergency organization may include administering medical care, fire fighting, hazardous materials containment or cleanup, rescue of entrapped workers, or search and rescue of trapped persons. Minimum-level functions include notification of public emergency services, evacuating and accounting for building occupants, sheltering occupants in place, locking down a building, supervision of building utilities and systems, salvage, and cleanup. Security of a site or building, investigation of suspicious packages, searching a building when a bomb threat has been received, and controlling or dispersing a crowd may be managed by on-site security staff with or without the assistance of sworn law enforcement officers.

Emergency Organization

Leader. The emergency organization should include a leader with authority to take immediate action to protect building occupants and persons capable of notifying public emergency services and warning building occupants to take protective action. The leader should be very familiar with the facility, its occupants, protection systems, utilities, hazards, and emergency response plan. The leader should be well known to members of the emergency organization and agencies that would respond to the facility. Deputies should be assigned to provide coverage whenever the facility is operational.

Teams. Industrial facilities, places of assembly, hospitals, schools, larger retail establishments, and certain structures, including high-rise buildings, underground buildings, and selected buildings with an atrium, are required by fire prevention codes to have fire emergency plans and trained personnel. Many jurisdictions have adopted more stringent requirements for the organization of fire safety teams and emergency action plans.

A team should be organized to ensure swift evacuation of all occupants from all buildings and accountability at evacuation assembly areas. Evacuation teams should also be trained to shelter occupants in place in the event of an exterior hazard. Lockdown procedures should be implemented and persons should be assigned to warn occupants to take cover if there is a suspected or armed intruder or potential or act of violence in progress. Members of the emergency organization should be provided and trained to assist persons with disabilities.

Additional functional teams can be organized for medical (administer first aid, CPR, or AED), fire fighting, technical search and rescue, or hazardous materials. A medical capability is required by OSHA if there is no infirmary, clinic, or hospital in near proximity to the workplace for the treatment of all injured employees.[4]

Industrial Fire Brigade. Fire fighting is not required by OSHA standards or the two model fire prevention codes; however, local laws in major cities may require appointment of a fire safety director and an emergency organization for high-rise buildings.* Duties of these organizations include supervision of a building's fire protection and utility systems. Facilities that choose to organize an industrial fire brigade must comply with OSHA Standard 29 CFR 1910.156, "Industrial Fire Brigades," and should follow NFPA 600, S*tandard on Industrial Fire Brigades,* and referenced documents therein. Options for industrial fire brigades include incipient-level fire fighting using portable fire extinguishers or advanced interior and exterior fire fighting.

Rescue and Emergency Services. OSHA Standard 1910.146, "Permit-Required Confined Spaces," requires employers to "develop and implement procedures for summoning rescue and emergency services, for rescuing entrants from permit spaces, for providing necessary emergency services to rescued employees, and for preventing unauthorized personnel from attempting a rescue." If the facility decides to provide rescue services, then the OSHA standard defines equipment, training, and other requirements for the rescue service. NFPA 1670, *Standard on Operations and Training for Technical Search and Rescue Incidents,* includes requirements not only for confined space rescue but also for structural collapse rescue, vehicle and machinery rescue, water rescue, and trenches and excavations rescue.

Hazardous Materials Response. OSHA 1910.120, "Hazardous Waste Operations and Emergency Response," dictates requirements for response to hazardous materials at hazardous materials cleanup sites, regulated hazardous waste treatment, storage, disposal facilities, or emergency response operations for releases of, or substantial threats of releases of, hazardous substances without regard to the location of the hazard.

NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents,* provides significant guidance on incident planning, response levels, safety, incident mitigation, and decontamination. NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents,* defines the competencies for responders at the awareness, operations, technician, incident commander, and specialist levels. It also

*Chicago's Title 13 Municipal Code of Chicago Chapter 13-78, "High Rise Buildings—Emergency Procedure." In New York City, Local Law 26 of 2004 requires "standards, procedures and requirements for the orderly evacuation of occupants from any office building, including evacuation of persons necessitated by explosion, biological, chemical or hazardous material incidents or releases, natural disasters or other emergency, or the threat thereof."

defines the competencies for technicians for differing storage tanks.

Organizational Statement. If a fire brigade or hazardous materials response team is organized, a statement or written policy that establishes the existence of each team should be prepared and maintained. The statement or policy should also define basic organizational structure; the type, amount, and frequency of training; the expected number of members on each team; and the functions that the teams are to perform.

Operational Procedures

Protective Actions. Every facility should have documented procedures for protection of building occupants—protective actions for life safety—as well as procedures for response to credible threat scenarios. Basic protective actions include partial, phased, or full evacuation of occupants from a building, shelter in place of occupants within a building when there is an exterior hazard, and lockdown of occupants when there is an intruder or armed perpetrator within a building.

Scenarios for evacuation planning should include not only fire and explosion but also bomb threats, suspicious packages, chemical hazards, and the release of chemical or biological agents. Evacuation planning should anticipate the obstruction of primary means of egress and plan for use of secondary means of egress. Use of the building's fire alarm, emergency voice communication, and public address systems to warn occupants and direct them to take threat-specific action is critically important. Multistructure campus-style environments may also incorporate pager, cell phone, PDA, and computer email messages that notify the occupants of an emergency requiring evacuation. Supervision of the building's ventilation system under the command of the incident commander should be assigned to competent members of the building staff. Procedures should be established for control of all systems based on potential threat scenarios. Protection of employees whose evacuation will be delayed while they shut down machinery or process systems must also be addressed.

Evacuation, shelter in place, and lockdown protective actions must address the needs of persons with disabilities including those with mobility, sensory, or cognitive impairments. Persons with disabilities should be identified; planning scenarios need to be determined; personnel and equipment resources to move them to safety should be determined; and persons to render assistance should be trained. Systems to warn occupants who may not hear evacuation signals, communications equipment to enable persons awaiting rescue assistance to communicate with emergency responders, special chairs (stair descent devices) to evacuate mobility-impaired occupants down stairwells, and personnel to provide immediate assistance to cognitive-impaired occupants who may become agitated or disturbed when confronted with the urgency of a potential life-threatening situation should be provided.

Procedures should be established for treatment of persons with injuries or illnesses. Procedures may be limited to notification of public emergency medical services (EMS) and directing arriving EMS responders to the location of the victim. However, in larger facilities and those with significant hazards, including chemical hazards, emergency procedures should address immediate lifesaving action required for exposure to on-site chemical hazards, including rescue, isolation, and decontamination procedures, and administration of first aid and CPR, or use of automated external defibrillators.

Private businesses also need to prepare for how they would respond in the event of a public health emergency such as pandemic disease. Pandemic flu is an example of a global disease outbreak that occurs when a new influenza virus emerges for which people have little or no immunity and for which there is no vaccine. The disease spreads easily person to person, causes serious illness, and can sweep across the country and around the world in a very short time. An especially severe influenza pandemic could lead to high levels of illness, death, social disruption, and economic loss. Everyday life would be disrupted because so many people in so many places become seriously ill at the same time. Impacts can range from business closings to the interruption of basic services such as public transportation and food delivery. Businesses should develop a plan incorporating human resource policies and procedures, crisis communications, and alternate operating strategies to maintain critical services caused by lack of personnel, goods, or services.

A search and rescue capability may be warranted for facilities located at a distance from public emergency services or facilities located in a seismically active region. A major earthquake could overtax the resources of the public fire service, and the facility's first responders may need to conduct immediate search and rescue.

Supporting Actions. Besides the immediate and urgent task of protecting life safety, the emergency organization should take action to assess damage in coordination with the business continuity team and initiate mitigation and recovery efforts as soon as it is safe. This includes debris removal and cleanup, repairing damage, and restoring utilities in conjunction with contractors and public utilities.

Emergency Procedures. Every facility should have documented procedures for response to credible hazards identified during the risk assessment process. Procedures should include fire, explosion, medical emergency (injury and illness), power failure or loss of another critical utility, severe weather, bomb threat, suspicious package, intruder or violent perpetrator, and acts of terrorism, including chemical, biological, and radiological weapons. Pipe breaks and water damage can be considerable, so documentation of the location and shutoffs of potable and fire protection water valves is essential.

Most facilities are threatened by one or more natural hazards including earthquake, hurricane, flooding, wildfire, landslide, subsidence, and possibly even volcano or tsunami. Plans should identify potential damage to the area, site, and building. Procedures should address property damage, interruption of business operations, and injuries. Consideration should be given to whether public agencies and emergencies services will be able to reach the facility in a timely manner if a regional disaster occurs. Facilities with significant exposure to earthquake

should plan for structural failure of buildings susceptible to seismic damage.

Procedures should be documented for spill or leakage of hazardous materials, including natural or LP-gas if used. Actions can be limited to evacuation; however, the locations and protection of gas piping should be addressed in the plan and communicated to emergency responders. The location of controls, procedures for shutdown of machinery and process systems, and rescue procedures for confined space entry should be immediately available. Facilities located in proximity to major transportation routes, such as highways, freight railways, and commercial shipping channels, should prepare shelter-in-place procedures to protect building occupants from incidents involving the release of hazardous materials in transit.

Retail establishments, properties with on-site banking services, or facilities containing valuables or precious metals should also develop procedures for robbery. Additional procedures may be warranted if there is a probability of strikes, civil disturbances, kidnap, or other security threats.

Detection, Notification, Alerting, and Warning. Procedures should identify the means for detection of a threat, so signs are not missed and the emergency organization is able to respond quickly. For example, overpressurization of a vessel constitutes an emergency requiring immediate shutdown of the equipment. Procedures for notification of trained personnel, the emergency response team, and public agencies should be documented along with the preferred means of notification. Up-to-date lists should be kept of telephone and pager numbers, radio channels, and the other means of notifying internal and external personnel.

Procedures should be documented for use of fire alarm, emergency voice communication systems, and public address systems for different scenarios. Responsibility should be assigned for competent individuals to use these systems to warn occupants when instructed by the incident commander when a fire detection or suppression system operates or when notified of an emergency. Scripts should be written to ensure life safety instructions are broadcast, the audibility of systems should be evaluated to determine whether broadcast messages can be heard and understood throughout the facility, and operator skills should be honed through periodic drills. During an emergency, important information should be broadcast early and the message repeated often to ensure all occupants hear the broadcast and understand what to do.

BUSINESS CONTINUITY

Companies large and small are developing business continuity plans for many reasons. First, business continuity planning may be required by laws and regulations. Financial services firms that process millions of transactions have little tolerance for downtime, and health care institutions have to protect confidential patient information and ensure its availability for life-saving treatments. Planning may be stipulated in contractual agreements with customers who require assurance that critical suppliers will be able to meet their needs. Homeland security standards for industries owning or operating critical infrastructure have requirements for recovery of operations.

Today's global business environment requires highly efficient, streamlined companies to achieve maximum profitability and growth. Unfortunately, highly efficient companies do not always have the redundancy in operations and excess capacity to deal with unforeseen shutdown of critical facilities or functions. Business continuity planning is now more important than ever.

Business continuity planning identifies the impact of potential losses and maintains viable recovery strategies and plans to ensure continuity of critical services. Business continuity begins with management commitment, appointment of a program coordinator, and organization of an advisory or steering committee. Business continuity planning requires a clear understanding of business objectives and how manufacturing or sales of products and the delivery of services achieve the business objectives.

Organization

The business continuity team should be led by the business continuity manager with functional teams for, and led by, managers of the following departments:

- Facilities
- Operations
- Manufacturing
- Logistics
- Information technology
- Finance
- Communications
- Human resources
- Legal

Each team is responsible for the development of the plan for its functional area and for response in the event of an extended interruption of business functions. In small to medium-sized organizations, the business continuity team would be responsible for and frequently will execute all of the business continuity activities. In a large organization, many additional teams will be required for each of the larger departments.

Business Impact Analysis

The impact of potential losses—referred to as the business impact analysis (BIA)—is derived from the analysis of hazards and their impact on business operations (the risk assessment process.) However, a business impact analysis requires a thorough analysis of the manufacturing or service delivery process to identify and quantify the loss of critical functions or activities that would prohibit the organization from achieving its business objectives.

BIA Goal. The intent of the BIA is to identify the downtime and financial impact resulting from the loss of business functions. The higher the loss potential, the stronger the justification for developing strategies for recovering, and allocating resources to recover, the function. Estimation of the loss potential requires not only an understanding of the financial loss potential (e.g., loss of sales) but also an assessment of indirect losses.

The BIA requires identification of critical business functions and assessment of their underlying processes. The goal is

to identify resource requirements and points of failure. An understanding of the time-sensitive nature of the process is needed to determine recovery time objectives—when the business function and underlying processes must be restored before irreparable harm is done to the business and the ability to achieve business objectives is lost. Most companies have numerous functions and not all are critical. Not all functions deemed critical have to be restored immediately after a loss or disruption. It would be prohibitively expensive to build that level of resiliency into any organization.

BIA Procedure. Begin the BIA by meeting with senior management who understand the direction of the company and the business units, products, and services that are most important to the financial success of the company and its future. Using this information about critical products and services, develop questionnaires specific to the organization, its business functions, and processes. Meet with managers of all functional areas of the company, including finance, customer service, human resources, purchasing, manufacturing, materials management, facilities, payroll, and others. Ask managers to identify major business functions and business processes. Ask them to identify the financial impact that a loss of the function would have on the company if the function were lost for 1 hour, 8 hours, 24 hours, 3 days, 1 week, 1 month, and longer.

The assessment must take into account the timing of any outage or loss. Catalog retailers experiencing shutdown of a call center in the weeks before Christmas may lose a high percentage of their annual sales. Likewise, manufacturers of seasonal equipment or materials would suffer their greatest loss when running at peak capacity to meet the seasonal demand for their product. The financial impact should include an analysis of the loss of revenue and impact on expenses.

The financial impact may result from loss or deferral of sales, loss of income from related goods or services, loss of contracts, loss of discounts, and so on. The impact on expenses could include emergency expediting expenses to procure replacement equipment or materials, overtime or temporary labor working to make up lost production, facility or equipment rentals, fines or penalties, insurance deductibles, and so on. There are also many intangibles that must be factored into the overall equation. These include negative impact on customer goodwill, image, reputation, quality, and the opportunity cost that occurs when the organization is unable to pursue additional business opportunities.

Piecing together the business impact analysis also requires an understanding of interdependencies between departments within a facility and interdependencies with other company-owned facilities, as well as external suppliers. An outage at one company facility could shut down operations at other company-owned facilities. The outage could result from loss of a common resource such as information technology or telecommunications, interruption of the supply chain, or disruption of infrastructure. The potential impact on multiple facilities from natural hazards, such as earthquakes, hurricanes, or flooding, should be analyzed.

Businesses run numerous computer applications, including customer ordering, procurement, inventory management, manufacturing planning, manufacturing control, machinery control, shipping, customer service, and general ledger functions. Businesses depend on electronic mail, intranets, extranets, and websites to communicate internally and externally. All of these applications are not critical and do not need to be restored immediately. The business impact analysis must assess each function, rank its priority, and identify the time frame that it must be recovered before serious harm is done to the company.

The interview process should be used to determine whether departments have identified critical machinery, equipment, suppliers, knowledgeable employees, contractors, vendors, records, and information in all forms that would be necessary to restore or replace a process or function. The analysis should identify whether contact names and telephone numbers have been documented to notify contractors, vendors, and staff to respond 24/7 to an outage. It should also determine whether specifications are available for the types, models, or other requirements necessary to procure replacement equipment and the procedures for the step-by-step restoration of functions and processes.

After critical functions have been identified, the underlying processes should be analyzed to determine the facilities, systems, equipment, staffing, technical knowledge, and information (all forms and media) needed to run the process. All department heads should be interviewed and asked to identify the support they provide to others.

Identification of Vital Information. The business impact analysis must also evaluate the loss of critical information. Electronic information can be lost when hardware fails, system security is breached, a virus or worm deletes or overwrites data, or an operator mistakenly deletes a file. Whatever the cause, information may be lost on primary computer media. The true loss is the gap between the information on the primary media and duplicate information on backup media. If the time between the loss and the last information backup is long, then the loss of information may be considerable. Therefore, the protection of information and the frequency of backups of vital information should be addressed as part of the business impact analysis.

Some paper records, drawings, specifications, and other documentation may also be essential to support critical business functions or to facilitate continuity and recovery efforts. Vital records should be identified and backup strategies employed to ensure vital information is available. This includes documentation of the off-site storage location, box numbers, and retrieval instructions.

Recovery Time Objectives

A recovery time objective (RTO) is the maximum allowable time to restore a critical function before irreparable harm is done to the business and the ability to achieve business objectives is lost. There is an inverse relationship between recovery time and recovery strategy cost. Reducing the time to recover a critical function requires more money. For example, if information technology is essential and no downtime is acceptable, then fully redundant facilities and equipment with sophisticated data mirroring are required. The cost for this high level of redundancy may be prohibitive.

Full recovery of a critical function is not always necessary in the initial hours following an interruption. For example, immediately upon activation of the business continuity plan, incoming calls can be rerouted to voice messaging systems for later callback. After 2 hours, calls can be redirected to another facility that has been equipped with phone lines and order entry terminals. After 24 hours, the number of incoming lines can be expanded as needed.

Alternate Operating Strategies

Alternate operating strategies are the means for an organization to run its business in the hours and days following a loss but before facilities, systems, and equipment are restored to their preloss condition and operational status. These strategies do not necessarily duplicate the function they are replacing; rather they are a creative means to bridge the gap.

Manual Workarounds. Manual workarounds are one example of an alternate operating strategy. Time and costs can be tracked manually, and checks can be issued manually or payroll services can be instructed to issue checks in the same amount as the prior period.

Hot Site Contracting. Strategies for data centers can include contracting with a commercial "hot site" (a fully equipped and operational data center ready for installation of client application software and backup data). Testing is required to ensure applications and data can be successfully run on the hot site's hardware, electronic data must be accessible, and connectivity with the company's data network must be established. Hot site contracts can be expensive and they may not be available in the event of a widespread disaster when numerous companies compete for the same data processing space.

Cold Site Configuration. Other alternatives include configuring a "cold site"—a room with utilities and minimum equipment at the same or a second company facility. If the primary facility were destroyed, computer hardware would have to be procured, but the setup time would be less because the facility would be preconfigured with utilities to support the hardware. This strategy may be less expensive than a hot site and would allow resumption of data processing soon after hardware is delivered.

Other Alternate Strategies. Use of other company-owned or company-controlled facilities that have the capacity to accommodate the production or service needed of the damaged facility is the easiest recovery strategy to employ. However, efforts to boost productivity and minimize expenses have eliminated excess production capacity in most firms. Therefore, this option may only be available if production demands are less than peak and excess capacity is available. Reciprocal agreements with competitors provide another means of maintaining critical functions. Competitors with similar products and manufacturing methods may be able to make up lost production and label products to meet competing brand requirements. Distribution companies may be able to arrange for direct shipment from manufacturer to customer or contract with third-party logistics services to receive and distribute products.

Procedures

Procedures must be established for damage assessment, declaration of a disaster, activation of the plan, mobilization of resources, execution of alternate operating strategies, resumption of "normal" operations, and demobilization of resources.

Damage Assessment. When normal operations are interrupted or disrupted, damage assessment should commence immediately. A determination should be made whether critical functions have been damaged, interrupted, or disrupted. If so, the leader of the business continuity team should be notified. The leader should be vested with the authority to declare a disaster and initiate business continuity and recovery efforts.

Plan Activation. The plan should include the names, telephone numbers, and functional responsibilities for the business continuity team. Procedures should be established for alerting members of the business continuity team along with procedures for alerting members of the emergency response and facility management teams. Members of the business continuity team should check in with the command post and report to the business continuity team's work site.

The business continuity plan is activated based on predefined criteria outlined in the plan. Activation may be ordered by the crisis management team when the emergency response team reports significant damage or when interruption of critical functions meets or is expected to meet predefined criteria. Upon activation, the business continuity team should convene at a predetermined location and assess the scope and expected duration of any interruption. If the expected duration exceeds the recovery time objective for any critical function, then the prescribed alternate operating strategies should be initiated. Members of the business continuity team may need to relocate to a predefined alternate location, and logistical support must be provided for transportation, food and shelter, and other needs. Coordination of the business continuity efforts should be managed through the organization's incident command system. Team members should also be mindful of their personal situations and should make sure they have made provisions to take care of the needs of their immediate family members.

When the facilities, systems, and or equipment have been restored to normal operating status, emergency operations are terminated. Facilities, systems, equipment, and members of the business continuity team are demobilized.

CRISIS MANAGEMENT

Defining a Crisis

A crisis is an event or a series of events that threatens an entity's brand, image, or reputation, or significantly and negatively impacts employees, customers, critical suppliers, or investors. Crises can result from natural or man-made disasters, accidental or intentional events, as well as improprieties that may have occurred at the company. The crisis may be apparent immediately, or it may develop over time. Unlike emergencies, however, crises take many days, if not weeks or months, to overcome.

The handling of an event or series of events and the actual or perceived impact will often determine whether the series of events becomes a crisis. The death of the well-known leader of a firm would be a crisis for a small business. However, it would probably not become a crisis for a large company—unless the company mishandles media inquiries into its succession plans and investors get jittery and dump their stock. If fire destroys a manufacturing facility, the result may not be material to earnings or shareholder value—if the facility is fully insured, a business continuity plan enables shifting of production to alternate sites, and a communication strategy quickly informs stakeholders the loss will not affect growth and earnings. If that facility employs a measurable percentage of a community's population and makes a sizeable contribution to the tax base, the loss would be considered a crisis for the community, however.

Early Warning Signs

Many signals and indicators may precede a crisis. Prompt detection and proper interpretation of these signals, understanding their potential implications, and notification of management in a position to remedy the underlying situation may avoid the crisis. A spike in calls to customer service after a new product has been launched may be dismissed as "to be expected." Days later, the news media report a fatality allegedly resulting from the defective product. Analysis of the initial series of calls may have identified a product defect and enabled warning of customers. A limited product recall may be required, but prompt action may limit the damage to a manageable level.

Complaints of harassment or discrimination or rumors of impropriety are often suppressed. When the pattern of activity becomes publicly known and widely publicized, the implications and consequences are magnified. Mandatory reporting and investigation of any allegation of harassment, discrimination, or impropriety may uncover problems before they become newsworthy and the subject of class action.

Close communication with suppliers will enable early warning of potential supply chain interruptions, allowing time to resource critical supplies from alternate vendors. Nokia and Ericsson were two leading manufacturers of mobile phones. A fire at Philips Electronics NV's Albuquerque, New Mexico, facility in March 2000 shut down production of computer chips. Nokia became aware of the impact on its supply of chips before Philips informed Nokia of the fire. Within two weeks, Nokia was able to redesign the chips it needed and restore its supply from available vendors. Unlike Nokia, Ericsson did not have backup suppliers for the chips and was millions short of its manufacturing needs. Ericsson subsequently reported a loss of at least $400 million in potential revenue prior to any insurance recovery.[5]

Organization

Crisis Management Team. Crises may jeopardize the future viability of an organization, so the highest level of management must manage the crisis. A crisis management team, composed of executive management and senior staff representing operations, finance, legal, human resources, and corporate communications, should be organized. Operations staff should include representatives from operating business units or divisions of the company.

Support Team. An incident support team should be organized to provide the logistical and technical support for the senior management crisis management team. Members of the support team should include staff from communications, legal, finance, human resources, operations (e.g., manufacturing, services, etc.), risk management, security, environmental health and safety, engineering, medical, and ad hoc members with expertise or experience as needed. A leader for the support team should be appointed and clerical and logistical support should be provided.

The support team's role is to gather information, conduct research, verify and assemble facts, communicate with affected sites, and prepare briefing papers for the crisis management team. Advance preparation by the incident support team will enable the crisis management team to quickly assess the situation, evaluate current and potential future impact, and determine a course of action.

Procedures

Notification and Escalation. Prompt alerting of management to events that involve fatalities, multiple injuries, significant property damage, business interruption, or contamination of the environment will enable management to react as quickly as possible to inquiries from the news media, stakeholders, regulators, customers, suppliers, or others. Objective criteria for events that require senior management notification should be established and communicated to all facilities. Communication channels, such as telephone, fax, and electronic mail, should be established for reporting events. Procedures should be established so that receipt of messages will be immediate, and management can be alerted 24 hours per day. Call lists with office, home, and cellular telephone numbers should be compiled, kept up-to-date, and made available to authorized persons.

Information Collection and Distribution. Information is critical for effective decision making. Unfortunately, in the early stages of a crisis, only limited information is available. Further compounding the problem, the available information may be conflicting or later prove to be false. Forms and instructions for prompt reporting of incidents should be prepared and distributed to all facilities and managers. Forms and procedures should be integrated with emergency response and business continuity plans and procedures. Use of forms and instructions will help ensure minimum and accurate information is gathered at the site and communicated up the organization's hierarchy.

The executive-level crisis management team must evaluate available information; determine the current and potential future impact of the events on the organization, its employees, shareholders, and business strategies; and then determine action to ameliorate the situation.

Crisis Communications

Understanding Your Audiences. Communication with stakeholders during a crisis is critically important. The message that reaches stakeholders will influence their perception of damage caused by the crisis and the organization's ability to meet their needs. An authoritative response that is clearly commu-

nicated can assuage stakeholders and calm their fears. If no statement is issued, stakeholders will listen to media reports and form their opinion based on information that will probably be limited at best and false at worst. Statements to the media that are poorly articulated, argumentative, or perceived as deceitful or covering up the facts can be injurious to the firm's reputation and fuel speculation about the firm and its ability to survive the crisis. The ability of the news media to broadcast a story to a worldwide audience in minutes requires a rapid capability to respond to the news media and provide responsible information.

Effective crisis communications requires understanding the stakeholders and other potential audiences. Identify who you must reach during a crisis, the message that you must communicate, and the most appropriate group to speak on behalf of the company. Create a list of your stakeholders and audiences and prioritize the order you will reach out to them. Identify the information that you must convey to each audience and the best method of communicating the information. Assign human resources, public affairs, legal, regulatory affairs, labor relations, and investor relations responsibility for defining their respective audience and preparing scripts for communication.

Your audiences include the community that may be directly or indirectly affected by an incident at your facility. The community's interest in the event could vary greatly depending on whether community members' health and safety are potentially at risk or whether their economic well-being is at risk. A chemical release that could be injurious to health or contaminate the groundwater surrounding a manufacturing facility would evoke a serious outcry from the community. A fire that destroys a major employer in the community would evoke serious concern but not necessarily an outcry unless there was some element of impropriety by the company whose facility was destroyed.

Other audiences include employees and their families. Crises resulting from events with fatalities or numerous injuries require communication with family members and special protocols for notification of next of kin. Employees need reassurance that their safety is not jeopardized, and they want to be reassured that steps have been taken to prevent a similar accident.

When an accident occurs, regulators may need to be notified. A release or spill of hazardous chemicals exceeding threshold quantities requires notification of environmental authorities. A workplace fatality or multiple workplace injuries require notification of OSHA. Reporting requirements for each facility should be identified and protocols and procedures for prompt reporting should be documented.

Another audience that is the lifeblood of most companies is its customers. If a business suffers a loss, customers may assume the worst and defect to competitors. Timely information should be broadcast to customers informing them if and when products or services will be delivered and the location and means to access alternate or temporary sites. Sales and marketing staff should develop a plan to reach out to customers if products or services could be or have been interrupted.

Communicate promptly with critical suppliers. Inform them to suspend shipments or where to redirect shipments so goods are not shipped to a facility that cannot receive them. Communicate with critical suppliers to protect your supply chain. Inform financial investors and analysts that the firm's finances are secure and insurance coverage is in place to cover the loss.

Communications and Briefing Center. Communications and media briefing centers should be established for receipt of inquiries from the news media, stakeholders, employees, customers, suppliers, regulators, employees, and other interested parties. Information gathering, preparation of scripts and statements, research, monitoring of news reports, and disseminating information are all done within the communications center. A media briefing center should be located in an easily accessible location away from the scene of emergency operations and away from the emergency operations center.

A protocol should be defined for coordinating the flow of information between all levels of the organization, including the affected sites, division or business units, and corporate. Identify who is authorized to speak to various audiences and how information is approved for release.

Script bulletins to provide information necessary to protect health and safety. This information may include security precautions for company employees traveling in an area that has experienced a disaster or is subject to acts of violence. Instruct employees how to communicate with management. Direct employees to sources of official information such as the company website, call centers, or radio stations. Establish a capability to communicate with the special needs population and procure equipment to communicate with stakeholders who are visually or hearing impaired.

Company officials should coordinate with public officials on site as part of a joint information center (JIC) established under the incident command system. Do not speculate on issues pertaining to law enforcement, cause and origin of a fire, or casualties. Private officials should express concern and sympathy for any victims, their families, and those affected directly or indirectly by the incident. Communicate that the company is working closely with and providing full support to public officials.

TRAINING, DRILLS, AND EXERCISES

Overview

The ability of the emergency response, business continuity, and crisis management teams to respond effectively depends on their knowledge of the program, its plans, procedures, and resources. Managers of the teams must be aware of hazards and the impact of hazards so they can develop an incident plan to protect people, property, operations, and the environment. Their collective ability depends on the effective use of all resources under the direction of a knowledgeable incident commander.

A pyramid of training, drills, and exercises is needed to educate all about the program and their roles and responsibilities as defined therein. Everyone should receive basic training in protective actions. Drills are required to hone skills, and exercises are needed to familiarize persons with the plan and to identify gaps in the ability to execute plans.

Program Goals and Objectives. The scope of training, drills, and exercises should be commensurate with the goals and objectives of the overall program explained at the beginning of this chapter. A training program should be designed to develop the level of knowledge required of all employees as well as members of emergency response, business continuity, and crisis management teams. Drills should be designed to hone specific skills or reinforce knowledge of basic protective actions, and exercises should be conducted to evaluate the firm's ability to carry out the overall program and individual plans and standard operating procedures.

Training and Education Curriculum. A training and education curriculum should be established to support the program (Figure 1.8.3). It should include three tiers or levels, beginning with a basic level of training for all employees. A second and higher level of training should be developed for members of emergency response, business continuity, and crisis management teams. Leaders of emergency response, business continuity, and crisis management teams require the highest level of training.

The training and education curriculum should include learning objectives specific to the audience (e.g., all employees, team members, and team leaders). Learning objectives should be determined after careful assessment of the knowledge base and skills required to achieve the stated program goals and objectives and the levels of knowledge, experience, and skill sets that currently exist. The curriculum must also comply with regulations that specify the scope and frequency of training. Adults learn from doing; thus, training should be interactive and as hands on as possible. Respect the knowledge and experience of team members and allow them to contribute without digressing off subject.

Incident Management System. Effective management of an incident requires use of a management system. All members of emergency response, business continuity, and crisis management teams should receive basic training in the incident command system (ICS). Training should include the ICS structure, assuming incident command, establishing an incident command post, operation of the emergency operations center, and appointment of leaders for operations, planning, logistics, and finance sections.

FIGURE 1.8.3 Emergency Response Training (Source: Donald L. Schmidt, Preparedness, LLC)

Frequency of Training. The frequency of training should be sufficient to develop and maintain the desired level of capability and comply with regulatory and certification requirements. Initial training is required for members of emergency response, business continuity, and crisis management teams. Follow-up training is required when hazards, plans, and procedures are changed. Annual evacuation drills may be required in many occupancies for all employees—more frequently in some jurisdictions and for occupancies like health care. More frequent training is required for members of fire brigades, hazardous materials response teams, and technical search and rescue teams.

Record Keeping. Records should be kept of all training. The date, duration, and subject matter of all training sessions should be documented in a master file. All participants should sign an attendance log, and the log should be filed with the master training file. Individual training records may be kept with human resource records. A system should be developed to identify persons who have not completed required training or whose certifications will soon expire. Records should be made available to authorized persons.

Regulatory Requirements. Numerous regulations dictate the scope and frequency of training, particularly for members of emergency response teams. However, the applicability of regulations vary depending on the functions and level of response of the emergency response team. For example, members of an industrial fire brigade that is organized and equipped for interior structural fire fighting must be medically fit to participate, receive considerable training, and participate in periodic drills and exercises, whereas persons trained to use fire extinguishers within their assigned work area need only receive annual training in the use of fire extinguishers along with basic emergency procedures. OSHA standards should be reviewed for fire fighting, medical response, hazardous waste operations and emergency response (HAZWOPER), and emergency action plans and fire prevention plans for employer training requirements. Fire prevention codes also specify training, drill, and exercise requirements for emergency response, including evacuation. Local laws and regulations should also be reviewed for additional requirements that may be more stringent than state and federal laws.

Drills

A drill is a coordinated, supervised activity employed to test a single task, procedure, or operation. Drills are commonly used to provide training on new equipment, develop or test new policies or procedures, or practice and maintain current skills.

Drills and exercises are an important element of the emergency management and business continuity program. Adults

learn from doing, and drills are one of the best means to hone specific skills. Can occupants of a building find a secondary exit if the primary exit is blocked? Do occupants know where to assemble after they have exited the building? Are members of the evacuation team able to account for all persons who have evacuated? Evacuation drills teach people what to do and allow them to practice their skills.

Drills are needed to hone the skills of all members of the emergency organization. Members who have to operate or supervise systems or equipment should participate in a drill that requires them to reach their assigned location and manipulate (or simulate operation of) controls under the supervision of someone who is knowledgeable and can instruct if necessary. For example, drills should include operation of a building's emergency voice communication system, shutting down a building's ventilation system, and using a portable fire extinguisher to suppress an incipient fire.

Exercises

There are different types of exercises that can be used to familiarize team members with the plan, their role, and how to manage different types of incidents.[6] These include orientation, tabletop, functional, and full-scale exercises. The orientation is simply a review of the organization, plans, and standard operating procedures.

Tabletop Exercises. Tabletop exercises (TTX) are typically held in a meeting or conference room (Figure 1.8.4). Discussion centers around a hypothetical incident or series of events that has been customized to the entity and its organization, operations, or facilities. A TTX is intended to enhance the understanding of concepts, identify strengths and weaknesses in a plan or the organization's ability to execute the plan, and to get team members to work together to assess the unfolding series of events and develop an incident action plan.

Participants should be encouraged to discuss issues in depth and develop plans through slow-paced problem solving rather than the rapid, spontaneous decision making that occurs under actual or simulated emergency conditions. Tabletop exercises require less planning, take less time, and, therefore, can be cost-effective when compared with functional or full-scale exercises. The effectiveness of a TTX is derived from the energetic involvement of participants and their recommended revisions to current policies, procedures, and plans.

FIGURE 1.8.4 Tabletop Exercise Training (Source: FEMA)

There are two types of tabletop exercises: basic and advanced. In a basic TTX, the scene set by the scenario materials remains constant. It describes an event or emergency incident and brings discussion participants up to the simulated present time. Players apply their knowledge and skills to a list of questions presented by the facilitator, problems are discussed as a group; and resolution is generally agreed on and summarized by the facilitator. In an advanced TTX, play revolves around delivery of pre-scripted messages to players that alter the original scenario. The exercise controller (moderator) usually introduces problems one at a time in the form of a written message, simulated telephone call, videotape, or other means. Participants discuss the issues raised by the problem, using appropriate plans and procedures.

Functional Exercises. Functional exercises, also known as command post exercises, are designed to test and evaluate individual capabilities, multiple functions or activities within a function, or interdependent groups of functions. Functional exercises are generally focused on exercising the plans, policies, procedures, and staffs of the direction and control nodes of incident command (IC). Generally, events are projected through an exercise scenario with event updates that drive activity at the management level. Movement of personnel and equipment is simulated.

The objective of a functional exercise is to execute specific plans and procedures and apply established policies, plans, and procedures under crisis conditions within or by particular functional teams. A functional exercise simulates the reality of operations in a functional area by presenting complex and realistic problems that require rapid and effective responses by trained personnel in a highly stressful environment.

Full-Scale Exercise. A full-scale exercise is the most complex type of exercise and typically involves multiple agencies and tests many facets of emergency response and recovery. They include many first responders operating under the incident command system (ICS) or unified command system (UCS) to effectively and efficiently respond to, and recover from, an incident. A full-scale exercise focuses on implementing and analyzing the plans, policies, and procedures developed in discussion-based exercises and honed in previous, smaller, operations-based exercises. The events are projected through a scripted exercise scenario with built-in flexibility to allow updates to drive activity. A full-scale exercise is conducted in a real-time, stressful environment that closely mirrors a real event. First responders and resources are mobilized and deployed to the scene where operations are conducted as if a real incident had occurred (with minor exceptions). A full-scale exercise simulates the reality of operations in multiple functional areas by presenting complex and realistic problems requiring critical thinking, rapid problem solving, and effective responses by trained personnel in a highly stressful environment.

PROGRAM EVALUATION AND MAINTENANCE

The emergency management and business continuity program requires continual maintenance to keep pace with changes in facilities, operations, hazards, regulations, staffing, funding, and resources. When a building is renovated, travel paths to exits may change or evacuation assembly areas may change. As processes are added or changed, new hazards may be introduced or the scope of a hazard may increase. Regulations change over time, reflecting our collective knowledge of hazards and how best to mitigate their impacts. Staffing changes over time. Many persons must contribute to the program, and, as they leave, others must be appointed and trained to continue the program. Changes in funding or the commitment of management to the program will also require changes to the program. The level of response may have to be reduced if funding is not available for personnel, equipment, training, or supplies. Changes in the availability and capability of external resources must also be assessed and the program changed as necessary.

Goals and Objectives

Goals and objectives established when the program was created should be periodically reviewed and validated to ensure they are acceptable to management and can be supported and funded over time. Goals and objectives should also be compared to regulatory requirements and resource constraints to determine whether they are realistic and attainable now and for the foreseeable future. These goals and objectives then become the overarching standard for evaluating elements of the program.

Reviews, Testing, Audits, and Evaluations

The emergency management and business continuity program should be reviewed whenever there is a change that could impact the program. The review should encompass the nature of the change and the impact on the program. If the change has a material impact on the program, then the program element should be revised as necessary.

Elements of the program that are regulated by the government should be reviewed on a schedule that is compliant with the regulation. Fire prevention codes require periodic drills and review of evacuation plans annually.

Most elements of the program are not tested but are rather evaluated to determine whether they meet current needs. Testing is limited to elements of the program that either pass or fail. For example, a fire alarm system is tested to ensure all occupants of the building can hear the evacuation signal. Occupants may or may not hear the signal. Elements of the business continuity plan are also tested to determine whether they work or not. For example, restoration of data and application software is tested on replacement computers to determine whether or not aspects of the information technology business continuity plan work.

Companies with multiple facilities may dictate standards for emergency management and business continuity programs. Facility management sets goals and standards for the program and must hold persons accountable for the development and implementation of program elements. Compliance with statutes and regulations is a requirement for some elements of the program. In all cases, audits enable management to learn whether the program meets standards, goals, objectives, or regulatory requirements. The criteria used by auditors should be carefully developed so auditors can objectively evaluate program elements. Auditors should assess both the availability and the capability of the resource—person, system, or equipment—to fulfill its function when an emergency occurs.

Evaluations are necessary whenever conditions that can have a material impact on the program change. For example, if a new chemical is introduced, a hazard analysis should evaluate whether additional mitigation efforts are needed to prevent a fire, explosion, or hazardous material spill or release. Emergency procedures should be evaluated to determine whether they address any hazard posed by the chemical. Resource needs should be evaluated to determine if additional fire-fighting equipment or supplies are needed.

Critiques of Drills and Exercises

Using objectives established in advance, critique drills and exercises. Utilize forms and checklists and assign sufficient observers to evaluate drills or exercises. Evaluate the ability of the emergency management and business continuity teams to execute established procedures within acceptable time frames. Identify gaps in procedures or knowledge of documented procedures. Also identify problems or limitations with the facility, equipment, and supplies. Discuss observations with team leaders and prepare recommendations for improvement. Address all recommendations through a defined corrective action process.

Post-Incident Critiques

After an incident has been stabilized, there is an excellent opportunity to review the response to the incident and identify ways to improve the response capability. A formal post-incident critique should be conducted for all incidents where there is personal injury, property damage, interruption to operations, or contamination of the environment. Informal critiques are encouraged for minor incidents that do not require a formal post-incident critique. The incident commander, or whoever was in charge of the response, should initiate the critique and prepare a summary report with any recommendations for improvement.

An informal critique involves an informal discussion of the events, facilitated by the incident commander. Members of the emergency organization informally discuss the various aspects of the incident. Discussion should continue with any outside agencies, internal departments, or others who were involved in the incident to describe their involvement in the incident. After the discussion of operations has been completed, everyone involved in the critique should be encouraged to ask questions and offer recommendations for improved response.

The discussion should follow the chronology of events and address the following:

- The initiating event
- Detection of the incident
- Notification, alerting, and warning procedures

- Implementation of incident command
- Interaction with public emergency services
- Adequacy of systems and equipment
- Effectiveness of protective actions (e.g., evacuation, sheltering, or lockdown)
- Effectiveness of threat-specific actions taken by the emergency response team to stabilize the incident

When the post-incident critique has been completed, management should be briefed and corrective action initiated as necessary. The incident commander or other designated and responsible individual should follow the corrective action process to ensure identified issues are resolved. A copy of the post-incident critique form should be filed for future review.

Corrective Action Process

The corrective action process is designed to address improvements to or shortfalls in the program including organization, standard operating procedures, training, and additions to or modification of facilities, systems, or equipment. Appropriate staff should be identified to review recommended improvements or to assess identified deficiencies. They should identify the root cause of any problem and identify the potential impact on the emergency management and business continuity program. Any historical problems that may relate to the issue should be identified. The most appropriate action should be selected to resolve the problem. The work that is needed should be described, the most appropriate means of addressing the work should be suggested, and the time and expense for budgeting or expenditure approval should be estimated. Recommendations should be submitted in order of priority to management at a high enough level to obtain necessary approval.

Some corrective actions might not be taken immediately due to constraints, such as budgets, staffing, or contracts, and might be deferred as a part of the long-range project. However, temporary actions should be taken to implement the desired option.

The progress of each recommendation should be monitored to ensure that priority issues are addressed and to ensure that action taken will satisfy the problem or address the issue. After work has been completed, the program coordinator or responsible person should verify that work has been satisfactorily completed. Future training, drills, exercises, or after-action reports should be evaluated to determine whether additional corrective action is needed.

SUMMARY

An effective emergency management and business continuity program is needed to protect people, property, operations, and the environment as well as the organization's finances, brand, image, and reputation. Basic emergency response procedures are also mandated by regulations in most jurisdictions. Business continuity plans have become a business necessity for most companies and a regulatory requirement for those operating critical infrastructure. A successful program begins with management commitment, direction, and support. Identification of hazards, probabilities of occurrence, and assessment of the vulnerability of buildings, operations, and the environment will determine potential impact. The magnitude of impact, the availability of resources, regulatory requirements, and management's aversion to risk all factor into management's decisions to invest in mitigation. In addition, the impact analysis provides the criteria for determining business continuity and recovery strategies.

Teams must be organized for immediate response to emergencies to protect building occupants. Businesses can opt to provide a higher level of emergency response including fire fighting, medical, hazardous materials response, and technical search and rescue. All plans and procedures should be coordinated with responding public agencies, and an incident management system should be implemented for effective command of all resources during an incident. Business continuity plans should include strategies for restoring critical functions before irreparable harm is done to the organization. Executive management should be organized into a crisis management team to provide strategic direction and to communicate with important stakeholders within and outside the organization. Training, drills, and exercises are essential to implement the program, maintain skill levels, and keep the program current.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on emergency management and business continuity discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code*™
NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 730, *Guide for Premises Security*
NFPA 1561, *Standard on Emergency Services Incident Management Systems*
NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs*
NFPA 1620, *Recommended Practice for Pre-Incident Planning*
NFPA 1670, *Standard on Operations and Training for Technical Search and Rescue Incidents*

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Chapter 9

Systems Approach to Fire-Safe Building Design

John M. Watts, Jr.

Chapter Contents

Design and Fire Safety
Introduction to the Fire Safety Concepts Tree
Fire Safety Concepts Tree and Fire Safety Design Strategies
Fire Prevention Strategies
Control Strategies
Fire Detection and Alarm Strategies
Suppression Strategies
Managing the Exposed

Key Terms

America Burning, fire detection and alarm, fire prevention, Fire Safety Concepts Tree, fire suppression, performance-based design, systems approach

Building design and construction practices have changed significantly during the past century. A little over 100 years ago, structural steel was unknown, reinforced concrete had not been used in structural framing applications, and the first "high-rise" building had just been built in the United States.

The design professions have also advanced significantly during the past century. The practice of architecture has changed markedly, and techniques of analysis and design that were unknown a century or even a generation ago are available to engineers today. Building design has become a very complex process, with many skills, products, and technologies integrated into its system.

Fire protection has made developmental strides in the building industry similar to those of other professional design disciplines. At the turn of the century, conflagrations were a common occurrence in cities. In later years, increased knowledge of fire behavior and building design enabled buildings to be constructed in such a manner that a hostile fire could be confined to the building of origin rather than to one or more city blocks. Progress has continued in the field of fire protection so that, at the present time, knowledge is available that enables a hostile fire to be confined to the room of origin or even to smaller spatial subdivisions in a structure.

See also Section 1, Chapter 3, "Codes and Standards for the Built Environment"; Section 3, Chapter 1, "An Overview of the Fire Problem and Fire Protection"; Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety"; Section 3, Chapter 11, "Overview of Performance-Based Fire Protection Design"; and Section 20, Chapter 1, "Assessing Life Safety in Buildings."

DESIGN AND FIRE SAFETY

Much activity is taking place today regarding fire safe building design. The general thrust is directed toward quantification procedures and identification of a rational design methodology to parallel or supplement the traditional "go or no go" specifications approach. Knowledge in the field of fire protection is undergoing development and reorganization that will enable buildings to be designed for fire safety more rationally and efficiently. Figure 1.9.1 provides an overview of the steps of performance-based design. The *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings*[1] describes this process in more detail. This chapter of the *Fire Protection Handbook* deals with a field that is changing dynamically in its analysis and design capabilities.

Role of *America Burning*

America Burning, the report of the National Commission on Fire Prevention and Control[2] identifies several hazards that building designers create unnecessarily, often unwittingly, for the building occupants. In some cases, these unnecessary hazards are the result of oversight or insufficient

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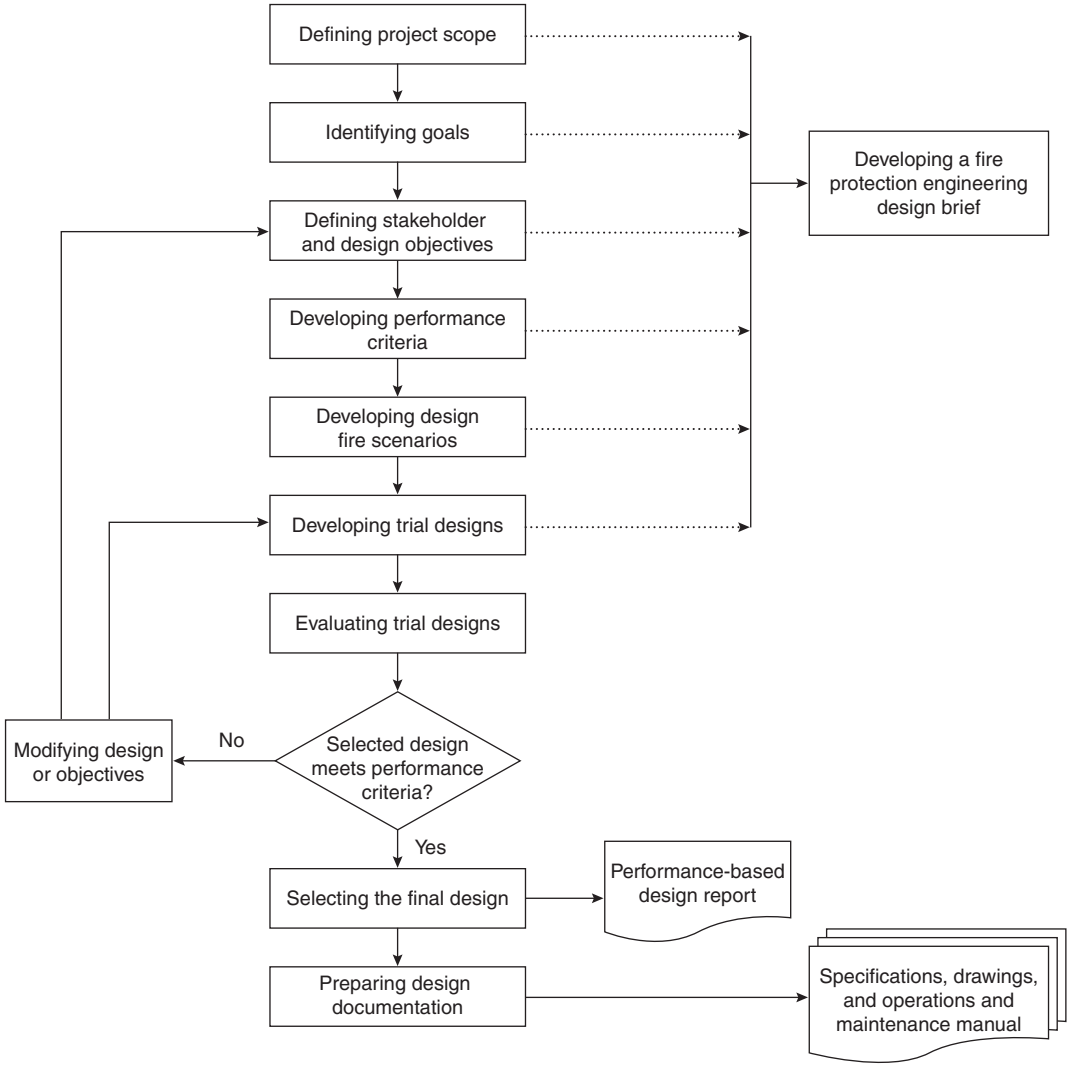

FIGURE 1.9.1 Steps in the Performance-Based Analysis and Design Procedure (Source: *SFPE Engineering Guide to Performance-Based Fire Protection,* 2007)

understanding of the interpretations of test results. In other cases, they are due to lack of knowledge of fire safety standards or failure to synthesize an integrated fire safety program.

The Commission's report cites the minimal attention designers often give to conscious incorporation of fire safety into buildings. Further, building designers and their clients are often content only to meet the minimum safety standards of the local building code. They both may assume incorrectly that the code provides completely adequate measures rather than minimal ones, as is actually the case. Building owners and occupants may also see fire as something that will never happen to them, as a risk that they will tolerate because fire safety measures can be costly, or as a risk adequately balanced by the provisions of fire insurance or availability of public fire protection.

Conditions arising from these attitudes need not continue. Information is available for design professionals to incorporate better fire protection into their designs. Use of this information requires that the various members of the building design team recognize that fire conditions are a legitimate element of their responsibilities. This in turn demands a greater understanding of the special loadings that fire causes on building elements and of countermeasures that can be incorporated into fire-safe designs.

Systems Approach

Fire safety in buildings encompasses an overwhelming number of variables, with only a limited understanding of the relationships of the variables; moreover, obtaining detailed data is often very difficult. The established approach of rigid specification codes and standards has limitations for many modern structures and for older buildings of historic significance. An alternative approach to dealing with fire safety is systems analysis. In the broadest sense, systems analysis is simply the methodical study of an entity as a whole. The objective is to define a credible process for making the best decision from among alternatives.

Interrelation, interaction, and relationships between numerous built-in features, systems, and operational criteria are carefully evaluated to establish the appropriate performance level.

Fire safety can be incorporated into building design by the following three methods:

1. Mandate that design and construction conform to prescriptive requirements in specification-oriented building codes and standards. Such requirements are based on fire experiences and are generally strict.

2. Use performance-based codes to overcome the inflexibility of specification codes. A present limitation of performance-based fire safety is that it is an evaluation procedure, not a design procedure. Once a design has been formulated, performance measures can be used to evaluate fire safety but the approach does not provide direct guidance on how to develop design concepts.

3. Use a systems approach that shows how various protection strategies meet fire safety objectives. Buildings can be designed with a systemic approach and then evaluated using either prescriptive or performance criteria or an appropriate combination of both. This approach to fire safety can require a high level of professional expertise; however, it allows greater flexibility and can achieve a greater level of cost-effectiveness.

The most widely accepted systems approach to fire safety is the NFPA Fire Safety Concepts Tree, a logic diagram that covers all known and conceived means of providing fire safety. This approach was developed by the NFPA Committee on Systems Concepts in the 1970s and continues to be applicable to both traditional and innovative building design. A brief introduction to the "Tree" is published as a technical document, NFPA 550, *Guide to the Fire Safety Concepts Tree.*

Objectives of Fire Safe Design

The conscious, integrated process of design for building fire safety, if it is to be effective and economical, must be integrated into the complete architectural process. All members of the building design team should account for emergency fire conditions in their design effort. The earlier in the design process that fire safety objectives are established, alternative methods of accomplishing those objectives are identified, and engineering design decisions are made, the more effective and economical the final results.

The first step in the process is clearly identifying the specific needs of the client regarding the function of the building. After building functions and client needs are understood, the designer must consciously ascertain both the general and the unique conditions that influence the level of fire safety acceptable for the building. The acceptable levels of safety and the focus of the fire safety analysis and design process objectives are concentrated in the following five areas:

1. Life safety
2. Property protection
3. Continuity of operations
4. Environmental protection
5. Heritage conservation

It is difficult to ascertain the level of risk that will be tolerated by the owner, occupants, and community. Often it is necessary to put a conscious effort into recognizing the sensitivity of the occupants, contents, and mission of the building as to the products of combustion. The levels of sensitivity can vary markedly depending on the focus of interest. Consequently, fire safety criteria often are not identified in a clear, concise manner that enables the designer to provide appropriate protection for the realization of the design objectives. Unfortunately, it is impossible to provide more than general guidelines to consider in building design for achieving the fire safety objectives in this handbook. Specific objectives must be developed for each individual building.

Life Safety. Adequate life safety design for a building is often related only to compliance with the requirements of local building regulations. This may or may not provide sufficient occupant protection, depending on the particular building function and occupant activities.

The first step in life safety design is to identify the occupant characteristics of the building. What are the physical and mental capabilities of the occupants? What range of activities and locations occur during the seven 24-hour periods each week? Are special considerations needed for certain times of the day or week? In short, the designer must anticipate the special life safety needs of occupants during the entire period in which they inhabit the building.

The identification of life safety objectives is usually not difficult, but it does require a conscious effort. In addition, it requires an appreciation of the time and extent to which the products of combustion can move through the building. The interaction of the building response to the fire and the actions of its occupants during a fire emergency determines the level of risk that the building design poses. Also, consideration for the safety of fire-fighting personnel responding to a building fire should be taken into account.

Property Protection. Specific items of property that have a high monetary or other value must be identified in order to protect them adequately in case of fire. In some cases, specially protected areas are needed. The establishment of fire safety objectives should ascertain whether the user of the building has property that requires special fire protection.

In some buildings, the value of the contents of a single room may be extremely high. This value may be due to the cost of highly technical equipment or unique artifacts such as art or rare books. The sensitivity of equipment and artifacts to the effects of heat, smoke, gases, or water must be addressed. In any event, the designer should protect the especially sensitive contents from products of a fire originating either inside or outside of the space.

Continuity of Operations. The maintenance of operational continuity after a fire is the third major design concern. The amount of downtime that can be tolerated before revenues are seriously affected must be identified. Frequently, certain functions or locations are more essential to the continued operation of the building than others. It is important to recognize those

areas particularly sensitive to building operations, so that adequate protection is provided for them. Often, these areas need special attention not required throughout the building. Availability of redundant or backup sites, duplicate records, and the ability to switch over to other locations can be considered in this part of the process.

Environmental Protection. Another important objective considers the impact of a fire on the environment. Problems such as runoff of chemicals housed in the building that may dissolve in fire department water need to be addressed. Waterborne or airborne products of combustion produced in buildings that house certain chemicals can affect the environment significantly.

Heritage Conservation. The preservation of heritage sites from destruction by fire is gaining worldwide importance. This involves providing a reasonable level of fire protection against damage to and loss of historic structures, their unique characteristics, and their contents. Objectives are similar to those of the preservation architect and require a design to minimize damage to historic structures or materials from fire and fire suppression while maintaining and preserving original space configurations and minimizing alteration, destruction, or loss of historic fabric or design.

Substantial renovation or modification to an historic building will often be a difficult challenge. Historic buildings, and spaces within such buildings, have a hierarchy of significance. Particularly for those historic buildings of higher significance, extraordinary attempts should be made to minimize alteration to the original space configurations and the historic design. Fire safety and fire protection features should be designed, implemented, and maintained so as to preserve the original qualities or character of the building, structure, or site.

INTRODUCTION TO THE FIRE SAFETY CONCEPTS TREE

The NFPA Fire Safety Concepts Tree, as described in NFPA 550 and illustrated in Figure 1.9.2, uses a branching diagram to show relationships of fire prevention and fire damage control strategies.

Fire safety features such as construction type, combustibility of contents, protection devices, and characteristics of occupants traditionally have been considered independently of one another. This can lead to unnecessary duplication of protection. On the other hand, gaps in protection can exist when these pieces do not come together adequately, usually as a result of lack of maintenance, modifications to construction features, or fire protection systems that take them out of compliance limits, or other circumstances that cause nonconformance, as evidenced by fire losses that continue to occur. The distinct advantage of the Fire Safety Concepts Tree is its systems approach to fire safety. The Fire Safety Concepts Tree provides an overall structure with which to analyze the potential impact of fire safety strategies. It can identify gaps and areas of redundancy in fire protection strategies as an aid in making fire safety design decisions.

The Fire Safety Concepts Tree shows the elements that must be considered in building fire safety and the interrelationship among those elements. It enables a building to be analyzed or designed by progressively moving through the various concepts in a logical manner. Its degree of success depends on how completely each level is satisfied. Lower levels on the tree, however, do not represent a lower level of importance or performance; they represent a means for achieving the next higher level. Rather than considering each feature of fire safety separately, the Fire Safety Concepts Tree examines all of them and demonstrates how they influence the achievement of fire safety objectives.

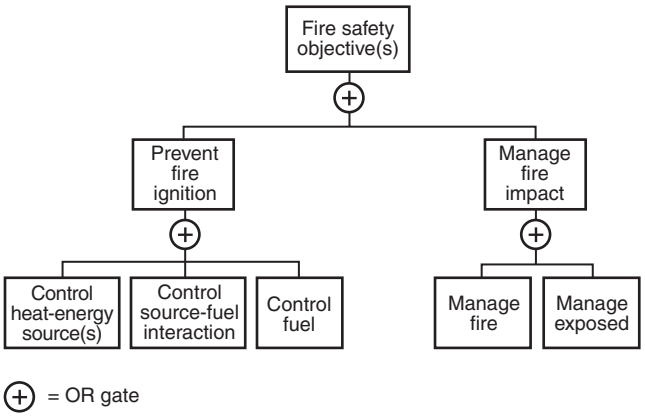

FIGURE 1.9.2 Principal Branches of the Fire Safety Concepts Tree

FIRE SAFETY CONCEPTS TREE AND FIRE SAFETY DESIGN STRATEGIES

The Fire Safety Concepts Tree provides the logic required to achieve fire safety; that is, it provides conditions whereby the fire safety objectives can be satisfied, but it does not provide the minimum condition required to achieve those objectives. Thus, according to the tree, the fire safety objectives can be met if fire ignition can be prevented or if, given ignition, the fire can be managed. This logical "OR" function is represented by the symbol (+) under fire safety objectives in Figure 1.9.2.

Evaluating a design for building fire safety represents a systematic approach to the principal fire safety strategies identified in Section 3, Chapter 1, "An Overview of the Fire Problem and Fire Protection." These strategies can be identified as follows:

1. Prevent fire ignition
2. Control combustion process
3. Control fire by construction
4. Detect fire early and provide notification
5. Automatically suppress fire
6. Manually suppress fire
7. Manage exposed (people or physical objects)

In general terms, each step represents an increase in the fire size, the areas affected, and the sophistication of the intervention or mitigation strategies necessary to control or extinguish the fire.

FIRE PREVENTION STRATEGIES

The first opportunity to achieve fire safety in a building is through fire (ignition) prevention, which involves separating potential heat sources from potential fuels. Table 1.9.1 lists common factors in fire prevention and identifies major candidate heat sources and ignitable materials, common factors that bring them together, and practices that can affect the success of prevention.

Most building fires are started by heat sources and ignitable materials that are brought into the building, not built into it. This means the design of the building, from the architect's and builder's standpoint, provides limited potential leverage on the building's future fire experience. The building's owners, managers, and occupants, however, will have numerous opportunities to reduce fire risks through prevention, and they should be urged to do so.

For design purposes, fire prevention will be enhanced by careful observance of codes and standards in the design and installation of the electrical and lighting system, the heating system, and any other major built-in equipment, such as cooking, refrigeration, air conditioning, and clothes washing and drying. Venting systems need to be designed carefully to carry carbon monoxide and potential fuels along specially designed and protected paths. These venting systems will need to be inspected and cleaned regularly.

TABLE 1.9.1 Fire Prevention Factors

1. Heat Sources
   a. Fixed equipment (including electrical energy sources)
   b. Portable equipment
   c. Torches and other tools
   d. Smoking materials and associated lighting implements
   e. Explosives
   f. Natural causes
   g. Exposure to other fires
2. Forms and Types of Ignitable Materials
   a. Building materials
   b. Interior and exterior finishes
   c. Contents and furnishings
   d. Stored materials and supplies
   e. Trash, lint, and dust
   f. Combustible or flammable gases or liquids
   g. Volatile solids
3. Factors That Bring Heat and Ignitable Material Together
   a. Arson
   b. Misuse of heat source
   c. Misuse of ignitable material
   d. Mechanical or electrical failure
   e. Design, construction, or installation deficiency
   f. Error in operating equipment
   g. Natural causes
   h. Exposure
4. Practices That Can Affect Prevention Success
   a. Housekeeping
   b. Security
   c. Education of occupants
   d. Control of fuel type, quantity, and distribution
   e. Control of heat energy sources
   f. Maintenance of electrical systems

Protection from lightning and exposure fires will affect the external design of the building, particularly in certain parts of the country, such as areas near urban/wildland interface zones. A fire in one building creates an external fire hazard to neighboring structures by exposing them to heat by radiation, and possibly by convective currents, as well as to the danger of flying brands of the fire. Any or all of these sources of heat transfer may be sufficient to ignite the exposed structure or its contents.

When considering protection from exposure fires, there are two basic conditions: (1) exposure to horizontal radiation and (2) exposure to flames issuing from the roof or top of a burning building when the exposed building is higher than the burning building. Radiation exposure can result from an interior fire where the radiation passes through windows and other openings of the exterior wall. It can also result from the flames issuing from the windows of the burning building or from flames of the burning facade itself. NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures,* provides guidelines and data on exposure protection.

Inside the building, design features may make incendiarism, arson, or other human-caused fires more or less likely by making security and housekeeping easier or harder to perform. The interaction of the design with these critical support activities should be thought through and planned into the design from the outset.

In the fire safety concepts tree, the "prevent fire ignition" branch shown as Figure 1.9.3 essentially represents a fire prevention code. Most of the concepts described in this branch require continuous monitoring for success. Consequently, the responsibility for satisfactorily achieving the goal of fire prevention is essentially an owner/occupant responsibility. The designer, however, may be able to incorporate certain features into the building that may assist the owner/occupant in preventing fires.

It is impossible to prevent completely the ignition of fires in a building. Therefore, to reach the overall fire safety objective, a high degree of success in the "manage fire impact" branch assumes a significant role. Essentially, this branch of the fire safety concepts tree may be considered as a building code by the design team. After ignition occurs, all considerations shift to the "manage fire impact" branch to achieve the fire safety objectives.

According to the logic of the tree, the impact of the fire can be managed either through the "manage fire" or "manage exposed" branches (see Figure 1.9.2). The "OR" (+) gate indicates that the objectives may be reached through either or both design branches, as long as the avenue selected completely satisfies the fire safety objective. Naturally, it is acceptable to do both, which will increase the likelihood of success over using one branch only.

Through the "manage fire" branch, the fire safety objectives can be achieved by managing the fire itself. Figure 1.9.4 shows

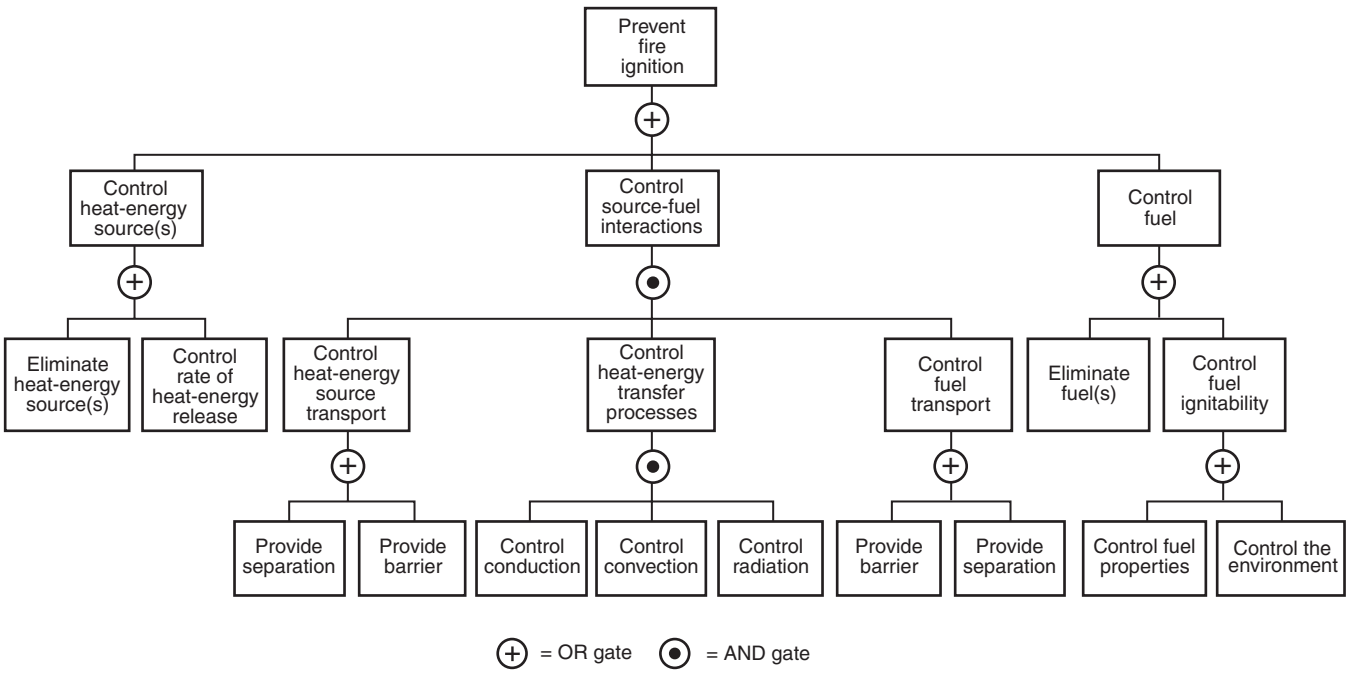

FIGURE 1.9.3 Prevent Fire Ignition Branch of the Fire Safety Concepts Tree

that this can be accomplished by: (1) controlling the combustion process, (2) suppressing the fire, or (3) controlling the fire by construction. Here, again, any one of these branches of the tree will satisfy the "manage fire" concept. In other words, sometimes success is achieved by the building construction controlling the fire, whereas other times success is from controlling the combustion process—through control of the fuel, the environment, or both.

CONTROL STRATEGIES

Combustion Process Control

The concern here is to slow the fire and provide other fire safety measures sufficient time to be effective. A systematic design for this purpose should address the possible ways that a specific quantitative hazard can grow rapidly—for example, flame spread rate, rapid growth in rate of heat release or rate of mass release, unusually toxic gases, unusual corrosivity, quantity of fuel available to feed the fire, and so forth. Each of these can be evaluated separately in terms of the threat to exposed people, property, and mission of the building.

In a building fire, the most common hazard to humans is from smoke and toxic gases. Most building-related fire deaths are directly related to these products of combustion. Death often results from oxygen deprivation in the bloodstream, caused by the replacement of oxygen in the blood hemoglobin by carbon monoxide. In addition to the danger of carbon monoxide, many other toxic gases present in building fires cause a wide range of symptoms, such as headaches, nausea, fatigue, difficult respiration, confusion, and impaired mental functioning.

Smoke, in addition to incorporating toxic and irritant gases, contributes indirectly to a number of deaths. Dense smoke obscures visibility and irritates the eyes and can cause anxiety and emotional shock to building occupants. Consequently, the occupant may not be able to identify escape routes and utilize them. Although heat injuries do not compare in quantity to those caused by inhalation of smoke and toxic gases, they are painful, serious, and cause shock to victims. In addition to deaths from thermal products of combustion, the pain and disfigurement caused by nonfatal burns can result in serious long-term physical and psychological complications.

Property also is affected by the thermal and nonthermal products of combustion, as well as by extinguishing agents. Smoke may damage goods located long distances from the effects of the heat and flames. Fires that are not extinguished quickly often result in considerable water damage to the contents and the structure, unless special measures are incorporated to prevent that damage. It should be noted, however, that the water damage caused in extinguishing a fire rarely exceeds the fire damage resulting from a fire that is not suppressed.

Fast flame spread over interior finish materials or building contents and vertical propagation of fire are serious concerns. The ability of the fire service to contain or extinguish a fire is diminished significantly if the fire spreads vertically to two or more floors. With a given potential for fire growth, the prevention of vertical fire spread is influenced principally by architectural and structural decisions involving details of compartmentation, which are discussed later.

Designing Countermeasures to Fire Growth

The building fire safety system can be organized around fire growth and its resulting products of combustion. The ease of generation and movement of these products is influenced

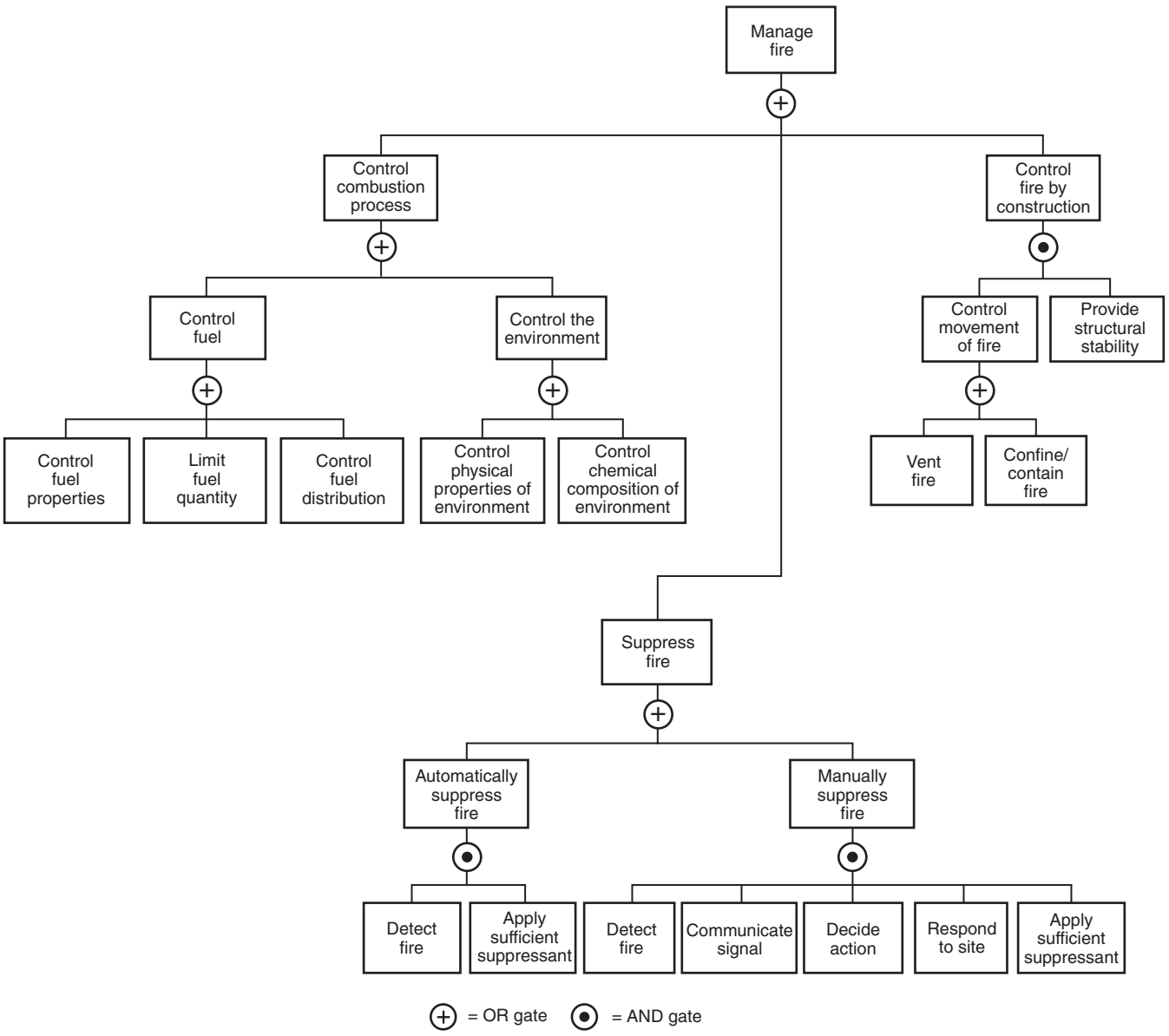

FIGURE 1.9.4 Manage Fire Branch of the Fire Safety Concepts Tree

by the countermeasures provided by the building. The effectiveness of the building fire safety systems determines the rate, quantity, and paths of movement of these products of combustion.

The speed and certainty of fire growth and development in rooms can vary greatly. The contents and interior finish in some rooms are quite safe, and, for this type of situation, it is unlikely that, once ignited, a fire can grow to full involvement of the room. On the other hand, the interior design of other rooms poses a high hazard which, if an ignition were to occur, could lead to an almost certain full room involvement when fixed fire suppression systems are not present.

The traditional method of describing the fire growth hazard has been through fire loads reflected in use and occupancy classifications. Building types, rather than rooms within buildings, have been grouped with regard to their relative hazard. A warehouse containing products that are essentially noncombustible would be considered low-hazard. Residential and educational occupancies are considered ordinary-hazard because they normally contain relatively small amounts of combustibles in the rooms. Mercantile buildings are also ordinary-hazard, even though they typically contain more fuel than other occupancies. Certain industrial and storage buildings may be considered high-hazard because they contain a high fuel load that includes materials that are flammable or even explosive.

Hazard classification is a basis for building and fire code requirements, and, historically, it has been quite useful. However, a more detailed look at the fire growth potential within the rooms of a building can be a valuable part of a detailed fire safety design. The fire growth hazard potential, which identifies

the speed and relative likelihood of a fire reaching full room involvement, is a useful base from which to design suppression interventions and to evaluate life safety problems. For example, situations in which fast moving, severe fires will occur may call for automatic sprinkler protection, even though it may not be required by a building or fire code.

The basis for a fire growth hazard analysis is the combustion potential in a room. Four main factors influence the likelihood and speed with which full room involvement occurs: (1) fuel load (i.e., the quantity and type of materials and their distribution); (2) interior finish of the room; (3) air supply; and (4) size, shape, and construction of the room.

Fire development in a room is neither uniform nor a guaranteed progression from ignition to full room involvement. Fires develop through several stages, sometimes called realms. Table 1.9.2 provides guidance on descriptions of the realms. Within any realm a fire may continue to grow or it may be unable to sustain continued development and die down. Table 1.9.2 includes a rough guide to the approximate flame sizes that may be used to describe the fire size of the realms. It also describes the major factors that influence growth within a realm. Absence of a significant number of the factors would indicate that the fire would self-terminate, rather than continue to develop.

Different rooms pose different levels of risk regarding the likelihood of reaching full room involvement and the time in which fire development takes place. Table 1.9.2 provides a general guide to the important factors.

If one were to focus on a single event that might be used to represent the relative level of hazard posed by the contents and interior finish in a room, it would be the ability of flames to reach the ceiling. The arrangement of contents and types of fuels where it would be difficult for a fire to grow to touch the ceiling pose a relatively low fire growth hazard potential. On the other hand, where furniture combustibility and density will allow a fire to develop to ceiling height, or when combustible interior finish is present, the fire growth hazard potential usually is comparatively high.

Controlling Fire by Construction

One of the most important aspects of fire-safe building design is basic construction. The structural framing and assemblies will typically endure for the life of the building whereas utilities, finishes, and contents may change over time. The aspects of building construction that influence fire safety are the inherent barriers to fire spread and the ability to avoid collapse in a fire.

Barriers. Walls, partitions, and floors separate building spaces. These barriers also delay or prevent fire (and sometimes products of combustion) from propagating from one space to another. In addition, barriers are important features in any fire-fighting operation.

The effectiveness of a fire barrier is dependent on its inherent fire resistance, the details of construction, and any penetrations, such as doors, windows, ducts, pipe chases, electrical raceways, and grilles. Although the hourly ratings of fire endurance do not always represent the actual time that the barrier can withstand a building fire, unpenetrated rated barriers seem to perform rather well. This may be due to the rather large factor of safety inherent in the codes. On the other hand, it is quite common for rated barriers to fail because of inattention to penetrations. For example, the fire resistance of a rated floor-ceiling assembly can be voided because of large or numerous pokethroughs. The fire resistance of a rated partition is lost when a door is left open.

Fire resistance requirements imposed by the regulatory system often have comparatively little meaning because of inattention to the functional and construction details. The myriad of tested and fire-rated assemblies provide extensive detail on not only construction of the assembly, but also on the process by which to manage and deal with most types of penetration in the assembly. To predict field performance of barriers, the penetrations and details of construction must be considered in addition to the fire endurance of the base construction.

TABLE 1.9.2 Major Factors Influencing Fire Growth

Realm	*Approximate Ranges of Fire Sizes*	*Major Factors that Influence Growth*
1. Preburning	Overheat to ignition	Amount and duration of heat flux, surface area receiving heat, material ignitability
2. Initial burning	Ignition to radiation point (10 in. [254 mm] high flame)	Fuel continuity, material ignitability, thickness, surface roughness, thermal inertia of the fuel
3. Vigorous burning	Radiation point to enclosure point (10 in. to 5 ft [254 mm to 1.5 m] high flame)	Interior finish, fuel continuity, heat feedback, material ignitability, thermal inertia of the fuel, proximity of flames to walls
4. Interactive burning	Enclosure point to ceiling point (5 ft [1.5 m]) high flame to flame touching ceiling	Interior finish, fuel arrangement, heat feedback, height of fuels, proximity of flames to walls, ceiling height, room insulation, size and location of openings, HVAC operation
5. Remote burning	Ceiling point to full room involvement.	Fuel arrangement, ceiling height, length/width ratio, room insulation, size and location of openings, HVAC operations

The major function of fire barriers is to prevent heat and flame spread from causing an ignition in an adjacent room or floor. It is useful to classify barrier failure in two categories. One is a massive barrier failure, which would occur when a part of the barrier collapses or when a large penetration, such as a door or a large window, is open. When a massive failure occurs, the adjacent space can become fully involved in a short period of time. The second type of failure is a localized penetration failure. This occurs when flames or heat penetrates small poke-throughs or small windows. A localized penetration failure causes a hot spot to occur which can lead to ignition of combustibles on the other side of the barrier. This was a common mode of fire propagation between floors in the February 1991 Meridian Plaza fire in Philadelphia, Pennsylvania.

Smoke and gases move through a building much faster and more easily than flames and heat. The time duration from ignition until a building space is untenable is an important aspect of fire safety, and the loss of tenability may be due to smoke and gases more often than flames and heat. Therefore, smoke barriers are also important components for controlling the effects of fire. In addition to its value as a means of containing the fire, compartmenting the interior building space also addresses specific needs for protection, such as structural integrity of the building and escape routes.

Structural Collapse. Failure of structural building elements can be a serious life safety hazard. Although prior to the World Trade Center it had not resulted in many deaths or injuries to building occupants, structural collapse has long been a hazard to fire fighters. A number of deaths and serious injuries to fire fighters occur each year because of structural failure. Although some of these failures result from inherent structural weaknesses, many are the result of renovations to existing buildings that materially, though not obviously, affect the structural integrity of the support elements. A building should not contain surprises of this type for fire fighters.

The potential for structural collapse must be determined. Building codes address this through construction classification requirements. The relationship between fire severity and fire resistance to collapse are the principal factors. Collapse can occur when the fire severity exceeds the fire endurance of the structural frame. However, this is comparatively rare. Structural collapse is more commonly associated with deficiencies in construction. These deficiencies are not evident under normal everyday use of the building. They become a problem when the fire weakens supporting members, triggering a local or global collapse.

The National Institute of Standards and Technology (NIST), working with industry experts, has prepared a comprehensive document that provides guidelines for owners and design professionals to help prevent progressive collapse of buildings in the event of certain abnormal loading conditions.[3] The document includes such topics as acceptable risk approach to progressive collapse mitigation and practical means for reducing the risk for new and existing buildings.

In the Fire Safety Concepts Tree, when considering the "control fire by construction" concept, structural integrity must be provided, and the movement of the fire itself must be controlled. As shown in Figure 1.9.4, this can be accomplished either by venting, confining, or containing the fire.

FIRE DETECTION AND ALARM STRATEGIES

Fire Detection Provisions

Fire detection provisions are needed so that automatic or manual fire suppression will be initiated, any other active fire protection systems will be activated (e.g., automatic fire doors for compartmentation and protection of escape routes), and occupants will have time to move to safe locations, typically outside the building.

One reason for concern over any rapid initial fire growth is that it can shrink the time available after detection for these life- and property-saving responses. Therefore, detection provisions must be designed systematically to reflect the building's other features, its occupants, and its other fire safety features.

For example, smoke is often the first indicator of fire, so a system of automatic detection based on smoke detectors often makes sense. In certain properties or areas, however, detectors based on heat or rate of increase in heat may be more appropriate based on the types of fires likely to occur in those areas or the potential for nonfire activations from environmental conditions. Whatever type of detection system is chosen, it is important that, for each area of the building, a realistic assessment be made of the implications for response time after the fire is detected and before a lethal or other high-hazard condition develops.

Alarm Provisions

Alarm provisions need not be linked to the detection sensor locations, but should be designed systematically to tell occupants what they need to do, based on where they are and their ability to respond. This would include the possible use of central annunciator panels and monitors to inform responsible staff, voice messages to provide instructions on occupant movements, and direct remote alarms to supervised stations or fire departments. All of these options will have an impact on the time available for some type of response and, possibly, on the efficiency of that response. A timeline can be constructed to provide a quantitative base for analysis and design of this and related building fire safety features.

SUPPRESSION STRATEGIES

Automatic Suppression

From the Fire Safety Concepts Tree, the "suppress fire" event and its branches are shown in Figure 1.9.4. In this figure, the symbol (•) represents a logical "AND" gate, and signifies that all of the elements in the level immediately below the gate are necessary to achieve the concept above the gate. To accomplish automatic suppression, for example, both concepts, that is, detecting the fire and applying sufficient suppressant, are

necessary. Similarly, to manually suppress the fire, five requirements must occur. The omission of any single concept is sufficient to break the chain and cause the failure of suppression to manage the fire.

For nearly a century and a half, automatic sprinklers have been the most important single system for automatic control of hostile fires in buildings. Many desirable aesthetic and functional features of buildings that might offer concern for fire safety because of the fire growth hazard can be protected by the installation of a properly designed sprinkler system. Among the advantages of automatic sprinklers is the fact that they operate directly over a fire and are not affected by smoke, toxic gases, and reduced visibility. In addition, much less water is used because only those sprinklers fused by the heat of the fire operate, particularly if the building is compartmented. Other automatic extinguishing systems, such as water mist, carbon dioxide, dry chemical, clean (halon replacement) agents, and high-expansion foam, may be used to provide protection for certain portions of buildings, specific hazards, or types of occupancies for which they are particularly suited.

An automatic sprinkler system has been the most widely used method of automatically controlling a fire. The major elements for determining the effectiveness of an automatic sprinkler system are (1) its presence or absence; (2) if present, its reliability; and (3) if reliable, its design and extinguishing effectiveness. Although automatic sprinkler systems have a remarkable record of success, it is possible for the system to fail. Often failure is due to a feature that could have been avoided if appropriate attention had been given at the time of the system's design, installation, or maintenance. Table 1.9.3 describes common failure modes and their causes. During the design stages, these factors should be addressed to increase the probability of successful extinguishment by the sprinkler system.

Manual Suppression

The protection offered by a community fire department has an important influence on building fire design. Some buildings are designed in a manner that helps the fire department extinguish fires while they are small; others are designed in a manner that hinders a fire department. Rarely does the designer consciously design the building for fire department emergency operations. The following discussion provides some guidelines for building design to enhance the building's ability to allow the fire department to extinguish a fire with minimal threat to life (including the lives of the first responders) and property.

Ideally, a building is designed so that should a fire occur, it can be attacked before it extends beyond the room of origin. If

TABLE 1.9.3 Common Automatic Sprinkler Failure Modes

Failure Mode	*Potential Causes*
Water supply valves are closed when sprinkler operates.	Valve supervision is inadequate. Owner's attitude is lackadaisical. Maintenance policies are not effective.
Water does not reach sprinkler.	Dry pipe accelerator or exhauster malfunctions. Pre-action system malfunctions. Maintenance and inspection are inadequate.
Sprinkler fails to open when expected.	Fire rate of growth is too fast. Response time and/or temperature of thermal element are inappropriate for the area protected. Sprinkler thermal element is protected from heat. Sprinkler thermal element is painted, taped, bagged, or corroded. Sprinkler skips.
Water cannot contact fuel. (Note: The intent of this failure mode is to ensure that discharge is not interrupted in a manner that will prevent fire control by a sprinkler.)	Fuel is protected. High-piled storage is present. New construction (walls, ductwork, ceilings) obstructs water spray.
Water discharge density is not sufficient.	Discharge needs are insufficient for the type of fire and the rate of heat release. Change in combustible contents occurs. Number of sprinklers open is too great for the water supply. Water pressure is too low. Water droplet size is inappropriate for the fire size.
Enough water does not continue to flow.	Water supply is inadequate because of original deficiencies, changes in water supply, or changes in the combustible contents. Pumps are inadequate or unreliable. Power supply malfunctions. System is disrupted.

that is not possible, the building design and construction features should retard fire spread so that the fire department will encounter a relatively small, easily controllable fire. The major aspects of this part of building design include (1) fire department notification, (2) initial agent application, (3) fire extinguishment, (4) ventilation, (5) water supply, and (6) barriers. These aspects are discussed briefly to provide guidance for incorporating features into the building that enable departments to be more effective and less harmful to the building. The importance of fire barriers was discussed in a previous section.

Fire Department Notification. The complete chain of events—that is, (1) detection of the fire, (2) decision to inform the fire department, (3) sending of the message, and (4) correct receipt of the information by the fire department—should be a part of every building fire safety design. It should be consciously designed, rather than left to chance. The time available from detection until agent application is very dependent on the speed of fire spread. Buildings have been lost from insufficient attention to the method of notifying the local fire department.

Agent Application. The next critical event is fire department application of agent to the fire. This involves three distinct events for its success: (1) arrival at the site, (2) nozzle entrance into the room, and (3) water discharge from the nozzle. Each of these events can be affected by site or building access considerations in the design, as well as training and resource levels on the fire ground.

Ideal exterior accessibility occurs where a building can be approached from all sides by fire department apparatus. This is not always possible. In congested areas, only the sides of buildings facing streets may be accessible. In other areas, topography or constructed obstacles can prevent effective use of apparatus in combating the fire. Buildings located some distance from the street can make the approach of apparatus difficult. If obstructions or topography prevent apparatus from being located close enough to the building for effective use, fire-fighting equipment—for example, aerial ladders, elevating platforms, and water tower apparatus—are rendered useless. Valuable time and labor must be expended to hand carry hose lines or ground ladders long distances.

The matter of access to buildings has become far more complicated in recent years, especially in light of the movement to secure buildings against possible terrorist attacks by establishing vehicle standoff distance criteria that precludes proximate vehicle access. The building designer must consider this important aspect in the planning stage. Inadequate attention to site details can place the building in an unnecessarily vulnerable position. If preventing adequate fire department access compromises its fire defenses, the building must compensate with more complete internal building protection. The arrival at the site is only a part of the agent application evaluation. The fire fighters then must be able to enter the building, reach the floor of the fire, and find the involved room or rooms. This is often a time-consuming, difficult task, especially in a high-rise environment. Considerable attention must be given to the problem of finding the fire and getting fire fighters and equipment to the fire.

Access to the interior of a building can be greatly hampered where large areas exist and where buildings have blank walls, false facades, solar screens, or signs covering a high percentage of exterior walls. Obstacles that prevent ventilation allow smoke to accumulate and obscure fire fighters' vision. Lack of adequate interior access also can delay or prevent fire department rescue of trapped occupants.

Windowless buildings and basement areas present unique fire-fighting problems. The lack of natural ventilation features such as windows contributes to the buildup of dense smoke and intense heat, which hamper fire-fighting operations. Fire fighters must attack fires in these spaces despite heat and smoke. This can result in lengthy times for fire extinguishment and greater damage by the products of combustion.

Fire Extinguishment. After the time-consuming and sequential events of notification and initial agent application have transpired, the fire department is ready to fight the fire. The size of fire present at the time of initial agent application determines the fire-fighting strategy and likelihood of success of the operation.

Broadly speaking, there are three types of fires. Comparatively small fires may be extinguished by direct application of water. When the fire is larger than can be directly extinguished, the building is opened (ventilated), and the hose streams drive the fire, heat, and smoke out of the building. Third, fires that are too large for this operation must be surrounded. In this last case, all available techniques of ventilation and heat absorption by water evaporation are used; however, the fire area is lost, and the main purpose of this strategy is to protect exposures, both external and internal.

Ventilation. Ventilation is an important fire-fighting operation. It involves the removal of smoke, gases, and heat from building spaces. Ventilation of building spaces performs the following important functions:

1. Protection of life by removing or diverting toxic gases and smoke from locations where building occupants must find temporary refuge.
2. Improvement of the environment in the vicinity of the fire by removal of smoke and heat. This enables fire fighters to advance close to the fire to extinguish it.
3. Control of the spread or direction of fire by setting up air currents that cause the fire to move in a desired direction. In this way, occupants or valuable property can be more readily protected.
4. Provision of release for unburned, combustible gases before they develop a flammable mixture, thus avoiding a backdraft or smoke explosion.

The building designer should be conscious of these important functions of fire ventilation and provide effective means of facilitating venting practices whenever possible. This may involve access panels, movable windows, skylights, or other means of readily opened spaces in case of a fire emergency. Emergency controls on the mechanical equipment or inclusion of an engineered smoke-control system may also be an effective means of accomplishing the functions of fire ventilation. Each building

has unique features, and, consequently, a unique solution should be incorporated into the design.

Water Supply. Water is the principal agent used to extinguish building fires. Although other agents may be employed occasionally (e.g., carbon dioxide, dry chemical, foams and surfactants, and clean Halon agent replacements), water remains the primary extinguishing agent of the fire service. Consequently, the building designer should anticipate the needs of both the fire department and automatic extinguishing systems and provide an adequate supply of water at adequate residual pressure.

Water normally is supplied to the building site by mains that are part of the water distribution system. Few cities can supply a sufficient amount of water at required pressures to every part of the city. Buildings that do not have an adequate, reliable water source for fire fighting must either provide supplemental water or incorporate other fire defense measures to compensate for this deficiency. Careful attention must be given to water supply, distribution, and pressure for fire emergencies. High-rise buildings are particularly sensitive in this respect because the water pressures required depend on building height. The water supply needs of large buildings must also be given careful attention.

Fire conditions that require operation of a large number of sprinklers or use of a large number of hose streams can reduce pressure in standpipe and sprinkler systems to the point where residual pressures in the distribution system are adversely affected. Fire department connections for sprinkler and standpipe systems are important components of building fire defenses. The building designer must carefully consider installation details of fire department connections to make sure they will be easily located, readily accessible, and properly marked. Locations should be approved by the local fire department.

MANAGING THE EXPOSED

As shown in Figure 1.9.5 from the Fire Safety Concepts Tree, fire impact can be lessened by managing the "exposed," that is, people, property, operations, environment, or heritage, depending on the design aspects being considered. In considering the "manage exposed" branch, success can be achieved either by limiting how much is exposed or by safeguarding the exposed. For example, the number of people as well as the amount or type of property in a space may be restricted. Often, this is impractical. If such is the case, the objectives can still be met by incorporating design features to safeguard the exposed.

The exposed people or property may be safeguarded either by moving them to a safe area of refuge or by defending them in place. For example, people in institutional occupancies, such as hospitals, nursing homes, or prisons, must generally be defended in place. To do this, the "defend exposed in place" branch shown in Figure 1.9.4 would be considered. On the other hand, alert, mobile individuals, such as in offices or schools, could be moved to safeguard them from fire exposure on either a short-term or long-term basis, depending on other key design

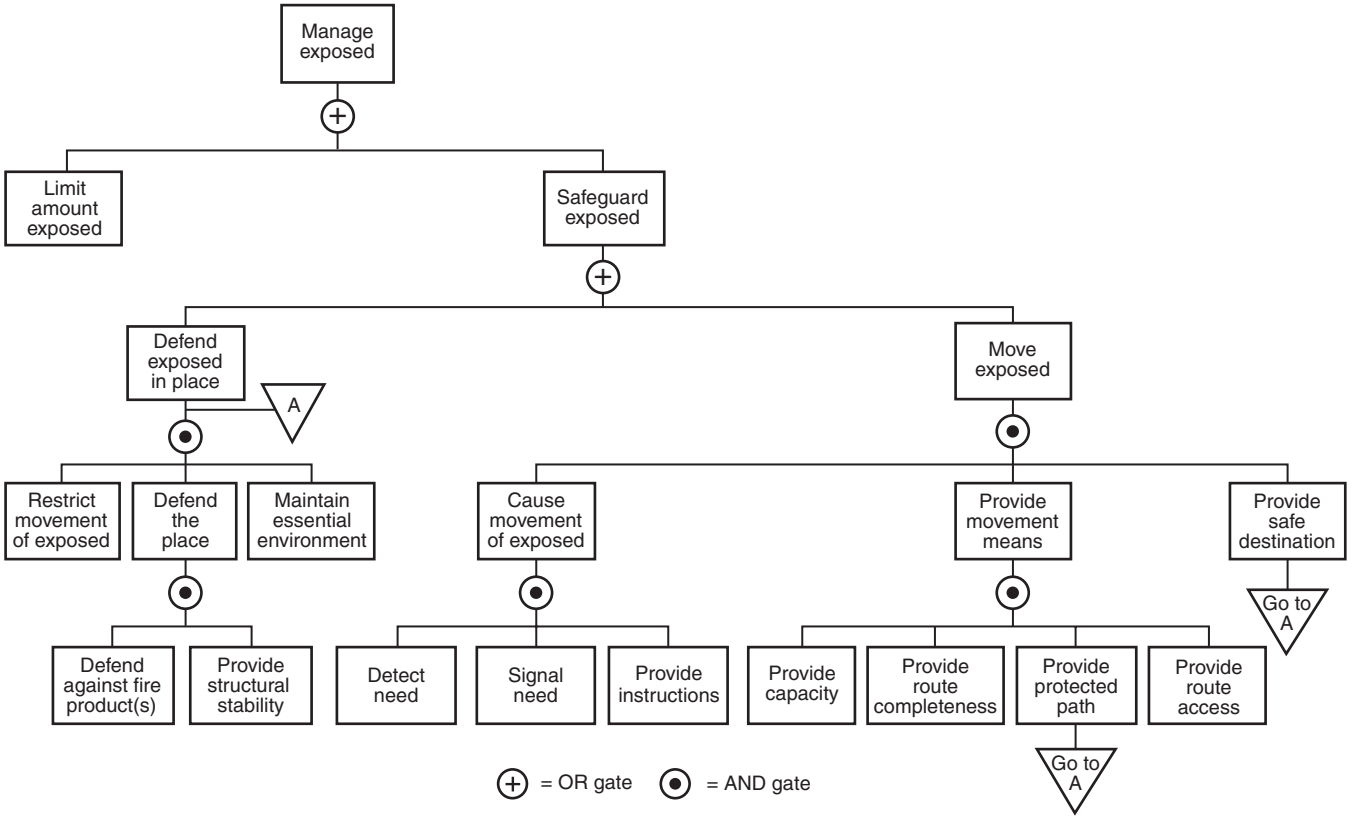

FIGURE 1.9.5 Manage Exposed Branch of the Fire Safety Concepts Tree (∇ = transfer/entry point)

elements. Strategies in high-rise buildings fall in between these two concepts. Occupants from the fire floor, the floor above, and the floor below are normally instructed to relocate to a lower floor and wait for the emergency to pass. Figure 1.9.5 illustrates the concepts that must be satisfied to meet fire safety objectives for exposed property and people.

The design for life safety may involve one or a combination of the following three alternatives: (1) evacuation of the occupants, (2) defending the occupants in place, or (3) providing an effective area of refuge or temporary shelter in place location. These alternatives can be evaluated by the likelihood that the building spaces will be tenable for the period of time necessary to achieve the expected level of safety. The criteria for tenability, therefore, become an important part of the design.

Evacuation

The design for building evacuation involves two major components: (1) availability of an acceptable path or paths for escape, and (2) effective alerting of the occupants in sufficient time to allow egress before segments of the path of egress become untenable.

Alerting occupants to the existence of a fire is a vital part of the life safety design. A useful performance objective could be to ascertain that occupants have adequate time to escape from fire before the escape route becomes blocked. To accomplish this, the designer either must ensure that the fire and the movement of its products of combustion will be slow enough to provide that time or incorporate special provisions into the building to achieve that objective.

Defending in Place

The second life safety design alternative is to defend the individual in place. This may be appropriate for occupancies such as hospitals, nursing homes, prisons, and other institutions. It may be an appropriate alternative for other buildings when the size or design may show that evacuation has an unacceptably low likelihood of success. Defend-in-place design also uses performance criteria of time and tenability levels. The performance criteria relating to time might state that the building space should be tenable for a sufficient period of time after the start of the fire. This duration could be longer than the duration of any expected fire. The definition of tenability may be quite different from that acceptable for evacuation because of the influence of both time and the products of combustion.

Refuge

The third alternative is to design for an area of refuge. In this context, the area of refuge under consideration is different from the area of refuge that is associated with accessible means of egress. This alternative involves occupant movement through the building to specially designed refuge spaces. This type of design is more difficult than either of the other two alternatives because it involves major design aspects of each. In certain types of buildings this may be a reasonable alternative. However, an evaluation of the effectiveness of the area of refuge design and its likelihood of success are extremely important.

The effectiveness of defending in place and areas of refuge may depend on the rescue capabilities of the local fire department or other emergency response service. Although traditional building codes do not address this issue, it is an important consideration in design of fire safe spaces.

Life safety design for a building is difficult. It involves more than a provision for emergency egress. It must also address the population who will be using the building and what they will be doing most of the time. Likewise, it is important to keep in mind that these same egress routes must also be robust enough to be used for "other than fire" events. Bomb threats, power failures, and release of chemical or biological agents can all initiate a phased or total building evacuation. Consideration must then be given to communication, the protection of escape routes, and temporary or permanent areas of refuge for a reasonable period of time for the building occupants to achieve safety.

Even occupants familiar with their surroundings often experience difficulty in locating means of egress. The problem is compounded for transients and occasional visitors to the building. Architectural layout and normal circulation patterns are important elements in emergency evacuation. For example, many large office buildings are a maze of offices, storage areas, and meeting rooms. Clearly marked emergency travel routes can enhance life safety features in all buildings.

Special attention to the needs of the disabled community must also be considered. Operational strategies and protocols, plus use of new technologies such as directional exit sounders should be considered.

SUMMARY

The Fire Safety Concepts Tree can be employed effectively in building design. If the architect incorporates the tree during the preliminary planning phase of design, many important decisions and alternatives can be defined more effectively. For example, decisions can be made regarding evacuation versus temporary refuge, including implications on the functions of the building. Specific needs with regard to design decisions are then recognized.

The tree also provides for the separation of the functions of fire prevention and building design. In this way, the responsibilities of the owner/occupant can be differentiated from those of the building design team. Those concepts that are eventually incorporated into the design can be identified with a specific member of the building design team.

This chapter describes in general terms the processes required to create such a design. More specific guidance requires joining the general processes described here with the more detailed guidance in later chapters on specific fire safety strategies. Building codes and NFPA standards are important factors in building design, and the Fire Safety Concepts Tree should not supersede them. Rather, the tree enables those documents to be interrelated and, consequently, used more effectively.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the fundamentals of fire-safe building design discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code*™
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 22, *Standard for Water Tanks for Private Fire Protection*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 70, *National Electrical Code*®
NFPA 72®, *National Fire Alarm Code*®
NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Areas*
NFPA *101*®, *Life Safety Code*®
NFPA 101A, *Guide on Alternate Approaches to Life Safety*
NFPA 220, *Standard on Types of Building Construction*
NFPA 221, *Standard for High Challenge Fire Walls, Fire Walls, and Fire Barrier Walls*
NFPA 232, *Standard for the Protection of Records*
NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations*
NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*
NFPA 550, *Guide to the Fire Safety Concepts Tree*
NFPA 909, *Code for the Protection of Cultural Resource Properties—Museums, Libraries, and Places of Worship*
NFPA 914, *Code for Fire Protection of Historic Structures*
NFPA 1142, *Standard on Water Supplies for Suburban and Rural Fire Fighting*
NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs*
NFPA 5000®*, Building Construction and Safety Code*®

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SECTION

2

Basics of Fire and Fire Science

Ronald L. Alpert

2.1 Physics and Chemistry of Fire
2.2 Physics of Fire Configuration
2.3 Flammability Hazard of Materials
2.4 Dynamics of Compartment Fire Growth
2.5 Basics of Fire Containment
2.6 Fundamentals of Fire Detection
2.7 Theory of Fire Extinguishment
2.8 Explosions

Effective fire protection relies not just on applying rules, but on understanding the physical science of fires and explosions. Section 2, in covering the basics of fire science, provides a snapshot of this technical foundation for fire protection systems and practice. Although it is the most technical of the 21 sections of the *Fire Protection Handbook®*, this section is nonetheless only a beginning of the physical science of fire protection. Readers needing more in-depth treatment are encouraged to consult the *SFPE Handbook of Fire Protection Engineering.*

In addition to discussing the various mechanisms of heat transfer, Chapter 1, "Physics and Chemistry of Fire," deals with the physical structure of the flame, the chemistry of flame reactions, and how these influence the composition of the combustion effluents. Changes in fire characteristics, such as flame orientation, flame heat transfer, and flame spread propensity, are discussed in a new Chapter 2, "Physics of Fire Configuration." The importance of configuration lies in the fact that, for a wide range of synthetic and natural polymer fuels and for combustible surface critical dimensions greater than the order of 1 m, the configuration of the combustible surface(s) determines a fire's characteristics.

Chapter 3, "Flammability Hazard of Materials," is also new to this edition. This chapter provides the physical basis for and a description of test methods by which the ignitability, heat release rate, flame spread propensity, smoke yield, and extinguishability components of flammability hazard are measured or characterized for solid combustibles.

The purpose of Chapter 4, "Dynamics of Compartment Fire Growth," is to provide a basic understanding of fire growth in enclosed spaces, from the time when burning is first established to the time when the fire involves the entire compartment and the burning rate is controlled by airflow into and out of the compartment's ventilation openings.

Chapters 5 through 7 provide the science that underlies fire protection strategies. Chapter 5, "Basics of Fire Containment," discusses the engineering basis for code provisions pertaining to structural fire resistance and related furnace test methodology and includes some fundamental concepts related to exterior fire spread and how this can be prevented by providing a safe separation distance. Chapter 6, "Fundamentals of Fire Detection," offers a simplified review of fire development in the context of detection and also covers fire signatures and detectable phenomena, thus setting the scene for Section 14, "Detection and Alarm." Chapter 7, "Theory of Fire Extinguishment," covers various physical mechanisms for affecting the combustion process with water and other agents. (Those mechanisms are treated in much more detail in Section 16, "Water-Based Fire Suppression Equipment," and Section 17, "Fire Suppression Systems and Portable Fire Extinguishers.")

The section closes with Chapter 8, "Explosions," which covers that specialized topic through a discussion of various types of explosions, energies released, peak pressures produced, and resulting blast waves.

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Chapter 1

Physics and Chemistry of Fire

Revised by
Dougal Drysdale

Chapter Contents

Heat Transfer
Flame Structure
Fire Chemistry
Chemical Reactions in Flames
Burning of Solids and Liquids

Key Terms

endothermic reaction, exothermic reaction, flame (diffusion), flame (premixed), gasification, heat (units of), heat flux, heat transfer, latent heat, mass flux, specific heat, Stefan-Boltzman constant, stoichiometric combustion, temperature (units of)

Fire is a complex process that involves many interactions between chemical and physical processes. The fundamentals are discussed in this chapter and interactions are identified when relevant. Some of these interactions are illustrated in Figure 2.1.1.

This simplified model of a burning surface shows how the flow of fuel vapors is maintained by heat transfer from the flames to the surface. The maximum rate of burning (as a mass flux, $\dot{m}''$) will be achieved when a steady-state condition is reached, as expressed by the following formula:

$$\dot{m}'' = \frac{\dot{Q}''_{\text{flame}} - \dot{Q}''_{\text{loss}}}{L_g} \text{ kg/sec} \quad (1)$$

where $\dot{Q}''_{\text{flame}}$ is the heat flux from the flame to the surface (kW/m^2), $\dot{Q}''_{\text{loss}}$ is the heat loss from the surface (kW/m^2) expressed as a flux through the surface, and L_g is the heat of gasification (kJ/kg). This formula and Figure 2.1.1 contain the essence of our understanding of fire and fire behavior—specifically, the role of heat transfer in determining the burning process.

In addition to discussing the various mechanisms of heat transfer, this chapter will deal with the physical structure of the flame, the chemistry of flame reactions, and how these reactions influence the composition of the combustion effluents. The physics of ignition and their relationship to the combustibility of materials are dealt with in Section 2, Chapter 2, "Physics of Fire Configuration." The processes that take place within flames are the source of smoke and hot fire products that flow from the seat of the fire, perhaps forming a ceiling layer that will contain smoke and toxic species and act as a source of radiant heat, which will promote the spread of fire beyond the items first involved (Section 2, Chapter 4, "Dynamics of Compartment Fire Growth"). The composition of the layer will determine the toxicity of the smoke that may spread throughout a building, and the reactions will promote the formation of particulate soot, which is the precursor of smoke. Predicting the amount of smoke that may be produced in a fire is almost impossible. Nevertheless, we can identify features of material properties, which will influence the yield of smoke, and indeed influence the rate at which fire will develop. These issues will be discussed in the following sections.

See also the following chapters in Section 2: Chapter 2, "Physics of Fire Configuration"; Chapter 3, "Flammability Hazard of Materials"; Chapter 4, "Dynamics of Compartment Fire Growth"; Chapter 7, "Theory of Fire Extinguishment"; and Chapter 8, "Explosions"; and various chapters in Section 6, "Characteristics of Materials and Products," including Section 6, Chapter 15, "Explosives and Blasting Agents."

HEAT TRANSFER

In considering many fire problems, it is common to think in terms of temperatures, such as the ignition temperature of a combustible solid, the softening points of thermoplastics, and the temperature

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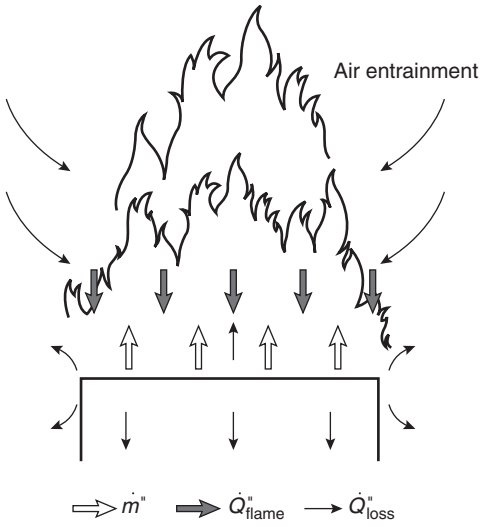


FIGURE 2.1.1 Diagram of a Burning Surface

of structural steel at which there has been sufficient weakening to cause concern. However, this view is too simplistic—it is much more important to consider how these temperatures are achieved as a result of heat transfer. Indeed, it is no exaggeration to say that heat transfer governs all aspects of fire, from ignition through to the fully developed fire and beyond to the failure of structural elements.

Heat transfer is driven by temperature difference: heat always flows from higher to lower temperatures. Before considering the various mechanisms of heat transfer, it is important to review the basic terms used, including the concept of temperature itself.

Temperature Units

Celsius. A Celsius (or centigrade) degree (°C) is 1/100th of the difference between the temperature of melting ice and boiling water at standard atmospheric pressure (101.3 kPa). On the Celsius scale, zero (0°C) is defined as the melting point of ice, and 100°C as the boiling point of water. The Celsius unit is approved by the International System (SI) of units.

Kelvin. A Kelvin degree or Kelvin (K) is the same size as the Celsius degree but the zero on the Kelvin scale is –273.15°C. Zero on the Kelvin scale is the lowest achievable temperature, known as "absolute zero"; thus, the Kelvin scale provides us with so-called *absolute temperatures*. The Kelvin is an approved SI unit. When expressing the units of a property such as specific heat, K is commonly used to indicate "degree" whether the Kelvin or Celsius scale is being referred to in the text. For example, the units of heat capacity are kJ/kg·K.

Fahrenheit. A Fahrenheit degree (°F) is 1/180 of the difference between the temperature of melting ice and boiling water at standard atmospheric pressure (101.3 kPa). On the Fahrenheit scale, the melting point of ice (0°C) is taken as 32°F; thus, 212°F is the boiling point of water (100°C).

Rankine. A Rankine degree (°R) is the same size as the Fahrenheit degree, but on the Rankine scale, zero is –459.67°F (–273.15°C). The Rankine scale provides us with absolute temperatures.

Fahrenheit and Rankine degrees are not approved SI units, and their use is greatly discouraged.

Temperature Measurement

Devices that measure temperature depend on physical change (expansion of a solid, liquid, or gas), change of state (solid to liquid), energy change (changes in electrical potential energy, i.e., voltage), or changes in thermal radiant emission and/or spectral distribution. The principles of operation of the more common temperature-measuring devices are discussed next.

Liquid Expansion Thermometers. These thermometers consist of a tube partially filled with a liquid. The tube measures expansion and contraction of the liquid by changes in temperature. The tube is calibrated to permit reading the level of the liquid in degrees of a temperature scale. The most common example is the mercury-in-glass thermometer.

Bimetallic Thermometers. Bimetallic thermometers are made from strips of two metals that have different coefficients of expansion. They are laminated together so that, as the temperature changes, the strip deflects because the metals expand or contract to different extents. The amount of deflection is measured on a scale that is calibrated in degrees of temperature.

Thermocouples. Thermocouples consist of a pair of wires of different metals or alloys welded together at a point to form a junction. A voltage is generated across this junction, the magnitude of which depends on the nature of the metals and the temperature. The magnitude is compared with a compensating junction at 0°C and the voltage difference is calibrated to give the temperature in degrees.

Pyrometers. Pyrometers measure the intensity of radiation from a hot object. Because intensity of radiation depends on temperature, pyrometers can be calibrated to give readings in degrees of temperature. Optical pyrometers measure the intensity of a particular wavelength of radiation.

Heat Units

Joule (J). Conventionally, the joule is defined as the energy (or work) expended when unit force (1 newton) moves a body through unit distance (1 m). The joule is the most convenient unit of energy to use and can be related to the calorie (*q.v.*), which is defined in terms of the heat energy required to raise the temperature of unit mass of water by 1°. The joule (J) is an approved SI unit, as are kJ (kilojoule) and MJ (megajoule) where 1 kJ = 1000 J and 1 MJ = 1000 kJ.

Watt (W). The watt is a measure of power or the rate of energy release (or consumption). One watt is equal to 1 joule per second (1 W = 1 J/sec). The rate of heat release from a fire can be expressed in kilowatt (kW) or megawatt (MW), units that

are familiar to the electrical engineer. The watt, kilowatt, and megawatt are approved SI units.

Calorie. One calorie is the amount of heat required to increase the temperature of 1 g of water by 1°C (measured at 59°F [15°C]). One calorie is equivalent to 4.183 J.

British Thermal Unit (Btu). The amount of heat required to raise the temperature of 1 lb of water by 1°F (measured at 60°F [15.5°C]) is called the British thermal unit. One Btu equals 1054 J (252 calories) or 1.054 kJ. Btu and calories are *not* approved SI units.

Heat energy has quantity as well as potential (intensity). For example, consider the following analogy. Two water tanks stand side by side. If the first tank holds twice as many liters as the second, then the first tank can hold twice the quantity of water as the second. However, if the level of water in the two tanks is equal, then their pressures or potentials are equal. If the two tanks are joined by a pipe at low level, water will not flow from one to the other because both tanks have the same equilibrium pressure. In a similar manner, one body may hold twice the quantity of heat energy (measured in joules) as a second body. However, if the potentials or temperatures of the bodies are equal, no heat energy will flow from one body to the other when they are brought into contact because the bodies are at equilibrium. If a third body at a lower temperature were brought into contact with the first body, heat would flow from the first to the third until both body temperatures became equal. The amount or quantity of heat flowing until this equilibrium is reached depends on the heat retention capacities of each body involved. (Note that, essentially, ignition involves the addition of sufficient heat [by heat transfer, *q.v.*] to raise the temperature to the appropriate value. On the other hand, extinction may be accomplished by the removal of heat. "Chemical" extinguishment works by another mechanism, i.e., by interrupting chemical reactions that are important in the combustion process.)[1]

Specific Heat

The specific heat of a substance defines the amount of heat it absorbs as its temperature increases. It is expressed as the amount of thermal energy required to raise unit mass of a substance by 1 degree, and its units are J/kg·K. Water has a specific heat of 4200 J/kg·K.

Specific heats vary over a considerable range from 460 J/kg·K for steel to 2400 J/kg·K for oak. Values of specific heat are relevant to fire protection because they define the amount of heat required to raise the temperature of a material to a point of danger or the quantity of heat that must be removed to cool a burning solid to below its firepoint. One reason for the effectiveness of water as an extinguishing agent is that its specific heat is higher than that of most other substances (4200 J/kg·K).

Latent Heat and Heat of Gasification

A substance absorbs heat when it is converted from a solid to a liquid or from a liquid to a gas. This thermal energy is called latent heat. Conversely, heat is released during conversion of a gas to a liquid or a liquid to a solid.

Latent heat is the quantity of heat absorbed by a substance passing between liquid and gaseous phases (latent heat of vaporization) or between solid and liquid phases (latent heat of fusion). A small number of compounds (e.g., naphthalene) go directly from the solid phase to the vapor phase without any chemical change, a transition known as sublimation. This is associated with a latent heat of sublimation. Latent heats are measured in joules per unit mass (J/kg). The latent heat of fusion of water (normal atmospheric pressure) at the freezing or melting point of ice (0°C) is 333.4 kJ/kg; the latent heat of vaporization of water at its boiling point (100°C) is 2257 kJ/kg. The large heat of vaporization of water is another reason for the effectiveness of water as an extinguishing agent. It requires 3 MJ to convert 1 kg of ice at 0°C to steam at 100°C. The latent heats of most other common substances are substantially less than that of water. Thus, the heat absorbed by water evaporating from the surface of a burning solid is a major factor in reducing its temperature and thus reducing the rate of pyrolysis and preventing flame spread to adjacent hot surfaces.

The term *heat of gasification* (L_g in Equation 1) is used to describe the amount of energy that is required to produce unit mass of flammable vapor from a combustible solid that is initially at ambient temperature. Unlike sublimation, chemical decomposition (pyrolysis) of the parent molecules occurs during the process. Heat of gasification is very important because it determines the amount of flammable vapor supplied to a fire in response to a given supply of heat to the pyrolyzing surface. (The fire hazard of some plastics can be reduced by adding inert fillers, such as alumina trihydrate, which increase the effective heat of gasification.)

Density. The density of a substance is the ratio of its mass to volume (expressed as g/cm^3 or kg/m^3).

Specific Gravity. Specific gravity is the ratio of the mass of a solid or liquid substance to the mass of an equal volume of water. (At 15°C, the mass of 1 cm^3 of water is 1 g.)

Gas Specific Gravity. Gas specific gravity is the ratio of the mass of a gas to the mass of an equal volume of dry air at the same temperature and pressure. It is equal to its molecular weight divided by 29, where 29 is the effective molecular weight of dry air (approximately 21% oxygen + 79% nitrogen), and can be derived by applying the ideal gas law (see below).

Buoyancy. Buoyancy is the upward force exerted on a body or volume of fluid by the ambient fluid surrounding it. If the volume of a gas has positive buoyancy, then it is lighter than the surrounding gas and will tend to rise. If it has negative buoyancy, it is heavier and will tend to sink. The buoyancy of a gas depends on both its molecular weight (see *gas specific gravity*) and its temperature.

If a flammable gas with a gas specific gravity greater than 1 leaks relatively slowly from its container, it will tend to sink to a low level. If the conditions are right, it can travel considerable distances and may be ignited by a remote source of ignition. If propane (C_3H_8, molecular weight 44) leaks from a cylinder, it will accumulate and spread at ground level with little dilution.

In a confined space, such as a basement or a boat with poor ventilation, this situation presents a serious hazard.

The density of a gas decreases as its temperature is increased. Thus, hot products of combustion rise. On the other hand, immediately following a spillage of liquefied natural gas (LNG, mainly methane, which has a molecular weight of 16), the vapor is heavier than air because it is at a very low temperature (the boiling point of methane is –161.5°C). As with propane at ambient temperature, LNG spills can be very dangerous because the vapor can spread over a wide area. However, the gas specific gravity of methane is only 0.55 (16/29) so that at ambient temperature the gas rises and disperses. In an enclosed area, it can create an explosion hazard very rapidly (see Section 2, Chapter 8, "Explosions").

Heat Transfer Mechanisms[2,3]

The three basic mechanisms of heat transfer, namely, conduction, convection, and radiation, must be considered together in any fire-related situation, although it is not uncommon for one to dominate the others. Each mechanism will be discussed in detail later, but it is appropriate first to summarize the basic equations. Conduction and convection are similar in that the rate of heat transfer is determined by a simple temperature difference $T = (T_1 - T_2)$, where temperatures can be expressed in °C or degrees Kelvin (K).

The equation for conductive heat transfer is given by

$$\dot{q}'' = \frac{k}{L}\Delta T \text{ kW/m}^2 \qquad (2)$$

This equation applies to heat transfer through solids, where k and L are the thermal conductivity (kW/m·K) and the thickness (m) of the material, respectively. (Caveat: rate of heat transfer may also be expressed in the unit W/m^2. Always check for consistency of units.)

For convective heat transfer between a solid (or a liquid) surface and a fluid (such as air) in contact with that surface, the equation is

$$\dot{q}'' = h\Delta T \text{ kW/m}^2 \qquad (3)$$

where h is the convective heat transfer coefficient (kW/m^2·K). This is not a material property, as will be discussed later.

Radiative heat transfer is quite different. Whereas heat transfer by conduction and convection requires an intervening medium, radiation can occur across a vacuum. The relevant equation for heat loss from a surface is given by

$$\dot{q}'' = \varepsilon\sigma T^4 \text{ kW/m}^2 \qquad (4)$$

where the temperature is in degrees Kelvin, σ is the Stefan-Boltzman constant (56.7×10^{-12} kW/m^2·K^4), and ε is the emissivity, or the efficiency with which the surface can radiate. The most efficient emitters are called *black bodies* and have an emissivity of 1.0.

Conduction[4]

Heat transfer through a solid (e.g., from a heated surface to the interior of the solid) is the process called *conduction.* The rate at which heat (energy) is transferred through a body under steady-state conditions is a function of the temperature difference and the conductance of the path involved. Conductance depends on the *thermal conductivity,* the *cross-sectional area* normal to the flow path, and the *length* of the flow path. The rate of heat transfer is simply the quantity of heat transferred per unit time, but it is convenient to normalize it to unit cross-sectional area and express heat transfer in terms of the heat "flux" (i.e., per unit surface area, normally given the symbol $\dot{q}''$ in which the dot over the q specifies per unit time and the double prime indicates per unit surface area).

Transient heat conduction problems can be extremely complex, despite the simplicity of Equation 2,[4] but simple steady-state problems can be used to illustrate a number of important concepts. For example, it is straightforward to calculate the steady-state heat flux ($\dot{q}''$) through a pane of glass (thickness 5×10^{-3} m and thermal conductivity 0.76×10^{-3} kW/m·K) if the temperatures of the "inside" and "outside" surfaces are known. Using Equation 2 and assuming that $T_{wi} = 25$°C and $T_{wo} = 5$°C (i.e., $\Delta T = 20$ K) [Figure 2.1.2(a)], the heat flux through the glass is

$$\dot{q}'' = \frac{k}{L}\Delta T = \frac{0.76 \times 10^{-3}}{5 \times 10^{-3}}(25 - 5) = 3.04 \text{ kW/m}^2 \qquad (2a)$$

However, this problem is not the one we normally wish to solve. If we want to calculate the rate of heat loss through a window, we normally know the inside and outside air temperatures (T_1 and T_2, respectively). Heat is transferred to the inside surface of the glass by convection. Under steady-state conditions, according to Equation 3, this rate will be given by

$$\dot{q}'' = h(T_1 - T_{wi}) \qquad (5)$$

where T_{wi} is the inner surface temperature of the glass (unknown). If the temperature of the outside surface of the glass is T_{wo} (also unknown), we use Equation 2 to calculate the rate of heat transfer by conduction through the glass, as follows:

$$\dot{q}'' = \frac{k}{L}(T_{wi} - T_{wo}) \qquad (6)$$

and the rate of heat loss to the outside air (by convection) will be

$$\dot{q}'' = h(T_{wo} - T_2) \qquad (7)$$

where T_2 is the external air temperature.

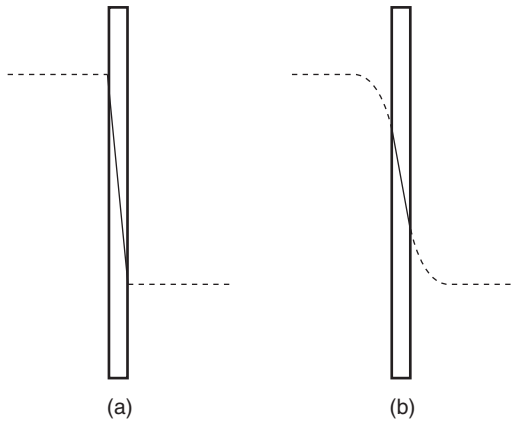


FIGURE 2.1.2 Heat Loss Through a Window

Under steady-state conditions, these three heat fluxes must be equal. If Equations 5, 6, and 7 are rearranged as follows

$$\frac{\dot{q}''}{h} = (T_1 - T_{wi})$$

$$\frac{\dot{q}''L}{k} = (T_{wi} - T_{wo})$$

$$\frac{\dot{q}''}{h} = (T_{wo} - T_2)$$

and added together, we get (after rearrangement)

$$\dot{q}'' = \frac{T_1 - T_2}{\frac{1}{h} + \frac{L}{k} + \frac{1}{h}} \tag{8}$$

This equation has the same form as the equation that describes the flow of an electrical current (I) induced by a voltage V along a wire of resistance R:

$$I = \frac{V}{R} \tag{9}$$

In Equation 8, the heat flux and the temperature difference are analogous to the current and the voltage, respectively, and the denominator is, effectively, a thermal resistance. Protection of structural steel by thermal cladding is an example of providing thermal resistance to the flow of heat into the steel.

Applying appropriate values for the quantities in Equation 7 for the rate of heat loss through the pane of glass (taking h = 0.01 kW/m^2·K), we get

$$\dot{q}'' = \frac{T_1 - T_2}{\frac{1}{h} + \frac{L}{k} + \frac{1}{h}} = \frac{25 - 5}{\frac{1}{0.01} + \frac{5 \times 10^{-3}}{0.76 \times 10^{-3}} + \frac{1}{0.01}} =$$

$$\frac{20}{206.58} = 0.0968 \text{ kW/m}^2$$

which is significantly less than that calculated previously when the surfaces of the glass were assumed equal to the air temperatures (Equation 2a). The actual surface temperatures can be backed out of Equations 5 and 7, substituting $\dot{q}''$ for, h, T_1, and T_2, giving T_{wi} = 15.3°C and T_{wo} = 14.7°C (each to one decimal place) [see Figure 2.1.2(b)]. Clearly, convective heat transfer at the two surfaces throttles the rate of heat loss from the room. This concept is very clearly illustrated if the sheet of glass is replaced by a sheet of mild steel of the same thickness but of high thermal conductivity, that is, 45.8 × 10^{-3} kW/m·K. According to Equation 8, the heat loss would be

$$\dot{q}'' = \frac{T_1 - T_2}{\frac{1}{h} + \frac{L}{k} + \frac{1}{h}} = \frac{25 - 5}{\frac{1}{0.01} + \frac{5 \times 10^{-3}}{45.8 \times 10^{-3}} + \frac{1}{0.01}} =$$

$$\frac{20}{200.11} = 0.09994 \text{ kW/m}^2$$

which is only 3 percent more than through the pane of glass.

The thermal conductivity of steel is so high that the temperature of the steel is virtually uniform. This can be shown by carrying out the same calculation as previously for the temperatures of the "inside" and "outside" surfaces of the steel. Thus, T_{wi} = 15.006ºC and T_{wo} = 14.994ºC, a difference of only 0.012 K between the faces, yet large enough to allow a heat flux of 0.0999 kW/m^2 to pass through. It is said to behave as a *thermally thin* solid under these specific conditions. The test for whether a sample will behave as thermally thin is to examine the dimensionless Biot number, $Bi = hL/k$, which is effectively the ratio of the rate of convective transfer to the surface to the rate of conductive transfer from the surface (into the solid). If the Biot number is less than 0.1, then any temperature gradient within the solid can be ignored and the material can be treated by the "lumped thermal capacity" approximation. The two examples (glass and steel) have Biot numbers of 0.65 and 0.011, respectively; that is, only the steel behaves as thermally thin in this case. Perhaps surprisingly, a 50-mm-thick slab of steel also behaves as (just) thermally thin (Bi = 0.11). It is for this reason that the "lumped thermal capacity" model can be used in calculations of the temperature response of steel elements and of fusible links in sprinkler heads when exposed to heat. This model makes transient heat transfer calculations much easier.

For example, consider a thermally thin combustible solid, which can be ignited when its temperature reaches T_{ig}ºC (the "firepoint"). Then we can estimate how long it would take for it to ignite if exposed to a defined heat flux. Taking a sheet of paper, for which L = 0.5 × 10^{-3} m and k = 0.1 × 10^{-3} kW/m·K, then if h = 0.015 kW/m^2·K, we can treat it as "thermally thin" because Bi = 0.07. If it is heated convectively by exposing it to air at T_∞ on both sides, then the rate of temperature rise will be

$$\frac{dT}{dt} = \frac{Ah}{V\rho c}(T_\infty - T) \tag{10}$$

where T is the temperature of the solid, which will be uniform across the full thickness (Bi < 0.1), A is the area through which the heat is transferred, and V is the associated volume of material to which the heat is transferred. This equation is a statement that the rate of temperature rise of the material is equal to the rate of heat transfer by convection $Ah(T_\infty - T)$ divided by the thermal capacity of the volume of material associated with surface area A.

Rearrangement and integration gives

$$\frac{T_\infty - T}{T_\infty - T_o} = \exp\left(-\frac{2ht}{x\rho c}\right) \tag{11}$$

where T_o is the initial temperature of the paper and $x = V/2A$. The factor of 2 appears because heat is being transferred to both faces, halving the effective thickness.

If the "firepoint temperature" is T_{ig}, through rearrangement a value for the time to ignition can be given by

$$t_{ig} = \frac{x\rho c}{2h} \ln\left(\frac{T_\infty - T_o}{T_\infty - T_{ig}}\right) \tag{12}$$

This equation shows that the time to ignition is proportional to the thickness x (or, more correctly, the thermal capacity per unit surface area). Moreover, T_∞ must be greater than T_{ig} for ignition to be possible. (The same equation provides the basis for the "response time index" of sprinkler heads.)

However, most materials of interest do not behave as thermally thin and temperatures cannot be assumed to be uniform—a

temperature gradient will exist. In the steady state, this gradient will be linear, but if one face of a slab, initially at a temperature T_o, is suddenly exposed to a convective (or a radiative) heat flux, then heat will be conducted into the slab as the surface temperature rises, developing a transient temperature profile through the slab thickness, as illustrated schematically in Figure 2.1.3. In that figure, profiles (a) through (c) (at 1, 5, and 10 minutes, respectively) are behaving as semi-infinite solids, but heat is being lost through the rear face in (d) and (e) (30 and 120 minutes, respectively). The dotted line identifies the initial temperature of the slab.

The ability of the slab to conduct heat from the surface will influence how rapidly the surface temperature can rise. Materials of high thermal conductivity (such as steel) feel cold to the touch because they draw the heat away from the surface. Alternatively, if you place your hand on the surface of a block of polyurethane foam, it feels warm because heat is not conducted away from the surface and heat losses from your hand are reduced.

The mathematics of transient heat transfer in thermally thick solids are not straightforward and it is easier to consider the semi-infinite solid for which a mathematical solution exists. A semi-infinite solid is one for which thermal loss from the rear face is not an issue because the "heat wave" never reaches the rear surface [see Figures 2.1.3(a), 2.1.3(b), and 2.1.3(c)]. The expression for the temperature rise of the surface of the semi-infinite solid is given by the following equation:

$$\frac{T - T_o}{T_\infty - T_o} = 1 - \exp\left(\frac{h^2 t}{k\rho c}\right) \cdot erfc\left(\frac{h\sqrt{t}}{\sqrt{k\rho c}}\right) \qquad (13)$$

in which t is time (sec) and the product k (thermal conductivity, kW/m·K) × ρ (density, kg/m^3) × c (heat capacity, kJ/kg·K) is known as the thermal inertia ($k\rho c$). A high value, associated particularly with a high value of k, means that the surface temperature will increase very slowly indeed, whereas the surface temperature of insulating materials (low value of k and, hence, low $k\rho c$) will show a very rapid temperature response. This is illustrated in Figure 2.1.4 for a range of materials.

Although the concept of the semi-infinite solid is an abstraction, the equation is valid for real solids when one face is exposed to a heat flux for a short period of time. This is shown in Figure 2.1.3(a) to (c). The surface temperature has increased, but the rear face is still at the initial temperature T_o. To all intents and purposes, a slab of finite thickness will behave as a semi-infinite solid until the rear face temperature starts to rise, that is, before there are significant heat losses from the rear face. This period of time (t) is defined for a thickness x by the expression $x = 4\sqrt{\alpha t}$, where $\alpha = k/\rho c$ (m^2/sec) is known as the thermal diffusivity, although $x = 2\sqrt{\alpha t}$ is a good approximation. Consequently, thick materials that ignite quickly when exposed to a high heat flux may still be behaving as semi-infinite solids. (This assumption can be made when analyzing the times to ignition for samples exposed to high heat fluxes in test equipment such as the cone calorimeter.)

Samples of material that behave in this way may be said to behave as thermally thick solids, the semi-infinite solid being the ultimate example for which the steady state can never be achieved. Real thicknesses, in principle, can reach the steady state, although in fires this is rare and probably of little relevance. It is the transient behavior that is important: How quickly can a combustible solid be ignited under a given heat flux? How rapidly will flames spread over surfaces? How quickly will an insulated steel column reach a critical temperature? and so on.

Convection

Convection involves the transfer of heat by a circulating fluid—either a gas or a liquid. Thus, heat generated in a stove is distributed throughout a room by heating the air in contact with the stove (by conduction across the stationary boundary layer in contact with the hot surface). The hot, buoyant air then rises, setting up convection currents that transfer heat to distant objects in the room. Heat is transferred from the air to these distant objects again by conduction across the boundary layer. Air currents can be made to carry heat by convection in any direction by use of a fan or blower (forced convection).

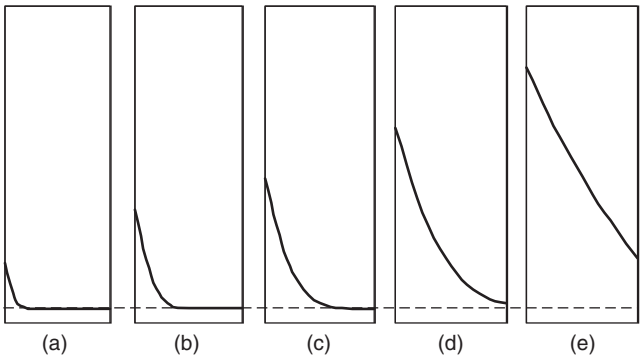


FIGURE 2.1.3 Temperature Profiles at Increasing Time Intervals Inside a Thick Solid as Heat Is Transferred Through the Left Face

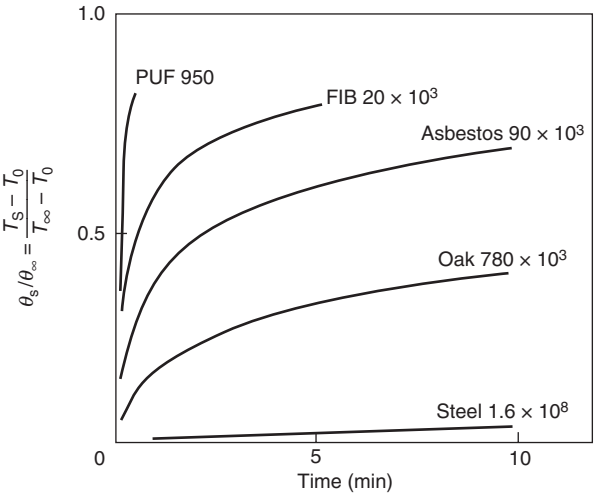


FIGURE 2.1.4 Effect of Thermal Insulation ($k\rho c$) on the Rate of Temperature Rise at the Surface of a "Semi-Infinite" Solid. The figures are values of $k\rho c$ in units W^{2}sec/m^{4}K^2. FIB = fiber insulation board; PUF = polyurethane foam.

In the present context, the term *convective heat transfer* is commonly used to describe the mode of heat transfer between a fluid and a solid surface. The corresponding convective heat transfer coefficient (h) is defined by Equation 3:

$$\dot{q}'' = h\Delta T \text{ kW/m}^2$$

where $\dot{q}''$ is the rate of heat transfer per unit surface area (kW/m^2), and ΔT is the temperature difference (K) between the fluid and the surface. The convective heat transfer coefficient h (kW/m^2·K) is defined by this expression, but it is not a simple material property. It depends on a number of factors, including the geometry of the system, the characteristics of the flow (laminar or turbulent), the properties of the fluid, and the temperature difference between the surface and the fluid.

The movement of the fluid may occur naturally, driven by density differences (buoyancy-driven flow) or it may be a result of an imposed flow (forced convection). In the former case, if a surface is at a higher temperature than the surrounding fluid (e.g., air), then the air adjacent to the surface will be heated and become less dense than the surrounding air and so rise. Density of air can be calculated using the ideal gas law, which describes the relationship between pressure, temperature, and volume for a gas:

$$PV = nRT \tag{14}$$

where P is pressure (Pa, or bar), V is volume (m^3), T is the temperature (K), R is the ideal gas constant (8.314 J/K·mol or 8.2×10^{-5} m^3·atm/K·mol), and n is the number of moles of gas involved.

This shows that for a given quantity of gas (i.e., n is constant), pressure is inversely proportional to volume at constant temperature (this is known as Boyle's law), whereas for a sealed container (constant n and V), pressure is directly proportional to temperature (Charles' law). Air, its constituent gases, and the "permanent gases" (H_2, He) obey this law closely, although higher molecular weight species tend to deviate from "ideal behavior." The easiest way of distinguishing between a gas that is likely to behave "ideally" and one that does not is to consider its boiling point. Gases that are close to their condensation temperature (i.e., just above the boiling point of the liquid) are likely to deviate strongly from ideal behavior: such gases are more properly described as "vapors."

Nevertheless, this equation is widely used in fire safety engineering calculations. In most cases, the extent of dilution of fire gases is so great that they consist mainly of air. The preceding equation is a satisfactory approximation to real behavior.

The density of air can be calculated using the ideal gas law (Equation 13); density (mass/unit volume) is given by the ratio $n \times MW/V$, where MW is the molecular weight of air (28.95 g). Thus

$$\text{Density of air} = \frac{n \times MW}{V} = \frac{P \times MW}{RT} \tag{15}$$

At ambient temperature (T = 293 K [20ºC]) and pressure (P = 1 bar), with $R = 8.2 \times 10^{-5}$ m^3·atm/K·mol:

$$\text{Density of air } (\rho_{air}) = 1204.9 \text{ g/m}^3$$

It is inversely proportional to the *absolute* temperature (degrees Kelvin), so that at 100ºC (373 K), ρ_{air} = 898.3 g/m^3. Air heated to this temperature will have significant buoyancy with respect to the surrounding air at 20ºC.

Experiments have shown that the convective heat transfer coefficient (h in Equation 2) can be expressed as a function of dimensionless groups, the Reynolds number, the Prandtl number, and the Grashof number. These are as follows:

$$\text{Reynolds:} \quad Re = \frac{v\rho L}{\mu} \qquad \left(\frac{\text{Inertial stress}}{\text{Viscous stress}}\right)$$

$$\text{Prandtl:} \quad Pr = \frac{C_p\mu}{k} \qquad \left(\frac{\text{Kinematic viscosity}}{\text{Thermal diffusity}}\right)$$

$$\text{Grashof:} \quad Gr = \frac{\beta g \Delta T L^3 \rho^2}{\mu^2} \qquad \left(\frac{\text{Buoyancy force}}{\text{Viscous drag}}\right)$$

where

L = Linear dimension (m)

v = Velocity (m/sec)

ρ = Density (kg/m^3)

μ = Viscosity (N.sec/m^2)

C_p = Specific heat (constant pressure) (kJ/kg·K)

β = Coefficient of thermal expansion

g = Gravitational acceleration (m^2/sec)

The heat transfer coefficient is normally expressed as the dimensionless Nusselt number, $Nu = hL/k$, in which k is the thermal conductivity of the fluid (in this case, air) and L is a characteristic length. Theoretically, it has been shown that for natural convection when buoyancy is important

$$Nu = f(Pr, Gr)$$

whereas for forced convection

$$Nu = f(Re, Pr)$$

Experimental values of convective heat transfer coefficients for different geometries are available in the literature. Generally, they are expressed in terms of the Nusselt number; typical expressions for forced convection and laminar convection are given in Table 2.1.1.

For example, for natural convection, laminar flow, at a vertical flat plate of length L

$$Nu = 0.59(Gr \cdot Pr)^{1/4}$$

whereas for forced convection,

$$Nu = 0.66 Re^{1/2} Pr^{1/3}$$

Further information on convective heat transfer coefficients can be found in any text on heat transfer, for example, Incropera and de Witt,[2] Welty et al.,[3] and many others.

Radiation

Thermal radiation is a form of energy that travels across a space without the need for an intervening medium, such as a solid or a fluid. It travels as electromagnetic waves in straight lines, behaving similarly to light, radio waves, and X-rays (Figure 2.1.5). In a vacuum, all electromagnetic waves travel at the speed of

TABLE 2.1.1 Some Recommended Convective Heat Transfer Correlations

Nature of the Flow and Configuration of the Surface	$Nu = \frac{hL}{k}$
Forced Convection	
Laminar flow parallel to a flat plate of length L ($20 < Re < 3 \times 10^5$)	$0.66Re^{1/2}Pr^{1/3}$
Turbulent flow, parallel to a flat plate of length L ($Re > 3 \times 10^5$)	$0.037Re^{4/5}Pr^{1/3}$
Flow round a sphere of diameter L (general equation)	$2 + 0.6Re^{1/2}Pr^{1/3}$
Natural Convection	
Laminar: natural convection at a vertical plate of length L ($10^4 < Gr{\cdot}Pr < 10^9$)	$0.59(Gr{\cdot}Pr)^{1/4}$
Turbulent: natural convection at a vertical plate of length L ($Gr{\cdot}Pr > 10^9$)	$0.13(Gr{\cdot}Pr)^{1/3}$
Laminar: natural convection at a hot horizontal length L (face up) ($10^5 < Gr{\cdot}Pr < 2 \times 10^7$)	$0.54(Gr{\cdot}Pr)^{1/4}$
Turbulent: natural convection at a hot horizontal length L (face up) ($2 \times 10^7 < Gr{\cdot}Pr < 3 \times 10^{10}$)	$0.14(Gr{\cdot}Pr)^{1/3}$

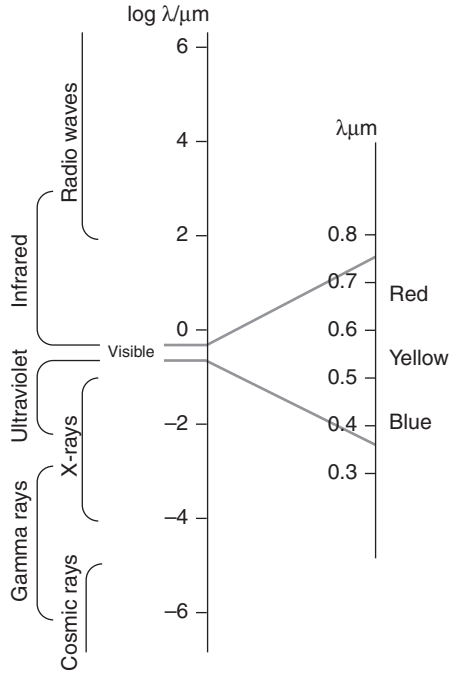


FIGURE 2.1.5 Electromagnetic Spectrum (Source: D. D. Drysdale, *An Introduction to Fire Dynamics,* 2nd ed., John Wiley & Sons, Chichester, UK, 1999, Figure 2.16. Copyright 1999. Copyright John Wiley & Sons Limited. Reproduced by permission.)

light (3×10^{10} m/sec). If these waves are directed onto the surface of a body, they can be absorbed, reflected, and/or transmitted. Visible light consists of wavelengths between 0.4×10^{-6} to 0.7×10^{-6} m, which correspond to the blue and red ends of the visible spectrum, respectively, whereas thermal radiation occurs principally in the infrared (and far-infrared) region (wavelengths greater than 0.7×10^{-6} m). Figure 2.1.5 shows that the range of wavelengths visible to the naked eye is tiny. A small fraction of radiation in the visible region is emitted by hot objects when the temperature is high enough. The visible radiation increases in intensity and changes in color as the temperature is raised, as indicated in Table 2.1.2.

The distinction between thermal radiation and convection can be illustrated by reference to a candle flame. The air that is required for combustion of the fuel vapors is drawn into the flame from the surrounding atmosphere by a process known as entrainment. The hot gases rise vertically upward as a plume that carries with it most of the heat (70%–90%) released by combustion (depending on the nature of the fuel). The rest of the heat is lost from the flame by radiation, which can be detected if a hand is held near the side of the flame. The sensation of warmth is caused by radiant heat transfer (i.e., thermal radiation), which is emitted from the flame in all directions. Up to 30 percent of the heat released in the flame is lost in this way, but the hand intercepts only a small proportion. If instead the hand is held over the top of the flame, in the plume of hot combustion products, it will intercept all of the "convected" heat and experience a much higher rate of heat transfer.

Most of the heat radiated from a diffusion flame arises from minute particles of soot (solid carbonaceous particles) formed in the complex series of reactions that occurs within the flame.[5] The mechanism of formation is described in the section on fire chemistry. The particles are the source of the characteristic yellow luminosity. They radiate over a wide range of wavelengths, mainly in the infrared: we see only that part of the emission that lies in the visible region. The gaseous combustion products H_2O and CO_2 also emit radiation but only within narrow wavelength bands in the infrared.[6] Fuels that do not produce soot (such as hydrogen, methyl alcohol, and polyoxymethylene) have nonluminous flames. As a rough guide, ≤ 10 percent of the heat of combustion is lost from the flame by radiation in these cases.

Larger fires (diameters > 0.3 m) involving "ordinary" fuels may release 30 percent to 50 percent of the total amount of energy as radiation, exposing nearby surfaces to high levels of radiant heat transfer. Radiation travels in straight lines. We would expect intuitively that the heat received from a small area source

TABLE 2.1.2 Color Variation with the Temperatures of Hot Objects (indicative only)

Temperature (°C)	*Appearance*
550	First visible red glow
700	Dull red
900	Cherry red
1100	Orange/yellow
1400	White

would be less than that received from a large radiating surface, provided the sources were at comparable distances and were emitting comparable energies per unit area (Figure 2.1.6).

Thermal radiation passes freely through gases that consist of symmetrical diatomic molecules, such as oxygen (O_2), and nitrogen (N_2) (the principal constituents of air), but is absorbed in narrow wavelength bands by water vapor (H_2O), carbon dioxide (CO_2) and other asymmetrical molecules such as carbon monoxide (CO) and sulfur dioxide (SO_2). Although their concentrations are low, the presence of carbon dioxide and water vapor in the normal atmosphere prevents solar radiation that lies in narrow bands around 2.8 μm (microns) and 4.4 μm (in particular) from reaching the surface of the earth.

Advantage is taken of this fact in the development of infrared flame detectors, which can be designed to be blind to solar radiation by responding only to 2.8 μm or 4.4 μm (see Section 14, Chapter 2, "Automatic Fire Detectors"). These wavelengths are emitted strongly by molecules of water and carbon dioxide in flames. On the same principle, water vapor and carbon dioxide in the atmosphere are responsible for the absorption of appreciable amounts of thermal radiation emitted from large fires: the effect is significant only at large distances from such fires. This absorption helps to explain why forest fires or large LNG fires are (relatively) less hazardous on days when humidity is high. Also, because water droplets absorb almost all the incident infrared radiation, mists or water sprays are effective attenuators of radiation.[7] This property is used by fire fighters for their protection. (It should be noted that suspended smoke particles absorb thermal radiation selectively but transmit a sufficient proportion to allow infrared cameras to "see" hot objects through smoke.)

When two bodies face each other and one body is hotter than the other, a net flow of radiant energy from the hotter body to the cooler body will ensue until thermal equilibrium is achieved. The ability of the cooler body to absorb radiant heat depends on the nature of the surface. If the receiving surface is shiny or polished, it will reflect most of the radiant heat away, whereas if it is black or dark in color, it is likely to absorb most of the heat.

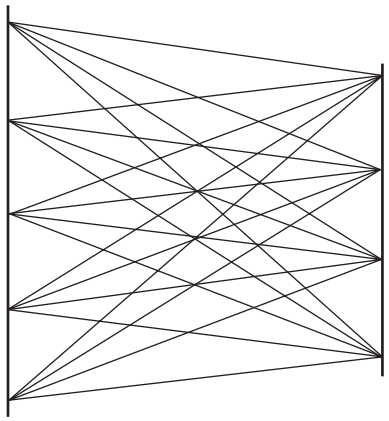


FIGURE 2.1.6 Radiation Exchange Between Two Surfaces

The *absorptivity* of the surface is simply the fraction of the incident radiant heat that is absorbed by the surface. A surface with an absorptivity of 1.0 (the maximum value) is called a *black surface.* Most nonmetallic materials are effectively "black" to infrared radiation, despite the fact that they may appear light or colored to the naked eye (i.e., visible radiation). Some substances, such as pure water and glass, are transparent to visible radiation and allow it to pass through them with minimal absorption; however, both liquid water and glass are opaque to most infrared wavelengths. Glass greenhouses and solar panels operate on the principle of being transparent to the sun's visible radiation while at the same time being opaque to the infrared radiation attempting to escape from the greenhouse or solar panel.

Shiny metallic materials are excellent reflectors of radiant energy and have low absorptivities (perhaps less than 0.1).[3] For example, aluminum foil often is used together with fiberglass in building insulation. Sheet metal is often used beneath stoves or on heat-exposed walls.

The Stefan-Boltzmann law states that the radiation emitted per unit area from a hot surface is proportional to the fourth power of its *absolute temperature.* The law is expressed in the formula:

$$\dot{q}'' = \varepsilon\sigma T^4 \text{ kW/m}^2 \tag{4}$$

where

$\dot{q}''$ = The radiant emission per unit surface area (also known as the emissive power)

ε = The surface emissivity (which is 1.0 for a black body or black surface)

σ = The Stefan-Boltzmann constant (equal to 56.7×10^{-12} kW/m^2·K^4)

T = The absolute temperature expressed in Kelvin (K)

It should be noted that the numerical values of emissivity and the absorptivity of a surface are equal (Kirkhoff's law).

To appreciate the importance of the fourth-power dependence, consider the following situation.

EXAMPLE: A heater is designed to operate safely with an external surface temperature of 260°C. What is the increase in radiation if the external surface temperature is allowed to increase by 100°C to 360°C and by 240°C to a maximum of 500°C?

SOLUTION: First, it is necessary to convert the temperatures from degrees Celsius to degrees Kelvin by adding 273: thus, 260°C becomes 533 K, 360°C becomes 633 K, and 500°C becomes 773 K. Next, if we assume that the surface is "black" (ε = 1.0), the radiant emission per unit area of the external surface (its "emissive power") for safe operation at 260°C is

$$\dot{q}'' = \varepsilon\sigma T^4 = 1.0 \times 56.7 \times 10^{-12} \times (533)^4 = 4.6 \text{ kW/m}^2$$

The corresponding emissive powers at the higher temperatures are

$$\dot{q}'' = \varepsilon\sigma T^4 = 1.0 \times 56.7 \times 10^{-12} \times (633)^4 = 9.1 \text{ kW/m}^2$$

$$\dot{q}'' = \varepsilon\sigma T^4 = 1.0 \times 56.7 \times 10^{-12} \times (773)^4 = 20.2 \text{ kW/m}^2$$

Thus, it can be seen that, by increasing the stove temperature by 100°C, the emissive power is approximately doubled from 4.6 to 9.1 kW/m^2. If the amount of heat radiated was only a function of the first power of the absolute temperature, then it would increase by only about 20 percent if the absolute temperature was increased from 533 to 633 K. Finally, if one were so careless as to allow the stove to reach 500°C, it would emit 20 kW/m^2, which is sufficiently high to lead to ignition of many typical home furnishings that might be in close proximity to the stove.

Because residential coal or wood stoves can sometimes undergo a temperature "runaway" if given too much air, it is important to keep all nearby furnishings well away from the stove to ensure that the maximum received radiant heat transfer is kept to safe levels. The radiant energy transmitted from a point-like source to a receiving surface will vary inversely as the square of their separation distance (Figure 2.1.7). If a stove is small relative to its distance from nearby objects, then it behaves like a point source; doubling its separation distance will decrease the incident radiant heat (per unit area) by a factor of 4. However, if the nearby object is close to the stove, the stove appears as a large surface and small changes in separation will have a lesser effect on the intensity of radiation falling on the receiving surface (e.g., a large stove located within a few centimeters of a combustible wall). In this case, one must protect the wall by some means such as a noncombustible board faced with a reflecting material (low absorptivity). The transfer of radiant heat between the two surfaces shown in Figure 2.1.6 can be calculated by using configuration factors that describe the geometrical relationship of the two surfaces, one to the other. It takes into account the heat radiated back to the hot surface as the temperature of the receiving surface increases.[2]

Generally, we have a good understanding of radiant heat transfer between solid surfaces.[2,6] If the emissive power of a surface is known (Equation 4), then it is possible to calculate the intensity of radiation falling at a point at a known distance from the surface. This is given by the equation

$$\dot{q}'' = \phi\varepsilon\sigma T^4 \text{ kW/m}^2$$

where ϕ is known as the "area to point" configuration (or "view") factor, defining the geometrical configuration between the area of the radiating surface and the distance between the radiator and the receiver (see Figure 2.1.7).[3,8] This configuration factor may be used to calculate the radiant intensity at a point on a surface that is exposed to radiant heat. For some applications, it may be necessary to calculate the radiation exchange between two surfaces as shown in Figure 2.1.6. A practical example would be the radiation exchange between a heated ceiling and the wall of a compartment. For this, the "area to area" configuration factor is required. Both types of configuration factor may be calculated from tables or nomograms that are available in most heat transfer texts.[2]

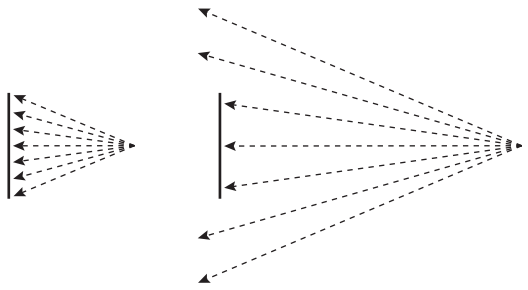


FIGURE 2.1.7 Schematic Diagram of Decreasing Intensity of Radiation from a Point Source as the Square of the Distance Between the Source and the Receiver

It is also possible to carry out reliable estimates of radiant heat absorbed or emitted by gases of a known composition and temperature, for example, from the gases in a combustion chamber, where the principal species present are carbon dioxide and water vapor. Detailed studies carried out by Hottel and his coworkers[9] provided an empirical method for calculating the amount of radiation emitted from these combustion products as a function of partial pressure of the vapor and the path length through which the radiation is being emitted. However, it is more difficult to estimate the amount of heat radiated from diffusion flames because of the presence of soot particles that act as individual black body emitters. The concentration of these particles must be known as well as the path length, which is effectively the thickness of the flame. There is, however, one useful rule of thumb: the total radiant output from flames from fires burning on a fuel bed of diameters more than approximately 0.3 to 0.5 m is usually about 30 percent of the total heat output. Most of the remaining energy (60%–70%) is carried away by convection, with the remaining fraction accounted for by incomplete combustion (carbon monoxide, soot, etc.). These figures are indicative only as the chemical nature of the fuel can make a significant difference (e.g., methanol produces no soot particles and the fraction radiated can be < 10%, as mentioned previously).

The emissivity of flames is strongly linked to the quantity of soot particles present, which in turn will depend on the nature of the fuel and on the structure and behavior of the flame. The potential of a fuel to produce soot and smoke can be assessed by measuring the smoke point.[10,11] For a given fuel, this is the minimum height of a laminar diffusion flame for which there is a release of soot particles at the flame tip (i.e., the tip becomes luminous). Fuels that contain the aromatic ring, such as polystyrene, have a very small smoke point and, consequently, yield a large amount of smoke. Polymethylmethacrylate and polyoxymethylene, on the other hand, produce relatively small amounts of smoke and have large smoke points. Alcohol fires, particularly those of methyl alcohol, burn with blue flames containing no soot particles. The radiating species in such flames are the gaseous molecules of water and carbon dioxide. They radiate very weakly, in comparison to soot particles, and for this reason, the temperatures of flames of alcohol fires are much higher than those of fires involving hydrocarbons. This was shown clearly by Rasbash and coworkers in the 1950s.[12]

FLAME STRUCTURE

The following are the two types of flame that we have to consider:

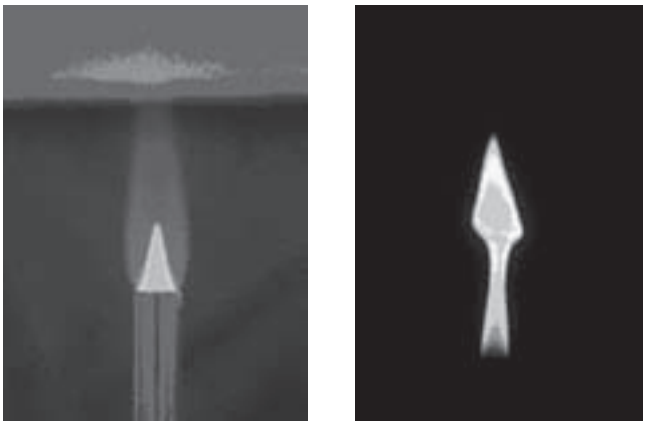
1. The premixed flame in which fuel and air are intimately mixed before ignition
2. The diffusion flame in which fuel and air are initially separate and burn in the region in which they mix

Although premixed burning is associated with the internal combustion engine and with gas explosions, it is important to distinguish between these modes of burning. It may not seem to be relevant to understanding uncontrolled fires, but it is relevant to our understanding of the ignition process and flame stabilization.

If a mixture of flammable gas in air is within the limits of flammability, introduction of an ignition source will initiate a flame that will then propagate throughout the mixture, wherever it is within the limits of flammability.[13] The thickness of the flame is of the order of 1 mm and it propagates at a rate of the order of 0.5 m/sec (for hydrocarbon fuels in a quiescent mixture). This means that the reaction is complete in approximately 2 milliseconds (2×10^{-3} sec).[14,15] Such rapid conversion of fuel and air to combustion products (with the release of the heat of combustion) is possible only because the fuel and air are intimately mixed. In the case of diffusion flames, the process of diffusion is very slow and becomes the rate-determining process, reducing the rate of combustion by two orders of magnitude. This difference may be illustrated by comparing the power densities of premixed flames (100 to 200 MW/m^3) and diffusion flames (0.5 to 1 MW/m^3).[16] This is reflected in the average temperatures of these flames. Because a diffusion flame is effectively diluted by excess air, the apparent (average) temperature is much lower than that of a premixed flame in which the flammable gas-air mixture is stoichiometric or near-stoichiometric. It is accepted that a premixed flame is unable to propagate unless it can produce a flame temperature greater than approximately 1300ºC (approx. 1600 K). Much lower (average) temperatures are measured in diffusion flames, although they will contain pockets of burning fuel/air mixture at much higher temperatures.

The topics associated with flammability limits and gas explosions are covered in Section 2, Chapter 8, "Explosions," and will not be discussed further in this chapter. However, it is important to understand the structure of the premixed flame and how it differs from the diffusion flame. They are compared in Figure 2.1.8: Figure 2.1.8(a) shows a premixed flame (propane + air) stabilized on a Bunsen burner, whereas Figure 2.1.8(b) shows a flame burning when pure propane is flowing from the same Bunsen burner. The premixed flame does not need to seek any additional air to burn, whereas the air for combustion of the propane has to be entrained from the surrounding atmosphere. The entrainment process is driven by the shear forces between the jet of propane and the surrounding air: the flame exists where propane and air have mixed by diffusion—laminar for small flames, turbulent for large flames (fire diameter > 0.3 m).

Early work on the structure of the diffusion flame was based on the hypothesis that the flame height was determined by the entrainment rate (see Drysdale[17]). It was assumed that the flame tip corresponded to the height at which the ratio of the fuel to entrained air was equal to the stoichiometric ratio, which implies that complete combustion will have occurred within the flame. However, this cannot be the case as at least a small amount of smoke (a sure sign of incomplete combustion)



(a) (b)

FIGURE 2.1.8 Bunsen Burner Flames. (a) Premixed flame. (b) Diffusion flame.

is normally seen to be released from the flame tip. In fact, the amount of air entrained is very much greater than that required for stoichiometric burning by a large factor (certainly > 4). This fact is clear evidence that within the diffusion flame the combustion process is not uniform. Mixing by diffusion is not efficient, and within the flame there will be a wide variation in the fuel concentration. A simplistic view is that combustion will take place in those regions where the fuel-air mixture is stoichiometric. However, this view does not account for the fact that the flame entrains excess air, and it is wrong to think of the flame in such idealized terms. A "stoichiometric surface" will not exist: instead, there will be a finite volume within which fuel and air are mixing and where reaction will occur, but is by no means uniform. It would be anticipated that burning would occur wherever the fuel-air mixture was within the relevant flammability limits. That is, combustion will be occurring across the spectrum of concentrations, from near the lower limit (fuel lean) to near the upper limit (fuel rich), remembering that at these elevated temperatures, the limits will be wider than those associated with ambient temperatures.

The following other two factors need to be considered:

- As diffusion continues, the localized combustion process can be quenched (interrupted) if mixed with excess air (or fuel) as a result of continuing mixing.
- Reactions can take place on the fuel-rich side of the reaction zone where there is insufficient oxygen present for premixed burning. These reactions include gas-phase pyrolysis, which is ultimately responsible for the formation of soot particles in the flame. These may be resistant to oxidation and can escape the flame to form smoke particles, which is discussed in the next section.

Studies of diffusion flames from 300-mm-square gas burners have shown that combustion is not uniform throughout the flame and that it is possible to map out the "combustion intensity" as a function of position within the flame.[18] What we see as the boundary of a diffusion flame corresponds to the outside region of the flame where the combustion intensity is very low

("flame" may be present for only 5% of the time). Within this flame envelope, there is a great deal of turbulence and large concentration and temperature gradients exist. The discussion of the "fire plume" in Section 2, Chapter 4, "Dynamics of Compartment Fire Growth," deals with the consequences of these features.

Modeling such behavior is extremely difficult, and in CFD codes it is necessary to make simplifying assumptions. One of the most commonly used is the laminar flamelet model in which combustion is assumed to occur in those small volumes where the mixture is stoichiometric. This topic is covered in detail elsewhere.

FIRE CHEMISTRY

This section presents basic definitions and concepts relevant to fire chemistry. It does not attempt to be comprehensive but is intended to present some of the background material applicable to this and other sections of this handbook.

Atoms and Molecules

Atom. Atoms are the building blocks of chemistry. They form the basis of all matter with which we are familiar. Each atom has a dense, positively charged nucleus, or core, which contains protons (positively charged) and neutrons (no charge), and around which negatively charged electrons swarm in a regularly structured pattern. The number of protons and electrons is equal, ensuring that the atom is electrically neutral. The precise structure of the electron "swarm" (or "cloud") determines the chemical nature and reactivity of the atom.

Atomic Number of an Element. The atomic number is the number of protons in the nucleus of the atom of an element. It determines the position of that element in the periodic table (Table 2.1.3), which reveals the underlying regularity in the properties of the elements.

Atomic Weight of an Element. The atomic weight of an element is proportional to the weight of its atom. The "scale" is based arbitrarily on the carbon-12 isotope (the isotope of carbon containing six protons and six neutrons). The mass of C-12 corresponding to 12 g contains 6.022×10^{23} atoms (known as Avogadro's number). The atomic weights of the elements are given in Table 2.1.4.

Element. Elements are substances that are composed of only one type of atom (e.g., pure carbon, C; nitrogen, N_2; bromine, Br_2).

TABLE 2.1.3 Periodic Table

	Alkali metals 1 A	Alkaline earth metals II A	Transition metals										Nonmetals					Noble gases O
			III B	IV B	V B	VI B	VII B		VIII		I B	II B	III A	IV A	V A	VI A	VII A	
Period 1	1 H 1.01 Hydrogen																	2 He 4.00 Helium
Period 2	3 Li 6.94 Lithium	4 Be 9.01 Beryllium											5 B 10.81 Boron	6 C 12.01 Carbon	7 N 14.01 Nitrogen	8 O 16.00 Oxygen	9 F 19.00 Fluorine	10 Ne 20.18 Neon
Period 3	11 Na 22.99 Sodium	12 Mg 24.31 Magnesium											13 Al 26.96 Aluminum	14 Si 28.09 Silicon	15 P 30.97 Phosphorus	16 S 32.07 Sulfur	17 Cl 35.45 Chlorine	18 Ar 39.95 Argon
Period 4	19 K 39.10 Potassium	20 Ca 40.08 Calcium	21 Sc 44.96 Strontium	22 Ti 47.88 Titanium	23 V 50.94 Vanadium	24 Cr 52.00 Chromium	25 Mn 54.95 Manganese	26 Fe 55.85 Iron	27 Co 58.93 Cobalt	28 Ni 58.70 Nickel	29 Cu 63.55 Copper	30 Zn 65.39 Zinc	31 Ga 69.72 Gallium	32 Ge 72.61 Germanium	33 As 74.92 Arsenic	34 Se 78.96 Selenium	35 Br 79.90 Bromine	36 Kr 83.80 Krypton
Period 5	37 Rb 85.47 Rubidium	38 Sr 87.62 Strontium	39 Y 88.91 Yttrium	40 Zr 91.22 Zirconium	41 Nb 91.91 Niobium	42 Mo 95.94 Molybdenum	43 Tc (98) Technetium	44 Ru 101.07 Ruthemium	45 Rh 102.91 Rhodium	46 Pd 106.4 Palladium	47 Ag 107.87 Silver	48 Cd 112.41 Cadmium	49 In 114.82 Iridium	50 Sn 118.71 Tin	51 Sb 121.74 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.29 Xenon
Period 6	55 Cs 132.91 Cesium	56 Ba 137.33 Barium	Lanthanide series (see below)	72 Hf (261) Hafnium	73 Ta 180.94 Tantalum	74 W 183.85 Tungsten	75 Re 188.21 Rhenium	76 Os 190.23 Osmium	77 Ir 192.22 Iridium	78 Pt 195.08 Platinum	79 Au 196.97 Gold	80 Hg 200.59 Mercury	81 Tl 204.38 Thallium	82 Pb 207.2 Lead	83 Bi 208.98 Bismuth	84 Po (209) Polonium	85 At (210) Astatine	86 Rn (222) Radon
Period 7	87 Fr (223) Francium	88 Ra 226.03 Radium	Actinide series (see below)	104 Rf (261) Rutherfordium	105 Df (262) Dubnium	106 Sg (263) Seaborgium	107 Bh (264) Bohrium	108 Hs (265) Hassium	109 Mt (266) Meiterium	110 (269)	111 (272)	112 (277)		114 (281)		116 (289)		118 (293)

Rare earth elements—Lanthanide series	57 La 138.91 Lanthanum	58 Ce 140.12 Cerium	59 Pr 140.91 Praesodymium	60 Nd 144.24 Neodymium	61 Pm (145) Promethium	62 Sm 150.4 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.93 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.93 Holmium	68 Er 167.26 Erbium	69 Tm 168.93 Thulium	70 Yb 173.04 Ytterbium	71 Lu 174.97 Lutetium
Actinide series	89 Ac 227.03 Actinium	90 Th 232.04 Thorium	91 Pa 231.04 Protactinium	92 U 238.03 Uranium	93 Np 237.05 Neptunium	94 Pu (244) Plutonium	95 Am (243) Americium	96 Cm (247) Curium	97 Bk (247) Berkelium	98 Cf (251) Californium	99 Es (252) Einsteinium	100 Fm (257) Permium	101 Md (258) Menelevium	102 No (259) Nobelium	103 Lr (260) Lawrencium

TABLE 2.1.4 The Chemical Elements

Element	*Symbol*	*Atomic No.*	*Atomic Weight*	*Element*	*Symbol*	*Atomic No.*	*Atomic Weight*
Actinium	Ac	89	(227)	Mercury	Hg	80	200.59
Aluminum	Al	13	226.98	Molybdenum	Mo	42	95.94
Americium	Am	95	(243)	Neodymium	Nd	60	144.20
Antimony	Sb*	51	121.75	Neon	Ne	10	20.18
Argon	Ar	18	39.95	Neptunium	Np	93	237.05
Arsenic	As	33	74.92	Nickel	Ni	28	58.71
Astatine	At	85	(210)	Niobium	Nb	41	92.91
Barium	Ba	56	137.34	Nitrogen	N	7	14.01
Berkelium	Bk	97	(247)	Nobelium	No	102	(254)
Beryllium	Be	4	9.01	Osmium	Os	76	190.20
Bismuth	Bi	83	208.98	Oxygen	O	8	16.00
Boron	B	5	10.81	Palladium	Pd	46	106.40
Bromine	Br	35	79.90	Phosphorus	P	15	30.97
Cadmium	Cd	48	112.40	Platinum	Pt	78	195.09
Calcium	Ca	20	40.08	Plutonium	Pu	94	(244)
Californium	Cf	98	(251)	Polonium	Po	84	(210)
Carbon	C	6	12.01	Potassium	K	19	39.10
Cerium	Ce	58	140.13	Praseodymium	Pr	59	140.91
Cesium	Cs	55	132.91	Promethium	Pm	61	(145)
Chlorine	Cl	17	35.45	Protoactinium	Pa	91	231.04
Chromium	Cr	24	52.00	Radium	Ra	88	226.03
Cobalt	Co	27	58.93	Radon	Rn	86	(222)
Copper	Cu	29	63.55	Rhenium	Re	75	186.20
Curium	Cm	96	(247)	Rhodium	Rh	45	102.91
Dysprosium	Dy	66	162.50	Rubidium	Rb	37	85.47
Einsteinium	E	99	(254)	Ruthenium	Ru	44	101.07
Erbium	Er	68	167.26	Samarium	Sm	62	150.40
Europium	Eu	63	151.96	Scandium	Sc	21	44.96
Fermium	Fm	100	(257)	Selenium	Se	34	78.96
Fluorine	F	9	19.00	Silicon	Si	14	28.09
Francium	Fr	87	(223)	Silver	Ag	47	107.87
Gadolinium	Gd	64	157.20	Sodium	Na	11	22.99
Gallium	Ga	31	69.72	Strontium	Sr	38	87.62
Germanium	Ge	32	72.59	Sulfur	S	16	32.06
Gold	Au	79	196.97	Tantalum	Ta	73	180.95
Hafnium	Hf	72	178.49	Technetium	Tc	43	98.91
Helium	He	2	4.00	Tellurium	Te	52	127.60
Holmium	Ho	67	164.93	Terbium	Tb	65	158.93
Hydrogen	H	1	1.01	Thallium	Tl	81	204.37
Indium	In	49	114.82	Thorium	Th	90	232.04
Iodine	I	53	126.91	Thulium	Tm	69	168.93
Iridium	Ir	77	192.20	Tin	Sn	50	118.69
Iron	Fe	26	55.85	Titanium	Ti	22	47.90
Krypton	Kr	36	83.80	Tungsten	W	74	183.80
Lanthanum	La	57	38.91	Uranium	U	92	238.03
Lawrencium	Lr	103	(257)	Vanadium	V	23	50.94
Lead	Pb	82	207.20	Xenon	Xe	54	131.30
Lithium	Li	3	6.00	Ytterbium	Yb	70	173.04
Lutetium	Lu	71	174.97	Yttrium	Y	39	88.91
Magnesium	Mg	12	24.31	Zinc	Zn	30	65.38
Manganese	Mn	25	54.94	Zirconium	Zr	40	91.22
Mendelevium	Md	101	(256)				

Note: Based on the assigned relative atomic mass of the carbon-12 isotope equal to 12.00. Most elements consist of isotope mixtures. Elements with atomic weights in parentheses are unstable isotopes.

*In some cases, the symbol bears no relationship to the English name of the element. These symbols are derived from the Latin names, thus: Ag (Silver, or Argentum), Au (Gold, or Aurum), Fe (Iron, or Ferrum), Hg (Mercury, or Hydrargyrum), K (Potassium, or Kalium), Na (Sodium, or Natrium), Pb (Lead, or Plumbum), Sn (Tin, or Stannum), and Sb (Antimony, or Stibium).

Isotope. Atoms that contain the same number of protons but different numbers of neutrons are called *isotopes.* Most elements have more than one isotope (e.g., C-12 and C-13 contain six protons, but they have six and seven neutrons, respectively).

Molecule. Molecules are groups of atoms combined in fixed proportions. Substances composed of molecules that contain two or more different kinds of atoms are called *compounds.* The molecules of a single compound are identical.

Chemical Formula. A chemical formula represents the number of atoms of the various elements in a molecule. For example, water is H_2O (two atoms of hydrogen and one of oxygen) whereas propane is C_3H_8, where C stands for carbon (see Table 2.1.4 for symbols of other elements). A formula may be written to indicate the arrangement of the atoms in the molecule. Thus, propane is $CH_3CH_2CH_3$.

Molecular Weight of a Compound. The molecular weight of a compound is the sum of the atomic weights of all atoms in its molecule. For example, from its chemical formula, the molecular weight of propane (C_3H_8) is $(3 \times 12 + 8 \times 1) = 44$. The *gram molecular weight* of a substance is the mass of the substance equal to its molecular weight in grams.

Mole. A mole of an element or compound is the amount that corresponds to the gram molecular weight. Thus, one mole of propane has a mass of 44 g. One mole of any element or compound contains 6.022×10^{23} molecules (see definition of *atomic weight*).

Chemical Reaction. A chemical reaction is a process by which *reactants* are converted into *products.* More often than not, the equation that is used to describe a chemical reaction hides the details of the mechanism by which the change takes place. Thus, the equation for the oxidation of propane is written conventionally as

$$C_3H_8 + 5O_2 = 3CO_2 + 4H_2O$$

However, the mechanism is very complex and involves highly reactive species called free radicals. Free radicals include atomic hydrogen and oxygen, the hydroxyl radical (OH), and many more. The conversion of propane to carbon dioxide and water involves hundreds of intermediate steps (*elementary reactions*), which create a chain reaction. Typical elementary reactions are

$$C_3H_8 + H = C_3H_7 + H_2$$

$$C_3H_8 + OH = C_3H_7 + H_2O$$

$$C_3H_7 + O_2 = C_3H_6 + HO_2$$

The radicals are highly reactive and very short-lived. The reaction of H atoms with molecular oxygen is particularly important because it leads to chain branching:

$$H + O_2 = OH + O$$

$$C_3H_8 + O = C_3H_7 + OH$$

in which one free radical (the H atom) is replaced by three (two OH and one C_3H_7). At high temperatures, the reaction begins to dominate and the conversion rate (propane to products) increases dramatically. If species that remove hydrogen atoms (e.g., halons) are added to a flame, then the conversion rate (i.e., the rate of burning) falls dramatically as explained in Section 2, Chapter 7, "Theory of Fire Extinguishment."

Stoichiometric/Stoichiometry. A stoichiometric mixture of fuel and air is one in which there is an exact equivalence of fuel and oxygen (in the air) so that after combustion all fuel has been consumed and no oxygen is left. The equation for the oxidation of propane (see above) defines the stoichiometric propane/oxygen mixture as 1:5 (by volume). As oxygen is approximately 21 percent of normal air, the stoichiometric propane/air mixture would be 1:(5/0.21), that is, 1:23.8 (by volume).

$$C_3H_8 + 5O_2 + 18.8N_2 = 3CO_2 + 4H_2O + 18.8N_2$$

This formula corresponds to a ratio of 1:15.7 by mass. Note that the nitrogen does not take part in the reaction, although the energy released by the reaction will be distributed between the reaction products CO_2 and H_2O and the nitrogen, which has the effect of reducing the flame temperature as the nitrogen acts as a "thermal sink." (The expected premixed flame temperature for a stoichiometric propane/oxygen mixture is of the order of 4500ºC whereas that for a stoichiometric propane/air mixture is approximately 2000ºC.)

Heat of Reaction. The heat of a chemical reaction is the energy that is absorbed or released when that reaction takes place. *Exothermic* reactions release energy when they occur whereas energy is absorbed when an *endothermic* reaction takes place. Combustion reactions are exothermic, implying that the products are more stable than the reactants. Endothermic reactions include the pyrolysis of solid fuels, as well as the decomposition processes that occur in concrete when chemically bound water is released at high temperature.

The chemistry of fire processes encompasses not only oxidation reactions in the gas phase but also thermal decomposition, or pyrolysis, reactions that are associated with the release of flammable vapors from combustible solids. Gas phase oxidation is an exothermic, self-sustaining reaction that is usually (but not necessarily) associated with the reaction of fuel vapors with atmospheric oxygen. In flaming combustion of solids and liquid fuels, vaporization is an essential part of the burning process. However, it should be remembered that some solids can undergo glowing combustion or smoldering in which oxygen reacts directly at the surface of the solid (see Ohlemiller[19] and Section 2, Chapter 3, "Flammability Hazard of Materials").

A flame represents a gas phase oxidation process. The premixed flame is much more efficient than a diffusion flame and the conversion of fuel into combustion products is very rapid (see above). As the oxidation process is exothermic, the mixture of combustion products and nitrogen (from the air) is at a high temperature (certainly more than 1600 K) and will occupy a greater volume if allowed to expand or create a high pressure, if confined (see Equation 16) (Section 2, Chapter 8).

Fuels include innumerable materials that, due to their chemistry, can be oxidized to yield more stable species, such as carbon dioxide and water; thus, for example,

$$C_3H_8 + 5O_2 = 3CO_2 + 4H_2O$$

Hydrocarbons, such as propane (C_3H_8), consist entirely of carbon and hydrogen and may be regarded as "prototype fuels." All common fuels, whether solid, liquid, or gaseous, are based on the element carbon, with significant proportions of hydrogen, and may also contain oxygen (e.g., wood, polymethylmethacrylate [PMMA]), nitrogen (e.g., wool, nylon), chlorine (e.g., polyvinyl chloride [PVC]), and so on.

In the present context, the most common oxidizing agent is molecular oxygen (O_2) in the air, which comprises approximately one-fifth oxygen and four-fifths nitrogen. However, certain chemicals are powerful oxidizing agents, such as sodium nitrate ($NaNO_3$) and potassium chlorate ($KClO_3$), which, if intimately mixed with a solid or liquid fuel, produce highly reactive mixtures. Thus, gunpowder is a physical mixture of carbon and sulfur (the fuel) with sodium nitrate as the oxidizer. If reactive groups, such as the nitrate group (NO_3), are incorporated chemically into a fuel, such as in cellulose nitrate or trinitrotoluene (TNT), the resulting species can be highly unstable and will decompose violently under appropriate conditions (see Section 6, Chapter 15, "Explosives and Blasting Agents").

There are circumstances involving reactive species in which combustion may take place without oxygen being involved. Thus, hydrocarbons may "burn" in an atmosphere of chlorine, whereas zirconium dust can be ignited in pure carbon dioxide.

Ignition. Before examining the detailed chemistry of fire, it is appropriate to identify the conditions under which liquid and solid fuels can be ignited. Ignition is the process by which self-sustaining combustion is initiated. Thus, for a flammable vapor/air mixture (i.e., the fuel concentration lies within well-defined flammability limits as discussed in Section 2, Chapter 8, "Explosions"), introduction of the ignition source in the form of a spark or small flame will result in a flame propagating through the mixture. The relevance of this process to condensed fuels (liquids and solids) is best illustrated by considering the concept of flashpoint for liquid fuels. Flashpoint defines the critical condition under which a fuel can be ignited and refers to the minimum temperature at which a flammable vapor-air mixture exists above the surface of the liquid. It can be measured in a closed cup apparatus. The closed cup flashpoint corresponds to the temperature at which the equilibrium vapor pressure is equal to the lower flammability limit. Introduction of a pilot ignition source into the headspace above the liquid surface gives rise to a flash of flame. It can be measured in the Pensky-Martens Closed Cup Apparatus.[20]

The open cup flashpoint is measured under conditions when the fuel vapor can diffuse away from the surface of the liquid. It is the lowest bulk liquid temperature at which a flash of flame is observed when an ignition source is present at the rim of the container that is specified in the standard test. All the fuel vapor within the flammability limits is consumed momentarily, but flaming does not persist. It is measured in the Cleveland Open Cup Apparatus.[21] (The open cup flashpoint is higher than the closed cup flashpoint although the behavior of methanol and ethanol is anomalous.[22])

For ignition to be followed by continuous burning of the liquid, its temperature must be raised to the firepoint, which may also be measured in the Cleveland Open Cup Apparatus. Introduction of an ignition source into the vapor-air mixture above the liquid surface will give a flash of flame, but this will be followed by sustained burning. The firepoint temperature is higher than the open cup flashpoint. To give an example, for *n*-decane (n-$C_{10}H_{22}$), the closed cup and open cup flashpoints, and the firepoint are 46°C, 56°C, and 64°C, respectively.

For both combustible liquids and solids, initiation of flaming occurs in the gas phase. Energy is required to convert sufficient fuel into the vapor phase to create a flammable vapor-air mixture in the vicinity of the surface. For most liquid fuels, this is simply a process of evaporation, but almost all solid fuels must undergo chemical decomposition before vapor is released. The minimum temperature associated with the formation of a flammable mixture at the fuel surface is easily determined for liquid fuels as the bulk temperature of the liquid. However, although exactly the same phenomena of flashpoint and firepoint can be observed for combustible solids, the process involves irreversible chemical changes and they can only be defined in terms of surface temperature. This surface temperature is not normally measured, and it is more common to determine the ignition characteristics of combustible solids as a function of imposed heat flux (see Section 2, Chapter 3, "Flammability Hazard of Materials"). It should be noted that this type of ignition requires the presence of a pilot ignition source. In practice, the piloted ignition temperatures of solids are influenced by air movement, the rate of heating, and the size and shape of the fuel bed. For this reason, measured ignitability characteristics of a solid depend on the specific test method used.

The ease with which a combustible solid may be ignited is determined in part by the chemical composition of the material, although it must be emphasized that the physical form of the material and the environment in which it is located can have a significant, if not an overriding, effect. The clearest examples of this effect are the effects of fuel thickness (wood shavings are easily ignited, whereas wooden planks are not) and of density (polyurethane foam can be ignited very easily because of its low thermal inertia, whereas solid polyurethane of high density will be relatively difficult to ignite; compare with the data presented in Figure 2.1.4).

The effect of chemical composition on "ease of ignition" can be illustrated by referring to two specific properties, the heat of combustion of the vapors and their reactivity. If the heat of combustion is high, then more energy will be available to sustain flaming after ignition. For example, the heat of combustion of the vapors arising from polypropylene is approximately 44 kJ/g whereas that for the vapors released from wood is about 14 kJ/g, and from PMMA c. 23 kJ/g.[11] These differences are partially offset by the fact that the firepoint temperature for polypropylene is 360°C, whereas those for wood and PMMA are approximately 300°C. The reactivity of the vapors will depend in part on the presence of flame-retardant elements such as chlorine and bromine in the formulation of the solid (e.g., PVC).

These species inhibit the reactions in the flame (see below) to an extent that higher temperatures will be necessary for combustion to take place.

CHEMICAL REACTIONS IN FLAMES

Our understanding of the processes that take place within a flame arise from detailed experimental studies of premixed flames. An oxidation reaction can be expressed, quite simply, as the balanced chemical reaction, showing reactants and products in their stoichiometric proportions; thus, for methane

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

However, this is simply a statement of the proportion of stable final products that results from this combustion process and it hides a complexity of detail as discussed earlier. The conversion takes place by a series of elementary reactions—"elementary" in the sense that they cannot be split into simpler chemical steps. These involve reactions of free radicals, highly reactive molecular fragments produced during the reaction sequence. The principal elementary reactions for the oxidation of methane (CH_4) are shown in Table 2.1.5.

The process can be initiated by an ignition source that introduces free radicals into the system. (Alternatively, at a high enough temperature, free radicals will be formed spontaneously by reactions a and b in Table 2.1.5.) In reaction a, dissociation of a methane molecule (energy being transferred during the collision with a third body [M]), produces two reactive species, the methyl radical (CH_3) and a hydrogen atom (H). The methyl radical will react readily with an oxygen molecule (reaction g) to produce formaldehyde (CH_2O) and the free hydroxyl radical (OH). CH_2O turns out to be the main source of the highly toxic species carbon monoxide (CO) via reactions h to m. CO is oxidized to CO_2 when it reacts with OH (reaction p), but if reaction p is interrupted due to a shortage of OH radicals, for example, then CO will be a product of "incomplete combustion." This will occur if the mixture is fuel rich and there is insufficient oxygen present to burn all the fuel.

TABLE 2.1.5 The Reaction Mechanism for the Oxidation of Methane

$CH_4 + M = CH_3 + H + M$	a
$CH_4 + O_2 = CH_3 + HO_2$	b
$CH_4 + H = CH_3 + OH$	c
$CH_4 + OH = CH_3 + H_2O$	d
$O_2 + H = O + OH$	e
$CH_4 + O = CH_3 + OH$	f
$CH_3 + O_2 = CH_2O + OH$	g
$CH_2O + O = CHO + OH$	h
$CH_2O + OH = CHO + H_2O$	i
$CH_2O + H = CHO + H_2$	j
$CHO + O = CO + OH$	k
$CHO + OH = CO + H_2O$	l
$CHO + H = CO + H_2$	m
$H_2 + O = H + OH$	n
$H_2 + OH = H + H_2O$	o
$CO + OH = CO_2 + H$	p
$H + OH + M = H_2O + M$	q
$H + H + M = H_2 + M$	r
$H + O_2 + M = HO_2 + M$	s

Methane is consumed by reactions c and d and, to a lesser extent, by reaction f. The higher the concentration of free radicals (H and OH, particularly), the more rapidly the methane will be consumed and the faster the overall process. The most important pair of reactions consists of reactions e and f, which lead to chain branching and a rapid acceleration of the overall reaction due to the increase in the number (and hence the concentration) of free radicals. As can be seen in reactions c, d, and h–m, the rate of consumption of methane and the rate of formation of H_2O, CO, and CO_2 are directly linked to their concentration. This link to their concentration is responsible for very high reaction rates and leads to rapid flame propagation through any methane-air mixture within the flammability range. The hydrogen atom is a key participant in this process and, as reaction e occurs during the oxidation of all hydrogen-containing fuels, the mechanism illustrated in the preceding sequence is common to all systems in which we are interested.

Detailed analysis of these oxidation reaction systems is beyond the scope of this chapter, but it is covered in detail elsewhere. Two points need to be emphasized here.

First, any process that reduces the rate of the branching reaction (reaction e) will have a disproportionate effect on the rate of the reaction as it will effectively stop the branching process from occurring. The most efficient flame suppressants, including the halons, work in this way and will render flammable vapor-air mixtures nonflammable at relatively low concentrations (typically 8% or less). Flammable mixtures may also be inerted by the addition of a gas, such as carbon dioxide, but will require much higher concentrations (approximately 30%), because the action is physical and not chemical. (It acts as a "heat sink," reducing the flame temperature to below the critical value of c. 1300°C.) For combustible solids, there is a range of flame-retardant additives, which can improve the fire properties, such as ignitability. These additives commonly contain chlorinated and brominated species, which are released when the material becomes involved in a fire or is exposed to an ignition source. These volatile species will be released at the same time as the fuel vapors. Hydrogen chloride and hydrogen bromide will be formed and will effectively scavenge hydrogen atoms and inhibit the flame. Chlorine and bromine atoms are relatively unreactive and cannot give rise to chain branching.

$$H + HCl = H_2 + Cl$$

$$H + HBr = H_2 + Br$$

Second, if there is any interruption of the reaction sequence, then intermediate species such as formaldehyde (CH_2O) or car-

bon monoxide (CO) in the preceding example will survive and escape the flame unburnt. This reaction can occur during fuel-rich combustion and is the source of toxic and harmful species that are associated with smoke from a fire. With more complex fuels such as propane and gasoline, the variety of intermediate products is very large, and the potential to generate a range of noxious gases is considerable. In a diffusion flame, this process will begin with the pyrolysis of the fuel vapor in the fuel-rich parts of of the flame. This can produce reactive species which can undergo polymerization in the flame, building up large molecules that are resistant to oxidation. These species form the minute soot particles within the flame that grow in size and radiate to produce the characteristic yellow luminosity associated with diffusion flames. If these escape from the flame, they agglomerate to form smoke particles. In general, the larger the fire, the greater the number of soot particles and the greater the yield of smoke.

In the preceding discussion, the emphasis has been on premixed combustion as it is this model that gives us the greatest understanding of the reactions that take place in a flame. However, in real fires, premixed combustion is relatively unimportant, and the flames that we observe are diffusion flames in which the mixing of fuel vapors and air involves laminar or turbulent diffusion and the concentrations of fuel and air are not uniform. As discussed earlier, the amount of air entrained into a diffusion flame greatly exceeds the stoichiometric requirement, yet combustion of the fuel vapor is seldom, if ever, complete for this reason.

The mechanism of soot formation in flames appears to involve the polymerization of small reactive molecules within the fuel-rich regions of the flame.[23,24] These build up to produce structures similar in nature to the aromatic ring that have a degree of resistance to oxidation.[25] Once formed, they can coalesce to produce the minute particles that will eventually escape from the flame as smoke. The yield of smoke from a fire will depend at least in part on the chemical nature of the fuels involved. However, if a fire is burning under poorly ventilated conditions, such as in a compartment with limited ventilation, the yield of smoke will be significantly higher. Under these circumstances, it is expected that the yield of carbon monoxide and other noxious species will also be higher. It is known that soot particles in the flame will compete with carbon monoxide for hydroxyl radicals (OH), thus reducing the rate of conversion of carbon monoxide to carbon dioxide according to reaction p.

During the early stages of fire development in a compartment (Section 2, Chapter 4, "Dynamics of Compartment Fire Growth"), the fire products accumulate under the ceiling and will radiate downward, increasing the rate of burning. As the fire grows in size, many reactions will occur in the hot gas layer, and the yields of partially burnt combustion products will increase. A number of studies have shown that as the equivalence ratio increases, the yield of carbon monoxide increases.[26,27] This increased yield of carbon monoxide is associated with an advanced stage in the preflashover fire when the flames are entering the smoke layer, temperatures are high, and the oxygen concentration is reduced. Smoke escaping from the upper layer into the rest of the building at this stage will be highly toxic.

BURNING OF SOLIDS AND LIQUIDS

In Section 2, Chapter 3, the concept of flammability of materials is discussed in detail. It consolidates much of the information contained in this chapter that is based on the relevant chemistry and physics of the fire process. The burning process itself can be understood in terms of heat and mass transfer associated with the burning surface (see Figure 2.1.1 and Equation 1). It is appropriate to emphasize that Equation 1 can be modified to take into account additional heat transfer provided by nearby heat sources or burning items.

$$\dot{m}'' = \frac{\dot{Q}''_{\text{flame}} + \dot{Q}''_{\text{ext}} + \dot{Q}''_{\text{loss}}}{L_g} \text{ kg/m}^2\cdot\text{sec}$$

where $\dot{Q}''_{\text{ext}}$(kW/m^2) represents the heat flux to the surface from other sources. The actual rate of burning is very sensitive to all three terms in the numerator, which is the reason why reproducibility is a major problem in fire experiments. This is particularly true in the standard tests, which are designed to capture one or more "properties" of a combustible material. Relatively minor changes to the apparatus can have a disproportionate effect on the result. To understand and appreciate why this should be the case, it is necessary to examine the fundamentals of the burning process, recognizing that there are many other factors that should be taken into account, including the geometry of the fuel surface, whether it is vertical or horizontal, whether it will melt and flow when it is heated, and if flame retardants are present.

SUMMARY

Fire is a complex phenomenon. To gain an understanding of fire behavior, it is necessary to have at least a basic knowledge of a range of subjects, including chemistry, physics, heat and mass transfer, and fluid dynamics. In this chapter, some of the chemistry and physics required to explain the most important aspects of fire behavior are presented. The relevant terminology is explained in detail and an attempt has been made to place the individual terms in context. It is important to use terminology that is consistent with scientific and engineering disciplines.

The underlying science of fire protection engineering rests on the following principles:

1. For combustion to take place, an oxidizing agent, a combustible material, and an ignition source are essential. (The exception is spontaneous combustion, which does not require an independent ignition source.)
2. The combustible material must be heated to its piloted ignition temperature before it can be ignited or can support the spread of flame.
3. Subsequent burning of a combustible material is governed by the heat feedback from the flames to the pyrolyzing or vaporizing combustible (Equation 1).
4. The burning will continue until one of the following happens:
   a. The combustible material is consumed.
   b. The concentration of oxidizing agent (normally, oxygen in the air) is lowered to below the concentration necessary to support combustion.

c. Sufficient heat is removed or prevented from reaching the combustible material, thus preventing further fuel pyrolysis.
d. The flames are chemically inhibited or sufficiently cooled to prevent further reaction.

All the material presented in this handbook for the prevention, control, or extinguishment of fire is based on the principles outlined in this chapter.

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Chapter 2

Physics of Fire Configuration

Ronald L. Alpert

Chapter Contents

Flammable Gas Jets and Liquid Sprays
Pools or Horizontal, Upward-Facing Surfaces
Walls or Vertical Surfaces
Ceiling or Horizontal, Downward-Facing Surfaces
Inclined Material Surfaces
Parallel Facing Vertical Surfaces
Ceiling-Corner Surface Combinations
Combustible Ducts

Key Terms

ceiling fire, corner fire, duct fire, fire growth, fire plume, flammable jet, flammable spray, flue fire, heat flow, heat release rate, heat transfer, King's Cross Station fire, pool fire, wall fire

The behavior of the flaming combustion zone in an accidental fire is highly scenario dependent, with the configuration, scale, and composition of the burning material being the salient factors. Configuration, however, is the most important of these factors since for a wide range of synthetic and natural polymer fuels and for combustible surface scales greater than the order of 3.3 ft (1 m) in height or width, fire characteristics are mainly determined by the configuration of the combustible surface. These defining characteristics include flame shape and motion, flame heat transfer, and flame spread rates that lead to propagation of the fire to new, uninvolved areas of fuel. The chapter discusses many of the defining characteristics of fires in the following configurations of the combustible surface:

- Fuel jets, sprays, and atomized combustible liquids
- Liquid pools or horizontal, upward-facing combustible surfaces
- Single walls or vertical combustible surfaces
- Ceilings or horizontal, downward-facing combustible surfaces
- Inclined upward-facing or downward-facing combustible surfaces
- Parallel, vertical combustible surfaces
- Ceiling-corner combustible surfaces
- Combustible ducts

The jet/spray configuration is applicable to gaseous and liquid fuels and the pool (or floor) configuration pertains both to liquid fuels and solid combustible surfaces, including those that melt rather than char. The remaining configurations, which relate only to solid combustible surfaces, include both single, isolated flat surfaces and combinations of flat or curved surfaces.

For related topics see also Section 2, Chapter 1, "Physics and Chemistry of Fire"; Section 2, Chapter 4, "Dynamics of Compartment Fire Growth"; and Section 21, Chapter 11, "Road Tunnels and Bridges."

FLAMMABLE GAS JETS AND LIQUID SPRAYS

Accidental leakage of gases and liquids pressurized in pipes or hoses can lead to gas jets or atomized liquid sprays that are easily ignited to form large, turbulent flames.[1] Such an accident scenario is a serious concern in many industries and has even resulted from natural gas leaks with domestic appliances. The mass flow of fuel to the jet or spray in these cases is not determined by flame heat transfer, as with other types of fires, but by the flow rate from the leakage orifice. If the fuel is a liquid, the combination of orifice size and pressure drop across the orifice determines the degree of atomization (i.e., the distribution of droplet sizes) of the liquid based on a critical Weber number.[2] Sufficiently small droplet sizes (e.g., less than 0.004 in. [0.1 mm] diameter) ensure that the fuel is burned completely in the spray, but larger drop sizes (e.g., greater than 0.04 in. [1 mm]) can result

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in some of the fuel "raining" out from the spray to form a liquid pool that may burn in a new configuration (see section below on pool fires).

Although close to the leak orifice the gas jet or spray may be a momentum-dominated, high-velocity flow, further from the orifice the flame behavior is dominated by buoyancy, tending toward a vertical fire plume. This buoyant flow of flame presents a significant thermal radiation hazard to the surroundings since flame lateral dimensions are often large enough to produce an optically thick radiant source of heat flux in the range of 10.6 to 14.1 Btu/ft^2·sec (120 to 160 kW/m^2) toward vulnerable targets near or within the flames.[3] In addition to the radiant flux, there is a significant (but smaller) convective heat flux due to the gas velocity in the jet/spray flame. Whereas the radiant flux is highest in the buoyancy-dominated region of the large-scale plume, the convective flux is highest in the high momentum region near the leak orifice.

Because of the high levels of radiant and/or convective heat flux in fuel-jet and spray flames, it is important to be able to estimate the length or height of these flames, since a structure (e.g., roof beams) engulfed by such flames could fail catastrophically. Flame length correlation formulas for gas jets[4] are similar to those for pool fires as long as the length of flame controlled by buoyancy is much greater than the high momentum region. For liquid spray flames, at least two correlation formulas are available.[1,5]

POOLS OR HORIZONTAL, UPWARD-FACING SURFACES

General Behavior of Flames

Flammable Liquid Fires. Liquid fuels from accidental leaks in tanks or piping generally flow to the lowest accessible surface. Such liquids are often contained by dikes, dams, or other obstructions (e.g., compartment walls) so that a pool is formed. Burning, if not already established in the liquid near the leakage origin, may then be initiated, depending on the presence of an ignition source and the flammability of the liquid. The resulting liquid pool fire has flames that pulsate by shedding roughly symmetrical ring vortices (see "smoke rings" in Figure 2.2.1) moving up from the pool surface to the flame tip at a distinctive, observable frequency, *f*. Vortex shedding is due to complex interactions between the inflowing air, the fire plume, and the pool boundary. The flame pulsation frequency is affected by the actual or equivalent diameter, *D*, of the burning pool such that[6]

$$f\left(\frac{D}{g}\right)^{1/2} \approx 0.5$$

Pool fire flames are strongly affected by the amount of *freeboard,* or the distance between the top edge of the pool boundary and the liquid surface. If the liquid is nearly flush with the top of the container, the flames neck immediately above the pool to form a relatively stable, slender fire plume.[7] As the freeboard increases, however, the base of the flames billows outward beyond the pool boundary and becomes more turbulent. Because of this change in pool fire flame shape, associated changes in heat flow back to the liquid fuel occur, leading to an increased burning rate as the freeboard increases from zero (the liquid at the top of the container) up to a maximum when the freeboard value is comparable to the pool scale.

FIGURE 2.2.1 Flames from 15 m × 15 m Crude Oil Pool Fire, Showing Pulsation Vortices ("Smoke Rings") and Smoke Mantle Covering Upper Portion of Flames (Source: NIST Building and Fire Research)

Another defining characteristic of pool fire flames occurs when the diameter or minimum dimension of the pool becomes greater than a critical value of 10 to 20 ft (3 to 6 m) for virtually all fuels (including even LNG).[8] At this critical pool dimension, a smoke mantle begins to form near the flame tip, covering the outer surface of the flame. The smoke mantle obscures more and more of the flame as the diameter or minimum dimension of the pool increases further above the critical value, as shown in Figure 2.2.1. Due to this flame obscuration, thermal radiant emission from the flame envelope where there is a smoke mantle is very low, less than 1.8 Btu/ft^2·sec (20 kW/m^2).

Fires on Solid Surfaces. Solid, upward-facing combustible surfaces, such as floors or carpeting, can produce pool fire flames similar to those from a liquid, once flaming has been established

on the surface (see below for further discussion on flame spread across solids and liquids). In the case of solid combustible materials, the fuel can be distributed not just on a flat, horizontal surface but also in complex arrays, for example, as a variety of storage arrangements or as the fully involved contents of one or more enclosures on one or more elevations of a structure. When the surface area of fuel involved in flaming combustion becomes sufficiently large (e.g., a stack of three or more wooden pallets), the height of flames in the fire plume may be much greater than the height of the combustible array or dimensions of any of the individual elements in the array. At this point, the flames have the appearance of those in a pool fire, with the pulsation and smoke mantle characteristics discussed earlier. In fact, there have been instances of an entire single-story warehouse fully involved in fire but with flames covered so completely by the smoke mantle, due to the size of the warehouse, that trucks were still able to pull trailers away from the loading docks at the periphery of the building during the fire.

Heat Flow

For small pool fires with equivalent diameters up to about 6 in. (150 mm), heat flow from the flame to the burning fuel is mostly due to convective heat transfer and to conduction heat loss to the container/boundary. For larger pool diameters greater than about 3.3 ft (1 m), however, this heat flow is dominated by flame radiation and radiation blockage near the pool surface. Because the flame thickness is greatest at the center of the pool and becomes much smaller at the edges, the radiation-dominated heat transfer rate to the combustible also attains a peak value near the center of the pool, typically reaching a value of 3.5 to 6.2 Btu/ft^2·sec (40 to 70 kW/m^2) for pools up to several meters across.[9] Note that this heat flux is well below the maximum emissive power (about 14.1 Btu/ft^2·sec [160 kW/m^2]) of pool fire flames[3] because of the absorption of roughly half the incident radiation near the pool surface by cooler, soot-laden fuel vapors.

Fire Growth

After flame spreads across the surface of a flammable liquid pool fire, a steady burning rate is established,[10] leading to heat release rates of 176 to 264 Btu/ft^2·sec (2000 to 3000 kW/m^2) for a wide range of hydrocarbon liquids. The time for flame spread will be very short for fuels with a boiling point near or below normal ambient temperature but will increase as the fuel boiling point increases above ambient. For flammable liquids with the highest boiling points, the rate of flame spread will be very low unless there is a substantial ignition source that raises the bulk temperature of the liquid. This flame spread time will be influenced by effects of surface tension and convective flow in the liquid and hence will be dependent on the depth of the liquid. Burning rate is also dependent on the liquid depth and, in fact, cannot be sustained if the liquid depth becomes less than a few millimeters.

An interesting feature of flammable liquid pool fires occurs when a fixed volume flammable liquid spills on a nearly level surface that is not bounded by dams or dikes. As the spill area increases due to a balance between gravity, liquid inertia, and liquid surface tension (not due to additional liquid added to the spill), the burning rate of the liquid also increases proportionally to the area, meaning that the fire duration will keep decreasing for a fixed amount of liquid. Hence, whereas flame heat flux at a given height above the pool can only increase up to a maximum value—that is, the emissive power of the flames, neglecting convection—the duration of application of this heat flux decreases the larger the pool area becomes.

For combustible solid materials on horizontal surfaces, steady burning may occur after a relatively slow "creeping" flame spread involves the entire material surface, assuming that flame spread is complete before there is significant burn-out or consumption of available fuel. Unlike upward fire propagation, "creeping" flame spread is a very stable, steady process, in which the flame front anchors to the surface at a point where an opposed flow of air, drawn in ahead of the flame, meets fuel vapor to sustain ignition conditions (hence the alternate name, *opposed flow flame spread*). If the flame spread front is roughly circular on the horizontal surface and because the outward "creeping" velocity, v, is nearly constant, then the radius, R, of the flaming region is increasing proportional to time, t ($R = vt$). The area of the active pool fire then increases as t^2 and the total heat release rate (HRR) also increases as t^2. As this same type of slow, constant, radial spread velocity can also occur within a complex array of combustible surfaces (e.g., pallets or box storage) to form an expanding area pool fire at the top surface of the array, it is often assumed that heat release rate increases as t^2 in real fires.

WALLS OR VERTICAL SURFACES

General Behavior of Flames

Fires established on vertical combustible surfaces are especially dangerous because of the potential for rapid upward fire spread, which will be discussed in detail below. Such surfaces are virtually everywhere in the built environment because of the presence of wall linings and decorations, as well as various storage arrangements attached to walls. In commercial establishments and institutions, the practice of storing boxed and open products to very great heights (e.g., from several meters in small stores and libraries up to tens of meters in warehouses) greatly increases the potential for a destructive fire if there is an accidental ignition.

Flames on vertical burning surfaces transition from a steady laminar flow to a turbulent flow near the flame base. With increasing height on the vertical surface, flame thickness increases proportionally, which results in increased thermal radiation both to the material surface and outward to potential targets.[11] This can be seen from the increase in flame brightness with height, as shown in Figure 2.2.2, where a 12 ft (3.66 m) high wall of polymethyl methacrylate (PMMA) polymer slab is burning between water-cooled sidewalls that confine the flames and produce near uniformity from side to side.[12] It can also be observed in Figure 2.2.2 that the flames extend above the burning surface (where the sidewalls are absent) a distance equal to less than half the slab height. When there is no sidewall confinement of flames on the burning wall, as in Figure 2.2.3, the flame extension above the burning region is much less. Figure 2.2.3 is

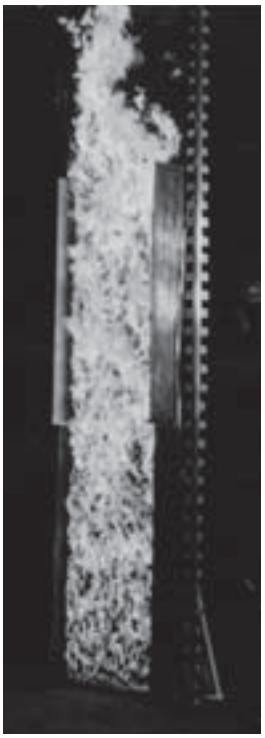

FIGURE 2.2.2 PMMA Wall Fire 12 ft (3.66 m) High with Water-Cooled Sidewalls

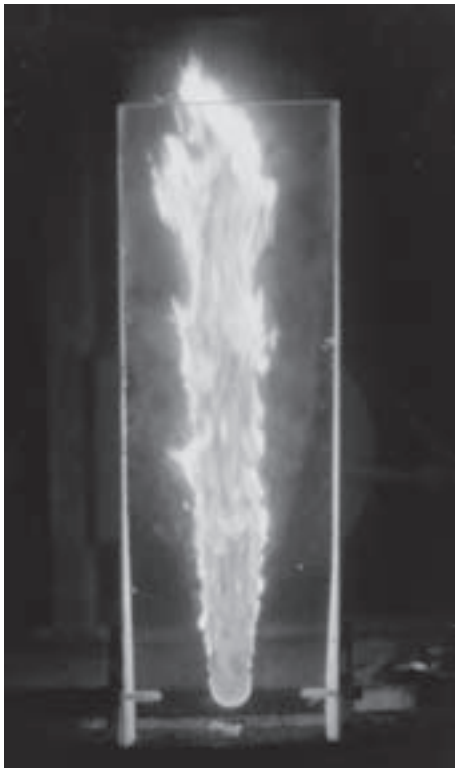

FIGURE 2.2.3 PMMA Wall Fire 1 ft (300 mm) High Ignited at a Single Point Near the Base

a view of flames from the back side of a model (1 ft [300 mm] high) slab of the same transparent polymer, in this case ignited at a single point near the base.

Heat Flow

Heat flow to the lowest 6 to 10 in. (150 to 250 mm) of the surface from the flames is dominated by convective heat transfer, but the remainder of the burning surface above this level is primarily subject to thermal radiation heat transfer. The burning vertical surface receives a roughly constant 0.9 Btu/ft^2·sec (10 kW/m^2) of convective heating, a low level partly due to the cooling effect of the flow of fuel vapors from the surface. Convective heating is somewhat greater above the actively burning region where flames cover the surface because a flow of fuel vapors is not yet established there. In contrast to convection, levels of radiant heat flux incident on the burning material surface increase steadily with height until flames become optically thick. As a result, heat fluxes over 8.8 Btu/ft^2·sec (100 kW/m^2) are possible. This is due to the fact that the layer of cool soot-laden vapor near the material surface is less effective in blocking the incident radiation for a wall fire than for a pool fire.

Fire Growth

Upward flame spread is driven by heat transfer (mainly radiation) in the region between the top of the active burning (fuel gasification) zone and the flame tip. As a result of the heat transfer in this region, as discussed above, ignition occurs after a time period controlled by thermal inertia. For a combustible surface that can support upward flame spread (also known as concurrent flow flame spread, because spread is in the same direction as the induced gas flow), the rate of increase of flame height is proportional to the current flame height, which translates into an exponential increase in flame height with time or a constant time to doubling of flame height. This is why vertical surface burning is so hazardous.

In contrast, lateral and downward flame spread on a vertical surface is opposed by the air flow induced by the flames themselves and thus is very similar to the creeping flow on a horizontal surface. This can be clearly seen in Figure 2.2.3 where the extent of flame spread horizontally and downward from the ignition point near the base of the PMMA wall is much less than the flame spread upward to the top of the wall.

CEILING OR HORIZONTAL, DOWNWARD-FACING SURFACES

Two types of ceiling fire scenarios are considered here, one with flames originating from a fire plume below an unobstructed combustible ceiling and the other with an ignition source at the surface of a combustible ceiling.

Flames from Fire Plume Below Unobstructed Combustible Ceiling

Flames originating from a fire plume below an unobstructed combustible ceiling (for a combustible ceiling obstructed by one

or more walls, see the section "Ceiling-Corner Surface Combination") lead to fire involvement of the ceiling material and the establishment of a flaming ceiling jet layer that moves radially outward from the point of impingement of the plume to form an axisymmetric flow. Heat transfer and flame spread rates in this configuration should be comparable to what occurs during upward flame spread on a vertical surface if the heat release rate associated with the impinging fire plume is at least as great as that associated with the involved ceiling material.

Ignition at Surface of Combustible Ceiling

An ignition source at the surface of a combustible ceiling can lead to active burning of the ceiling material. Heat flow and fire growth for such a configuration is different from that for a fire on a vertical or a horizontal, upward-facing surface. In this second scenario, a set of flame "cells" is produced,[13] with individual cells moving in different directions over the ceiling surface. The resultant cellular burning process is distinctive in appearance. Cellular burning has the potential to produce intense thermal radiation heat transfer because the cells extend a significant distance below the ceiling, resulting in a thick flame layer.

INCLINED MATERIAL SURFACES

Flame Attachment and Heat Flow

Based on a series of experiments[14] with a rectangular gas burner designed to simulate burning surfaces having a channel (or trench) flow confined by sidewalls and a burning surface length greater than 2.1 ft (0.65 m), results summarized in Figure 2.2.4 were obtained. Note that the solid symbols in the figure represent flame separation from the burning surface (as in pool fires). "B" is the solid-fuel mass transfer driving force being simulated by the gas burner setup, with B = 1 approaching a real flammable material. For an ordinate of 1.0 in the figure, the mass transfer flux is 0.002 lb/ft^2·sec (10 g/m^2·sec).

The following conclusions can be drawn from the experimental correlation in Figure 2.2.4 regarding the effect of angle of inclination on fire characteristics:

- Flames attach to upward-facing burning surfaces inclined more than 15° from horizontal, making flame spread and heat flow along the incline much more like that on a vertical surface than on a horizontal one. If the upward-facing burning surface is inclined less than 15°, flames are detached and much thicker, with the appearance and high heat transfer rates typical of pool fire flames.
- Flames attach to downward-facing burning surfaces inclined more than 12° from horizontal, increasing flame spread rates. If the downward-facing burning surface is inclined less than 12° from horizontal, flames detach and thicken to form the characteristic cellular pattern of a ceiling fire. Near this 12° transition, the formation of a cellular ceiling fire leads to increased heat transfer rates.

These results from the gas burner channel/trench experiments of deRis and Orloff,[14] which have yet to be superseded, indicate that as a given length of large-scale burning surface inclines from upward facing horizontal to vertical, then continues to incline 78° further to downward facing, 12° from horizontal, net heat transfer rates to the burning surface steadily decrease by roughly a factor of 2 or more. A further inclination of the downward-facing surface from 12° to 0° from horizontal to form a cellular ceiling fire results in a small increase in heat flow to the burning surface, still well below that in pool and vertical wall fires.

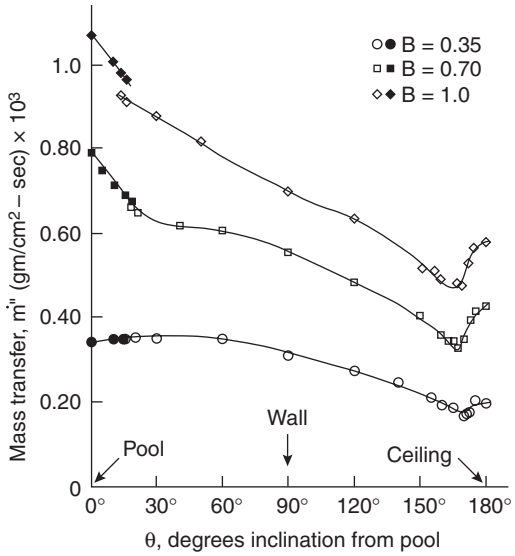

FIGURE 2.2.4 Mass Transfer Rate Versus Burner Inclination for Pool, Wall, and Ceiling Fires (0°, 90°, and 180° Inclination Angles, Respectively). Note: The burning rate of a given material associated with a "driving force" B is simulated here by the mass transfer flux of gaseous fuel from a burner (mass transfer ordinate) inclined at various angles to represent pool, wall, and ceiling fires. (Source: de Ris and Orloff, 15th Symposium on Combustion, 1975, pp. 175–182)

King's Cross Underground Fire Example

Fire in London's King's Cross Underground station on November 18, 1987, propagated much more rapidly than expected up the 30° incline of a wooden escalator (Figure 2.2.5), trapping many people in the ticketing area at the top end of the escalator. It had been assumed that a localized fire at any point along the escalator would grow laterally similar to the creeping flame spread in a pool fire configuration. However, the angle of inclination of the escalator channel was more than double the angle needed to cause flames to become attached to the inclined surface, based on the correlations from de Ris and Orloff.[14] Such attachment resulted in the rapid flame spread characteristic of vertical surface fires. This scenario has been confirmed by scale-model experiments[15] and by extensive field model calculations.[16]

PARALLEL FACING VERTICAL SURFACES

This configuration can occur in a variety of storage arrangements (e.g., rows of piled boxes) or in structural fixtures (e.g., facing rows of vertical cable trays). Because of the reduced area where

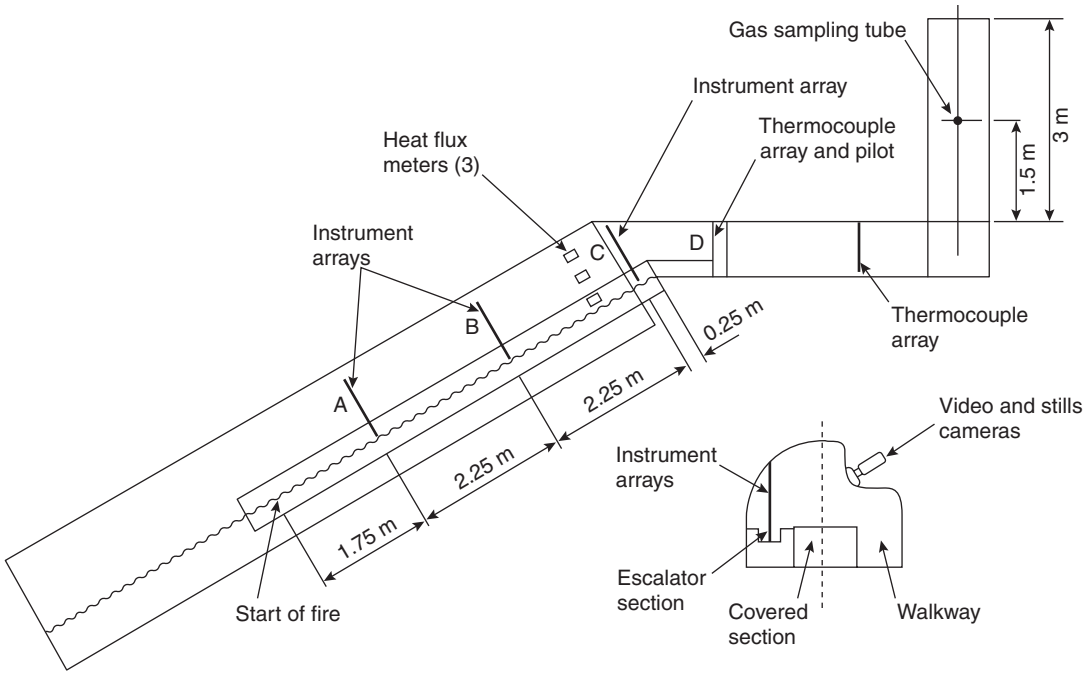

FIGURE 2.2.5 King's Cross Underground Station Fire Scenario (Source: Reprinted from K. Moodie and S. F. Jagger, "The King's Cross Fire: Results and Analysis from the Scale Model Tests," *Fire Safety Journal,* Vol. 18, 1992, p. 92. Crown copyright. Reproduced with permission of the Health and Safety Laboratory, UK.)

radiant thermal energy can escape, heat losses from the burning material surfaces (especially char-forming surfaces that have elevated temperatures) and from the flames on these surfaces are reduced significantly. As a result, (1) a much smaller heat source is required to initiate self-sustained burning and accelerated fire growth and (2) heat fluxes to the combustible surfaces from the combined surface flames can be substantial since flames can more easily approach an optically thick condition. The fire behavior that can be expected for a given material composition is dependent on two quantities: the ratio of the width (i.e., the horizontal dimension) of the combustible surface to the minimum (separation) distance between the two surfaces and the ratio of the height of the surfaces to the separation distance.

If the width to separation distance ratio of the parallel surfaces is greater than or equal to 2, the roughly 50 percent reduction in heat losses results in fire growth on a wide variety of materials for a small initiating heat source. As an example, with a surface width of 2 ft (600 mm) and a separation distance of 1 ft (300 mm), only a 57 Btu/sec (60 kW) heat release rate (2 ft [0.6 m] high flame) from a propane sand burner covering the 2 ft × 1 ft (600 mm × 300 mm) space between the surfaces is required to initiate fire growth on a wide variety of fire-resistant materials.

Figure 2.2.6 illustrates this specific configuration where a HRR of only 24 Btu/sec (25 kW) has initiated a fire on polymer surfaces. The heat flux to the parallel surfaces in this example reaches a peak of 2.6 to 3.5 Btu/ft^2·sec (30 to 40 kW/m^2), depending on the surface composition. As the scale of the parallel surface configuration increases or decreases for the same width to separation ratio, different heat source intensities are required to initiate fire growth and different heat fluxes to the burning surfaces (fluxes of 8.8 Btu/ft^2·sec [100 kW/m^2] have been measured) will result. This behavior could be used in a test method to simulate different fire scenarios.

The ratio of surface height to separation distance can also affect fire behavior. It is known that flame thickness for a PMMA wall fire is about one-sixteenth of the height of the single burning vertical surface[12] and the same should apply to most other material compositions. Although the induced gas flow for parallel vertical surfaces will tend to reduce this flame thickness, a height to separation distance ratio greater than the range of 10 to 16 will tend to reduce flame ventilation, leading to reductions in fire growth and burning rates.

CEILING-CORNER SURFACE COMBINATIONS

Vertical combustible surfaces intersecting at a 90° (corner) or 180° (a flat wall) included angle that are combined with a ceiling (or downward-facing combustible surface) occur frequently in all types of compartments and enclosed spaces, whether in rooms and hallways or the interior of building fixtures and equipment. This configuration provides some of the same trapping of thermal radiation from flames and hot surface char discussed in relation to parallel vertical surfaces, above, when a fire is initiated at the base of the surface intersection.

There are distinctive patterns of fire growth in these ceiling-corner or ceiling-wall configurations, depending on the corner angle (whether 90° or 180° or other angle) and whether or not flames from the corner surfaces reach the ceiling. Figures 2.2.7

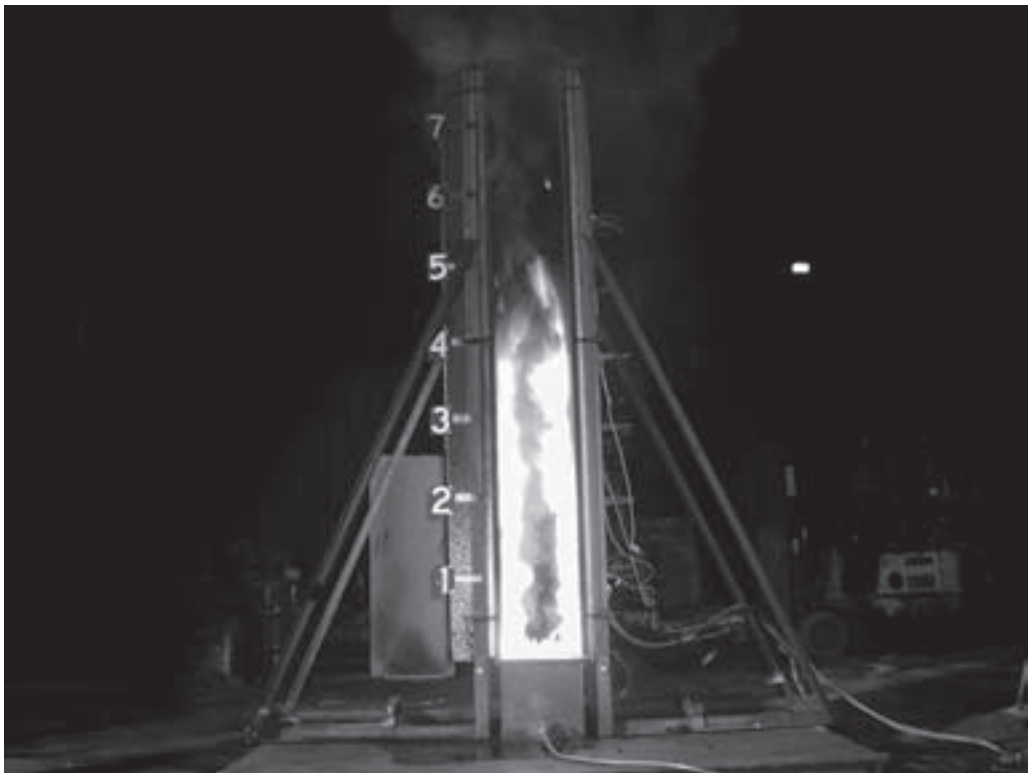

FIGURE 2.2.6 Fire Between Parallel Facing Combustible Polymer Walls

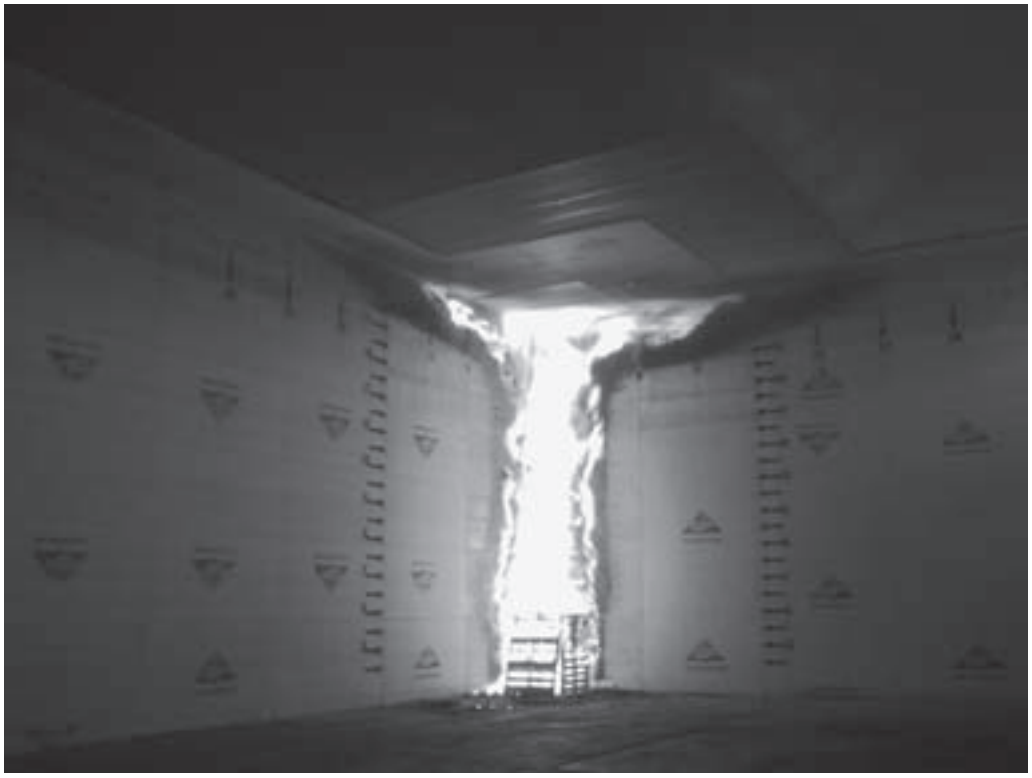

FIGURE 2.2.7 Peak Growth Phase of Fire in Corner Formed by Fire-Retardant Plywood Walls and Inert Ceiling

and 2.2.8 illustrate these patterns in a fire in a 90° corner formed by fire-retardant plywood walls and an inert ceiling during the growth and decay phases, respectively. In Figure 2.2.7 note that all surfaces labeled "GP" are inert cement board.

An extensive survey of past experimental work by Mitler[17] and careful observations of fire growth in such configurations by Saito[18] have shown that upward flame spread rates near a 90º wall intersection are increased, roughly by a factor of 3 compared to a flat wall, due to radiative reinforcement and the convective induced flow that controls flame position. In addition, vertical surface flames that impinge on an inert or combustible ceiling tend to spread most rapidly along the wall-ceiling intersection, forming a "T" shape that leads to rapid involvement of the upper wall at great distances from the point of flame impingement. Once there is fire involvement of the vertical wall surfaces at the corner and ceiling intersections, further flame spread occurs by the slow "creeping" or opposed flow mechanism (see the discussion of flame spread in the previous section "Pools or Horizontal, Upward-Facing Surfaces") laterally from the corner on the vertical surfaces and downward from the ceiling intersection.

COMBUSTIBLE DUCTS

Vertical or horizontal ducts that exhaust or transport corrosive vapors in process industries are often composed of combustible polymers, either as an internal lining or as the entire duct structure. In such cases, flames from a small fire outside the duct can be drawn into the duct and lead to the rapid growth of duct fire flames due to trapping of thermal flame radiation and radiant heat transfer forward to new sections of the duct. Whether flames are transmitted extensively along the duct length depends to a great extent not only on the composition of the duct polymer but also on the adequacy of ventilation, that is, the supply of fresh air for continued fire spread.

SUMMARY

Defining characteristics of fires in different geometric configurations have been discussed in terms of flame behavior, heat flow, and fire growth. The potential impact of a fire on the local environment is strongly dependent on the configuration and scale of the combustible surfaces that become involved. Generally, pool or horizontal, upward-facing surface fires are associated with the lowest rates of flame spread (a constant spread velocity that results in a t^2 HRR dependence), the highest heat flux from the flame envelope, and the highest burning rates. Wall or vertical surface fires are associated with the highest rates of upward flame spread (an exponential increase of flame height with time) and somewhat lower flame heat fluxes and burning rates than for pool fires of the same scale. Ceiling or horizontal, downward-facing, surface fires are characterized by thick, moving cellular flames. Small changes in the inclination of both upward-facing and downward-facing surfaces can result in abrupt changes in flame behavior and the heat flux environ-

FIGURE 2.2.8 Decay Phase of Fire in Corner Formed by Fire-Retardant Plywood Walls and Inert Ceiling

ment. Finally, configurations that represent combinations of the preceding single combustible surfaces have distinctive flame behavior and heat transfer characteristics that are important in many practical fire scenarios.

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Chapter 3

Flammability Hazard of Materials

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Key Terms

ASTM, calorimeter, char, corner test, fire test, flame, flame propagation, flame spread, flammability hazard, gasification, heat flux, heat release rate (HRR), heat transfer, ignitability, ignition temperature, ignition time, intumescence, pyrolysis, smoke generation, smoke yield, smoldering, thermal inertia

Any material capable of burning with a flame is considered flammable.[1] A flame is a stream of the gaseous fuel and oxidizing agent involved in the combustion process that produces heat (including radiant energy and usually visible light, according to NFPA 921, *Guide for Fire and Explosion Investigations*) and combustion products. The most elementary view of flammability is provided by the fire triangle, which indicates that three components, fuel, oxidizing agent, and heat, are necessary to start a fire. However, the fire triangle does not describe all the conditions for a flaming fire because it does not include the chemical chain reactions and reactive molecules in flame gases. Highly reactive molecular species, referred to as free-radicals, must be present in sufficient concentrations to insure the continuation of chemical chain reactions. Otherwise, flames are extinguished. A more complete visual image of flammability is therefore provided by the fire tetrahedron, which recognizes that in order for flames to exist and not be extinguished, uninhibited chain reactions are necessary in addition to fuel (in a gaseous or vapor state), oxidizing agent, and heat. Whereas the fire triangle identifies the conditions necessary to start a fire, the fire tetrahedron recognizes the conditions sufficient for a flaming fire. These conditions include the availability of gaseous fuel or fuel vapors, which can only be generated if there is sufficient heating from external sources or heat feedback from a burning material's own flames.

The flammability hazard posed by a material is really a quantification of the conditions under which copious amounts of fuel vapors capable of supporting uninhibited chemical chain reactions will be generated in typical occupied environments. Quantification of flammability hazard is usually expressed in terms of ease of flaming ignition, damaging heat and product output from flames, and spread of flame to involve new material surfaces or new locations in damaging flame behavior. In addition, the difficulty of extinguishment of the burning material should be included as part of flammability hazard, following Emmons.[2]

Although it may be simple to determine if a material is capable of supporting flaming combustion, measuring or predicting the flammability hazard of a material is a challenging and complex task. The flammability hazard of a material is dependent on many parameters of its fuel content, including the chemical composition and physical properties of the fuel (see Section 2, Chapter 1, "Physics and Chemistry of Fire"), the geometric configuration of the fuel (see Section 2, Chapter 2, "Physics of Fire Configuration") and the products of combustion. Flammability can also be dependent on scenario factors such as ventilation, oxygen concentration, and radiation feedback from the surroundings. There is no single test or simple index for flammability that adequately captures all these fuel parameters and scenario factors. As a result, performance in one type of

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flammability test cannot easily be extrapolated to determine performance for a different type of flammability test.

Given the number of parameters that affect the flammability hazard of a material, it is not surprising that there are many standardized test methods for characterizing flammability. The development and acceptance of each test method can easily take a decade of research and validation, resulting in extensive documentation. Standardized fire test methods are used to compare the behavior or response of different materials to a given or limited set of test conditions. These test conditions may, or most likely may not, represent the material's response under actual fire conditions. If data from such test methods are to be used directly for fire safety design or assessment, the test conditions should be compared carefully with the conditions assumed for the design fire scenario or fire conditions of interest. Property data derived from these numerous test methods can also be used in analytical models to predict flammability hazard for a range of actual fire conditions.

This chapter will provide background information and a description of test methods by which the ignitability, heat release rate, flame spread propensity, smoke yield, and extinguishability components of flammability hazard are measured or characterized for solid combustibles. The discussion of flammability test methods is introduced by a review of how solid combustibles may respond to heat flux from flames or other sources, which begins the process of generating fuel vapors.

See also Section 2, Chapter 1, "Physics and Chemistry of Fire"; Section 2, Chapter 2, "Physics of Fire Configuration"; Section 2, Chapter 7, "Theory of Fire Extinguishment"; Section 6, Chapter 1, "Fire Hazards of Materials"; Section 6, Chapter 2, "Combustion Products and Their Effects on Life Safety"; and Section 6, Chapter 3, "Concepts and Protocols of Fire Testing."

MATERIAL RESPONSE TO INCIDENT HEAT FLUX

When a material is heated, depending on its chemical composition and physical properties, it may respond in a variety of ways. Each of the material responses described below results not only in degradation of the material initially exposed to heat flux but also in life safety and physical damage effects on the surroundings.

Smoldering

Smoldering is a slow, exothermic surface reaction. Smoldering is usually characterized by glowing, or incandescence, and smoke production (NFPA 921). There is no flaming. Since smoldering is a surface effect it is strongly dependent on environmental conditions in addition to the properties of the fuel and the availability of oxygen. Smoldering is a serious fire hazard for two reasons: (1) it is an inefficient form of combustion so carbon monoxide will form a larger percentage of the combustion products relative to flaming fire conditions,[3] and (2) smoldering provides a means to flaming from heat sources normally too small to generate a flame.[4] Figure 2.3.1 illustrates two examples of smoldering.

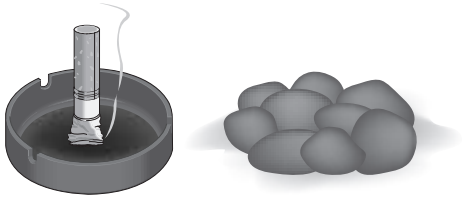


FIGURE 2.3.1 Cigarette and Charcoal/Wood as Examples of Smoldering Combustion

Pyrolysis and Heat of Gasification

Pyrolysis is the chemical decomposition of a material into one or more other substances due to heat alone (NFPA 921). All solid combustibles must undergo pyrolysis in order to generate gaseous fuel vapors for flaming combustion. The process of converting a solid to gaseous vapors can take many physical paths depending on the chemical composition of the fuel. Cellulosic materials, such as wood, decompose directly to gaseous vapors when heated, leaving behind a residue. Thermoplastics such as polypropylene undergo a two-step pyrolyzation process. As the thermoplastic is heated it melts and turns into a liquid, and then this liquid melt is vaporized into the gaseous fuel. Other materials such as flexible polyurethane foams can decompose by different mechanisms which can produce liquid polyols and gaseous isocyanates[5] (Figure 2.3.2).

The energy required to convert a solid material into a vapor through pyrolysis is termed the *heat of gasification.* This quantity can be obtained from laboratory calorimeters having a controlled atmosphere capability (for example, the Fire Propagation Apparatus[6] described in ASTM E2058, *Standard Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus [FPA]*), by substituting pure nitrogen for the air or oxidant normally flowing in the calorimeter and then measuring the mass loss flux from a specimen in nitrogen at different applied heat flux values covering the range expected for real-scale burning objects. In general, the heat of gasification determined from this type of laboratory measurement is not a constant, independent of the heat flux or independent of time during pyrolysis, but for many materials, a representative average heat of gasification can legitimately be defined. The lower the heat of gasification, the greater will be the flammability hazard, since less heat will be required to produce fuel vapor that can react in a flame. As will be discussed later, it is actually the ratio of the heat of combustion to the heat of gasification that is important, since it is the parameter controlling heat release rate and hence, flammability hazard.

Physical Changes During Pyrolysis

A variety of physical changes result from pyrolysis, including char development, intumescence, melting, and vaporization.

Char. Char is a black, carbonaceous, porous residue. The char is a thermal degradation (physical change) of the material being pyrolyzed (chemical decomposition). Organic materials such as wood, wood products, thermoset plastics, and some thermoplas-

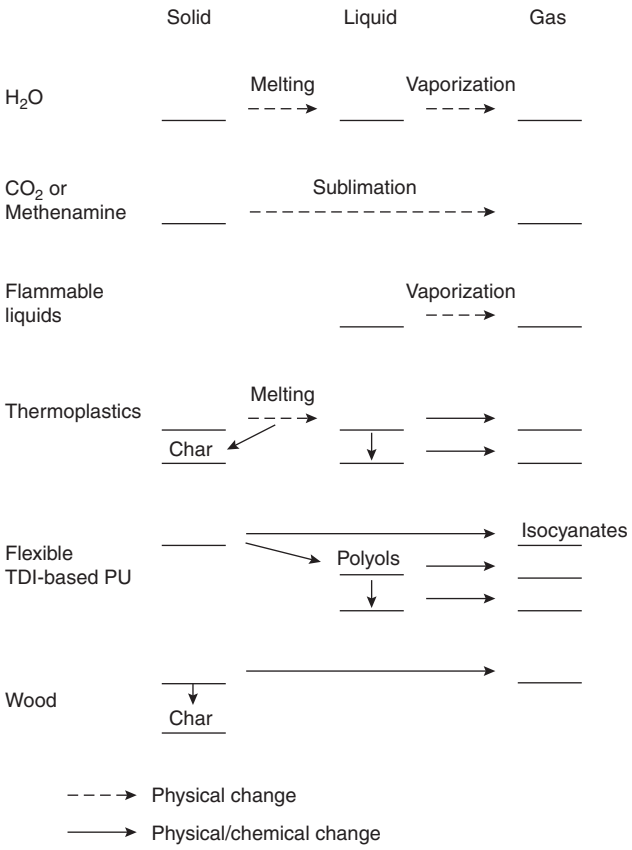


FIGURE 2.3.2 Physical and Chemical Changes During Thermal Decomposition (Courtesy Society of Fire Protection Engineers)

FIGURE 2.3.3 Charred Wood and a Charred Thermoset Plastic (Courtesy of National Institute of Standards and Technology)

tic polymers form a char layer as they are pyrolyzed. As the char layer develops, it acts as an insulating barrier between the external heat source and the unpyrolyzed fuel under the char. This will slow the pyrolysis rate unless the external heat flux increases to compensate for the insulating char layer.[5] Thermoplastics when exposed to heat tend to soften and melt without forming char. For example, polymethylmethacrylate (PMMA) pyrolyzes with very little melt and leaves no residue. However, rigid polyvinyl chloride (PVC) chars when burned, as do some polyurethane foams.[7,8] Examples of charred wood and a charred thermoset are shown in Figure 2.3.3.

Intumescence. Intumescence is defined as the process of swelling up or bubbling up. There are many intumescent coatings on the market for fire protection purposes. These coatings, when heated, increase in volume and decrease in density, simulating the development of a char layer. As the intumescent "char" layer is formed, a blowing agent (a substance used to create bubbles in the material) is released, which creates a low-density, relatively thick carbonaceous layer. Intumescent reactions are typically endothermic due to chemically bound water in hydrates. As the material expands the water is released, maintaining the surface temperature. Once the water has been expended, the remaining "char" layer acts as insulation to the material underneath. The "char" can expand 50 to 100 times the original thickness of the intumescent coating.[9–12]

Melting. When most thermoplastic materials are heated, they melt or soften prior to being vaporized (Figure 2.3.4). The rate at which melting occurs compared to the burning rate and the melt viscosity, are important for determining the fire hazard.[5] For example, if initial exposure to a heat flux and subsequent burning produces a copious amount of melt having a low viscosity, then there is the potential for extensive fire spread to the surroundings as this melt, possibly supporting flames, comes in contact with new material surfaces. This would be especially dangerous if the melting substance is part of a wall or ceiling lining.

IGNITABILITY

Ignitability is the ease of initiating self-sustained flaming combustion due to a heat flux exposure. To determine the level of flammability hazard based on ignitability, the primary information needed is the time it takes to ignite the material with a given heat flux exposure. For a given initial heat flux exposure scenario, the greatest flammability hazard results from a material configuration and composition that requires the shortest

FIGURE 2.3.4 Melted Plastic (Source: Figure 4.11, *User's Manual for NFPA 921,* 2005 edition, courtesy Jones and Bartlett Publishers)

time for ignition. Hence, data on ignitability that gives predicted or estimated ignition times for a variety of heat flux exposures with different fuel configurations and compositions will be most valuable for determining this particular aspect of flammability hazard.

Ignition Energy and Critical Heat Flux for Ignition

As defined in NFPA 921, the ignition energy of a material is the quantity of heat energy per unit exposed surface area that must be absorbed by the material in order to pyrolyze, ignite, and burn. This energy is the product of the heat flux absorbed by the material and the time of exposure until ignition. A material with a given ignition energy will ignite faster if exposed to a high incident heat flux and slower if the incident heat flux is low. The amount of energy required for ignition also depends on the physical and chemical properties of the material, especially its thermal inertia and ignition temperature. However, the heat flux exposure must be greater than a certain critical value. For a heat flux less than or equal to this value, the ignition time is effectively infinite; i.e., ignition will not occur. This is the definition of the *critical heat flux for ignition.*

Thermal Inertia

The thermal inertia of a material is the direct product of three physical properties: thermal conductivity (k), density (ρ), and heat capacity (C). Thermal inertia characterizes the rate of surface temperature rise of the material when exposed to heat. Low values of thermal inertia lead to elevated surface temperatures for a given applied heat flux scenario, and hence, to more rapid ignition and a greater flammability hazard if the material is combustible. Although values for thermal conductivity, density, and heat capacity can be found for some materials in the literature, the way that the properties are measured can affect the resulting thermal inertia magnitude. Table 2.3.1 presents data on thermal conductivity, density, and heat capacity for selected materials.

TABLE 2.3.1 Thermal Properties of Selected Materials

Material	*Thermal Conductivity (k) (W/m·K)*	*Density (ρ) (kg/m³)*	*Heat Capacity (C_p) (J/kg·K)*
Copper	387.00	8940	380
Concrete	0.8–1.4	1900–2300	880
Gypsum plaster	0.48	1440	840
Oak	0.17	800	2380
Pine (yellow)	0.14	640	2850
Polyethylene	0.35	940	1900
Polystyrene (rigid)	0.11	1100	1200
Polyvinyl-chloride	0.16	1400	1050
Polyurethane foam*	0.034	20	1400

*Typical values; properties vary.
C_p = Heat capacity at constant pressure.
Source: Drysdale, D. D., *An Introduction to Fire Dynamics,* 2nd ed., 1999, p. 33. Copyright John Wiley & Sons Limited. Reproduced with permission.

Many materials are not homogeneous in their composition. Therefore they may have varying values for thermal conductivity, density, or heat capacity. Although this may not be a surprise when considering modern composites with visible layers of different materials, it may be surprising to find that wood is not homogeneous. The thermal conductivity of wood is higher in the direction parallel to the grain of the wood. As a result, to ignite the end grain of a piece of wood would require more energy and or more exposure time for a given heat source than to ignite the surface of the wood where the heat flow is perpendicular to the grain.[13] The higher thermal conductivity transfers heat through the wood faster, thereby slowing the storage of heat at the wood surface and increasing the time for reaching the ignition temperature. The thermal conductivity in wood may not only vary with position, but it can also vary with direction at a fixed position. This is an example of a nonisotropic material property.

Further as the wood increases in temperature, the thermal conductivity, density, and specific heat will change due to the evaporation of moisture in the wood. As would be expected, it takes more energy to ignite a piece of wood with higher moisture content.[14] As the wood begins to pyrolyze and a char begins to develop, the physical properties of the wood continue to change. This may also have an impact on the amount of ignition energy required. Hence the assumption that wood, or other materials, behave as inert materials until they ignite is false.[15] These changes are most significant during the ignition process.

Even though there are many variables to consider when assessing the ignitability of a material, average values can still be useful to compare the potential for ignition of two materials. For example, compare the properties given for pine in Table 2.3.1 with those for polyurethane foam. Even though the values for pine may vary during the ignition process, given that the thermal conductivity is more than 4 times that of polyurethane, the density more than 30 times greater, and the heat capacity

is 2 times greater, it is clear that polyurethane cannot transfer heat away from its surface as effectively as wood and therefore would require less ignition energy.

A fire occurred on the night of February 20, 2003, in The Station, a nightclub at 211 Cowesett Avenue, West Warwick, Rhode Island. A band performing that night used pyrotechnics. The sparks from the pyrotechnics ignited polyurethane foam insulation that was installed on the walls and ceiling of the platform being used as a stage. The fire spread quickly along the walls and ceiling area over the dance floor. Smoke was visible in the exit doorways in a little more than one minute, and flames were observed breaking through a portion of the roof in less than five minutes. Egress from the nightclub was hampered by crowding at the main entrance to the building. One hundred people lost their lives in the fire.

In experiments conducted by NIST after the tragedy, birch veneer plywood paneling and ether-based polyurethane foam were exposed to pyrotechnic devices similar to the ones used in the nightclub. The wall-mounted polyurethane foam ignited within 10 seconds. The sparks from the pyrotechnics did not have enough energy to ignite the plywood.[16]

Ignition Temperature

As defined in NFPA 921, ignition temperature is the minimum temperature a solid material must attain in order to ignite under specific test conditions. Generally, the ignition temperature will be within the range of temperatures at which a material begins to pyrolyze and produce copious vapors, whether by mainly thermal mechanisms controlled by thermal inertia as previously discussed or by chemical bond-breaking processes or a combination of both. The ignition temperature is related to the ignition energy, but it is less fundamental because the manner in which the material is heated, the rate of energy transfer to the material, and the physical and chemical composition of the material affect the ignition temperature. The lower the ignition temperature, the greater the flammability hazard due to ignition.

A review of research literature on the ignition temperature of solid wood shows that the ignition temperature increases as the incident heat flux (energy transfer to the material surface) increases. The ignition temperatures ranges from a minimum of 250ºC to initiate smoldering combustion with a low incident heat flux on the order of 5 kW/m^2 to approximately 360ºC with a "medium" incident heat flux on the order of 20 kW/m^2 for the piloted ignition of softwoods.[17]

Ignition Time

Ignition time is the time between the application of an ignition source (usually an imposed heat flux) to a material and the onset of self-sustained flaming either on or near the material. Just as with the ignition energy and the ignition temperature, the time to ignition is also a function of the rate of heat transferred from the ignition source, as well as the physical and chemical properties and geometric configuration of the material. As outlined in previous sections, high incident heat flux, low thermal inertia, and weak chemical bonds will result in faster time to ignition and greater flammability hazard due to ignition.

IGNITION TEST METHODS

There are many test methods[18] that have been developed to examine the ignitability of a material. Most of these test methods are not quantitative in the sense that a prescribed heat flux is not provided or the test method does not yield quantitative data useful for an engineering prediction of ignition time and hence the ignition aspect of flammability hazard. Although not a standardized test, NFPA 705, *Recommended Practice for a Field Flame Test for Textiles and Films,* is a recommended practice for field flame testing of fabrics and plastic films, to determine their tendency to ignite and sustain burning. It is mentioned here because it is the most basic flammability test, which fire safety professionals can use to determine if further testing is required. The procedure calls for a material sample, at least 12.7 mm × 101.6 mm to be exposed to an open flame from a common wood kitchen match for 12 seconds. The flame should not extend the length of the sample or a distance of 101.6 mm for longer samples. There should not be more than 2 seconds of afterflame on the sample, and materials that break or drip flaming particles on the floor below the sample would fail if the materials continue to burn after reaching the floor. If the test results in the ignition and rapid consumption of the sample, clearly the material is a flammability hazard. On the other hand, if the test results in no ignition, it does not mean that the material complies with applicable fire safety standards. The test results can be affected by environmental conditions, sample size, and flame exposure size. Additional testing is required to quantify the flammability of the material.

The few quantitative test methods that provide data on the ignition aspect of flammability are listed below:

1. Cone calorimeter[19] (NFPA, ASTM and ISO versions; see description later in this chapter), in which a horizontal or vertical 100 mm by 100 mm specimen is exposed to a known heat flux from a conical heater and the time to ignition is measured.
2. Fire propagation apparatus[6] (NFPA and ASTM versions; see description later in this chapter), in which a 100 mm circular horizontal specimen is exposed to a known heat flux from tungsten-quartz heaters and the time to ignition is measured. From data on ignition time at various applied heat flux values, the test method yields the minimum heat flux required for ignition and also the product of the square root of thermal inertia and the excess of ignition temperature above ambient for the test specimen.
3. Lateral ignition and flame spread (LIFT) apparatus[20] (ASTM and ISO versions; see description later in this chapter), in which a vertical 155 mm by 155 mm specimen is exposed to a known average heat flux from a gas-fired radiant panel and the time to ignition is measured. From data on ignition time at various applied heat flux values, the test method contains formulas that yield the minimum heat flux required for ignition and also the ignition temperature and thermal inertia of the test specimen.
4. Intermediate-scale calorimeter (ICAL)[21] (ASTM and ISO versions; see description later in this chapter), in which a 1 m by 1 m vertical specimen is exposed to a known heat flux from a gas-fired radiant panel and the time to ignition is measured

HEAT RELEASE RATE

Heat release rate is probably the most important quantity used to characterize the flammability hazard represented by a given material. It is a measure of the rate at which a burning item releases chemical energy and is usually expressed as heat released per unit exposed surface area of a burning material or specimen (i.e., kW/m^2). Used as an input to a computer fire model, the heat release rate can provide information on fire size, fire growth rate, available egress time, and suppression system impact if all the parameters affecting heat release rate are known (see below). The heat release rate of a burning item is the product of mass loss rate (i.e., the mass burning rate) per unit of exposed surface area and its actual (not complete or theoretical) heat of combustion under the conditions of interest. When this heat of combustion is known, the heat release rate can be estimated from the measured mass burning rate. Alternatively, the heat release rate can be determined directly from measurements of the composition of product gases collected in an exhaust hood of a calorimeter. Generally, the greater the heat release rate per unit of exposed surface area of material or per unit floor area of a complex material configuration, the greater is the flammability hazard.

Laboratory calorimeters can provide useful information concerning heat release rate using small material specimens. However, these calorimeters often do not represent the actual performance of a material when used in real life. Laboratory calorimeters do not usually test the same size materials as found in most fire scenarios and the laboratory results can be influenced by the relative closeness of the material edges to the center of the flame zone. There is also little or no geometry consideration included in small-scale tests. Intermediate and large-scale calorimeters attempt to provide a more realistic scenario for testing of materials.

Parameters Controlling HRR

Although the heat release rate (HRR) of real material configurations can be obtained from full-scale tests (see discussion below), it is impractical to test materials in every possible configuration and fire scenario (e.g., within enclosed spaces of different sizes or in different warehouse storage arrangements) to determine the flammability hazard due to heat release rate. For this reason, materials are often tested in a reference fire scenario, such as a room test or a corner test or a commodity evaluation test having one or two geometric scales that are characteristic of a wide range of practical situations. Even these full-scale reference tests can be expensive, so predictions of flammability hazard due to heat release rate that are based solely on laboratory property measurements would be highly desirable. For this to be done, the parameters controlling heat release rate must be identified and then characterized by practical test methods.

Similar to the case for ignition, the net heat flux absorbed by a material and the heat of gasification of a material determine the mass loss flux of fuel vapors from a burning material surface. Here, the net heat flux is the heat flux absorbed from a material's own flames and from any heat source surrounding the burning material (e.g., from other burning objects, from a hot gas layer in an enclosure, or from heated enclosure surfaces) minus any heat losses from a material's own pyrolyzing hot char or melt layer (such as the glow of wood char in a fireplace). In the simple situation of a constant net heat flux and constant heat of gasification, it is the ratio of net heat flux to heat of gasification that yields the fuel mass loss flux. As noted above, the product of the mass loss flux and the relevant heat of combustion then yields the heat release rate of the burning material. Hence, it is the ratio of the heat of combustion to the heat of gasification, together with the net absorbed heat flux, that determines the heat release rate. The greater the magnitude of this ratio, which has been called the heat release parameter (HRP) by Tewarson,[22] the greater is the flammability hazard. HRP can often be measured directly in a laboratory calorimeter if there is a linear dependence of heat release rate on the applied heat flux to a material specimen over a range of applied heat flux and material thermal thickness estimated to cover the fire scenarios of interest. If such is the case, HRP is simply the slope of the linear relationship. Otherwise, the heat of combustion and heat of gasification can be measured individually in a calorimeter, the former as the ratio of total heat released to total mass lost and the latter from mass loss data at several precisely known imposed heat fluxes in a nitrogen environment.[6]

Tabulation of HRP values[22] shows that materials known to have a very low flammability hazard typically exhibit an HRP approaching unity while more hazardous materials have an HRP greater than 10. Alpert[23] has developed an algebraic model utilizing HRP values obtained from heat of gasification tests in nitrogen together with flame heat flux values determined from calorimeter data on smoke yield (discussed in the next section). This algebraic model predicts both heat release rates and the propensity for fire propagation in a parallel panel configuration, thus yielding a prediction of flammability hazard (see Parallel Panel Test later in this chapter). Nam[24] has extended and perfected this parallel panel model.

Flame Heat Transfer

In any prediction of heat release rate and hence flammability hazard, the heat flux from the flame of a burning material is critical, as explained above. If heat release rate is not being measured in a full-scale fire scenario by a large-capacity calorimeter, then flame heat transfer must be simulated in a laboratory calorimeter by using electrical or gas-fired radiant heating elements in the calorimeter apparatus. Obviously, the heat release rate measured in the apparatus will be determined by the choice of the imposed heat flux. To avoid the problem of choosing an imposed heat flux that accurately simulates full-scale flames, the heat release rates of many material specimens are often compared by testing at the same imposed heat flux selected to be representative of what would be expected in typical fire scenarios. However, materials having flames with a higher flame heat transfer than simulated in the apparatus would presumably have a higher flammability hazard and those with lower flame heat transfer a lesser hazard. Typically, materials are tested in laboratory calorimeters at an imposed heat flux of 50 to 75 kW/m^2, which is a flux known to occur in many types of real scale fires. Under such conditions, measured heat release rates less than 50 to 100 kW/m^2 often indicate a relatively low flammability hazard.

The heat transfer from real-scale flames is primarily due to thermal radiation, which, as discussed in Section 2, Chapter 1, "Physics and Chemistry of Fire," depends both on flame temperature and flame emissivity primarily determined by soot concentration profiles within the flame. The configuration of the burning material will also affect flame heat transfer, as discussed in Section 2, Chapter 2, "Physics of Fire Configuration." Significant progress is being made to understand flame heat transfer through the development of empirical correlations (e.g., in room-corner configurations[25] and in parallel panel configurations[25]) guided by simplified models.[26] These correlations show that the smoke yield of the flame for a burning material specimen, as obtained in a laboratory apparatus, is a critical determinant of flame heat transfer levels. Generally, higher smoke yields imply sootier flames with higher flame heat transfer and a greater flammability hazard. Note that at a sufficiently high smoke yield, combustion efficiency, or the actual heat of combustion, will be reduced to such an extent that heat release rates (and hence the flammability hazard) are reduced in spite of enhanced flame heat transfer.

HRR TEST METHODS

The heat release rate of actual material configurations can be measured in large-scale calorimeters, some of which are capable of safely handling tens of megawatts. In that case, the measured heat release rate (either peak or average values) can be used directly to estimate flammability hazard. Otherwise, laboratory-scale calorimeters must be used to obtain quantitative data from material specimens ranging in size from 100 mm up to 1 m across.

Measurement of Heat Release Rate

The oxygen consumption method has been identified as the most accurate means for determining heat release rate. This technique was refined in the late 1970s and early 1980s by researchers at the National Bureau of Standards. Using the principle of oxygen consumption, it is possible to calculate the heat release rate of burning materials when the products of combustion are collected in an exhaust hood. Thornton[27] found in 1917 that many organic materials produced almost the same amount of heat per unit mass of oxygen consumed. Hinkley et al.[28] suggested using oxygen concentration in exhaust gases to determine the heat release rate of wood cribs in 1968. Parker[29] used this technique to determine the heat release rate of specimens in the ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials,* tunnel test. Huggett[30] calculated an average value for the heat release from a fire involving typical organic fuels to be 13.1 MJ per kilogram of oxygen consumed. However, for materials with very low heat release rates (e.g., below 100 kW/m^2) or very sooty flames, comparable or greater accuracy can be obtained by measuring the generation rate of product gases such as carbon dioxide and carbon monoxide, as long as the elemental composition of the material specimen is known (or measured by readily available and inexpensive laboratory techniques).[31]

The calculation of heat release rate of fires burning in normal air, whether using oxygen consumption or product gas generation, requires a minimum of two measurements, the flow rate of the products of combustion through the exhaust system and product gas concentration in the exhaust products. Parker[32] presents several sets of equations for calculating heat release rate using oxygen consumption. The appropriateness of each set of equations depends on the combustion products being measured.[31] A paper by Janssens[33] proposes a form of the equations for calculating heat release rate specifically for full-scale fire test applications. These equations use mass flow rates instead of volumetric flow rates. Volumetric flow rates can lead to confusion because of the need to choose an arbitrary reference temperature and pressure. Figure 2.3.5 shows a schematic of a sampling system for measuring heat release rates.

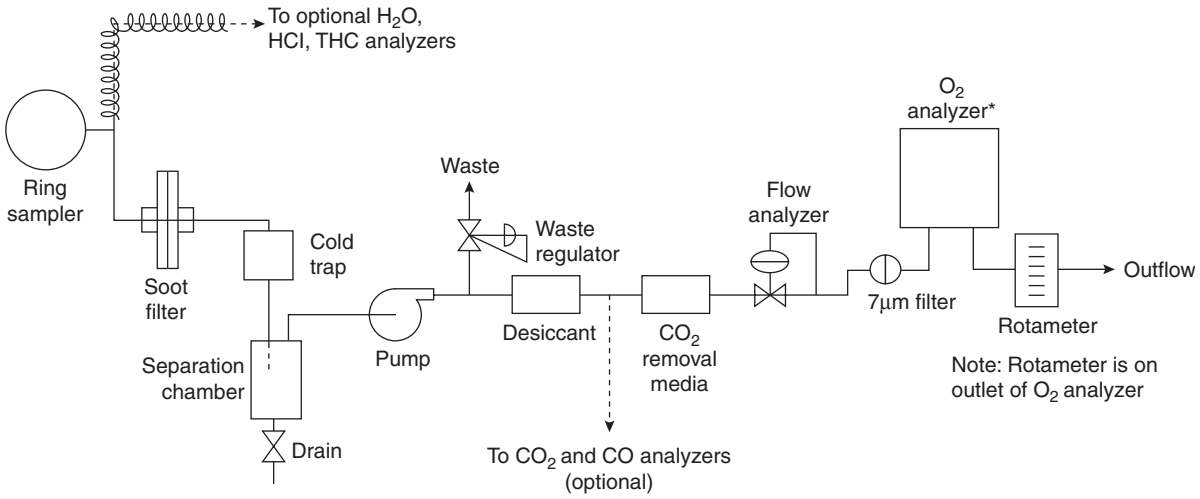


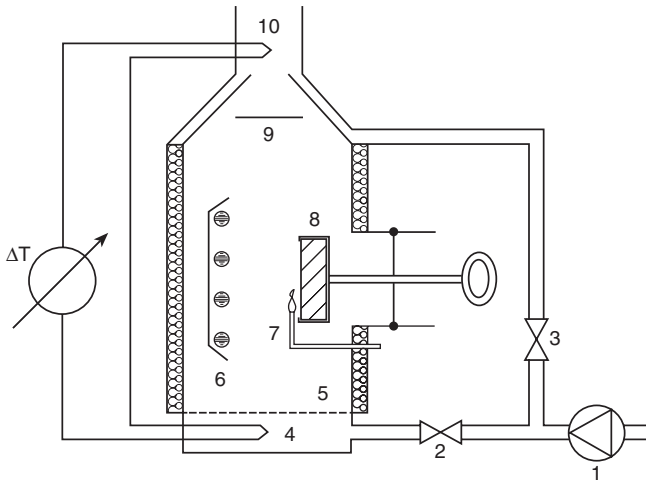
FIGURE 2.3.5 Schematic of Sampling System for Measuring Heat Release Rates from Burning Items. *To include absolute-pressure transducer. (Source: National Institute of Standards and Technology)

Laboratory-Scale Calorimeters

Early calorimeters functioned by measuring the temperature increase in the exhaust stream resulting from the combustion of a flammable item.[34] Developed in 1959, the FM Global Construction Materials calorimeter is probably the earliest example of a device designed to measure heat release rate using the potentially very accurate substitution principle.[35] The test specimen, approximately 1.22 m by 1.22 m and oriented face-down, was exposed to an oil burner fire. A second test would be conducted with a noncombustible blank exposed to the oil burner flames while auxiliary propane gas burners were adjusted to reproduce the measured exhaust gas temperature increase. The energy release rate from the propane burners would correspond to (or "substitute for") the energy release rate of the test specimen. This device was considered cumbersome, requiring two tests for each specimen and did not see widespread use. Subsequently, a similar calorimeter using a 0.46 m by 0.46 m sample mounted vertically was built by the U.S. Forest Products Laboratory.[36]

The National Bureau of Standards NBS-I calorimeter improved upon earlier calorimeter designs with the addition of a feedback loop.[37] As the specimen burned, the system would reduce the quantity of propane being added to the system, thus keeping the energy in the system constant. The energy release accounted for by the reduced propane flow would represent the heat release rate of the flammable item. The NBS-I could expose vertically oriented samples 114 mm by 152 mm and up to 25 mm thick to a maximum heat flux of 100 kW/m^2 for short durations. Although this system eliminated some of the early problems, its complexity, sensitivity to exhaust pressure fluctuations, and long equilibrium times limited its widespread use. The NBS-I inspired the development of a similar calorimeter at Stanford Research Institute with a maximum heat release rate measurement capability of 120 kW/m^2.[38]

OSU Apparatus. The Ohio State University (OSU) calorimeter, designed by E. E. Smith, is one of the most widely used bench-scale calorimeters.[39] Unlike many other bench-scale calorimeters that functioned by adding or substituting an energy source, this calorimeter operated by measuring the temperatures of the incoming air and the exhaust gases while the sample burns in an insulated box. This method of operation was referred to as the "sensible enthalpy rise method." Although attempts were made to limit heat losses, it was impossible to totally eliminate them. Therefore, calibration runs using a gas burner were still necessary to develop a correlation between heat release rate and exhaust gas temperature. Using radiant heaters, vertically oriented specimens, up to 0.15 m by 0.15 m, could be exposed to a peak heat flux of 65 kW/m^2. Sample size was limited to 0.11 m by 0.15 m and a peak heat flux of 50 kW/m^2 when tested horizontally using an aluminum reflector. The OSU calorimeter was adopted as ASTM E906, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products,* in 1983.[40] Although the ASTM standard test method has changed little since its adoption, a number of researchers have modified the OSU calorimeter for oxygen consumption measurements. Figure 2.3.6 illustrates the OSU calorimeter.



1 Air supply fan
2 Main flow control
3 Bypass flow control
4 TC cold junctions
5 Air distributor plate
6 Heating elements
7 Gas pilot
8 Sample and holder
9 Baffle plate
10 TC hot junctions

FIGURE 2.3.6 Schematic of the OSU Apparatus (Courtesy Society of Fire Protection Engineers)

Fire Propagation Apparatus. At FM Global in 1975, Tewarson first described a small-scale flammability apparatus for measuring heat release rate.[41] The convective component of the total heat release rate was obtained from measurements of the enthalpy of the exhaust stream. The total heat release rate was calculated from the specimen mass loss rate, oxygen bomb heat of combustion, and the generation rates of carbon dioxide and carbon monoxide. Alternative calculations using oxygen consumption or carbon dioxide and carbon monoxide generation in lieu of oxygen bomb measurements were also implemented. Test specimens, up to 100 mm in diameter and 50 mm thick, could be exposed to a peak heat flux of 65 kW/m^2 using tungsten/quartz heaters. A larger version of this calorimeter was implemented as the intermediate-scale flammability apparatus with a capability to expose samples up to 305 mm in diameter and 75 mm thick. The intermediate-scale apparatus could test items with heat release rates up to 500 kW, whereas the small-scale apparatus was limited to peak heat release rate measurements of 10 kW. In 2000, test methods based on the small-scale apparatus were adopted as ASTM E2058, *Standard Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus (FPA).*[6] In 2001, test methods based on the same apparatus with smoke and corrosion measurement capabilities added to characterize the hazards of materials in commercial cleanrooms were adopted as NFPA 287, *Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using a Fire Propagation Apparatus (FPA).* Figure 2.3.7 illustrates the Tewarson fire propagation test apparatus. Figure 2.3.8 illustrates the ASTM E2058 apparatus.

Cone Calorimeter. The cone calorimeter is probably the most versatile oxygen consumption method for measuring heat re-

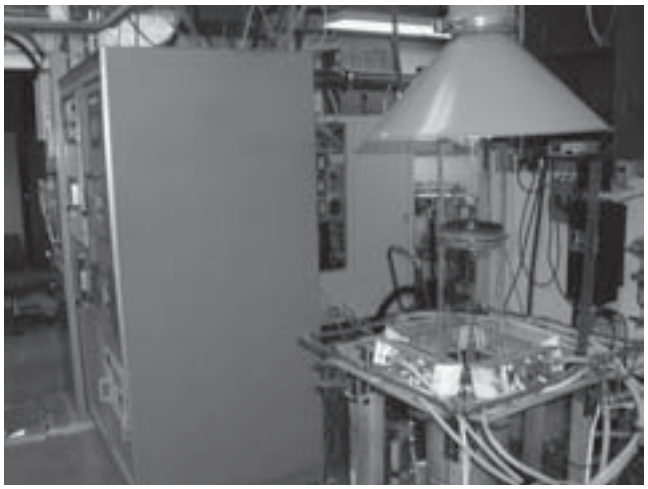


FIGURE 2.3.7 Quartz Heaters and Controlled Combustion Environment of the Fire Propagation Apparatus (Courtesy Ronald Alpert)

lease rate. It was developed at NIST in the 1980s[42] and is presently the most commonly used bench-scale rate of heat release apparatus.[43] The cone calorimeter has been adopted as ASTM E1354, *Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*.[19] It has also been adopted by the National Fire Protection Association in NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter,* and as an international standard, ISO 5660-1.[44]

The cone calorimeter consists of a heater, spark ignitor, sample holder, and load cell located underneath an exhaust hood. Typically, the sample is located in the open with free access of air to the combustion zone. The heater consists of a 5 kW electrical heating element inside an insulated stainless-steel conical shell. Samples can be tested in either a horizontal or vertical orientation. When tests are performed in the horizontal configuration, the specimen is positioned approximately 25 mm beneath the bottom plate of the cone heater. Flames and products of combustion pass through a circular opening at the top of the heater. The heater can expose samples to a maximum irradiance of approximately 100 kW/m^2. Figure 2.3.9 is a schematic of the cone calorimeter.

For piloted ignition tests, an electric spark ignitor is positioned at the top of vertical samples and over the center of horizontal samples. Samples are typically 100 mm by 100 mm, and they can be wrapped with aluminum foil to minimize edge effects. Combustion products and dilution air are extracted through the hood and exhaust duct by a high temperature fan. The flow rate can be adjusted between 0.01 and 0.03 m^3/sec.

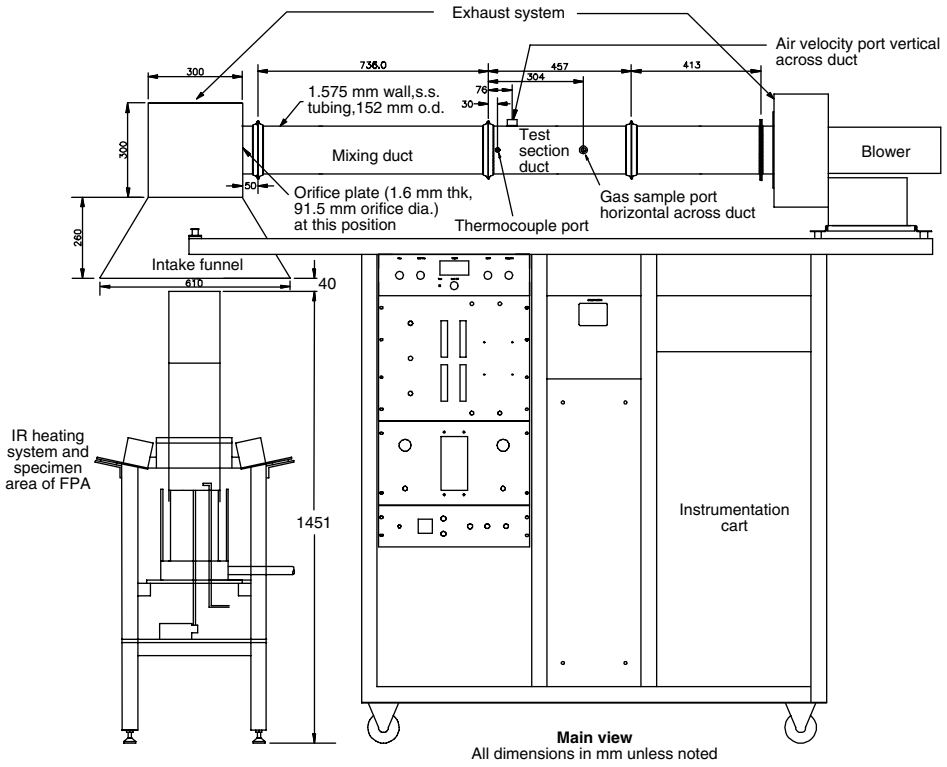


FIGURE 2.3.8 ASTM E2058 Apparatus (Source: Reprinted, with permission, from ASTM E2058, *Standard Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus (FPA),* Annex A1, copyright ASTM International, W. Conshohocken, PA)

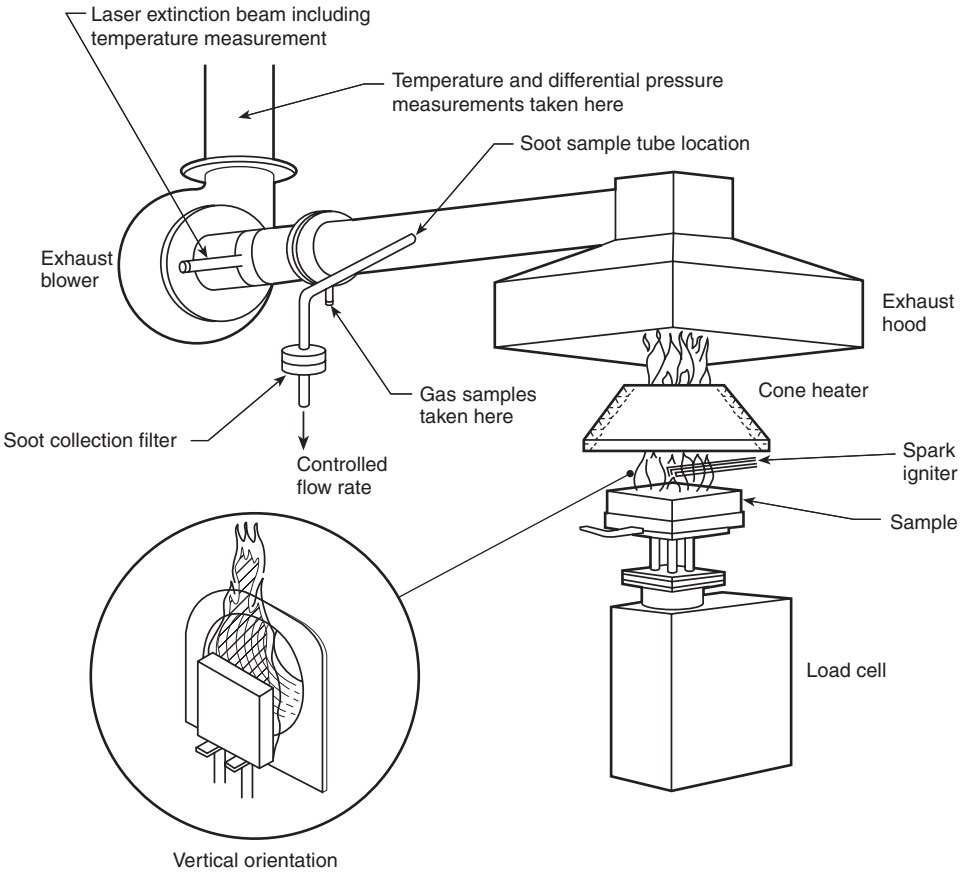


FIGURE 2.3.9 Schematic View of the Cone Calorimeter (Courtesy Society of Fire Protection Engineers)

The volumetric flow rate is kept constant during testing. The sample is mounted on a load cell to determine mass loss rate during a test, and smoke obscuration is measured using a laser light source. The gas flow rate in the exhaust duct is calculated from the pressure drop across and temperature at an orifice plate in the duct. Finally, the concentrations of oxygen, carbon dioxide, carbon monoxide, and other gases are measured using appropriate instruments. Heat release rate is calculated from the gas concentration and mass flow measurements.

Single Burning Item Test. The single burning item test method, or EN 13823, is a CEN (European) standard[45] with the objective of reproducing the transient heat release rate results from the full-scale ISO 9705 room-corner test (discussed later). Two heat release parameters are measured: the ratio of the peak heat release rate to the time at which this peak HRR occurs, or the fire grow rate (FIGRA) index, and the total heat release over the first 600 seconds of the test (THR600). Whether this 1.5-m-high corner test accomplishes the stated objective is definitely open to question since the 31 kW heat release rate of the initiating propane flames from a triangular gas burner produces a rather small incident heat flux on the test specimen. In particular, test specimens consisting of sandwich panels with a combustible insulating core and a metal covering have not yielded the same result in the EN 13823 test as in the ISO 9705 room since the exposure heat flux has not been sufficient to penetrate the metal cover.

Large-Scale Calorimeters

The oxygen consumption technique has been successfully implemented in a number of intermediate and large-scale calorimeters. These large-scale calorimeters have been developed to measure heat release rate from an assortment of different flammable items. These items range from single pieces of furniture, such as couches or mattresses, to entire rooms. Typically, the item or items of interest are burned under a large collection hood or in a room vented to this large hood. The hood would be instrumented to measure the temperature and velocity of the exhaust gases. In addition, the concentrations of oxygen, carbon dioxide, and carbon monoxide would also be measured during the experiments. Burning materials inside a room enclosure has the advantage of including the impact of the room; however, the potential lack of oxygen in the room would prevent the complete combustion of the items of interest. The calorimeter would be unable to distinguish between burning of the object in the room and burning of the gases outside of the room. Measuring the heat release rate from an item burning in the open with excess

oxygen would allow for complete combustion and a better measure of the item's total heat release rate.

Room-Corner Fire Test for Surface Linings. Several standard room fire tests have been developed. A room calorimeter developed at Monsanto Chemical was one of the earliest attempts to build a room-size calorimeter.[46] This test used exhaust gas temperature measurements and statistical analysis to determine heat release rate in lieu of oxygen consumption calorimetry. The American Society for Testing and Materials developed a standard room fire test in the early 1980s,[47] which was standardized in 2003 as ASTM E2257, *Standard Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies*.[48] The ASTM room measures 2.4 m by 3.7 m in size and is 2.4 m high. The room has a single doorway in one wall measuring 0.76 m wide by 2.03 m high. A standard guide, ASTM E603, *Standard Guide for Room Fire Experiments,* for conducting and instrumenting room fire tests[49] is also available. Many years ago, the work on room fire tests in ASTM inspired the ISO 9705 standard[50] that has been designated in Europe as a reference fire scenario for the evaluation of surface lining flammability hazard. NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth,* is a slightly different version of this ISO standard. Another room fire test was developed for use as a potential standard room fire test by NORDTEST.[51]

Furniture Calorimeters. A number of open calorimeters have been developed by various research organizations throughout the world. One of the first was the NBS Furniture Calorimeter.[52] This device used oxygen consumption to determine heat release rate. In addition, mass loss, smoke concentration, and heat flux were measured during combustion of the sample. Other open calorimeters have been developed by NORDTEST,[53] Underwriters Laboratories,[54] FM Global Research,[55] and Statens Provningsanstalt.[56]

ICAL. The ICAL is an intermediate-scale calorimeter that has been designed to measure heat release rate, mass loss rates, and visible smoke development from a 1 m × 1 m vertically oriented, nonmelting material under well-ventilated conditions. The test sample is exposed to a uniform heat flux up to 50 kW/m^2 from a gas-fired radiant panel. This device is documented in ASTM E1623, *Test Method for Determination of Fire and Thermal Parameters of Materials, Products and Systems Using an Intermediate Scale Calorimeter (ICAL)*[21] as well as in ISO 14696.[57] Figure 2.3.10 illustrates the ICAL calorimeter.

Commodity Fire Tests. Several test methods have been developed for measuring the heat release rate from various commodities in specific arrangements. Standards exist for testing stacked chairs,[58] upholstered chairs,[59] and mattresses[60] in open calorimeters as well as in room enclosures while test methods have been established in the United States and Europe to determine the extinguishability of commodity array segments using an applied water droplet flux during the measurement of heat release rate by collecting combustion products in an exhaust hood (see Section 2, Chapter 7, "Theory of Fire Extinguishment").

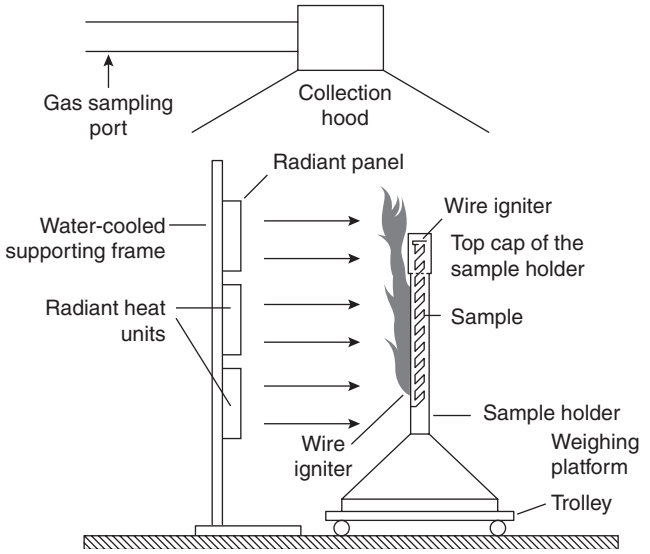


FIGURE 2.3.10 Intermediate-Scale Calorimeter (ICAL) (Source: Reprinted, with permission, from ASTM E1623, *Standard Test Method for Determination of Fire and Thermal Parameters of Materials, Products, and Systems Using an Intermediate Scale Calorimeter (ICAL),* copyright ASTM International, W. Conshohocken, PA)

Certain interior finish materials are tested in a room-corner arrangement, described in NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Coverings on Full Height Panels and Walls,* and NFPA 286. The heat release rate data obtained from these larger calorimeters can be used as an estimate of the hazard potential from the respective item. In the United States, several of the nongovernmental fire test laboratories—FM Global, Underwriters Laboratories, and Southwest Research Institute—have increased the size of their large scale calorimetry labs in order to accommodate larger commodity fire testing.

FLAME PROPAGATION PROPENSITY

Another important parameter for determining the flammability hazard of an item is its propensity to support flame spread. The buoyancy flow induced by a fire and natural wind flow can aid the spread of flames or hinder it. When the flames spread in the direction of the fire-induced flow or with the wind, it is termed "wind-aided" spread (e.g., flame spread up a vertical surface, as discussed in Section 2, Chapter 2, "Physics of Fire Configuration"). "Opposed-flow" flame spread occurs when the flame motion is opposite the direction of fire-induced air flow or into the wind[61] (e.g., flame spread down or laterally on a vertical surface and flame spread over a horizontal surface, as discussed in Section 2, Chapter 2, "Physics of Fire Configuration"). The flame spread across the surface of a solid material is characterized by two moving boundaries or fronts. The front where visible flaming occurs in the gas phase and a pyrolysis region moving through the solid phase within the flame front. The

velocity of this flame front and the associated pyrolysis front can be useful for determining fire hazard, especially in the case of opposed-flow flame spread where such velocities are easily measured. However, in the case presenting the greatest danger, namely wind-aided or upward flame spread, it may be equally important to determine whether or not a material configuration and fire scenario will lead directly to self-sustained flame spread, which could result in rapid movement of the flame and pyrolysis front over the entire upward extent of the material surface. Obviously, the greater the velocity and/or extent of flame spread on a material, the greater the flammability hazard.

Upward or wind-aided flame spread propensity or velocity on a single vertical surface can be used to characterize flammability hazard in test methods. However, conclusions in this case may be incorrect because radiant heat losses from charring materials can prevent flame spread altogether whereas spread velocities for noncharring, nonmelting materials may be very high and not very reproducible. Lateral, downward, or opposed-flow flame spread velocity and the extent of flame spread on surfaces can also be used in test methods to characterize flammability hazard. The disadvantage with test methods involving opposed-flow flame spread is that such configurations are not sensitive to flame radiant heat transfer and hence may not correctly predict flammability hazards in realistic configurations and sizes. Tests involving wind-aided (upward) flame spread propensity in a parallel panel configuration, by eliminating much of the radiant heat losses, have provided useful measures of flammability hazard for materials ranging from wood to highly fire-resistant, engineered polymers. In addition, the propensity for limited (a steady flame front) or unlimited (an accelerating flame front moving upward) flame spread in the parallel panel configuration has been modeled successfully.[23,24]

FLAME SPREAD TEST METHODS

Tunnel Test

The Steiner tunnel test is one of the earliest test methods developed for assessing the flammability hazard of materials through measurement of flame spread. This test, ASTM E84,[62] provides a normalized flame spread rating for materials mounted on the ceiling of the test apparatus under forced-flow conditions. A test specimen 7.6 m long and 1.67 m wide is mounted on the ceiling of a tunnel measuring 8.7 m long by 0.45 m wide and 0.31 m high. The sample is exposed at one end to a 79 kW gas burner with a forced draft through the tunnel of 1.2 m/sec. Relative indexes of flame spread and smoke developed are determined from measurements obtained during the 10 minute test. The test materials are compared to test performance of inorganic cement board and red oak flooring, which have flame spread indexes of 0 and 100 respectively. While the values obtained from this apparatus have been used for regulatory purposes over the last several decades, its relationship to real-world applications has not been established. The requirement to mount a test specimen on the ceiling, its limited ability to test materials that melt and drip, and the limited ventilation available for some polymer foams that produce high volumes of pyrolysis and combustion products are some of the limitations of this apparatus. This test is also documented in NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*.

Radiant Panel Test

Unlike the tunnel test, which is considered a wind-aided flame spread configuration, the radiant panel test provides a measure of downward, opposed-flow flame spread.[63] This test method has also been used extensively in building codes for regulatory purposes. The apparatus measures the surface flammability of materials using a gas-fired radiant panel. A specimen approximately 152 mm × 457 mm is exposed to a radiant panel that is 305 mm × 457 mm. The specimen is sloped away from the panel at a 30° angle with the top of the specimen being closest to the panel. The slope provides a decreasing heat flux along the specimen. A relative index of flame spread is calculated based on the distance the sample burns. This test method is referenced for building products as ASTM E162, *Standard Test Method for Surface Flammability of Materials using a Radiant Energy Source*[64] and for cellular plastics as ASTM D3675, *Standard Test Method for Surface Burning Characteristics of Building Materials*.[65] Figure 2.3.11 illustrates the radiant panel test apparatus.

LIFT Apparatus

Another test apparatus to measure opposed-flow flame spread is referenced in ASTM E 1321, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*.[20] This apparatus, often referred to as the lateral ignition and flame spread test (LIFT), uses a gas-fired radiant panel to measure surface ignition and lateral spread of flames on materials under opposed-flow conditions. The radiant panel is installed at a 15 degree angle to

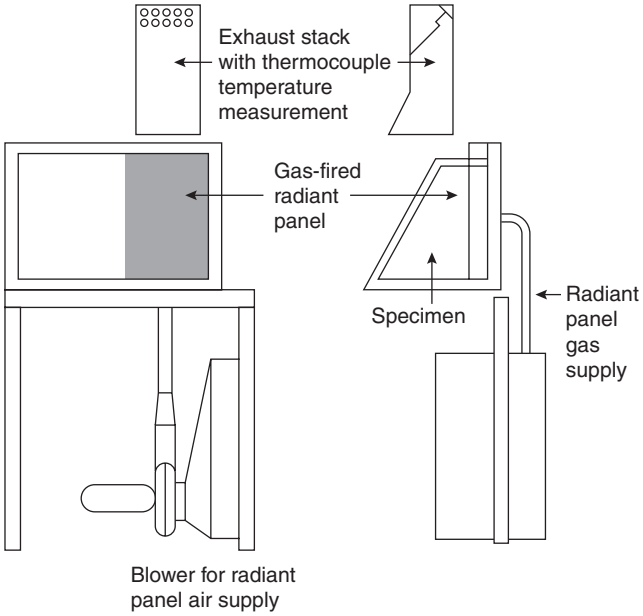


FIGURE 2.3.11 Radiant Panel Test Apparatus from ASTM E162 (Source: National Institute of Standards and Technology)

the test specimen and can provide up to 65 kW/m^2 of heat flux at the 50 mm position. The sample size is 155 mm by 800 mm. A modified version of the test with a different sample orientation is identified as the horizontal ignition and flame spread test (HIFT). Unlike many older test methods, this apparatus provides information in engineering terms. Data obtained from these tests (LIFT and HIFT) allow the flame spread velocity and external heat flux required for flame spread to be determined. The resulting information can be used to evaluate the potential opposed-flow flame spread flammability hazard of many different materials. The LIFT apparatus is also used to examine the flammability of marine surface finishes, and ASTM E1317, *Standard Test Method for Flammability of Marine Surface Finishes,* governs its use for maritime applications.[66] ISO 5658-2[67] is a version of the apparatus nearly identical to ASTM E1321.

Radiant Panel Flooring Test

As a result of some major fires where flame spread on carpeting was a major factor, a radiant panel flooring test was developed at NBS. This test method was adopted as ASTM E648, *Standard Method of Test for Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source*[68] or NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*. A 1 m long test specimen is mounted horizontally beneath an air-gas-fueled radiant panel. The panel is inclined at 30°, providing a heat flux on the test specimen varying from 10 kW/m^2 at the point closest to the panel to 1 kW/m^2 at the farthest point. The critical radiant flux corresponds to the flux at the point of maximum flame propagation. This parameter can also be used in engineering analysis of fire performance of materials. A similar test designed to evaluate attic insulation is referenced in standard ASTM E970, *Standard Test Method for Critical Radiant Flux of Exposed Attic Floor Insulation Using a Radiant Heat Energy Source*.[69]

Vertical Burn Test

The UL 94 vertical burn test provides a measure of a thin material's resistance to self-sustained ignition in an upward flame spread configuration.[70] This test method can be used to select materials for use in electronic devices or applicances. A standard laboratory Bunsen burner (ASTM D5025, *Specification for a Laboratory Burner Used for Small-Scale Burning Tests on Plastic Materials,* burner at 105 mL/min flow rate)[71] is used to produce a 50 W premixed methane-air flame for the ignition source. The flame is applied for 10 seconds and is intended to simulate a short duration ignition such as from an electrical short. The test method utilizes a sample 125 mm long and 13 mm wide mounted 30 cm above a piece of loose cotton. The tested material receives a V-rated classification based on the results from a set of five tests. If the material fails to meet any of the criteria, a V-fail or V-not rating is assigned. The V-ratings are summarized below.

V-0 Classification

1. The afterflame time for each individual specimen is less than 10 seconds.
2. The total afterflame time for any condition set is less than 50 seconds.
3. The cotton indicator is not ignited by flaming particles or drops.

V-1 Classification

1. The afterflame time for each individual specimen is less than 30 seconds.
2. The total afterflame time for any condition set is less than 250 seconds.
3. The cotton indicator is not ignited by flaming particles or drops.

V-2 Classification

1. The afterflame time for each individual specimen is less than 30 seconds.
2. The total afterflame time for any condition set is less than 250 seconds.
3. The cotton indicator is ignited by flaming particles or drops.

An important caveat associated with this test method is that even the V-0 classification does not ensure the material will not spread flames in real fire scenarios. (The 50 W [not 50 kW] exposure flame is meant to reproduce a very small ignition source. The danger of course is that someone not knowledgeable about flammability hazards will misinterpret the applicability of these ratings.)

Parallel Panel Test

A parallel panel apparatus for evaluating the fire propagation hazard of exposed polymer materials was developed at FM Global Research in the 1970s. This parallel panel configuration has most often been used to determine if polymeric materials represent a flammability hazard when installed in wall linings and equipment in highly sensitive commercial fabrication areas where even a small fire cannot be tolerated, such as a cleanroom in a fabrication facility. The apparatus, which now qualifies materials for use in commercial semiconductor clean rooms[72] following the ANSI FM 4910 protocol,[73] consists of two parallel 2.4 m high × 0.6 m wide panels separated by a 0.3 m × 0.6 m horizontal sand burner. Each panel is faced with a test specimen attached to a 25 mm thick sheet of calcium silicate board, which, in turn, is attached to a 13 mm thick sheet of plywood. The test specimen panels are exposed to the sand burner flames for 20 minutes only after the burner has reached a steady heat release rate of 60 kW. During the test, the total heat release rate and smoke generation rate of the panel assembly are obtained from gas and soot concentration measurements in an exhaust hood, the mass loss rate of the assembly is obtained from load transducer measurements, panel flame heat flux is obtained from imbedded gauges and video observations are recorded of flame front position beyond the 0.6 m height of the exposure flames. All of these measurements are used to determine the flammability hazard of the panel specimen in a specific fire scenario. This test is sufficiently large that, as in most dangerous fires, flame radiation is dominant. There is also ample air access and confinement of heat so that the test is rigorous and realistic.

The relatively simple test geometry both increases the likelihood of modeling success and provides access to instrumentation. Yet the surface area of the material specimen required is small enough to make testing economical.

The parallel panel configuration and sand burner has also been used with double height panels (4.88 m high instead of the usual 2.44 m) to evaluate flame spread on polymer insulated cables in a simulated vertical cable tray configuration, which provided the technical basis for the FM 3972 cable standard.[74] Results from this larger configuration when there is negligible flame spread beyond the exposure fire are in excellent agreement with the UL 910/NFPA 262, *Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces,* plenum cable test based on the ASTM E84 tunnel apparatus. Research on the parallel panel configuration now in progress[24] has shown that by increasing the scale of the panels and the heat release rate of the sand burner, it is very likely that a correlation can be obtained with flame spread results in very large-scale corner tests (see below).

Large-Scale Corner, Room and Façade Tests

There are several large-scale test methods[75–78] that expose wall and ceiling lining materials (in many cases, only sandwich-type panels of metal covering polymer foam core) or external façade materials to a high heat flux exposure over significant specimen heights from 4 to 10 m. Heat flux exposure is generated by large-scale flames from pallet stacks, wood cribs, or gas burners that are adjacent to open corners, within rooms, or near façades. During the various tests, observations are made to determine if self-sustained flame spread occurs to the top or lateral boundaries of the apparatus. Such flame spread indicates the presence of a flammability hazard for the particular type of fire scenario that is being simulated by the test method.

SMOKE YIELD

Smoke has long been identified as the most significant hazard to people during fire.[79] Smoke and the toxic gases contained in it are the primary cause of fatalities in fires. Smoke can also impair visibility and prevent escape from threatened areas. The rate of production of smoke and other products of combustion is very dependent on the fire scenario (type and configuration of material burning, flaming or nonflaming combustion, level of external heat flux) as well as the scale of the fire. In addition, the ventilation air supply and stage of the fire (pre- or postflashover) will also significantly influence the production of smoke and other species. Building codes have attempted to regulate the amount of smoke likely to be produced by various materials during a fire. Specifically, interior finishes are often required to have a smoke developed rating less than 450 when measured using the ASTM E84 tunnel test.[80] The smoke-developed rating is determined by comparing the light absorption curve from a test material to the light absorption results from inorganic cement board and red oak flooring, which have smoke-developed indexes of 0 and 100 respectively.

Smoke production is measured by weighing the particulates collected on a filter, by determining the optical density of a quantity of smoke collected in a known volume, or measuring the optical density as an assumed plug flow of smoke moves through an exhaust duct. The optical density measurements in a duct flow are most convenient but also provide only an indirect measure of smoke production. Typically, the smoke produced during a test is reported as a smoke yield, which is a mass of smoke per unit mass of material burned,[81] with a higher smoke yield representing a greater flammability hazard for two reasons: (1) a higher yield implies that combustion products from a fire will produce more direct damage to life and property for each unit of material that burns and (2) a higher yield implies that there may be more soot in the flame to enhance radiant flame heat transfer, leading to higher heat release rates, more extensive flame spread, and higher burning rates.

Note that every test method for flammability hazard that uses an exhaust collection hood or duct to measure heat release rate will also provide a measure of smoke generation rate using the optical density data coupled with the exhaust duct flow rate. This measurement, together with the mass loss measurement, if available, allows the smoke yield to be calculated for the evaluation of flammability hazard. Although the ASTM E84/NFPA 255 tunnel test does not measure heat release rate, this test method does provide an index representing the amount of smoke produced by the burning sample. The index is determined by using a white light source and a photocell to measure the light absorption occurring in the exhaust duct and is referenced to red oak which has a value of 100 (NFPA 255).

The cone calorimeter and fire propagation apparatus are two laboratory calorimeters that can also be used to obtain smoke obscuration data.[82] The attenuation of light from a He-Ne laser beam passing through the exhaust duct is measured as a function of time. An extinction coefficient is calculated from the data and used to determine a specific extinction area in the cone test methods whereas a smoke yield is calculated from a smoke generation rate in the fire propagation apparatus test methods. These equivalent quantities can be regarded as an effective material property and measure of flammability hazard. Figure 2.3.12 depicts the smoke measuring portion of cone calorimeter and fire propagation apparatus.

SMOKE YIELD TEST METHODS

Smoke Chamber Test

The NBS smoke chamber was developed specifically to measure obscuration by smoke particulates.[83] The apparatus consists of a 3 ft (0.914 m) wide, 3 ft (0.914 m) high, and 2 ft (0.61 m) deep enclosure. A 3 in. × 3 in. (75 mm × 75 mm) specimen is exposed in the vertical orientation to an electric heater. Tests can be conducted with or without small pilot flames impinging at the bottom of the specimen. A white light source is located at the bottom of the enclosure, and a photomultiplier tube is mounted at the top to measure obscuration and optical density of the smoke as it accumulates inside the enclosure. This method is described in ASTM E662, *Standard Test Method for Specific Optical Density Generated by Solid Materials*.[84] Three tests are conducted at a heat flux of 25 kW/m^2 with pilot flames and without pilot flames. These conditions are referred to as

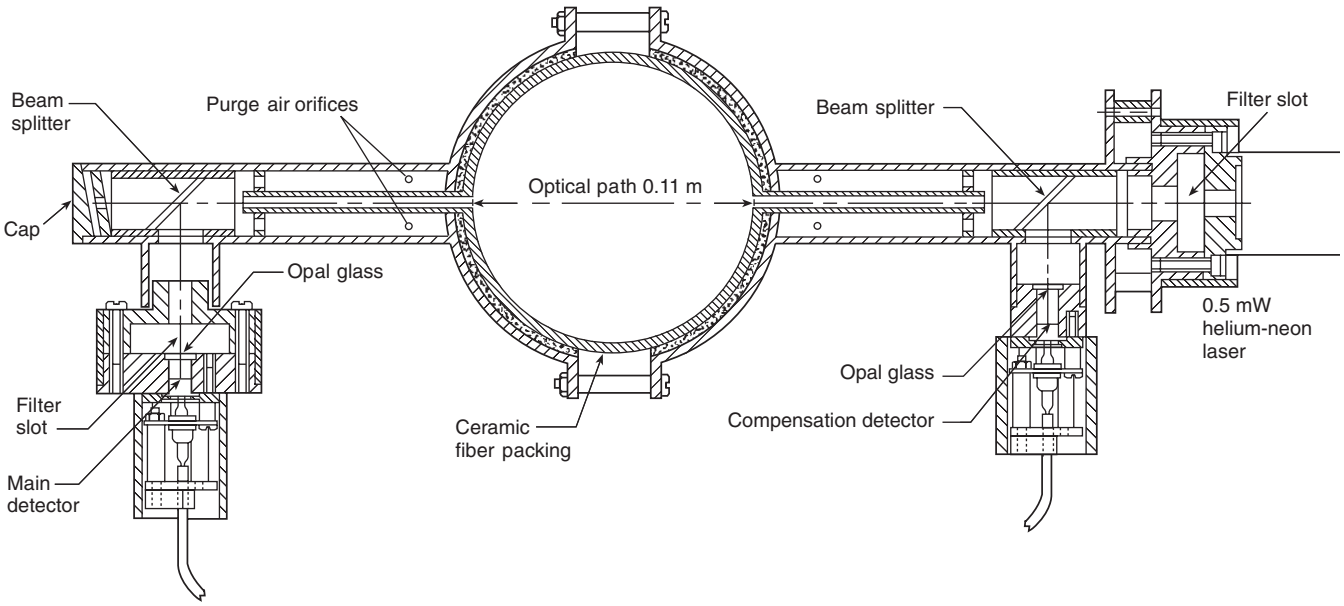


FIGURE 2.3.12 Schematic of Laser Photometer or Smoke Measuring Portion of Cone Calorimeter (Courtesy Society of Fire Protection Engineers)

the flaming and nonflaming modes, respectively. The latter is misleading because specimens often ignite spontaneously, leading to flaming combustion without the pilot flames. The test has been subjected to criticism because the smoke generated by the specimen accumulates inside the chamber and eventually affects combustion. The test conditions, therefore, are not well controlled and partly depend on the burning behavior of the product itself.

Guide for Measurement of Fire Gases

Fires can generate not only smoke particulates but also toxic products of combustion, primarily in gaseous form. A wide range of techniques is used to measure toxic gas concentrations in fire tests, ranging from simple qualitative sorption tube methods to sophisticated spectroscopy techniques. ASTM E800, *Standard Guide for Measurement of Gases Present or Generated During Fires,*[85] describes the most common analytical methods and sampling considerations for many gases. Fourier transform infrared (FTIR) spectroscopy has emerged in recent years as the method of choice for real-time continuous analysis of fire gases. Animal tests have been used to determine toxic potency, but their use has become increasingly limited. One of the test procedures which minimizes the number of animal tests is described in ASTM E1678, *Standard Test Method for Measuring Smoke Toxicity for Use in Fire Hazard Analysis*[86] and NFPA 269, *Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling*. In this test procedure, a specimen is exposed to a radiant heat flux of 50 kW/m^2 and the products of combustion are collected in a 0.2 m^3 (7 ft^3) chamber. Test duration is 30 minutes. A mathematical correction is made to the analytical measurements to account for the increase in CO production in underventilated postflashover fires. This is important because the majority of U.S. fire deaths occur remote from the fire room, especially for fires that have proceeded past flashover. Figure 2.3.13 illustrates the smoke density test apparatus used in ASTM E1678.

EXTINGUISHABILITY

There are very few engineering methods to determine the extinguishability of materials or material systems for use in the evaluation of flammability hazard. One method already mentioned in connection with heat release rate is the large-scale required delivered density of water (RDD) test for storage commodities (see a full description in Section 2, Chapter 7, "Theory of Fire Extinguishment"), in which a material array (typically cartons with vertical and horizontal flue spaces) burns under

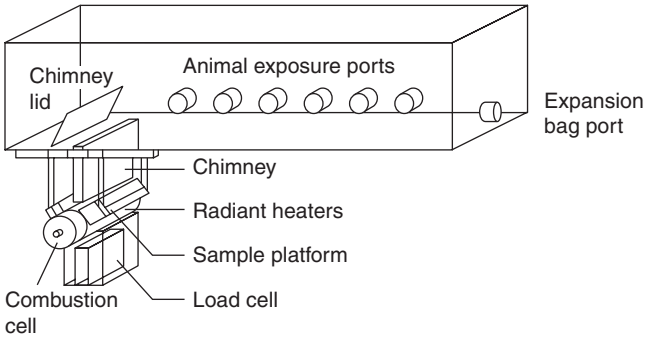


FIGURE 2.3.13 Smoke Toxicity Test Apparatus from ASTM E1678 (Source: National Institute of Standards and Technology)

an exhaust measurement hood. A fixed, known water flux is applied to the top surface of the commodity array at the time when sprinkler actuation would be expected to occur. Through multiple tests of this type, the critical water flux that will cause a permanent decay in heat release rate after the initial peak value can be determined. With regard to the flammability hazard of an isolated material surface, a laboratory measurement method to determine the critical water flux for extinguishment of horizontal (facing upward) or vertical burning material panels was described by Magee and Reitz[87] in the 1970s (see Section 2, Chapter 7, "Theory of Fire Extinguishment"). Obviously, the greater the water flux required for extinguishment, the greater is the flammability hazard.

SUMMARY

By definition, any material capable of burning with a flame is considered flammable, but the flammability hazard of a material in a specific fire scenario is not easily quantified. Different aspects of flammability hazard can be defined or categorized and for each such category, a test method is available to measure the magnitude of a material characteristic that can be used to evaluate, if not quantify, flammability hazard. These different aspects of flammability include type of response to heat flux, ease of ignition, generation of heat and smoke, extent of flame spread, and ease of extinguishment. The flammability of a material is dependent on many parameters, such as its chemical composition, physical properties, geometric configuration, and combustion products. As a result, flammability is really a characterization of multiple fire hazards. There is no single measure that will adequately describe a material's performance in a real fire scenario.

Given the large number of parameters that play a role in determining flammability hazard, it is important to use a variety of flammability test methods and models in order to have a more reliable and accurate assessment applicable to realistic fire scenarios.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the flammability hazard of materials discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 260, *Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture*
NFPA 261, *Standard Method of Test for Determining Resistance of Mock-Up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes*
NFPA 262, *Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces*
NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Coverings on Full Height Panels and Walls*
NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*
NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*
NFPA 287, *Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using a Fire Propagation Apparatus (FPA)*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*
NFPA 705, *Recommended Practice for a Field Flame Test for Textiles and Films*
NFPA 921, *Guide for Fire and Explosion Investigations*

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Chapter 4

Dynamics of Compartment Fire Growth

Richard L. P. Custer

Chapter Contents

Fire Growth
Classifications of Fire
Effects of Compartment Boundaries on Fire

Key Terms

compartment fire, fire dynamics, fire growth, fire (stage of), flashover, fuel load, heat release rate, incipient fire, plume, steady-state fire, *t*-squared fire

Over the past 25 years, research scientists and engineers have worked to develop an understanding of the factors and physical processes that enter into and control the growth and spread of fire and its products. Much of the work has focused on two general types of fires: (1) the pool fire and (2) the compartment fire. Research on pool fires has developed an understanding of energy production from a burning liquid surface and the dynamics of the plume of hot gases and other products of combustion that rise from the surface. Understanding of compartment fires, in part, is built on the work involving pool fires in order to define the characteristics of a simplified fire plume environment, without the effects that compartment boundaries (such as walls and ceilings) and compartment openings or vents (such as doors and windows) have on the development of the growth rate of the fire. Other work has produced literally hundreds of test fires in compartments with varying fire sources, compartment dimensions, materials of construction, and venting arrangements. As a result of this work, it is now possible to quantify many aspects of pool and compartment fires in order to predict their effect for use in hazard analysis, analysis and design of fire protection systems, and fire reconstruction. Fire spread and growth in the context of this chapter is limited to the compartment of origin and the fuel packages within it.

The purpose of this chapter is to provide the reader with a basic understanding of the concepts involved in modern-day applied fire dynamics as the basis for using the calculation methods described elsewhere in this handbook. It is intended to introduce the general concepts of fire growth in a compartment, not to focus on the detailed mathematics involved. A few equations, however, are provided to demonstrate some of the basic relationships. Further references to other chapters of this handbook and to the published literature will be provided, as needed, to guide the reader to sources of information for additional study.

For the purpose stated above, the discussion will deal with fire growth from the time of established burning to the time when the fire involves the entire compartment and the burning rate is controlled by airflow into and out of the compartment vents.

Established burning is defined as the point in fire development when the size of the flame on a burning material is sufficiently large that flaming combustion will continue without an independent external ignition source and the fire will grow to the extent permitted by the amount of fuel or oxygen present. The flame height at established burning is frequently considered to be approximately 10 in. (254 mm) on a horizontal fuel surface. It is suggested that, at this point, there is sufficient energy feedback from the flame to the fuel so that there will be adequate production of fuel vapors for combustion and the flame will not go out without external influences such as oxygen depletion or fire extinguishment activities.

See also Section 2, Chapter 1, "Physics and Chemistry of Fire"; Section 2, Chapter 2, "Physics of Fire Configuration"; Section 2, Chapter 3, "Flammability Hazard of Materials"; Section 3, Chapter 5, "Introduction to Fire Modeling"; Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations"; and Section 6, Chapter 3, "Concepts and Protocols of Fire Testing."

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FIRE GROWTH

The following discussion assumes that ignition has taken place and the fire has reached the point of established burning. Beginning with the first materials ignited, the early stages of a fire provide the driving force for growth and spread, both within the compartment and to other portions of the building. The fire serves not only as a source of energy, providing flame and heated gases for the spread of fire, but also as the source of smoke particulates and the toxic and corrosive gases that form the products of combustion. The rate and amount of energy produced by the initial fire in a compartment will frequently determine whether the fire will spread beyond that compartment.

The fuel available for fire growth and spread can be characterized in two ways: (1) the rate at which it burns and releases energy into the compartment environment and (2) the total energy available that could be released from the fuel. Each of these characteristics is used to describe compartment fire hazard or potential fire severity in a compartment.

Rate of burning is commonly described in terms of how fast energy is being released at a given time, using *heat release rate* (HRR) measured in kilowatts (Btu per second) to quantify this aspect of fire growth. The higher the HRR in a given compartment, the faster the compartment fills with hot gases and products of combustion.

The concept of potential hazard or fire severity is expressed as fire loading or fuel loading and is based on the amount of energy that would be available if all the fuel were to be consumed, not on how fast the material burns. Fire or fuel load is generally expressed in terms of kilograms of fuel per square meter (pounds per square foot) of floor area of the space being evaluated. Fuel load can also be expressed in energy terms as megajoules (MJ) per square meter (Btu per square foot). Fuel loading does not consider the speed at which the fuel burns or the rate at which the fire grows, but rather addresses the issue of how long a fire might burn until the fuel is consumed. A high fuel load does not necessarily mean a dangerously fast-growing fire. These concepts are discussed in detail in the following sections.

Heat Release Rate

The amount of heat released by a fire per unit of time (HRR) depends on its heat of combustion (which is the amount of energy produced for each unit of fuel mass burned), the mass of fuel consumed per unit of time (mass loss rate), and the efficiency of the combustion process. The HRR is then determined by multiplying the mass loss rate (mass consumed/unit of time) by the heat of combustion (energy available/unit of mass) and the combustion efficiency (fraction of the mass converted to energy) to yield the HRR, in units of energy produced per unit of time. Various units are used, such as kilowatts (kW), Btu/sec, or J/sec. The kilowatt (1055 Btu/sec) is the most common unit. The HRR is important during the growth phase of the fire, when air for combustion is abundant and the characteristics of the fuel control the burning rate. During this phase, the instantaneous HRR increases over time. Equation 1 describes this relationship between the HRR ($\dot{Q}$), mass loss ($\dot{m}$), and heat of combustion (h_c):

$$\dot{Q} = \dot{m}\Delta h_c \qquad (1)$$

The burning rate of a given fuel is controlled both by fuel chemistry, by fuel configuration or geometry, and its form. Fuel chemistry refers to the composition of the fuel—for example, cellulosic versus petrochemical. Cellulosic materials include wood, paper, cotton, fabric, and so on. Petrochemical materials, in general, refer to petroleum liquids or to plastics that are largely composed of formulations derived from petroleum. The configuration of the material—that is, its size, shape, and arrangement—also has an effect on the burning rate, as explained in Section 2, Chapter 2, "Physics of Fire Configuration."

One way of looking at the fuel configuration is in terms of the surface area available to burn compared to the mass of the material, which is called the surface-area-to-mass ratio. In the case of cellulosic materials, for example, a solid block of wood weighing 2.2 lb (1 kg) will burn much more slowly than will the same mass if converted into thin sheets of paper, and may burn explosively if converted into very fine wood dust and dispersed throughout a compartment volume. This concept can be applied to understanding the difference in burning behavior between expanded and unexpanded as well as melting and nonmelting polymer materials, as discussed below.

Foamed, expanded polymers, in general, burn more rapidly than a similar formulation in rigid, unexpanded form. Two examples are (1) flexible urethane versus solid, rigid urethane and (2) Styrofoam™ versus rigid polystyrene. The flexible, expanded foam is of low density and generally has a higher HRR than the rigid, unexpanded material. Another difference in physical characteristics related to burning characteristics of plastics is whether or not the plastic melts when it burns. Those polymers that produce a liquid melt when heated are referred to as thermoplastics. The melting may produce a pool with a large surface area, thereby releasing energy more rapidly than those polymers that remain solid when heated. The latter are referred to as thermosetting plastic materials. Thermosetting materials generally tend to form a char layer and burn more slowly. It should be noted that the peak HRR for ignitible liquids is related to the amount of surface area that is burning. Table 2.4.1 provides some examples of peak

TABLE 2.4.1 Representative Peak Heat Release Rates (Unconfined Burning)

Fuel (lb)	*Peak HRR (kW)*
Wastebasket, small (1.5–3)	4–18
Trash bags, 11 gal (46.6 L) with mixed plastic and paper trash (2½–7½)	140–350
Cotton mattress (26–29)	40–970
TV sets (69–72)	120–290
Plastic trash bags/paper trash (2.6–31)	120–350
PVC waiting room chair, metal frame (34)	270
Cotton easy chair (39–70)	290–370
Gasoline/kerosene in 2 ft^2 (0.61 m^2) pool	400
Christmas trees, dry (14–16)	500–650
Polyurethane mattress (7–31)	810–2630
Polyurethane easy chair (27–61)	1350–1990
Polyurethane sofa (113)	3120

Source: NFPA 921, *Guide for Fire and Explosion Investigations,* 2004 edition, Table 5.4.2.1.

burning rates of representative materials and products. Although this is not an exhaustive discussion of fuel burning characteristics, it does present some factors that the reader might consider in assessing the potential HRR or growth rate of a fire, given certain types of fuels. More detailed discussions of individual fuels are found in the appropriate chapters of this handbook.

Fuel Loading

The concept of fuel loading is one way of characterizing the hazard of a compartment fire or building fire in terms of the length of time the building would be expected to burn, based on the total amount of fuel available and the total energy produced.

Fuel loading is determined by adding up all fuel present and dividing it by the plan area of the compartment or fire space. The fuel load can be expressed as the mass of fuel equivalent to wood. When plastics or other materials are present, multiplying the number of pounds (kilograms) of plastic or other materials by the heat of combustion for those materials and dividing by the heat of combustion for wood provides a conversion. This conversion produces an equivalent number of pounds (kilograms) of wood for plastics or other materials present.

Fuel loading is related to the expected length of time a fire will burn once it is controlled by the amount of air available for the fuel to burn at a steady rate. The air that is supplied through openings, such as doors and windows, controls the amount of heat produced by a fire during this time. For fire duration analysis, all doors and windows are generally assumed to be open.

A fire burning at a constant HRR burns fuel mass at a constant rate as well. Given the mass of material being burned per minute and the amount of material available to be burned, it is possible to estimate the total burning time.

CLASSIFICATIONS OF FIRE

It is frequently useful to classify fires in order to simplify communication regarding certain common characteristics. Fires have been characterized in four general ways: (1) type of combustion process, (2) growth rate, (3) ventilation, and (4) fire stage.

Classification by Type of Combustion Process

Perhaps the simplest description of a fire classification would be to divide the fire into three regimes: (1) precombustion, (2) smoldering combustion, and (3) flaming combustion. No specific sequence is necessarily implied by this classification. Precombustion is the process of heating fuels to their ignition point, during which time vapors and particulates are released from the fuel. Smoldering is defined as glowing combustion on the fuel surface and may or may not be related in any way to the oxygen content in the vicinity of the smoldering process. What is implied here is that the fuel vapor production rate and temperatures involved may not be sufficient to support flaming combustion. Flaming combustion is almost self-explanatory in that the production of sufficient energy and a fuel vapor mixture with air in a flammable range is the condition that underlies and supports the presence of flame.

These conditions of burning may exist simultaneously within a given fire. As flames spread from one point to another on a given item of fuel or within the building, the precombustion or preignition situation will exist at the perimeter of the fire. The presence of both smoldering and flaming, even in the same compartment, is quite common as the fire spreads through different types of fuels by different mechanisms.

Classification by Rate of Growth

Fires may also be classified on the basis of growth rate. Fire growth can be either positive (increasing growth rate) or negative (decreasing growth rate).

A fire that increases its instantaneous energy output or heat release rate over time is said to be a growing fire. Typically, growing fires have more air available than is needed for combustion of the fuel gases being generated and will continue to grow until limited either by the amount of fuel available or the amount of air for combustion.

A second category based on growth rate is the steady-state fire. Under steady-state conditions, the fire's heat output or heat release rate remains relatively constant over time. This is not to say that there will not be variations, but there is no rapid continuing increase or continuing decrease in energy release rate. An example of this phenomenon might be a flammable liquid pool fire of fixed diameter where, once the entire surface is involved in flame, the amount of energy produced is controlled by the surface area and will be essentially constant until the fuel is exhausted. Another example would be the production of energy from a fire becoming limited due to air supply. In situations where the air supply is increased, perhaps by breaking of windows, a steady-state fire may resume growing if there is sufficient fuel available.

A third category is the burnout or decay condition, where there is plenty of air for combustion but the HRR is decreasing, as fuel is consumed.

See Figure 2.4.1 for a graphical representation of growing fire, steady-state fire, and decay.

Growth rate, or the speed at which growth accelerates, is another way to classify fires. Such fires are considered "time-dependent" fires. Typical fires in buildings such as residences

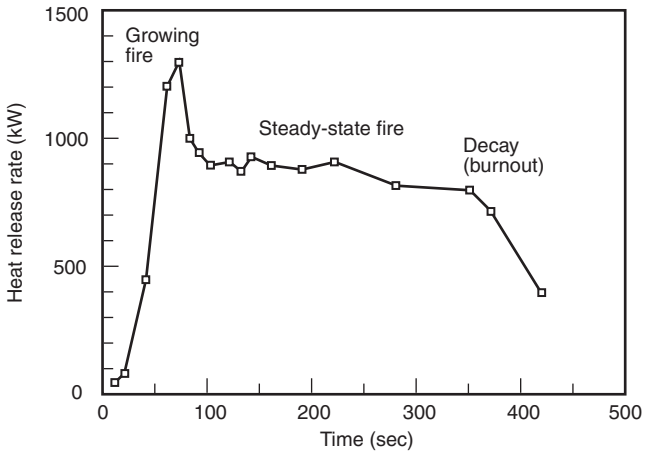

FIGURE 2.4.1 Categories of Fire Growth, Based on Growth Rate

and offices have been determined to grow as a function of the square of time and are referred to as "*t*-squared" fires. The *t*-squared fire can be characterized by Equation 2.[1]

$$\dot{Q} = \alpha t^2 \quad (2)$$

where

$\dot{Q}$ = Heat release rate at a given time

α = Fire growth constant

t = Time

The fire growth constant (α) represents the combined effects of fuel chemistry and configuration on the speed of fire growth governed by the *t*-squared relationship. For many fire protection applications such as prediction of systems actuations or onset of hazardous conditions, *t*-squared fires are classified based on the fire growth constant as follows:[1]

Slow	$\dot{Q} = 0.00293t^2$
Medium	$\dot{Q} = 0.01172t^2$
Fast	$\dot{Q} = 0.0469t^2$
Ultrafast	$\dot{Q} = 0.1876t^2$

Typically, upholstered furniture fires would fall in the range of fast fires while ignitable liquid fires would fall in the range of ultrafast fires.

Classification on the Basis of Ventilation

Fires may also be classified based on whether the fire is controlled by the amount of fuel available to burn or by the amount of oxygen or air available for the combustion process to continue. When a fire is burning in the open, or is in the early stages of development within a compartment where there is excess air for combustion, the fire is said to be fuel-controlled. In a compartment fire with sufficient fuel available, the window or door openings may ultimately serve to control the amount of air available for combustion within the compartment. Once the fire develops to a point where it produces more fuel vapors than can be consumed in the compartment with the available air, it is considered to be a ventilation-controlled fire. The effect of ventilation on HRR is related to the dimensions of the ventilation opening as shown in Equation 3.[2]

$$\dot{Q} \propto A\sqrt{h} \quad (3)$$

where

$\dot{Q}$ = Heat release rate

A = Area of the opening

h = Height of the opening

As noted above, with regard to classification by burning rate, changes in ventilation conditions can affect the fire behavior classification. In this case, an increase in compartment ventilation, such as from opening doors or breaking windows, would result in a fuel-controlled condition as long as this results in excess air compared to the fuel vapors being produced.

Classification by Fire Stage

It is often useful for the purposes of general discussion to classify fires by stage based on the concurrent energy production conditions. Four stages are commonly used, as follows:

- Incipient fire
- Fire growth
- Steady state
- Fire decay

Incipient fire refers to that stage when there is smoldering but insufficient flaming for established burning. The *fire growth* stage represents increasing fire growth with respect to heat release over time. During this stage the fire would be considered fuel controlled. When the heat release rate is basically constant the fire is considered to be in the *steady-state* stage. Here the heat release rate may be controlled by the fuel package size and geometry (i.e., the surface area available to burn) or by the available ventilation to support combustion (i.e., a ventilation-controlled fire). In the *fire decay* stage, the heat release rate is decreasing over time. This may be due to consumption of fuel in a fuel-controlled fire or continued oxygen depletion in a ventilation-controlled scenario. In the latter situation, a change in the enclosure conditions, such as a window or wall failure, may return the fire to the growth stage and possibly reach steady state depending to the amount of fuel present and the ventilation conditions.

EFFECTS OF COMPARTMENT BOUNDARIES ON FIRE

The presence of compartment boundaries, such as ceilings and walls, can have a significant influence on the manner in which a fire grows and spreads by affecting and controlling heat losses and the HRR.

Fire in the Open

The simplest arrangement of a fire is in the open where it is unaffected by either walls or ceilings. A fire in the open is considered a free-burning fire and is fuel controlled. Figure 2.4.2 shows a steadily burning fire in the open, with no confining ceiling or walls. This situation can either represent a fire outdoors, a fire in a compartment with a high ceiling or an atrium, or the early stages of a compartment fire that has not grown to the size that the compartment boundaries have an influence.

Directly above the fire shown in Figure 2.4.2, a column of partially or completely visible flame and combustion products that include smoke particles and hot gases rises into the air. This column is referred to as the fire plume. Under stable conditions, the plume will be symmetrical about the center or axis of the fire.* The action of the hot gases rising due to buoyancy causes cooler air to flow in along the boundaries between the plume and the ambient surroundings. This process is called entrainment. Above any flames, which have relatively constant temperatures, both the temperature and the upward velocity on the

*This is referred to as an axisymmetric plume.

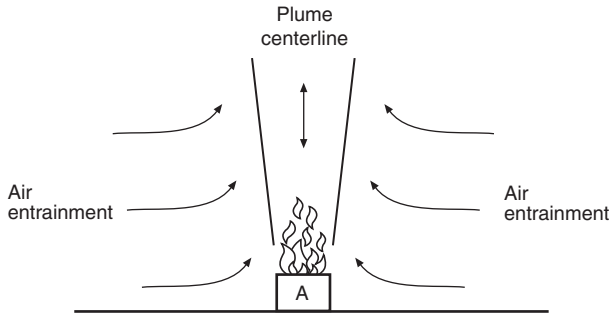

FIGURE 2.4.2 Fire in the Open. Note: A = source of fire.

plume centerline decrease with height due to the cooling effects of the entrained air. At the same time, the plume diameter above the flames increases with height due to the additional volume of gases entrained. Within the flame region, upward gas velocity on the plume centerline will increase from near zero at the base of the flames (the lowest fuel elevation actively burning) up to a maximum value at about half the flame height, remaining at that value up to the flame tip, before decreasing with height in the plume, as noted. At locations outward from the plume centerline, temperature and velocity profiles have a Gaussian contour, decreasing gradually and approaching ambient values at the plume periphery. When the temperature at the plume centerline reaches the temperature of the surrounding air, the gases and smoke stop rising. This phenomenon is frequently observed, particularly on a calm day when smoke from a chimney or industrial stack rises to a certain level and suddenly stops and begins to spread out horizontally, since there is no longer a buoyant force causing the gas to rise vertically. These same conditions can develop in tall spaces within buildings, such as in atria, resulting in stratification of the smoke and hot gases. Such a phenomenon may result in delayed operation of sprinklers or detectors or, in some cases, failure to operate at all.

An additional feature of a fire in the open, which is evident when the minimum base dimension of the fire plume is greater than 6 to 19 ft (1.8 to 5.8 m), is the presence of an obscuring mantle of smoke, beginning near the flame tip and covering more of the flame as the fire plume base dimension increases above the preceding values. For very large-scale fires, such as the total involvement of a large warehouse, the resultant smoke mantle will almost totally obscure the flames, with only brief glimpses of flame being visible from time to time above a bright flame band at the base of the fire plume. This flame obscuration, as expected, sharply reduces the radiant output from the flame portion of the plume since the obscuring smoke is relatively cool. There is presently no comprehensive model that can accurately predict the extent and properties of the smoke mantle under a wide range of burning conditions, such as the nature and size of the fire.

Fire Under an Unobstructed Ceiling

When a ceiling is located above a fire plume, the rising hot gases and combustion products impinge on the ceiling and begin to flow radially outward away from the plume centerline. On a smooth, flat (nonsloping) ceiling, this flow would ideally be equal in all directions. The radially outward flow due to fire plume impingement is defined as a ceiling jet. Figure 2.4.3 shows the general effects of a ceiling. When a plume impinges on a ceiling, the flow near the ceiling can be considered to have two regions: (1) the impingement or turning region, comparable in diameter to that of the plume, and (2) the ceiling jet region, which extends outward along the ceiling from the turning region until obstructed by walls, draft curtains, or beams. In the turning region, the plume centerline upward velocity changes in direction, but not significantly in magnitude, as the flow turns parallel to the ceiling. At the same time, the plume centerline gas temperature decreases only slightly due to heat losses at the ceiling surface. Since the ceiling surface area in the impingement region is rather small, these temperature decreases are minimal.

In a ceiling jet that is not caused by direct flame impingement, maximum temperature and velocity decrease steadily as the radial distance from the plume centerline increases due to a combination of air entrainment from below the jet and heat loss to the ceiling above the jet. As a result, plume velocities and temperatures are much greater than nonflaming ceiling jet velocities and temperatures. For the axisymmetric ceiling jet resulting from plume (not flame) impingement on an unobstructed ceiling, the thickness of the ceiling jet tends to be reduced as radius increases but is increased by addition of ambient air entrained from below. As a result, the thickness of the axisymmetric, nonflaming ceiling jet tends to a nearly constant value equal to about 10 percent of the ceiling height above the base of the fire plume when the flame height is negligible compared to the ceiling height. When flame height is such that there is direct flame impingement on an unobstructed ceiling, the length of flame along the ceiling plus the flame height in the plume below the ceiling is roughly equal to the total flame height in effect if there were no ceiling present.

It should be noted that for a line fire (e.g., a flammable liquid burning in a long trench), where the depth of the flames is very much less than the length of burning material, the variation

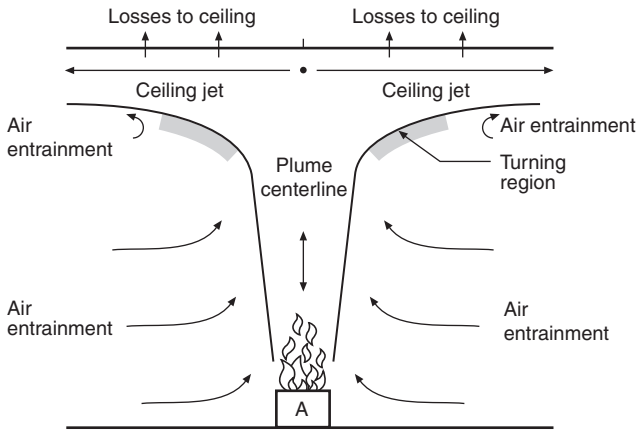

FIGURE 2.4.3 Fire Under Ceiling, Far from Walls. Note: A = source of fire.

of centerline plume velocity and temperature with height and the variation of maximum ceiling jet velocity and temperature with distance along the ceiling from the impingement zone differ from the axisymmetric situation described above. In a line fire, the thickness of the ceiling jet increases steadily as the flow moves outward from the location of plume impingement.

Research has shown that one set of relationships holds for the impingement or turning region where the plume turns to flow out horizontally underneath the ceiling. In this region, the flow gas is buoyancy-dominated, and the temperatures and velocities are a function primarily of the height of the ceiling above the base of the fire, since the height affects the amount of entrainment. Although the actual temperature in the plume is related to the heat release rate of the fire, for any given fire, the temperature along the centerline or inside the turning radius of an axisymmetric, nonflaming plume can be predicted by the general relationship given in Equation 4.[3]

$$\Delta T = 16.9\frac{\dot{Q}^{2/3}}{H^{5/3}} \quad \text{for} \quad \frac{r}{H} \le 0.18 \tag{4}$$

where

ΔT = Temperature rise above ambient

$\dot{Q}$ = Heat release rate

H = Height of ceiling above fire

r = Radius of the plume at the ceiling

The temperature of the axisymmetric, nonflaming ceiling jet outside of the turning region is a function of the distance or radius from the plume. Temperatures will decrease as the radius increases, due to heat losses to the ceiling and to the entrainment of cooler air from the surroundings. A general relationship for this phenomenon is given in Equation 5.[3]

$$\Delta T = 5.38\frac{(\dot{Q}/r)^{2/3}}{H^{5/3}} \quad \text{for} \quad \frac{r}{H} > 0.18 \tag{5}$$

Flow rate outside the turning radius is dominated more by momentum (the force of the moving mass of gas) than by buoyancy (the force due to temperature differences between hot and cool gases).[1]

Understanding plume and ceiling jet relationships based on fire growth and compartment geometry is important for several reasons. The plume and ceiling jet act as the transport mechanisms for the heated gases and other products of combustion such as smoke and toxic species and thus affect the operation of sprinklers and heat and smoke detectors. This aspect is discussed in Section 2, Chapter 1, "Physics and Chemistry of Fire," and Section 2, Chapter 2, "Physics of Fire Configuration." The plume and ceiling jet also act to develop a layer of hot gases that affect the conditions in a compartment fire and the onset of full room involvement and spread to other compartments as discussed below.

Fire in a Compartment

Figure 2.4.4 represents the early stages of a compartment fire with a single vent where there is no effect of the compartment. There are two items in the compartment: A and B. A is the source of the fire, and B is an initially unignited target sufficiently far from A that it cannot be ignited directly.[4] A thin layer of hot gases and smoke begins to accumulate at the ceiling.

As the heat release from the fire in object A increases, the gases accumulating at the ceiling spread out and become trapped by the soffit of the door. As the fire continues to produce smoke and hot gases, the layer at the ceiling will thicken and begin to flow out under the soffit into the next compartment, which may be another room or a hallway (Figure 2.4.5). If the fire stops growing or becomes steady state at this time, the thickness of the upper layer in the fire compartment will become essentially constant, with the excess combustion products leaving the compartment at a constant rate.

However, if the fire continues to increase in heat release rate and the opening is too small to carry away the combustion products at the rate at which they are generated, the upper layer will continue to increase in thickness and descend to the floor, even though there is a vent (Figure 2.4.6).

At this time, it is useful to take a look at the various component parts of the compartment fire "system." A simple con-

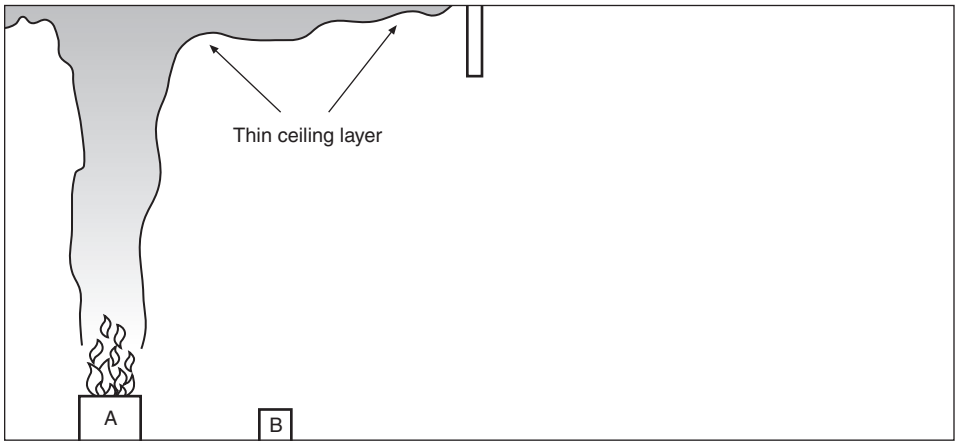

FIGURE 2.4.4 Initial Ceiling Effect. Note: A = source of fire. B = target fuel.

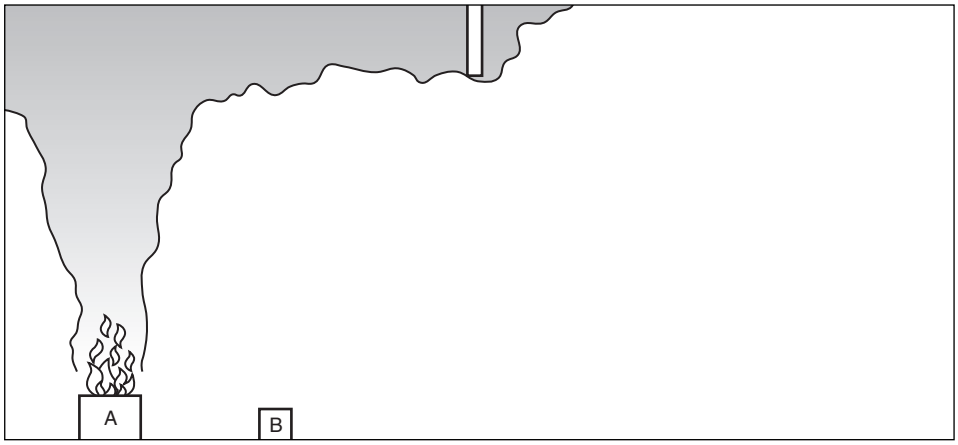

FIGURE 2.4.5 Initial Smoke Discharge from Compartment of Origin. Note: A = source of fire. B = target fuel.

ceptual model for this compartment fire system consists of a plume of hot gases above the initially burning object or objects, a heated upper gas layer, and a cool layer below. This model is commonly referred to as a 2-layer zone created by the hot gases inside and the cool gases outside (Figure 2.4.7). This results in a positive pressure in the hot gases leaving the compartment, relative to the outside of the compartment, and a negative pressure in the cool gases relative to the inside. The resulting airflow is shown in Figure 2.4.8, along with the ceiling layer and plume. In the doorway, there will be a boundary layer between the outflowing hotter gases (resulting from the positive pressure) and the inflowing cooler gases (resulting from the negative pressure). This boundary layer or boundary zone is commonly referred to as the neutral plane—that is, neutral or equal with respect to pressure inside and outside the room.

Figure 2.4.7 can also be used to discuss the general heat balance within the zones of a compartment fire. Energy is generated in the combustion region of the fire. The plume acts as a pump to provide combustion products and hot gases to the upper layer. This is the $\dot{Q}_{\text{fire}}$ in Figure 2.4.7. Energy in the hot upper layer is lost in a number of ways. Heat is lost by radiation from the hot gases to the cool area below and by convection of hot gases out the door. Heat is lost to the wall and the ceiling materials by conduction from the hot gas layer. If the fire is burning at a constant heat output, the layer thickness and the losses through the door or vent and to the compartment boundaries will remain constant after some period of time to establish an equilibrium between the heat generated and the heat lost. If the fire continues to grow, conditions will change. Temperatures in the upper layer will continue to rise, and the thickness of the upper layer will continue to increase. The increasing layer temperature and the decreasing distance of the layer from the floor results in greater radiation heat transfer to unignited objects elsewhere in the compartment.

The development of the ceiling layer plays a significant role in compartment fire growth. In addition to acting as a radiator to heat other objects in the room, radiation from the layer also increases the burning rate of the items already ignited.[5]

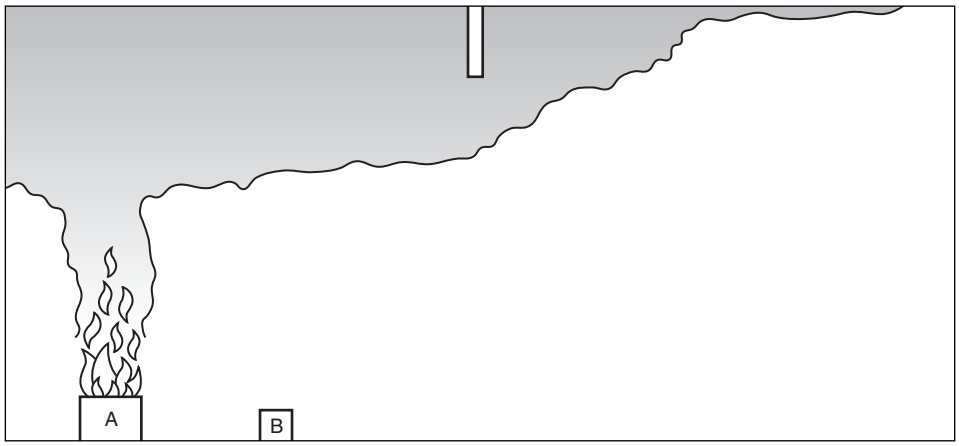

FIGURE 2.4.6 Increasing Fire Size and Layer Depth. Note: A = source of fire. B = target fuel.

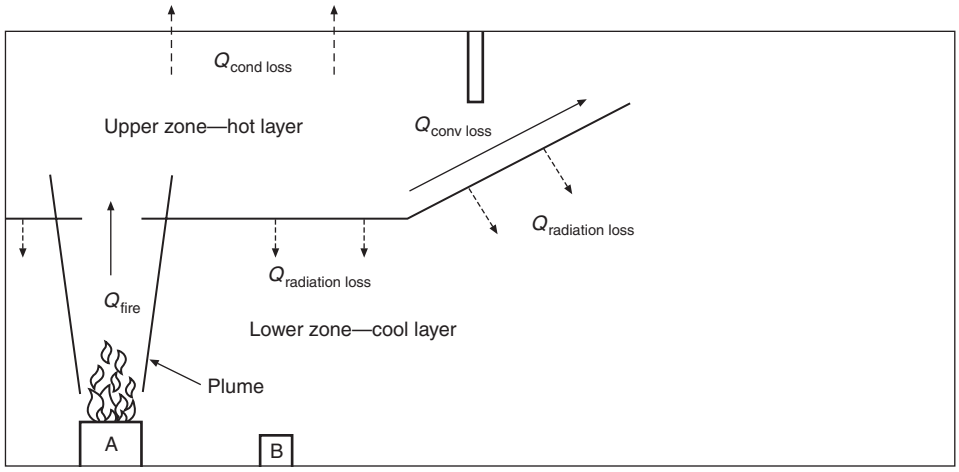

FIGURE 2.4.7 Compartment Fire Zones and Heat Transfer. Note: A = source of fire. B = target fuel.

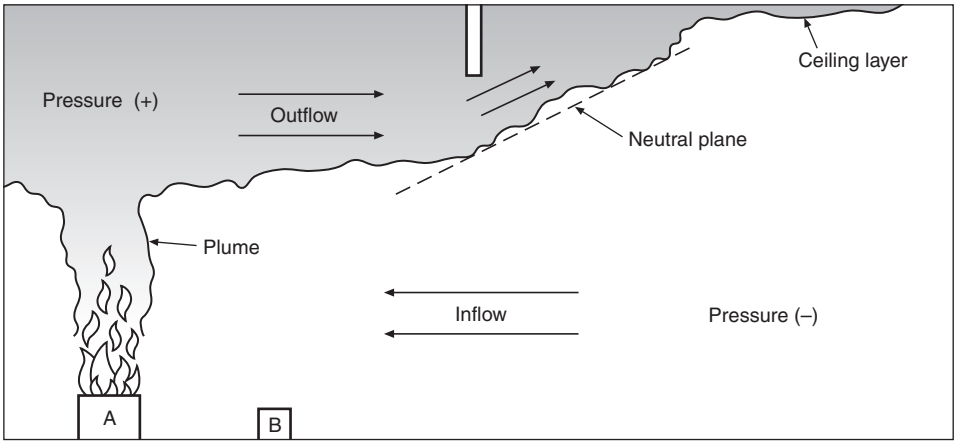

FIGURE 2.4.8 Compartment Fire Pressure and Airflow. Note: A = source of fire. B = target fuel.

Typically, as the fire continues to grow in the compartment, with a corresponding increase in the thickness and temperature of the upper gas layer, a transition will occur from a fire that is dominated by the first materials ignited to a fire that is dominated by the burning materials throughout all of the room. This transition is called *flashover.* Ventilation at flashover becomes controlled by the size of the room openings and the position of the layer in the opening. As the layer descends, the effective ventilation area of the opening is decreased.

The triggering conditions[6] for the flashover transition are reached when (1) the upper gas layer is approximately 600°C and (2) the radiant flux on unignited materials in the room is approximately 20 kW/m^2. Figure 2.4.9 represents flashover, the transition stage between preflashover and the fully involved compartment fire (called *full-room involvement*).

Full-room involvement, as shown in Figure 2.4.10, is characterized by the production of excess fuel vapors that cannot be consumed within the compartment with the combustion air available. This results in flame extension through vent openings into adjacent compartments or out of windows, should they fail. Window failure generally occurs shortly before or after flashover conditions are reached and can provide additional ventilation area. The HRR needed for flashover is related to the vent openings of the compartment and can be generally predicted using Equations 6 and 7.[2]

$$\text{Babrauskas' equation: } \dot{Q}_{fo} = 750A_0\sqrt{H_0} \tag{6}$$

$$\text{Thomas' equation: } \dot{Q}_{fo} = 7.8A_T + 378A_0\sqrt{H_0} \tag{7}$$

where

$\dot{Q}_{fo}$ = Heat release for flashover (kW)

A_0 = Area of vent opening (m^2)

H_0 = Height of venting (m)

A_T = Total area of compartment enclosing surfaces (m^2)

Flashover is not an inevitable result of a compartment fire. In the event that the fuel is limited or that there is a sufficiently large

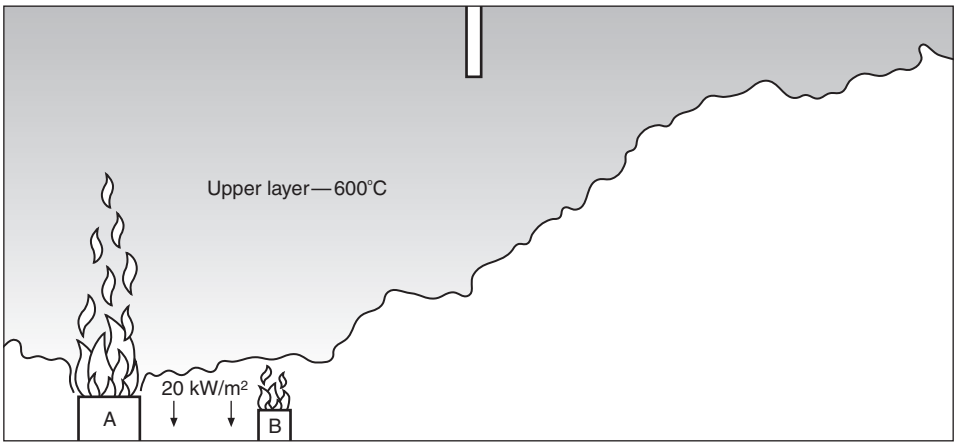

FIGURE 2.4.9 Flashover—Transition to Full-Room Involvement. Note: A = source of fire. B = target fuel.

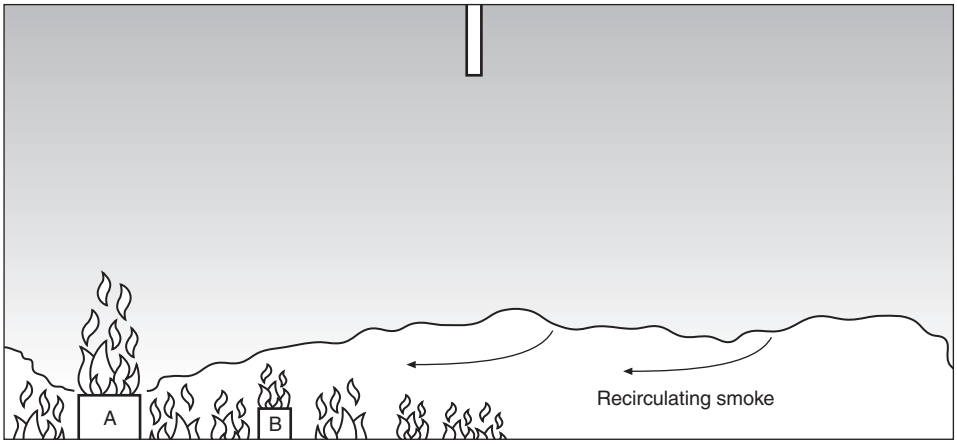

FIGURE 2.4.10 Full-Room Involvement (Postflashover). Note: A = source of fire. B = target fuel.

ventilation opening, the ceiling layer may not develop adequately to make the transition through flashover to full-room involvement. Application of suppression agents, either automatically or manually, can also interrupt the process at or prior to flashover. It should be noted that some research indicates that the heat release rate of burning objects, such as mattresses, can be increased by a factor of two in a postflashover or full-room involvement fire.[5]

Once flashover occurs and full-room involvement begins, the fire approaches ventilation control. Smoke from under the neutral plane is frequently recirculated back toward the fire, along with smoke that may be accumulating in adjacent compartments in the hallway. This process, called *vitiation,* reduces the oxygen available for combustion, causing a reduced heat release rate. Under these conditions, the fire approaches steady-state burning.

Effects of Fire Location in a Compartment

Under some circumstances, the location of the fire in a compartment can have an effect on the rate of growth of the fire, in terms of ceiling jet temperature and velocity.[3] When a fire is burning in a compartment far from walls, air is free to be entrained into the plume from all directions (Figure 2.4.11). If the fire is very close (i.e., virtually in contact) to a wall or in a corner, the amount of air entrainment into the plume is reduced, leading to higher temperatures and velocities and a reduced volume of gases. These effects can be simulated by making adjustments for heat release rate in the correlations used to calculate temperature and velocity. For fires adjacent to a wall, $2Q$ is substituted for Q; for a fire in a 90° corner, Q is multiplied by 4 in the correlations. It should be noted, however, that experiments have shown that if a circular burner is placed so that only one point is in contact with the wall, the fire behaves almost identically to a fire away from the wall.[7]

SUMMARY

This discussion was presented to provide the reader with an overview of the processes involved in fire growth and spread in

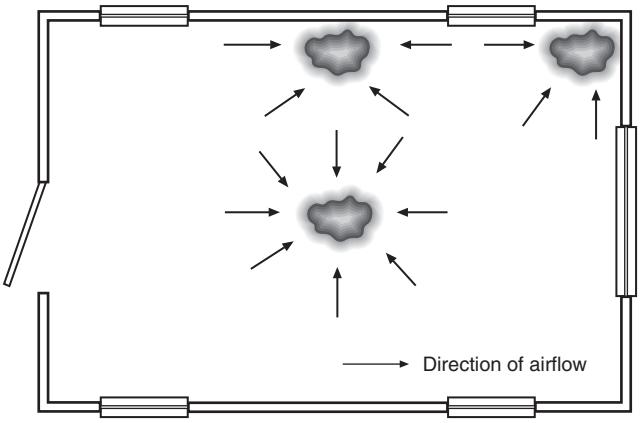

FIGURE 2.4.11 Effect of Fire Location on Air Entrainment

and beyond the compartment. For additional information, the reader is encouraged to study the equations and relationships discussed elsewhere in this handbook.

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Chapter 5

Basics of Fire Containment

Marc L. Janssens

Chapter Contents

Terminology
Fire Resistance
Exterior Fire Spread
Safe Separation Distance

Key Terms

active fire protection, assembly, code equivalency, compartmentation, design load, exterior insulation and finish system, firebrand, fire resistance, fire testing, flashover, heat flux, model building code, passive fire protection, performance-based code, prescriptive code, World Trade Center

An acceptable level of fire protection is accomplished in the design stage of a building through compliance with local regulations, which are typically based on national *model building codes.* Fire protection of buildings addresses all aspects of fire safety and consists of a combination of active and passive measures. *Active fire protection* devices require manual, mechanical, or electrical power for their operation. *Passive fire protection* measures do not require any external power. There are essentially the three following types of passive fire protection measures:

1. *Rate of fire growth.* The rate of fire growth inside or outside a building can be controlled to some extent by using interior finishes or external cladding/roofing with specific ignition, flame spread, and heat release characteristics. A slow-growing fire leaves more time for safe egress of building occupants and generally results in reduced property damage at the time of manual or automatic suppression.

2. *Containment.* Should a fire inside a building grow to full involvement of the enclosed space of origin, an important objective is to contain the fire within that enclosed space or a nearby area, at least for a certain time. Thus, fire spread to other parts of the building or adjacent buildings is delayed or prevented. This containment process for interior fires is referred to as *compartmentation.* It is accomplished by providing fire-resistive floor, wall, and ceiling assemblies and by protecting openings and penetrations through enclosure boundaries. Containment of interior fires also involves protecting structural elements and assemblies to avoid or delay partial or total collapse in the event of fire. Should a fire be initiated and grow to a hazardous scale outside of a building, an important objective is to maintain a sufficient fuel-free space or fire break around the building so that the integrity of the building envelope is preserved when exposed to the external fire hazard. This containment process for exterior fires is referred to as providing a safe separation distance. Containment of external fires also covers measures to prevent ignition of, surface flame spread over, and penetration through exterior wall and roof surfaces should there be a nearby ignition source such as firebrands or flames ejected from windows.

3. *Emergency egress.* The third type of passive fire protection measure pertains to emergency egress. Escape corridors, doors, and stairways have to be wide enough to accommodate the flow of people in case of emergency evacuation. Occupants must have access to a sufficient number of emergency exits within a maximum allowable distance so that they can reach a safe area before conditions become untenable.

This chapter provides a discussion of the engineering basis for model building code provisions that pertain to several aspects of fire containment, including some fundamental concepts related to providing a safe separation distance. For both fire containment and safe separation distance, the fundamental objective is to prevent damage from flame heat fluxes that are greater than a critical material ignition or system endurance level.

The building code provisions pertaining to fire containment have traditionally been prescriptive, meaning that they consist of specific requirements for building materials, products, and elements that are based on performance in a test. Fire safety objectives are not explicitly stated in traditional building codes, and it is assumed that an acceptable level of fire safety is obtained if the prescriptive code requirements are fulfilled. The main objective of building codes is life safety of

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building occupants and fire fighters. The protection of neighboring property is secondary. The model building codes do not directly provide for property conservation. However, any fire protection features that contribute to meeting the primary objective are also likely to reduce property and indirect fire losses.

Sometimes it is not possible to meet the containment requirements in the model building codes. For example, changing the use of a building may lead to a new set of fire protection requirements that cannot be accomplished through retrofitting. Another common example is when the architect wants to use an innovative system that cannot be tested according to the accepted procedures. All model building codes have a clause that allows the authority having jurisdiction (AHJ) to accept a noncompliant design. A technical rationale or engineering analysis, or both, usually has to be presented to demonstrate that the level of fire safety of the proposed design is at least as good as that of a comparable code-compliant building. This process is referred to as *code equivalency.*

New types of building codes, known as performance-based codes, have emerged in recent years. These codes focus on building performance by requiring that specific fire safety goals and objectives be met. Increased design flexibility and opportunities for cost savings are the main advantages of performance-based codes over the traditional prescriptive approach. (See Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety," for more information.)

The chapter begins with a discussion of the test and design procedures that serve as the basis for fire containment requirements in the model building codes. Alternate methods that demonstrate prescriptive code equivalency or performance-based code compliance are also discussed. How the safe separation distance requirement would be calculated in a performance-based environment is then presented. First, however, some important terminology is defined.

See also Section 2, Chapter 1, "Physics and Chemistry of Fire"; Section 2, Chapter 2, "Physics of Fire Configuration"; Section 2, Chapter 4, "Dynamics of Compartment Fire Growth"; Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety"; and Section 6, Chapter 3, "Concepts and Protocols of Fire Testing."

TERMINOLOGY

General Terms

Active Fire Protection. The operation of active fire protection devices requires manual, mechanical, or electrical power. For example, a sprinkler system requires sprinklers to open and a water supply at a sufficient flow rate and pressure after activation to be delivered through the system. A smoke control system relies on roof vents that open or a mechanical system to operate when a fire is detected. A detection and alarm system requires electric power to operate.

Code Equivalency. Code equivalency is the process of demonstrating compliance with the intent of prescriptive code provisions through technical reasoning, engineering analyses, or both.

Compartmentation. Large buildings are typically segmented into smaller compartments with fire-resistive boundaries and protected openings through the boundaries. The objective of compartmentation is to confine a fire to a limited area for a specified time and thus slow down fire spread through a building to leave more time for safe evacuation of the building and to reduce property and indirect losses.

Fire Resistance. The fire resistance of a building element characterizes its ability to confine a fire or to continue to perform a given structural function, or both.

Fire Resistance Rating. The fire resistance rating of a building element is a measure of the elapsed time during which the element continues to exhibit fire resistance when exposed to a standard fire in a furnace test. The rating corresponds to the time to failure in the furnace test. Failure criteria are based on thermal penetration, integrity, or structural collapse.

Heat Flux. The rate of heat transferred per unit area perpendicular to the direction of heat flow is referred to as heat flux (see Section 2, Chapter 1, for a discussion of heat transfer modes and the importance of each). Heat flux is a measure of the potential for damage. For example, most common combustibles ignite when exposed to a heat flux of 0.9–1.8 Btu/sec·ft^2 (10–20 kW/m^2).

Model Building Code. Local building codes and regulations are based on national model codes that are developed by a consensus process. The model code groups in the United States are International Code Council (ICC) and National Fire Protection Association (NFPA). Some jurisdictions have adopted a model code verbatim, either by reference or by transcription, whereas others have made significant amendments. The extent of changes that can be made at the local level varies from state to state.

Passive Fire Protection. Passive fire protection does not require any external power but relies instead on specific construction features and the use of materials, products, and building elements that meet well-defined fire performance requirements.

Performance-Based Code. Performance-based codes are concerned with the performance of the building as a whole and require that specific fire safety goals and objectives be met. No specific methods are mandated to demonstrate compliance. The code-conforming design process involves an engineering analysis, often supported by standard or ad hoc fire test data and fire statistics. A detailed discussion of the steps involved in such a design process is provided in the *SFPE Engineering Guide to Performance-Based Fire Protection.* Increased design flexibility and opportunities for cost savings are the main advantages of performance-based codes over the traditional prescriptive approach.

Plan Dimensions. The dimensions of an object in the plan view (i.e., the projection of an object onto a horizontal plane generally at the base of the object) are the plan dimensions. For a rectangular burning material assembly that is the source of a fire, the plan dimensions are the length and width of the footprint of the assembly.

Prescriptive Code. Model building codes and other fire safety regulations are largely prescriptive and consist of specific requirements for building materials, products, and elements that are based on performance in a test. They also include prescriptive provisions to establish adequate means of egress. The fire safety objectives are not explicitly stated, and it is assumed that an acceptable level of fire safety is obtained if the prescriptive requirements are fulfilled.

Wildland Vegetation. Extensive areas of forest, living plants, and brush are termed *wildland vegetation.* This vegetation may extend for great distances, interfacing with buildings and the built environment in many locations.

Terminology of Materials, Products, and Assemblies

Materials form the basic ingredients of the components and contents of structures. Materials are combined into *products* in a form that is suitable for practical application. For example, gypsum, paper, glass fibers, and other fillers are combined in the form of sheets that are used as protective membranes in the construction of fire-rated wall and ceiling assemblies. One or more products are used in the construction of *assemblies.* For example, wood-frame wall assemblies consist of wood studs that are protected on one or both sides by a membrane such as gypsum board or plywood, and the cavities between the studs may be filled with thermal insulation. Fire resistance requirements pertain to assemblies.

FIRE RESISTANCE

Despite the active and passive fire protection measures affecting the growth stage, fires often develop beyond *flashover.* (Flashover is a transition phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space, resulting in full room involvement or total involvement of the compartment or enclosed space.) The objective of passive measures is then to contain the fire to a limited area for a specified duration. This is accomplished by subdividing buildings into smaller compartments that are separated from each other by fire-resistive wall and floor/ceiling assemblies. Openings in the separations, such as doors and cable penetrations, need to be protected to avoid or delay fire spread from one compartment to another. Structural members need to fulfill their load-bearing function for the specified duration because premature collapse will allow fire spread to a larger area. The fire resistance of a building element is usually determined through furnace testing, which is discussed in detail in the following three subsections. Alternative approaches based on analytical methods and computer modeling form the subject of the next two subsections. This section concludes with some pertinent findings and recommendations by the National Institute of Standards and Technology (NIST) as a result of its investigation of the World Trade Center disaster.

General Concepts of Fire Resistance Furnace Testing

Wall and floor/ceiling assemblies, roof structures, doors, windows, and so on are mounted in a vertical or horizontal frame. The frame is placed against an open wall furnace or on top of an open ceiling furnace and is exposed to the standard fire. The latter is quantified by a specified furnace temperature-time curve. Figure 2.5.1 shows an example of a wall assembly shortly after the start of a test. The specimen consists of a double swinging glass door mounted in a glass wall. The burner flames and furnace interior can be observed during the first few minutes of the test. The glass consists of several panes separated by a transparent film. When the film reaches a critical temperature, it expands and forms a thick insulating layer.

Fires can spread from the fire compartment to a neighboring compartment if the heat transfer results in a temperature rise that is high enough to ignite common combustibles on the side not exposed to the fire or if cracks develop that allow the passage of flames and hot gases. End-point criteria for separating non-load-bearing assemblies in fire resistance furnace tests are, therefore, based on heat transmission and integrity. Heat transmission is measured with thermocouples attached to the unexposed side of the assembly. The end-point criteria for heat transmission are exceeded when the temperature rise of the thermocouples, either on average or individually, reaches a specified limit. The integrity of an assembly is maintained as long as there is no passage of flames and gases hot enough to ignite cotton waste on the unexposed side. The time when the first end point is reached determines the fire resistance rating of the assembly and is reported to the nearest minute.

Fires can also spread when load-bearing assemblies or structural members cease to support the load. The resulting partial or total building collapse adversely affects life safety of building occupants and fire fighters and dramatically increases property loss and indirect fire costs. Fire resistance furnace tests on load-bearing assemblies and structural members, therefore, also determine whether the test specimen is capable of supporting the applied load for a specified duration. Steel and concrete columns are generally not tested under load, and failure is based on the temperature at which the structural or reinforcing steel starts to yield. This approach cannot be used for wood columns and testing under load is necessary. The National Research Council of Canada and Underwriters Laboratories are the only fire testing laboratories in North America that are capable of performing column tests under load. Columns and beams can be tested with full or partial exposure of the perimeter, depending on simulated end-use conditions.

Steel-framed floor/ceiling and roof assemblies are tested under restrained or unrestrained conditions. The former uses a stiff frame that resists the forces due to thermal expansion of structural steel. Testing under restrained conditions is required for building elements that are part of a structure that is capable of resisting substantial thermal expansion throughout the range of anticipated elevated temperatures. Wood-frame assemblies do not need to be tested under restrained conditions because thermal expansion is negligible. See also Section 6, Chapter 3, "Concepts and Protocols of Fire Testing."

FIGURE 2.5.1 Vertical Furnace Test on a Glass Door and Wall Assembly (Courtesy Southwest Research Institute)

Experimental Variables in Fire Resistance Furnace Testing

Although all standard fire resistance furnace test methods are based on the same concepts, there are significant differences in the details between methods. As a result, some methods are more stringent than others and the resulting fire resistance rating of a building element will be different even if the same end-point criteria are used. The effect of different experimental variables on the severity and the results of the test are discussed in this subsection.

Thermal Exposure Conditions. The fire resistance of a building element is a function of the severity of the fire. In order to provide a uniform basis for measuring the fire resistance in the laboratory, a number of standard fires have been defined. These standard fires are expressed in the form of a furnace temperature-time curve. Figure 2.5.2 shows three commonly used temperature-time curves. The test standards specify that the furnace be controlled so that the average of the readings of a specified number of thermocouples follows the standard temperature-time curve within acceptable tolerances. The standards typically require that at least nine thermocouples (eight for immersed columns exposed from four sides) are distributed in the furnace to measure the furnace temperature near all parts of the specimen.

Based on the standard temperature-time curves one would conclude that ISO 834, *Fire-Resistance Tests—Elements of Building Construction,*[1] is slightly more severe than ASTM E119, *Standard Test Methods for Fire Tests of Building Con-*

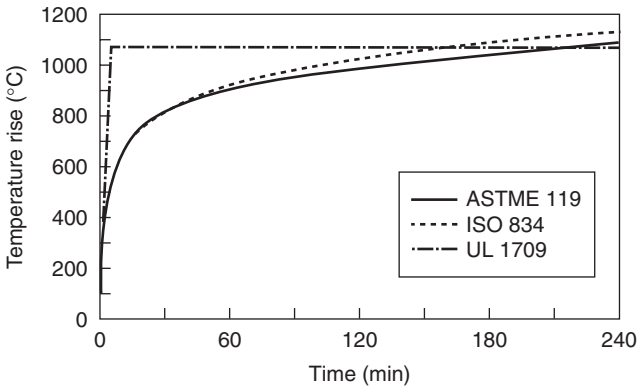

FIGURE 2.5.2 Three Commonly Used Time-Temperature Curves (Courtesy Southwest Research Institute)

struction and Materials.[2] However, the severity of the test is not only a function of the temperature-time curve but also depends on how the furnace temperature is measured. ASTM E119 specifies that thermocouple assemblies be enclosed in a porcelain or steel pipe so that the time constant is between 5 and 7.2 minutes. The 1975 edition of ISO 834 specifies exposed-junction thermocouples with a time constant of 2 minutes or less. The recent revision of ISO 834-1, *Fire-Resistance Tests—Elements of Building Construction—Part 1: General Requirements,*[3] prescribes the use of plate thermometers to control the furnace temperature-time curve. The plate thermometer (see Figure 2.5.3) was originally developed in Sweden and introduced to harmonize between fire resistance furnaces in different countries of the European Union.[4,5] The exact reasons are not completely known, but the improved consistency is probably due to the fact that the plate thermometer temperature is affected primarily by the incident heat flux and is less sensitive to convection than exposed-junction thermocouples. Although plate thermometers have a slower response than exposed-junction thermocouples, they respond significantly faster than the shielded thermocouples specified in ASTM E119. The net result is that ASTM E119 is more severe than ISO 834-1, in particular during the first 10 minutes of a test.[6] The directional flame thermometer[7] is similar to the plate thermometer and is currently being considered by ASTM E05.11 as a device for measuring and controlling the thermal environment in fire resistance test furnaces.

Furnace Pressure. The pressure in a room due to a fire varies with height. Figure 2.5.4 shows a simplified situation of a room with an open window and a closed door. The pressure difference between inside and outside the room is positive at the top

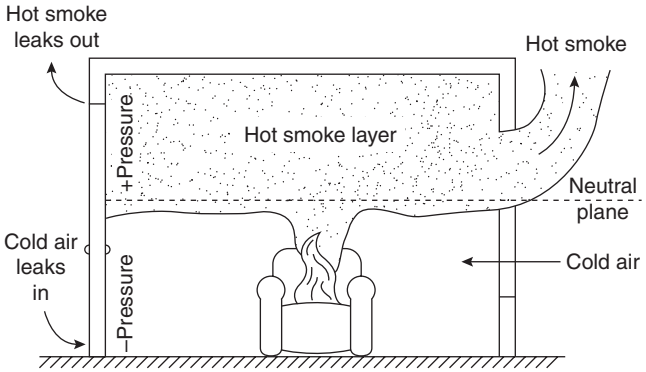

FIGURE 2.5.4 Pressure Effects in a Room Fire (Courtesy Southwest Research Institute)

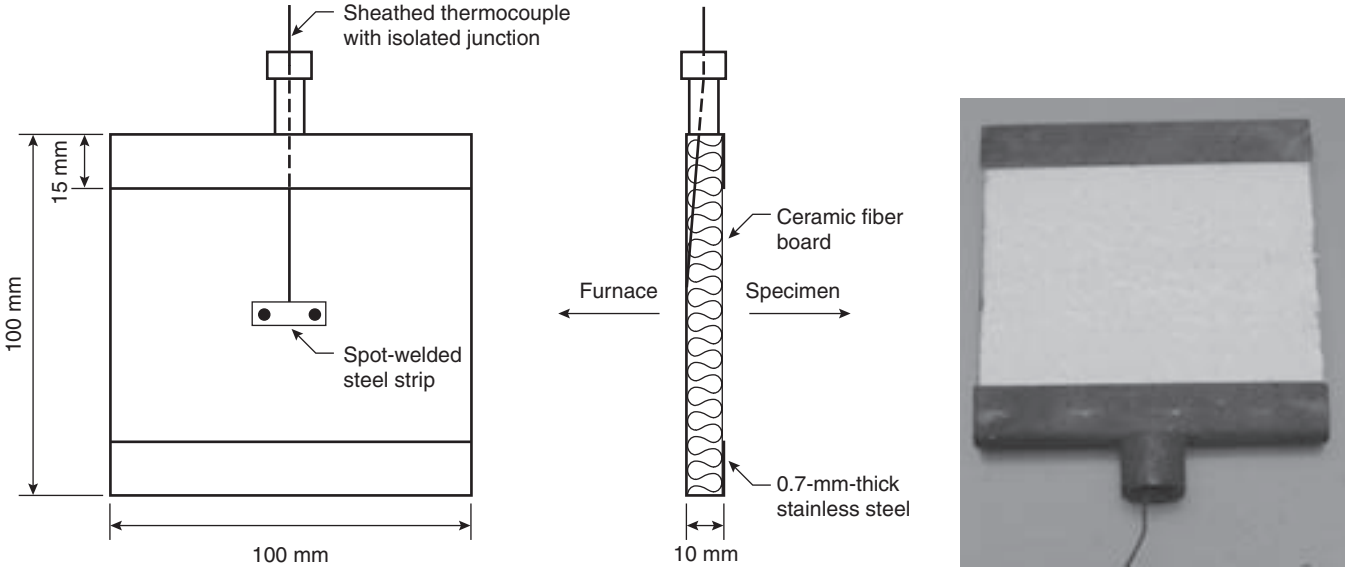

FIGURE 2.5.3 (a) Plate Thermometer Schematic and (b) Plate Thermometer (Courtesy Southwest Research Intitute)

of the door and negative at the bottom. The height at which the pressure differential is zero is referred to as the neutral plane. If the door is not completely sealed, which is typically the case, cold air will flow into the room around the perimeter of the door pane below the neutral plane and hot gases will leak from the fire room above the neutral plane. The location of the neutral plane and the direction and magnitude of flows are affected in actual fires by factors such as wind, stack effect in high-rise buildings, and so on.

The discussion in the previous paragraph indicates that the differential pressure between the fire side and the cool side is likely to be positive over the upper part of a door. Hot gases leaking from the fire room above the neutral plane can have an adverse effect on the ability of a door to maintain its separating function. Therefore, it seems to make sense to conduct fire resistance tests on doors and similar assemblies under positive pressure over the top half of the test specimen. North American fire resistance test standards have traditionally not specified the furnace pressure, which in practice resulted in door tests being conducted with the neutral plane at the top of the test specimen. An extensive research program resulted in recent changes to the fire resistance test standards for doors and windows so that these tests now have to be conducted under slightly positive pressure.[8–10] For example, as a result of the research ASTM E152, *Standard Test Methods of Fire Tests of Door Assemblies,*[11] and ASTM E153, *Standard Test Methods of Fire Tests of Window Assemblies,*[12] have been withdrawn on January 1, 1995, and were replaced by ASTM E2074, *Standard Test Method for Fire Tests of Door Assemblies, Including Positive Pressure Testing of Side-Hinged and Pivoted Swinging Door Assemblies,*[13] and ASTM E2010, *Standard Test Method for Positive Pressure Fire Tests of Window Assemblies,*[14] respectively. Fire resistance testing under positive pressure has been common practice in other parts of the world for a very long time.

The questions remain of what the magnitude of the positive pressure should be and how it should be measured. Differential pressures in room fires are due to differences in density between cold and hot gases. This is similar to the stack effect illustrated in Figure 2.5.5.

The pressure at the bottom of the stack is equal to the pressure at the top of the stack plus the pressure due to the weight of the hot gas column in the stack:

$$p_1 = p_0 + \rho_h g H \tag{1}$$

where

p_1 = Pressure at the bottom of the stack (psf or Pa)

p_0 = Pressure at the top of the stack (psf or Pa)

ρ_h = Density of the hot gas in the stack (slug/ft^3 or kg/m^3)

g = Acceleration of gravity (32.174 ft/sec^2 or 9.81 m/sec^2)

H = Height of the stack (ft or m)

The pressure outside the stack at the same height as the bottom of the stack is given by

$$p_2 = p_0 + \rho_\infty g H \tag{2}$$

where

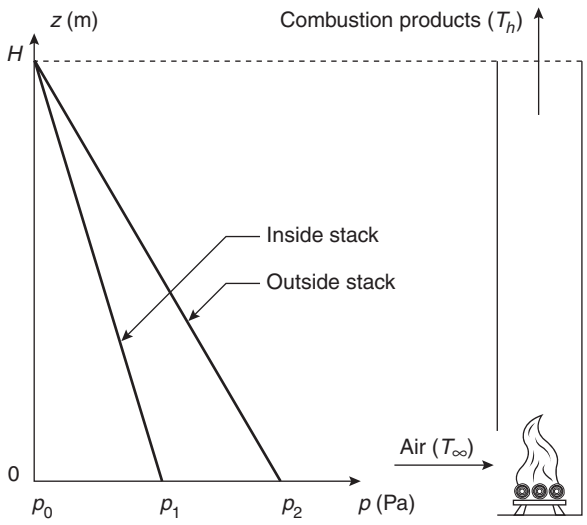

FIGURE 2.5.5 Stack Effect (Courtesy Southwest Research Institute)

p_2 = Pressure outside the stack at the height of the bottom of the stack (psf or Pa)

ρ_∞ = Density of ambient air (slug/ft^3 or kg/m^3)

The differential pressure at the bottom of the stack is, therefore, given by

$$\Delta p = p_1 - p_2 = (\rho_h - \rho_\infty) g H \approx C\left(\frac{1}{T_h} - \frac{1}{T_\infty}\right) H \tag{3}$$

where

C = Constant (39.59 in English units or 3455 in SI units)

T_h = Temperature of the hot gases in the stack (°R or K)

T_∞ = Ambient temperature (°R or K)

Note that the expression on the far right of Equation 3 is obtained from the ideal gas law at constant pressure, assuming that the composition of the gases in the stack is close to that of ambient air. This is a reasonable assumption because combustion air is usually supplied at a rate that far exceeds the stoichiometric rate. Moreover, the primary component of combustion products is nitrogen, which accounts for approximately 79 percent by volume of dry air. It is also reasonable to assume constant pressure because p_0 is of the order of 10^5 Pa, whereas the rightmost term on the right side of Equations 1 and 2 is at least three orders of magnitude smaller. Note that the density of dry air at 492°R (273 K) and atmospheric pressure is equal to 0.0025 slug/ft^3 (1.29 kg/m^3). The density of air at temperature T_h and the same pressure can, therefore, be estimated from

$$\rho_h \approx \frac{\rho_r T_r}{T_h} = \frac{C}{T_h} \tag{4}$$

where

ρ_r = Density of air at the reference temperature (0.0025 slug/ft^3 or 1.29 kg/m^3)

T_r = Reference temperature (492°R or 273 K)

C = Constant (1.2275 in English units or 352 in SI units)

Since $T_h > T_\infty$, Equation 3 indicates that the differential pressure at the bottom of the stack is negative. This implies that ambient air is drawn into the stack at the bottom to support combustion. The hot products of combustion rise due to buoyancy. The differential pressure per unit stack height is shown in Figure 2.5.6 as a function of $T_h - T_\infty$ with T_∞ = 527°R = 68°F (293 K = 20°C). Positive pressure testing according to ASTM E2074 requires that the positive pressure differential at the top of the door is approximately 0.21 psf (10 Pa). Figure 2.5.6 implies that the neutral plane is located approximately 4.25 ft (1.3 m) below the top of the door after 5 minutes of testing (i.e., when the standard furnace temperature rise is 1018°F [548°C]). The neutral pressure plane is located approximately 3.6 ft (1.1 m) below the top of the door after 120 minutes of testing (i.e., when the furnace temperature rise is 1777°F [987°C]).

Load. Fire resistance furnace test standards require that load-bearing assemblies and structural members be loaded so that the maximum stresses in the specimen are equal to the allowable design stresses. If the test specimen is loaded below its capacity, the resulting fire resistance rating is only valid if the structure is designed based on the load and the stresses applied in the test. This is inconsistent with the guidelines in ASCE 7, *Minimum Design Loads for Buildings and Other Structures,*[15] which allows for a significant reduction of the load for fire design. The recommendations in ASCE 7 are based on the observations that it is unlikely that a structure will be exposed to the full dead and live loads that are used for structural design at the same time when a fire occurs.

The load in fire resistance tests is typically applied using hydraulic jacks. Figure 2.5.7 shows a load-bearing masonry wall assembly. The forces from the jacks are transferred to the test specimen via a stiff steel distribution beam. The pressure of the hydraulic oil in the jacks is maintained during the test so that the wall is stressed to the specified level.

Floor/ceiling assemblies are usually tested under a uniform load. This can be accomplished by distributing concrete blocks or water-filled barrels over the unexposed surface of the assembly. The drawback of this approach is that the blocks or barrels affect the heat transfer from the unexposed side. This problem can be avoided by using a hydraulic loading system. Such a system is very complicated if the load has to be distributed over a large number of points (Figure 2.5.8).

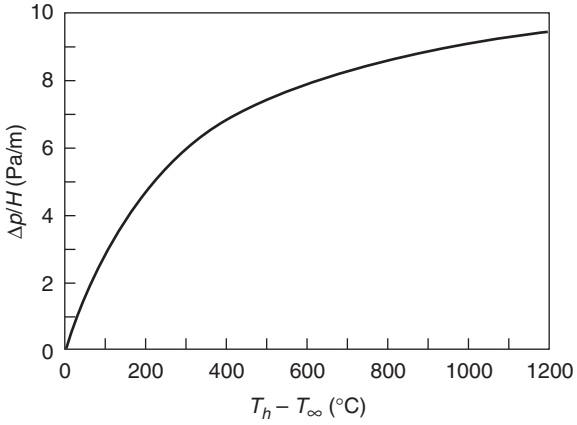

FIGURE 2.5.6 Differential Pressure Due to Stack Effect (Courtesy Southwest Research Institute)

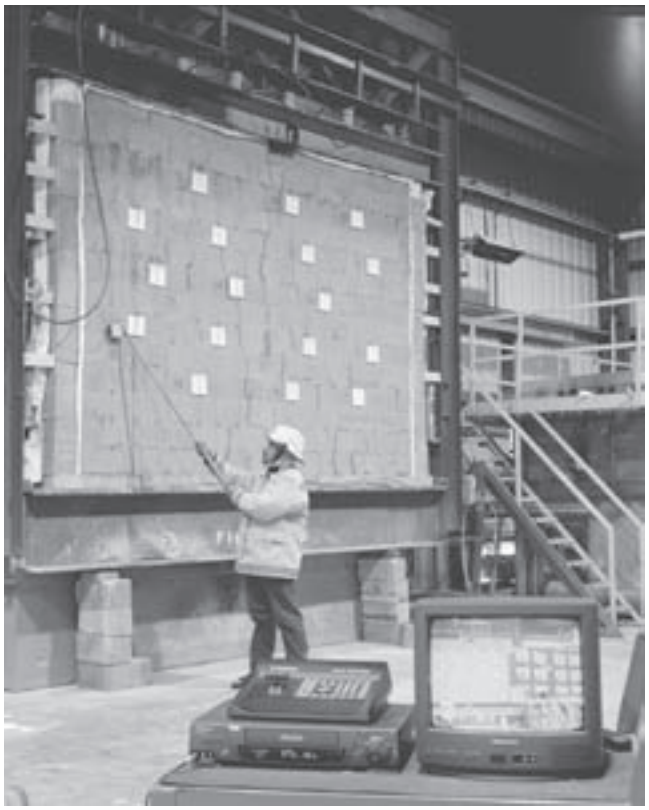

FIGURE 2.5.7 Fire Resistance Test on Loaded Masonry Wall Assembly (Courtesy Southwest Research Institute)

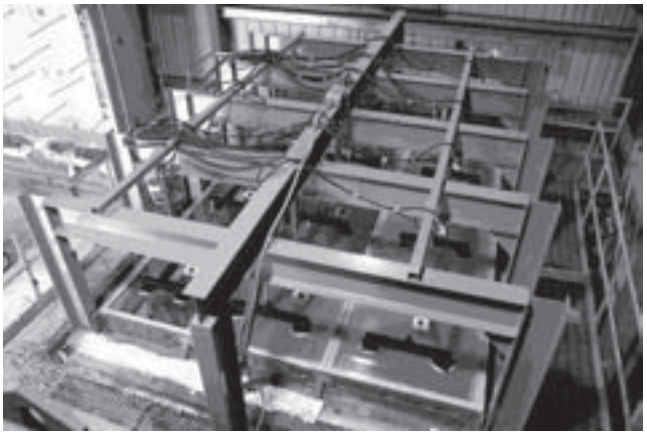

FIGURE 2.5.8 Hydraulic System to Distribute the Load on a Glass Floor Assembly (Courtesy Southwest Research Institute)

End-Point Criteria. Three end-point criteria are used to determine the fire resistance of a test specimen. Although similar criteria are specified in most fire resistance test standards, the following are some subtle differences that are worth noting:

1. *Heat transmission.* Transmission of heat through the test specimen is usually quantified on the basis of the unexposed-side temperature measurements. Each standard specifies the minimum number of thermocouples that must be attached to the unexposed side of the specimen. The end point for heat transmission is reached when the average of all thermocouple readings reaches a limit (typically approximately 250°F or 140°C) or when any of the individual thermocouple readings exceeds a higher limit (typically approximately 325°F or 180°C). The limits are well below the ignition temperature of common combustible materials.[16]

The unexposed-side temperature measurements are a function of how the thermocouples are attached to the surface of the specimen. Typically this is accomplished by covering the thermocouple junction with a felted pad that is glued to the specimen surface. The dimensions and material of the pad affect the temperature measurements. For example, ASTM E119 specifies 6 in. × 6 in. × ⅜ in. (150 mm × 150 mm × 10 mm) pads with a density of 19 pcf (300 kg/m^3). ISO 834-1 requires a pad size of 77/64 in. × 77/64 in. × 5/64 in. (30 mm × 30 mm × 2 mm) and specifies a density of 56 pcf (900 kg/m^3). The heat losses through the ASTM pads are obviously much smaller than those though the ISO pads. Since the temperature limits are essentially identical in both standards, ASTM E119 is more stringent in terms of heat transmission end-point criteria.

Heat transmission through some types of test specimens such as glazing is measured with a radiometer that is located at a specified distance from the unexposed side of the specimen. The end point in this case is a maximum allowable radiant heat flux that is transmitted through the specimen and/or emitted from the unexposed surface of the specimen.

2. *Integrity.* The integrity end point is reached when gases or flames emerging through cracks in the specimen are hot enough to ignite a cotton pad on the unexposed side. Whether ignition occurs or not depends on the size of the cotton pad, the time that it can be held at a particular location, and the distance between the pad and the specimen surface.

3. *Load-bearing capacity.* Structural collapse is an obvious indication that the specimen is no longer able to support the load. Fire resistance tests are usually terminated long before collapse occurs and a maximum deflection or rate of deflection limit is often used to define structural failure.

Specimen. The test specimen has to be representative of the building element as it is installed in the field. Above all, this implies that the specimen must have a minimum size. If the specimen is too small, the test result may not be representative of how the building element will perform in an actual fire. Some building elements, such as cable and pipe penetration fire stops, can perhaps be tested on a small furnace, but most elements need to be evaluated on a furnace that can accommodate vertical elements that are 8 to 10 ft (2.4 to 3 m) in height or horizontal elements that are 13 to 17 ft (4 to 6 m) in span.

Moisture has a significant effect on the performance of many types of building elements in a fire resistance test. A large amount of energy is needed to evaporate water and a high moisture content, therefore, usually improves the fire resistance of a building element. This is not always the case. For example, prestressed concrete with a high moisture content is more susceptible to spalling. Fire resistance test standards require that specimens be dried and cured to reduce the moisture content to a level that is representative of end-use conditions in the field. Sometimes that is not practical as it would require several months of conditioning. In that case a shorter drying period is allowed and the test results may have to be corrected to account for the excessive moisture in the test specimen. For example, ASTM E119 describes a procedure to correct the fire resistance rating of concrete floor slabs based on the actual moisture content during the test versus the typical in-service moisture content.

Standard Fire Resistance Furnace Tests

This section provides an overview of the most commonly used fire resistance furnace test standards. ASTM test standards are discussed first, followed by other domestic and international standards.

ASTM Test Standards. The American Society of Testing and Materials was the first standards development organization in the United States to publish a fire resistance furnace test standard.[17,18] The Baltimore conflagration on February 7, 1904, resulted in the formation of ASTM Committee P on Fireproofing Materials. In 1910 the designation of the committee was changed to C5, and 35 years later it was changed again to E05. From its inception until 1927 the committee was chaired by Professor Ira H. Woolson of Columbia University. Professor Woolson was chosen to lead the committee because a few years earlier he had established the first U.S. station for fire resistance testing in New York City. In 1907 ASTM Committee P issued its first fire resistance furnace test standard. This standard, designated C2, specified a procedure to evaluate floor systems based on tests conducted earlier at the Columbia test station. A wall partition standard, C3, followed in 1909. In 1916 and 1917, the American Society of Testing and Materials and the National Fire Protection Association held a series of meetings to revise the C2 and C3 standards. The resulting standard, C19, superseded standards C2 and C3 and specified the standard temperature-time curve that is still used today. The current version of the standard, now designated ASTM E119, is essentially unchanged from the first edition published in 1918.

ASTM E119 provides procedures for measuring the fire resistance of wall and floor/ceiling assemblies, roof structures, beams, and columns. Variants of this basic standard have been developed to provide specific details for fire resistance testing of doors, windows, and other types of building elements that are not covered by the general standard. A list of the ASTM and equivalent NFPA fire resistance test standards is given in Table 2.5.1. These test standards, with the exception of ASTM E1725, *Standard Test Methods for Fire Tests of Fire-Resistive Barrier Systems for Electrical System Components,*[19] prescribe a supplemental hose stream test procedure to evaluate the ability

TABLE 2.5.1 ASTM and NFPA Fire Endurance Test Standards

ASTM Designation	*NFPA Designation*	*Subject*
E119[2]	255	General
E814[20]	—	Through-penetration fire stops
E1529[21]	—	Simulated hydrocarbon pool fire exposure
E1725[19]	—	Barriers for electrical system components
E2074[13]	252	Door assemblies
E2010[14]	257	Window assemblies
E2226[22]	—	Hose stream test

of the construction to resist disintegration under adverse conditions. The hose stream test is either performed after termination of the fire resistance test or on a duplicate specimen that has been exposed to the standard fire for half the duration of the desired fire resistance classification. A hose stream test is not required for columns, floor/ceiling assemblies, and roof structures; wall assemblies with a fire resistance rating of less than 1 hour; and 20-minute-rated door assemblies. The hose stream requirement is unique to North America and is described in a separate standard, ASTM E2226, *Standard Practice for Application of Hose Stream.*[22]

The fire resistance of a building element is determined on the basis of the time that one of the end-point criteria for heat transmission, integrity, and/or structural performance is first exceeded. The fire resistance time is rounded down to 20 minutes, ½ hour, 1 hour, 1½ hours, 2 hours, 3 hours, 4 hours, and so on.

Other Fire Resistance Furnace Test Standards. The National Fire Protection Association (NFPA), Underwriters Laboratories (UL), and Underwriters' Laboratories of Canada (ULC) each published a general fire resistance furnace test standard that is essentially identical to ASTM E119. The designations of these standards are NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials;* UL 263, *Fire Tests of Building Construction and Materials;*[23] and ULC/CAN-S101-M89, *Standard Methods of Fire Endurance Tests of Building Construction and Materials,*[24] respectively. NFPA and UL also published test standards for doors (NFPA 252, *Standard Methods of Fire Tests of Door Assemblies;* UL 10A, *Fire Tests of Tin-Clad Fire Doors;*[25] UL 10B, *Fire Tests of Door Assemblies;*[26] and UL 10C, *Positive Pressure Fire Tests of Door Assemblies*[27]) and windows (NFPA 257, *Standard on Fire Test for Window and Glass Block Assemblies,* and UL 9, *Fire Tests of Window Assemblies*[28]) that are very similar to the corresponding ASTM standards.

Both NFPA and UL also maintain a number of fire resistance furnace test standards that do not have an ASTM equivalent. For example, NFPA 415, *Standard on Airport Terminal Buildings, Fueling Ramp Drainage, and Loading Walkways,* is used to determine the fire resistance of aircraft loading walkways exposed to the standard ASTM E119 temperature-time curve. UL 1709, *Rapid Rise Fire Tests of Protection Materials for Structural Steel,*[29] is a commonly used fire resistance furnace test standard that does not have an ASTM equivalent, although ASTM E1529 is somewhat similar. The rapid-rise UL 1709 temperature-time curve shown in Figure 2.5.2 simulates the exposure conditions of a large hydrocarbon pool fire. The furnace temperature reaches 1093°C within 5 minutes and remains at that level for the duration of the test. The corresponding heat flux is 18 Btu/sec·ft^2 (204 kW/m^2). UL 1709 is specified to determine the fire resistance of structural members that may be exposed to hydrocarbon pool fires, for example, on offshore installations or in petrochemical plants. UL 1709 is also specified in Appendix A of MIL-PRF-32161, *Performance Specification—Insulation, High Temperature Fire Protection, Thermal and Acoustic,*[30] to determine the fire resistance of U.S. Navy bulkheads and decks.

Outside North America, fire resistance test procedures are based on ISO 834. The general procedure is described in part one,[3] whereas detailed guidelines for testing of different types of building elements are provided in parts three to nine.[31–37] The furnaces used in other parts of the world are conceptually very similar to those used in the United States and Canada. The temperature-time curve specified in ISO 834 is similar to that in ASTM E119 (see Figure 2.5.2). IMO Resolution A.754, *Recommendation on Fire Resistance Tests for "A", "B" and "F" Class Divisions,*[38] describes a furnace test procedure to determine the fire resistance of marine bulkheads and decks. This method is based on the 1975 edition of ISO 834, which uses exposed-junction thermocouples to control the furnace as opposed to plate thermometers that are specified in the recent revision of the ISO standard.

History of Fire Resistance Tests. At the time that ASTM C19 was developed, the relationship between the standard temperature-time curve and real fires was not well understood. Pioneering work by Ingberg at the National Bureau of Standards in the 1920s provided some insight into this question. Ingberg performed a series of room fire tests to establish a relationship between the standard fire and actual fires and introduced the equal-area concept.[39] According to this concept, the duration of standard fire exposure of equivalent severity to an actual burnout fire can be determined on the basis of equal areas under the temperature-time curve as illustrated in Figure 2.5.9. In other words, the severity of a fire can be characterized on the basis of a single parameter, the fire load, which is equal to the area under the temperature-time curve. There are some obvious limitations to the approach. For example, referring to Figure 2.5.9, if a component of the test specimen breaks down at 1832°F (1000°C), the longer standard fire will not be equivalent to the real fire because the critical temperature will not be reached in the test.

The fire resistance requirements in the U.S. building codes are still largely based on Ingberg's relationship between the fire load and the time to burnout of a fully developed compartment fire.[40] The objective is that fire-resistive elements be able to survive complete burnout of a compartment. Each type of occupancy has an associated hazard that is quantified in terms of its fire load.

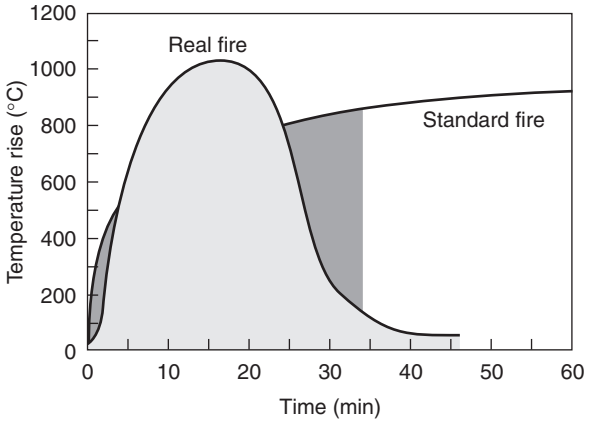

FIGURE 2.5.9 Ingberg's Equal-Area Concept (Courtesy Southwest Research Institute)

Research in Japan in the 1950s demonstrated that the severity of room fire is also affected by the ventilation conditions and the thermal properties of the room boundaries.[41] Room fire tests in the 1960s and 1970s identified the porosity and nature of the fuel as additional variables. The additional effects and variables can be accounted for through mathematical modeling (discussed later). The modeling approach may be used to demonstrate code equivalency or performance-based code compliance.

Analytical Methods to Calculate Fire Resistance

A number of analytical methods have been developed in North America[42] and other parts of the world[43] on the basis of years of experience and extensive fire endurance testing. These calculation methods are accepted by the model building codes in lieu of test results. However, the scope of these methods is limited to relatively simple concrete, masonry, steel, and wood construction in the following ways:

- Analytical methods for concrete slabs and columns specify the thickness of concrete cover that is needed to limit the reinforcing or prestressing steel temperatures.
- The fire endurance of clay and concrete masonry walls is specified as a function of the thickness of the wall.
- The fire endurance of steel columns and beams is a function of the area to heated perimeter ratio and the thermal characteristics and thickness of protective materials (gypsum board, sprayed-on fireproofing, etc.).
- The component additive method estimates the fire endurance rating of a light wood-frame wall, floor/ceiling, or roof assembly on the basis of times assigned to the individual components of the assembly, that is, the protective membrane(s), thermal insulation, structural members, and so on.
- Analytical methods for heavy timber beams and columns estimate the reduction of the load-bearing cross section of the member as a function of time on the basis of experimental charring rate data for wood obtained under standard fire conditions. The estimated fire endurance corresponds to the time when the remaining section is no longer able to support the load.

Structural Fire Modeling

Finite difference or finite element conduction heat transfer models are also used to predict the temperature distribution in building elements exposed to fire.[44] Some of these models have been coupled with strength and stiffness calculations to predict structural performance under fire conditions.[45] The acceptance of this type of computer fire modeling is not as widespread as that of the analytical methods described in the previous section. However, it is a useful tool to demonstrate code equivalency or to support performance-based design. One of the main problems is that accurate thermal and mechanical material properties are needed at elevated temperatures. Such property data are often not available and are difficult to measure. A major advantage of this approach is that the exposure conditions are not limited to the standard fire conditions. Predictions can be made for real fire exposure conditions. These exposure conditions can be based on experimental measurements or on predictions obtained with a model of fully developed compartment fires, such as COMPF2[46] or BRANZFIRE.[47]

NIST Investigation of the World Trade Center Disaster

The National Institute of Standards and Technology (NIST) conducted a 3-year investigation of the collapse of New York City's World Trade Center structures following the terrorist attacks of September 11, 2001. The results of this investigation are described in detail in the final report.[48] This investigation is by far the most comprehensive effort to model structures in fires. NIST's Fire Dynamics Simulator (FDS) was used to simulate the fire environment and a commercial finite element code (ANSYS) was chosen to model the response of the structure.

As part of the investigation, four ASTM E119 fire resistance furnace tests were conducted on the floor assembly of the twin towers as follows:

- Test 1: 35 ft (10.67 m) floor span, ¾ in. (19 mm) insulation, restrained
- Test 2: 35 ft (10.67 m) floor span, ¾ in. (19 mm) insulation, unrestrained
- Test 3: 17 ft (5.18 m) floor span, ¾ in. (19 mm) insulation, restrained
- Test 4: 17 ft (5.18 m) floor span, ½ in. (13 mm) insulation, restrained

The restrained 35 ft (10.67 m) floor system (Test 1) obtained a 1½ hour rating, whereas the unrestrained system (Test 2) obtained a 2 hour rating. This implies that restraining the floor assembly makes the test more stringent. The 17 ft (5.18 m) assembly in Test 3 obtained a 2 hour rating whereas the 35 ft (10.67 m) assembly in Test 1 obtained a 1½ hour rating. This result raises the question of whether fire resistance test results on a 17 ft (5.18 m) floor assembly can be extrapolated to longer spans. Note that there are no laboratories in the United

States that can test assemblies with a span greater than 18 ft (5.49 m).

The NIST report concludes with a list of 30 recommendations for action in the areas of increased structural integrity, enhanced fire resistance of structures, new methods for fire resistant design of structures, enhanced active fire protection, improved building evacuation, improved emergency response, improved procedures and practices, and education and training. Several recommendations pertain to fire resistance testing and fire-resistant building design. For example, NIST recommends (#4 and #5) that the technical basis for the standard fire resistance test (ASTM E119), resulting fire resistance ratings, and pertinent code requirements be improved. NIST also recommends (#8 and #9) that procedures and practices used in the fire-resistant design of structures be enhanced and based on performance objectives.

EXTERIOR FIRE SPREAD

Flame spread over exterior surfaces and heat transmission through the structure from external flame and fire exposure are major concerns. Various test methods have, therefore, been developed to determine the fire performance of facades and roof structures.

Upward Fire Spread over Facades

Exterior Insulation and Finish Systems (EIFS) are very common in the construction of exterior walls for high-rise buildings. Because the systems typically consist of plastic foam insulation and other combustible components, the potential exists for rapid upward flame spread over facades to stories above the fire room. NFPA 285, *Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components,* describes a test method intended to evaluate the capability of such wall assemblies to resist vertical and, to some extent, lateral flame propagation over the exterior and interior faces and within the core of the assembly.

A full-scale test procedure was developed in 1980 for evaluating the fire performance of EIFS construction using an outdoor 26 ft (8 m) tall two-story building. This procedure became Uniform Building Code (UBC) standard 17-6, *Method of Test for the Evaluation of Flammability Characteristics of Exterior, Non-Loadbearing Wall Panel Assemblies Using Foam Plastic Insulation,*[49] which was incorporated in the 1988 version of the UBC. In 1994 the designation of the test method was changed to UBC 26-4. One of the limitations of the test method was that the facility was located outdoors and affected by the weather.

In the early 1990s, an intermediate-scale indoor version of the UBC 26-4 test apparatus was developed. Comparable performance was obtained in the intermediate-scale tests for wall systems that both passed and failed the UBC 26-4 test. The resulting intermediate-scale test method was recognized by the UBC as an alternate to UBC 26-4 and was published in the 1997 UBC as test standard 26-9, *Method of Test for the Evaluation of Flammability Characteristics of Exterior, Non-Loadbearing Wall Assemblies Containing Combustible Components Using the Intermediate-Scale Multistory Test Apparatus.*[50] NFPA 285, which is functionally identical to UBC 26-9, was first adopted by NFPA in 1998. ASTM recently developed a test method to determine the fire resistance of perimeter fire barriers (i.e., the joint between an exterior wall assembly and the floor system). The resulting test standard, ASTM E2307, *Standard Test Method for Determining Fire Resistance of Perimeter Fire Barriers Using Intermediate-Scale, Multi-Story Test Apparatus,*[51] uses a slightly modified version of the intermediate-scale multistory test apparatus described in NFPA 285.

The NFPA 285 test structure consists of two stories. The interior dimensions of the first- and second-floor rooms are identical and equal to 10 ft (3.05 m) wide by 10 ft (3.05 m) deep by 7 ft (2.13 m) high. Both rooms are constructed of concrete block walls and concrete slabs and are fully enclosed except for the front side. The interior surfaces of the bottom room are protected with gypsum board and ceramic fiber insulation.

The test assembly is mounted against the front of the test structure and covers both stories. There is a window opening of 78 in. (1.96 m) wide by 30 in. (0.76 m) high at 30 in. (0.76 m) from the floor of the first-floor room. The main burner is located inside the first-floor burn room and is supplied with gas so that its heat output increases according to a prescribed regime from approximately 664 Btu/sec (700 kW) at the start of the test to approximately 853 Btu/sec (900 kW) at the end of the 30 minute test. A second burner is located inside the window opening so that flames hit the window soffit, which is the most vulnerable part of the exterior wall assembly for flame penetration into the core (Figure 2.5.10). The heat output of the window burner increases from 0 Btu/sec (0 kW) at the start of the test to approximately 379 Btu/sec (400 kW) at the end of the 30 minute test duration. Acceptance criteria are based on visual observations of flame propagation over the exterior surface and temperature measurements above and at a lateral distance from the window opening.

A similar test method to evaluate upward fire spread over facades is specified in ISO standard 13785-2, *Reaction to Fire Tests for Facades, Part 2: Large Scale Tests.*[52] However, this standard contains a 90° wall corner on one side of the window opening to concentrate heat from the window flames and also uses a high heat release rate propane burner only inside the burn room. The heat flux exposure specified by ISO 13785-2 is 4.84 Btu/sec·ft^2 (55 kW/m^2) at three positions 600 mm above the window opening, which is substantially greater than the heat flux expected at a similar position in the NFPA 285 test. The ISO test method is representative of the situation when there is a corner on the exterior of a building or when there is storage in close proximity to a building facade, which could result in higher heat fluxes than for the case of flames issuing from a window.[53]

Ignition of Exterior Claddings

Model building codes address the problem of fire spread from one building to an adjacent building due to radiant ignition of combustible exterior facades by specifying a minimum distance to the property line. This distance is based on the assumption that the exterior cladding is wood. The commonly accepted threshold for piloted ignition of wood is 1.10 Btu/sec·ft^2 (12.5 kW/m^2).

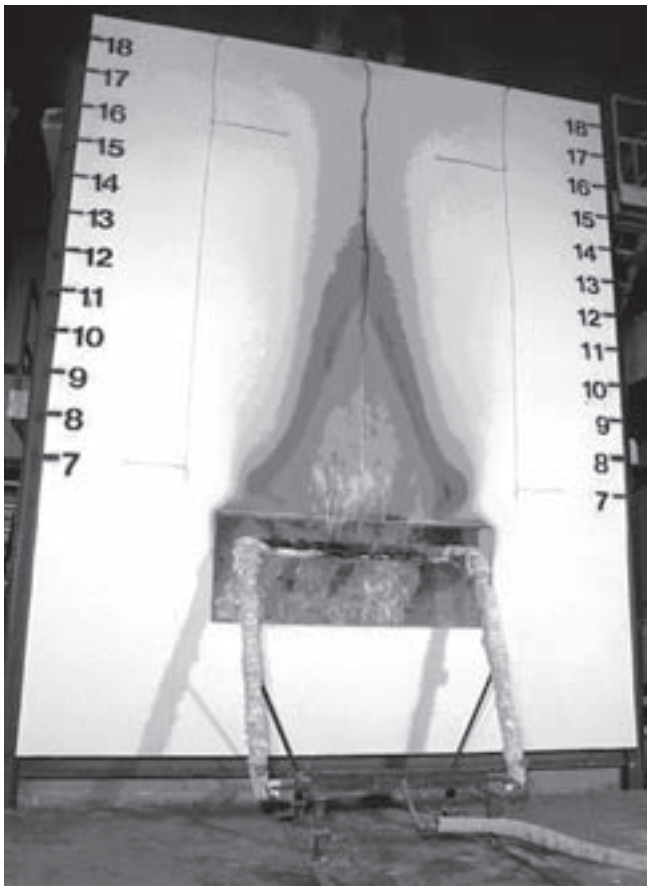

FIGURE 2.5.10 NFPA 285 Intermediate-Scale Multistory Apparatus (Courtesy Southwest Research Institute)

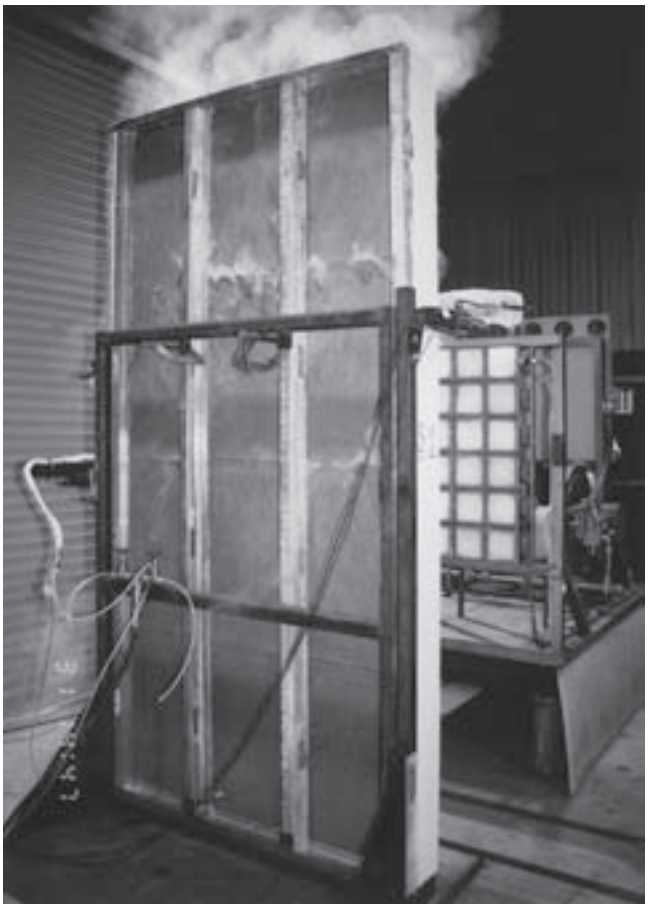

FIGURE 2.5.11 Radiant Panel Test to Measure Ignitability of Exterior Wall Claddings (Courtesy Southwest Research Institute)

However, many different types of exterior wall claddings are now available in the marketplace. To ensure that the model building code provisions are adequate for these products, it is necessary to verify that their ignition threshold is equal to or higher than that for wood. NFPA 268, *Standard Test Method for Determining Ignitability of Exterior Wall Assemblies Using a Radiant Heat Energy Source,* describes a test method that can be used to perform this verification.

The apparatus consists of a vertical 3 ft × 3 ft (0.91 m × 0.91 m) propane-fired radiant panel that exposes the 4 ft × 8 ft (1.22 m × 2.44 m) specimen to a radiant heat flux that is equal to approximately 1.10 Btu/sec·ft^2 (12.5 kW/m^2) over a central 1 ft × 1 ft (0.3 m × 0.3 m) region (Figure 2.5.11). A spark igniter is mounted on the vertical centerline of the test specimen at a point 18 in. (0.46 m) above its horizontal centerline and at ⅝ in. (15.9 mm) from its surface. A product passes if ignition does not occur during the 20 minute test exposure.

Ignition and Fire Spread over Roof Structures

Other possible mechanisms of fire spread involve burning brands landing on a roof surface or flames propagating over a roof covering. ASTM E108, *Standard Test Methods for Fire Tests of Roof Coverings,*[54] and NFPA 256, *Standard Methods of Fire Tests of Roof Coverings,* describe a procedure to measure the relative fire characteristics of roof coverings under simulated fire originating outside the building (Figure 2.5.12). The roof covering is mounted on a 40 in. × 52 in. (1 m × 1.3 m) deck at the required incline. The procedure involves three different tests: an intermittent flame exposure test, a spread of flame test, and a burning brand test. Only the spread of flame test is required for roof coverings mounted on a noncombustible deck. For each test there are three levels of exposure (severe, moderate, and light), leading to Classes A, B, and C, respectively. Additional flying brand tests are required for roof coverings that can be subjected to firebrands, leading to Class A for roofing that can resist ignition from a large burning array of wood sticks, Class B from a moderate-size burning array, and Class C from a burning notched wood block. Rain tests are required when the fire-retardant characteristics of the roof covering or construction may be adversely affected by water.

SAFE SEPARATION DISTANCE

To eliminate ignition and damage at potential target locations on the roof or facade of a building due to likely exterior fire

FIGURE 2.5.12 Burning Brand Test on Roof Covering (Courtesy Southwest Research Institute)

sources, a separation distance between the building and these potential fire sources must be provided. The separation should result in sufficiently low radiant fluxes and/or sufficiently small firebrands arriving at the target during the duration of the exterior fire source. This definition, in essence, is what is meant by a safe separation distance for passive protection of buildings from damaging exposure due to fires in other nearby buildings, outside storage, or even wildland vegetation. In a regulatory environment where model codes prescribe the type of fire protection measures that are required, NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures,* can provide the information necessary to determine safe separation distance. However, in a performance-based environment, the adequacy of a safe separation distance must be demonstrated based on concepts discussed in the following sections.

Radiant Exposure from Outside Fire Sources

Radiant Flux at Target. As discussed in Section 2, Chapter 1, the radiant flux from an outside fire source to a target on the outside wall or roof of a building is given by the product of the flame emissive power and the configuration (or view) factor. The maximum flame emissive power, typical of hazardous outside fire sources, is about 14 Btu/sec·ft^2 (160 kW/m^2) but is influenced by the amount of smoke produced in the flames, as explained in the next section. To determine the configuration factor, any blockage of radiation by intact walls of a burning building must be taken into account. Most importantly, the shape, orientation, and dimensions of the flame radiant source must be considered, as discussed later.

Smoke Mantle. Fires outside of a building involving an intact or collapsed structure, various types of storage arrays, or vegetation (forests, brush) produce a plume of flame and smoke. It is the exposed flame portion of this plume that is responsible for radiant heat transfer to distant targets (see Section 2, Chapter 1). Once the minimum plan dimension of a fire source is more than a few meters, smoke begins to obscure the upper portion of the flame plume (starting at the flame tip) with the smoke mantle obscuring a greater and greater fraction of the flame as the minimum plan dimension of the fire source increases. Since the smoke is relatively cool compared to the flame, thermal radiation from a plume partially covered by a smoke mantle is reduced significantly (see Figure 2.2.2 in Section 2, Chapter 2). Hence, it is important to be able to estimate either the average emissive power (see Section 2, Chapter 1, Equation 5) of the smoke-covered total flame height as a function of the fire source dimension, following the method of Sokri and Beyler,[55] or to estimate the height of the exposed (smoke-free) flame zone above the fire source but below the smoke mantle as a fraction of the total flame height. The latter method would potentially be more accurate but is much more difficult until better correlations are available or until techniques are perfected to calculate realistic plume flow combustion dynamics.

Radiant Source Shape and Orientation. To determine the configuration factor, information on the general shape of the flame radiant source (i.e., whether cylindrical/conical or planar, etc.) and the effect of wind on flame orientation must be derived from the fire scenario(s) assumed for design purposes. A burning building or outside storage that has a nearly square plan area leads to a cylindrical or conical shape for a radiant source, whereas an elongated structure or a vegetation fire generally leads to a planar radiant source. In either case, wind can tilt the radiant source toward the target and this tilt angle has

been correlated with wind speeds above a critical value. When a flame radiant source tilts toward a target, not only is the distance to the target decreased but the source height and, hence, the apparent area of the source viewed from the target also decreased. Calculation of the configuration factor for this case shows that the reduction in source height is the more important factor (leading to a slight reduction in radiant flux at the target) as long as the flame source is never actually above the target (i.e., as long as the flame length is less than the separation distance).

Radiant Source Dimensions. To determine the configuration factor, both the lateral extent (width) and height of the radiant source must be estimated from the fire scenario(s) assumed for design purposes. Horizontal dimensions of the source are obtained from the prescribed fire scenario(s) either in terms of fire initiation within specified combustibles (e.g., a building or a storage item) or in terms of known lateral fire propagation or flame spread rate and the burning duration at each point in the combustibles. Vertical dimensions of the source are obtained from flame height correlations, which depend on fire heat release rates and to a lesser extent on horizontal dimensions of the burning material. Again, the assumed fire scenario will be needed to determine the identity and, hence, the heat release rate of the fire. Note that for a fire source of unlimited length in one direction, leading to a planar radiation source, the flame height depends on the heat release rate per unit length. If the plan area of the outside fire is sufficiently large, there will not be a single, well-defined fire plume but rather a group of plumes at random locations in the burning material. There are correlations for predicting the existence and flame height associated with this so-called "mass-fire" situation.

Damage Due to Heat Flux. Once a radiant heat flux level is obtained for a given separation distance from an outside radiant fire source, damage due to this heat flux must be estimated. The damage estimation should include a consideration of the critical heat flux needed for ignition of cladding or roofing materials on a building, as obtained from the NFPA 268 test method or from small-scale test methods such as the Cone Calorimeter or the Fire Propagation Apparatus. For exterior building surfaces that are not combustible but have been tested in a furnace apparatus similar to ASTM E119, the exposure flux from the outside source should be compared with the average radiant flux determined from the (fourth power of the) measured furnace temperature during the test duration. If no ignition or damage is expected from the radiant flux exposure, a safe separation distance has been confirmed.

Firebrand Exposure from Outside Fire Sources

Firebrands are carried aloft by the upward gas motion in a fire plume and then, once aloft, are carried by the wind to distant building targets. Upward gas velocity in a fire plume increases from near zero at the base of the plume (the lowest elevation at which material is burning) to a maximum value at the end of the continuous flaming region, a distance of more than half the plume height (see Section 2, Chapter 4). Therefore, the largest firebrands, which require the highest upward velocity to be lofted, must originate from the highest elevations of a burning building, storage array, or vegetation that are still immersed in the fire plume. In addition to maximum fuel elevation, other parameters that affect the lofting height and downwind propagation of a firebrand are firebrand characteristics (shape, burning mode, and density), fire heat release rate, and maximum wind speed. The largest firebrands with high wind-drag shapes, high-temperature glowing char, and lowest density will be lofted the greatest distances and do the most damage. Clearly, upward gas velocities in the plume for lofting firebrands will be highest as heat release rates increase and downwind propagation will be enhanced at the highest wind speeds. All of these parameters can be inferred from the fire scenario(s) assumed for design purposes. Once the foregoing parameters are settled, the size of the largest firebrands that can be carried downwind a given distance from the assumed location of the outside source fire to a target location on a roof can be readily determined.[56] If firebrands of this maximum size will not cause damage at the target location, as demonstrated for example, by the ASTM E108 rating for the roofing material, then smaller-size firebrands of the same type also will not cause damage, as the ignition heat flux from smaller brands is lower. In this case, a safe separation distance from a potential source fire location has been confirmed.

SUMMARY

Fire protection of buildings addresses all aspects of fire safety and consists of a combination of active and passive measures. Active fire protection devices require manual, mechanical, or electrical power for their operation. Passive fire protection does not require any external power. This chapter deals with one aspect of passive fire protection: fire containment. This type of passive fire protection includes test methods to evaluate the performance of interior and exterior assemblies and structural members when exposed to fully developed fire conditions, as well as measures needed to provide a safe separation distance from exterior fire sources.

Fully developed postflashover fires are contained to the enclosed space of origin by using fire-resistive separating and load-bearing building elements. The fire resistance of a building element is determined through furnace testing. The element is exposed to the furnace environment, which follows a standard temperature-time curve. Structural elements are subjected to their design load during the fire test. Steel-frame floor assemblies may have to be tested under restrained conditions. End-point criteria are based on heat transmission and integrity for separating elements and load-bearing capacity for structural members. North American fire resistance furnace test standards may require that the test specimen be subjected to a hose stream test after the fire test is terminated.

Experimental variables that affect the severity and results of a fire resistance furnace test are discussed. These variables include thermal exposure conditions, furnace pressure, load, end-point criteria that are used, and specimen characteristics such as size and moisture content.

The most commonly used ASTM, NFPA, UL, ULC, ISO, and IMO fire resistance furnace test standards are briefly de-

scribed. The relationship between fire resistance furnace tests and real fires, in particular Ingberg's equal-area concept, is discussed. Alternative methods are identified to determine the fire resistance of building elements based on analytical calculations and mathematical fire modeling. Some analytical methods are accepted by the U.S. model building codes in lieu of furnace testing.

The chapter concludes with a discussion of test methods to measure ignition, flame spread, and heat transmission characteristics of exterior building elements such as facades and roof structures and a discussion of the various factors influencing the radiant heat flux and the size of firebrands generated from distant to nearby fires in outside buildings, material storage, or vegetation.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the basics of fire containment discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*
NFPA *101®*, *Life Safety Code®*
NFPA 220, *Standard on Types of Building Construction*
NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 252, *Standard Methods of Fire Tests of Door Assemblies*
NFPA 256, *Standard Methods of Fire Tests of Roof Coverings*
NFPA 257, *Standard on Fire Test for Window and Glass Block Assemblies*
NFPA 268, *Standard Test Method for Determining Ignitibility of Exterior Wall Assemblies Using a Radiant Heat Energy Source*
NFPA 285, *Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components*
NFPA 415, *Standard on Airport Terminal Buildings, Fueling Ramp Drainage, and Loading Walkways*

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Chapter 6

Fundamentals of Fire Detection

Richard L. P. Custer ❏ James A. Milke

Chapter Contents

Simplified Fire Development
Fire Signatures

Key Terms

aerosol, aerosol signature, ceiling jet, energy release signature, entrainment, fire detection, fire growth, fire plume, fire signature, gas signature, gas yield, multiple signature detection, thermal lag

Most fires, no matter how large they may become, begin as small fires. Small fires, if detected, are easily controlled manually or by fixed fire suppression systems. The earlier a fire is detected, the more likely building occupants are to escape with little or no impact from exposure to fire products. Furthermore, the earlier a fire is detected, the sooner suppression methods can be brought to bear on the fire, thereby reducing damage to property and the environment.

For additional information, see Section 14, Detection and Alarm, of this handbook.

SIMPLIFIED FIRE DEVELOPMENT

In the earliest stages of fire development, fuel materials are heated by an ignition source even before smoldering (i.e., glowing combustion) occurs. Large numbers of extremely small invisible particles are produced and distributed into the surrounding atmosphere. At this point in fire development (prepyrolysis), very little energy is produced to distribute these particles, and they are generally transmitted with the existing air motion. Smoldering fires produce large particles and gases such as carbon monoxide (CO) and carbon dioxide (CO_2).

Following the development of flame, a column of hot gases rises as a plume.[1] As the plume rises, uncontaminated air is drawn or "entrained" into the plume, increasing its volume. As a result of dilution of the hot gases in the plume by the entrained cool air, the gas velocity and temperature in the plume are reduced. Entrainment of air is discussed in Section 18, Chapter 3, "Smoke Movement in Buildings."

For any space, there is a minimum fire size necessary to provide sufficient energy to the plume to enable it to reach the ceiling. Until the smoke reaches the ceiling, ceiling-mounted smoke and thermal detectors are not able to respond.[2]

In some tall atria and indoor sports arenas, the fire size needed to drive the smoke to the ceiling is substantial. This situation is made worse if a hot layer is present before the start of the fire, for example, due to the presence of a solar heat load at the ceiling. In such cases, the smoke may stop rising at a point below the ceiling. This situation is referred to as "intermediate stratification."[3] In these situations, the response of ceiling-mounted detectors is delayed until the fire grows large enough to provide sufficient buoyancy to the plume to force its way through the hot air layer. This may cause a substantial time delay if ceiling-mounted detectors are the only initiating devices present.

If there is a ceiling above the fire, the vertically rising plume will be deflected, and the gases will travel horizontally across the ceiling. The upward movement of the hot gases is accomplished by a mechanism commonly referred to as *convection.* Convection is a combination of heat transfer between the air molecules and the motion of the air resulting from buoyancy.[4] Convection in the plume extends to the horizontal movement of air just below the ceiling, which is called a *ceiling jet.*[5] The plume and ceiling jet transport the smoke particles or aerosols from their point of

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generation to a detector. Generally, ceiling-mounted detectors respond to heat or smoke transported vertically by the plume and horizontally by the ceiling jet.

As the fire progresses, a layer of hot gases forms at the ceiling, descending over time and spreading to adjacent spaces through open doorways.

FIRE SIGNATURES

Characteristics of Fire Signatures

Custer and Bright first proposed the concept of fire signatures in 1974.[6] From the very beginning, a fire produces a variety of changes in the surrounding environment. Any product or result of a fire that changes the ambient condition is referred to as a *fire signature* and has the potential for use in detection. Production of smoke particles, for example, results in a decrease in light transmission. Not all fire signatures, however, are practical for fire detection purposes. To be useful, a fire signature should generate a measurable change in ambient conditions. In addition, the magnitude of the change must be greater than normal background variations. For example, a sudden increase in temperature could be due to either a fire or normal start-up of a heating appliance.

The magnitude of change in the ambient condition is the signal from a fire signature; the background level, with its normal variations, is referred to as the *noise.* All other factors, such as hazard level at detection and hardware costs, being equal, the preferred fire signature will be one that can generate the highest signal-to-noise ratio at the earliest time in the fire's development.

The best signatures for most applications are those associated exclusively with fire and found in a wide variety of fuels. Fuel-specific signatures, such as the release of hydrogen chloride from polyvinyl chloride (PVC) wire insulation, may be particularly valuable in telecommunications facilities, but they may be of little use for general-purpose applications. Individual signatures are discussed below.

Aerosol Signatures

The process of combustion produces very large numbers of solid and liquid particles, ranging in size from 5×10^{-4} to 10 microns (μm). These particles, suspended in air, are called *aerosols.* The characteristics of smoke aerosols produced in a fire depend on the composition of the fuel, the combustion state (smoldering or flaming), and the amount of air available.

Aerosols resulting from fire actually represent two different fire signatures: invisible and visible. Particles less than 0.3 μm do not scatter light efficiently and are therefore classified as invisible. The larger particles do scatter light and are classified as visible aerosols. Smoke aerosols may change with respect to their particle size distribution. Smoke particles or droplets can collide and adhere to each other. Smoke may coagulate, become deposited on surfaces, and settle out by sedimentation over time.

Invisible aerosols are among the earliest appearing fire signatures and are produced at very low energy levels from the fire. Invisible aerosols can be detected through air sampling systems such as VESDA (very early smoke detection apparatus) or incipient fire detection systems.[6] Larger smoke aerosols can be detected by light-scattering, photoelectric, or ionization detectors. For a discussion of the operating principles of these detectors, see Section 14, Chapter 2, "Automatic Fire Detectors," and the *National Fire Alarm Code® Handbook.*[7]

Additional information on smoke aerosols can be found in the *SFPE Handbook of Fire Protection Engineering.*[8]

Energy Release Signatures

There are two types of energy release signatures: radiative and convective energy release.

Radiative Energy Release Signatures. Throughout its course, fire continuously releases energy into the surrounding environment, producing several detectable signatures. The earliest detectable energy signature is radiated energy. Radiation is emitted across a wide range of wavelengths:

- Ultraviolet (0.10–0.35 μm)
- Visible (0.35–0.75 μm)
- Infrared (0.75–22.00 μm)

The specific wavelength of radiation from a heated material is highly dependent on the characteristics of the material itself. Ultraviolet fire signatures appear in flames as emission from hydroxyl (OH) ions, CO_2, and CO in the 0.27–0.29 μm range.[9] Devices often respond to both ultraviolet and infrared signatures. Video fire detection systems are being developed that block visible light and only pass infrared to the video camera. The detection principle is based on an increase in the area emitting infrared versus time. Curves have been developed such that fires involving different fuels can be recognized.[10]

Infrared emissions from hydrocarbon fuels (with the exception of acetylene and other highly unsaturated hydrocarbons) are particularly strong in the 4.4 μm region due to CO_2 and in the 2.7 μm region due to water vapor.[11] Infrared detectors employ sensors designed to respond to infrared over narrow ranges associated with these frequencies.

Radiant energy sensing devices are generally limited to line-of-sight applications with a field of vision generally represented by a cone.* The size of fire that can be detected is a function of the distance between the detector and the radiant energy source. Because radiation intensity decreases as the square of the distance from the source, detectors generally need to be placed relatively close to the area being protected.

Convective Energy Release Signatures. Convective energy from a fire rises toward the ceiling, resulting in increased air temperature at ceiling-mounted heat detectors. The response time for heat detectors depends on the heat release rate of the fire, the distance between the fire and the ceiling, and the thermal response characteristics and exact location of the detector. The thermal response characteristics relate to the time that it takes for the detector to reach the temperature of the surround-

*Infrared sensors, however, may respond to surfaces that are heated by fires not in the direct line of sight.

ing hot gases. This time is called *thermal lag*. Detectors having low mass and high surface area respond to a given fire more quickly than detectors with high mass and low surface area.

Detectors designed to respond to convected thermal energy may activate at a fixed temperature or a specified rate of rise in temperature. If such detectors are located too far below the ceiling, they will be outside of the ceiling jet and will not respond.

Gas Signatures

A fire may produce several different gases. The type and production rate of gases produced in fires depends on the fuel composition, fire size, ventilation conditions, and burning mode.

Carbon-containing fuels produce CO and CO_2. Well-ventilated, flaming fires involving such fuels generally yield 100 to 1000 times more CO_2 than CO. Conversely, for underventilated or smoldering fires of carbonaceous fuels, the amount of CO_2 and CO produced may be similar. In addition to CO_2 and CO, hydrocarbon fuels also produce a variety of gases containing carbon, hydrogen, and oxygen, such as formaldehyde (HCHO) and acrolein (CH_2CHCHO).

Other gases produced by carbonaceous fuels depend on the presence of other elements in the fuel. For example, fuels that contain chlorine, such as polyvinyl chloride (PVC), produce hydrogen chloride (HCl) and chlorine gas (Cl_2). Fuels that contain nitrogen, such as wool and polyurethane, produce hydrogen cyanide (HCN), ammonia (NH_3), and nitrogen oxide compounds (NO_x). Sulfur-containing fuels produce sulfur dioxide (SO_2) and hydrogen sulfide (H_2S).

Estimating the concentration of selected gases from fires requires knowledge of the yield of each gas of interest and the total mass loss from the fuel involved in the fire. The yield is defined as the ratio of the mass of each gas generated per unit of fuel mass consumed. Yield factors for CO and CO_2 are most available for flaming, well-ventilated fires.[12] The availability of yield factors for other gases, nonflaming fires and underventilated fires are relatively sparse.

In addition to the ventilation and burning mode, the rate of production of any particular gas in a fire is affected by the size of the fire, expressed in terms of the heat release rate of the fire. In general, the rate of production of a particular gas from a well-ventilated, flaming, 500 kW fire is five times that from a well-ventilated, flaming, 100 kW fire.

Currently, gas sensors are used primarily for industrial safety applications, that is, to detect the release of a particular chemical. Some manufacturers have considered incorporating CO and CO_2 sensors in fire detectors.

Other Fire Signatures

Although the human body is well designed to feel heat and smell smoke, some evidence suggests that sounds associated with a burning fire can be the first cues received. Sounds caused by fire arise from a variety of causes such as nonuniform expansion of heated materials, boiling of trapped moisture, and bursting of gas bubbles. Experiments have been conducted to demonstrate the feasibility of using acoustic signatures of fire as the bases for fire detection.[13,14]

The human nose recognizes an odor of smoke by detecting a group of airborne gases and particles and associating that array of gases with a particular source. Some individuals are able to distinguish between different fuels producing the smoke, for example, burning leaves versus burning electrical insulation. Currently, artificial noses are used in some industrial process control applications, such as to determine when coffee beans have been sufficiently roasted or to detect spoiled food. However, current efforts to develop an artificial nose for fire detection are limited to research activities.[15]

Multiple Signature Detection

An emerging technology addresses the problem of unwanted alarms and improving response time to unwanted fires. Chemical sensors, for example, are being investigated to detect fire precursors.[16] Considerable research has been conducted on using combined gas/fire signatures for fire detection. Combining CO and CO_2 sensors and evaluating the CO/CO_2 ratio has been shown to be an effective means for detection of fire.[17] Additionally, CO/CO_2 concentrations have been used to discriminate between smoldering and nuisance fires.[18] Experiments have also been conducted using light obscuration; temperature; CO, CO_2, and O_2 concentrations; and signals from metal oxide sensors. By employing neural network and statistical methods, a system was developed to distinguish between fire and nonfire sources. Flaming and nonflaming fires could also be differentiated.[19,20]

Data on the response of individual sensors in full-scale fire tests has been analyzed to explore the benefits of multi-sensor detectors. This includes residential applications with commercial smoke detectors and CO[21] and combined optical, thermal, and CO sensors.[22] Analysis of the data from the Home Smoke Alarm Project[23] resulted in suggested algorithms involving the magnitude and rate of rise of several combinations of temperature, CO_2, and commercial smoke alarms. Similarly, data from experiments involving shipboard fire scenarios was analyzed to explore the benefits of the response of combinations in the signal and rate of rise of CO, CO_2, and commercial smoke alarms.[24,25]

SUMMARY

A variety of technologies exist for detecting the products of combustion generated at different stages of fire growth and spread. These technologies are based on detecting one or more unique fire signatures and have been growing in sophistication as the fire community becomes more adept at measuring fire and its effects.

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Chapter 7

Theory of Fire Extinguishment

Revised by

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Chapter Contents

Mechanisms for Affecting the Combustion Process
Extinguishment with Water
Extinguishment with Aqueous Foams
Extinguishment with Water Mist
Extinguishment with Inert Gases
Extinguishment with Halocarbon Agents
Extinguishment with Dry Chemical Agents
Special Cases of Extinguishment

Key Terms

actual delivered density (ADD), aqueous foam, automatic sprinkler system, carbon dioxide, chain reaction, combustion, dry chemical agent, dry ice, flame, flammable liquid, halocarbon agent, inert gas, premixed combustion, pre-wetting density (PWD), pyrolysis, required delivered density (RDD), water mist

One or more of the following mechanisms—more often, several of them simultaneously—can be used to extinguish a fire:

- Physically separating the combustible substance from the flame
- Removing or diluting the oxygen supply
- Reducing the temperature of the combustible or of the flame
- Introducing compounds that modify the combustion chemistry

For example, when water is applied to a fire of a solid combustible burning in air, several extinguishing mechanisms are involved simultaneously. The solid is cooled by contact with water, causing its rate of pyrolysis, or gasification, to decrease. The gaseous flame is cooled, causing a reduction in heat feedback to the combustible solid and a corresponding reduction in the endothermic pyrolysis rate. Steam is generated, which, under some confined conditions, may prevent oxygen from reaching the fire. Water in the form of fog may also block radiative heat transfer.

As another example, consider the application of a blanket of aqueous foam to a burning pool of flammable liquid. Several mechanisms may operate. The foam prevents the fire's radiant heat from reaching the surface and supplying the needed heat of vaporization. If the fire point of the flammable liquid is higher than the temperature of the foam, the liquid is cooled and its vapor pressure decreases. If the flammable liquid is water soluble, such as alcohol, then, by a third mechanism, it will become diluted by water from the foam, and the vapor pressure of the combustible will be reduced.

As yet another example, when dry chemical is applied to a fire, the following extinguishing mechanisms may be involved:

- Chemical interaction with the flame
- Coating of the combustible surface
- Cooling of the flame
- Blocking of radiative energy transfer

Ideally, any fully successful theory of fire extinguishment should be able to predict the quantity and rate of application of the extinguishing agent needed for a given fire. Such a theory would be better than empirical measurements that yield the same information, because the empirical data would be fully reliable only in circumstances identical to those employed in the empirical testing. Furthermore, the theory would provide guidance for improvement of extinguishment performance.

Unfortunately, the agents mentioned above—water, foam, and dry chemical—each work by a combination of several mechanisms and the relative importance of the various contributions varies with circumstances. The degree of complexity resulting from each situation, as well as other

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problems, has up to now prevented completion of a quantitative fundamental theory of extinguishment action. However, much is known about the various extinguishment modes, and this knowledge is outlined herein. A more detailed treatment can be found in Friedman.[1]

See also Section 2, Chapter 1, "Physics and Chemistry of Fire"; Section 16, Chapter 8, "Water Mist Fire Suppression Systems"; Section 17, Chapter 2, "Chemical Extinguishing Agents and Application Systems"; Section 17, Chapter 4, "Foam Extinguishing Agents and Systems"; Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems"; and Section 17, Chapter 7, "Application of Gaseous Agents to Special Hazards Fire Protection."

MECHANISMS FOR AFFECTING THE COMBUSTION PROCESS

Much scientific information has been developed about the combustion process, the understanding of which is central to the understanding of fire extinguishment. For details, one may refer to Section 2, Chapter 1, "Physics and Chemistry of Fire," and the texts by Friedman,[1] which is rather elementary; Drysdale[2] and Glassman,[3] which are more advanced; or Strehlow,[4] which is the most advanced. Only combustion concepts especially relevant to fire extinguishment are presented in this chapter. These relevant concepts include combustion, flaming, pyrolysis, and chain reactions.

Combustion, Flaming, and Pyrolysis

The term *combustion* usually refers to an exothermic, or heat-producing, chemical reaction between some substance and oxygen. The concern in fire protection is generally with the type of combustion reactions between various materials and the oxygen of the air that involves a flame. A *flame* is a gaseous oxidation reaction that (1) occurs in a region of space much hotter than its surroundings and (2) generally emits light. Familiar examples include the yellow flame of a candle and the blue flame of a gas burner. When a solid such as a match or candle burns, a portion of the heat of the gaseous flame is transferred to the solid, causing the solid to vaporize (Figure 2.7.1). This vaporization can occur with or without chemical decomposition of the molecules. If chemical decomposition occurs, the process is called *pyrolysis.*

Flaming combustion requires a high temperature, and the chemical reactions must proceed fast enough at this high temperature to generate heat as fast as it is dissipated, so that the reaction zone will not cool down. If anything is done to upset this heat balance, such as introducing a coolant, it is possible that the combustion will be extinguished. It is not necessary for the coolant to remove heat as fast as it is being generated, because the combustion zone in a fire is already losing some heat to the cooler surroundings. In some cases, only a modest additional loss of heat is needed to tip the balance toward extinguishment (see Figure 7.3 in Friedman[1]).

Extinguishment can be accomplished by cooling either (1) the gaseous combustion zone or (2) the solid or liquid combustible. In the latter case, the cooling prevents the production of combustible vapors. This is probably the primary mode of action when a wood fire is extinguished by applying water.

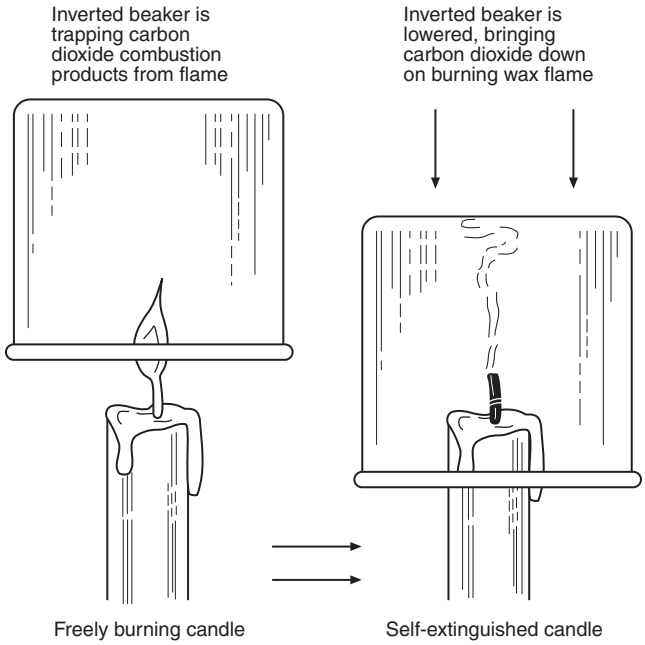

FIGURE 2.7.1 Flaming Combustion (Left) and Extinguishment by Its Own Combustion Products (Right) of a Wax Candle

As an alternative to removing heat from the combustion zone to slow the reactions, it is also possible to reduce the temperature of the flame by modifying the air that supplies the oxygen that feeds the flame. Air is 21 percent oxygen by volume, the remainder being almost entirely the inert gas nitrogen. The nitrogen, which is drawn into the flame along with the oxygen, absorbs heat, with the result that the flame temperature is much lower than it would be in a fire burning in pure oxygen. If additional nitrogen or some other chemically unreactive gas, such as steam, carbon dioxide, or a mixture of combustion products, were to be added to the air entering the flame, the heat absorbed by these inert molecules would cause the flame temperature to be even lower.

The flame temperature is so important because the rate of a key combustion reaction ($H + O_2 \rightarrow OH + O$) is very sensitive to temperature. A small decrease in temperature causes a disproportionately large decrease in the rate of this reaction, according to Arrhenius' law, which states that chemical reaction rates vary exponentially with temperature.

Chain Reaction

The symbol H denotes a free hydrogen atom, as contrasted with the ordinary stable form of hydrogen, H_2. Combustion consists of rapid *chain reactions* involving these hydrogen atoms and other active species, hydroxyl free radicals OH, and free oxygen atoms O. The sequence of reactions occurring in a hydrogen-oxygen flame is illustrated in Figure 2.7.2.

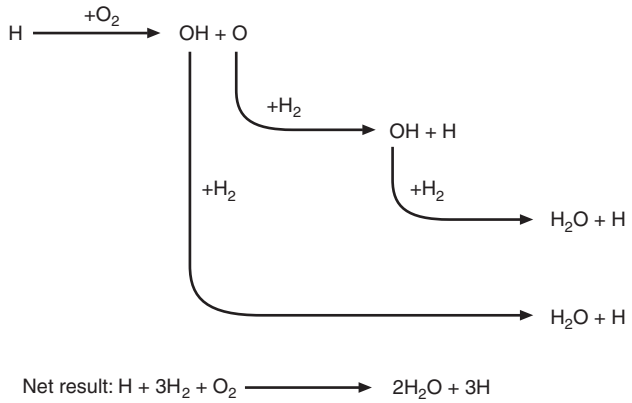

FIGURE 2.7.2 Chain Reaction Mechanism in a Hydrogen-Oxygen Flame

Figure 2.7.2 shows that a single H atom, when introduced into an H_2-O_2 mixture at an elevated temperature, will be transformed in a fraction of a millisecond to form two molecules of H_2O and three new H atoms. Each of these new H atoms can immediately initiate the same sequence, resulting in a branching chain reaction, which continues until the reactants are consumed. Then, the remaining H, O, and OH species recombine according to the reactions

$$H + O \rightarrow OH$$

and

$$H + OH \rightarrow H_2O$$

Similar chain reactions occur in flames of any hydrogen-containing species. Hydrogen is present in the vast majority of combustibles, except for metals and pure carbon.

The ability of hydrogen atoms to multiply rapidly in a flame depends, then, on the prevailing temperature in the flame, which is modified by heat loss or by inert gases, thus leading to extinguishment.

Hydrogen atoms or other active species may also be removed from the flame by purely chemical means—that is, by introducing a species capable of chemical inhibition, which will be discussed later in this chapter.

Accordingly, the following are two fundamental ways of reducing combustion intensity in a flame and ultimately causing extinguishment:

1. Reducing the flame temperature
2. Adding a chemical inhibitor to interfere with the chain reaction

Consider the effect of adding additional nitrogen to a fuel vapor-air mixture. Suppose the fuel vapor is methane, CH_4. Figure 2.7.3 shows that if more than about 35 percent additional nitrogen is added to a 9.5 percent methane-air mixture at 77°F (25°C), the resulting mixture is nonflammable. This nonflammability is caused by the reduction of flame temperature from about 3452°F (1900°C) to about 2192°F (1200°C), since the added nitrogen absorbs heat.

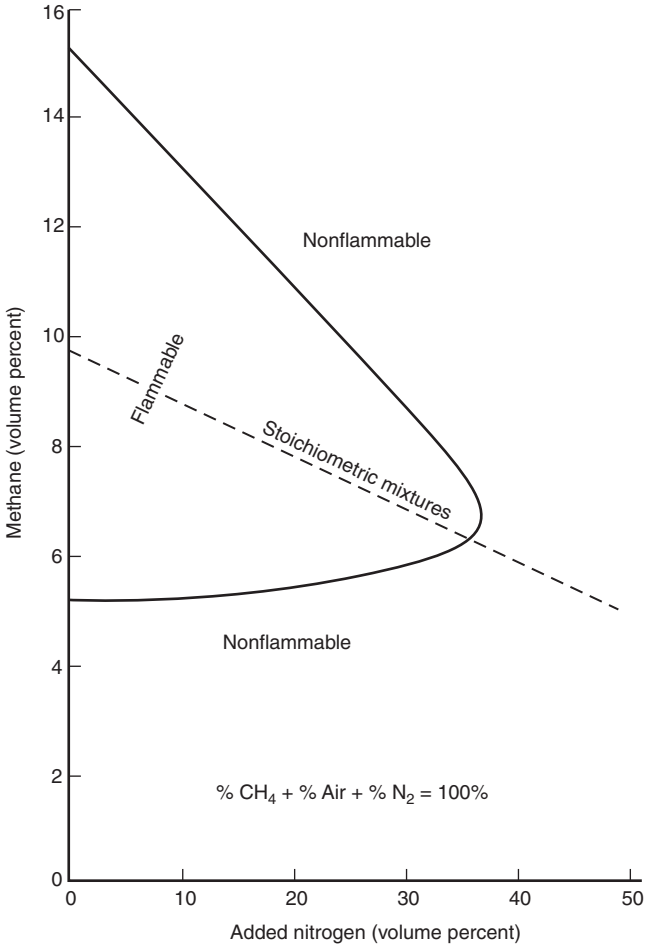

FIGURE 2.7.3 Limits of Flammability of Various Methane-Air-Nitrogen Mixtures at 77°F (25°C) and 1 atm (Source: M. G. Zabetakis, "Flammability Characteristics of Combustible Gases and Vapors," 1965[5])

But why is the flame unable to burn when its temperature is below 1200°C? This is not fully understood. If we had an ideal flame, burning in a place with no gravitational field (e.g., a space station), and also with negligible radiative heat loss, it is believed that there would still be a flammability limit, caused by the competition between chain-branching and chain-breaking chemical reactions. Chain-branching reactions are known to be much more temperature-sensitive than chain-breaking reactions; therefore, below a critical temperature, chain-breaking reactions will dominate and the flame can no longer burn.

However, a real flame, on earth, will be in a gravitational field, and when the dilution of the flame reduces the burning velocity to a value lower than the free-convective motions (buoyancy) of the burning region surrounded by colder gases, then the burning surface will be "strained" and disrupted, and extinguishment will result. Another effect is the radiative heat loss from the flame to the surroundings, which can cause instability when the rate of heat loss becomes a sufficient fraction of the rate of heat generation. The relative importance of the various effects for various flames has not been fully established yet.

For practical purposes, the measured flammability limits can be relied on.

Notice also from Figure 2.7.3 that a 9.5 percent methane-air-nitrogen mixture can be made nonflammable by adding not only nitrogen but also additional air or additional methane. Such additions would produce an excess of one of the reactants and, therefore, a dilution and reduction of flame temperature.

The foregoing discussion of flammability limits applies to *premixed combustion,* or combustion of a uniform mixture of fuel and air and possibly a third component. This is often the case for explosions, but fires are generally diffusion flames with buoyancy-induced large-scale turbulence rather than premixed flames. That is, a solid or liquid combustible is vaporizing, and air approaches the vapor cloud from the sides. The flame burns at the interface of the interdiffusing, turbulent combustible vapors and air. The hot turbulent combustion products then rise in a fire plume because of buoyancy.

A turbulent diffusion flame is clearly more complex than a premixed flame, but much the same principles apply to its extinguishment. If more inert gas is added to the air feeding a diffusion flame, extinguishment will occur when the temperature of the individual flamelets within the turbulent diffusion flame is reduced to about 2192°F (1200°C) or 2372°F (1300°C). However, another important way of extinguishing a diffusion flame over a solid or liquid is to cool the solid or liquid enough to interrupt the gasification process. If the gasification rate can be reduced to less than a few grams per square meter per second, the flame becomes unstable and can no longer sustain itself.

EXTINGUISHMENT WITH WATER

One might suppose that water is the most widely used extinguishing agent because of its low cost and ready availability, relative to other liquids. However, quite aside from cost and availability, water is superior to any other known liquid for fighting the majority of fires.

Characteristics of Water

Water has a very high heat of vaporization per unit mass, at least four times higher than that of any other nonflammable liquid. It is also outstandingly nontoxic; even a chemically inert liquid, such as liquid nitrogen, can cause asphyxiation. Water can be stored at atmospheric pressure and normal temperatures. Its boiling point—212°F (100°C)—is well below the 482°F (250°C) to 842°F (450°C) range of pyrolysis temperatures for most solid combustibles, and therefore evaporative cooling of the pyrolyzing surface is efficient. No other liquid, regardless of cost, can match these properties. However, water is not an absolutely perfect extinguishing agent. It does freeze below 32°F (0°C). It does conduct electricity. It can irreversibly damage some items, although, in many cases, it is practical to salvage water-damaged items. When applied in bulk or in sprays consisting of large droplets, water may not be effective for flammable liquid fires, especially flammable liquids that are insoluble in water and float on water, such as hydrocarbons. Water is not compatible with certain hot metals or certain chemicals. With fires in these materials, other agents, for example, aqueous foam, inert gases, environmentally-friendly halocarbons, and dry chemicals, are preferred.

Water may extinguish a fire by a combination of mechanisms—cooling the solid or liquid combustible; diluting water-soluble flammable liquids; cooling the flame itself; generating steam that prevents oxygen access; and as fog, blocking radiative transfer. Although all these mechanisms may contribute to extinguishment, probably the most important is cooling a gasifying combustible.

For a solid to burn, a portion of the solid must be at a high enough temperature so that pyrolysis occurs at a sufficient rate to maintain the flame. For most solids, this temperature is 572°F (300°C) to 752°F (400°C), and the pyrolysis rate must be a few grams per square meter per second. If even a small amount of liquid water, with its high heat of vaporization, can reach this region, the solid can be cooled sufficiently to reduce or stop the pyrolysis, and the flame will be extinguished. Even deep-seated fires can be suppressed in this way. Accordingly, water is the obvious agent of choice for burning solids.

Water as an Extinguishing Agent

The two most common means of applying water are by (1) a solid stream or spray from a hose and (2) spray from automatic sprinklers. The practical aspect of manual fire fighting and the use of sprinklers are discussed elsewhere in this handbook. From a scientific viewpoint, studies reviewed by Heskestad[6] and Rasbash[7] have investigated the minimum rate of water application to a burning solid surface that will cause extinguishment.

In an important paper by Magee and Reitz,[8] burning slabs of various plastics, horizontal and vertical, were simultaneously heated with radiant heaters and cooled with controlled water sprays. Extinguishment conditions were then determined. Figure 2.7.4 shows a linear relationship between the radiative heating rate and the water application rate required for extinguishment. The reciprocal of the slope of the line is found to be approximately the heat of vaporization of water, as theory would predict.

To extinguish burning polymethyl methacrylate (acrylic sheet), enough water must be applied to reduce the burning rate to less than about 4 g/m^2·sec. Depending on the intensity of the externally imposed radiative flux—up to 18 kW/m^2—a water application rate of 1.5 g/m^2·sec to 8 g/m^2·sec was required. This is a very small application rate of water. For extinguishment with no external radiative flux, it was only necessary to spray enough water so that the heat absorbed by its vaporization was 3 percent of the heat of combustion.

Experiments with other plastics and with wood cribs have given similar results; only a few grams per square meter per second of water must be applied to the burning surface to cause extinguishment, and the rate of heat absorption by the water is only a few percent of the rate of heat generation by the fire before water application.

The reason for this high efficiency is well understood. Consider a horizontal slab of polymethyl methacrylate, 0.3 m × 0.3 m, which is burning steadily on its top surface. Measurements[1] have shown that only about 12 percent of the energy

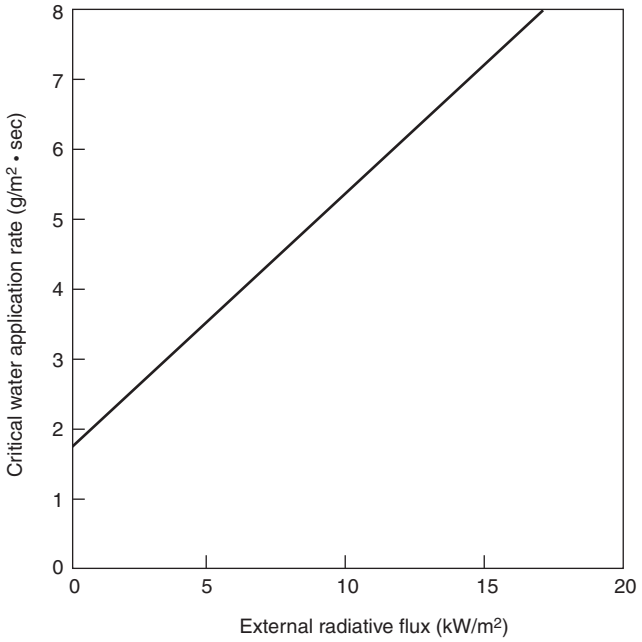

FIGURE 2.7.4 Water Application Rate Needed to Extinguish a Fire on a Vertical Polymethyl Methacrylate Sheet

released by combustion is transferred back to the surface. Of this energy arriving at the surface, primarily by radiation from the flame above, about 40 percent is reradiated from the hot surface to the surroundings, and only 60 percent of 12 percent, or 7 percent of the available combustion energy, is used to decompose and gasify the plastic. It is only necessary to apply enough water to the surface to drain off a substantial portion of this 7 percent of the combustion energy, and the rate of burning is then reduced to a point at which the flame can no longer sustain itself.

For combustibles arranged in warehouse rack-storage configurations, Yu et al.[9] found that the required water fluxes for fire extinguishment were greater than those obtained from the small-scale experiments described above. Fire suppression experiments were conducted by applying uniform water fluxes to the top of the entire storage array at different fire development stages. The experiments examined the fire suppression requirements for different storage heights. One of the combustibles investigated was corrugated paper cartons, for which the critical water flux for fire extinguishment per unit carton surface area exposed to water application was found to be 6 g/(m^2·sec). This is greater than the 2.7 to 5.5 g/(m^2·sec) reported by Heskestad for wood cribs.[6] Heskestad also reported that the critical water flux for wood crib fires and wood pallet fires is higher than that for wood slab fires. It appears that a combustible's morphology, configuration, and storage arrangement all affect the critical water flux for fire extinguishment due to the influence of heat feedback from the fire, even though the combustible in each case is made of the same base material. Note that the Magee and Reitz[8] experiments showed that a higher water flux was needed when there was a higher imposed radiant flux on the burning surface. In large-scale storage arrangements, burning fuel surfaces are exposed to elevated radiant flux levels from flames on nearby burning surfaces, which leads to a greater water flux requirement.

Of course, the evaporation of the water produces steam that dilutes the flame and reduces the flame temperature, causing some reduction in the rate of burning, but this effect is generally small (except when water is applied in mist form, as discussed in the section "Extinguishment with Water Mist") and need not be considered in a first-approximation model of the extinguishment process. It is interesting to note that in ignition experiments, a solid surface is progressively heated, with a gradual increase in the rate of pyrolysis, or gaseous decomposition, but it is not possible to ignite the vapors to obtain a self-sustaining flame until the pyrolysis rate reaches a certain minimum value. This is roughly the same value to which the pyrolysis rate must be reduced when water is applied to a burning surface to accomplish extinguishment.

In practical fire fighting, water must be applied at 10 to 100 times the rates used in the research described above because of the difficulty of delivering the water directly to the burning surface.

Water and Automatic Sprinklers

In the case of fire suppression by use of sprinklers at the ceiling, it is possible to calculate the fraction of the water droplets able to penetrate the fire plume and arrive at the burning surface beneath. Such a calculation is complex.[10] It is necessary to know the distribution of heat release rate relative to the location of nearby ceiling sprinklers and several different water-spray distribution functions. These include the angular distributions of droplet size, water flux, and droplet velocity at or near the sprinkler deflector, which are usually unknown and have to be determined indirectly by matching the calculated results with spray data further downstream where measurements are feasible. As a result, such calculations to date always have an uncertainty regarding the actual starting condition of the sprinkler spray. Some information on droplet size distribution is available from previous specialized studies.[11] The droplet size distribution of the water depends not only on the sprinkler design but also on the pressure drop across the sprinkler. For geometrically similar sprinklers, the mean droplet size varies inversely with the cube root of the pressure drop and is proportional to the two-thirds power of the orifice diameter. The droplet size also depends on the surface tension of the water, which could be modified with additives. Once accurate starting conditions are available, the calculation will then take into account the aerodynamic drag on the downward-moving droplets encountering the upward-moving fire gases, and calculate the change in motion of the fire gases because of the downward momentum of the water spray. Droplet evaporation and cooling of the fire gases are included in the calculation.

The effectiveness of sprinkler sprays penetrating the fire plume can be quantified by measurements as a practical alternative to the preceding calculation. For instance, Figure 2.7.5 shows an apparatus developed to measure the water fluxes generated by sprinkler sprays under a fire plume which reproduces

FIGURE 2.7.5 An ADD-PWD Apparatus for Measuring the Effectiveness of Sprinkler Spray Penetration Through the Fire Plume (Source: Copyright © 2008 FM Global. Reprinted with permission. All rights reserved.)

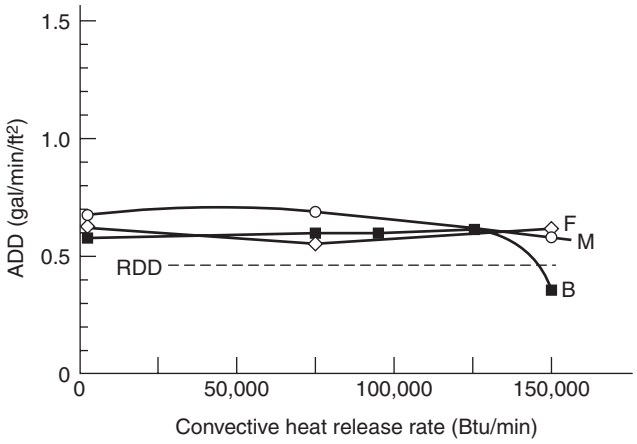

FIGURE 2.7.6 ADD-RDD Concept (Source: *ESFR Update,* Vol. 2, No. 2. Copyright © 1985 FM Global. Reprinted with permission. All rights reserved.)

the thermal flow environment of a realistic fire of interest.[12] Measured water fluxes include *actual delivered density* (ADD), defined as the average water flux that has penetrated the fire plume in the fire area and the *pre-wetting density* (PWD), defined as the average flux just outside the fire area. Basically, the apparatus consists of a movable ceiling whose height can be adjusted easily, a fire plume generator, and a set of instrumented water collection pans arranged at the desired locations. Such apparatus have been used by fire sprinkler developers and approval laboratories.

Suppression of fires in certain arrays of solid combustibles by overhead water sprays has been investigated by measuring the water flux that must be delivered to the top surface of the array in order to achieve a lasting decay in the fire heat release rate. This measured fire suppression water flux is defined as the *required delivered density* (RDD).[13] The RDD is related to the critical water flux for fire extinguishment per unit combustible surface and the total combustible surface area for water exposure.[9] Suppression in this case can be achieved if the ADD is always greater than the RDD associated with a particular heat release rate growth and decay history. Figure 2.7.6 illustrates the ADD-RDD concept.[14] Prototype sprinklers F and M achieve fire suppression when the sprinkler is located directly over the fire source at about 2.7 m clearance, but prototype B does not. In this particular illustration, Sprinkler B's ADD drops below the RDD when the fire grows to 150,000 Btu/min (2640 kW). As a result, Sprinkler B cannot suppress the fire. The other two sprinklers suppress the fire because the corresponding ADD is always greater than the RDD before the fire intensity decreases.

When ADD is less than RDD, the fire will spread beyond its origin if the water flux applied to its surrounding area is not enough to sufficiently wet the combustibles outside the fire area. To control fire spread, an adequate PWD has to be applied. The lower the ADD, the greater is the fire intensity, so a higher PWD is required to stop or minimize fire spread beyond the fire origin.

For a fire hazard, a comparable fire damage area could result from different combinations of ADDs and PWDs. However, the higher ADD combination tends to provide a better overall fire control result, in terms of total amount of combustibles burned, building structure damage, smoke damage, and water damage.

In some cases—for example, a purely gaseous fire—water may extinguish the fire by cooling the flame rather than the source of the fuel vapor. The theory of this action has been discussed previously.

For a pool fire of a flammable liquid with a high flashpoint (e.g., diesel oil), water can be effective by reducing the temperature of the liquid below its flashpoint. However, water impinging on the flammable liquid with high velocity can cause burning liquid to be scattered, increasing the fire intensity. Water applied as a foam or as a fine mist avoids this situation.

EXTINGUISHMENT WITH AQUEOUS FOAMS

Also see Section 17, Chapter 4, "Foam Extinguishing Agents and Systems."

Aqueous Foams and Flammable Liquid Fires

Aqueous foam agents are principally used for fighting flammable liquid fires. If the flammable liquid is lighter than water and is insoluble in water, then application of water would simply result in the flammable liquid floating on it and continuing to burn. If the flammable liquid is an oil or fat, the temperature of which is substantially above the boiling point of water, then the water will penetrate the hot oil, turn into steam below the surface, and cause an eruption of oil that will accelerate the burning rate and possibly spread the fire. Foams are the primary tools for fighting fires that involve substantial quantities of petroleum products, such as those found at refineries, tankers, and storage areas.

If the flammable liquid is water soluble, such as alcohols, then the addition of sufficient water will dilute the liquid to the

point where it is no longer flammable. If there is a deep pool of water-soluble flammable liquid rather than a shallow spill, however, the time required to obtain sufficient dilution might be so great that an aqueous foam would be a better extinguishing agent. If the nature of a liquid is unknown, aqueous foam might be chosen instead of the direct application of water.

Another important application of aqueous foam agents is on liquids or solids that are burning in difficult-to-access spaces, such as a room in a basement or the hold of a ship. The foam is used to flood the compartment completely.

Characteristics of Fire-Fighting Foam

Fire-fighting foam is a mass of bubbles formed by various methods from aqueous solutions of specially formulated foaming agents. Because foam is much lighter than any flammable liquid, it floats on the liquid, producing an air-excluding, cooling, continuous layer of vapor-sealing, water-bearing material that can halt or prevent combustion.

Fire-fighting foams are formulated in several ways for fire-extinguishing action. Some foams are thick and viscous, forming tough heat-resistant blankets over burning liquid surfaces and vertical areas. Other foams are thinner and spread more rapidly. Some foams are capable of producing a vapor-sealing film of surface-active water solution on a liquid surface, and some are meant to be used as large volumes of wet gas cells for inundating surfaces and filling cavities. There are various methods for applying foams, which are fully described in Section 17.

The use of foam for fire protection requires attention to its general characteristics. Foam breaks down and vaporizes its water content when under attack by heat and flame. Therefore, it must be applied to a burning surface in sufficient volume and rate to compensate for this loss and to provide an additional amount to guarantee a residual foam layer over the extinguished portion of the burning liquid. Before starting to apply foam to a large fire, a sufficient amount of foam concentrate to do the job must be accumulated. Nothing will be accomplished by putting out only part of a fire and then running out of foam, because the fire will build back to its original intensity.

Foam is an unstable air-water emulsion and can be broken down easily by physical or mechanical forces. Certain chemical vapors or fluids can destroy foam quickly. When certain other extinguishing agents are used in conjunction with foam, severe breakdown of the foam can occur. Turbulent air or violently uprising combustion gases can divert light foam from the burning area.

There is no theoretical basis available to serve as a guide to the needed rates of application of the various types of foams in different situations. The guidelines come from experience or from empirical tests. One useful laboratory measure of foam effectiveness is to fill a graduated cylinder with foam and observe the time required for a certain fraction of the water in the cylinder to drain to the bottom. The more stable the foam, the slower it will drain.

Clearly, the time for collapse of a foam layer should be greater than the time required to coat the entire surface of a large spill with foam. Thus, a basis is available for calculating the necessary rate of application. Of course, fire causes foam to break down at a greater rate than indicated by the drain test in a cylinder; therefore, empirical information is still needed.

Another laboratory tool useful for formulating film-forming foams is the measurement of surface tension of the foam solution, F, the flammable liquid, L, and the interfacial tension between the two liquids, FL. The film will spread over the surface only if F plus L is greater than FL.

EXTINGUISHMENT WITH WATER MIST

There has been recent interest in developing equipment for applying a fine mist of water to a fire as an alternative to halogenated agents. The following three methods can be used to distribute water mist:

1. Fixed installation, in which a fine mist is used to inert a compartment in which a fire may occur, perhaps in a concealed and unpredictable location
2. Fixed spray nozzles positioned around or above the site of an anticipated fire
3. A portable extinguisher using a fine spray or mist

Application Mechanisms

Four mechanisms by which water mist application might extinguish a flame are as follows:

1. The mist droplets, while evaporating, remove heat, either at the surface of the combustible or within the gaseous flame. This cooling can cause extinguishment, as discussed previously.
2. The fine droplets evaporate in the hot environment even before reaching the flame, generating steam that dilutes the oxygen percentage in the air approaching the flame, thus causing extinguishment by a mechanism similar to that of an inert gas—for example, carbon dioxide.
3. The mist blocks radiative heat transfer between the fire and the combustible.
4. The induced gas current helps overall cooling and dilution and even blows off the flame from the burning surface.

In those tests in which mists have successfully extinguished fires, some combination of the above effects appears to have occurred in each case.

In regard to the first mechanism, it is much easier for a large drop to reach a burning surface than for a very fine drop (mist), which would tend to be blown away from the surface by the pyrolysis gases, if indeed fine droplets could get through the upward velocity of the fire plume to the vicinity of the underlying surface in the first place. This difficulty disappears when the fine mist is directed at the burning surface with high momentum.

It has been shown experimentally that as the droplet size decreases, less water flux is required to extinguish a flammable liquid pool fire, following the typical trend shown in Figure 2.7.7.[7,15] Qualitatively, the trend may be explained as follows. The smaller the droplets, the more readily they are vaporized to cool the fire gases and pool surface. As droplets become smaller, they more nearly follow the gas current. Therefore, when nozzles are pointed toward a flammable liquid pool, the propensity

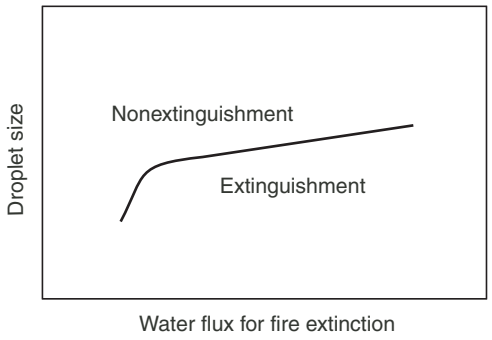

FIGURE 2.7.7 Typical Relationship Between Droplet Size and Required Water Flux for Fire Extinguishment for Non-Water-Soluble Flammable Liquids (Sources: D. J. Rasbash, "The Extinction of Fire with Plain Water: A Review," 1986[7]; M. M. Braidech, J. A. Neale, A. F. Matson, and R. E. Dufour, "The Mechanism of Extinguishment of Fire by Finely Divided Water," 1955.[15]

of droplets to splatter on or penetrate into the pool surface decreases as the drop size decreases. As a result, finer droplets have a lower tendency to cause sputtering on the pool surface and emulsification in a non-water-soluble pool. The pool surface sputtering, in turn, tends to produce flammable liquid droplets above the pool and thus makes the pool fire more difficult to extinguish. For a hot non-water-soluble flammable liquid pool whose temperature is much higher than 212°F (100°C), emulsification may also make fires more difficult to extinguish. The large temperature difference between the immersed droplets and the flammable liquid could initiate bubbling nucleation in the immersed water droplets; the burst of the bubbles as they rise in the pool releases fine flammable liquid droplets above the pool and results in more challenging fires. Consequently, higher water fluxes are required for larger droplets to compensate for the fire intensification.

In regard to cooling the flame gases rather than the burning surface, a sufficiently high concentration of water mist in the approaching air must be achieved. This is estimated to be at least 15 percent water mist by weight in air. This can be achieved if the mist is sprayed directly at the flame, but if the mist is sprayed in some random direction into a compartment, the buildup to a high concentration is hampered by the settling of some mist droplets to the floor of the compartment. Table 2.7.1 shows settling times of water droplets of various sizes.

The settling rate is negligible (assuming the goal is extinguishment in a few tens of seconds) for droplets finer than about 10 microns diameter. It is very difficult to produce droplets this fine with conventional atomization methods.[17] However, it is possible to produce mist in the 5 to 10 micron range with gas-assist nozzles by substituting steam for the air or inert gas conventionally used in this type of nozzle. Mawhinney et al.[18] classify mists as Class 1 sprays (at least 10 percent of the spray less than 100 microns) or Class 2 sprays (at least 10 percent of the spray less than 200 microns). The bulk of the droplets in sprays just meeting the Class 1 requirement settle out in a very few seconds, according to Table 2.7.1; thus, it is very difficult

TABLE 2.7.1 Settling Velocities of Water Droplets

Diameter (microns)	*Time (sec) to Settle 1 ft (0.305 m)*
5	391
10	99
20	25
50	4

Source: S. Friendlander, *Smoke, Dust, and Haze,* Wiley, New York, 1977.[16]

to build up an adequate concentration in the compartment for droplets in this range. Such mist spray classifications were adopted in the 1996 edition of NFPA 750, entitled *Standard for the Installation of Water Mist Fire Protection Systems.* However, the classifications were dropped in its 2000 edition.

The blockage of radiation by a mist will often be effective in reducing the intensity or spread rate of a fire, but will rarely be sufficient in itself to extinguish a fire.

Water mist sprays induce gas currents by transferring the droplet momentum to the surrounding gases. The gas currents help extinguishment by cooling the burning surfaces and diluting fuel vapor. The gas currents may be so strong that flames are displaced or even blown off from the burning surface. This mechanism is more pronounced for mist sprays produced with gas-assist atomizers than with single-fluid nozzles.

Water Mist Effectiveness

In summary, the effectiveness of a fine mist depends on (1) the momentum and direction of the spray relative to the fire, (2) droplet size, and (3) the compartment geometry and size and the size and location of openings. In general, for enclosure fires protected with total flooding water mist systems, the effectiveness of the water mist protection increases with increasing fire size and decreases with increasing enclosure and opening size. On the other hand, a fire in an open space becomes more difficult to extinguish as the fire becomes larger. Further discussion of water mists can be found in Mawhinney et al.[18] and the International Conference on Water Mist Fire Suppression Systems.[19]

See also Section 16, Chapter 8, "Water Mist Fire Suppression Systems."

EXTINGUISHMENT WITH INERT GASES

Extinguishment Mechanism of Inert Gases

Water acts to extinguish fires primarily by cooling, although the formation of steam helps to dilute the concentration of oxygen. On the other hand, inert gases act to extinguish a fire primarily by dilution. Carbon dioxide is the most commonly used inert gas, although nitrogen or steam could be used. Theoretically, helium, neon, or argon could be used, but they are expensive, and there is no reason to use them except in certain special cases, such as magnesium fires.

TABLE 2.7.2 Minimum Required Volume Ratios of Carbon Dioxide or Nitrogen to Air That Will Prevent Burning of Various Vapors at 77°F (25°C)

	Carbon Dioxide		Nitrogen	
Vapor	CO_2/Air	$\%\ O_2$	*Extra* N_2/Air	$\%\ O_2$
Carbon disulfide	1.59	8.1	3.00	5.2
Hydrogen	1.54	8.2	3.10	5.1
Ethylene	0.68	12.5	1.00	10.5
Ethyl ether	0.51	13.9	0.97	10.6
Ethanol	0.48	14.2	0.86	11.3
Propane	0.41	14.9	0.78	11.8
Acetone	0.41	14.9	0.75	12.0
n-Hexane	0.40	15.0	0.72	12.2
Benzene	0.40	15.0	0.82	11.5
Methane	0.33	15.7	0.63	12.9

Source: R. Friedman, *Principles of Fire Protection and Physics,* 3rd ed., 1998.[1]

Table 2.7.2 presents the minimum proportions of carbon dioxide or nitrogen gas that if added to air will form an atmosphere in which various vapors will not burn. On a volume basis, carbon dioxide is substantially more effective than nitrogen. Note, however, that a given volume of carbon dioxide is 1.57 times as heavy as nitrogen (44 to 28 molecular weight ratio), so the two gases have nearly equal effectiveness on a weight basis. Either gas in sufficient quantity will prevent the combustion of anything except certain metals or unstable chemicals such as pyrotechnics, solid rocket propellants, hydrazine, and so on.

If available, steam also can be used as an inert extinguishing agent. The percentage by volume required is intermediate between that required for carbon dioxide and for nitrogen.

Table 2.7.2 shows that the required addition of either carbon dioxide or nitrogen reduces the oxygen level to a point at which exposed humans will suffer undesirable effects. In the case of carbon dioxide, an additional serious physiological effect will occur at the concentrations required to extinguish a fire.

Table 2.7.2 refers only to vapors, but the data are relevant to liquids or solids because they burn only by vaporizing or pyrolyzing. Accordingly, application of an inert gas can extinguish the flame over a liquid or solid. However, if the inert gas dissipates after several minutes, because, for example, the enclosure is not airtight, it is possible that a glowing ember or hot metal could reignite the fire. Reignition is common for a deep-seated fire, such as what might occur in upholstered furniture or in a carton of documents.

Forms of Carbon Dioxide

Some explanation of the physical forms of carbon dioxide is appropriate. Carbon dioxide is unusual in that it can exist only as a gas or solid at normal atmospheric pressure, but not as a liquid. Figure 2.7.8 shows the phase diagram of carbon dioxide.

The solid form of carbon dioxide, commonly known as *dry ice,* at atmospheric pressure, exists only below –110°F (–79°C),

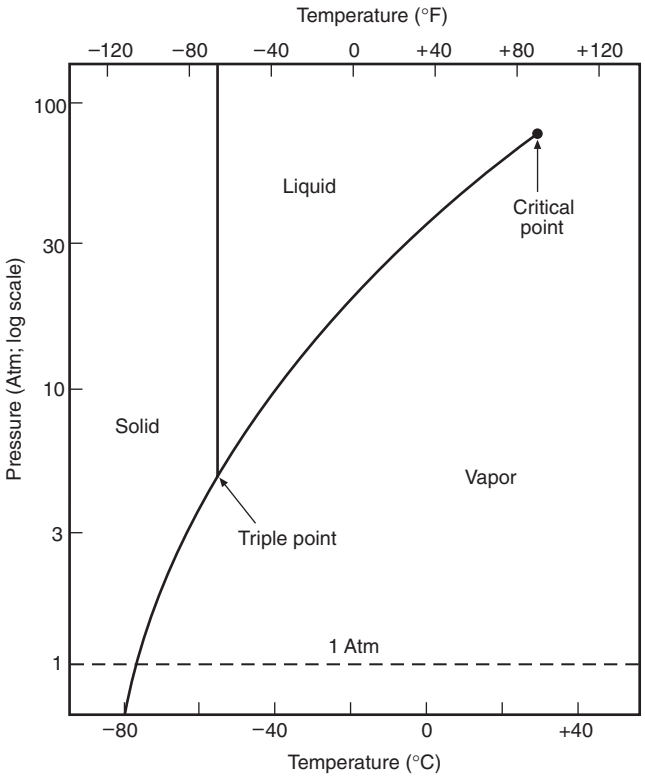

FIGURE 2.7.8 Phase Diagram of Carbon Dioxide

at which temperature it undergoes sublimation directly to vapor, without melting. However, liquid carbon dioxide can exist at elevated pressures, as long as the temperature is above –71°F (–57°C) and the pressure is above 5.2 atm. This temperature and pressure condition is known as the triple point of carbon dioxide because it is the only condition at which solid, liquid, and vapor can coexist.

Liquid carbon dioxide can be kept in a pressure vessel at any temperature between –71°F (–57°C) and 88°F (31°C) (the critical temperature). Above the critical temperature, there will no longer be a liquid-gas interface in the pressure vessel; therefore, the fluid in the vessel would be a gas. A pressure vessel at 70°F (21°C) containing liquid carbon dioxide would be at a pressure of 58 atm, which is the vapor pressure of carbon dioxide at that temperature. This pressure is used to expel liquid carbon dioxide from a cylinder in fire fighting. The cylinder normally would contain an internal dip tube reaching to the bottom so that liquid rather than vapor would be discharged. As the liquid droplets emerge from a nozzle into the lower-pressure environment, instantaneous evaporation occurs, with evaporative cooling of the residual liquid in each drop. This process causes solidification of the residual portion into dry ice particles at –110°F (–79°C). If the liquid was originally at 70°F (21°C), about 75 percent of the discharged liquid would have evaporated and about 25 percent would have been converted to dry ice particles.

Some of the dry ice particles might impinge on a combustible surface and have a cooling effect. However, because the heat of sublimation of carbon dioxide is only about one-fourth the heat

of vaporization of water and because only about one-fourth of the carbon dioxide discharged is converted to dry ice, the cooling effect on a hot surface is only about one-sixteenth that produced by water discharged at an equal rate (on a mass basis).

In comparing carbon dioxide and nitrogen, carbon dioxide has the advantage that it can be stored in a cylinder as a liquid at a relatively moderate pressure of 58 atm at 70°F (21°C), whereas nitrogen at the same temperature must be stored as a gas, usually at about 140 atm. A given size of cylinder at 70°F (21°C) and these pressures could hold about three times as large a volume of carbon dioxide as nitrogen (measured after expansion, at atmospheric conditions). Nitrogen also could be stored for short periods more compactly as a cryogenic liquid at –321°F (–196°C) and 1 atm. However, long-term storage results in continuous loss of nitrogen. As a result of these factors, carbon dioxide is used more commonly than nitrogen as an inerting gas.

Semipermeable membranes have been developed that can inexpensively separate the oxygen and nitrogen of the air. Such systems make it practical in certain cases to provide permanent nitrogen-inerting of hazardous spaces that do not require human presence. A reduction of the oxygen percentage in the air from 21 percent to 10 percent by volume would make fires and explosions impossible, except for a few special gases—for example, hydrogen, acetylene, or carbon disulfide, which would require greater dilution.

EXTINGUISHMENT WITH HALOCARBON AGENTS

Halocarbon agent extinguishing systems are a relatively recent innovation in fire protection, but despite this, the first generation of these agents no longer can be produced as of January 1, 1994, by international agreement due to the effect of these first-generation agents on depletion of the earth's ozone layer. As a result, a new generation of halocarbon agents has been developed that not only is compatible with the ozone layer but also less likely to be involved in global warming. For additional details on this topic, see Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems," and Section 17, Chapter 7, "Application of Gaseous Agents to Special Hazards Fire Protection."

Halocarbons are chemical derivatives of methane (CH_4) or ethane (CH_3-CH_3), in which some or all of the hydrogen atoms have been replaced with fluorine, chlorine, bromine, or iodine atoms, or by some combination of these halogen elements. These agents are liquids when stored in pressurized tanks at normal temperatures, but most of them are gases at atmospheric pressure and normal temperatures.

Halocarbon agents can be used for fire applications such as those discussed previously for carbon dioxide and other inert gases. For example, they can be used on electrical fires, in cases where water or dry chemicals would cause damage, or for inert-gas flooding of compartments.

Halogenated agents have the following two principal advantages over carbon dioxide:

1. Certain halogenated agents are effective in low volumetric concentrations such that sufficient oxygen remains in the air after compartment flooding for comfortable breathing.
2. For several halogenated agents, only partial vaporization occurs initially during flow from a nozzle, allowing the liquid to be projected farther than carbon dioxide.

The drawbacks of using even the new generation of halocarbon agents relate to agent toxicity and the toxicity and corrosivity of agent decomposition products during a fire.

Of the first-generation halocarbons, Halon 1301 (bromotrifluoromethane) was by far the most commonly used in fire protection because it has the lowest toxicity as well as the highest effectiveness on a weight basis, including the highest volatility, which is desirable for flooding applications. If a halocarbon liquid was needed for direct application to a burning surface to accomplish cooling as well as inerting of the nearby region, however, a less volatile compound, such as Halon 1211 (bromochloro-difluoromethane) or Halon 2402 (dibromotetrafluoroethane), was the first-generation agent preferred.

Physical Properties and Inerting Capabilities

Table 2.7.3 gives the physical properties of these three halocarbons. They are all liquids at normal temperatures when stored in pressurized tanks. They can be stored under high-pressure nitrogen if the liquid must be expelled from the tank more rapidly than under the vapor pressure of the halon alone. The use of nitrogen for pressurization is especially important for outdoor storage in the winter.

The inerting capabilities of Halon 1301 and Halon 1211 are shown in Table 2.7.4. If methane in any proportion is combined with a mixture containing 5.4 volumes of Halon 1301 and 100 volumes of air, at 77°F (25°C), then no combustion can result. By contrast, a mixture containing 33 volumes of carbon dioxide and 100 volumes of air is required to obtain the same result. This suggests that a molecule of Halon 1301 is 6.1 (33/5.4) times as effective as a molecule of carbon dioxide. Note, however, that the molecular weight of Halon 1301 is 149, whereas that of carbon dioxide is 44, so the ratio of molecular weights is 3.39 (149/44). Accordingly, on a weight basis, Halon 1301 is only 1.8 (6.1/3.39) times as effective as carbon dioxide for methane fires.

TABLE 2.7.3 Physical Properties and Chemical Formulas of Three Halon Extinguishing Agents

Property	*Halon 1301 (CF_3Br)*	*Halon 1211 (CF_2ClBr)*	*Halon 2402 (C_2F4Br_2)*
Boiling point (°C)	–58.00	–4.00	+47.00
Liquid density at 68°F (20°C) (g/cc)	1.57	1.83	2.17
Latent heat of vaporization (J/g)	117.00	134.00	105.00
Vapor pressure at 68°F (20°C) (atm)	14.50	2.50	0.46

TABLE 2.7.4 Minimum Required Volume Ratios of Halons to Air at 77°F (25°C) That Will Prevent Burning of Various Vapors

	Halon 1301		Halon 1211	
Vapor	*1301/air*	*% O_2*	*1211/air*	*% O_2*
Hydrogen	0.290	16.2	0.430	14.7
Carbon disulfide	0.150	18.2	—	—
Ethylene	0.130	18.5	0.114	18.8
Propane	0.073	19.5	0.065	19.7
n-Hexane	—	—	0.064	19.7
Ethyl ether	0.070	19.6	—	—
Acetone	0.059	19.8	0.054	19.9
Methane	0.054	19.9	0.062	19.7
Benzene	0.046	20.0	0.052	19.9
Ethanol	0.045	20.0	—	—

Source: Calculated from tabulations in J. M. Kuchta, "Investigation of Fire and Explosion Accidents in the Chemical, Mining, and Fuel-Related Industries—A Manual," 1985.[20]

Table 2.7.4 shows that the inerting proportion of halon needed varies somewhat, depending on the nature of the combustible, and substantially more halon is needed for hydrogen, carbon disulfide, or ethylene fires than for most other combustibles. Table 2.7.4 also shows that Halon 1301 and Halon 1211 have similar effectiveness on a volume basis for most combustibles.

Table 2.7.4 is based on experiments in which a strong ignition source is applied to a uniform combustible-air-halocarbon mixture, and the occurrence or nonoccurrence of a propagating flame is noted. A somewhat smaller quantity of halocarbon would be needed to cause an existing flame on a burner to become unstable and then extinguish itself; the quantity needed will depend on the details of the burner. A flame burning on a solid is even more easily extinguished. Grant[21] found that flames on most solids could be extinguished with 4 to 6 percent by volume of Halon 1301 in the surrounding atmosphere. Still, the discussion in the previous section about problems with extinguishment of deep-seated fires by carbon dioxide or nitrogen is equally valid when a halocarbon agent is used. Unless a sufficient quantity of the halocarbon in liquid form can reach the seat of the fire and cool all the solid sufficiently, reignition can occur after the agent has dissipated. If the halocarbon reaches the combustible as a gas by compartment flooding, then no such cooling can occur, and the effect of the gaseous agent is to extinguish the flame without affecting the pyrolysis or smoldering.

Table 2.7.4 also shows that the addition of Halon 1301 or 1211 needed in the air will only reduce the oxygen percentage from 21 percent to about 19 percent for most combustibles, whereas the required amount of carbon dioxide would have reduced the oxygen level to 14 percent or 15 percent. Furthermore, the physiological effects of carbon dioxide on humans at the concentrations needed for inerting are greater than those of Halon 1301.

Effectiveness of CF_3Br and CF_2ClBr

It would, of course, be highly desirable if chemists discovered a perfect, environmentally benign substitute for Halon 1301 or Halon 1211 that provided both fire protection and breathability qualities. Such a perfect substitute has not yet been found, but many second-generation agents have been developed with substantial fire protection effectiveness. In considering the possibility of discovering even more efficient chemical agents, a review follows of what is known about why the CF_3Br and CF_2C1Br molecules are so effective.

Figure 2.7.9 shows a methane-air flammability limit diagram as modified by various volumetric proportions of bromotrifluoromethane or carbon dioxide. The enormous difference is obvious. It has been established that carbon dioxide acts by absorbing heat and reducing the flame temperature from about 3452°F (1900°C) for a stoichiometric fuel-air mixture to about 2192 to 2372°F (1200 to 1300°C). Below these temperatures, most flames can no longer burn.

If nitrogen were added to a stoichiometric fuel-air mixture instead of carbon dioxide, a somewhat larger volume of inert agent would be needed because the heat capacity of the nitrogen molecule is less than that of the carbon dioxide molecule. Similarly, if argon were added—argon has an even lower heat capacity per molecule—an even larger volume of argon would be needed for inerting. In each case, the flame would go out when the temperature dropped below 2192 to 2372°F (1200 to 1300°C). However, if a small volume of bromotrifluoromethane were added to a flame, so that the temperature dropped to only about 2732°F (1500°C), the flame would be extinguished. Clearly, the mechanism is different.

The important chemical reactions in flames involve the free atoms H and O and the free radical OH, which undergo chain reactions with the fuel and oxygen. In particular, the branching chain reaction $H + O_2 \rightarrow OH + O$ is very important. It is believed that the CF_3Br molecule decomposes in the flame to form HBr, and HBr then acts to remove H atoms and OH radicals by the following two combustion reactions:

$$HBr + H \rightarrow H_2 + Br$$

and

$$HBr + OH \rightarrow H_2O + Br$$

HF and HCl cannot react as rapidly with H or OH as can HBr, so bromine appears to be essential to the inerting molecule. It has been found that hydrogen iodide, HI, is about as effective as HBr, but iodine is more expensive and heavier than bromine as well as quite toxic, and so iodine offers no advantage over bromine for flame extinguishment. In addition to the destruction of chain carriers, it has been speculated that a secondary contribution of halons to flame extinguishment comes from the extreme sootiness of halogen-containing flames. The more sooty or luminous the flame, the greater the radiative heat loss and the lower the temperature.

The role of fluorine in halocarbon agents is twofold. First, fluorine atoms replace hydrogen atoms in methane or ethane, thereby reducing the flammability of the inerting agent itself. Second, the toxicity of the agent is reduced. For example,

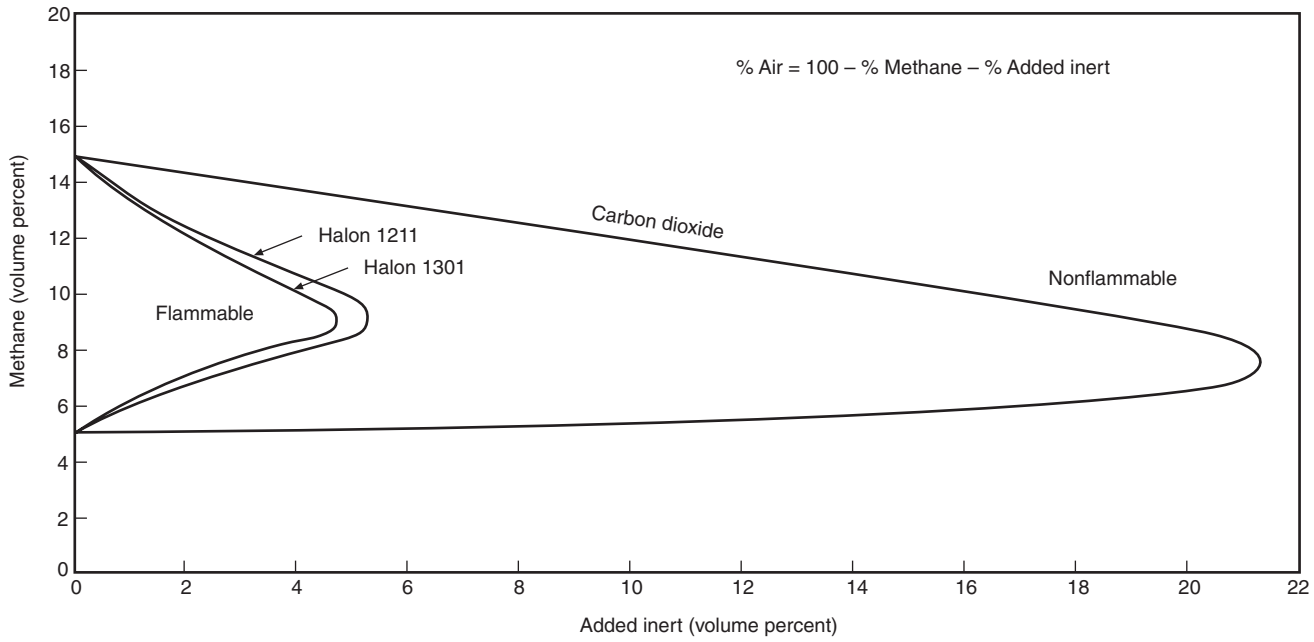

FIGURE 2.7.9 Flammability Limits for Methane-Air Mixtures with Added Inerting Agents (Source: J. M. Kuchta, "Investigation of Fire and Explosion Accidents in the Chemical, Mining, and Fuel-Related Industries—A Manual," *Bulletin 680,* 1985[20])

CH_3Br is much more toxic than CF_3Br, and, again, CH_2C1Br is much more toxic than CF_2C1Br.

EXTINGUISHMENT WITH DRY CHEMICAL AGENTS

See also Section 17, Chapter 2, "Chemical Extinguishing Agents and Application Systems."

Dry chemicals provide an alternative to carbon dioxide or the halons for extinguishing a fire without the use of water. These powders, which are 10 to 75 microns in size, are projected by an inert gas. Of the five types of dry chemicals in use, only one, monoammonium phosphate, is effective against deep-seated fires because of a glassy phosphoric acid coating that forms over the combustible surface. All forms of dry chemical act to suppress the flame of a fire. One reason that dry chemical agents other than monoammonium phosphate are popular is corrosion. Any chemical powder can produce some degree of corrosion or other damage, but monoammonium phosphate is acidic and corrodes more readily than other dry chemical agents, which are neutral or mildly alkaline. Furthermore, corrosion by other dry chemicals is stopped by a moderately dry atmosphere, whereas phosphoric acid, a product of decomposed monoammonium phosphate, has such a strong affinity for water that an exceedingly dry atmosphere would be needed to stop corrosion.

Application of any dry chemical agent on electrical fires is safe, from the viewpoint of electric shock, for fire fighters. However, these agents, especially monoammonium phosphate, can damage delicate electrical equipment. For the special case of kitchen fires involving hot cooking oil, monoammonium phosphate is not recommended because it does not create a foam layer (saponification) on the surface of the oil. An alkaline dry chemical, such as sodium bicarbonate, is preferred.

Table 2.7.5 lists the chemical names, formulas, and popular or commercial names of various dry chemical agents. In each case, the particles of powder are coated with an agent, such as zinc stearate or a silicone, to prevent caking and to promote free flowing. The effectiveness of any of these agents depends on the particle size: the smaller the particles, the less agent is needed, as long as particles are larger than a critical size.[22] The reason for this is believed to be that the agent must vaporize rapidly in the flame to be effective.[23] However, if an extremely fine agent were used, it would be difficult to disperse and apply to the fire.

It is difficult to compare precisely the effectiveness of one dry chemical with another because a comparison to reveal chemical differences would require that each agent have iden-

TABLE 2.7.5 Dry Chemical Agents

Chemical Name	*Formula*	*Popular Name(s)*
Sodium bicarbonate	$NaHCO_3$	Baking soda
Sodium chloride	NaCl	Common salt
Potassium bicarbonate	$KHCO_3$	"Purple K"
Potassium chloride	KCl	"Super K"
Potassium sulfide	K_2SO_4	"Karate Massiv"
Monoammonium phosphate	$(NH_4)H_2PO_4$	"ABC" or Multipurpose
Urea + potassium bicarbonate	$NH_2CONH_2 + KHCO_3$	"Monnex"

tical particle size, which is difficult to achieve. Furthermore, gaseous agents can be compared by studying the flammability limits of uniform mixtures at rest. If particles were present, however, they would settle out unless the mixtures were agitated, thus modifying the combustion behavior.

It seems clear that the effective powders act on a flame by some chemical mechanism, presumably forming volatile species that react with hydrogen atoms or hydroxyl radicals. However, the precise reactions have not been firmly established. Although the primary action is probably removal of active species, the powders also discourage combustion by absorbing heat; by blocking radiative energy transfer; and, in the case of monoammonium phosphate, by forming a surface coating. The potassium-bicarbonate-based agent, often referred to as "Purple K," is about twice as effective on a pound-per-pound basis as ordinary sodium-bicarbonate-based dry chemical.

SPECIAL CASES OF EXTINGUISHMENT

Metal Fires

Water is usually the wrong agent for fires involving metals because a number of metals can react exothermically with water to form hydrogen, which, of course, burns rapidly. Furthermore, violent steam explosions can result if water enters molten metal.[24] As an exception, extinguishment has been accomplished when large quantities of water were applied to small quantities of burning magnesium, in the absence of pools of molten magnesium.

Table 2.7.6 lists extinguishing agents used for various metal fires. In general, metal fires are difficult to extinguish because of the very high temperatures involved and the correspondingly long cooling times required. Note that certain metals react exothermically with nitrogen; therefore, the only acceptable inert gases for these metals are helium and argon. Halocarbons should not be used on metal fires.

TABLE 2.7.6 Extinguishing Agents for Metal Fires

Agent	*Main Ingredients*	*Used On*
Powders		
"Pyrene" G-1 or "MetalGuard"	Graphitized coke + organic phosphate	Mg, Al, U, Na, K
"Met-L-X"	$NaCl + Ca_3(PO_4)_2$	Na
Foundry flux	Mixed chlorides + fluorides	Mg
"Lith-X"	Graphite + additives	Li, Mg, Zr, Na
"Pyromet"	$(NH_4)_2H(PO_4)$ + NaCl	Na, Ca, Zr, Ti, Mg, Al
"T.E.C."	$KCl + NaCl + BaCl_2$	Mg, Na, K
Dry sand	SiO_2	Various
Sodium chloride	NaCl	Na, K
Soda ash	Na_2CO_3	Na, K
Lithium chloride	LiCl	Li
Zirconium silicate	$ZrSiO_4$	Li
Liquids		
"TMB"	Trimethoxyboroxine	Mg, Zr, Ti
Gases		
Boron trifluoride	BF_3	Mg
Boron trichloride	BCl_3	Mg
Helium	He	Any metal
Argon	Ar	Any metal
Nitrogen	N_2	Na, K

Source: A. S. Prokopovitsh, "Combustible Metal Agents and Application Techniques," *Fire Protection Handbook,* 16th ed., 1986.[24]

Chemical Fires

In addition to metals, certain inorganic chemicals are not compatible with water. For example, alkali and alkaline earth carbides, of which the best known is calcium carbide, react with water to form acetylene, which is highly flammable. Lithium hydride, sodium hydride, or lithium aluminum hydride react with water to produce hydrogen. Peroxides of sodium, potassium, barium, and strontium react exothermically with water. Cyanide salts react with acidified water to form a highly toxic gas, hydrogen cyanide. Even if these chemicals are not combustible themselves, they could be packed in combustible cartons and thus become involved in a fire or they could be stored in racks above combustible items.

Certain organic peroxides used as polymerization catalysts in plastics manufacturing are so unstable that they are stored under refrigeration to avoid exothermic heating. If water at normal room temperature were to be applied, it would provide heat to the peroxide and promote its exothermic decomposition.

A problem in applying water to fires involving toxic chemicals, such as pesticides, is associated with the runoff of contaminated water, which could cause groundwater pollution. In cases where no other agent but water is available or practical, the only alternatives might be to use the minimum quantity of water possible or to allow a building to burn, thus producing downwind air pollution if the fire does not completely destroy the toxic chemicals.

SUMMARY

The fundamentals of combustion science, which relate to fire extinguishment, are briefly reviewed and references are provided to more detailed treatments. Limits of flammability are discussed. Chemical chain reactions and the possibility of inhibiting these reactions are reviewed.

Details of how water extinguishes a fire or a burning solid are presented. The role of aqueous foams in fighting flammable liquid fires is discussed in terms of extinguishment mechanism. Discussion is provided of extinguishment by mists, by inert gases, by halocarbon agents, and by dry chemical agents. Metal fires and chemical fires are mentioned as examples of special extinguishment situations.

Reference is made to the textbook *Principles of Fire Protection Chemistry and Physics,* by R. Friedman, for more information.

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Chapter 8

Explosions

Robert Zalosh

Chapter Contents

Fundamental Explosion Principles
Types of Explosions

Key Terms

blast mitigation, blast wave, chemical reaction explosion, deflagration, detonation, dust explosion, energy release duration, explosion, peak pressure, projectile fragment, steam explosion, vapor cloud explosion, vapor explosion

The *Random House Dictionary of the English Language* defines *explosion* as a violent expansion or bursting with noise. The violent expansion is due to a sudden release of energy or an energy transformation that causes a region of high pressure and/or temperature, which propagates away from the source as a blast wave. Therefore, a more scientific definition for *explosion* would be *a sudden, rapid release of energy that produces potentially damaging pressures.*

One way to categorize various types of explosions is in terms of the energy source. Fire protection professionals are familiar with combustion energy sources that cause gas explosions and dust explosions when the fuel and air are premixed and confined before being ignited. Other energy sources that can be released or transformed rapidly enough to produce explosions include condensed phase explosives, chemical reactions other than combustion, nuclear energy, potential energy due to compression, and extremely rapid vaporization. This chapter discusses the fundamental nature of various types of explosions, beginning with a brief overview of the energies released and the associated peak pressures produced. A general discussion of blast waves and primary and secondary fragments is also provided.

See also Section 6, Chapter 15, "Explosives and Blasting Agents"; Section 6, Chapter 17, "Tables and Charts"; and Section 18, Chapter 6, "Deflagration (Explosion) Venting."

FUNDAMENTAL EXPLOSION PRINCIPLES

The amount of energy released determines the strength of the blast wave—that is, the pressure disturbance—at a given distance far away from the energy release site. The peak pressure (i.e., the maximum pressure) at the explosion site itself depends on the energy released per unit volume. However, a more complete understanding of both the damage potential and various explosion protection alternatives also requires knowledge of the approximate time duration of the energy release. Therefore, it is helpful to characterize the various types of explosions in terms of their peak pressures, energies, and energy release durations.

Peak Pressure, Energy, and Energy Release Duration

Figure 2.8.1 shows a very rough plot of the peak pressures and energy release durations in various types of explosions. Nuclear explosions release by far the greatest amount of energy per unit volume, and therefore generate the highest peak pressures, which are of the order of many millions of pounds per square inch (psi). This pressure is generated within a millionth of a second (microsecond) as the fission or fusion products and expanding bomb debris compress and heat the air at the release site.[1]

Condensed Phase Explosives. Commercial and military condensed phase explosives are usually divided into two categories: high explosives and low explosives. High explosives tend to detonate, that is, to have a reaction propagation speed greater than the speed of sound in the reacting material. High explosives can generate peak pressures in the range 10^4 to 10^6 psi (700 to 70,000 bar).

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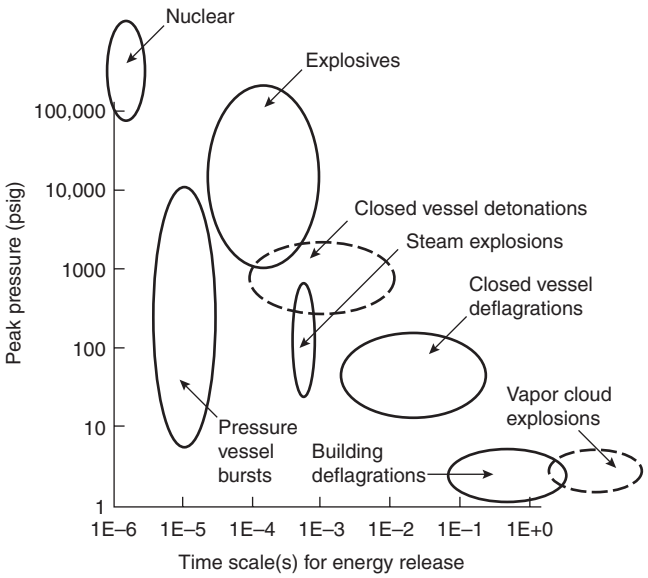

FIGURE 2.8.1 Peak Pressures and Energy Release Time Scales in Various Types of Explosions

The energy release time-scale for a high explosive is equal to the length of the explosive material divided by its detonation speed. For example, the detonation propagation speed of dynamite is approximately 16,000 ft/sec (4900 m/sec), so that a 1 ft (0.3 m) long stick would release its energy in 1/16th of a millisecond (ms). Detonation speeds for other high explosives are in the range of 2000 to 8200 m/sec.[2]

Low explosives tend to deflagrate, that is, to have a reaction propagation speed that is less than the speed of sound in the reacting material. The actual speeds can vary from hundreds of meters per second down to millimeters per hour.[3] Peak pressures produced by low explosives are orders of magnitude lower than those of high explosives.

The current UN/U.S. DOT classification system for explosives consists of six categories, depending on their propensity to detonate in their entirety, their susceptibility to accidental initiation, and whether they present projectile hazards, blast wave hazards, and/or fire hazards (NFPA 495, *Explosive Materials Code*). Standardized testing and classification procedures are described in 49 *CFR,* Parts 173.57 and 173.58. NFPA 495 also has tables of recommended separation distances of condensed phase explosive storage from inhabited buildings and roadways.

Energies released by condensed phase explosives and military weapons are often quoted in terms of the TNT (trinitrotoluene) equivalent weight. One kilogram of TNT has an explosive energy of 4.2×10^6 joules (J), so that one kiloton of TNT is equivalent to 4.2×10^6 kJ. Most condensed phase high explosives have an explosive energy per unit mass that is similar to that of TNT. For example, the explosive energy of pentolite (50/50) is 5.1×10^6 J/kg, and that of RDX is 5.4×10^6 J/kg. The corresponding TNT equivalent of pentolite is 5.1/4.2 = 1.2 kg-pentolite/kg-TNT, and that of RDX is 5.4/4.2 = 1.3 kg-RDX/kg-TNT.[2,4]

A burst pressure vessel releases its energy of compression in the time it takes for a crack to propagate sufficiently far to allow the metal shell to split open. This is typically on the order of 10 μsec. The peak pressure is approximately equal to the vessel pressure at the time of bursting, P_b. The isentropic expansion energy, E_{burst}, for an ideal gas released during the vessel burst is[4]

$$E_{burst} = \frac{(P_b - P_a)V}{\gamma - 1} \quad (1)$$

where

P_b = Vessel pressure at the time of bursting

P_a = Pressure of ambient air (1 atmosphere = 14.7 psia = 101 kPa at sea level)

V = Vessel volume

γ = Ratio of specific heats for the gas in the vessel ($\gamma = 1.4$ for air)

Using Equation 1, one can calculate the burst energy for a 10 m^3 vessel that ruptures when it is filled with air at a pressure of 1000 psia (6890 kPa). At sea level, $(P_b - P_a) = 6890 - 101 = 6789$ kPa. For a vessel filled with air, $(\gamma - 1) = 1.4 - 1 = 0.4$. Therefore, $E_{burst} = (6789 \times 10^3 \text{ Pa})(10^3)/0.4 = 172 \times 10^6$ J, which is equivalent to 172/4.2 = 41 kg (90 lb) of TNT.

Gas Explosions. Gas explosions can be either deflagrations or detonations, depending on whether the flame speed is less than or greater than sound speed in the unburned fuel-air mixture. (Sound speed is approximately equal to 335 m/sec if the fuel concentration is small compared to the air concentration.) Peak pressures and the form of the pressure-time loading are fundamentally different for deflagrations and detonations. Separate discussions of deflagrations and detonations are provided later in the chapter. For now, it is sufficient to say that the peak pressures generated in detonations are at least twice as large as those in deflagrations, and the time scale is often at least an order of magnitude smaller, as indicated in Figure 2.8.1.

Pressures generated in gas or dust deflagrations in buildings are often of the order of 1 psig because most building structures will fail at pressures of that order of magnitude. The structural failure, either planned (deflagration venting) or unplanned, releases the confined burned and unburned gases and usually prevents further pressure rise even though the fuel continues to burn. Deflagrations in process equipment often lead to higher pressures than in buildings because the equipment can withstand higher pressures prior to failure and because there is more likely to be a flammable mixture throughout the enclosure volume. The energy release time-scale is shown smaller for equipment than for buildings because the smaller volumes allow for more rapid rates of pressure rise.

Vapor Cloud Explosions. Vapor cloud explosions refer to external deflagrations of very large clouds of flammable gas or vapor in a highly obstructed or partially confined area. Peak pressures in vapor cloud explosions are of the same order of magnitude as those in building deflagrations, but the energy re-

lease times are usually longer because the flammable clouds are usually much larger than those that form inside buildings.

Blast Waves

Pressure disturbances propagating into the atmosphere away from the energy release region are called *blast waves.* The propagation of a blast wave that started as a detonation wave is shown in Figure 2.8.2 as a series of pressure versus distance profiles at six different times. In all six profiles, a shock wave (sudden discontinuous increase in pressure) occurs as the leading edge of the pressure wave, and the pressure decays behind the shock wave. As the blast wave propagates away from the energy release site, the amplitude of the shock wave decreases, and the time duration of the pressure disturbance increases. It eventually develops a characteristic N wave shape at time t_6, that is, in the far field at distances far from the explosion site.

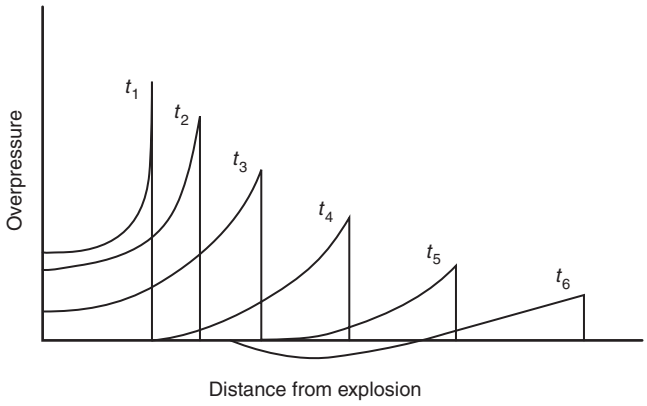

FIGURE 2.8.2 Blast Wave Propagation Away from Detonation Site

The parameters used to characterize far-field blast waves are identified in Figure 2.8.3. The shock wave amplitude is denoted as P_{s0}, and the area between the pressure curve and the ambient pressure, P_0, is called the specific impulse, i_s. Because there is a portion of the blast wave in which pressures are smaller than P_0, there is a positive specific impulse and a negative specific impulse. The blast wave damage and injury potential depends on the magnitudes of the shock pressure, P_{s0}, and the positive i_s. Various correlations and theoretical models of ideal blast waves (produced from instantaneous, point source releases of energy) have shown that P_{s0} can be correlated with an energy-scaled distance of the following form:

$$\frac{z}{E^{1/3}} \text{ or } \frac{z}{W_{\text{TNT}}^{1/3}}$$

where

z = Distance from the explosion site

E = Blast wave energy

W_{TNT} = The TNT equivalent weight for the same blast wave energy

Figure 2.8.4 shows the correlations between P_{s0} and $\frac{z}{W_{\text{TNT}}^{1/3}}$ and between i_s and $\frac{z}{W_{\text{TNT}}^{1/3}}$ (in ft/lb$^{1/3}$ or m/kg$^{1/3}$) for a condensed phase explosion at ground level.

Criteria for blast wave damage and injuries generally involve considerations of both pressure (P_{s0}) and impulse (i_s). However, at large distances from the explosion site, the impulse is usually large enough that structural damage depends primarily on P_{s0}. Table 2.8.1 shows the consequences of representative values for overpressure and the associated TNT equivalent-scaled distance.

The scaled distances in Table 2.8.1 were developed from correlations of explosions at various altitudes and from the incident blast wave pressures at the various types of targets listed

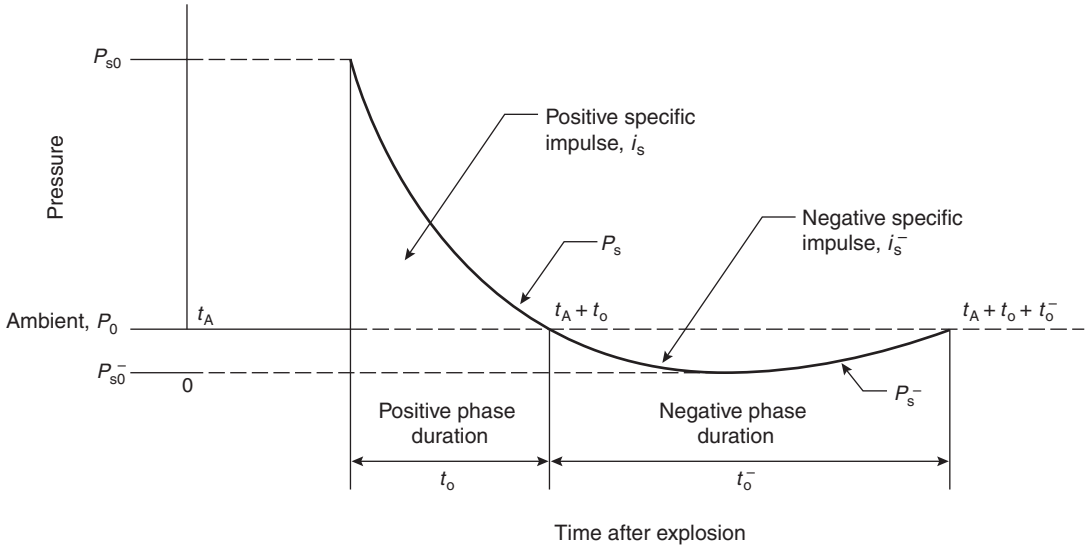

FIGURE 2.8.3 Pressure-Time Variation for a Far-Field Blast Wave (Source: U.S. Department of Defense[5])

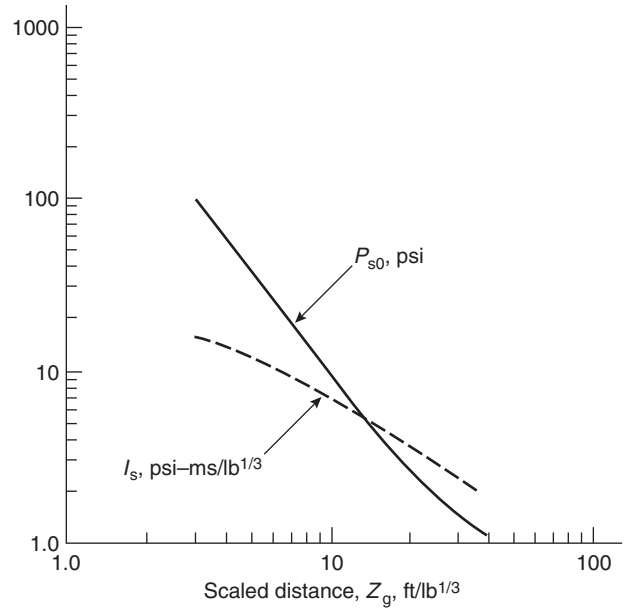

FIGURE 2.8.4 Decay of Blast Wave Pressure and Specific Impulse with Distance from Explosion Site (Source: U.S. Department of Defense[5])

in the table. One complication in using this data is that explosions at ground level produce hemispherically expanding blast waves, whereas elevated explosions produce spherically expanding blast waves that are reflected off the ground. The usual way of accounting for the reflection effect is to use double the blast wave energy when applying the correlations for spherically expanding blast waves to ground level explosions. This doubling of the blast wave energy would be needed in using the scaled distances in Table 2.8.1, whereas the correlations in Figure 2.8.4 do not need any corrections because they come directly from ground level explosions.

Consider the previous example of the 10 m^3 pressure vessel burst as an example of the how to use Table 2.8.1 and Figure 2.8.4. Suppose we want to find the distance from the vessel to the location at which P_{s0} would be 1 psig (6.9 kPa), in other words, to the blast wave distance at which personnel would be knocked down, windows shattered, and thin sheet metal panels buckled, according to Table 2.8.1. If we use the scaled distance in Table 2.8.1 of 44 ft/kg$^{1/3}$ (13.4 m/kg$^{1/3}$), the blast wave distance is calculated as follows:

$$(44 \text{ ft/kg}^{1/3})(2 \cdot 41 \text{ kg})^{1/3} = 191 \text{ ft}$$

If we use the correlation for P_{s0} in Figure 2.8.4 extrapolated slightly to 1 psig, the calculated distance is

$$(45 \text{ ft/lb}^{1/3})(90 \text{ lb})^{1/3} = 202 \text{ ft}$$

Thus, the distance would be approximately 200 ft (61 m) in both cases. However, if we are evaluating blast damage potential for a structural surface that directly faces the explosion, we would have to account for the reflected blast wave pressures. The ratio of reflected blast wave pressure to incident pressure is approximately 2 for values of P_{s0} less than about 2 psig. Thus, if the exposed persons and structures are facing the pressure vessel at the time of rupture, the corresponding effects could be experienced

TABLE 2.8.1 High Explosives Overpressure Consequences

Scaled Distance Z (ft/kg$^{1/3}$)	*Overpressure (psi)*	*Consequences*
3000–890	0.01–0.04	Minimum damage to glass panels
420–200	0.1–0.2	Typical window glass breakage
200–100	0.2–0.4	Minimum overpressure for debris and missile damage
82–41	0.5–1.1	Windows shattered, plaster cracked, minor damage to some buildings
44–32	1.0–1.5	Personnel knocked down
44–28	1.0–1.8	Panels of sheet metal buckled
44–24	1.0–2.2	Failure of wooden siding for conventional homes
28–20	1.8–2.9	Failure of walls constructed of concrete blocks or cinder blocks
20–16	2.9–4.4	Self-framing paneled buildings collapse
20–16	2.9–4.4	Oil storage tanks ruptured
16–12	4.4–7.3	Utility poles broken off
16–12	4.4–7.3	Serious damage to buildings with structural steel framework
11–10	10.2–11.6	Probable total destruction of most buildings
15–9	5.1–14.5	Eardrum rupture
14–11	5.8–8.7	Reinforced concrete structures severely damaged
14–11	5.8–8.7	Railroad cars overturned
6.7–4.5	29.0–72.5	Lung damage
3.8–2.7	102–218	Lethality
2.4–1.9	290–435	Crater formation in average soil

Note: 1 psi = 6.9 kPa.
Source: Kinney and Graham.[6]

at a value of P_{s0} as low as 0.5 psig, corresponding to a TNT-equivalent scaled distance of 82 ft/kg$^{1/3}$, as per Table 2.8.1.

Blast wave vulnerability assessments and incident investigation analyses often need to account for complications such as multiple and oblique shock wave reflections associated with building features, adjacent structures, and other effects of either a congested urban environment or uneven natural terrain. A wide variety of blast wave computer codes has been developed for these effects and for convenience in using even the simplified blast wave correlations. Although many of these computer codes have restricted distributions, some can be obtained commercially, and others can be accessed through the original code developers. For example, Luccioni et al. (2006) have described the use of one commercially available Computational Fluid Dynamics (CFD) code called AUTODYN-3D to conduct simulations of the blast wave generated in a blast attack in Buenos Aires. Clutter and Stahl (2004) describe the use of their special CFD code called Computational Explosion and Blast Assessment Model. Many other types of codes are listed on the U.S. Army Corps of Engineers software website: https://pdc.usace.army.mil/software. Code distribution restrictions, where applicable, are also described on this website. The National Academies 1995 report on Blast-Effects Mitigation Technology has an older compilation of computer codes used for blast assessment evaluations.

Primary and Secondary Fragments

Casualties from explosions are often caused by projectile fragments, either from the exploding container (primary fragments) or from structures damaged by the explosion blast wave (secondary fragments). Fragmentation of the exploding container depends on the type of container or explosive case, and is usually approached via statistical analysis of test and accident data. High explosives and weapons usually produce a large number of casing fragments, whereas burst pressure vessels produce relatively few, but larger, fragments.

Primary fragment statistical correlations for condensed phase explosives are described by Baker et al.[7] Calculations for burst pressure vessels involve first estimating the number and size of fragments and then using the results of projectile calculations to determine how far the fragments can fly. This procedure is explained in Baker et al.[7] and CCPS.[8]

Primary fragment projectile distances often determine the safe standoff distance for a pressure vessel exposed to a fire. Correlations shown in the *Guidelines for Consequence Analysis* and *Guidelines for Chemical Process Quantitative Risk Analysis* (1999) show approximately 80 percent of the fragments from LP-gas BLEVEs land within about 1000 ft (305 m) from the vessel; however, one fragment in a Mexico City incident traveled about 3000 ft (915 m). In the case of horizontal cylindrical vessels, more fragments are projected in the axial direction than in the lateral direction, but emergency responders need to be wary of the danger of fragments in all directions. Two volunteer firefighters in Iowa were killed in 1998 when they were about 100 ft (30.5 m) from the side of an LP-gas vessel that eventually failed as a BLEVE and projected fragments in all directions.[9]

Secondary fragment hazards have been documented and generalized through analyses of damage and casualties at major explosions. Oswald et al.[10] conducted such an analysis for five buildings damaged in the 1995 Oklahoma City bombing. The 4000 lb (1800 kg) ammonium nitrate fuel oil explosion in that incident had an estimated TNT equivalence of 3400 lb (1540 kg). Using data from that and other incidents, Oswald et al. developed a correlation for the percentage of building occupants that are expected to experience life-threatening injuries due to glass shard projectiles, building roof damage, and wall damage. Implementation of the Oswald et al. model requires calculations of blast wave impulse at the location of the exposed building as well as specifications of the type of building wall and roof construction. Hu and Chen (2006) have recently developed a new computer model to simulate the synergistic effects of blast and fragment loadings, but they acknowledge that additional experimental, analytical, and computational effort is needed before this type of model can be used for general blast load applications.

Blast Mitigation Technology

In 1997, the U.S. Department of Defense (DOD) initiated a Blast Mitigation for Structures Program aimed at improving the technology for protecting people within civilian and military buildings from bomb blast attacks. Similar efforts are underway in several other countries. These programs have led to an assortment of blast mitigation technology that has been tested and commercialized recently. Although many of the new products involve blast-resistant construction for new buildings, some of the new products are intended as retrofits for existing buildings and structures. A database for the various products is available at the following DOD website: https://bmag.usace.army.mil/index.php.

Examples of the new blast-resistant construction products include shock absorbing walls, blast-resistant cladding panels, and spray-on polymers for interior wall surfaces, blast-resistant wraps, and blast-resistant fences. One example of a blast-resistant foam cladding is honeycombed layered sacrificial metallic foam that can absorb large amounts of blast energy via plastic deformation. Ma and Ye (2006) have recently developed an analytical model to assess the ability of the cladding and protected structure to withstand the combined blast peak pressure and impulse loads. One example of a blast-resistant wrap is a sandwich of blast-resistant filler material such as glass beads between two laminated films. The wraps are intended to be used either as wall or ceiling linings, as a suspended free-standing barrier, or as a wrap for containers. The spray-on polymers for interior wall surfaces can contain or mitigate wall fragments resulting from blast loadings. An analogous product is shatter-resistant-window-film to contain glass window fragments. Both the spray-on polymers and the shatter-resistant-window-films can be applied in varying thicknesses to achieve varying levels of blast resistance.

DOD test facilities have been used to evaluate the effectiveness of these and other new blast mitigation products. Their effectiveness is sometimes expressed in terms of a reduced standoff distance between the target structure and an explosive with specified blast energy. For example, recent tests with one readily available type of spray-on polymer have shown that the standoff distance to achieve either no damage or only slight

damage can be reduced in half over a wide range of blast energies. A recent National Academy of Science panel report (2003) on implementation of the new blast mitigation technology has provided seven recommendations for improved transfer of the new technology to the civilian sector. One recommendation is to gear the technology transfer effort toward products and methods that can achieve protection against multiple hazards such as fire and extreme winds, as well as blast effects.

TYPES OF EXPLOSIONS

Flammable Gas and Vapor Deflagrations

Ignition of a gas-air mixture usually results in a deflagration; that is, a flame propagation at subsonic speed away from the ignition site. The pressure developed in the enclosure depends on the extent of flame propagation, the temperature and composition of the burned gas, and the size and location of any vent area. If the flame has propagated throughout an unvented enclosure, the ratio of the deflagration pressure to the initial pressure in the enclosure can be obtained from the ideal gas equation as it applies to the postdeflagration and predeflagration gas-air mixtures, both of which occupy the same enclosure volume. Thus,

$$\frac{P_m}{P_0} = \frac{n_b T_b}{n_0 T_0} \tag{2}$$

where

P_m = Pressure developed at the completion of a closed vessel deflagration

P_0 = Initial pressure in the enclosure

n_b = Number of moles of burned gas at the completion of the deflagration

n_0 = Number of moles of gas-air mixture initially in the enclosure

T_b = Temperature of the burned gas at the completion of the deflagration

T_0 = Initial temperature of the gas-air mixture

Conservative estimates of burned gas temperature and composition can be obtained using the assumption that there is no heat loss from the flame to the enclosure walls. Assuming there is no heat loss or venting, various computer codes are available to calculate the burned gas temperature, composition, and pressure at the completion of the deflagration. Calculations obtained with the STANJAN code are shown in Figure 2.8.5 for the closed vessel deflagration pressures for methane-air, propane-air, and hydrogen-air mixtures of varying concentration. The fuel concentration used in Figure 2.8.5 is the equivalence ratio, defined as the fuel-to-air ratio divided by the stoichiometric fuel-to-air ratio. In terms of the fuel volume fraction, x, the equivalence ratio is equal to $\frac{x(1-x_{st})}{x_{st}(1-x)}$ where x_{st} is the stoichiometric volume fraction of fuel. The stoichiometric fuel volume fraction for methane-air is 0.095, for propane-air 0.040, and for hydrogen-air 0.296. The maximum pressures for each flammable gas occur at fuel equivalence ratios in the range 1.1 to 1.2, that is, at slightly richer than stoichiometric concentrations. These worst-case deflagration pressures are in the range of 8 to 9.6 atm absolute (118 to 140 psia) for an initial pressure of 1 atm, that is, the ratio P_m/P_0 is 8 to 9.6. Experimental measurements of closed vessel deflagration pressures agree well with the theoretical values of P_m at near-stoichiometric concentrations, but are significantly less than the theoretical values at concentrations near the lower and upper flammable limits because of incomplete flame propagation and heat losses for marginally flammable mixtures.

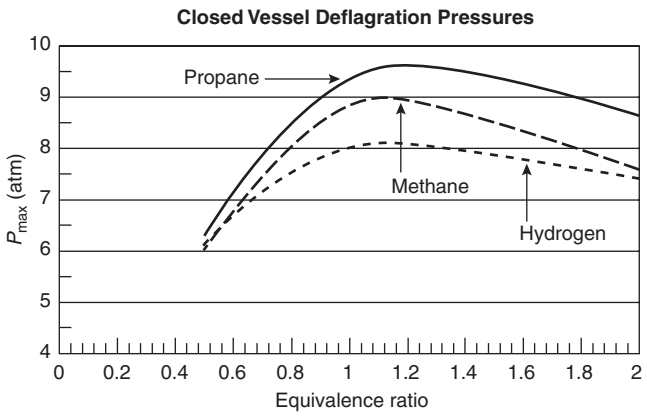

FIGURE 2.8.5 Calculated Adiabatic, Constant Volume Pressures as a Function of Equivalence Ratio

Similar P_m/P_0 pressure ratios occur for closed-vessel deflagrations initiated at other initial pressures. One example of a deflagration initiated at a lower initial pressure is the Center Wing Tank explosion that occurred during the TWA 800 flight on July 17, 1996. The flammable vapor in the Center Wing Tank of the Boeing 747 on that flight came from a small quantity of Jet A fuel in the tank. Although the composition of Jet A is complicated, many of the volatile constituents have flame temperatures and deflagration pressures similar to those of methane and propane. As the fuel was heated from air conditioning equipment under the Center Wing Tank, and the partial pressure of tank air was reduced as the Boeing 747 climbed after takeoff, the fuel-air equivalence ratio increased well into the flammable range. Ignition occurred at an altitude of 14,000 ft (4300 m), at which the ambient pressure is 0.585 bar (8.6 psia). A deflagration pressure ratio of 6 at that initial pressure would correspond to a P_m of 6 (8.6 psia) = 52 psia, and $P_m - P_0 = 43$ psi (3.0 bar). This pressure difference was significantly higher than the strength of the Center Wing Tank structures, leading to a massive breakup of the Boeing 747.

The rate of pressure rise in a gas or vapor deflagration is a crucial factor in determining the effectiveness of protection measures such as deflagration venting and suppression. Flame speeds, enclosure volume, and the value of P_m are the primary parameters governing the rate of pressure rise. Theoretical models described in the chapter on explosion protection of the *SFPE Handbook of Fire Protection Engineering*[11] allow the transient pressure rise to be calculated for any gas-air mixture with a known burning velocity (rate of flame propagation rela-

tive to the unburned gas velocity). Calculated pressure histories for three different sets of conditions are shown in Figure 2.8.6. During the early stages of the deflagration, the pressure rise varies as $(S_u t/a)^3$ where S_u is the mixture burning velocity and a is the radius of a sphere with the same volume as the enclosure. The burning velocities of 45 cm/sec and 300 cm/sec used for the calculations represent laminar burning velocities for near-stoichiometric propane-air mixtures and hydrogen-air mixtures, respectively. Flame speeds are often significantly higher than the burning velocities because they include the velocity of the unburned gas as it is compressed by the expanding burned gases behind the flame front.

The curve in Figure 2.8.6 for a 1-m-radius enclosure containing a gas-air mixture with a burning velocity of 45 cm/sec shows the pressure rising to 2 psig (0.14 bar) in about 0.2 second. If the damage threshold for the enclosure is 2 psig (0.14 bar), deflagration venting or suppression would have to be actuated within 0.2 second of ignition to prevent damage in this case. The pressure developed in a vented or suppressed deflagration is denoted by P_{red}. Methods and guidelines for determining P_{red} are discussed elsewhere in this Handbook, and in NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* and NFPA 69, *Standard on Explosion Prevention Systems.*

If the deflagration pressure causes the enclosure to open (because of either deflagration venting or structural failure), a blast wave will exert pressure loads on adjacent structures. Blast waves emitted from vented deflagrations are very different than those discussed earlier from condensed phase explosives and burst pressure vessels. The blast wave energy is difficult to define and locate because the combustion energy is released both inside and outside the enclosure. Correlations discussed by Forcier and Zalosh[12] indicate that the blast wave pressure is proportional to P_{red}/d where d is the line-of-sight distance from the enclosure vent.

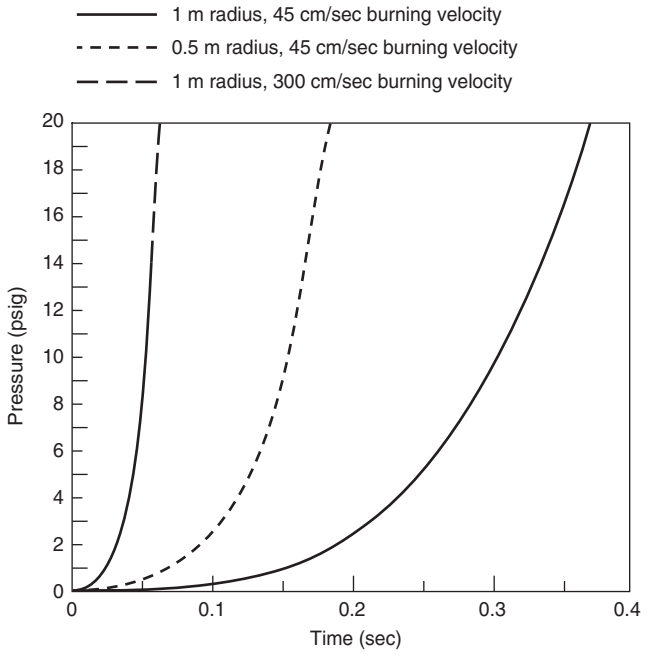

FIGURE 2.8.6 Calculated Pressure Versus Time During the Early Stages of Three Different Deflagrations

Flammable gas or vapor deflagrations that may occur within irregular or obstructed enclosures produce more highly accelerated and distorted flame propagation patterns. Calculations of transient pressure loadings in these complicated applications are often conducted with special CFD codes containing algorithms to simulate the turbulent combustion chemistry that is coupled to the flow field. FLACS is an example of a computer code that was developed precisely for this type of application.

Gas Detonations

A detonation is an explosion in which the flame propagates at supersonic speeds through the unburned fuel. Detonations are fundamentally different from the closed vessel deflagrations described in the previous section of this chapter. As flames in a deflagration propagate at speeds well below the speed of sound, whereas pressure disturbances propagate at sound speed, the pressure increase during a deflagration occurs virtually uniformly throughout the enclosure as the explosion evolves. In contrast, the pressure rise during a detonation is highly nonuniform and occurs virtually instantaneously as the shock wave propagates through the gas-air mixture. If the flame speed is slightly less than the speed of sound, such that the pressure rise is nonuniform but shock waves do not occur, the explosion is called a quasi-detonation.

The practical significance of this fundamental difference between detonations and deflagrations is that they require different approaches to explosion protection. The sudden, spatially nonuniform pressure rise during a detonation or quasi-detonation precludes the use of explosion venting or explosion suppression systems. Furthermore, the high-peak, short-duration detonative pressure loads warrant special considerations in the evaluation of structural resistance. Methods for designing and analyzing detonation resistant structures are discussed in *Structures to Resist the Effects of Accidental Explosions.*[5]

Peak pressure during a detonation can be calculated from the classical Chapman-Jouguet theory, which is a combination of thermochemical equilibrium and gas dynamic conservation equations across the detonation front. Figure 2.8.7 shows calculated detonation pressures as a function of fuel concentration for seven different flammable gases. A good approximation to the Chapman-Jouguet detonation pressure, P_{CJ}, is $P_{CJ} = 2P_m$, that is, twice the closed vessel deflagration pressure. This approximation represents a much simpler alternative to the Chapman-Jouguet theory of calculating detonation pressures. As indicated in Figure 2.8.7, P_{CJ} for a near-stoichiometric gas-air mixture initially at atmospheric pressure is in the range 16 to 20 atmospheres.

The different pressure loads during deflagrations and detonations produce characteristically different structural failure modes on equipment and structures. The slower pressure loadings in deflagrations usually cause ductile metals to fail by bulging out and stretching. The rapid impulsive loads in detonations often cause sharp fractures of metal, plastic, and wood structures. Photographs of the detonation fracture patterns on

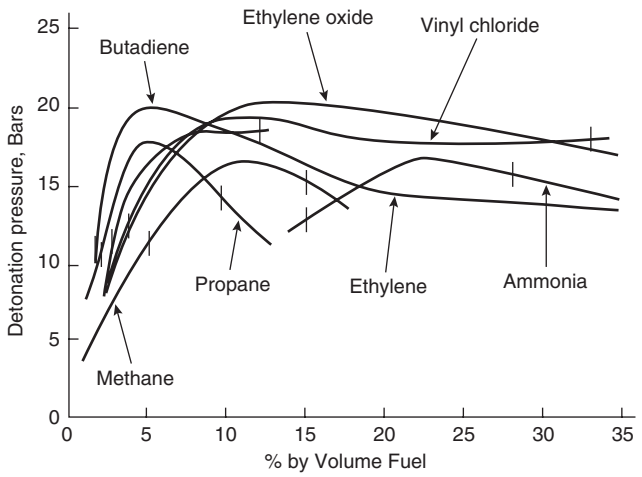

FIGURE 2.8.7 Calculated Chapman-Jouguet Detonation Pressures

the fragments of a large reactor vessel are included in the Jacobs et al. paper describing the detonation that destroyed a large petroleum refining unit in Indiana.[13]

What is the likelihood of a detonation occurring rather than a deflagration? Most accidental explosions are deflagrations. However, detonations can occur in very flammable gas mixtures if there is an exceptionally strong or large ignition source (flame jet ignition, for example), a highly elongated or obstructed geometry, or an exceptionally high level of turbulence to promote flame acceleration.

In the case of a weak (typical accidental) ignition source in a pipe or some other elongated enclosure, the deflagration-to-detonation transition (DDT) distance depends on the following parameters:

- *Mixture reactivity (burning velocity).* The more reactive the mixture, the more rapid the flame acceleration to DDT.
- *Enclosure or pipe wall roughness and the presence of obstruction.* The rougher the pipe interior surface or the more obstructions present, the shorter the transition length to DDT.
- *Enclosure or pipe diameter.* The larger the enclosure or pipe diameter, the shorter the transition to DDT.
- *Initial pressure and temperature.* The higher the initial temperature and pressure, the shorter the transition length to DDT.
- *Initial turbulence level.* The more turbulence or initial gas velocity in the enclosure, the shorter the DDT transition length.

In the absence of any obstructions and initial turbulence, data reviewed in Zalosh[11] indicate that length-to-diameter ratios greater than 100 are needed for DDT in most hydrocarbon-air mixtures. Thus, detonations are much more likely to occur in large piping systems rather than in building explosions or process vessel explosions. This demonstrates the importance of preventing long propagation lengths by using the various deflagration isolation systems described in NFPA 69.

Combustible Dust Deflagrations

Clouds of combustible dust in an enclosure also produce deflagrations when they are ignited while the dust concentration is greater than the minimum explosive concentration (MEC) for a particular material. The MEC depends on dust particle size as well as material composition, with smaller particles having smaller MECs than larger particles have. Typical lower explosive limits for dusts with characteristic particle sizes less than about are in the 30–60 g/m^3 range. Some examples for representative dusts and particle sizes are shown in Table 2.8.2.[14]

The other parameters shown in Table 2.8.2 are the maximum deflagration pressure in a closed vessel, P_{max}, and the K_{st} parameter defined as follows:

$$K_{st} = \left(\frac{dP}{dt}\right)_{max} V^{1/3} \tag{3}$$

where

$(dP/dt)_{max}$ = Maximum rate-of-pressure rise measured in a test vessel of volume V

Laboratory tests are usually conducted in a 20 L spherical vessel per the ASTM E1226 standard. The magnitude of K_{st} depends on the dust reactivity, the particle size, and the level of turbulence used to generate the dust cloud. Higher turbulence levels produce higher rates of pressure rise. The larger the K_{st} value, the more difficult it is to achieve effective deflagration venting or suppression. Thus, K_{st} for dusts plays a similar role as the burning velocity, S_u does for flammable gases.

Dust cloud concentrations above the MEC values are experienced routinely in process equipment such as dust collectors, blenders, dryers, pulverizers/grinders, conveying systems, and silos/bunkers. Tabulations of dust explosions in Germany from 1965 to 1985 indicate that 78 percent of all dust explosions originate in this equipment. Ignition sources that have occurred in dust explosions in Germany and in U.S. grain elevator explosions are shown in Table 2.8.3. The most frequent ignition source reported in the German dust explosions is mechanical sparks—presumably impact or friction sparks. Impact sparks are often attributable to tramp metal in either conveying systems or pulverizers/grinders. The most frequent ignition source in U.S. grain elevator explosions investigated by Kauffman[15] is mechanical heating/friction of belt drives in bucket elevators. Electrostatic discharges have been responsible for initiating explosions of dusts and powders, such as tantalum, with high resistivities and low ignition energies.[16] Guidance on eliminating these dust explosion ignition sources is provided in NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids.*

Most of the damage and casualties in destructive dust explosions occurs as a result of secondary explosions. A secondary dust explosion is caused by dust layers on floors, equipment, and structures being dispersed by the blast wave of the primary explosion, and then being ignited by the flame emitted from the primary explosion. This process, illustrated in Figure 2.8.8, is particularly destructive when it occurs in confined and occupied areas. Accounts of 14 grain dust explosions investigated in Kauffman[15] indicate that 17 of 20 fatalities, 58 of 65 injuries,

TABLE 2.8.2 Explosibility Data for Representative Powders and Dusts

Material	*Median Particle Size (μm)*	*Minimum Explosive Concentration (g/m^3)*	P_{max} *(bar g)*	K_{ST} *(bar-m/s)*
Activated carbon	18	60	8.8	44
Aluminum	<10	60	11.2	515
Ascorbic acid	39	60	9.0	111
Calcium stearate	<10	30	9.2	99
Coal, bituminous (high volatility)	4	60	9.1	59
Corn starch	<10	—	10.2	128
Epoxy resin	26	30	7.9	129
Fructose	200	60	7.0	28
Methyl cellulose	37	30	10.1	209
Milk powder	165	60	8.1	90
Napthalene	95	15	8.5	178
Paper tissue dust	54	30	8.6	52
Phenolic resin	<10	15	9.3	129
Polyethylene, l.d.	<10	30*	8.0	156
Polyethylene, l.d.	150	125	7.4	54
Polyvinylchloride	25	125	8.2	42
Rubber	80	30	8.5	138
Silicon	<10	125	10.2	126
Sugar	10	60	8.3	75
Zinc	<10	250	6.7	125

*This value was measured in a 1.2 L vessel; all other values were measured in either a 20 L vessel or a 1 m^3 vessel.
Source: *Dust Explosions in the Process Industries,* by Rolf K. Eckhoff. Reprinted by permission of Butterworth-Heinemann.

TABLE 2.8.3 Ignition Sources in Dust Explosions

Ignition Source	*Percentage of Dust Explosions in Germany*[a]	*Percentage of Dust Explosions in U.S. Grain Elevators*[b]
Mechanical sparks	26.2	4.6
Smoldering nests	11.3	13.6
Mechanical heating, friction	9.0	22.7
Electrostatic discharges	8.7	0
Fire	7.8	9.1
Spontaneous ignition	4.9	0
Hot surfaces	4.9	9.1
Cutting/welding	4.9	6.8
Electrical equipment	2.8	15.9
Unknown/Others	19.5	18.2[c]

[a]Based on Table 1.7 of Eckhoff.[14]
[b]Based on data reported in Kauffman.[15]
[c]Includes 13.6 percent gas explosion initial events.

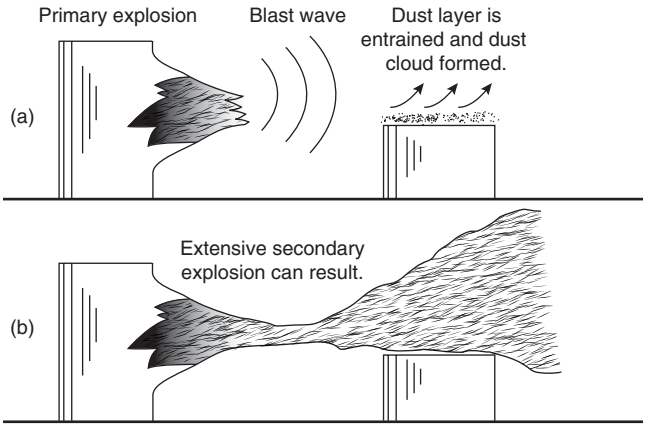

FIGURE 2.8.8 Secondary Dust Explosion Schematic (Source: Eckhoff[14])

and $36 million of the $37 million in property damage were due to the secondary explosions in these incidents. Prevention of these secondary explosions requires using effective protection measures for the primary explosion *and* minimizing dust accumulations in surrounding areas. However, this is a major challenge because dust layers as thin as 1 mm can generate an average dust cloud concentration of 100 g/m^3 (above the MEC for most combustible dusts) when dispersed throughout a 5-m-high room.[14] Partial dispersal over a lesser height can generate a still larger concentration, with correspondingly increased damage potential.

Chemical Reaction Explosions

Uncontrolled chemical reactions can cause explosions in two ways. First, they can produce gaseous reaction products that can overpressurize vessels that are not equipped with an adequate relief vent area. Second, runaway exothermic reactions can generate sufficient heat to increase rapidly the pressure of the existing gases and vapors in the vessel and possibly vaporize other materials.

Fire protection personnel are familiar with hydrocarbon combustion reactions, which produce carbon dioxide and water vapor as complete reaction products. There are also several other types of generic chemical reactions that can occur as fast as or faster than hydrocarbon combustion reactions at elevated temperatures, and can also produce multiple gaseous reaction products. These reactions include decompositions and polymerizations of inherently unstable compounds, rapid oxidation-reductions, nitrations, diazotizations (formation of a salt containing two nitrogen atoms and an aromatic hydrocarbon group), and hydration of water-reactive materials. Several of these reactions are autocatalytic in the sense that reaction products catalyze the reaction of the remaining reactants.

Examples of chemical reaction explosions are shown in Table 2.8.4.

The last two incidents in Table 2.8.4 have some remarkable similarities. They were both multiple fatality incidents caused by the detonative decomposition of hydroxylamine (NH_2OH). In both cases, the aqueous solution hydroxylamine concentration was significantly higher than the normal recommended practice (< 50% HA). Laboratory tests have shown that these high concentrations, together with trace contaminants, can lead to particularly violent decomposition reactions, often in the form of a detonation.

How can chemists and regulatory authorities recognize the potential for chemical reaction explosions and take appropriate actions to prevent them? The AIChE Center for Chemical Process Safety has published guidelines[23,24] to answer this question. These guidelines call for a combination of the following:

1. Reviewing lists of unstable materials[25] and potentially dangerous reactive combinations of materials
2. Using software to help identify incompatible chemicals[26] and to characterize the reaction energy associated with unstable chemicals[27]
3. Conducting reactivity laboratory screening tests to determine reaction onset temperatures, concentrations, and sensitivities
4. Having experts review the material storage/handling/processing conditions and results of screening tests, literature review, and software calculations

Additional guidelines are being developed by the Reactivity Management Roundtable under the aegis of the Center for Chemical Process Safety.

The design of process controls and emergency vents to accommodate these hazardous reactions requires scale-up calculations based on the reaction chemistry, material thermodynamic properties, expected heat transfer rates, and the possible presence of two-phase vent flow regimes.[28] After the design is completed, on-site audits are necessary in view of the reported poor record of many facilities in properly installing and maintaining pressure relief devices.[29]

TABLE 2.8.4 Examples of Chemical Reaction Explosions

Date	*Location*	*Chemicals*	*Cause of Accident*	*Casualties*	*Reference*
March 11, 1997	Tokai, Japan	Asphalt, sodium nitrate, sodium nitrite, sodium carbonate, and sodium bicarbonate	Excessive concentration of sodium bicarbonate lowered the reaction onset temperature	37 people received some radioactive contamination	Hasegawa and Li[17]
March 26, 1997	Haskell, Oklahoma	Printing ink solvents and oxidizers	Mixing of incompatible chemicals	1 fatality, 2 injuries	EPA[18]
April 8, 1998	Patterson, New Jersey	Ortho-nitrochlorobenzene, 2-ethylhexylamine	Delayed cooling of reactor, inadequate emergency vent	9 injuries	Chemical Safety Board[19]
October 13, 1998	South Baltimore, Maryland	Powdered aluminum, aluminum chloride, and water	Excessive steam addition rate produced uncontrolled reaction with aluminum.	5 injuries	Chemical Safety Board[20]
February 19, 1999	Hanover Township, Pennsylvania	Hydroxylamine	Excessive concentration of unstable material	5 fatalities, 14 injuries	Chemical Safety Board[21]
June 10, 2000	Gunma, Japan	Hydroxylamine	Excessive concentration of unstable material, high concentration of iron from coated steel tube	4 fatalities, 58 injuries	Tamura[22]

Steam Explosions: Melt-Water Explosive Interactions

A steam explosion is a physical explosion caused by the extremely rapid vaporization of water due to heat transfer from a second liquid that is at a temperature far in excess of the water boiling point and in direct contact with the water. As the second liquid is usually either molten metal or some other melt, a steam explosion is a violent melt-water interaction. If the water is replaced with some other liquid that has a much lower boiling point than the hot liquid, the more general term is *vapor explosion.*

Steam explosions occur only if certain thermodynamic and hydrodynamic conditions are satisfied. The thermodynamic condition is that the liquid–liquid contact surface temperature, T_{con}, must be greater than the spontaneous nucleation temperature, T_{sn}, for water, that is, the temperature at which vapor bubbles first appear in the absence of any heated surfaces. The equation for T_{con} follows:[30]

$$T_{con} = \frac{T_H + T_C \sqrt{(k\rho c)_c/(k\rho c)_H}}{1 + \sqrt{(k\rho c)_c/(k\rho c)_H}} \qquad (4)$$

where

T_H = Hot liquid temperature

T_C = Cold liquid temperature

$k\rho c$ = Product of thermal conductivity, density, and specific heat for either the hot liquid or cold liquid, depending on the subscript

For example, if molten copper at a temperature of 1400°C is immersed in 20°C water, the interfacial contact temperature as per Equation 4 is 1341°C. If molten cuprous oxide at a temperature of 1330°C is immersed in 20°C water, the calculated interfacial contact temperature is 954°C.[31] In both cases, the contact temperature is substantially higher than the spontaneous nucleation temperature for water, which is very sensitive to surface tension changes due to additives or contaminants, but can be as high as 270°C. Thus, molten copper interactions with water can indeed be explosive. Similar results are observed with many other molten metals and with kraft smelt immersions into water. The latter have been associated with black liquor recovery boiler accidents at paper mills.

The liquid temperature criterion is a necessary, but not sufficient, condition for the occurrence of steam explosions. For the vaporization to occur rapidly enough and in sufficient volume to generate potentially damaging pressures, it is necessary to have ample liquid–liquid interfacial contact area. The consensus among steam explosion researchers[32] is that a large-scale steam explosion also requires premixing of the liquids, triggering of vapor film collapse, and rapid propagation of vapor zone collapse subsequent to triggering, as illustrated in Figure 2.8.9.

The upper left diagram in Figure 2.8.9 shows numerous drops of melt falling through water, which is the required premixing. The upper right sketch shows that each melt drop is surrounded by a water vapor film associated with film boiling of water around the perimeter of the drop. The lower right-hand diagram shows the vapor film being penetrated by a small jet of

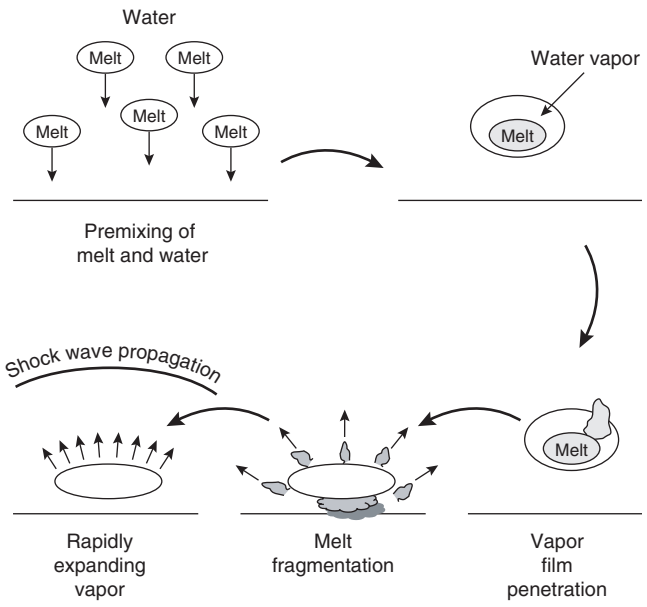

FIGURE 2.8.9 Steam Explosion Phenomena

melt, thus triggering film collapse. The lower middle diagram shows the interaction continuing via the fragmentation of the original drop into numerous jet fragments. As the jet fragments are propelled into the surrounding water, they explosively vaporize the water in a rapidly expanding region shown in the lower left-hand corner of Figure 2.8.9. This rapid vaporization/expansion provides the energy needed to drive a shock wave through the liquid and the adjacent area.

Our current limited understanding of the phenomena illustrated in Figure 2.8.9 does not allow a priori predictions of all the conditions that may result in steam explosions as opposed to less violent vaporization interactions. On the other hand, there have been several interesting empirical studies to help us anticipate the kinds of melts, containers, and mixing conditions that are more likely to lead to steam explosions. For example, Nelson[33] reports that smelt-water explosions do not occur when the water temperature is greater than 187°F (86°C), and Zyskowski[31] reports that molten tin-water explosions do not occur at water temperatures above 60°C. Long[34] did some pioneering experiments that showed how the bottom surface of the water container influences the likelihood of an explosion when molten aluminum was poured into the container. A rusty container base would promote steam explosions, whereas a greased or oil-coated or painted container base would prevent such explosions. These surface treatments change the wettability of the surface and the probability of a water film being trapped beneath a molten aluminum puddle. Later experiments have confirmed that molten aluminum-water explosions will not occur without either a wetted solid wall or high-velocity injection of one liquid into the other.[30] Other experiments have shown how water additives can change the likelihood of molten metal-water or smelt-water explosions by altering the water viscosity or surface tension.

When a steam explosion does occur, it often produces peak pressures in the range of 30 to 1000 psig (2 to 70 bar), with

pressure rise times of the order of a millisecond. Significantly lower pressures have also been observed under marginal conditions that produce rapid vaporization in the absence of shock waves. Vapor explosions have also been observed during at least some mixing conditions with the following pairs of liquids: Freon-22 and heated mineral oil, water and liquid nitrogen, liquid ethane and water,[30] molten nuclear reactor fuel and water, and molten zirconium oxide and water.[32]

Vapor Cloud Explosions

A vapor cloud explosion is a combustion explosion that follows the release of a large quantity of flammable gas or vapor in an outdoor area with conditions that promote rapid flame speeds and associated pressure increases. The following conditions promote rapid flame speed:

- Turbulent jet releases
- Partial confinement due to large structures or buildings in the release area
- Repeated obstructions usually due to congested process equipment and piping
- Ignition delays that allow the formation of large clouds with vapor-gas concentrations above the lower flammable limit

Flame speeds needed to generate potentially damaging overpressures in a virtually unconfined area are of the order of 100 m/sec. As the level of confinement increases, the required flame speeds decrease.

The levels of turbulence or obstructions and the size of the cloud needed to generate such flame speeds depend on the reactivity of the flammable gas or vapor. Highly reactive gases or vapors with large laminar burning velocities and those more prone to flame accelerations are more likely to be involved in vapor cloud explosions. Some of the vapors that have been involved in large numbers of vapor cloud explosions include propane, propylene, ethylene, and various aromatic hydrocarbons.

Table 2.8.5 lists the vapor cloud explosion incidents described in the CCPS guidelines.[35] The gas or vapor, quantity released, and the numbers of reported casualties are shown in the table. The large number of fatalities in the 1948 Ludwigshafen incident was due to the release occurring in a populated area. The large number of fatalities in the 1989 Ufa incident was due to the cloud being ignited as two passenger trains were passing each other. These incidents, and the Flixborough and Pasadena incidents, demonstrate that vapor cloud explosions can be the most catastrophic of all accidental explosions. The same conclusion can be drawn from considerations of property damage. Lenoir and Davenport[36] have provided a much more extensive compilation of vapor cloud explosion incidents.

A better understanding of how vapor cloud explosions differ from nonexplosive ignitions of large vapor clouds can be obtained from a review of the flame acceleration factors in these incidents. The Ludwigshafen, Raunheim, Flixborough, Pasadena, and Kuwait incidents all occurred in petrochemical processing facilities with highly obstructed processing areas containing pipe racks, process columns, tanks, and so on. The Kuwait incident is particularly interesting because there were eight separate processing areas, each one corresponding to a blast center with damage caused by relatively high pressures. According to *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVE,*[35] the Port Hudson explosion was ignited inside a concrete block warehouse, and then propagated outside into a rural area. The Ufa explosion was ignited by one of two passing trains. Trees in a heavily forested area around the tracks may have also contributed to the flame acceleration in the Ufa explosion.

Predictions of pressure damage from vapor cloud explosions consist of two parts. In the vicinity of the cloud, pressures depend on estimated flame speed and level of confinement. Theoretical calculations performed by Strehlow et al.[37] and described in the CCPS guidelines show how the pressure generated in the cloud varies with flame speed. Guidance on estimating flame speeds and confinement for vapor cloud explosion predictions have been developed by Baker et al.,[7] and the resulting method is called the Baker-Strehlow method.

TABLE 2.8.5 Noteworthy Vapor Cloud Explosion Incidents

Date	*Location*	*Flammable Gas or Vapor*	*Quantity Released (kg)*	Casualties	
				Deaths	*Injuries*
July 28, 1948	Ludwigshafen, Germany	Dimethyl ether	30,400	207	3818
January 16, 1966	Raunheim, Germany	Methane	500	1	5
December 9, 1970	Port Hudson, Missouri	Propane	23,000	0	10
June 1, 1974	Flixborough, UK	Cyclohexane	30,000	28	36
March 26, 1980	Enschede, The Netherlands	Propane	750	0	0
June 3, 1989	Ufa, Russia	Natural gas liquids	?	645	>1000
1989	Pasadena, Texas	Ethylene	?	25	?
July 2000	Kuwait	C3 + C4 hydrocarbon condensate	~80,000	7	~3

Source: AIChE Center for Chemical Process Safety[35] and NTSB Report PAR-72-1, 1972.

Predictions of blast wave pressures outside the cloud entail using curves of shock pressure, P_{s0}, versus an energy-scaled dimensionless distance, defined as follows:

$$\bar{R} = \frac{rP_0^{1/3}}{E^{1/3}} \quad [5]$$

where

r = Distance from the blast epicenter

P_0 = Atmospheric pressure

E = Combustion energy that contributes to the blast wave

The computation of E involves estimating the amount of flammable vapor released and the yield; that is, the fraction of the theoretical combustion energy contributing to the blast wave. An essential part of the Baker-Strehlow method is the choice of an appropriate yield value for gases or vapors of various reactivity classes. Another important step in the method is the selection of the appropriate flame speed or Mach number curve to use, again based on the gas/vapor reactivity category. The effect of using the Baker-Strehlow curves, or similar curves generated by other researchers, is that the blast wave pressure at a given energy-scaled distance is higher than what would be predicted using the curve shown in Figure 2.8.3, which was based on correlations for blast pressures produced by condensed phase explosives. Thus, vapor cloud explosions represent a more extensive damage and injury potential for a given blast wave energy. This is consistent with the observed areas of destruction in many of the large vapor cloud explosion incidents.

SUMMARY

An overview of explosion fundamentals is provided in terms of the relationship between peak pressure and energy release magnitude and duration for various types of explosions. Ideal blast wave propagation and scaling relations are also discussed, along with a brief summary of primary and secondary fragmentation effects. The following specific types of explosions are briefly described: flammable gas and vapor deflagrations, gas detonations, combustible dust deflagrations, chemical reaction explosions, steam explosions, and vapor cloud explosions.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on explosions discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 495, *Explosive Materials Code*
NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*

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SECTION

3

Information and Analysis for Fire Protection

Richard L. P. Custer ❑ **John R. Hall, Jr.**

3.1 An Overview of the Fire Problem and Fire Protection
3.2 Fire Loss Investigation
3.3 Fire Data Collection and Databases
3.4 Use of Fire Incident Data and Statistics
3.5 Introduction to Fire Modeling
3.6 Applying Models to Fire Protection Engineering Problems and Fire Investigations
3.7 Fire Hazard Analysis Techniques
3.8 Fire Risk Analysis
3.9 Closed Form Enclosure Fire Calculations
3.10 Performance-Based Codes and Standards for Fire Safety
3.11 Overview of Performance-Based Fire Protection Design

The practice of fire protection revolves around decision making: deciding how to best meet a code requirement or a client objective. The principal tools of decision making are information (whether in the form of statistics or investigative findings), analysis, (through, for example, calculations or modeling), and the application of codes and design techniques. Section 3 of the *Fire Protection Handbook*® focuses on these decision-making tools of fire protection. Because this section describes a more explicitly engineered approach to fire protection, its chapters include extensive references to the guides and works published by the Society of Fire Protection Engineers. Anyone who is interested in pursuing the kinds of analysis described in this section is strongly encouraged to seek out the SFPE materials and members for further guidance.

Chapter 1, "An Overview of the Fire Problem and Fire Protection," provides a statistical perspective on the size, trends, and patterns of the U.S. and global fire problems. Chapter 2, "Fire Loss Investigation," concentrates on the more detailed information available from an individual fire incident and includes a discussion of the role of NFPA 921, *Guide for Fire and Explosion Investigations.* Chapter 3, "Fire Data Collection and Databases," and Chapter 4, "Use of Fire Incident Data and Statistics," describe the sources (particularly the U.S. National Fire Incident Reporting System) used for statistical analysis of fire experienced in the real world and how data source issues affect the analysis process.

The section next addresses fire modeling through two chapters. Chapter 5, "Introduction to Fire Modeling," explores the principal types of models (zone, computational fluid dynamics, and probabilistic) used to predict the growth of fire and the spread of fire effects. Chapter 6, "Applying Models to Fire Protection Engineering Problems and Fire Investigations," addresses model applications and considerations for selecting and using fire models.

Chapter 7, "Fire Hazard Analysis Techniques," introduces techniques to determine the expected outcome of a specific set of conditions, called a fire *scenario.* Topics covered include hazard identification, developing and quantifying design fire scenarios, and other steps in fire hazard analysis. Chapter 8, "Fire Risk Analysis," describes a comprehensive form of analysis that can be applied to any fire safety choice when fire hazard analysis of scenarios is expanded to include issues of scenario likelihood, identifying a comprehensive set of representative fire scenarios, and risk evaluation.

Chapter 9, "Closed Form Enclosure Fire Calculations," presents equations that can be solved using calculators to estimate conditions during the preflashover fire growth phase of a compartment fire.

In its final two chapters, the section considers performance-based approaches to fire safety. Chapter 10, "Performance-Based Codes and Standards for Fire Safety," contrasts performance-based

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and prescriptive-based regulations and describes the role of codes and standards in performance-based design. Chapter 11, "Overview of Performance-Based Fire Protection Design," summarizes the performance-based design process, compares deterministic hazard assessment and probabilistic risk assessment in the context of performance-based design, and presents a new case study in the use of performance-based design.

SECTION 3

Chapter 1

An Overview of the Fire Problem and Fire Protection

John R. Hall, Jr. ❏ Arthur E. Cote

Chapter Contents

Fire Loss Trends
Fire Prevention
Fire Protection
Materials, Products, and Environments
Detection and Alarm
Suppression
Confining Fires
Evacuation of Occupants
Systems Approaches for Property Classes
Organizing for Fire Protection

Key Terms

automatic sprinkler system, conflagration, evacuation, explosion, fire confinement, fire detection and alarm, fire fighter safety, fire loss, fire prevention, smoke alarm, systems approach

When the first *Fire Protection Handbook* was published in 1896, it contained no information on the size, trends, or patterns of the U.S. fire problem. Like most scientific and engineering handbooks, especially in years gone by, the first *Fire Protection Handbook* merely compiled a series of rules, tables, and formulas, which the knowledgeable fire safety professional of that time would find useful. One had to read between the lines to realize that the information provided in that handbook said nothing about hazards to life and limb and little about fire prevention as a strategy to reduce fire loss. (One also saw very little about such related hazards as electrical shock, hazardous materials, and environmental risks, topics that later editions have steadily expanded.)

In the century since that first edition appeared, the field of fire protection has grown tremendously. This edition of the *Fire Protection Handbook* is more than an order of magnitude larger than the original edition. With that growth of information has come an increasing need for context, perspective, and systematic approaches to organizing knowledge.

This chapter has two goals. One is to provide a perspective on the size, trends, and patterns of the U.S. fire problem and the global fire problem as well. Special attention has been paid to the incidents that led to changes in codes and standards—and the changes in fire experience that followed those code and standard changes. The other goal is to provide a basic structure for the elements of fire protection—a structure that can be tied to particular measures of the fire problem and that is carried forward in the first-level organization of this handbook. In the handbook, Sections 2–4 cover basic information and methods. Sections 5–11 cover prevention through education or engineering and other safety measures defined by materials, equipment, other products, processes, services, or facilities. Sections 12–13 cover the fire service; Section 14 covers detection and alarm; Sections 15–17 cover suppression; and Sections 18–19 cover confinement and structural protection. Sections 20 and 21 cover occupancy type. Accordingly, this chapter begins with basic information on the U.S. and world fire problem, follows with material organized by stage of fire protection, and concludes with information on different occupancies and information on the fire service.

To understand the sequencing of the sections, think of fire protection as a series of opportunities to intervene against a hostile fire, arrayed along a timeline of potential growth in fire severity. First, there are the opportunities to prevent the fire entirely, by education or by changes to products, whether heat sources or combustible materials (addressed in Sections 5–11). Second, there are opportunities to slow the initial growth and spread of fire or to reduce the severity of fires through the design, selection, and handling of materials and products (also addressed in Sections 5–11). Third, there are opportunities to detect fire early, permitting effective intervention before damage becomes too severe (addressed in Section 14). Fourth, there are opportunities for automatic or manual suppression (addressed in Sections 15–17). Fifth, there are opportunities to confine the fire in space through compartmentation and other passive fire protection methods (addressed in Sections 18–19). Sixth, there are opportunities to move occupants to safe locations, taking advantage of the extra time provided by the earlier steps to move people from hazardous locations to safety or to defend them where they are (addressed primarily in Sections 20–21, along with occupancy-specific aspects of the topics covered in Sections 5–11 and

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14–19). Before examining each of these fire protection strategies, it is useful to assess the size of the fire problem that faces us and the success achieved in reducing it over the past decades.

See also Section 1, Chapter 1, "Challenges to Safety in the Built Environment"; Section 1, Chapter 3, "Codes and Standards for the Built Environment"; Section 3, Chapter 4, "Use of Fire Incident Data and Statistics"; and Section 20, Chapter 1, "Assessing Life Safety in Buildings."

FIRE LOSS TRENDS

Fire in the United States

Table 3.1.1 and Figures 3.1.1 through 3.1.4 show that the number of fires has declined over the past quarter century. Civilian fire deaths were stuck at around 6000 annually during 1982 to 1988, but have declined by roughly half during the past quarter century. Civilian fire injuries showed no consistent trend up or down, until the mid-1990s, when they began to decline consistently. Direct property damage has risen dramatically, but most of that is due to inflation, although there have been years when individual fires of historic size have driven the total, adjusted for inflation, to new heights.

Table 3.1.2 and Figure 3.1.5 provide a longer perspective on U.S. fire deaths by switching to trends in the death certificate database. (NFPA uses this database only for long-term trend analysis, where there is no alternative database with as much consistency in methodology. Fires involving postcrash vehicle fires or arson are often excluded or missed from the fire totals in the death certificate database.)

Fire deaths have fallen by roughly two-thirds in the past nine decades since their peak levels around World War I. Fire death *rates* have fallen by a factor of 9. The decline in fire deaths was fairly irregular until the mid-1960s, in part because indi-

TABLE 3.1.1 The U.S. Fire Problem

Year	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage*
1977	3,264,000	7395	31,190	$4,709,000,000
1978	2,817,500	7710	29,825	$4,498,000,000
1979	2,845,500	7575	31,325	$5,750,000,000
1980	2,988,000	6505	30,200	$6,254,000,000
1981	2,893,500	6700	30,450	$6,676,000,000
1982	2,538,000	6020	30,525	$6,432,000,000
1983	2,326,500	5920	31,275	$6,598,000,000
1984	2,343,000	5240	28,125	$6,707,000,000
1985	2,371,000	6185	28,425	$7,324,000,000
1986	2,271,500	5850	26,825	$6,709,000,000
1987	2,330,000	5810	28,215	$7,159,000,000
1988	2,436,500	6215	30,800	$8,352,000,000
1989	2,115,000	5410	28,250	$8,655,000,000
1990	2,019,000	5195	28,600	$7,818,000,000
1991	2,041,500	4465	29,375	$9,467,000,000
1992	1,964,500	4730	28,700	$8,295,000,000
1993	1,952,500	4635	30,475	$8,546,000,000
1994	2,054,500	4275	27,250	$8,151,000,000
1995	1,965,500	4585	25,775	$8,918,000,000
1996	1,975,000	4990	25,550	$9,406,000,000
1997	1,795,000	4050	23,750	$8,525,000,000
1998	1,755,500	4035	23,100	$8,629,000,000
1999	1,823,000	3570	21,875	$10,024,000,000
2000	1,708,000	4045	22,350	$11,207,000,000
2001	1,734,500	6196	21,100	$44,023,000,000
2002	1,687,500	3380	18,425	$10,337,000,000
2003	1,584,500	3925	18,125	$12,307,000,000
2004	1,550,500	3900	17,785	$9,794,000,000

Source: NFPA survey data, NFPA's Fire Incident Data Organization (FIDO).

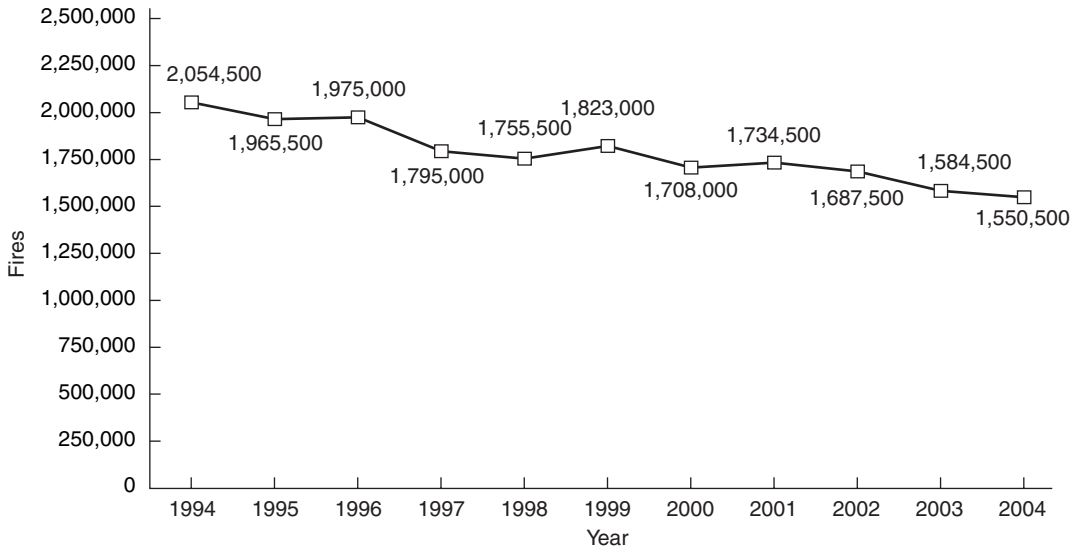

FIGURE 3.1.1 U.S. Fire Incident Trend, 1994–2004 (Source: NFPA National Fire Experience Survey)

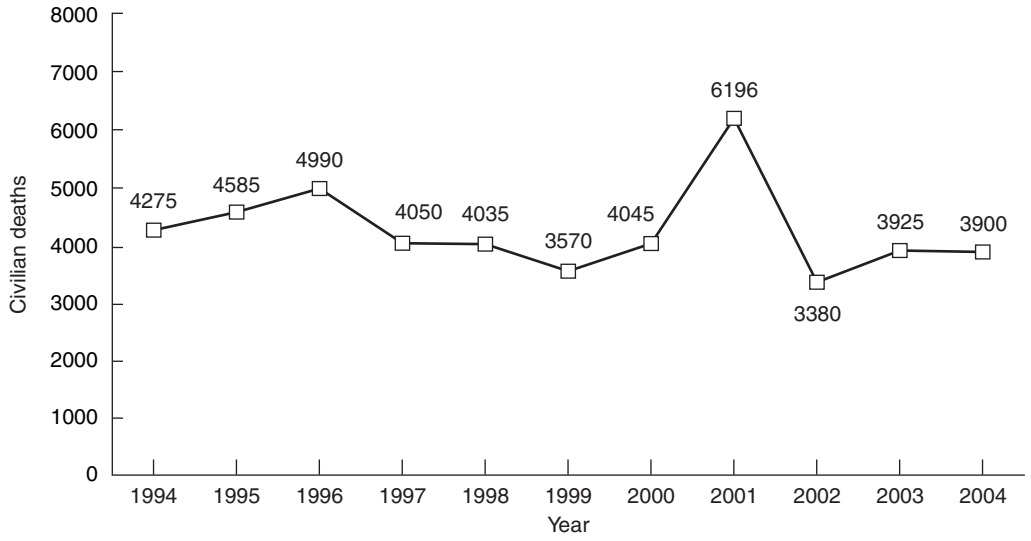

FIGURE 3.1.2 U.S. Civilian Fire Death Trend, 1994–2004 (Source: NFPA National Fire Experience Survey)

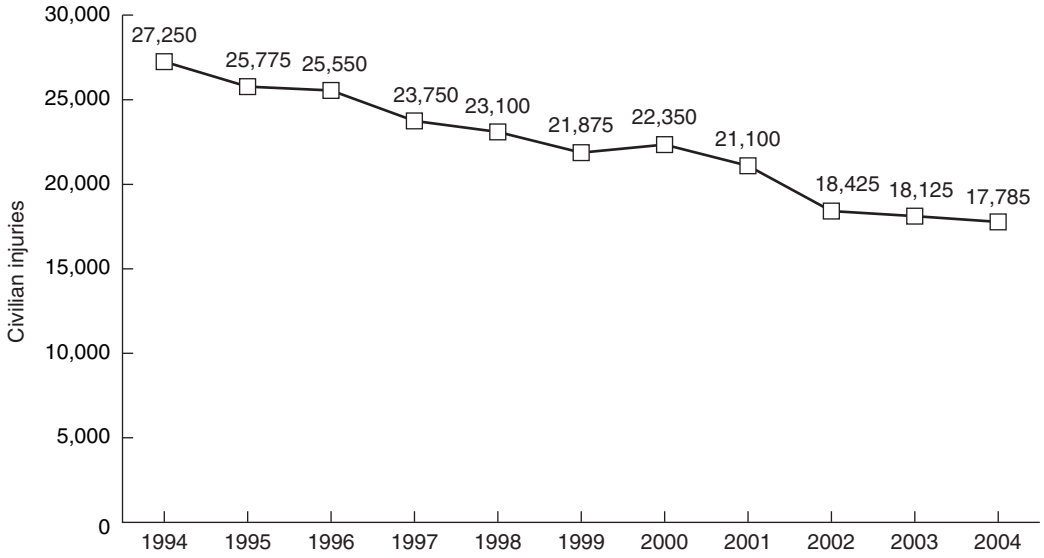

FIGURE 3.1.3 U.S. Civilian Fire Injury Trend, 1994–2004 (Source: NFPA National Fire Experience Survey)

vidual incidents with death tolls in the hundreds used to occur with some regularity. A few such incidents could significantly affect the total U.S. fire death toll in a given year. From 1955 to the present, there have been only five U.S. incidents with a death toll of 100 or more—the Lexington, Kentucky, restaurant fire in 1977; the Oklahoma City, Oklahoma, office building bombing of 1995; the Florida inflight fire of 1996; the terrorist attack on the World Trade Center in 2001; and the 2003 Station nightclub fire in Rhode Island. By contrast, the previous 55 years (1900 through 1954) produced 44 incidents involving death tolls of 100 or more, a decline from nearly one fire per year of that severity to less than one per decade.[1]

America Burning,[2] the report of the National Commission on Fire Prevention and Control (NCFPC), set a goal in 1973 of reducing the U.S. fire death toll by one-half in a generation, which is usually understood to mean 25 years. With that generation now gone, fire deaths measured by death certificates did fall by roughly one-half.

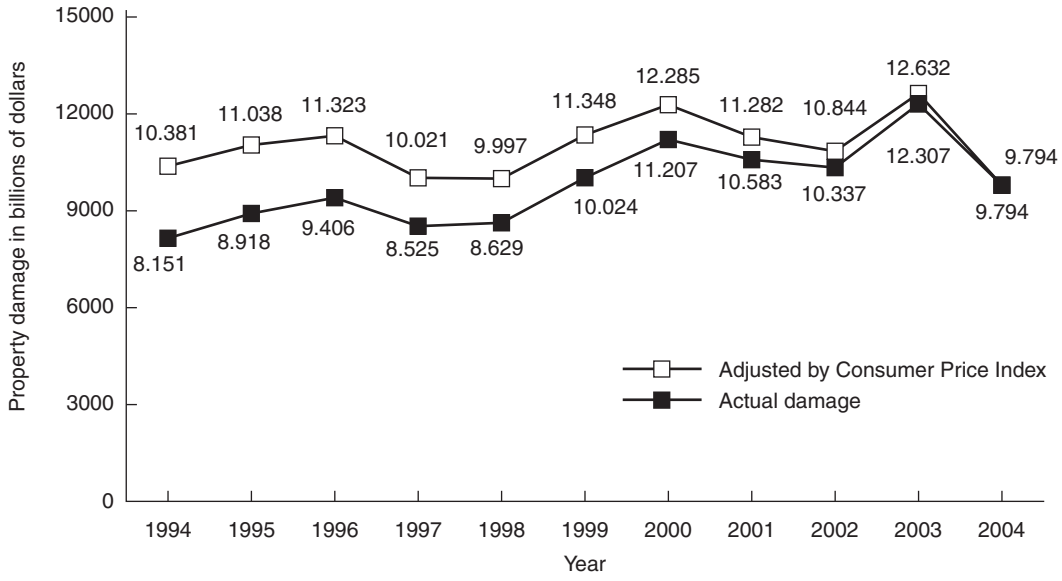

FIGURE 3.1.4 U.S. Direct Property Damage Trend, 1994–2004. Note: 2001 figures exclude the $33.44 billion loss at the World Trade Center. (Source: NFPA National Fire Experience Survey)

TABLE 3.1.2 History of U.S. Fire and Burn Fatalities

Year	*Fire Deaths**	*Fire Deaths per 100,000 Population*
1913	8,900	9.1
1918	10,200	9.9
1923	9,100	8.1
1928	8,400	7.0
1933	6,800	5.4
1938	6,500	5.0
1943	8,700	6.5
1948 (old)	7,700	5.3
1948 (new)	6,800	4.7
1953	6,600	4.2
1958	7,300	4.2
1963	8,200	4.3
1968	7,300	3.7
1973	6,500	3.1
1978	6,200	2.8
1983	5,000	2.2
1988	5,000	2.0
1993	3,900	1.5
1998	3,300	1.2
2003	3,400	1.5

*Fire deaths are calculated on the basis of death certificates and are given to the nearest hundred. Fire deaths involving arson or postcollision vehicle fires may be omitted. Classification changes in 1968, 1958, and especially 1948 limit comparability of figures.

Source: *Injury Facts,* 2005–2006 ed., National Safety Council, Itasca, IL.

Table 3.1.3 provides a longer perspective on property damage in fire, using estimates from the Insurance Services Office (ISO). (NFPA uses this database only for long-term trend analysis, where there is no alternative database with as much consistency in methodology. The database has considerable uncertainty due to its adjustments for uninsured and unreported losses.) Fire losses have grown more than 250 times in the past 124 years, but this reflects a factor of five decline in the purchasing power of the dollar and a more than 60-fold increase in the nation's economy measured by gross national product (GNP) after adjustment for those changes in purchasing power. As a fraction of GNP, fire loss has declined by a factor of five since the turn of the century, a large decline though not as large as the decline in the fire death rate relative to population.

Fire Around the World

Figure 3.1.6 shows fire death rates in many countries of the world, especially Europe. It is possible that the completeness of reporting varies from country to country. As an example, fire statistics jumped in the Russian Federation after the society became more open at the urging of President Boris Yeltsin. The highest fire death rates tend to be in parts of the former Soviet Union.

Figure 3.1.7 looks at a quarter century of trend data on fire death rates for three countries where comparable data have been consistently available for this long period. The United States and Canada have tracked together throughout this period, and both have narrowed the gap in fire death rates with the United Kingdom and Japan, passing the latter in the 1997. The U.S. and Canadian rates were twice as high in the late 1970s, roughly 50 percent higher in the late 1980s, and nearly the same in the late 1990s. The gap is closing because the United States and Canada

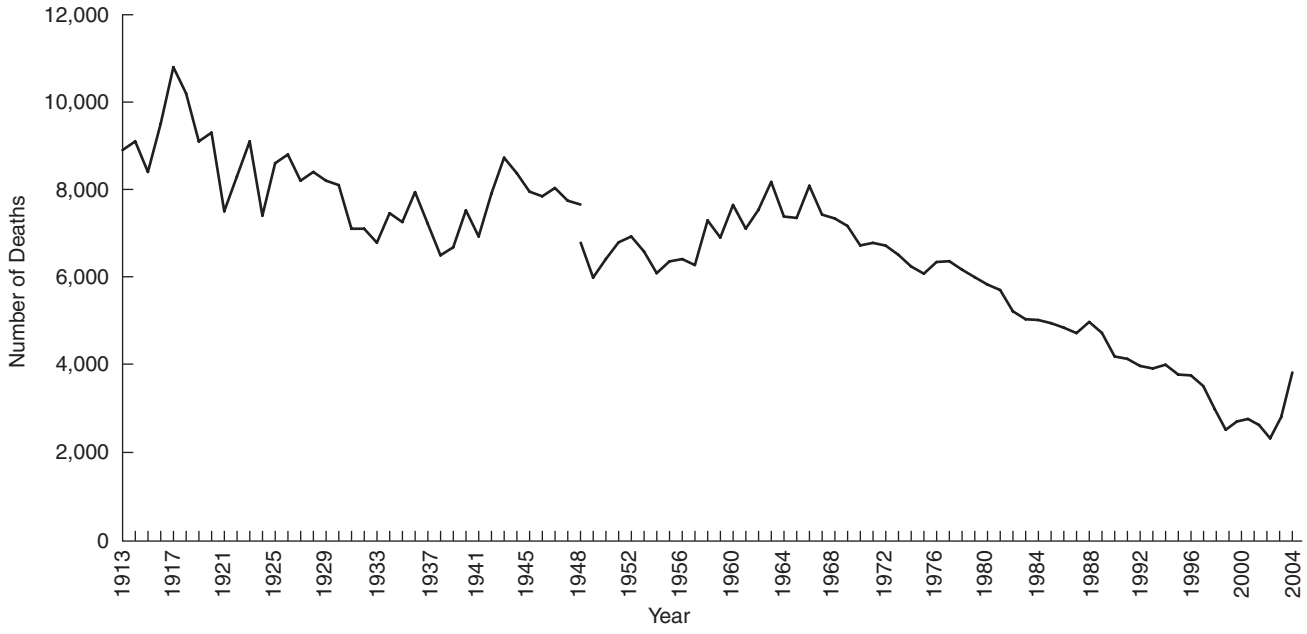

FIGURE 3.1.5 U.S. Fire and Burn Deaths, 1913–2004 (Source: *Injury Facts,* 2005–2006 ed., National Safety Council, Itasca, IL)

TABLE 3.1.3 U.S. Fire Incident Trend, 1880–2004

Year	*Property Damage (in Millions of Dollars)*[a]	*Property Damage (in Millions of 2004 Dollars)*[b]	*Property Damage per Capita (in Dollars)*[c]	*Property Damage per Capita (in 2004 Dollars)*	*Property Damage as Percentage of GNP*[d]
1880	75	1,454	1.49	28.93	0.67
1890	109	2,279	1.73	36.14	0.83
1900	161	3,635	2.11	47.76	0.86
1910	214	4,316	2.32	46.71	0.61
1920	448	4,216	4.21	39.60	0.49
1930	502	5,670	4.08	46.06	0.56
1940	286	3,852	2.17	29.20	0.29
1950	649	5,083	4.29	33.60	0.23
1960	1,108	7,053	6.18	39.32	0.22
1970	2,238	10,867	11.01	53.45	0.23
1980	5,579	12,790	24.63	56.45	0.20
1990	9,495	12,609	38.06	50.55	0.16
1995	11,887	14,713	45.24	56.00	0.16
2000	13,457	12,276	47.90	52.50	0.14
2004	18,874	18,874	64.55	64.55	0.16

[a]Insurance Services Office Estimates, including adjustments for estimated uninsured and unreported losses, as reported by Insurance Information Institute, *The Fact Book: 1992 Property/Casualty Insurance Facts,* Insurance Information Institute, New York, 1992, p. 6; and Insurance Information Institute, *The Ill Fact Book 2006,* Insurance Information Institute, 2006.

[b]Based on consumer price index, as calculated by the U.S. Bureau of Labor Statistics, including estimates for historical times by the U.S. Bureau of the Census.

[c]Based on U.S. residential population.

[d]Based on gross national product estimates by the U.S. Bureau of Economic Analysis, including estimates for historical times by the U.S. Bureau of the Census.

Source: NFPA National Fire Experience Survey.

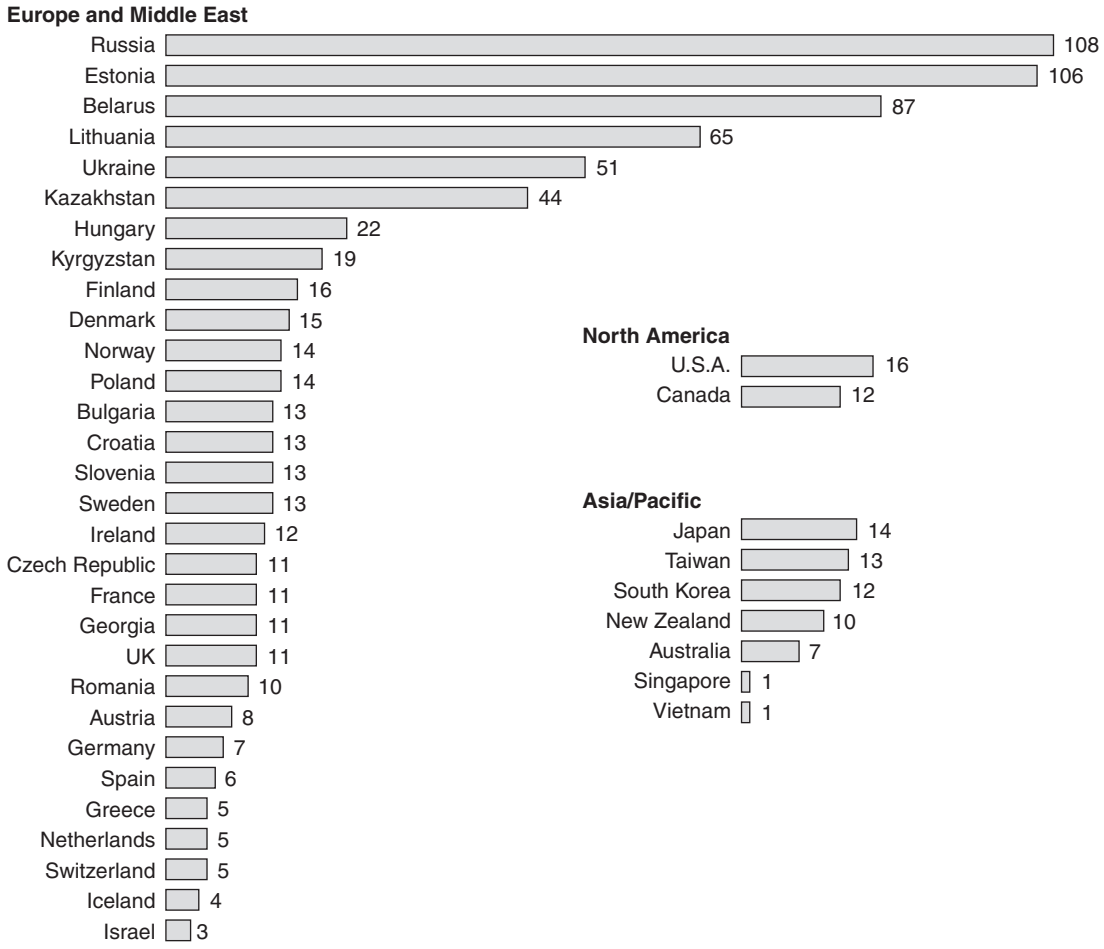

FIGURE 3.1.6 Fire Deaths Around the World, per Million Population, 1993–2002. Note: Countries were included only if they had rates for at least 7 of the 10 years. (Source: CTIF Center of Fire Statistics, *Fire Statistics,* No. 10, 2004, Table 5)

have been improving fire safety faster than other countries. Throughout, analysis has shown that the United States does well in holding down the average severity of fire (i.e., deaths per fire) but fares poorly in holding down the fire incident rate (i.e., preventing fires).

Figure 3.1.8 shows 2000–2002 property loss to fire as a fraction of gross domestic product, based on the estimates of the World Fire Statistics Centre (WFSC). The WFSC analysts make a number of adjustments to nationally reported loss data, in order to improve comparability. Comparable data on fire loss are not readily available outside North America, Europe, and Japan.

Most of the visibility of the fire problem and a large share of the public's fear and concern centers on very large fires. Table 3.1.4 lists the 10 deadliest U.S. fires and explosions through 2004. Except for the World Trade Center attacks of September 11, 2001, the most recent incident on the list is a 1947 incident involving shipping and industrial port facilities. Table 3.1.5 lists the 10 deadliest U.S. fires and explosions of the decade 1995–2004. The list is led by two terrorist attacks on office buildings. There are two aircraft fires, two nursing home fires, a nightclub fire, two industrial fires not involving buildings, and a wildland fire. Note that there are three wildland fires on the list of all-time deadliest fires.

Table 3.1.6 lists the 10 deadliest fires and explosions of all time in the world. The death tolls in two Japanese earthquake fires dwarf every other incident on the list. The other incidents are major conflagrations, industrial explosions, and the World Trade Center attacks.

Table 3.1.7 lists the 10 deadliest fires and explosions of all time in Central and South America and the Caribbean. This list shows more recent fires than any of the other all-time lists.

Table 3.1.8 lists the 10 costliest U.S. fires and explosions of all time adjusted for inflation, and Table 3.1.9 lists the 10 costliest U.S. fires and explosions of the decade 1995–2004. The all-time list includes four long-ago citywide conflagrations (one triggered by an earthquake), four recent wildland fires, one recent industrial explosion and fire incident, and the World Trade Center attacks. The top 10 for the decade 1995–2004 includes four wildland fires, four industrial incidents, one inflight airline fire, and the World Trade Center attacks. Except for the wildland/urban interface, the risk of

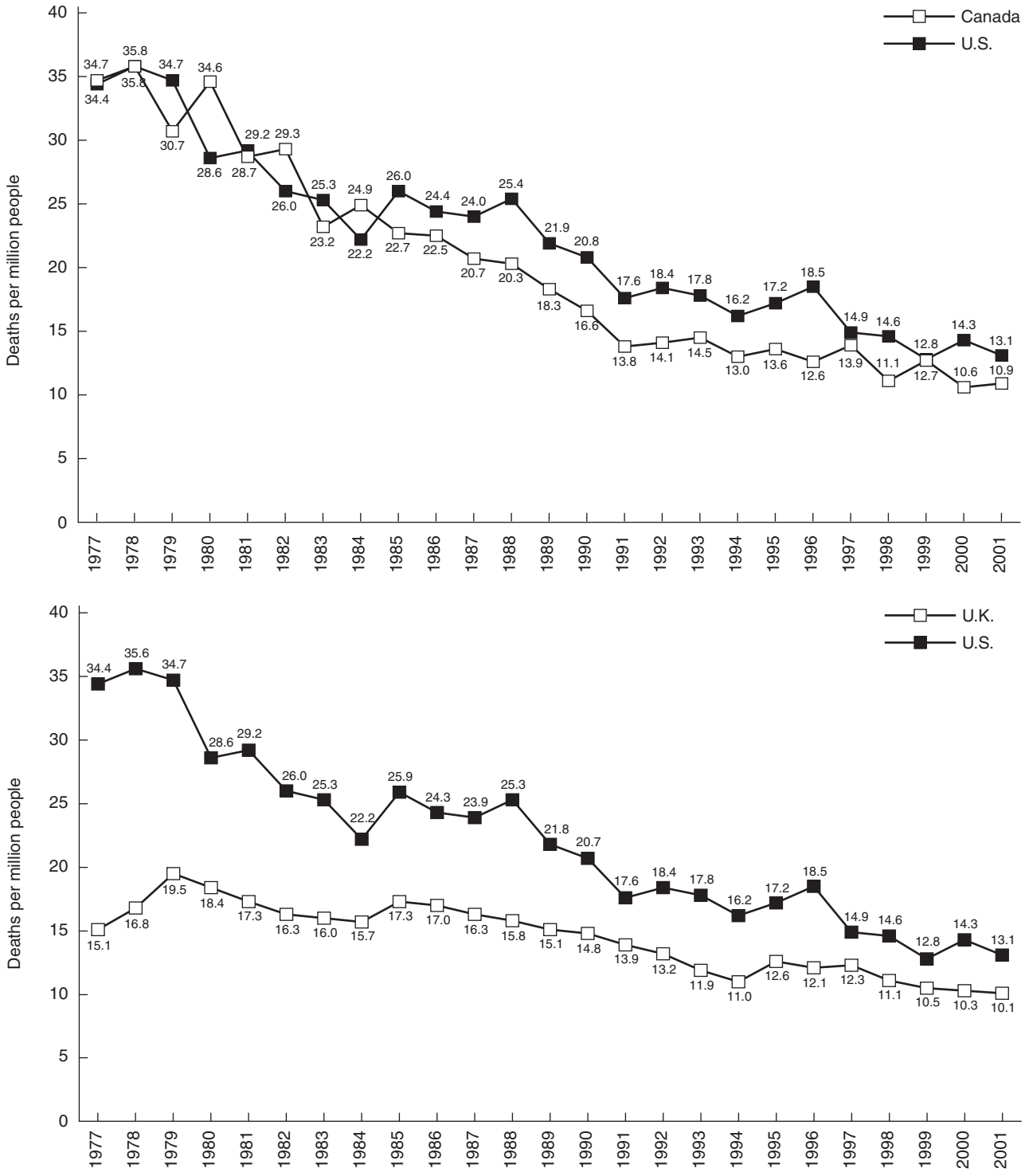

FIGURE 3.1.7 Fire Death Rates for Four Countries, 1977–2001. Note: 2001 U.S. rate excludes events of September 11, 2001. (Sources: Data from NFPA Survey, U.S. Census Bureau, annual reports from Canadian Fire Marshals and Fire Commissioners, UK Home Office, Japan's *White Book* [Dr. Ai Sekizawa])

conflagration has declined significantly from the pattern of a century ago.

Conflagration lacks a fully standardized definition. The definitions used to code death certificates use the term *conflagration* to mean any building fire. More often, conflagration is used colloquially to mean any large fire with significant flame showing outside. NFPA generally uses the term *conflagration* to describe a fire with major

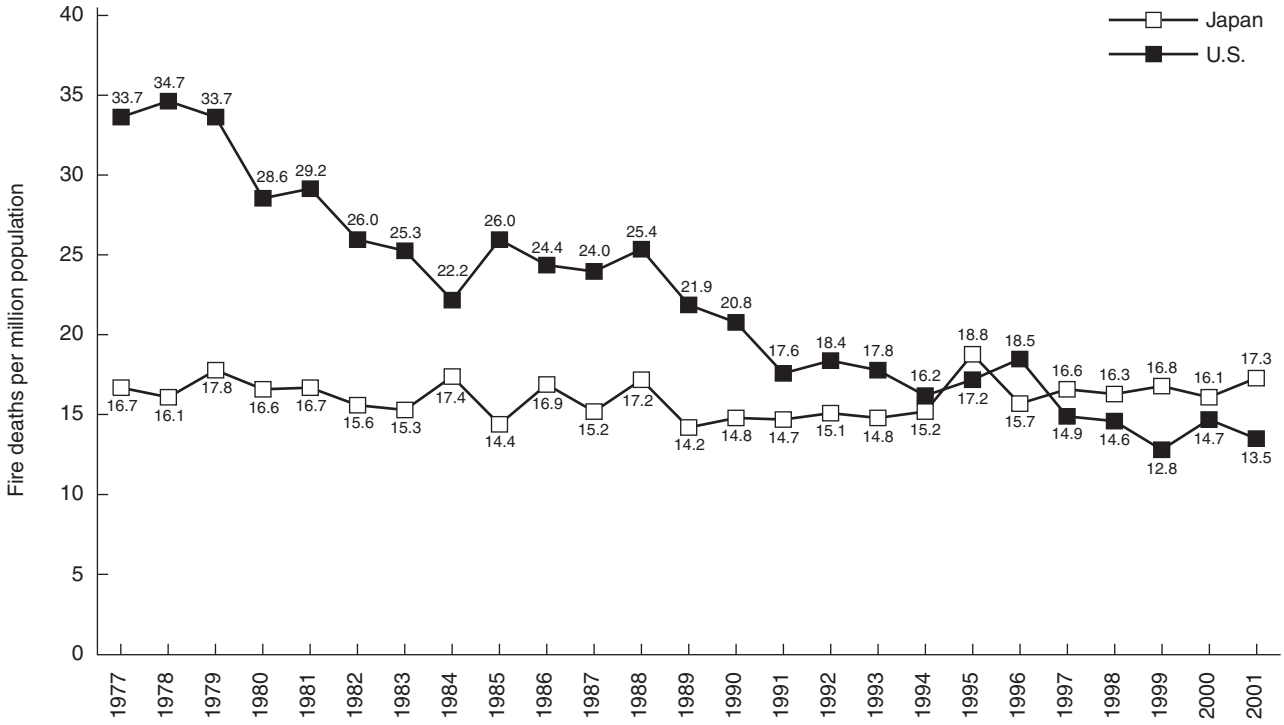

FIGURE 3.1.7 Continued

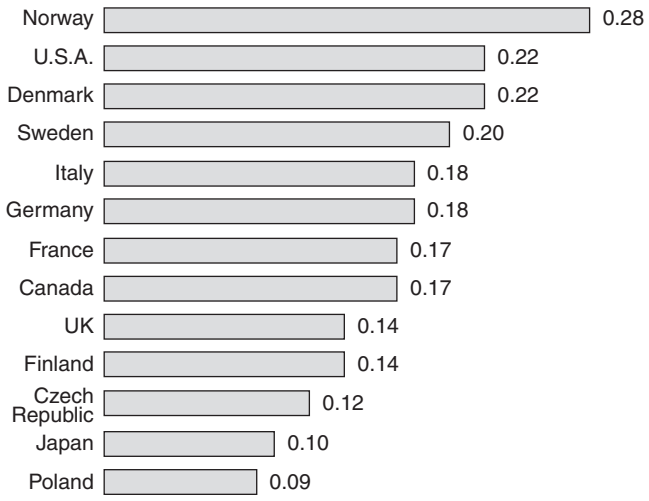

FIGURE 3.1.8 Property Loss to Fire Around the World—Direct Property Damage as a Fraction of Gross Domestic Product, 2000–2002. Note: Countries were included only if they had data for all 3 years. Estimates by the WFSC involve changes for consistency and may differ substantially from nationally reported figures. (Source: World Fire Statistics Centre Bulletin #21, The Geneva Association, Geneva, Switzerland, Oct. 2005, Table 1)

building-to-building flame spread over some distance. Significant building-to-building fire spread within a complex or among adjacent buildings is typically called a *group fire,* but again the usage is not standardized. In Japan, where many

TABLE 3.1.4 Ten Deadliest U.S. Fires and Explosions Through 2004

		Number of Deaths
1.	World Trade Center, New York, NY, September 11, 2001	2666
2.	S.S. Sultana steamship boiler explosion and fire, Mississippi River, April 27, 1865	1547
3.	Forest fire, Peshtigo, WI, and environs, October 8, 1871	1152
4.	General Slocum excursion steamship fire, New York, NY, June 15, 1904	1030
5.	Iroquois Theater, Chicago, IL, December 30, 1903	602
6.	Forest fire, northern MN, October 12, 1918	559
7.	Cocoanut Grove nightclub, Boston, MA, November 28, 1942	492
8.	S.S. Grandcamp and Monsanto Chemical Company plant, Texas City, TX, April 16, 1947	468
9.	Forest fire, Hinckley, MN, and environs, September 1, 1894	418
10.	Monongah Mine coal mine explosion, Monongah, WV, December 6, 1907	361

Sources: NFPA's Fire Incident Data Organization and other NFPA fire incident records.

TABLE 3.1.5 Ten Deadliest U.S. Fires and Explosions, 1995–2004

		Number of Deaths
1.	World Trade Center attack, New York, September 11, 2001	2666
2.	Office building bombing, Oklahoma, April 19, 1995	169
3.	Airplane in flight, Florida, May 11, 1996	110
4.	Nightclub, Rhode Island, February 20, 2003	100
5.	Nursing home, Connecticut, February 26, 2003	16
6A.	Nursing home, Tennessee, September 25, 2003	14
6B.	Collision of two planes on runway, Illinois, November 19, 1996	14
8A.	Coal mine explosions, Alabama, September 23, 2001	13
8B.	Wildland/urban interface, California, October 25, 2003	13
10.	Pipeline explosion, New Mexico, August 19, 2000	12

Note: Excludes nonfire deaths in incidents with both.
Source: NFPA's Fire Incident Data Organization.

large postearthquake fires have occurred, the term *city fire* is often used for a conflagration.

Table 3.1.10 describes different types of conflagrations, or group fires, and gives recent examples of each. The first type listed is also the most common conflagration scenario in recent years, which is the forest fire or brush fire that spreads to nearby buildings in what is called the urban/wildland interface. The classic conflagration scenario of the last century, involving narrow streets and closely packed buildings, is now comparatively rare. The 1973 Chelsea, Massachusetts, conflagration is the premier example in recent decades. The construction and density conditions for such fires are largely confined to the old manufacturing areas of some older cities, particularly in the Northeast. A more common problem, particularly in the Southwest, is the phenomenon of conflagrations driven by strong, hot, dry winds and untreated wood shingles. This problem has been around for as long as NFPA has been collecting information on major fires.

FIRE PREVENTION

Every hostile fire requires an initial heat source, an initial fuel source, and something to bring them together. That something

TABLE 3.1.6 Deadliest Fires or Explosions in the World of All Time Excluding Bombings and Wartime Attacks

1.	Tokyo to Yokohama, Japan September 1, 1923 Most of 142,807 total deaths	Earthquakes resulted in fires that caused most deaths
2.	Tokyo, Japan March 21, 1857 Most of 107,000 total deaths	Earthquake resulted in fires that caused most deaths
3.	Kiev, U.S.S.R. April 26, 1986 31 immediate deaths plus 7,000–8,000 deaths of exposed clean-up workers.	Nuclear power plant chemical explosion led to release of nuclear radiation
4A.	Constantinople (now Istanbul), Turkey 1729 7,000 deaths	Urban conflagration
4B.	Chiang-king, China September 3, 1949 7,000 deaths	Fire
6.	Bhopal, India December 3, 1984 3,849 deaths by chemical fumes	Pesticide plant explosion released deadly chemical fumes
7.	Johanngeorgendstadt, East Germany November 29, 1949 3,700 deaths	Uranium mine explosions
8.	Brescia, Italy 1769 3,000+ deaths	Gunpowder explosion in arsenal
9.	New York, New York, USA September 11, 2001 2,749 civilian and fire fighter deaths	Office buildings collapsed due to fire started when airliners were flown into upper floors
10.	Chungking, China September 2, 1949 1,700 deaths	Riverfront conflagration; reported separately from 4B, which occurred the next day

Note: These are incidents known to NFPA and deemed to fit within the eligibility parameters, based on best available information. Terrorist incidents using explosives are excluded, but other terrorist incidents are not treated as wartime incidents and are not excluded. Incidents involving warships but not arising from conflict are not excluded.

TABLE 3.1.7 Deadliest Fires or Explosions of All Time in Latin America and the Caribbean Excluding Bombings and Wartime Attacks

	Number of Deaths
1. Santiago, Chile, church fire December 8, 1863	1488–2500
2. Cali, Colombia, explosion of seven dynamite trucks August 7, 1956	1100–1200
3. Cubatão, Brazil, oil pipeline explosion February 25, 1984	508
4. Lagunillas, Venezuela, conflagration November 14, 1939	500
5. Suburb of Asuncion, Paraguay, supermarket fire August 1, 2004	426
6. Mexico City, Mexico, gas storage area explosion November 19, 1984	334
7. Niterói, Brazil, circus fire December 17, 1961	323
8. Lima, Peru, fireworks explosion at fireworks stand in crowded shopping area of stores and sidewalk stalls December 29, 2001	276
9. Guatemala City, Guatemala, mental hospital fire July 14, 1960	200–225
10. Guadalajara, Mexico, explosion of chemical released into sewers April 22, 1992	190–200

Note: These are incidents known to NFPA and deemed to fit within the eligibility parameters, based on best available information. Terrorist incidents using explosives are excluded, but other terrorist incidents are not treated as wartime incidents and are not excluded. Incidents involving warships but not arising from conflict are not excluded.

TABLE 3.1.8 Ten Costliest U.S. Fires and Explosions of All Time (in 2004 dollars)

	Loss in Year Fire Occurred (in Dollars)	*Adjusted Loss (in 2004 Dollars)*
1. The World Trade Center, New York City, New York September 11, 2001	33.4 billion	35.6 billion
2. San Francisco earthquake and fire, San Francisco, California April 18, 1906	350 million	7.3 billion
3. Great Chicago fire, Chicago, Illinois October 8–9, 1871	168 million	2.6 billion
4. Oakland fire storm (wildland/urban interface), Oakland, California October 20, 1991	1.5 billion	2.1 billion
5. Great Boston fire, Boston, Massachusetts November 9, 1872	75 million	1.2 billion
6. Polyolefin plant, Pasadena, Texas October 23, 1989	750 million	1.1 billion
7. Wildland fire (wildland/urban interface), Los Alamos, New Mexico May 4, 2000	1.0 billion	1.1 billion
8. Wildland fire (cedar), Julian, California October 25, 2003	1.1 billion	1.1 billion
9. Baltimore conflagration, Baltimore, Maryland February 7, 1904	50 million	1.0 billion
10. Wildland fire (old), San Bernardino, California October 25, 2003	975 million	1.0 billion

Source: NFPA Fire Incident Data Organization and other NFPA fire incident records.

nearly always has a human component, usually an immediate act or omission that brings heat and fuel together or sometimes the delayed effects of an error in design or installation. Fire also requires oxygen and sustainable chemical chain reactions, both of which can be useful points of attack for some suppression systems. Nevertheless, the three components of heat, fuel, and human error are central to nearly all fires and can be used as a framework for thinking about fire prevention, without much fear of oversimplification.

Fire Prevention Actions

It is important to remember that prevention can occur through successful action on the heat source, the fuel source, or the behavior that brings them together. No one line of attack is clearly preferable to the other, and success is most likely to come if all three components are treated as real options at all times.

Product redesign is the means by which a heat source or a fuel source is changed. Such a change can come about in several ways: (1) regulation, (2) design to a set of voluntary consensus codes and standards, (3) a voluntary industrywide program to change product designs, not driven by laws or codes, and (4) product redesign in response to consumer demand.

Changing behavior means education, which also may be done by targeting a variety of audiences. Schoolchildren are a group that can be reached when they are ready and able to learn substantial quantities of information. Manufacturers' labels and instructions reach consumers when they may be most disposed to learn rules for the fire-safe use of products. Product advertisements and public service announcements (PSAs) have the potential to reach large audiences. Brochures, educational kits, community meetings, and the like can reach small, motivated

TABLE 3.1.9 Ten Largest U.S. Fire Losses, 1995–2004 (in 2004 dollars)

	Loss in Year Fire Occurred (in Millions of Dollars)	*Adjusted Loss (in Millions of Dollars)*
1. World Trade Center, New York, NY September 11, 2001	33.400	35,606
2. Wildland fire (cedar), Julian, CA October 25, 2003	1,060	1,088
3. Wildland fire (wildland/urban interface), Los Alamos, NM May 4, 2000	1,000	1,096
4. Wildland fire (old), San Bernardino, CA October 25, 2003	975	1,001
5. Power plant, (auto manufacturing complex), Dearborn, MI February 1, 1999	650	736
6. Textile mill, Methuen, MA December 11, 1995	500	619
7. Cargo plane in-flight fire, near Newburgh, NY September 5, 1996	395	475
8. Wildland fire, Florida May–June, 1998	395	456
9. Aluminum plant explosion, Gramercy, LA July 5, 1999	300	340
10. Warehouse, New Orleans, LA March 21, 1996	280	337

Source: NFPA Fire Incident Data Organization.

TABLE 3.1.10 Illustrative Recent Conflagrations and Group Fires

1. Urban/wildland interface, Los Alamos, NM, 2000
   A fire that began as a prescribed burn under the control of the National Park Service ultimately spread over 48,000 acres (compared to the intended 900 acres), resulting in a total estimated loss of $1 billion.
   Four of the costliest U.S. fires and explosions of all time are wildland/urban interface fires.

2. Congested, combustible district, Chelsea, MA, 1973
   The fire began in a yard area of a congested district of combustible buildings, including multifamily housing and storage properties. The heavy fuel load inside and outside the buildings and the narrow separations between buildings created an ideal environment for rapid multibuilding fire growth. The wind was strong, gusting up to 48 mph (80 kph). The water supply was inadequate to support master streams, and some sprinklered properties had broken piping that depleted the water supply without fighting the fire. Eventually, hundreds of buildings over 17 blocks were destroyed. Damage was estimated at $4 million.
   More recently, a 2004 fire in Richmond, Virginia, spread over 20 city blocks and involved more than 25 properties. Wind gusting up to 23 mph (38 kph) caused flaming brands and embers to travel the short distances to neighboring buildings.

3. Untreated wood shingles, San Jose, CA, 2002
   A fire began in a two-to-seven-story residential and shopping complex under construction. Sprinklers were installed in about 20 percent of the complex at that point, but all were turned off because of ongoing work. Flying brands and embers spread fire up to a half mile (nearly a kilometer) downwind to an apartment and townhouse complex with wood shake roofs built in the 1970s. Total loss was estimated at $90 million.
   A 1982 Anaheim fire also involving wood shingles resulted in an estimated loss of $50 million. The fire, initially reported as a tree fire, spread over several blocks. Untreated wood shingles provided a ready source of secondary ignitions and firebrands, which were transported by high winds, gusting up to 60 mph (100 kph). These hot, dry Santa Ana winds spread damage to 53 structures, for total estimated damages of $50 million.

Source: NFPA Fire Incident Data Organization.

audiences who can act as change agents. And Fire Prevention Week, of which NFPA is the originator and a sponsor, provides heightened attention to fire safety each October.

People can be educated and motivated if approached in the right way. Addressing people effectively may involve nothing more than emphasizing what to do rather than what not to do. This is why an important milestone of the late 1970s was the introduction into the nation's schoolrooms of fire safety education based on sound behavioral principles and good learning techniques.[3]

Product design strategies need to be carefully examined and not treated as simple technological quick fixes. Many design improvements can be undone by product users if the users have not also been educated to the importance of fire-safe product usage. Some product design proposals have high costs relative to the problem they address, and some involve the loss of other significant product performance features, even nonfire safety features. And with any product design strategy, except one driven by consumer demand, there should be concern over the loss of freedom of choice.

Educational programs have concerns, too. Comprehensive, proven fire and life safety curricula are still in very limited use in U.S. schools. Although many schools have some fire safety education, there is a danger that brief exposure to fire safety slogans will be considered an adequate means of teaching fire-safe behavior. This is not the case.

Also, in any fire prevention program, the highest-risk groups tend to be the hardest to reach. The poor may not be able to afford safer products. Small rural communities are too

scattered to be reached efficiently by targeted means of communications. Preschool children are harder to reach with curriculum programs. Elderly people may resist changes in products and practices. This means that a program with less-than-national coverage is likely to miss a disproportionate number of those most in need. The challenge to fire prevention is to recognize this danger and design programs that reach everyone. It can be done. For example, universal fire safety education, particularly in the schools but also in neighborhoods, seems to be a crucial factor in the still lower fire death rates in western Europe and Japan.

Leading Causes of Fire

As noted, hostile fire requires an initial heat source, an initial fuel source, and usually a behavioral error. Therefore, causes can be defined and ranked in terms of any of these three components. Table 3.1.11 provides a consolidated list of leading causes for 1999–2002 U.S. structure fires, based on behaviors and on equipment and other heat sources.

Cause patterns can be quite different between different occupancy groups, as is illustrated in Tables 3.1.12 and 3.1.13, which provide similar leading-cause listings for homes and nonhome structures. Cause profiles for more detailed occupancy groups are updated annually by NFPA's One-Stop Data Shop.

Smoking materials are the number one cause of civilian fire deaths, accounting for more than a quarter of deaths, and most begin with ignition of upholstered furniture, mattresses, or bedding. The ignitability of these items by lighted tobacco products has been declining for some time, due to a federal law restricting mattress construction and a voluntary program by the upholstered furniture industry. The growing popularity of state requirements for fire-safe (reduced ignition strength) cigarettes offers the promise of improvements in the near future.

Intentional fires are the number one cause of property damage for structure fires, accounting for nearly one of every five

TABLE 3.1.11 Leading Causes of U.S. Structure Fires, 1999–2002 Annual Averages*

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Cooking equipment fire	126,800	(25%)	280	(9%)	4,570	(26%)	665	(8%)
Identified cooking equipment	90,200	(17%)	280	(9%)	4,050	(23%)	644	(7%)
Confined cooking fire	36,700	(7%)	0	(0%)	520	(3%)	21	(0%)
Heating equipment fire	65,000	(13%)	340	(11%)	1,470	(8%)	867	(10%)
Confined heating equipment fire	15,500	(3%)	0	(0%)	40	(0%)	11	(0%)
Identified heating equipment	49,500	(10%)	340	(11%)	1,440	(8%)	856	(10%)
Intentional	59,500	(12%)	600	(19%)	1,800	(10%)	1,592	(18%)
Electrical distribution or lighting equipment	45,700	(9%)	240	(8%)	1,210	(7%)	1,087	(13%)
Smoking materials	35,100	(7%)	890	(28%)	2,130	(12%)	627	(7%)
Candle	20,900	(4%)	170	(5%)	1,750	(10%)	468	(5%)
Exposure to other fire	25,500	(5%)	30	(1%)	120	(1%)	497	(6%)
Playing with heat source	17,800	(3%)	220	(7%)	1,430	(8%)	304	(4%)
Clothes dryer or washer	17,300	(3%)	10	(0%)	410	(2%)	118	(1%)
Contained trash or rubbish fire	13,600	(3%)	0	(0%)	40	(0%)	2	(0%)
Lightning	8,000	(2%)	10	(0%)	60	(0%)	295	(3%)

Note: These are the leading causes, obtained from the following list: intentional (from the NFIRS field "cause"); playing with fire (from factor contributing to ignition); confined heating (including confined chimney and confined fuel burner or boiler fires), confined cooking, and contained trash or rubbish (from incident type); identified heating, identified cooking, clothes dryer or washer, torch (including burner and soldering iron), electrical distribution and lighting equipment, medical equipment, and electronic office or entertainment equipment (from equipment involved in ignition); smoking materials, candles, lightning, and spontaneous combustion or chemical reaction (from heat source); and mobile property involved (from mobile property involved in ignition). The statistics on smoking materials and candles include a proportional share of fires in which the heat source was heat from an unclassified open flame or smoking material. Exposure fires include fires with an exposure number greater than zero, as well as fires identified by heat source or factor contributing to ignition when no equipment was involved in ignition and the fires were not intentionally set. Because contained trash or rubbish fires are a scenario without causal information, they are shown at the bottom of the table if they account for at least 2% of the fires. Causal information is not routinely collected for these incidents. The same fire can be listed under multiple causes, based on multiple data elements. Details on handling of unknowns, partial unknowns, and other underspecified codes may be found in the Appendix.

These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest ten, and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation.

*Excluding the events of September 11, 2001.

Source: NFIRS and NFPA survey.

TABLE 3.1.12 Leading Causes of U.S. Structure Fires in Homes, 1999–2002 Annual Averages

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Cooking equipment fire	105,400	(28%)	270	(9%)	4,230	(28%)	519	(10%)
Identified cooking equipment	75,600	(20%)	270	(9%)	3,750	(25%)	509	(9%)
Confined cooking fire	29,800	(8%)	0	(0%)	470	(3%)	10	(0%)
Heating equipment	53,700	(14%)	320	(11%)	1,270	(8%)	637	(12%)
Identified heating equipment	40,300	(11%)	320	(11%)	1,240	(8%)	628	(12%)
Confined chimney or flue fire	10,600	(3%)	0	(0%)	10	(0%)	7	(0%)
Confined fuel burner or boiler malfunction or fire	2,900	(1%)	0	(0%)	10	(0%)	2	(0%)
Intentional	34,400	(9%)	550	(19%)	1,500	(10%)	738	(14%)
Electrical distribution or lighting equipment	32,400	(9%)	220	(8%)	960	(6%)	679	(13%)
Smoking materials	24,800	(7%)	850	(29%)	1,900	(12%)	455	(8%)
Candle	18,200	(5%)	160	(5%)	1,640	(11%)	392	(7%)
Exposure to other fire	15,800	(4%)	30	(1%)	90	(1%)	319	(6%)
Playing with heat source	14,000	(4%)	220	(8%)	1,360	(9%)	249	(5%)
Clothes dryer or washer	13,300	(4%)	10	(0%)	280	(2%)	97	(2%)

Note: These are the leading causes, obtained from the following list: intentional (from the NFIRS field "cause"); playing with fire (from factor contributing to ignition); confined heating (including confined chimney and confined fuel burner or boiler fires), confined cooking, and contained trash or rubbish (from incident type); identified heating, identified cooking, clothes dryer or washer, torch (including burner and soldering iron), electrical distribution and lighting equipment, medical equipment, and electronic office or entertainment equipment (from equipment involved in ignition); smoking materials, candles, lightning, and spontaneous combustion or chemical reaction (from heat source); and mobile property involved (from mobile property involved in ignition). The statistics on smoking materials and candles include a proportional share of fires in which the heat source was heat from an unclassified open flame or smoking material. Exposure fires include fires with an exposure number greater than zero, as well as fires identified by heat source or factor contributing to ignition when no equipment was involved in ignition and the fires were not intentionally set. Because contained trash or rubbish fires are a scenario without causal information, they are shown at the bottom of the table if they account for at least 2% of the fires. Causal information is not routinely collected for these incidents. The same fire can be listed under multiple causes, based on multiple data elements. Details on handling of unknowns, partial unknowns, and other underspecified codes may be found in the Appendix.

These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest ten, and direct property damage is rounded to the nearest million. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey.

dollars lost. More than half of all the people arrested for arson are juveniles.

Cooking equipment is the leading cause of structure fires and structure fire injuries, and is involved in the majority of unreported home fires. Unattended cooking is the principal behavioral factor.

Heating equipment is the second leading cause of structure fire incidents. Most involve portable or other space heaters; however, the current size of the heating fire problem is much smaller than the peak it reached shortly after the rapid growth in usage of portable and other space heaters in the 1970s and early 1980s.

Child fire play, typically involving matches or lighters, accounts for only 1 of every 14 fire deaths.

Electrical distribution system equipment accounts for a much smaller share of the fire problem than many people realize, ranking no higher than fourth among the leading cause categories for any measure of loss, except for property damage, where it ranks second, reflecting the fact that many such fires are in concealed spaces and are hard to attack. The widespread use and enforcement of NFPA 70, *National Electrical Code*®, is probably the primary reason why electrical systems are not among the leading causes of fire. Moreover, even a fire cause such as this, which seems to be solely an equipment problem, usually involves human error. One benchmark study found that 61 percent of home electrical fires involved code violations, particularly the general workmanship provisions.[4] Exposed elements, such as cords, are even more subject to abuse by occupants.

FIRE PROTECTION

Recognizing that prevention will never be 100 percent successful, it is necessary to plan and design so as to mitigate damages when fire occurs. The various strategies to do this constitute what is usually called fire protection. It is important to remember that fire protection requires the development of an integrated system of balanced protection that uses many different design features and systems to reinforce one another and to cover for

TABLE 3.1.13 Leading Causes of U.S. Nonhome Structure Fires, 1999–2002 Annual Averages*

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Intentional	25,100	(18%)	40	(22%)	300	(12%)	872	(27%)
Cooking equipment fire	19,100	(14%)	10	(4%)	320	(13%)	126	(4%)
Identified cooking equipment	12,300	(9%)	10	(4%)	270	(11%)	114	(4%)
Confined cooking fire	6,800	(5%)	0	(0%)	50	(2%)	11	(0%)
Electrical distribution or lighting equipment	13,200	(9%)	20	(9%)	250	(10%)	399	(12%)
Heating equipment fire	10,900	(8%)	10	(8%)	210	(9%)	212	(7%)
Identified heating equipment	8,900	(6%)	10	(8%)	200	(8%)	209	(7%)
Confined heating equipment fire	2,000	(1%)	0	(0%)	10	(0%)	3	(0%)
Smoking materials	9,900	(7%)	40	(24%)	220	(9%)	153	(5%)
Exposure to other fire	9,700	(7%)	0	(2%)	30	(1%)	159	(5%)
Contained trash or rubbish fire	9,000	(6%)	0	(0%)	20	(1%)	1	(0%)
Torch, including burner or soldering iron	4,300	(3%)	10	(5%)	120	(5%)	127	(4%)
Playing with heat source	3,900	(3%)	0	(2%)	90	(4%)	56	(2%)
Clothes dryer or washer	3,800	(3%)	0	(0%)	130	(5%)	17	(1%)
Lightning	2,300	(2%)	0	(1%)	10	(0%)	95	(3%)
Spontaneous combustion or chemical reaction	2,100	(2%)	0	(0%)	20	(1%)	67	(2%)

Note: These are the leading causes, obtained from the following list: intentional (from the NFIRS field "cause"); playing with fire (from factor contributing to ignition); confined heating (including confined chimney and confined fuel burner or boiler fires), confined cooking, and contained trash or rubbish (from incident type); identified heating, identified cooking, clothes dryer or washer, torch (including burner and soldering iron), electrical distribution and lighting equipment, medical equipment, and electronic office or entertainment equipment (from equipment involved in ignition); smoking materials, candles, lightning, and spontaneous combustion or chemical reaction (from heat source); and mobile property involved (from mobile property involved in ignition). The statistics on smoking materials and candles include a proportional share of fires in which the heat source was heat from an unclassified open flame or smoking material. Exposure fires include fires with an exposure number greater than zero, as well as fires identified by heat source or factor contributing to ignition when no equipment was involved in ignition and the fires were not intentionally set. Because contained trash or rubbish fires are a scenario without causal information, they are shown at the bottom of the table if they account for at least 2% of the fires. Causal information is not routinely collected for these incidents. The same fire can be listed under multiple causes, based on multiple data elements. Details on handling of unknowns, partial unknowns, and other underspecified codes may be found in the Appendix.

These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest ten, and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation.

*Excluding the events of September 11, 2001.

Source: NFIRS and NFPA survey.

one another in case of the failure of any one. Defense in depth and engineered redundancy are concepts that are also relevant here. The process of achieving that integration, balance, and redundancy to attain fire safety objectives is the essence of fire protection engineering, including codes and standards.

This means that success is not measured by the extent of use of any one technology or system or code. Success is measured by the extent of use of effectively designed, integrated fire protection systems. No one system should be considered disposable, and no one system should be considered a panacea.

Once fire has started, the first opportunity to reduce its impact comes in the design of burnable items, that is, the choice of materials and products and their environments. Both the growth of the fire from small to large and its spread along vertical or horizontal surfaces may be slowed through such design.

Active fire protection systems provide the next opportunity. Automatic detection systems will tend to activate first, followed by automatic sprinklers or other automatic suppression systems, although this will vary depending on the design of the detection and suppression systems.

Passive fire protection provides the final opportunity to stop the fire and smoke but also plays an essential role in providing automatic systems with a manageable fire to act on. Passive protection is designed to confine fire and smoke in zones, a concept called compartmentation. Special attention is given to protection of the building's structural integrity and the spaces through which occupants will move to safety.

Occupant evacuation depends on effective detection and a system to alert occupants, along with a total fire safety design that will defend the occupants where they are or provide

protected routes to safe refuges, inside or outside the building. Evacuation also depends on the knowledge of the occupants.

MATERIALS, PRODUCTS, AND ENVIRONMENTS

If prevention fails, the first opportunity to reduce fire damage comes in the design of materials, products (including assemblies), and environments so as to slow down the growth and spread of fire. Tables 3.1.14 through 3.1.16 show that most structure fires never grow beyond the first involved room, but most deaths and property damage occur in the 29 percent of fires that do. This pattern holds for homes and for structures other than homes. Clearly, then, a fire that can be slowed in its growth so that it can be discovered and controlled before fire leaves the first room is likely to result in far less damage to people and property. (Injuries are something of an exception, as they are almost as likely to occur in small fires as in large ones.)

The following are some of the fire protection approaches that may be taken under this overall strategy:

1. Restrict materials used in contents and furnishings.
   - Reduce the heat release rate.
   - Reduce the smoke generation rate.
   - Prevent unusual toxic hazard relative to quantity of smoke generated.
2. Add fire retardant to materials.
   - Slow the growth of the heat release rate.
3. Use fire-resistive barriers.
   - Slow the spread of fire to large secondary items.
4. Restrict the total fuel load.
   - Limit contents based on total fuel potential.
5. Restrict linings of rooms to prevent rapid flame spread.
   - Restrict wall coverings.
   - Restrict ceiling coverings.
   - Restrict floor coverings.
6. Restrict materials in concealed spaces.
   - Restrict concealed combustibles.
   - Restrict concealed space linings.
7. Require safe handling of large quantities of potential fuel.

With regard to the last point, large quantities of combustible or flammable liquids or gases are the most obvious examples of materials that could make a small fire huge very quickly. It is important to handle and store these materials safely, following procedures such as those in NFPA 30, *Flammable and Combustible Liquids Code,* NFPA 54, *National Fuel Gas Code,* and NFPA 58, *Liquefied Petroleum Gas Code.* Unusually hazardous environments, such as oxygen-enriched atmospheres, also receive special attention.

DETECTION AND ALARM

The impact of automatic detection and alarm systems has been particularly great in homes. From less than 5 percent of homes

TABLE 3.1.14 Sizes of Structure Fires, 1999–2002

	Fires (%)	*Civilian Deaths (%)*	*Civilian Injuries (%)*	*Direct Property Damage (%)*
Confined or contained fire	13	0	3	0
Confined to object of origin	32	6	18	7
Confined to room of origin	26	17	37	13
Extended beyond room of origin	29	77	41	80
Total	100	100	100	100

Source: National estimates based on NFIRS and NFPA survey data.

TABLE 3.1.15 Sizes of Home Fires, 1999–2002

	Fires (%)	*Civilian Deaths (%)*	*Civilian Injuries (%)*	*Direct Property Damage (%)*
Confined or contained fire	13	0	3	0
Confined to object of origin	31	6	16	7
Confined to room of origin	29	17	37	15
Extended beyond room of origin	28	78	43	79
Total	100	100	100	100

Source: National estimates based on NFIRS and NFPA survey data.

TABLE 3.1.16 Sizes of Nonhome Fires, 1999–2002

	Fires (%)	*Civilian Deaths (%)*	*Civilian Injuries (%)*	*Direct Property Damage (%)*
Confined or contained fire	13	0	3	1
Confined to object of origin	35	12	30	8
Confined to room of origin	20	19	33	10
Extended beyond room of origin	32	70	34	81
Total	100	100	100	100

Source: National estimates based on NFIRS and NFPA survey data.

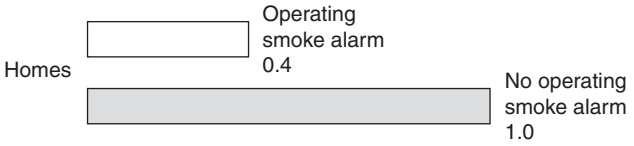

FIGURE 3.1.9 Death Rate per 100 Reported Fires by Smoke Alarm Status (Source: NFPA Fire Analysis and Research)

having smoke alarms in 1972, the United States has risen to a position where 96 percent of homes had at least one smoke alarm in 2004.[5] Smoke alarms cut the risk of dying in a home fire by more than half (Figure 3.1.9 and Table 3.1.17). Thousands of lives have been saved through the widespread use of home smoke alarms.

This success has been achieved in several stages. The initial surge in smoke alarm usage was driven primarily by manufacturer advertising of an attractive, affordable product and secondarily by public service announcements promoting home smoke alarms. Since then, state and local laws have come along to help complete the process of equipping U.S. homes with smoke alarms, which is important, because more than 40 percent of reported home fires occur in the tiny fraction of homes without smoke alarms. In 1977, most states had no home smoke alarm requirements of any kind. By 1983, most states had a home smoke alarm law, but most states still did not cover existing single-family homes, by far the largest segment of the population. By 1988, most states had laws that extended to all homes, new or existing, but most still did not mandate code-compliant, every-level coverage. The trend in state laws is clear—more complete and more thorough laws—but the process is still far from complete.

TABLE 3.1.17 Smoke Alarm Status in Homes, 1999–2002

Smoke Alarm Status	*Fires (%)*	*Civilian Deaths (%)*	*Death Rate per 100 Fires*
Smoke alarm operated in nonconfined fire	25	26	0.7
Smoke alarm alerted occupants in confined fire	18	0	0.0
Subtotal—operating smoke alarm	43	26	0.4
Smoke alarm present but failed to operate in nonconfined fire	9	19	1.5
No smoke alarm present in nonconfined fire	32	55	1.2
Smoke alarm did not alert occupants in confined fire	11	0	0.0
Subtotal—no operating smoke alarm	52	74	1.0
Fire too small to operate smoke alarm in nonconfined fire	5	0	0.0
Total	100	100	0.7

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire.

Source: NFIRS and NFPA survey.

Based on reported nonconfined fires, as shown in Table 3.1.17, about one in four smoke alarms does not operate when challenged by a fire large enough to operate it. Nonoperational smoke alarms typically are that way because of dead or missing batteries. Frustration over nuisance alarms, which typically outnumber real fire alarms by an order of magnitude, may be a factor in battery removal. Sensitivity drift, which is a gradual shift in the range of fire effects that will activate the smoke alarms, is an example of the problems that can affect older units. Smoke alarms more than 10 years old should be replaced, and this affects tens of millions of units now in use.

The success of smoke alarms in the home—and the importance of completing the job of providing complete coverage by operational smoke alarms in all homes—should not obscure the fact that automatic detection and alarm systems are an important part of an integrated system of fire protection in *any* property class. Major life-loss fires frequently cite problems with detection or alarm as significant contributing factors. Among the frequently cited problems in major fires with large loss of life are (1) the absence of needed systems, (2) misapplication, that is, using equipment or systems that were not appropriate for the property, (3) lack of maintenance, and (4) improper response by occupants to notification of the fire.

SUPPRESSION

Automatic sprinklers are highly effective elements of fire protection systems design for buildings. When sprinklers are present, the chances of dying in a fire and property loss per fire are cut by one-half to two-thirds, compared to fires reported to fire departments where sprinklers are not present.[6] Furthermore, this simple comparison understates the potential value of sprinklers, because it is based on data that combines not only all sprinklers, regardless of type, coverage, or operational status, but all types of automatic extinguishing systems. When new data coding is fully in place and complete, well-maintained, properly installed and designed systems can be isolated, sprinkler effectiveness would be seen as even more impressive.

The new coding is sufficiently well established to support estimates that sprinklers operate in 93 percent of fires that are in their coverage area and large enough to activate them. When they operate, they are deemed effective in 96 percent of cases. Therefore their operating reliability is estimated as 93 percent and their effective reliability is estimated as 89 percent (93% × 96%).[6] Figure 3.1.10 shows how operational reliability varies by property use. Note that the storage category extends to sheds, garages, silos, and other buildings quite different from warehouses.

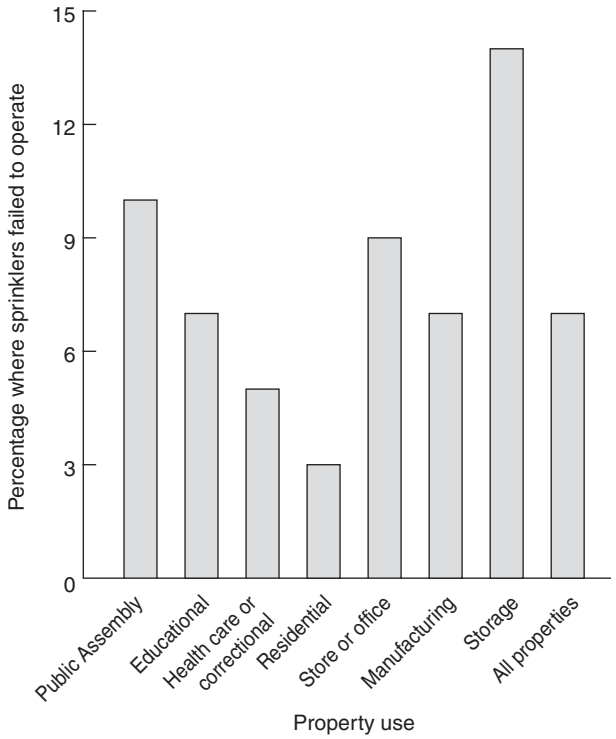

FIGURE 3.1.10 Estimated Operating Reliability of Sprinklers. Note: Figures exclude confined fires and fires coded as too small to test operationality. Data have been recoded when reported performance conflicted with reported reasons for unsatisfactory performance. (Source: 1999–2002 NFIRS and NFPA survey)

When sprinklers fail to operate, the reason given in 65 percent of the cases is that the system was shut off. Other reported reasons are defeating of the system by manual intervention (16%), lack of maintenance (11%), inappropriate system for type of fire (5%), and damage to system component (3%).

When operating sprinklers are not effective, the reason given in 55 percent of the cases is that agent did not reach the fire. Other reported reasons are not enough agent released (31%), inappropriate system for type of fire (7%), damage to system component (5%), and defeating of the system by manual intervention (2%).

In recent years, particular attention has gone to fast-response residential sprinklers for the home. The evidence of their potential for substantial reductions in loss of life and property is clear, but usage is still quite limited. Several communities have adopted requirements for these new sprinklers in new housing developments, and their experience provides the principal real-world proof to date of the tremendous fire protection value such systems deliver. The 2006 edition of NFPA *101*®, *Life Safety Code*®, for the first time mandates the installation of automatic sprinklers in all new one- and two-family dwellings.

The suppression strategy for fire protection involves much more than home sprinklers or even sprinklers in general. A 2002 survey found that 69 percent of U.S. households had at least one fire extinguisher.[7] A 2003 survey found a very similar 71 percent of U.S. households reported having at least one extinguisher, including 34 percent that reported having more than one extinguisher.[8] As with home smoke alarms beginning in the 1990s, it appears that many home fire extinguishers in use are past the age at which they need to be replaced

Non-water-based automatic extinguishing systems are important for some hazards. At eating and drinking establishment fires, for example, only 43 percent of reported automatic extinguishing systems are sprinklers, while another 43 percent are dry chemical systems, such as stovetop or duct protection systems.[6]

In the second half of the 1980s, the world became aware of and concerned about the potentially adverse environmental impacts of suppression systems using halogenated agents (the so-called halon/ozone problem). This development has led to research on alternative fire protection technologies and new agents for critical electronic facilities. It also serves to underline the importance of considering major nonfire factors in any fire protection design.

CONFINING FIRES

The design of building features to contain fires and their effects effectively is one of the most technically complex aspects of fire protection and is certainly the most difficult to evaluate statistically. In all the other phases—prevention, detection, suppression, evacuation—systems thinking also is essential, but it is at least possible to focus attention on one set of products or systems or occupants. But in fire confinement systems, thinking is both essential and unavoidable, because one must deal with every facet of building design and operation. One must consider not only the direct effects of wall assemblies, ceiling/floor assemblies, door assemblies, and the like on fire confinement but also their effectiveness in creating the design conditions assumed by every other part of the overall fire protection system.

The effectiveness of detectors and sprinklers can be demonstrated to some degree by comparisons of fire experience in buildings that have these systems to buildings that do not. Unfortunately, however, every building has walls, floors, ceilings, and doors, and the various types of assemblies have proved too diverse to be routinely documented in the national fire databases. The best analysis possible with existing statistics shows that, for many property classes, the proportion of fires confined to the room of origin rises as the type of construction becomes more fire protective, from unprotected wood frame to fire-resistive.

Problems with building in effective fire confinement tend to be more subtle, too. For detectors and sprinklers, the leading problem is turning off or disabling the equipment—a clearcut, yes/no change that is easy to document. For fire confinement features, the problems tend to be more a matter of degree—that is, barriers partially breached for utility networks, some but not all doors blocked open, and so forth.

Setting the context for this important strategy therefore must be approached in other ways. One is to point out the strong correlation between fire damage (i.e., to life and property), and fire spread, as was done in Tables 3.1.14 through 3.1.16. Also, the majority of fatal fire victims, including roughly one-third of the victims of fatal fires in structures other than homes, are

located away from the room of fire origin. What these figures indicate is that there are still many fatal victims of fire who might be saved by strategies that block or delay the passage of fire and smoke between rooms and floors—strategies of fire protection design for fire confinement.

Patterns are quite different in the United Kingdom. Whereas a majority of fatal U.S. fire victims are located outside the room of fire origin, a clear majority of fatal UK fire victims are located in the room of fire origin. Part of the reason may be that UK dwellings typically use a less open floor plan, with more separation of rooms by walls and doors. By keeping these doors closed to lower heating costs, UK households would also be expected to reduce the spread of fire and smoke beyond the room of origin, thereby reducing the number and share of fatal victims outside the room of fire origin as well. Some of the options available for fire confinement are the following:

1. Use construction barriers to block fire spread between zones.
   - Wall assemblies
   - Ceiling/floor assemblies
   - Barriers between occupied and concealed spaces
   - Firestopping in concealed spaces
   - Exterior barriers to vertical spread between floors
2. Design doors and windows to block fire spread between zones.
   - Fire door assemblies
   - Window restrictions to block spread between buildings
3. Separate buildings enough to prevent fire spread between buildings.
4. Regulate design and operations of ducts to permit shutoff of air movement in fires.
5. Regulate design and operation of systems for heating, venting, and air conditioning to prevent their serving as mechanisms to transfer smoke and gases into uncontaminated occupied areas.

Barriers around concealed spaces are of importance for two reasons. First, fires in concealed spaces cannot hurt people until smoke or flames break out into occupied spaces. Second, fires in occupied spaces may spread faster if they break into concealed spaces because many interior barriers do not extend into concealed spaces. For example, fire may spread vertically through concealed wall spaces if they are not firestopped at each floor or horizontally through concealed floor/ceiling spaces if the walls do not extend past the suspended ceilings that many buildings have below their main ceilings.

Exterior flame spread can occur in several ways, all of which must be addressed. Flying brands or heat from other fires can ignite exterior materials. Flames from one floor can "lap" up the exterior walls to ignite combustible materials on other floors by radiation from flame fronts.

Large losses of life or property are virtually unknown in buildings that comply with the fire protection requirements of modern codes. This is clear evidence of their effectiveness. Nevertheless, large losses continue to occur because so many buildings are not in compliance with modern codes. A major reason is the frequent exclusion of existing buildings from many requirements by "grandfathering" or a lack of retroactive application of codes. Even where good codes are on the books, enforcement may be hurt by a scarcity of resources in overburdened building and fire departments. And some communities do not routinely update their codes, which can create areas of vulnerability. Sustained, consistent attention to fire safety is key to the long-term success of an integrated system design for fire protection. Furthermore, universal application is essential to make a substantial impact on the fire problem.

Balanced fire protection really works, but there are no simple, one-time quick fixes. The installed system must be maintained every day. If this is done, however, such systems will virtually eliminate large losses of life or property. In fact, very large fires usually involve multiple major failures of fire protection design, but sometimes one or two deficiencies can be enough to produce disaster in a building with many excellent features. Remember that fire protection succeeds or fails as a system and is therefore only as sound as its weakest link.

Universality means, in simple terms, that any successful program must go where the fires are, including poor neighborhoods, rural communities, big-city neighborhoods, preschoolers, the elderly, and existing buildings. These are among the hardest groups to reach and the most frequently overlooked in the design of programs. But the fight for U.S. fire safety will largely be won or lost in these areas.

EVACUATION OF OCCUPANTS

Most fire protection strategies are designed to slow or divert the movement of smoke and fire, not stop it, so key questions are whether, where, and how to move the occupants. The occupant evacuation strategy, which includes defending in place and safe interior refuges as possibilities, involves both building design principles and behavioral/educational elements.

Building Design Principles

The building design principles include the following:

1. Two ways out from any location
2. Adequate numbers, sizes, and spacing of exits
3. Adequate capacity of all escape route parts
4. Protection for escape paths
   - Mark exit paths clearly and light them.
   - Restrict fuel loads and finishes in exit paths.
   - Enclose stairways.
   - Use construction barriers to keep fire out.
   - Use smoke control methods to protect atmosphere in exit paths.
   - Ensure structural integrity of exit path.
5. Escape to outside or to protected places, or adequate defense of places where occupants should remain
6. Avoidance of makeshift security systems

Protection of the exit paths begins with construction barriers to separate hallways from other rooms where fire may begin. Stairways need to be enclosed to separate them from all other spaces. Exits from any room or area must be adequate for the number of people those exits will serve. This dictates minimum

numbers and sizes of exits. Multiple exits from a room must be sufficiently separate to provide two distinct paths from the room to the outside so that escape will still be possible if one escape route is blocked. The paths themselves must not involve long distances, which dictates maximum distances from any occupied room to a stairway access or to access to some other protected area. Restrictions on the fuel loads and finishes in areas that serve as parts of exit paths also are needed to prevent rapid spread of fire into and through these paths.

Fire Escape Principles

Once the building is designed for safe evacuation, the occupants have to be educated about the principles of escape behavior:

1. Know whether to escape and where to go (e.g., stay in place, go to safe refuge, go outside).
2. Know two ways out.
3. Get out fast.
4. Practice escape.
5. Check paths for safety before proceeding (e.g., feel the door).
6. Crawl low under the smoke.

It is worth emphasizing the need for practice. Learning the rules of safe escape as slogans is not enough. (That is why it is a matter of concern that in 1999 three-fourths of U.S. households had not developed and rehearsed an escape plan.) If fire occurs, one does not have time to make the mistakes that typically occur during learning. To use an analogy, suppose one has read about driving a car and even passed the state's written test. One does not want the first time behind the wheel to be a drive to the hospital emergency room. The lack of learned confidence in the key behavior could cost time when it can be least afforded.

Most people have not seen a real hostile fire. They have no idea how fast fire can grow or how bad it can get. They are not familiar with the phenomenon of flashover. Therefore, they spend time they cannot afford confirming that there is a fire or gathering up valuables. They also may try to leave by their customary route, even in the face of serious fire hazard. Rehearsing safe behaviors is the only way to be sure that they will be used when necessary.

Special mention should be made of the problems posed by unusually vulnerable groups. Small children will need help to escape and are likely, on their own, to think hiding makes them safe. People who are elderly, handicapped, or impaired by substance abuse are likely to have physical or mental limitations that may present a need for help in escaping. Patients in health care facilities and inmates of confinement facilities present the largest problem, as they are large groups that cannot evacuate on their own. Specific plans need to be developed and rehearsed to address these situations.

SYSTEMS APPROACHES FOR PROPERTY CLASSES

In applying the general principles of fire protection, it usually becomes clear that particular property classes have special considerations that must be understood for an effective systems approach. Figures 3.1.11 to 3.1.14 show the relative importance of different broad property classes in U.S. fires and associated deaths, injuries, and property damage. Note that outdoor fires in trash, brush, and wildland account for half of all fires, but relatively little loss. Homes account for four out of five deaths, three out of four nonfatal injuries, and over half of all direct property damage. Vehicle fires account for nearly three times as many fires deaths as structures other than homes. Home fires account for roughly two-thirds more property damage than fires in all structures other than homes. Table 3.1.18 shows the relative importance of major occupancy groups within the larger category of nonresidential structures excluding dwelling garages.

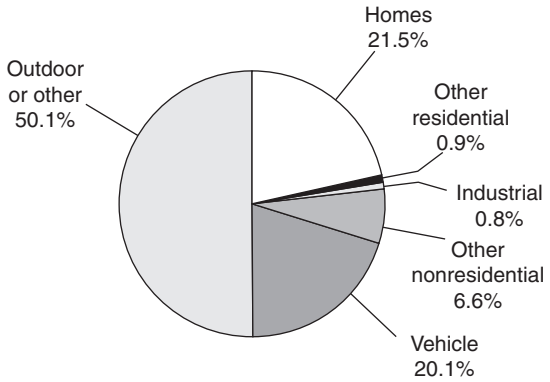

FIGURE 3.1.11 U.S. Reported Fires by Major Property Class, 2000–2004. Note: Excludes deaths and damages from September 11, 2001. (Source: NFPA National Fire Experience Survey)

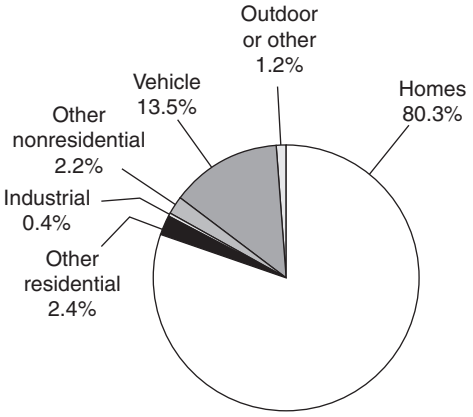

FIGURE 3.1.12 Civilian Deaths in U.S. Reported Fires by Major Property Class, 2000–2004. Note: Excludes deaths and damages from September 11, 2001. (Source: NFPA National Fire Experience Survey)

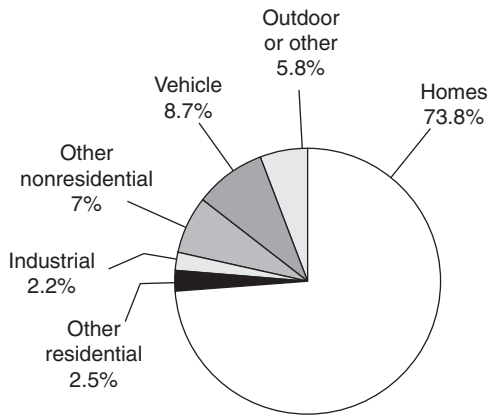

FIGURE 3.1.13 Civilian Injuries in U.S. Reported Fires by Major Property Class, 2000–2004. Note: Excludes deaths and damages from September 11, 2001. (Source: NFPA National Fire Experience Survey)

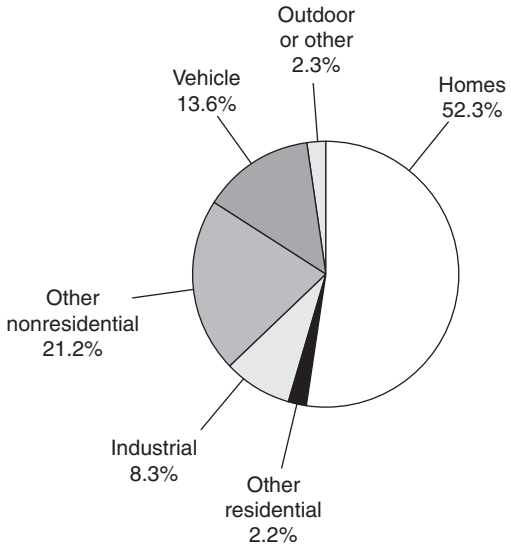

FIGURE 3.1.14 Direct Property Damage in U.S. Reported Fires by Major Property Class, 2000–2004. Note: Excludes deaths and damages from September 11, 2001. (Source: NFPA National Fire Experience Survey)

Notable Fires

Historically, fires resulting in a major loss of life have resulted in important changes in building and fire codes and in standard fire protection or prevention practices. In the early 1900s, four building fires—the Iroquois Theatre in Chicago (1903), the Rhoades Opera House in Boyertown, Pennsylvania (1908), the Lakeview Grammar School in Collinwood, Ohio (1908), and the Triangle Shirtwaist Factory in New York City (1911)—were largely responsible for the appointment in 1913 of the NFPA Committee on Safety to Life. The opening summary of the "Origin and Development of *101*" in the current NFPA *101* states:

> For the first few years of its existence, the Committee devoted its attention to a study of the notable fires involving loss of life and in analyzing the causes of this loss of life. This work led to the preparation of standards for the construction of stairways, fire escapes, etc., for fire drills in various occupancies, and for the construction and arrangement of exit facilities for factories, schools, etc., which form the basis of the present *Code.*

The 1937 fire at the Consolidated School in New London, Texas, tragically pointed out the need for state laws to protect public buildings not subject to municipal ordinance and inspection. Then, in the 1940s, a series of multiple-death fires—including those at the Rhythm Club; the Cocoanut Grove; and the La Salle, Canfield, and Winecoff Hotels—focused national attention on the need for adequate exits and other fire safety features in hotels and public buildings. These fires resulted in major changes to the *Building Exits Code* (as NFPA *101* was then known) over a period of almost 2 decades. NFPA 102, *Standard for Grandstands, Folding and Telescopic Seating, Tents, and Membrane Structures* (included in NFPA *101* since 1994), was the result of still another multiple-death fire of the 1940s—the 1944 Hartford, Connecticut, circus tent fire in which 168 people were killed.

What follows are other examples of code changes following major fires in certain occupancy groups. NFPA has been a force for fire protection and fire safety for more than 100 years. In that time, most of NFPA's influence has come through its codes

TABLE 3.1.18 U.S. Nonresidential Fires and Losses by Major Occupancy Group

Occupancy	*Fires (%)*	*Civilian Deaths (%)*	*Civilian Injuries (%)*	*Direct Property Damage (%)*
Storage excluding dwelling garage	19	19	12	17
Mercantile and office	19	15	19	27
Public assembly	13	8	11	13
Industrial and manufacturing	12	19	26	29
Special property	11	4	4	2
Health care, board and care, correctional	7	15	16	1
Educational	6	0	6	4
Unclassified or unreported	13	19	6	6
Total	100	100	100	100

Source: 1999–2002 NFIRS and NFPA survey data.

and standards, which have changed the rules that guide building specifications and operations and, in that way, have changed the environments in which people live. As in past editions of the *Fire Protection Handbook,* this edition cites examples of major NFPA code changes that responded to needs demonstrated in major fire incidents.

This section describes several of the most dramatic examples of fire experience, organized by occupancy groups, which responded favorably to changes in codes or to changes in the extent of compliance with codes. Because most codes and standards focus on the risk of large fire losses outside the home, this section focuses on major incidents outside the home involving multiple loss of life. In particular, NFPA's fire incident record keeping is best for incidents in which 10 or more people died, and these incidents are used here as the principal tracking mechanism for the impact of codes, standards, and other fire protection requirements. In keeping with the normal approach used by NFPA's statisticians, most incidents are cited anonymously, to keep the emphasis on statistical patterns. In general, only incidents involving 50 or more deaths are given specific identifiers.

Schools

Since NFPA was founded in 1896, NFPA's fire incident records show a total of nine school fires in which at least 10 people died. Two of these are among the deadliest single-building fires in U.S. history. The first of the nine was also the only one not to involve grades K–12. It was a 1903 university building fire in which 11 people died. NFPA files indicate the building had no fire exits and escape was cut off. The second incident, in 1908, was also the second deadliest school fire in history. Inadequate fire escapes, inadequate fire drills, and a building layout that created bottleneck exit paths all contributed to the death toll of 176 at the Lakeview Grammar School in Collinwood, Ohio. A parochial school fire in 1915 was the third of the nine fires and cost 21 people their lives. After the fact, the exits were deemed inadequate, even though they complied with existing laws. Again, the failure to include all exits in fire drills made those drills inadequate and proved critical in this fire, as many exits were not used when they could have made a difference.

The first of three incidents in the 1920s was a 1923 fire that killed 77 people. Fleeing occupants jammed the only stairway serving the Cleveland School of Beulah, South Carolina, and it collapsed during the evacuation. A 1924 fire in a one-room schoolhouse spread rapidly from its origin in a Christmas tree. The fire department's report of the fire said, "the struggling crowd became wedged in the doorway, which was only 3 ft (0.9 m) wide." A total of 33 people died. Finally, a 1927 incident led to 46 deaths when a "crazed farmer" used dynamite to bomb a school.

The deadliest school incident in history stemmed from a gas explosion; 294 people died in the Consolidated School of New London, Texas, in 1937. The next school incident killing at least 10 people came in 1954, when a faulty heating system led to a gas buildup in the attic of a school. Ignition by an undetermined heat source produced a flash fire in an unoccupied area. Delayed discovery allowed the fire to spread into occupied areas, and 15 people died.

The last three incidents took place over 2½ decades, from 1927 to 1954, and all three involved rapidly developing situations—two explosions and a flash fire—that were unlike the earlier incidents. Officials might have been forgiven for believing that the older school fire problem, consisting of too many ordinary combustibles and insufficient or inadequate exits, was essentially under control. If so, that belief proved illusory when the 1958 Our Lady of the Angels School fire occurred in Chicago, Illinois, killing 95 people, 92 of them children.

The reaction to that fire was more rapid, more sweeping, and arguably more effective than the reaction to any other single fire in U.S. history. NFPA codes and standards were quickly revisited, and stricter requirements for interior finish and exiting were established. An April 1959 issue of the *Journal of American Insurance* caught the mood of the country at the enforcement end, noting in an article subhead: "U.S.A., aroused by Chicago lesson, is overhauling its school buildings as never before."

In the nearly four decades since the Our Lady of the Angels fire, there has *never* been another school fire killing 10 or more people. In recent years, no incident has even come close. In the period from 1994 through 1998, grades K–12 averaged one civilian fire death per year—a typical annual death toll for schools since at least 1980. Detailed examination of fatal school fires by NFPA analysts indicates that the few deaths that do occur are all or nearly all adults (e.g., maintenance workers) or juvenile firesetters fatally injured by the fires they set. Innocent children are no longer the victims in school fires. Few lessons have been learned as thoroughly as the ones from the Our Lady of the Angels incident appear to have been learned.

Hospitals

A similar story applies to U.S. hospitals. There were a similar number of incidents in which 10 or more people died, including a 1929 fire that killed 125 people in the Cleveland Clinic Hospital of Cleveland, Ohio, a 1949 fire that killed 74 people in St. Anthony's Hospital of Effingham, Illinois, and a 1950 fire at Mercy Hospital in Davenport, Iowa, that killed 41. The last hospital fire to kill 10 or more people was the Hartford Hospital fire of 1961, in which 16 people died in Hartford, Connecticut. Reports on the fire focused on combustible ceiling tile that led to rapid flame spread down a corridor, delayed reporting to the fire department, and the fact that all the deaths involved doors left open to the corridor. Closed doors meant survival in every case.

The NFPA *Building Exits Code* of 1961 already mandated complete sprinkler systems for hospitals for many combinations of height and construction. The next edition after the Hartford Hospital fire was the 1963 edition, which extended this requirement to even more combinations of height and construction. The 1966 edition changed the name of the document to a wordier version of today's NFPA *101,* signaling right from the cover that this code was not just about exits, as it had not been for some time.

By 1980, when NFPA first developed its nationally representative statistics on the use of sprinklers in buildings that had fires, nearly half (44%) of all fires in facilities that care for the sick were in properties with sprinklers. This undoubtedly meant that most hospitals were sprinklered by then, because it is known from occasional special studies on sprinkler usage that reported fires are more likely to occur in unsprinklered properties. By 1998, the latest year for which statistics are available, 71 percent of fires in facilities that care for the sick were in properties with sprinklers. Because hospitals and clinics are required to comply with NFPA *101* to receive reimbursement under Medicare and Medicaid, other provisions of NFPA *101* are undoubtedly also in nearly universal use. This helps explain why, in the latest available statistics, hospitals averaged fewer than one civilian fire death per year between 1999 and 2002.

The characteristics of the people who still die in hospital fires underline the extent to which NFPA codes have solved the type of hospital fire problem they targeted decades ago. About four of every five hospital fire deaths involve a victim who is so close to the start of the fire as to be described as "intimate with ignition." Smoking and incendiaries dominate the causes of fatal fires in facilities that care for the sick. These circumstances involve very rapid fatal injuries, often too rapid to be reliably prevented by even the best fire protection provisions. Fire prevention strategies are needed and, indeed, the past decade has seen widespread adoption of more aggressive controls and prohibitions on smoking.

Homes for Especially Vulnerable People

During a 4 year period from 1970 to 1973, there were eight care-of-aged facility fires, each killing at least 10 people and collectively killing 112 people. This rapid succession of catastrophic fatal fires stimulated action in a way that the deadliest nursing home fire of all time, which occurred in isolation at the Golden Age Nursing Home of Fitchville, Ohio, on November 23, 1963, and killed 63 people the day after President John F. Kennedy was assassinated, could not. A pattern was found of insufficient fire protection and sprawling, undivided construction based on adding extensions to aging, converted farmhouses. Codes were re-examined, and the new Medicare program provided clout by tying reimbursement eligibility to code compliance with NFPA *101*.

During the period from 1976 through 1985, attention shifted to boarding homes, spurred by a rash of major fatal fires in those facilities in 1979 through 1981. Six severe fires, causing 114 deaths in all, with the first three fires all occurring in the same month, commanded attention. During the period from 1979 to 1984, boarding home residents had a risk of dying in a multiple-death fire that was five times the risk for residents of other residential properties. Analysis of these incidents and other smaller fatal fires showed that many of the residents had characteristics of age or chronic mental illness that should have received ongoing medical attention that the facilities were not licensed or equipped to provide. This gap between the fire protection and other features of the facilities and the needs of their occupants was a more difficult problem than the one posed by the nursing home fires because there were fewer mechanisms to enforce codes.

The factors in what came to be called the "board-and-care" home fire problem were all too familiar and can be summarized as an overall lack of basic fire protection provisions. Contributory factors include inadequate means of egress, combustible interior finishes, unenclosed stairways, lack of automatic detection or sprinkler systems, and lack of emergency training for the staff and residents. Many of the facilities were either licensed as something other than a boarding home (such as a hotel) or were unlicensed, "underground" boarding homes. None of the facilities was provided with automatic sprinkler protection.

There is no particular mystery about how to reduce these risks, either. Enclosed stairs, providing two ways out, avoiding the use of combustible interior finishes, compartmentation, providing automatic detection and sprinkler systems, and training staff and residents in emergency procedures all would greatly reduce the risk of multiple deaths if fire occurs.

These analyses and others consistently point to the difficulty of delivering fire protection to and enforcing codes and standards on the facilities that cater to the poorest and most vulnerable populations. Simply creating and adopting good codes and standards is not enough. State and local authorities must adopt them and enforce them, being sure to pay attention to existing buildings, or this knowledge will lack practical impact where it is most needed.

In 2003, nursing home fires in Connecticut and Tennessee, killing 16 and 14 people respectively, restarted the debate on whether these especially vulnerable Americans are as safe as we believed and wished them to be. NFPA Technical Committees again reviewed the evidence and the options to develop a consensus answer to this question. The *Life Safety Code* added requirements for the sprinklering of all nursing homes, including all existing nursing homes, in the 2006 edition.

Hotels and Motels

From 1900 to the present, 4 of the more than 100 U.S. fires and explosions that killed at least 50 people involved hotels or motels. This compares to 8 in industrial settings, 5 that involved ships, 2 that involved industrial settings and nearby ships, 8 that involved places of assembly, 4 in schools, and 59 in mines. Three of the four hotel fires occurred in a 4 year period, 1943 through 1946—the Gulf Motel fire in Houston, Texas, in 1943, which killed 54 people; the LaSalle Hotel fire in Chicago, Illinois, in 1946, which killed 61 people; and the Winecoff Hotel fire in Atlanta, Georgia, in 1946, which killed 119 people. National conferences on hotel fire safety were convened in early 1947, one by NFPA and another by President Harry Truman; the result included significant changes to the hotel section of NFPA's *Building Exits Code* and model legislation for hotel fire safety, prepared by the Fire Marshals Association of North America, NFPA's member section for fire marshals.

A third of a century later, the 1980 MGM Grand Hotel fire, in Las Vegas, Nevada, inspired an industry response that combined unprecedented widespread code compliance with fire safety provisions that often ran ahead of code requirements. The result has been a dramatic change both in the fire death toll in hotels and motels and in the use of proven fire protection systems in that industry.

In 1981, NFPA published an overview of hotel and motel fire experience leading up to the 85 deaths in the MGM Grand Hotel fire. In the two decades from 1961 through 1980, NFPA

documented 53 hotel or motel fires that each killed at least five people. (In those days, the threshold for a multiple-death fire was three deaths in any property; today, it is five deaths in residential properties.) With more than two fires a year causing at least five deaths apiece, chronic public concern over fire safety when traveling was understandable.

The MGM Grand Hotel fire was not the only fire that shaped public concerns at this time. Certainly, the MGM Grand Hotel fire ran counter to the conventional industry wisdom that fire problems were primarily a matter of older or poorer facilities. MGM Grand was neither. But the MGM Grand fire also was not an isolated incident. Two months after the MGM Grand fire, a second Las Vegas, Nevada, hotel, this one part of a national chain, had a fire that killed 8 people. Then, the year after that, 12 more people died in a fire in another hotel of the same chain. A second chain lost 10 people in each of two fires during each of the 2 years preceding the MGM Grand Hotel fire. These five incidents in a 4 year period combined to create a picture of an industry in need of improvement.

Led by strong industry associations and fire safety–conscious professionals at the major chains, the industry began to respond. In 1980, the year of the MGM Grand Hotel fire, sprinklers were reported present in only one of every nine hotel or motel fires reported to U.S. fire departments. Detectors were reported present in just over one-fourth of reported hotel or motel fires.

An industry-sponsored study of sprinkler usage in 1988 found sprinklers present in roughly half of all properties, suggesting the percentage today is much higher still. The latest data show smoke detectors in more than 80 percent of hotel and motel fires and automatic sprinklers in 40 percent of hotel and motel fires and more than three-fourths of high-rise hotels. It is reasonable to assume that the new level of built-in fire protection had much to do with the dramatic drop in the number of hotel and motel fires since 1980. NFPA statistics from 1988 through 1997 indicated that sprinklers cut the chances of dying in a given fire by 91 percent and also reduced the average property loss per fire by 56 percent.

In terms of the deadliest fires, beginning in 1983, only two hotel or motel fires have killed 10 or more people, and each of them was on the outer fringes of the industry. A 1984 fire killed 15 people in a facility that called itself a rooming house but was classified as a hotel by NFPA because it had too many occupants to qualify as a rooming or boarding house. This facility also included a number of deinstitutionalized former mental patients among its occupants, raising questions about the health care needs of the occupants versus the fact that no such care was provided by the facility. A 1993 fire killed 20 people in a facility licensed for, and principally run for, long-term residents; yet the fire began in, and most deaths occurred in, a section housing transient guests.

In terms of the more familiar names in the lodging industry and the bulk of the facilities in operation, the changes of the past 15 years have moved the fire experience picture in hotels and motels to roughly the same position as nursing homes and hospitals. That is, a steadily shrinking number of fatal victims tend more and more to be people who die in fires they caused or that began very close to them. As with schools and hospitals, so with hotels and motels: the past century has seen dramatic accomplishments—a clear sequence from major fires to major code changes to major changes in the practices in the concerned facilities to major declines in the loss of life due to fire.

Places of Assembly

Seven of the 11 deadliest single-building fires and explosions in U.S. history have involved places of assembly. (The other four were two school fires discussed above, one prison fire, and the 1995 bombing of an Oklahoma City, Oklahoma, office building.) They include the Brooklyn Theater fire of 1876, which killed 285 people and preceded NFPA's founding. Both the Iroquois Theater fire of 1903, which killed 602 people in Chicago, Illinois, and the Rhoades Opera House fire of 1908, which killed 170 people in Boyertown, Pennsylvania, occurred early in NFPA's life and led to an early focus on the dangers posed by inadequate exiting provisions and the kinds of combustible loads that make rapid fire development likely.

From 1909 through 1939, three incidents killed 10 or more people in places of assembly, one of which involved an explosion. A 1919 Louisiana restaurant and dance hall fire led to 25 deaths when relatives rushing into the building to try to save occupants collided with occupants fleeing onto the only exit stairway, leading to the collapse of that stairway. A 1928 dance hall incident, started by ignition of gasoline fumes, killed 38 people. A 1929 nightclub fire spread rapidly via the decorations, and many of the 22 who died took refuge in rooms with no way out.

In 5 years, from 1940 to 1944, three of the worst fires in U.S. history occurred, all involving places of assembly. More than one-fourth of the 746 occupants of the Rhythm Club in Natchez, Mississippi, died in a 1940 fire. Overcrowding, inadequate exits, and highly combustible decorations were all cited as factors in the 207 deaths. Nearly half of the more than 1000 occupants of the Cocoanut Grove nightclub in Boston, Massachusetts, died in a 1942 fire. Overcrowding, inadequate exits, and highly combustible decorations again were cited as key factors in the 492 deaths, with roughly 200 trapped behind one revolving door alone. And 168 of the roughly 7000 patrons at the Ringling Brothers Barnum & Bailey Circus in Hartford, Connecticut, died in a 1944 fire, many of them children.

These three incidents, particularly Cocoanut Grove, are credited with inspiring a rush of tougher codes, focusing on exiting provisions and the use of combustible materials, but also pushing a more comprehensive and appropriate definition of places of assembly. Incredibly, many jurisdictions excluded eating and drinking places from the classification "place of assembly" prior to Cocoanut Grove.

In the half-century since 1944, no incident in a place of assembly has matched the death toll in any of these three incidents, and only one incident came close—the 1977 Beverly Hills Supper Club fire in Kentucky, which killed 165 people. This fire echoed many of the problems of the 1940s incidents. The 165 victims represented less than 10 percent of the 2400 to 2800 occupants reportedly on site, but those occupants represented two to three times the facility's capacity, indicating severe overcrowding. All types of exiting problems were also recorded. More recently, the 2003 Station nightclub fire in Rhode Island, where 100 people died, also involved materials that promoted

rapid fire spread, but also involved an unusual and unsafe heat source—indoor fireworks. And, far more than in the earlier incidents, there was an awareness of how much protection was lost because of the absence of sprinklers.

In terms of accomplishments, the post–Cocoanut Grove code changes worked. Large-loss-of-life fires have not occurred where code compliance has been observed, except for rapid-onset situations, such as explosions. But large-life-loss incidents do continue to occur—less severe individually but still too large and too frequent to be acceptable—because of spotty enforcement. One type of incident, most dramatically embodied in the Happy Land social club fire of 1990, in New York City, has occurred in each of the last five decades and is worthy of special attention—an arson fire using accelerants started in a location that interferes with normal exiting.

The first of these incidents is also the least well documented. A 1947 gambling hall fire began when a gallon of gasoline was thrown on the floor and ignited. The exiting provisions are not known, but 15 people died in the fire. A 1965 restaurant fire began when an arsonist poured gasoline at the main entrance. The 40 to 50 occupants may have encountered a security delay at the rear exit, which also was too narrow; 13 people died, or roughly one-fourth to one-third of the number present.

The succeeding fires involved even worse exiting problems and death tolls that accounted for even larger fractions of the total occupants. A 1973 lounge fire was set in the stairway of the lounge's normal exit. The second exit was poorly marked, and the windows were blocked or barred. The death toll of 32 people represented roughly half of the occupants present. A 1976 fire was set in the only exit of a New York City social club, leaving only windows for escape. The death toll of 25 represented roughly half of the occupants present.

A 1990 arson fire was set in the main exit of New York City's Happy Land social club. There were no other marked exits, nor were the windows useable for escape. Only six of the 93 occupants survived, five by going out an obscure, normally locked door that one of them had a key to, and the sixth by literally running through the fire at the entrance, sustaining critical burns.

None of these properties had complete sprinkler systems or sprinklers in the area of the fire, so they emphasize the value of such systems. But taken together, they also illustrate how the consequences become worse as the deviation from code-compliant exiting provisions becomes worse. If there is literally nowhere to go, everyone will die.

As a result of the 2003 Station nightclub fire, the 2006 *Life Safety Code* was amended to require automatic sprinklers in all new nightclubs with an occupancy load of 50 or more and all existing nightclubs with an occupant load of 100 or more.

Property Classes and Code Compliance

Finally, consider what it will take to accomplish even more in terms of life safety from fire in any of the types of properties discussed thus far. People who die in fires do so in either the *kinds of fires* that codes do not reach or the kinds of *properties* that codes do not reach due to lack of adoption or lack of enforcement.

For schools and hospitals, codes reach nearly everywhere. These properties are tightly controlled. Nursing homes and the lodging industry are not quite so tightly controlled, but are very broadly compliant. Both have active industry associations that have broad membership and are sensitive to fire safety. Both industries have difficulty primarily in exerting control over properties on the fringes of the industry, such as board and care homes. Notwithstanding the emergence in recent years of legitimate board and care homes that provide only personal care to residents who need nothing more, a sizable group of facilities, long referred to as board and care homes, provides only lodging to residents who legitimately need health care as well.

Places of assembly have the problem of widespread noncompliance far more than do hotels or nursing homes. Proportionally fewer properties belong to national chains, which in other industries often lead the move to greater fire safety. Industry associations have less of a track record as leaders in fire safety and, more importantly, capture a smaller proportion of their industry's operating facilities. There is more, and more frequent, turnover in these facilities, which also hampers enforcement efforts, because educating owners and managers about fire safety is a gradual, incremental process, which has to start all over whenever an existing facility "goes under" and a new facility takes its place.

Despite all this, the deadliest fires (i.e., 50 or more deaths) in places of assembly are less frequent and less deadly than they were a half-century ago, which suggests that enforcement and sensitivity to fire safety is better among at least the largest facilities. This is an achievement worth building on.

Manufacturing Facilities

Manufacturing properties are worthy of note because they also include a significant single incident that led to dramatic changes in NFPA codes. The 1911 Triangle Shirtwaist Company fire in New York City still ranks as the deadliest manufacturing facility fire (excluding explosions) in U.S. history. NFPA code requirements for the workplace, particularly exiting provisions, were substantially changed as a result of that fire.

Since NFPA's founding, according to NFPA records, most fires or explosions in manufacturing facilities causing 10 or more deaths involved explosions, or to a lesser extent flash fires or fuel spills. Few such fires are truly comparable to the Triangle Shirtwaist Company fire. One such fire took place only 2 years after the Triangle Shirtwaist Company fire and also involved a New York state clothing manufacturer. The death toll in that fire reached 35 because an external fire escape was engulfed in flames early in the incident.

More than 40 years later, two more garment factory fires, one like the Triangle Shirtwaist Company located in New York City, occurred in 1957 and 1958, killing 15 and 24 people, respectively. In the former, one stairway was open and filled early with smoke, and one fire escape was enveloped in flames and collapsed. In the latter, fire filled a key stairway early when the door to the stairway was wedged open. In 1991, a North Carolina food processing plant fire killed 25 people. NFPA investigators and the U.S. Occupational Safety and Health Administration (OSHA) both pointed to the similarities between this incident and the Triangle Shirtwaist Company fire, in terms of grossly inadequate exiting provisions.

A battle for life safety in manufacturing facilities is still being fought with respect to explosions, which involve a number

of different NFPA codes. During the five decades from 1916 through 1965, the United States averaged just over four manufacturing facility explosions per decade that each killed 10 or more people. During the three decades of 1966 through 1995, the average was just under three such incidents per decade. It is on the thin reed of one fewer incident per decade, on average, that we can say there has been some progress, but the 2000 New Mexico pipeline explosion is a reminder that this hazard still causes significant life loss.

As with fire safety in places of assembly, but even more so, an undeniable century of accomplishment in writing safer codes has been undercut by far less clearcut progress in achieving code compliance. OSHA and the U.S. labor movement, both strong champions of a safer industrial workplace in years gone by, have been substantially weakened in recent years. Perhaps they can still be part of a revitalized coalition, with NFPA, concerned state and local authorities, and the thousands of responsible fire safety–conscious owners and managers of the better manufacturing sites, to improve a situation that still has much room for improvement.

Mines

Mining is cited here to end this section on a true high note, even though NFPA had little input into what has been one of the most remarkable centuries of accomplishment in any class of properties. Most of the 101 U.S. fires and explosions that have killed 50 or more people from 1900 to 1999 have been in mining, specifically coal mining. (Only three of the 59 mining incidents were not coal mines; they were metal mines.)

In the first decade that NFPA tracked, from 1900 through 1909, 15 of the 59 mining incidents occurred, killing a total of 2286 people. At the start of the second decade, from 1910 through 1919, the U.S. Bureau of Mines was formed (in 1910). In that second decade, there were 18 incidents, killing a total of 1882 people. Sometime in the second and third decades, the U.S. Bureau of Mines began issuing rules and guidelines, because by the end of the third decade (1929), they were publishing summaries of what they issued. In the third decade, from 1920 through 1929, there were a total of 14 incidents, killing a total of 1407 people.

In the fourth decade, from 1930 through 1939, during the Great Depression, there were only two incidents, killing a total of 136 people. NFPA 493, *Spontaneous Heating and Ignition of Coal and Other Mining Products,* was first issued in 1936, but, by then, the big decline in the frequency of serious incidents had already occurred.

In the fifth decade, from 1940 through 1949, which includes the wartime demands of World War II, there were seven incidents, killing a total of 533 people. The next 3 decades had one incident each, killing a total of 288 people. The decades from 1980 through 1989 and 1990 through 1999 have had no such incidents. Even though the 2001 Alabama coal mine explosion was one of the 10 deadliest of its decade, its 13 deaths fell far short of the threshold of 50 that was regularly exceeded in the early 20th century.

A natural question, which also applies to the fire experience of garment manufacturing facilities discussed previously, is how much the reduction in fire deaths reflects a reduction in economic activity and associated exposure. Employment in coal mining peaked around the end of the second decade of the twentieth century and declined dramatically until about 1970, when it rose sharply for about a decade, then began declining again to its present levels, the lowest in this century. The decline in mining incidents killing 50 or more people and in the number of people killed in those incidents has been even steeper than the decline in employment in the industry.

ORGANIZING FOR FIRE PROTECTION

Fire department organization is a critically important element of fire protection. The effectiveness of the organization and management of U.S. fire departments determines whether the more than $28 billion (2003 dollars) in annual expenditures for local fire protection are spent well or badly. More important, it also determines whether the more than one million U.S. fire fighters will be used effectively and safely. Protecting the community and protecting themselves are dual responsibilities of a fire department, and both are more likely when planning and preparation are fully used.

Table 3.1.19 gives a brief overview of the resource base of local fire departments. Only 12 percent of local fire departments are composed entirely or mostly of career fire fighters, but they protect 61 percent of the population, and 27 percent of all local fire fighters are career fire fighters. The majority of volunteer fire fighters serve in small rural communities of less than 2500 population.

Figure 3.1.15 shows that the workload for fire departments more than doubled from 1980 to 2004, led by a nearly threefold (179%) increase in emergency medical calls, which constitute now three-fifths of all fire department calls (Figure 3.1.16). Since a third of communities still do not offer emergency medical service, those that do may find medical calls running at 80 to 90 percent of their calls.

TABLE 3.1.19 Selected U.S. Local Fire Department Resources, 2005

Resource	*Number*
Career fire fighters	294,100
Volunteer fire fighters	807,150
Total fire department expenditures (in 2003)	$27.9 billion
Fire departments	30,500
Fire stations	48,400
Pumper trucks (at least 500 gpm)	81,200
Percentage of departments providing emergency medical services (EMS)	67
Percentage of departments providing hazardous materials response	80
Percentage of departments providing wildland fire fighting	85
Percentage of departments providing technical rescue service	57

Source: USFA/NFPA Second Fire Service Needs Assessment Report.

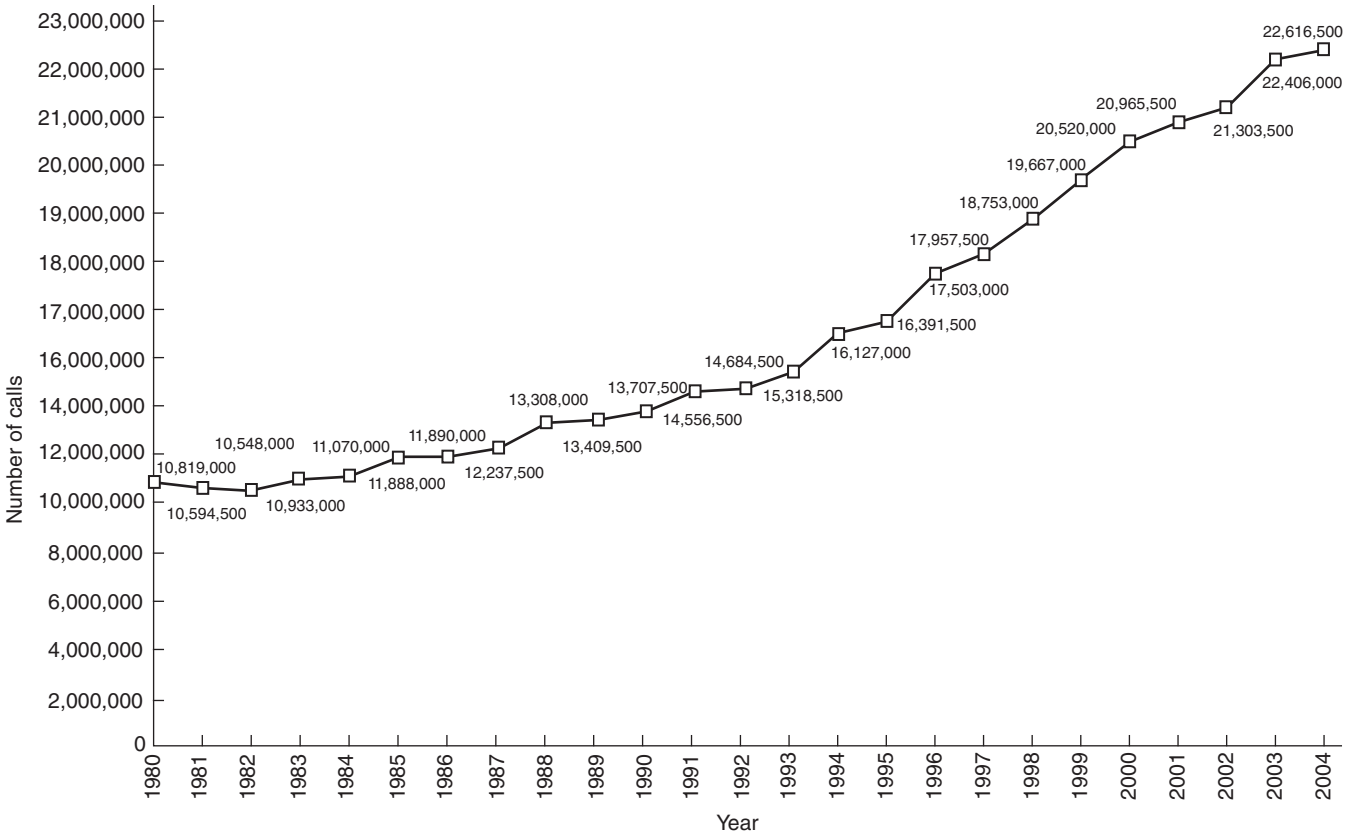

FIGURE 3.1.15 Fire Department Emergency Calls, 1980–2004 (Source: NFPA National Fire Experience Survey)

Fires now constitute only 1 of every 14 fire department calls, or 1 of every 9 mutual-aid calls (see Figure 3.1.16). But fire calls demand the majority of fire department resource utilization, including stress on people and equipment. The potential to overload a department's total resources still comes primarily from fires.

Hazardous materials calls are a small fraction of the total but they also can involve a lot of resources per incident. False alarms today are more often nonemergency activation of automatic detection systems and less often the malicious box-alarm activations that were of so much concern in the 1960s and 1970s. Since 1997, false alarms have been more common than fires.

The increasingly diverse responsibilities of the modern fire department are both an opportunity and a challenge. On the one hand, more duties mean more value delivered to the community. On the other hand, more duties mean a greater chance of overloading the system with simultaneous major calls. Since the rapid rise in calls for service has occurred during a period of generally declining or level staffing, the risk of overload is real.

A more subtle challenge comes from the need to design an emergency response system to cope with different types of emergencies having very different patterns. Emergency medical calls require swift response with a minimum of equipment and personnel. Fire calls require swift response with a large complement of equipment and personnel and may tend to occur in different parts of the community than those where emergency medical calls are concentrated. These competing bases for decision making require sophisticated planning. In many major cities, fire fighters are now required to be trained also as paramedics or emergency medical technicians (EMTs).

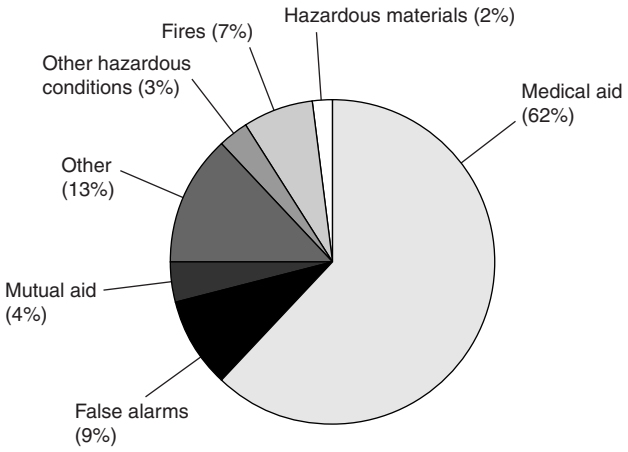

FIGURE 3.1.16 Fire Department Calls, 2004 (Source: NFPA National Fire Experience Survey)

Organizing Before Fire Occurs

Preparing for fire begins with the promotion of fire prevention and built-in fire protection, which fire departments can do in a variety of ways. First, fire departments typically are involved as inspectors and sometimes as certifiers for a wide range of fire-related regulations. Sometimes fire departments support building inspectors in their reviews of building code requirements for new and remodeled buildings. More often, fire departments handle ongoing fire code requirements for commercial buildings. Various permit requirements, from the general ones, such as occupancy permits and business licenses, to specific permits for hazardous materials and processes, also may be handled by fire departments. Smoke alarm laws are among the few examples where existing homes may be covered by these activities. These code and permit inspections not only empower fire departments to control fixed hazards, but also provide an excellent opportunity to educate and motivate occupants on general rules of fire safety. Research has shown this educational effect can reduce the frequency of fire significantly.

Second, fire departments investigate the causes of fires and pass on what they learn to a community whose attention is focused by the immediacy of a recent tragedy. Support for prosecution of arson cases is the most obvious example of the effect investigations can have. Changes in codes and standards can result from these findings, too.

The fire department is also the one constant in local programs to educate the public about fire safety, even though other groups may have primary authority for some programs. Fire departments can serve as catalysts for, and participants in, programs to counsel juvenile firesetters or to teach fire safety to schoolchildren. Fire departments often arrange for extensive programs of fire safety speeches to community groups, increasing community attention to the special programs of Fire Prevention Week in October. Fire departments can circulate fire safety messages by promoting local media use of fire safety public service announcements and by pointing out lessons from news coverage of local fires. Some fire departments are able to pursue even more ambitious programs, such as home fire inspections, using their own resources or acting as change agents to enlist a group of volunteers to do the job.

In summary, the fire department is central to local fire prevention and protection, and fire prevention and protection is central to the duties of the modern fire department.

With regard to preparing for nonfire emergencies, fire departments are increasingly called on to serve as the local agents for enforcement of federal and state laws to achieve "cradle-to-grave" control of hazardous materials. This enforcement may involve regulations on storage, use, and transportation. In many communities, fire department resources for gathering, processing, and acting on information in this new area are severely lacking. Control of hazardous materials is one of the areas in which local fire departments are most in need of help to do the new jobs that are now expected of them.

Organizing Effectively at Fires

Effective fire suppression requires clear policies and objectives, with tactics that follow logically from those policies. A suppression policy or objective is a concise description of priorities for the use of resources available at a fire. Particularly in properties with large numbers of people, containment of fire and protection of large numbers of people outside the fire-involved zone may need first priority, ahead of any efforts to save people and property in areas already involved in fire. Some losses, such as injury or even death of occupants in the room of fire origin, occur so early in a fire that they cannot be consistently prevented by any suppression strategy of the fire department alone.

Objectives imply tasks, such as forcible entry, rescue, application of water, ventilation, and salvage. And each task implies needs for staffing, equipment, the water delivery system, and response time. These needs are also affected by the level of on-site prevention and protection the community or the particular building has adopted.

For example, suppose a building has a certain size and a set of on-site hazards associated with the kind of business or use at the property. These imply a potential fire size for planning purposes. The potential fire size implies a required number of gallons per minute, gpm (L/min), of water that would be needed to control and suppress that fire. The gpm (L/min) requirement, in turn, implies needs for water pressure and pipe sizes serving the nearest hydrants and for hose sizes and pumping capacity in the fire department apparatus that respond. All these requirements also imply a certain staffing level to handle all the needed fireground activity, including (1) forcing entry if necessary, (2) finding and evacuating or protecting any occupants in certain zones of the building, (3) ventilating as necessary, (4) carrying the needed hoses to the potentially distant fire location, and (5) applying water there until the fire is controlled and extinguished. This process is a task analysis of suppression resources and their use. Implicitly or explicitly, such an analysis should underlie all resource decisions.

It should be clear from this example that on-site sprinkler protection or limitations on quantities of burnable materials on site can change the potential fire size, which might permit longer response times or smaller personnel complements. However, if anything and everything is permitted on site, the fire department must plan for the worst, and if they lack the resources to do so, disaster is there, just waiting to happen.

Pre-incident planning can range from the review and rehearsal of strategy and tactics for a single facility to the elaborate planning required to prepare for natural disasters or civil defense emergencies. Large-scale planning of the latter type may involve the development and maintenance of multiagency coordination systems and large-scale incident command and control systems.

Protecting Fire Fighters

Fire fighter deaths on duty declined from the early 1980s to the early 1990s, but have been stuck around a 100 a year in most years since (Figure 3.1.17). The high death tolls up to the early 1980s were led by career fire fighters, but the death tolls since then have been dominated by volunteers. These totals reflect both immediate and delayed effects of acute injuries or illnesses but do not reflect deaths due to long-term chronic illnesses, such as cancer.

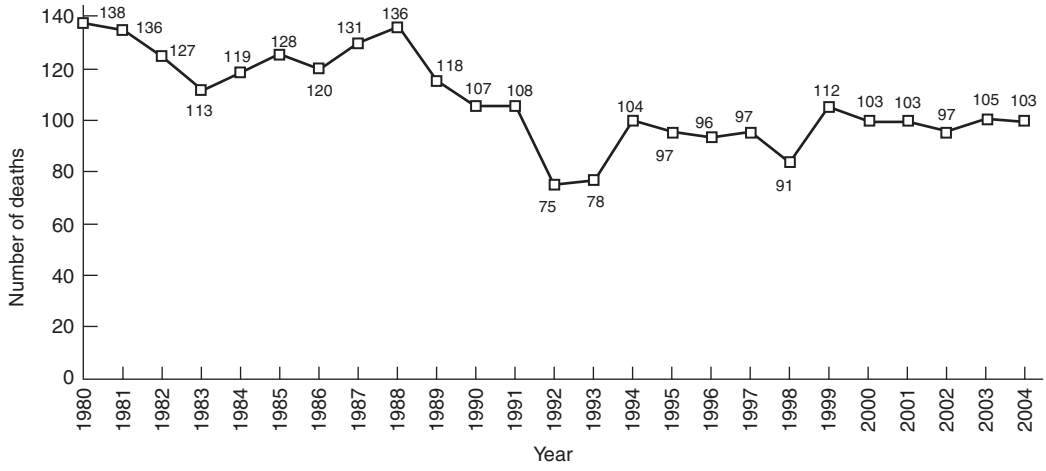

FIGURE 3.1.17 U.S. Fire Fighter Death Trend, 1980–2004. Note: Excludes 330 fire fighter deaths at the World Trade Center in 2001. (Source: NFPA FIDO)

In a typical year, nearly half of all fire fighter deaths in the line of duty involve heart attacks. These deaths are nearly always limited to older fire fighters, at least 38 years of age, and are particularly prevalent in volunteer fire departments, where older fire fighters are more likely to serve. A large fraction of these heart attack deaths involve fire fighters with serious pre-existing health conditions, including arteriosclerosis, hypertension, and previous heart attacks. Since nearly half of all fire fighter deaths involve heart attacks, physical fitness is one of the most important elements of an occupational health and safety program.

In a typical year, one-fourth to one-third of on-duty fire fighter deaths occur during response to, or return from, an emergency call. Vehicular collisions and heart attacks while operating vehicles are both major causes. This scenario affects volunteers more than career fire fighters. Driver training is needed to prevent vehicle accidents. Safe passenger practices must be emphasized because falls from vehicles are also a major cause of fire fighter deaths. Careful attention to the safety of the vehicles themselves, including inspection, maintenance, and repair, is needed, too. Aircraft operations at major wildfires are a special case that results in on-duty fire fighter deaths nearly every year,

Fire fighter safety on the fireground depends on good equipment. Protective clothing for fire fighters is sometimes referred to as the "protective envelope." Many of the advances in this equipment in recent years have come about as a result of a program of research in the late 1970s and early 1980s, under the name Project FIRES, sponsored by the U.S. Fire Administration. NFPA maintains and regularly updates standards for each type of protective clothing and equipment, including those needed for special environments, such as hazardous material incidents or airplane crash fire rescue.

Fire fighter injuries on duty had been stuck at about 100,000 a year until the mid-1990s when they began to decline, falling below 76,000 in 2004. Injuries at the scene of a fire emergency have declined from 65 percent of the total in 1981 to 49 percent in 2004. One reason the total has not fallen is that injuries at the scene of a nonfire emergency have been increasing, from 9 percent of the total in 1981 to 17 percent in 2004.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the fire problem and fire protection discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 54, *National Fuel Gas Code*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 70, *National Electrical Code*®
NFPA *101*®, *Life Safety Code*®
NFPA 102, *Standard for Grandstands, Folding and Telescopic Seating, Tents, and Membrane Structures*

Chapter 2

Fire Loss Investigation

Richard L. P. Custer ■ David T. Sheppard

Chapter Contents

Organizations Involved in Fire Loss Investigation
Access to Fire Scenes for Investigations
Role of NFPA 921
Reconstruction and Failure Analysis Process
Organization for Fire Investigation
Education and Training of Fire Investigation Personnel

Key Terms

benchmark event, failure analysis, fire investigation, fire investigator, fire loss investigation, fire reconstruction, fire scene investigation, fire testing, prefire event, transfire event

Data gathered during a fire loss investigation have several applications, ranging from filling out the fire department incident report to creating a detailed engineering reconstruction and failure analysis of the incident. Understanding the fire origin and cause of a fire can lead to targeted inspection, public education programs, or, perhaps, proposed code changes. An engineering reconstruction and failure analysis can reveal factors concerning the fuel, building, and fire suppression that resulted in the ultimate extent of flame and smoke movement. Building codes and fire safety design standards involved would be included in this analysis, as would construction, operation, and maintenance practices. Results of a failure analysis provide input to insurance loss adjustment and underwriting, improved design practice, and civil and criminal litigation. Failure analysis can also result in changes to codes and standards.

In most fires, origin and cause are expressed in terms of the area of fire origin, the heat of ignition, the materials involved, and the factors that brought them together. (See NFPA 921, *Guide for Fire and Explosion Investigations.*) In the past, only fires that resulted in large loss of life or property received the attention of a complete investigation. In these cases, the engineering reconstruction and failure analysis was often conducted months or years after the fire, when only fragmentary evidence, if any, remained. In these situations, the depth and accuracy of the fire department report can be critical. Recently, insurance claims, subrogation activities, and greatly increased litigation have been concerned with smaller and smaller losses. Thus, more detailed examination is needed of all fires that result in a loss, almost regardless of the extent of the loss.

This chapter discusses fire loss investigation by examining organizations that are involved in fire loss investigations and the reconstruction and failure analysis process. See also Section 3, Chapter 6, "Applying Models to Fire Protection Engineering Problems and Fire Investigations." Information for the fire investigator is located throughout the *Fire Protection Handbook;* however, Section 2, "Basics of Fire and Fire Science," and Section 6, "Characteristics of Materials and Products," are particularly recommended.

ORGANIZATIONS INVOLVED IN FIRE LOSS INVESTIGATION

Organizations involved in fire investigation can be separated into two types: (1) public agencies, or those required by law to investigate fires at the local, state, and federal levels, and (2) private sector organizations.

Local and State

Of the public agencies, the local fire department generally has the primary responsibility to document a fire and to provide an initial determination of the origin and cause. If the department conducts incident reporting as part of the National Fire Incident Reporting System (NFIRS), factors

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that affected the ultimate course of the fire, such as flame spread and the performance of fire protection features, may be included.

When a fire department investigation determines that the fire may have been of incendiary origin, in other words, deliberately set, other organizations may be assigned the legal responsibility for determining fire cause and for the investigation pursuant to suspect identification and possible criminal action. In much of the United States and in all Canadian provinces, the state or provincial fire marshal's office is responsible for investigating incendiary fires. In states or jurisdictions where this is not the case, the local fire marshal or the local police or fire department may have investigative responsibility, either directly by statute or by delegation from the state.

Federal

U.S. federal agencies are also involved in investigating fires. These agencies are generally charged with investigating incidents to determine compliance with federal regulations and to provide input for the regulatory process to reduce human and property losses.

For example, the National Transportation Safety Board (NTSB) conducts complete reconstruction and failure analysis of accidents, including fire-related incidents, which involve air, rail, and highway transportation. Investigations of pipeline incidents and maritime fires are under the authority of the Department of Transportation (DOT). Other federal agencies involved in fire investigations include the Occupational Safety and Health Administration (OSHA) of the Department of Labor; the Bureau of Mines (BoM) of the Department of the Interior; the Federal Bureau of Investigation (FBI); the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) of the Department of Justice; the Consumer Product Safety Commission (CPSC); the Nuclear Regulatory Commission (NRC); and the National Institute of Standards and Technology (NIST) of the Department of Commerce.

The Federal Emergency Management Agency (FEMA) conducts detailed investigations of fire and hazardous materials incidents and prepares reports that can be obtained through the U.S. Fire Administration. Other agency reports are available from the National Technical Information Service (NTIS) in Atlanta, Georgia.

In addition to investigating fires under their jurisdiction, these federal agencies may serve as resources for lab analysis and technical information for state and local fire officials.

Committees of the U.S. House of Representatives and the Senate are often very interested in the results of these investigations, particularly when the incidents under investigation deal with timely public policy topics, such as standards for elderly care facilities, prison fire safety, and terrorism.

Private Sector Organizations

Most of the complete reconstruction and failure analyses of fires other then those that fall under government jurisdiction are conducted by private sector organizations for education, improved design, insurance, and litigation purposes.

NFPA. The National Fire Protection Association's (NFPA) fire investigations program is a long-standing data collection and engineering analysis activity. The purpose of the program is to collect, analyze, and report detailed fire experience data through on-site investigations. This activity assists NFPA in analyzing and documenting facts about fires for technical or educational value; distributing the information to the fire protection community to help prevent future similar fire losses; publishing investigation reports as individual reports, as well as in the *NFPA Journal* and on the NFPA home page; providing technical assistance to state and local officials as an integral service of the NFPA investigation process; determining important "lessons learned" for input to NFPA technical committees and technical programs; and contributing to an increasing fire incident database for analysis purposes.

Several NFPA fire investigations have included or been supplemented by analysis of human behavior patterns, where the discovery of the fire and subsequent evacuation occurred in sufficient time to permit analysis. Human behavior studies have been conducted through on-site interviews with survivors or mailed surveys and have generally been carried out by NFPA staff in combination with leading authorities on human behavior in fire.

NFPA frequently works with fire departments and code organizations during the on-scene investigation. Results of most of these investigations are published as special studies or as reports in various fire protection periodicals.

Insurance Industry. The insurance industry often investigates and reconstructs a fire incident to evaluate the merits of claims submitted or to identify parties for possible subrogation action. Reconstruction may be conducted by insurance company personnel, by an adjustment bureau, or by a consultant.

Individual consultants or consulting firms perform reconstruction and failure analysis for a variety of clients, including property owners, industrial organizations, criminal prosecution and defense and the insurance industry. Consultants are also retained for litigation purposes by law firms to evaluate fire origin and cause, code compliance, conformance with applicable design standards, and other technical aspects of fire loss.

When major financial consequences are linked to investigators' conclusions, it is not uncommon for two or more parties to retain investigators and for two or more theories of fire origin and development to be presented. The need to resolve such disputes is a major reason for the increasing interest in applying state-of-the-art scientific methods and computer fire models, analytical procedures, and test results to fire investigations.

ACCESS TO FIRE SCENES FOR INVESTIGATIONS

Most fire scene investigations take place on private property and fire investigators, whether public or private sector, must assure that they have a legal right to be on the scene; otherwise, their findings may not be admissible in court. The three primary mechanisms for conducting a legally valid scene investigation are exigent circumstances, permission of the owner, or a search warrant.

Exigent Circumstances

Exigent circumstances exist when the fire department arrives on the scene and there is a need to assess whether there is a continuing risk. Exigent circumstances exist while the fire department retains custody of the scene and often ends when there is any break in the on-scene presence of fire department personnel. Rules on the allowable duration of the exigent circumstances depend on the specific jurisdiction.

Permission of the Owner

Permission of the owner is the primary legal mechanism by which public and private fire investigations investigate on scene, after the exigent circumstances have expired and while no criminal act is suspected. Fire investigators will typically obtain the owner's permission in writing to document that they had a legal right to be on scene with the understanding that the owner can limit the areas that can be investigated and revoke permission for scene investigation at any time. Investigators representing insurance companies can usually depend on the owner's permission but should clear access directly with the insurance company or their legal representatives.

Search Warrant

A search warrant is a third mechanism by which public sector investigators gains access to fire scenes. Search warrants are issued by judges and magistrates and such documents are used when an incendiary fire or a crime scene is suspected.

ROLE OF NFPA 921

History of NFPA 921

In 1984, the NFPA Standards Council initiated a project to develop guidelines for fire and explosion investigation under the consensus process used to develop and maintain NFPA standards. At this time the Technical Committee on Fire and Explosion Investigations was established.

Public comments received by the Committee are reviewed and the Committee actions documented in a final proposal that is subject to further public review to permit a commenter to respond to the Committee actions and raise questions during the final approval process. This open procedure results in a document that is representative of the investigative community although there may be individuals who disagree on specific points.

NFPA 921, *Guide for Fire and Explosion Investigations,* was first issued in 1992 and has been revised on a 3 year basis through 2004. To keep from becoming outdated, if there were no new editions proposed, NFPA 921 would have to be opened to public comment and reviewed by the Committee every 5 years.

Use and Contents of NFPA 921

NFPA 921 is widely used for state and local training programs throughout the United States and serves as the basis for the performance criteria in NFPA 1033, *Standard for Professional Qualifications for Fire Investigator.* It is also recognized for training by the International Association of Arson Investigators (IAAI) and the National Association of Fire Investigators (NAFI).

The 2004 edition included chapters on the following:

- Basic Methodology
- Basic Fire Science
- Fire Patterns
- Building Systems
- Electricity and Fire
- Building Fuel Gas Systems
- Fire-Related Human Behavior
- Legal Considerations
- Safety
- Sources of Information
- Planning the Investigation
- Documenting the Investigation
- Physical Evidence
- Origin Determination
- Fire Cause Determination
- Analyzing the Incident for Cause and Responsibility
- Failure Analysis and Analytical Tools
- Explosions
- Incendiary Fires
- Fire and Explosion Deaths and Injuries
- Appliances
- Motor Vehicle Fires
- Wildfire Investigations
- Management of Major Investigations

RECONSTRUCTION AND FAILURE ANALYSIS PROCESS

The complete reconstruction and failure analysis process involves developing a time history for the incident, identifying the location of the fire origin, and establishing the factors that led to ignition and that increased or lessened the severity of the loss. The reconstruction includes prefire history, as well as "transfire" events, or those that occur from the point of established burning to extinguishment. Failure analysis is concerned with the design, construction, and performance aspects of the incident. It is also important in the reconstruction to document the successes. For example, did fire protection features inhibit the spread of fire within a portion of the building?

Time is the framework for reconstruction and failure analysis, and it can be viewed in two scales: the macro scale, where time is measured in increments of days, weeks, and years, and the micro scale, where the increments are in seconds, minutes, and hours. Macro time is prefire, whereas micro time may apply to both pre- or transfire events.

The best way to organize reconstruction and failure analysis information is through the use of timelines or event sequences. In constructing a timeline, it is important to establish benchmark events. A benchmark[1] event can be described as an event that is well documented in time and space and that serves as a point of reference because it can be assumed to have created a set of specific conditions or initiated a sequence of actions that

had a significant impact on the fire. The issuance of a building permit or the time of arrival of the fire department apparatus are good examples of benchmark events. Using time of arrival as a reference event, other events for which the time of occurrence is unknown can be placed approximately in time either before or after arrival of the fire department apparatus. Other examples of typical benchmark events are explosions and the collapse of walls or roofs or calling for multiple alarm response.

A single timeline can be adequate for fires in which only a few events occurred. For more complex situations, separate timelines on the same scale can be used for the history of the building, the evolution of the "model codes," the installation and maintenance history of a suppression system, human activity, or any other time-related aspect of the incident. STEP (sequentially timed events plotting) procedures have been developed to deal with complex accident situations such as major fires.*

Prefire timeline information can be obtained from building permits, plans and specifications, inspection reports, fire and building codes, and fire research and engineering literature. Sources of information for use in the development of transfire timelines include the fire department incident report; recordings of fire department radio transmissions during the incident; photographs and video footage shot during the event by news media, private citizens, or fire department personnel; and interviews with fire fighters and other witnesses.

It should be pointed out that, in many cases, only parts of the reconstruction and failure analysis process are carried out. Many different organizations may be involved in the investigation, often at different times. Because people may have to rely on information gathered by others, an understanding of the whole process makes it easier to obtain the most complete and accurate data at each step.

The basic steps of overall reconstruction and failure analysis are examination of the scene, collection of background data, testing, incident reconstruction, and specific failure analysis. Many of these steps are outlined in NFPA 921.

Examination of the Scene

Examining the fire scene is critical to the entire reconstruction and analysis process. It is here that the physical and photographic evidence is gathered and the fire damage is documented through maps and diagrams.

Transition to Digital Cameras

In the past, 35mm format photography has been the most common method of photographic documentation. Recent trends have favored the use of digital images. One advantage of digital photography is the instant confirmation that a difficult photograph, which is often taken in poor lighting conditions, has been taken properly. Although there has been concern that digital images can be altered or enhanced, it should be noted that similar changes can be made with film as well and that brightness and color balance is often adjusted during commercial film processing. It is important that an original archival copy of each film or digital image be maintained that can be testified to in court as a "fair and accurate representation" of what was seen by the investigator(s).[2]

Fire Scene Documentation

As many photographs as possible should be taken at the scene, and each photograph should be documented on a diagram with a description of the direction of view and contents of the photograph. The techniques of fire-scene photography have been well reported and can be applied to reconstruction and failure analysis.[3–5] Color photography is recommended.

In addition, maps and diagrams should be prepared that include dimensions and interior layout of the building, the location and degree of fire damage, the location and types of fuel materials, and the locations of victims. The location of fire protection features, such as firewalls, detectors, and suppression systems, should also be noted.

In many cases the first indication of the fire will come from activation of security devices transmitted to alarm companies from passive infrared (PIR) or ultrasonic motion detectors or from perimeter security contact sensors on doors or windows. Activation may indicate the presence of heat from a fire or entry into the premises. For this reason, the location and orientation of PIR sensors and the location of contact sensors and any associated signal wire should be documented. Evidence of activation can often be recovered from local alarm panels if undamaged or from fire alarm or security devices. It is also helpful to determine the prefire location and nature of fuel items as well as the prefire location and activities of fire victims.

Often, buildings will be modified considerably over their lifetimes, and an individual reviewing the original plans could receive a false impression of the building at the time of the fire. Thus, it is important to record the architectural, construction, and fire protection features of a structure, both as built *and* at the time of the fire.

When fire suppression systems are present, the positions of valves, the locations of discharge nozzles, and the locations and types of detectors used to operate the system should be noted. It may also be necessary to evaluate the water supply in order to determine if it was adequate. With special systems, such as those that use halon, CO_2, dry chemicals, or any clean agent fire extinguishing systems such as those described in NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems,* agent storage tanks should be checked to determine whether the system discharged as designed.

It is important to interview or review the interviews of fire department responders to determine what actions they took on the scene. Some of the damage may have occurred during fire fighting and overhaul and not as a direct result of the fire. For example, ventilation of a building to facilitate fire suppression activities may result in an increased burning rate at the area of venting, thus increasing the damage at that point.

A careful study of the damage patterns, combined with on-site interviews and a knowledge of the ignition sources, location of fuel materials present immediately before the fire, and fire

*Any event for which the actual time of occurrence is known is a "benchmark" event. A "hard time" timeline has benchmarks for each event. A "soft time" or "relative time" timeline has the sequence of events known, relative to each other, but not all of the actual times. Benchmark events are exceptions in a relative time timeline, and their known times of occurrence often can set bounds on the times of other events.

dynamics, should be used by an investigator to determine the area of origin. If possible, the source and form of heat of ignition and the type and form of the materials first ignited should be determined. Burn patterns, such as a "V," low burns, and multiple "points of origin," can often be misleading and should only be used to establish origin and cause when they are unambiguous or are supported by other physical evidence. The investigator should collect evidence, develop hypotheses or theories about the origin and cause, and test these theories to see which the evidence supports.

The investigator should keep in mind that the burn patterns seen after a fire represent the total burning history of the event, including damage that may have occurred during extinguishment and overhaul. As a rule, patterns observed in fires that are extinguished early in their development are more meaningful and useful than those remaining after the near-total destruction of a building or a portion of a building.

Indicators, such as depth of char, should be used with care. The burning rate of wood traditionally has been calculated as approximately 1.4 in. in 60 minutes (0.6 mm/min). This figure has been used to estimate the time of burning and to detect the presence of flammable liquids. Research has shown that the traditional calculation varies substantially, depending on the radiant heat flux and ventilation. The rate of burning can be as high as 10 in./hr (4.3 mm/min).[6]

Investigators should also be careful not to assume that certain burn patterns can be used as sole proof of the presence of flammable liquids. Factors such as ventilation, room flashover, floor clutter, room contents, fire duration, fire-fighting activities, and overhaul can affect the patterns seen by investigators. Corroborative evidence, such as pertinent chemical traces or the detected absence of an appropriate prefire fuel load, is needed to establish the presence of flammable liquids. The color of observed smoke is not necessarily evidence of the presence of flammable liquids. A number of recent studies have been carried out to identify some of the patterns that can develop from different ignition and ventilation scenarios.[7–9]

In visualizing conditions in the area of origin, it is often helpful to reconstruct the scene physically by replacing the carpet, furniture, and other items in their original locations. Although interviews are conducted at many different times in the reconstruction and failure analysis process, those taken at or close to the time of the incident also can be very useful, particularly in describing the course of the fire. Whenever possible, events described in interviews should be related to benchmark events.

Arc Fault Mapping

The path of electrical supply wiring circuits that were energized at the time of the fire should be examined for the presence of arcing because the location of the arcs may be used to assist in determination of the progression of the fire, a technique called arc fault mapping.[10,11]

On-Scene Fire Investigation

Private sector investigators are often not called in to evaluate a fire scene until well after the incident. Frequently, the scene has been disturbed, or, in some cases, the building has been restored or removed. In these situations, the investigator should review physical evidence collected and photographic evidence. Examination of photographs using 7- to 10-power binocular microscopy can often reveal details, particularly when low-speed film has been used. If possible, copies of all photos and videotapes taken of the scene should be obtained. Grouping them for study, chronologically and by area depicted, is useful in documenting the amount of scene disturbance over time. Fire, police, and autopsy reports, as well as witness statements, should be reviewed.

Although an actual on-scene investigation of a fire is most desirable, careful analysis of a well-documented fire can lead to reliable conclusions or assessment of conflicting opinions regarding the origin and cause of many fires, as well as provide information for failure analysis. The effectiveness of a delayed investigation and analysis depends on the extent of the fire, as well as the degree of documentation. In some cases where there has been total or near-total destruction, neither an on-scene well-documented investigation nor subsequent delayed analysis can establish origin or cause.

Collection of Background Data

Although some of the background data, such as accounts of activities immediately before the fire, can be gathered at the scene very soon after the fire, much of the information needed for the investigation will be gathered later.

Building plans, permits, and the codes in effect at the time of approval should be obtained, along with the specifications and drawings for the building fire protection features. If any major modifications were made to the building or its fire protection systems or if there was a change of occupancy, the codes, plans, and permits should be obtained as well. These materials should be reviewed as part of the reconstruction process, because the changes may have influenced the course of the fire.

Other background data include instruction or training manuals, maintenance records, data on construction and interior finish materials, the previous fire history of the building or equipment involved, the amount of any previous fire damage, the location of contents, and the physical and burning characteristics of the contents. Maintenance records can often reveal problems with equipment that might have been part of the cause of a fire. This step also involves obtaining detailed statements from the building occupants to determine the circumstances leading up to ignition and established burning.

For many fire scenes there can be a number of investigators involved such as the fire department, insurance companies, owner's representative, and experts for potential or actual litigants conducting independent investigations concurrently. Although the investigative data and reports of other investigators may not be available in the early stages of an investigation, it is important that, to the extent possible, investigators evaluate this information during later stages of their investigation to assess whether their determinations should be revaluated with the addition of new data.

Testing

See also Section 6, Chapter 3, "Concepts and Protocols of Fire Testing."

In collecting samples for testing, it is important to know the sizes and/or amounts of the sample needed for each test, as well as the conditions under which the samples should be transported. This information can be obtained from a testing laboratory or by reviewing a copy of the test method.

There are several types of tests that are commonly utilized by fire investigators: (1) identification tests of unknowns, (2) flammability tests, (3) performance tests, and (4) demonstration tests.

Identification of Unknowns. Identification of unknown materials is performed by analytical laboratories using techniques such as gas chromatography and mass spectroscopy to identify unknown materials, particularly for identification of possible ignitable liquids that may have been used as accelerants. Such analysis should be conducted in accordance with the following appropriate ASTM standards: ASTM E1385, *Standard Practice for Separation and Concentration of Ignitable Liquid Residues from Fire Debris Samples by Steam Distillation;* ASTM E1386, *Standard Practice for Separation and Concentration of Ignitable Liquid Residues from Fire Debris Samples by Solvent Extraction;* ASTM E1387, *Standard Test Method for Ignitable Liquid Residues in Extracts from Fire Debris Samples by Gas Chromatography;* ASTM E1388, *Standard Practice for Sampling of Headspace Vapors from Fire Debris Samples;* ASTM E1412, *Standard Practice for Separation of Ignitable Liquid Residues from Fire Debris Samples by Passive Headspace Concentration with Activated Charcoal;* ASTM E1413, *Standard Practice for Separation and Concentration of Ignitable Liquid Residues from Fire Debris Samples by Dynamic Headspace Concentration;* ASTM E1618, *Standard Test Method for Ignitable Liquid Residues in Extracts from Fire Debris Samples by Gas Chromatography-Mass Spectrometry;* and ASTM E2154, *Standard Practice for Separation and Concentration of Ignitable Liquid Residues from Fire Debris Samples by Passive Headspace Concentration with Solid Phase Microextraction (SPME).*

Other useful analysis techniques for identification of unknown materials include FTIR (Fourier transfer infrared) analysis, EDS (energy dispersive spectroscopy), and metallurgical or X-ray analysis. These methods can identify various molecules or atomic components of the unknown for comparison to data from known materials.

Flammability Tests. Properties of material flammability and combustion that may be determined by test include ignition temperature, flame spread of materials, fabric flammability, flashpoint, and rate of heat release, among others.[12–19] It is important to remember that the reported results from most flammability tests are not intrinsic properties of the materials, but instead are dependent on the specific test method used.

Cone calorimeter testing is among the many types of flammability tests conducted and can provide information on the heat release rate of materials. Figure 3.2.1 illustrates the cone calorimeter apparatus.

Performance Tests. Performance tests are conducted to evaluate conditions of fire protection systems at the fire scene. Examples of performance tests include waterflow tests on sprinkler systems, flow rate or leakage tests on natural gas or propane distribution systems, and many others. The performance tests should be conducted using standard methods. The investigator must be cognizant of the conditions during the performance tests that may be different than those that existed during the fire and be ready to compensate for them or explain the effects on test results.

FIGURE 3.2.1 The Cone Calorimeter (Courtesy Fire Testing Technology Ltd.)

Demonstration Tests. Although special nonstandard tests, sometimes called "demonstrations," can often be revealing in understanding the course of a particular fire, results of these demonstrations can be misleading because the test may not be truly representative of the actual event. Factors such as ventilation, arrangement and types of the fuels, or even the point of ignition can have a significant effect on the outcome of the test. In other words, a great deal needs to be known about the specific conditions at the time of the fire, and these conditions must be reasonably reproduced and fully documented in the demonstration. Special tests or demonstrations should be conducted by personnel familiar with full-scale fire testing under laboratory conditions to permit control of such variables as ambient temperature, relative humidity, and wind effects. It is also important that someone with advanced knowledge of fire dynamics has evaluated the special test and can explain why the results of the special test can be applied to understanding the fire scene

despite the inevitable difference between the test setup and the actual fire scene.

Figure 3.2.2 illustrates a demonstration test conducted by the Bureau of Alcohol, Tobacco, Firearms, and Explosives.

Reconstruction and Analysis

Fire reconstruction is an organized, step-by-step portrayal of the most likely course of the fire under study, from the ignition sequence through established burning to the limits of flame and smoke movement at the time of extinguishment. Fire reconstruction is based on the facts developed through on-scene investigation, background studies, and testing. The reconstruction should explain the speed and direction of fire growth and smoke spread within the compartment or area of origin and beyond. It also should explain the effects of barriers and automatic suppression systems on fire spread and growth and the effects of manual extinguishment. The reconstruction should also evaluate the performance of the building's life safety features relative to injury or loss of life.

In sorting through the facts to develop the reconstruction, it is often useful to apply the system safety techniques of failure modes and effects analysis (FMEA) and fault tree analysis.[20] These methods help identify alternative sequences of events that could have led to the observed fire situation, such as the development of room flashover or fire breaching a fire wall. The alternatives can then be evaluated against the evidence to determine the most likely scenario. These techniques are particularly valuable where complex or interrelated machinery, buildings, or human activities are involved.

Computer modeling techniques can also be used to predict the outcome of a series of possible fire causes and growth scenarios. The model results can be compared to actual events to narrow down the likely scenarios for a given event or to evaluate the possible effects that fire protection equipment, such as detectors or sprinklers, might have had on the outcome of a fire. The analyses of the DuPont Plaza and the First Interstate Bank fires are examples of model applications.[21,22]

Analysis of the ignition sequence (fire cause) is concerned with three specific items: (1) size, nature, and source of the ignition energy; (2) physical and chemical fire properties of the materials ignited; and (3) circumstances, either human or mechanical, that brought the energy in contact with the fuel. In selecting the most likely ignition source, the energy available from a candidate source must be compared with the ignition energy requirements of the fuel in its given form. For example, given the same material and heat source, ignition is more likely if the material is present in a finely divided form than if it is in a solid mass. Energy available at the source, such as temperature and thermal radiation, distance from the fuel to the energy source, and time of exposure to the source of energy, are also factors that need to be considered in ignition sequence analysis. The term *competent ignition source* is used to describe a source that has sufficient energy and temperature to raise a particular fuel to its ignition temperature during the postulated exposure time. For example, an electric arc may be at a temperature well above the ignition temperature of a particular fuel but be of short duration and not provide enough total energy to result in ignition.

FIGURE 3.2.2 Setup for a Demonstration Test (Courtesy Bureau of Alcohol, Tobacco, Firearms, and Explosives)

Circumstances that result in ignition generally involve human factors or equipment failure. Careless welding, poor housekeeping, and improper selection or misuse of materials are examples of human factors. Valve rupture and combustion control failure could be considered equipment failures. Ultimately, most equipment failures can be traced to design, manufacturing, installation, or maintenance problems or to misuse.

An extensive compilation of data on materials, ignition sources, and ignition scenarios is available in Babrauskas.[23] If established burning is achieved after ignition, it must be determined why the fire continued to grow to full room involvement—that is, flashover, or, in the absence of compartmentation, such as that in a warehouse or industrial building, why it reached a certain extent. In providing answers, a number of factors must be evaluated, including the rates of heat release of the fuels, continuity of the fuels (i.e., the proximity of fuel packages to each other) and location of fuels relative to walls, compartment ceiling height, ventilation, and interior finish.

Heat release rate is one of the more important factors in analysis. In many instances, a fire reported to have grown or spread "unusually fast" is characterized as suspicious or incendiary when, in fact, the growth rate may have been due to a combination of the burning properties of the materials and the nature of the compartment in which the fire burned.

It is important to note that it is not possible at this time to calculate the heat release rate of complex materials and that the only accurate heat release rate data come from experimental tests. A number of experimental studies have been carried out to characterize the burning rates of actual materials and furnishings.

A number of studies have been carried out to characterize the burning rates of materials and furnishings. Data can be found in NIST reports and in Appendix B-2.2 of *NFPA 72®*, *National Fire Alarm Code®*.[19,24–27] The roles of heat release rate, fire location, and ceiling height in fire development have also been reported.[28] Alpert's work includes methods to estimate ceiling temperatures and ceiling gas velocities. Guidance on estimating the likelihood that a given fire size and room ventilation combination can develop flashover also is provided in NIST reports and the *SFPE Handbook of Fire Protection Engineering*.[29–31] See also Section 2, Chapter 4, "Dynamics of Compartment Fire Growth," of the *Fire Protection Handbook*.

The performance of automatic suppression systems in controlling the growth and spread of the fire also must be evaluated in the reconstruction process. Here, the factors to be reviewed include the appropriateness of the agent being used; the system response time, as related to the detection devices used, relative to ceiling height and fire growth rate; location of the agent discharge nozzles relative to the source of the fire; agent availability, including rate of discharge, pressure, and adequacy of supply; and conformance of the system design and installation with NFPA standards, industry design, and installation manuals. For example, a sprinkler system may have failed to control a fire due to a very high ceiling that delayed the response time, combined with low water pressure that could not produce the needed waterflow rate.

Another component of the reconstruction is barrier performance. Barrier performance evaluation focuses on the nature of the barrier, whether rated or not rated, barrier construction, the thermal stresses to which it was exposed, and the manner in which the barrier failed. Barriers can fail by passage of flame or hot gases through a small opening, by a hot spot failure, by movement of flame and hot gases through open doors, or by barrier collapse, resulting in a massive failure. Failure of opening protection, poor construction practices, modifications to the barrier after construction, and fire stresses that exceed those assumed in the design can be significant transporters of products of combustion beyond design limits.

Manual suppression activities, whether by a municipal fire department or a plant fire brigade, can have a significant effect on the outcome of a fire. In the absence of fire suppression systems, the response time of the fire department for a given fire will influence the size of the fire at the time of agent application. For ease of analysis, the response time can be broken down into the following segments: detection time, alarm transmission time, dispatch time, travel time, and time from the arrival of fire suppression personnel to agent application. Problems resulting in delays in any of the above time segments will extend the limits of flame and smoke travel. Examples of factors that could cause delays are the absence of automatic detectors, the absence of people in the building, or an improperly designed detection system. Equipment failure or out-of-service fire apparatus can also delay response time. Weather, terrain, traffic, and the condition of apparatus can extend travel time to the incident. Frozen hydrants, blocked access, and shortage of personnel are also examples of factors that could delay application of fire suppression agents.

The reconstruction process must also consider the performance of the building life safety system. This includes the detection and alarm system, the building egress system, and the smoke control system. In addition to the factors discussed above that affect detector response, the audibility of alarms plays a role in life safety. Guidance on this topic can be found in work by Nober,[32] in *NFPA 72,* and in the *SFPE Handbook of Fire Protection Engineering.*[33] Building egress factors include the capabilities of the occupants and the number, capacity, and protection of the egress routes. The movement of smoke in buildings is related to the temperature of the fire gases; differences between inside and outside temperatures, or the stack effect; effects of the building's heating and air conditioning systems; and effects of wind.

Failure Analysis

In a fire safety context, failure can be defined as a fire that results in personal injury, death, or property or monetary losses, or in conditions that prevent buildings or mechanisms from functioning as designed. In fire failure analysis, the objective is to use on-site and background data, testing results, and reconstruction to identify the primary and contributing causes of the failures and their sources. The sources of failures include basic design, material or equipment selection, material or equipment defects, construction or assembly, testing, postconstruction modifications, service conditions, and unanticipated conditions or abuse.

The analysis is made by comparing the causes of failures with codes, standards, design practices, and the state-of-the-art technology present at the time of the fire. In the analysis, it is important to identify noncompliance with the standard practices, but it is even more important to note where compliance with the standards failed to provide the expected or needed degree of fire safety. In either event, failure analysis should provide recommendations for how the failures could have been prevented or how the knowledge gained can be applied to preventing similar failures in the future.

ORGANIZATION FOR FIRE INVESTIGATION

It is a good idea to be prepared in advance for the investigation of a fire. The preparation may range from identifying an individual or company to hire as needed to the organization of a permanent fire investigation unit complete with full-time staffing, vehicles, and a laboratory. The level of organization selected depends on the size of the organization, the frequency of need, the resources available, and the legal or statutory requirements. One other factor to be considered is whether or not the organization is in the public sector—the fire department, police department, state and federal government, and so on—or in the private sector—insurance company, product manufacturer, major hotel chain, and so on. Frequently, public sector needs will include more than just the ability to conduct a fire scene investigation. Should it be determined that the possibility of arson exists, the likelihood of criminal or civil action often requires the involvement of the police or persons trained in the legal aspects of arson and fraud investigation.

Public Sector

In the public sector, the fire department personnel responding to the scene carry out most initial investigations. If the cause is easily determined and does not appear to be of a potentially criminal nature, the investigation ends at that level. When the cause cannot be determined, a fatality is involved, or arson is suspected, additional help is generally dispatched. In a small fire department, the local police or the county or state fire marshal's office may be contacted. In some jurisdictions, the assistance may come from the county or state police.

In large cities, a fire investigation unit is usually formed. The unit may be made up of fire department personnel and be wholly within the fire department, or the unit may be within the police department. Regardless of where the unit is placed organizationally, it is generally recommended that both fire investigation and police functions be represented in the background and training of personnel. This objective is often accomplished by selecting individuals from both departments to serve in the fire investigation unit.

In some jurisdictions, an investigations unit is established in the local criminal prosecutor's office. Such a unit will usually have arson detection and prosecution as its major focus where the caseload is high. A special prosecutor is often assigned specifically for arson, and that individual frequently is trained in fire investigation techniques.

In many instances, fire investigation units in both the fire and police departments are called arson investigation units. Determination of arson can usually come only after a thorough fire investigation in which other possible causes are ruled out and physical evidence of an incendiary fire is established. This provision should be stressed to investigative personnel so they do not come to believe that their role is to find arson. The term *fire investigation* is more appropriate to the work that is done than arson investigation. If arson is a major problem in a community, special arson task forces can be established to identify arson-for-profit groups, associating real estate buying and selling and insurance patterns with arson and arson prevention activities. This work is less concerned with actual fire scene investigation, and deals more with the establishment of motivation, insurance manipulation, and patterns of arson occurrence.

Some federal agencies, such as the General Services Administration or the military services, have personnel who investigate fires involving their facilities. These personnel are generally assigned fire investigation in addition to other functions such as facility safety or fire protection design. In the event of a major fire, an agency may conduct its own investigation or use an outside consultant to assist its own personnel.

Private Sector

In the private sector, large insurance companies may have investigative units that conduct fire scene investigations and perform arson and fraud detection and control functions. Some companies employ adjustment bureaus or private investigators to make the initial cause determination, and follow up with their own personnel if it appears that arson or fraud is involved or if there is a particularly large loss. Small companies may rely exclusively on outside investigation services.

A number of large industrial companies also maintain a fire investigative capability, often located in their risk management or loss prevention groups. These groups or individuals may investigate fires in company facilities or fires involving products or systems designed, manufactured, supplied, or installed by the company. These investigations may be for the purpose of future loss prevention or plant safety programs, or they may be carried out in response to actual or potential litigation. An important function of this type of investigation is the identification of the causative factors in the fire that could lead to improved design, manufacturing, installation, or operating practices.

Organizations such as NFPA and the U.S. Fire Administration also investigate fires in order to determine "lessons learned" for broad reporting purposes.

Small companies may not be able to afford their own investigation staffs. In such cases, an appropriate outside capability should be identified in advance for use if the need arises. The individual or firm selected should either have or be given some knowledge of the specific products, facilities, or operations that are likely to be involved.

EDUCATION AND TRAINING OF FIRE INVESTIGATION PERSONNEL

The nature and extent of education, training, and experience needed by investigators obviously varies greatly with the specific goals and objectives for fire investigations set by the organization where they are employed and by budget resources. Some basic performance requirements for fire investigators are provided in NFPA 1033. The level of knowledge needed by a fire ground officer faced with a residential fire extinguished early in its development will be less than that needed by an investigator from the department's fire investigation unit. This investigator will have to deal with fires extinguished in more advanced stages, where the evidence of cause is often much less clear. In addition, this investigator will have to deal with fires in the full range of occupancies found in the unit's jurisdiction. This could include residences, office structures, warehousing, manufacturing, and heavy industry.

The private sector investigator employed by a petrochemical company may need a degree in chemistry or chemical or fire protection engineering in addition to the basic fire scene investigation skills. The specialist in arson investigation will need education and experience in the legal aspects of civil or criminal investigations, or possibly both.

Today, research and development is ongoing in areas of knowledge related to fire investigation, and the investigative techniques that were used in the past are being refined. For this reason, fire investigators should stay current with the latest innovations and knowledge in their field. As the state-of-the art in fire investigation develops, previous determinations may need to be reevaluated based on the current state of knowledge.

Education

In the past decade, a great deal of data regarding the nature of the ignition process and the forces that control fire spread and growth has emerged. Research by university, government, and insurance laboratories has developed information that can explain much of the evidence remaining after a fire has been extinguished and assist in determining origin and cause.

To determine adequately the origin and cause of a fire, the modern investigator needs a basic knowledge of physics and

chemistry, preferably at the postsecondary-school level. The investigator should be familiar with the concepts of heat release rate, fire plume and ceiling layer development, compartment flashover, and full room involvement. The investigator should also have knowledge of electrical power distribution systems and the failure modes of common electrical equipment and appliances.

All fire investigators should also have some knowledge of the legal aspects of investigations, such as how to gain access to a scene, how to take and handle evidence, and how to question witnesses.

Fire science courses offered at many postsecondary schools today can provide much of the needed background. Where such facilities are not available, basic science courses supplemented by independent reading can be employed. In some areas of the country, the U.S. Fire Administration's Open Learning Program is also available through selected local colleges and universities.

In fire investigation units to which both police and fire personnel are assigned, personnel should be cross-trained in basic fire science and law enforcement. Departments that become familiar with each other's technology and terminology benefit from enhanced communication, more complete and thorough investigations, and more successful prosecutions.

Advanced education might include college-level courses in such areas as forensic science, industrial safety, insurance, accident investigation, and fire protection engineering.

Training

All investigators should be trained in the basics of fire scene investigation, which include adequate documentation of the scene, origin determination, and cause determination. Specific emphasis should be placed on techniques for debris removal and scene reconstruction. Although much of this knowledge can be gained by studying text materials, there is no substitute for field experience. Even limited hands-on work can be of great value in relating the text materials to "the real world."

SUMMARY

Fire loss investigation ranges in complexity from completing a fire incident report to detailed engineering reconstruction and failure analysis. Once rare, fire loss reconstruction and failure analysis is becoming more common. As described in this chapter, that process may include examination of the fire scene, collection of background data, testing, and the organized, step-by-step portrayal of the most likely course of the fire under study.

The complexity of the fire loss investigation dictates the complexity of training needed to conduct the investigation. NFPA 1033 prescribes minimum basic competencies. In addition, a basic knowledge of physics and chemistry is needed. College-level study in areas such as forensic science, insurance, accident investigation, and fire protection engineering is needed for the successful and credible investigation and reconstruction of complex fires.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information about loss investigation discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 72®, National Fire Alarm Code®
NFPA 422, *Guide for Aircraft Accident/Incident Response Assessment*
NFPA 904, *Incident Follow-Up Report Guide*
NFPA 921, *Guide for Fire and Explosion Investigations*
NFPA 1033, *Standard for Professional Qualifications for Fire Investigator*
NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*

Chapter 3

Fire Data Collection and Databases

Marty Ahrens ❑ Stan Stewart

Chapter Contents

History of NFIRS
NFIRS—A Three-Tiered System
NFIRS Definitions
Getting to NFIRS 5.0
Computers and NFIRS
Getting the Big Picture on Fires
Other Sources of Data

Key Terms

Consumer Product Safety Commission (CPSC), Fire Incident Data Organization (FIDO), incident record, National Electronic Injury Surveillance System (NEISS), National Fire Incident Reporting System (NFIRS), National Fire Information Council (NFIC), Uniform Crime Reporting System (UCR), United States Fire Administration (USFA)

How do we know what we know about fire? Where do the statistics come from? Although some tests can be done in laboratories, laboratory tests do not explain what causes the largest number of fires or how often fire kills people. In this chapter, several real-world data sources for fire analysis are described. Most of this chapter will focus on the U.S. National Fire Incident Reporting System (NFIRS), the largest and most detailed fire incident database in the world and the source of most of what we know about fire.

NFIRS provides a standard format for data collection, enabling aggregation of and comparisons across stations, communities, and states. NFIRS was designed to meet the needs of both the people collecting the data and the people who use it.

NFIRS has been widely used since 1980 and has added and dropped data elements at several times in different versions. Version 5.0 of NFIRS, first introduced in a few areas in 1999, was designed to give local fire officers greater ability to document their department's activities and experiences and represents a major departure from the structure of earlier versions. By 2003, the vast majority of U.S. fire departments participating in NFIRS were using the Version 5.0 system.

NFPA's annual fire department survey, the source of the "big picture" on fire problems and the scaling ratios to be used with NFIRS will also be discussed in some detail. Additional information will be provided on the following:

- NFPA's Fire Incident Data Organization (FIDO), an anecdotal database
- The death certificate database
- The National Electronic Injury Surveillance System (NEISS), a system that tracks injuries treated at emergency rooms
- The FBI's Uniform Crime Reporting System (UCR), the source for data on arson arrests
- Some fire incident data collection systems elsewhere in the world and international fire data collection efforts

The use of fire data and the implications of NFIRS Version 5.0 for fire data analysis are discussed in Section 3, Chapter 4, "Use of Fire Incident Data and Statistics."

HISTORY OF NFIRS

The need to collect aggregated fire data was realized and identified in 1972 when President Nixon's Commission on Fire Prevention and Control issued the report *America Burning.*[1] Among other things, the report noted that the United States had one of the highest fire death rates at that time in the industrialized world. As a result of the report, it had become painfully obvious that we had a serious fire problem in the United States, yet we knew very little about its exact nature. This alarming fact led directly to the National Fire Prevention and Control Act, Public Law (P.L.) 93-498, in 1974. The act directed the formation of the U.S. Fire Administration (originally called the National Fire Prevention and Control Administration) in order to initiate a national focus on the fire problem. Section 9 of the act established the National Fire Data Center to "provide an accurate, nationwide

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analysis of the fire problem, identify major problem areas, assist in setting priorities, determine possible solutions to problems, and monitor the effectiveness of programs to reduce fire losses." The National Fire Data Center established the National Fire Incident Reporting System to meet their charter.

Early data collection efforts varied throughout the country. Many local fire departments used their own systems of documentation. For small fires, the department log was often the only documentation that an incident occurred. Most reports were simply narratives of the incident and actions taken to manage it. Pulling meaningful information or even simple statistics from narratives, however, is an exercise in frustration at the local level and nearly impossible at the state and national levels. Fire service leaders and NFPA had recognized this as a problem for a long time.

By 1969, NFPA had already identified data elements and developed standardized classifications for recording and reporting fire incidents. NFPA 901, *Uniform Coding for Fire Protection,* provided the classification system for the then new National Fire Incident Reporting System (NFIRS). (Some data elements in the standard were not included in NFIRS.) The 1976 edition of the incident and civilian casualty codes and the 1981 edition of fire service casualty codes were used until NFIRS 5.0 was released in 1999.

The first *Fire in the United States* report was published by the U.S. Fire Administration's National Data Center in December 1978. The authors noted that better fire data were needed: "The most detailed data on fire causes were available for a full year for only two states—California and Ohio. A few other states had detailed data, but not in a form that was easily comparable. The limited State data available this year were supplemented by data from seven cities (in other states) with compatible data systems."[2] California's data were for 1975, and Ohio's data were for 1976.

The second *Fire in the United States* was published in 1982.[3] This report looked at fires in 1978 and included full-year data for 15 states. Other volumes have appeared since then, usually on an annual or biannual basis. In the late 1970s and early 1980s, the USFA provided states with funding and other resources to help implement NFIRS in their states. By April 1981, 38 states and the District of Columbia were either participating in NFIRS or preparing to participate.

One of the long-term goals of NFIRS is to promote local fire incident reporting. Because of fiscal, technical, or personnel issues, some participating states have had years in which they were unable to submit data. Consequently, it is hard to precisely define which states are or are not participating in the national system.

NFIRS—A THREE-TIERED SYSTEM

Local fire departments, state fire agencies, and the federal government all play critical roles in collecting NFIRS data.

NFIRS at the Local Level

Fire officers and fire fighters at the local level provide the basis of the system. Without their efforts, this system could not work. By completing a fire report, a fire officer does three important things. First, he or she is making a legal public record that documents the incident. Second, the fire officer's report provides information to senior officers and fire department managers so that they are kept informed about what is happening within their areas of responsibility. This allows them to evaluate the performance of their units at the incident and to talk intelligently about the incident to the media and others. Good information about a fire can motivate change in fire protection approaches in a community or even the nation. The MGM Grand Hotel fire in Las Vegas, Nevada, in 1980 helped to trigger a wave of improvements in fire safety.[4] More recently, the 2003 Station Nightclub fire in Rhode Island led to more requirements for sprinklers in these properties.[5]

Finally, the fire report provides data on the fire problem to fire service management so that they can track trends, gauge the effectiveness of fire prevention and fire suppression measures currently in practice, evaluate the impact of new methods, and indicate those areas that may require further attention.

For the first two purposes, the report format may vary considerably. The report may be as brief as a basic fact statement or as lengthy as an extensive discussion of the fire, supported by photographs, witness statements, laboratory test results, and physical evidence. The length and complexity of the report will depend on the size and nature of the fire, the local fire service manager's need for specific data, and the resources available for obtaining information and completing reports. They also depend on the training and motivation of the person filling out the report.

A fire report should include, at some level of detail, a time-staged description of the circumstances related to the initiation, discovery, growth, and termination of the fire, along with a description of any casualties or damage resulting from the incident. This report should be in the words of the fire officer and must be complete so that people who were not at the fire scene can understand what happened.

A standardized format is required before statistics can be extracted to meet the third purpose. Statistics can reveal patterns or trends, enable comparisons across jurisdictions, and play an important part in service and program evaluations. NFIRS provides a format to make it possible to obtain these statistics.

Fire officers who use NFIRS to document incidents are simultaneously collecting and providing data on the time of the incident, the occupancy, the area where a fire started, what caught fire, what started the fire, property damage, casualties, whether sprinklers and detection equipment were present, and whether they worked. Using the NFIRS structure and codes, these fire officers provide data on what worked to keep small fires from growing in addition to documenting what went wrong at big fires. The reports may be handwritten or entered directly into a computer. The older systems were built around paper formats, although the data may have been entered directly into a computer. Version 5.0 was designed as a modular, computer-based system in which the user is shown the questions that must be answered. Paper forms are still used but seem cumbersome because all questions must be shown, including those that are not relevant to all incidents. Figure 3.3.1 shows an example of an NFIRS 5.0 basic module report form.

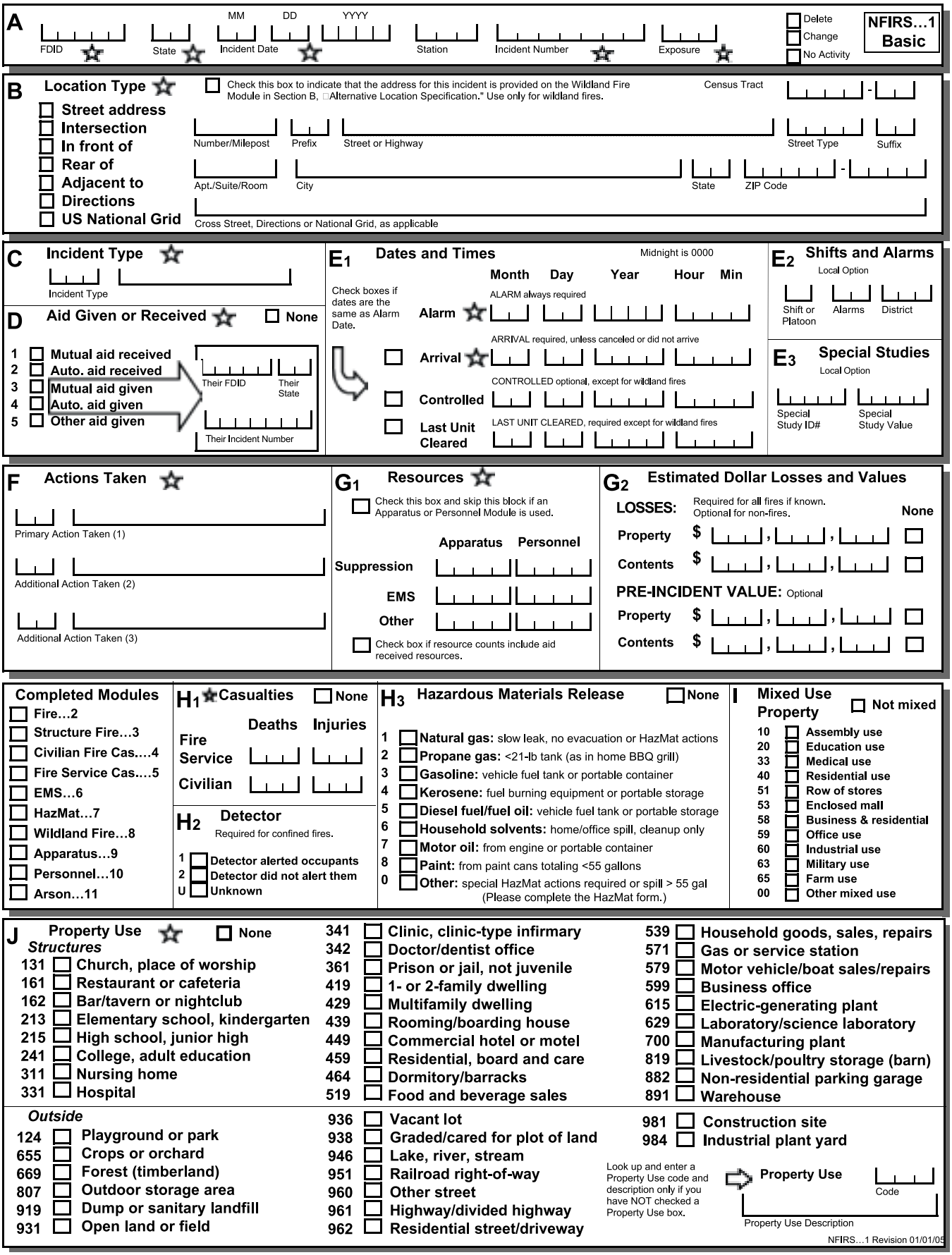

FIGURE 3.3.1 Example of NFIRS 5.0 Basic Module Report Form

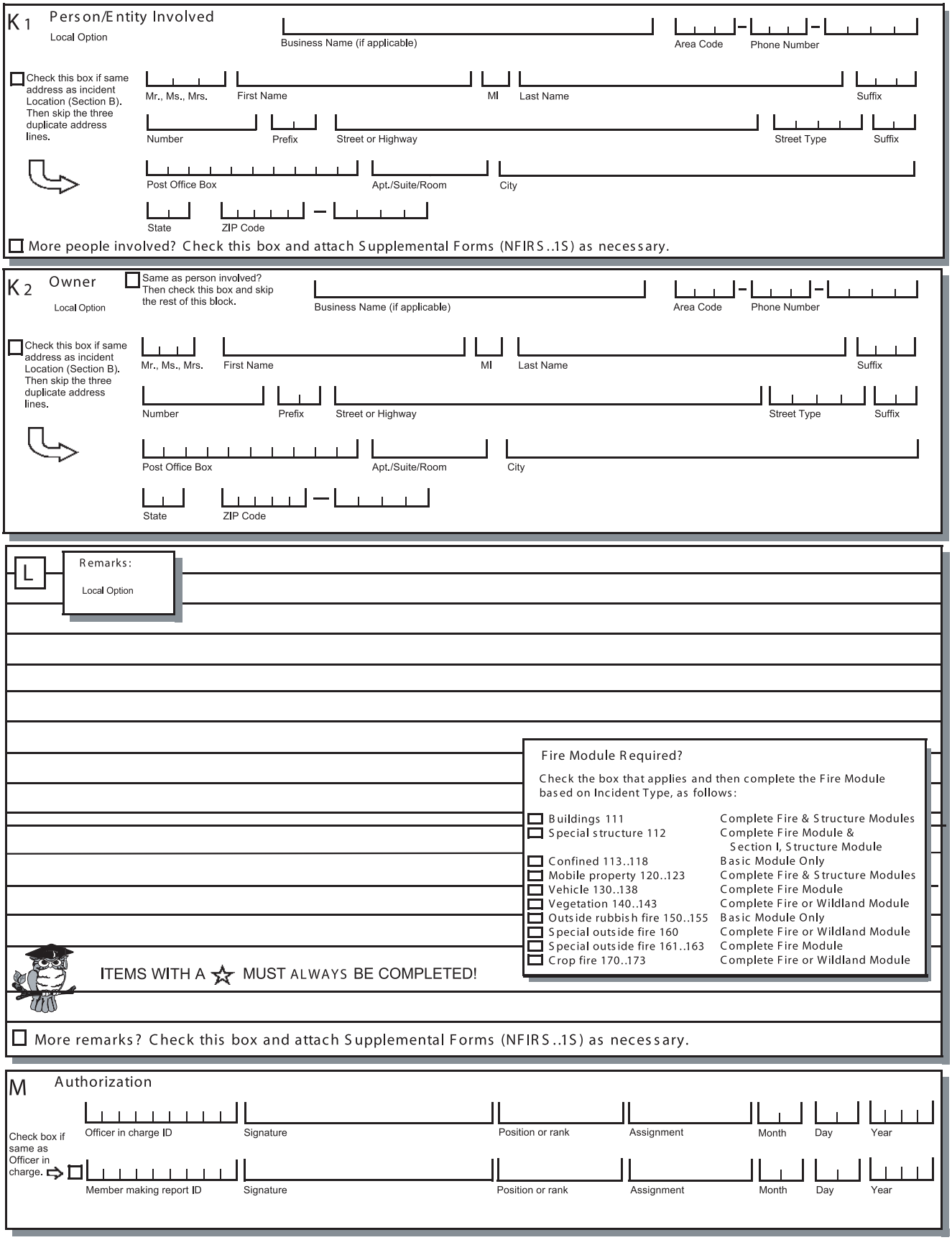

FIGURE 3.3.1 Continued

All the data in the National Fire Incident Reporting System originally come from local fire officers and fire fighters. More than 19,000, or over 60 percent, of the nation's fire departments reported at least one incident to NFIRS in 2004.[6] More and more fire departments see NFIRS as a tool for local use. As computers have become more powerful and software easier to use, the NFIRS system has become a vital management tool. Because Version 5.0 was designed to capture data about all types of incidents, not just fires, it can provide essential information about department activities. A fire chief can see which companies are busiest, what the leading fire problems were last year, and how many incidents of each type occurred. Some departments use the statistics to justify budgets or apply for grants. Departments seeking funds under the 2006 Assistance to Firefighters Federal Grant Program must participate in NFIRS.[7]

Some departments integrate NFIRS data with information concerning other department activities to create a comprehensive management information system (MIS). Some systems transfer computer-aided dispatch (CAD) information directly into the appropriate incident report fields.

NFIRS Reports as Local Records. Although analysts think of NFIRS as a tool for research about fire, at the local level it is first an organized record-keeping system. The incident report describes where and when the incident occurred, the resources used, and the services performed. It provides the framework to collect information about how the fire started, how fire protection systems worked, and the nature of any injuries. These reports are public records. At times, the needs of the researcher for details and the needs of the fire service for efficiency conflict; the needs of the fire service will take priority. At times, coding practices may violate NFIRS rules but make perfect sense. The field "item first ignited" describes the shape or form as the object or substance is customarily used, such as upholstered furniture, fuel, or clothing. The field "type of material first ignited" captures information about the composition of the object or substance, such as cotton, sawn wood, or gasoline.[8] Under these rules, it is inconsistent to see a fire in which the form of material first ignited was upholstered furniture and the type of material was gasoline. However, from a documentation standpoint, this may be a very accurate description of an incendiary fire. In the old days of paper forms, a fire officer might have written, "Gasoline poured on chair cushion." NFIRS training should encourage consistency between these two fields and further explanation of specific circumstances in the narrative.

Cause and Origin Skills Essential Parts of Local NFIRS. The persons responsible for reporting the data should be trained and capable of investigating a fire to determine the origin, cause, and circumstances of the fire. Their determinations become the data used by the system. Weaknesses here can undermine the validity of the data and of any analyses performed on the data.

The fire department should have certain standards that apply to all its record-keeping operations. Such standards will help make the data more uniform from report to report and application to application. Standardization aids all users of the data, makes analysis more accurate, and is essential if data is to be automated. Some areas where department standards should be developed include the following:

- Methods of entering the names of persons and businesses on records (NFIRS 5.0 provides a clear system for people's names but businesses are trickier)
- Recording addresses of buildings with multiple or ambiguous addresses, as well as nonstructure locations, such as those on highways or at street intersections
- Designating apparatus. Should it be done by company assigned? Serial number? Shop number?
- Designating employees. Should it be done by name? Badge number?
- The common abbreviations that are acceptable to use

Updating incident reports is crucial to an accurate fire data system. The updating of incident reports as better or more complete information becomes available is often not done. This is a major problem in the quality of information available. The lack of updates is especially common for fatal fires and large-loss fires, for which the initial incident report is left incomplete pending an investigation but does not get updated after the investigation is complete.

Each department should have detailed written procedures explaining how to perform each step in report compilation. These procedures should address such issues as how the reports are to be edited, processed, and filed; within what time frame; and how they are to be corrected or updated. Everyone responsible for completing any portion of the report should understand the procedures and schedule for completing, correcting, and forwarding the data. Delays in submitting data will result in delays in assembling the complete report and in making it available for use.

Record Retention. Local fire officials must obtain or develop a record retention schedule for all their records. There should be a written policy that details the length of time a report is to be retained in the active files, the length of time it should be kept in inactive storage, and when it can be discarded. The community attorney's office can help to determine legal requirements for retaining records; that office should review the final written policy before its implementation.

Obviously, paper records require storage space. Storage space costs money. As the files become more voluminous, the likelihood that material will be lost or misfiled also increases. On the other hand, costs for electronic data storage have decreased in recent years. There may be different retention requirements for computerized records, which require less space and are useful for multiyear analysis.

Ongoing changes in the computer industry pose challenges for record retrieval. As new technology and programs replace old, will the older electronic records be accessible? It is now hard to find a machine that can read data on a 5¼-in. floppy disk. Because the media can deteriorate, duplicate copies of archived records are advised. Before discarding old software, users should confirm that a new version or system can retrieve old records in an acceptable format.

Motivation to Complete Reports. Better data come from fire fighters who see, use, and understand the compiled statistics. Although far more fire fighters will complete the forms than actually access the data, data quality will improve if the fire

fighters collecting the data understand something about how it is analyzed. Training officers and command staff are encouraged to share reports describing activities at their own department, their state's annual reports, and statistical reports produced by the USFA and NFPA with their fire fighters to ensure that they know their completed reports are used.

NFIRS at the State Level

States generally set the minimum requirements for data collected by local departments. Some states use the standard NFIRS forms or layout without modification and allow or encourage local departments to use the federal NFIRS software. Others have arrangements with specific software vendors. Still others encourage their departments to find the commercial software that best meets their needs. Some states have added a few additional data elements or changed the format slightly.

Vendors selling NFIRS software in a state must check with the state authority to be sure that their software collects all the information the state requires. Local departments should also check with the state before making a purchase. Many states now accept only data collected in Version 5.0. Many no longer accept paper reports.

State fire agencies administer NFIRS in a variety of ways. In some states, one person has primary responsibility for the whole system—the training, quality control, entry, analysis, and report writing. In others, these responsibilities are divided among several individuals or divisions.

NFIRS at the Federal Level

Periodically, after the NFIRS data have been entered and checked for errors, state NFIRS administrators send the compiled data from each incident or release the incidents to the USFA via the federal server. The power of NFIRS at the national level comes from having the details of individual incidents as opposed to a collection of state totals. It is impossible to predict all of the questions that will arise. Although a few fields are not forwarded, most are. This makes it possible to run new queries on specific items.

The USFA provided states with software that may be used to run NFIRS at the state level. The USFA also provides and maintains basic software for local fire department use. This software allows users to enter data directly into a federal server with state partitions or maintain a local database of NFIRS data. State program managers monitor the quality and reporting status of their fire departments.

The USFA also maintains the NFIRS Support Center. People may contact the support center via telephone at 1-888-382-3827 or online through http://www.usfa.dhs.gov/fireservice/nfirs/support/. The Support Center answers questions about NFIRS, the USFA software, specific coding questions, and requests for data information or reports. The center also provides information about NFIRS training and makes referrals when technical assistance is required. The National Fire Data Center processes the data after it is submitted or released by the states. It periodically publishes *Fire in the United States,* the Topical Fire Research Series, and other analyses. After the data are compiled nationally, other users, such as the NFPA, the U.S. Consumer Product Safety Commission (CPSC), and private entities, may obtain the data for their own analyses.

NFIRS Training

The USFA, through the National Fire Academy (NFA), sponsors an NFIRS program management course at the NFA. The course enables participants to promote, support, and manage NFIRS data collection. The content includes data collection, processing, analysis, and presentation of useful, timely, and accurate information about fire department activities. It is designed for new and experienced state, metropolitan, and fire department NFIRS program managers. Participants learn from both structured classes and from each other.

The USFA also provides NFIRS training through the State Weekends training program. States may select NFIRS as one of the available state weekend offerings.

NFIRS DEFINITIONS

One of the benefits of NFIRS or any systematic data collection effort is the standardization of terminology. However, this means taking the time to examine terms or words that are familiar in everyday usage but have very specific meanings in the system's context.

Defining *Fire*

The *American Heritage Dictionary* (3rd ed., 1994) gives two relevant definitions for the word *fire:* (1) "A rapid, persistent chemical change that releases heat and light and is accompanied by flame, esp. the burning of a combustible substance and (2a) Burning fuel or (2b) A destructive burning."[9]

Yet fires in NFIRS include only those fires that are considered "hostile." Appendix C, Glossary and Abbreviations, in the *NFIRS 5.0 Reference Guide* defines *fire* as "Any instance of destructive and uncontrolled burning, including explosion, of combustible solids, liquids, or gases." Fire does not include the following, except when they cause fire or occur as a consequence of fire:

- Lightning or electrical discharge
- Rupture of a steam boiler, hot water tank, or other pressure vessel due to internal pressure and not to internal combustion
- Explosion of munitions or other detonating material
- Accident involving ship, aircraft, or other vehicle
- Overheat condition[10]

Fire department responses to someone burning with a permit or unauthorized burning would not be considered hostile fires and would not be counted as fires at all unless they got out of control.

Structure Fire

Structures include buildings but are not limited to them. Tents, storage tanks, tunnels, and covered walkways would all be considered structures but not buildings. In older versions of NFIRS, any fire inside a structure whether it involved the structure or

not, or any fire under or touching a structure that involves the structure would be considered a structure fire. This is still true in Version 5.0, with one notable exception. In older versions, a vehicle burning inside a structure was considered contents of, or the equipment involved in, a structure fire. Judging from the large number of vehicle fires that occurred at parking garages, it is clear that this convention was not always observed. Under the Version 5.0 rules, a vehicle burning inside a structure would be considered a vehicle fire unless the structure became involved. At that point, the incident becomes a structure fire, but vehicle information can be picked up in the mobile property section.

Under the rules established for Version 5.0, abbreviated reporting is allowed for certain types of confined structure fires, including fires confined to cooking vessels, chimneys, incinerators, fuel or oil burners or boilers, trash compactors, and trash or rubbish with no flame damage to the structure or its contents. This means that only the Basic Module would be completed. States and local fire department officials may elect to require full reports on all of these fires. Because no causal information would be collected on abbreviated reports, full reports are suggested when incidents might be incendiary.

Civilian and Fire Service Casualties

Distinctions are generally made in discussing civilian and fire service injuries and deaths. Civilians include anyone, including the police or other emergency personnel, who is not a member of the fire service.

Different data collection systems have defined fire deaths somewhat differently. According to NFIRS, fire deaths include anyone who dies as a result of the fire within one year of the fire. Although smoke inhalation and burns are the most common causes of fire deaths, a person would be considered a fire fatality if fatally injured while jumping out of a burning building or if a fatal heart attack struck during a fire. In some cases, particularly vehicle fires that were caused by collisions, it may be necessary to obtain autopsy results to determine whether an individual should be counted as a fire fatality. People who died immediately of trauma would not be counted.

NFPA uses death certificates to compare fire death rates among the states.[11] The National Center for Health Statistics (NCHS) uses the International Classification of Disease codes,[12] now in the 10th edition, to document external causes of mortality on death certificates. Different organizations use different combinations of these codes to identify fire deaths. NFPA and the National Safety Council[13] use the underlying or external cause of injury codes denoting exposure to smoke, fire, and flames, which fall into the larger category of "non-transport, unintentional injuries." The USFA also includes smoke, fire, and flame deaths resulting from intentional self-harm or assault (in the suicide and homicide categories); pathological fire setting (in the habit and impulse disorder category); discharge of firework (in the explosion category); and exposure to smoke, fire, and flame with undetermined intent.[14] In Version 5.0 of NFIRS, however, the incident type for a fireworks explosion with no fire is not included in the fire category, and such a fatality would not be counted as a fire death.[15] Death certificates may list fire deaths caused by collisions simply as motor vehicle accidents. A fire death from these incidents could only be identified by looking at fatalities with the primary cause of death listed as burns, smoke inhalation, or a combination of the two. When a body is found at an arson scene, it is necessary to determine whether the victim died before or as a result of the fire. The NFPA and USFA track fire fighter fatalities individually and do not place a time limit on the death.

Equipment Involved in Ignition

"Equipment involved in ignition" refers to the equipment that provided the heat that started the fire. This does not mean that the equipment malfunctioned in any way. Even if the equipment was misused, if it provided the heat, it should be documented. An upholstered chair may be too close to a space heater. An iron may have been left on. Also, fixed wiring inside the wall should be considered a type of equipment.

Arson, Incendiary, Suspicious, and Intentional Fires

Many people are interested in arson. Older versions of NFIRS had two categories of ignition factors that, for statistical purposes, were generally grouped together as arson. *Incendiary* was used when a legal decision had been made or physical evidence indicated that a fire was deliberately set. *Suspicious* was used when circumstances indicated that the fire may have been deliberately set, multiple ignitions were found, or there were suspicious circumstances and no natural or unintentional cause could be found. Although suspicious was not appropriate as a final cause following an investigation, many fires were not fully investigated, and this cause could serve as a flag.

Intentional replaces the terms *incendiary* and *suspicious* on the Fire Module cause categories of Version 5.0. (*Incendiary* is still a choice on the Wildland Module.) When older data are converted to Version 5.0, *incendiary* and *suspicious* are converted to *intentional.*[16] None of these terms correspond exactly to the term *arson,* and this distinction will need to be explained. Because Version 5.0 can capture data about the age of the person involved, it is quite possible to see a fire intentionally set by a five-year-old. This would be below the age of responsibility in most, if not all, states.

The Fire Module is not required for certain confined structure fires, including contained trash or rubbish fires, or for outside rubbish fires. If these forms are not voluntarily completed when a fire appears incendiary, the level of information gathered may be insufficient to pursue an investigation.

Substantial shares of these trash fires were considered incendiary or suspicious under older versions of NFIRS. Dropping the suspicious choice and required causal coding for certain incidents is likely to result in an artificial drop in arson incidents. This will make reliable trend analysis of the subject extremely difficult during the transition.

GETTING TO NFIRS 5.0

The previous material alluded to some of the changes in Version 5.0. What other changes have been made? Who decided what would change?

On the basis of feedback from state program managers and departments in the late 1980s, the USFA began entertaining the possibility of a revision of the NFIRS 4.1 version. Although the initial plan was for an incremental change to version 4.1, it soon became apparent from user feedback that nothing less than a sweeping revision would be acceptable. The U.S. Fire Administration, through its cooperative partnership with the National Fire Information Council (NFIC), sponsored a series of workgroups made up of fire departments, NFIRS state program managers, national data users, and fire software vendors whose charter was to examine every aspect of the way data were being collected in previous versions, apply the lessons learned, and develop consensus requirements for a new NFIRS system. (The USFA had funded NFIC, an organization of NFIRS program managers from participating states, the District of Columbia, and fire departments protecting populations of at least half a million from the early 1980s through 2004. NFIC provides specialized training to its members and advice from the field to each other and the USFA. Due to budget cutbacks, these cooperative agreements have not been funded in recent years.) The process took seven years to complete and included input from users of the system and its data at all levels. The results were some dramatic changes in the NFIRS system.

The USFA and NFIC began working on the new NFIRS in 1989. NFIC members surveyed fire departments of different sizes to see what they liked and did not like about the existing system. NFIRS consumers, such as the NFPA, the Consumer Product Safety Commission (CPSC), the National Highway Traffic Safety Administration (NHTSA), and private industry groups, were consulted about their data needs.

Choosing Data Elements

All agreed that the data requested must be (1) reportable, that is, something that could be described in a codable or quantifiable manner, (2) collectable—the information must be readily available without spending an excessive amount of time to obtain it and users must be willing to report it, and (3) usable. Code developers want very specific information, but sometimes they want more detail than fire fighters can be expected to provide. Even if the data can be collected, if that particular information is not used, it is a waste of time to collect it. Fire fighters also indicated that they had difficulty with certain data elements and questioned the reliability of those elements. For example, it was difficult to accurately determine whether all openings were protected, a critical piece of information in determining the type of construction. Consequently, the field "construction type" has been dropped from Version 5.0.

Fire fighters also resented filling out the same information repeatedly on many of their minor fires. By expanding the "situation found" ("incident type" in Version 5.0) to three digits, specific codes could be assigned for confined food on stove fires and confined chimney fires. For certain types of confined structure fires and for outdoor rubbish fires, fire fighters will complete little more than basic dispatch information. Table 3.3.1 summarizes the changes in NFIRS 5.0.

Different Circumstances Triggering Different Modules

NFIRS 5.0 is modular in design and uses only the modules necessary to describe the incidents. Identifying and dispatch data such as dates, times, incident type, and occupancy are collected for all incident types in the Basic Module. Local authorities may also require owner and occupant information and narratives. That is the extent of the information required by the NFIRS for nonfire incidents, confined structure fires, and outside rubbish fires.

More detailed information is collected in other modules to further describe specific circumstances of an incident. The modules used by NFIRS 5.0 are as follows:

- Basic Module (mandatory)
- Fire Module (mandatory)
- Structure Fire Module (mandatory when the fire is a structure fire)
- Civilian Casualty Module (mandatory when there is a civilian fire casualty)
- Fire Service Casualty Module (mandatory when there is any fire service casualty)
- EMS Module
- Hazmat Module
- Wildland Fire Module
- Apparatus or Resources Module
- Personnel Module
- Arson Module
- Juvenile Firesetter (submodule of the Arson Module)
- Supplemental Module

Basic Module. The modules identified as mandatory must be used when triggered by incident type or casualty data entries in the Basic Module.

Fire Module. For nonconfined fires in their jurisdiction, fire fighters must complete the Fire Module that collects information about property details and on-site materials, fire causes, any equipment or mobile property involved, the area of origin, material first ignited, human factors, and any fire suppression factors.

A broad cause category has been introduced that contains the following choices:

1. Intentional
2. Unintentional
3. Failure of equipment or heat source
4. Act of nature
5. Cause under investigation

U. Cause undetermined after investigation

Code 5, "Cause under investigation," makes it possible to identify reports that might need revisions. Local departments must have procedures to update these records when new information becomes available. These causal data are not required for the specified confined structure fires or outside rubbish fires. The field "Factors contributing to ignition" provides the opportunity to document more specific causal factors when the Fire Module is used.

TABLE 3.3.1 Summary of Changes in NFIRS 5.0

Elements Dropped in Version 5	*New Basic or Fire Data*	*New Structure Fire Data*	*Other New Data*
Method of alarm	Three-digit incident types	Type of detector, sprinkler	Optional Modules: EMS, Wildland, Hazmat, Arson, Juvenile Firesetter, Personnel, Resources, Supplemental
Method of extinguishment	Expanded mutual aid data	Sprinkler and detector effectiveness	
Extent of smoke damage	Reduction in property use codes	Sprinkler heads operating	
Avenue of smoke travel	Abbreviated reporting for certain confined structure fires, outside trash fires	Reason for detector or sprinkler failure	
Type of material generating most smoke	Suppression factors	Structure status (vacant, occupied, under renovation)	
Form of material generating most smoke	Broad causal factor categories including pre- and post-investigation undetermined	Number of stories above and below ground	
Construction type	Human factors	Material contributing to flame spread	
Fire fighter injury equipment unless a factor in injury	On-site materials	Number of stories by flame damage	
	Mobile property identified only if involved in ignition		
	Multiple actions taken, factors contributing to ignition		
	Pre-incident property value		
	Separate loss fields for contents and structure		
	Expanded, more specific equipment involved in ignition		
	Separate fields for equipment portability, power		
	Numeric entries for number of units, buildings, acres burned		
	Codes on basic form for minor hazardous releases		
	Incident types indicate fires in mobile buildings		

Structure Fire Module. The Structure Fire Module is completed for building fires. Only the question on structure type is completed for structures other than enclosed or portable or mobile structures. This includes tents, open platforms, fences, and the like. The Structure Fire Module captures information on building status and size, the floor or story of fire origin, the extent of and material contributing to flame spread, and detection and automatic suppression system performance.

Civilian and Fire Service Casualty Modules. The Civilian Casualty Module is required for, and used only for, civilian fire injuries. It captures information such as the cause of injury, the victim's location, and factors contributing to injury. Race and ethnicity are now captured in this casualty module.

Several fields have been added to the Civilian Casualty Module that may be of particular interest to those dealing with performance-based codes. These include the story or floor of the injured occupant, first, at the time of ignition and, second, at the time of injury, if different. In addition to location at ignition, information is now required on the location at time of injury.

Severity gradations of minor, moderate, severe, life threatening, and death are now provided, instead of just injury or death, the choices in older versions. Human and other factors contributing to the injury are also captured. The victim's name, age, and gender and the cause, activity at time, and the nature and severity of injury are captured on both types of casualty modules.

The Fire Service Casualty module is used for all fire service injuries, including those resulting from events other than fires. This module captures information about whether the victim was a career or volunteer fire fighter, lost time injuries, type of location at injury, and the nature of any protective equipment failures that contributed to the injury.

The Basic, Fire, Structure Fire, Civilian Casualty, and Fire Service Casualty Modules are the mandatory modules associated with NFIRS. State or local authorities may require completion of the new Emergency Medical Services (EMS), Hazardous Material, Wildland Fire, Arson, and Juvenile Firesetter Modules when appropriate.

EMS Module. In its infancy, fire department activity reporting was limited to fires only, at least on a national level. Little recognition was given to the other activities that fire departments were performing on a daily basis. As fire department management became more responsive to the budgetary concerns and restrictions of fiscal policy, the need to justify all activities and expenditures grew. Many local fire departments began to collect data on their own, using the NFIRS program to attempt to gather management information concerning all of those other activities and stretching the program in directions that were never anticipated.

Recognizing that emergency medical services (EMS) activities represent a significant portion of what fire departments are currently doing, an EMS reporting module was included in NFIRS 5.0. The starting point for development of the EMS Module was the Final Report of the 1993 Uniform Pre-Hospital Emergency Medical Services (EMS) Data Conference sponsored by the National Highway Traffic Safety Administration (NHTSA).[17] This document contains the 80 EMS data points and their definitions as agreed upon by the participants of the conference as being "essential" or "desirable" for EMS data systems.

Upon review of the NHTSA data elements, the NFIRS 5.0 development team concluded that many of the data elements did not pass the test for collectable, reportable, or usable. As a result, patient care reports and EMS data forms from fire departments and state EMS agencies across the country were assembled and compared for data elements that were universally collected and reported. As much as was practical, NHTSA codes and definitions were retained to provide linkage to databases that employ these codes.

The EMS Module is not intended to replace or otherwise interfere with state or local EMS patient care reporting requirements, nor is it intended to be a comprehensive EMS patient care report. Instead, the data elements in this module should be viewed as "core elements" around which a complete patient care report can be built.

Hazmat Module. The Hazmat (hazardous material) Module captures the substance, container size, amount released, cause and circumstances of release and mitigation, evacuation information, and disposition for hazmat incidents. Multiple substances and associated containment activities may be documented in this module. Common, minor releases (such as gasoline leaking from a vehicle fuel tank or propane gas escaping from a grill cylinder) that do not require specialized resources can be documented in the Basic Module.

Wildland Fire Module. The Wildland Fire Module may, if local or state authorities permit or require, be used to document brush, grass, forest, crop, or other vegetation fires, as well as incidents of unauthorized, controlled, or prescribed burning. Unauthorized, controlled, and prescribed burning incidents are not counted as hostile fires.

This module allows for alternative forms of incident location, such as latitude and longitude or township. Area type, property ownership type, fire causal data, weather information, number of buildings ignited or threatened, crops burned, National Fire Danger Rating System (NFDRS) fuel model at origin, and fire behavior are collected in this module. If an identified person was involved in the ignition, the age, gender, and activity data are also collected.

Apparatus or Resource and Personnel Modules. The NFIRS 5.0 system includes the optional Apparatus or Resource Module and Personnel Module. After completing an incident report, an officer can identify the apparatus and personnel that were dispatched and how they were used to handle the incident. This provides the means to examine resource needs and deployment, something that could not be done with previous versions of NFIRS. These modules are generally for local use and completed at the discretion of the local authority.

Arson and Juvenile Firesetter Modules. The Arson Module captures motivational factors, group involvement, and specific circumstances of the crime. The Juvenile Firesetter Module captures information about the child, family, and risk factors. Disposition is captured on both of these modules. Names of individuals are not part of these modules or the EMS module. If the Juvenile Firesetter module is completed, a juvenile's age may not be recorded on the Fire Module.

Supplemental Module. Information about additional persons or entities involved, special studies, and remarks are captured in the Supplemental Module.

Legacy Data

Because many fire departments continue to collect data using the older version, the data they collect for the dropped data elements (construction type, method of alarm, method of extinguishment, extent of smoke damage, avenue of smoke travel, and form and type of material generating most smoke) is still included as legacy data in the national database.

Better Documentation of Nonfire Incidents

Anyone involved with the fire service or fire protection knows that fires are only part of the story. As was mentioned previously, earlier versions of NFIRS provided limited ability to track nonfire incidents. With the exception in recent years of some hazardous material incidents, nonfire incidents were not compiled by the USFA. This changed with Version 5.0. The fire ser-

vice can now obtain more detailed information about EMS-type calls and other nonfire emergencies. They are also better able to track calls by station and mutual or automatic aid incidents.

Fire Protection Systems

The three-digit incident type provides specific information about false alarms and indicates whether the detection equipment was designed to respond to heat, smoke, or carbon monoxide. The fire protection community has been plagued by a lack of information about sprinkler systems. Incident type codes in the Basic Module capture sprinkler activations due to unintentional tripping or malfunctions. Data from the Structure Fire Module indicate whether an automatic extinguishing system was present in the fire area, the type of system present (wet, dry pipe, dry chemical, foam, halogen, or carbon dioxide), whether it was effective, how many heads operated, and the reason if the system failed or was not effective.

Similar detailed information is collected on fire detection systems, including detector type (smoke, heat, combination smoke and heat, sprinkler with waterflow detection, more than one type present, and other), detector power supply, detector operation, detector effectiveness in terms of alerting occupants, and failure reason if the detector failed to operate.

Occupancy Groups or Property Use

The number of property use codes has been dramatically reduced. Residential occupancy code choices include one- and two-family dwellings, multifamily dwellings, rooming houses, hotels or motels, residential board and care, sorority or fraternity houses, barracks or dormitories, other dormitory-type residences, and other residential. A separate entry documents the number of units in each. (When older property use data with number of units are converted forward, a midpoint value is generally assigned.) Similar reductions have been made in the mercantile, basic industrial, manufacturing, and storage categories. Code 700 now covers all manufacturing or processing. The specifics are captured by documenting on-site materials and indicating whether these materials were used in or stored as (1) bulk storage or warehousing, (2) processing or manufacturing, (3) packaged goods for sale, or (4) repair or service. Up to three on-site materials may be listed.

The general property use classification is captured in the Basic Module. The Fire Module captures details about number of units and on-site materials.

Structure Status

The Structure Fire Module also collects information about the status of the structure. In the older versions of NFIRS, separate occupancy or fixed property use codes identified vacant buildings or buildings under renovation or demolition. However, many were still coded according to their intended use. Every fire fighter knows that fighting a fire in an abandoned mill is different from fighting one in a vacant dwelling. Separate codes indicate whether the structure was under construction, occupied and operating, idle, under major renovation, vacant and secured, vacant and unsecured, or being demolished.

Property Damage

Direct property damage provides one measure of fire problem severity. In older versions of NFIRS, when this field was left blank, the dollar loss was assumed to be zero. A checkbox in Version 5.0 indicates that there was no loss. While the information is required when known, presumably the field will be left blank if unknown. Property damage estimates are provided by the fire service. Sometimes they have input from insurance adjusters; in many cases, they do not. Loss figures are estimates on the basis of the expected replacement cost of the property damaged. Property damage for the property and its contents are now separated into two fields. Pre-incident property and contents values are optional. Caution should be used when comparing these values. In many cases, it would be inappropriate to claim credit for saving all of the nondamaged property. These data are collected in the Basic Module.

One of the frustrations with older versions of NFIRS was the inability to accurately gauge the severity of a fire. Dollar loss was influenced by the value of the property. When extent of flame damage was confined to the structure, the damage might have been to just one exterior wall. Version 5.0's Structure Fire Module captures data on the number of stories with minor (1–24%), significant (25–49%), heavy (50–74%), and extreme (75–100%) damage. The "extent of flame damage" field is still present, although the code for "confined to part of room or area of origin" was dropped. The size or dimensions of the main floor are now required.

Direct Entry of Numeric Data

Users of NFIRS data from the older systems were often frustrated by fields in which numeric values, such as number of stories or fire fighter responses before injury, were coded. Too often, it was unclear whether the individual completing the form was using the codes or using the raw numbers. In Version 5.0, these are direct entries. Version 5.0 also captures the number of stories above and below grade.

More Specific Choices for Equipment Involved

The equipment involved in ignition (or release on the Hazardous Material Module) field has far more specific choices than in older versions. In addition, portability is now a separate field. A portable space heater might be coded as a heater, excluding catalytic and oil-filled (code 141), and in the portability box, portable would be checked. In the past the fuel or power source for equipment was generally found in the "form of heat of ignition" field. That field has been functionally divided into two: "heat source" and "equipment power."

Suppression Factors

Up to three suppression factors may be entered in the Fire Module. Suppression factors are circumstances that contributed to the growth or spread of the fire. These include specific building construction or design factors; an act or omission, such as blocking a fire door; the building contents or fuel load; delays; problems with protective equipment such as water supply,

suppression systems, or fire protection assembly; egress or exit factors, such as overcrowding, window type, or occupant characteristics; and natural conditions.

Human Factors

Life safety educators are very happy to see the ability to capture data about human factors in the Version 5.0 Fire Module. Some of these factors could be captured for civilian casualties in older versions but not for fires without casualties. Human factors include asleep, possibly impaired by alcohol or drugs, unattended (or unsupervised) person, possibly mentally disabled, physically disabled, multiple persons involved, and age (with another field to record the age). An additional field captures the gender of the principal person involved when age was a factor. Similar data are captured on the casualty report for any civilians injured by fire.

Factors Contributing to Injury

A new field in the Civilian Casualty Module, "factors contributing to injury," allows up to three entries. These include the following:

- Various egress problems, such as crowd situations with limited exits, locked exits, or security bars
- The fire pattern itself, such as trapped above or below, vision impaired by smoke, clothing igniting while escaping, or exits blocked by flame or smoke
- Escape difficulties, such as choosing inappropriate exit route or reentered building
- Collapse of the roof, floor, or wall
- Vehicle related factors
- Equipment related factors such as unvented heating equipment or improper use of heating or cooking equipment
- Other factors, such as clothing burning before the individual tried to escape

Other Differences and Options

In some cases, similar data are collected in different modules. Either the state or local fire department will determine whether the Wildland Module or the Fire Module will be completed for forest fires. These modules use the same codes for some fields, but the broad cause codes are different.

Because different jurisdictions have different data needs, and because many information needs cannot be anticipated, Version 5.0 has the ability to generate "plus one" codes by adding an extra character to the codes in each field. These extra codes are not a part of the national database. Local fire departments should check with their state authorities before implementing their own "plus one" codes to ensure that no conflict exists between the state and local needs.

Several fields in the Supplemental Module have been set aside for special studies. Fire officers must know what the codes cover. Version 5.0 has the ability to provide much more detailed documentation and data about fires. However, this can happen only if the fire fighters who complete the forms know that the codes exist. The developers of 5.0 worked hard to make the system easier for and more responsive to the fire service. A danger exists that, in this era of pull-down menus, individuals may not even know that a particular optional field is relevant or that a certain code is available. Dry as the material is, anyone who completes NFIRS forms should occasionally thumb through the coding manual as a reminder of the type of information collected in each field.

Difficulty of Change

The transition to NFIRS 5.0 involved changes in what and how data are recorded, in data and editing specifications, in computer systems, training, manuals, and analysis. With such a major overhaul, the transition has sometimes been difficult. The USFA established the previously mentioned NFIRS Support Center with a 24-hour toll-free number (1-888-382-3827) and online e-mail capability at http://www.usfa.dhs.gov/fireservice/nfirs/support to facilitate the process and enable fire fighters to quickly obtain answers to their NFIRS questions.

Version 5.0 of NFIRS has been implemented at varying speeds across the country. NFIRS 5.0 brought major changes in the underlying logic of the system. It provides significant new data in terms of expanded incident types, human factors, and fire protection systems. Implementation practices have varied by state according to the state's needs and priorities. Consequently, the national NFIRS database from 1999 through at least 2003 contains data collected in Version 5.0 and data collected in older versions that have been converted to Version 5.0. Because data definitions and data elements in the versions are not identical, the conversion is not exact. This makes accurate analysis of the combined data more challenging. An understanding of both Version 5.0 and the older systems is required for accurate analyses of merged data.

COMPUTERS AND NFIRS

Computers have made it easier to enter and use the data. On-screen look-ups assist the fire officer in choosing the correct classification.

Quality Control

Quality control issues can become more complicated with computer-generated reports. Most programs do some error checking for allowable values and some checks to see whether the data make sense. Computers, however, have no common sense. As long as the data meet the criteria, they will pass through the system. It is often easier to spot inconsistencies or patterns of problems through a visual scan of paper forms than by working with coded electronic data. A detailed narrative is more important than ever with an automated or paper checkbox system. Before checkboxes and computers, a fire officer would write words describing the event witnessed. In many cases, one code covers multiple items such as "portable appliance designed to produce heat, other" or "storage area, tank or bin." "Electric foot warmer" or "500-gallon propane tank" would be more specific. If that information is not entered elsewhere, it will be lost. At least one vendor provides users with the ability to generate

a preliminary narrative based on the coded information in the incident report. To be meaningful, this narrative must be supplemented with the specifics of an incident.

To protect the integrity and data quality of the information collected from departments, standard NFIRS edit checks exist and are documented in the *NFIRS 5.0 Design Documentation* maintained by the USFA. The edits consist of both allowable and relational edit checks and must be implemented in a standard way by all developers of NFIRS 5.0 data collection software. System edits prevent many common data entry errors such as transposing the incident alarm time and the time that the department arrived at the incident scene. Software edit checks are typically done at the time of data entry, and the corrections are made at the department level. Incidents that fail validation are either corrected by the state NFIRS program manager or returned to the department for correction and resubmission.

NFIRS Software

The USFA has developed bare-bones software for Version 5.0 to enable states to manage their systems. If the state authority permits, local fire departments may also use this software. However, the state authority, not the USFA, is expected to provide the support, and some do not feel they have the resources to do so. Some states have purchased software or licenses for their fire departments from commercial vendors.

Data Retrieval and Analysis

In many fire-reporting systems, a great deal of effort is devoted to data collection, and then very little effort is given to making good use of the data. Data analyses should be of two kinds: (1) routine, periodic reports that summarize the fire problem and that provide management data and (2) special reports that answer queries about particular problems or evaluate programs, support budget requests, and the like.

Data analysis can begin with a simple tally of incident types or other data element. Data analysis should also consider the interrelationship between various data elements or various databases. For example, relating fire data to socioeconomic data by census tract shows the population groups that are most affected. Comparing fire losses over the years to inflation rates and increasing property values may show that fire protection is currently more effective, even though in raw numbers the total loss is greater.

Nearly all NFIRS reporting software comes with a suite of canned reports. USFA makes web-based NFIRS reporting available to all NFIRS users that have an account to use the browser-based reporting tool. Each NFIRS state reporting office determines who may use the reporting tool within each state. The USFA reporting tool provides many standard NFIRS reports with filtering capabilities that run against the data contained in the NFIRS database. States and departments may use the USFA tool exclusively or use it to supplement existing vendor reporting tools or other custom local reporting tools. Since getting answers from raw data can be difficult for those not trained in data analysis, canned reports ensure standard and accurate answers to commonly asked questions about the data. Many incident reporting software packages also include powerful data-filtering features so that the usefulness of the standard reports is greatly extended. For example, the standard Tally report counts the frequency of occurrence for each code within a data field. Running this report on the Incident Type field with no data filter results in a count for each type of run done by the department. By using a data filter, the department can also limit the report output to just fires, just arson fires, or just fires in single-family homes started with a candle. In this way, multiple questions can be answered with the same canned report. Several commercial vendors of NFIRS software include NFPA's annual fire department experience survey in their packages.

More information on data analysis can be found in Section 3, Chapter 4, "Use of Fire Incident Data and Statistics."

NFIRS Support Materials on USFA Website

The USFA's website (http://www.nfirs.fema.gov) has downloadable coding manuals for NFIRS 4.1 and 5.0, active vendors and procedures, and other relevant information.

GETTING THE BIG PICTURE ON FIRES

NFIRS can provide a great deal of information, but it is important to remember what it cannot do. Because of the time lag in compiling data, some time will pass before a new problem can be identified. NFIRS by itself cannot be used to determine risk. Denominators such as prevalence in the population are needed. As was mentioned earlier, different states have different reporting policies. NFIRS is not a census of all fires; it is not even a full listing of all fires reported to fire departments. Such a listing does not exist. How do we tell how big the fire problem is in the United States?

NFPA's Annual Fire Department Survey

Each January, NFPA sends its survey to all fire departments protecting 100,000 or more and a random sample, stratified by population, of the smaller departments. In 2004, NFPA sent out almost 13,000 surveys and received a total of 2,830 back, a response rate of 22 percent, with higher response rates from the larger communities. The departments that did respond protect about 36 percent of the U.S. population.[18] The data are used to develop national estimates of the fire problem. A press release about the number of fires and fire deaths is issued each summer. An abbreviated version of the full report *Fire Loss in the United States* is published in a fall issue of *NFPA Journal.* The report is also available on NFPA's website to all visitors.

NFPA's survey is not terribly detailed. It asks about fires by type and broad occupancy class, intentional structure and vehicle fires, and civilian and fire fighter deaths and injuries. NFIRS has far more detail, although it usually lags substantially behind the survey in terms of timeliness.

By comparing the totals from NFPA's survey to corresponding totals in NFIRS, analysts estimate what fraction of total U.S. fires and associated deaths, injuries, and property damage were captured by the NFIRS sample. These fractions are inverted into ratios that are used to "scale up" the NFIRS numbers on

specific fire problems to "national estimates" of the total size of these problems. Different ratios are used for residential structure fires, nonresidential structure fires, vehicle fires, and other fires. Within each group, analysts use different ratios for fires, injuries, deaths, and direct property damage.[19]

Many fire fighters have wondered why, if they faithfully complete their fire incident reports, they are also asked to complete NFPA's survey. The reason is that because different states have different reporting practices, NFIRS cannot estimate the total number of reported fires per year. Analysts need to use the survey results and NFIRS together to develop national estimates. In the older versions of NFIRS, nonfire responses (except for hazardous material incidents in Version 4.1) were not forwarded to the USFA. Until all fire departments around the country report using NFIRS 5.0 to states that are processing all incidents, the NFPA survey is the only national source of this data. Because the survey is completed by summer each year, it can produce numbers about a year earlier than NFIRS.

What Is Not Included in the Statistics

Neither the survey nor NFIRS captures data on fires that were not reported to fire departments. Consequently, fires that are handled by private brigades or individuals will not be counted. The NFPA survey samples only municipal fire departments, including career and volunteer departments. Fires reported to wildland fire agencies or military agencies will also not be captured. Figure 3.3.2 illustrates how fires in communities protected by municipal fire departments are or are not captured in the data.

If a fire is handled privately, with no fire department notification, as far as these two databases are concerned, it never happened. If the fire department responded but did not complete a report, the fire will not be counted. If the report was completed but not sent forward to the state, it will not become part of the state or national NFIRS database. If a fire report has a serious or fatal error or inconsistency, it will also be excluded from the NFIRS database. If the fire department was in the NFPA sample and it responded, then the fire will be counted by the survey. If the state does not collect or forward NFIRS data to the USFA, then that state's communities generally will not be in the NFIRS database. Exceptions have been made for large metropolitan fire departments reporting directly to the USFA with state permission.

Because of the large number of fires reported to NFIRS, reliable analyses can be done on most common types of problems even though many jurisdictions are not included. Difficulties arise, however, with unusual circumstances, such as nonhome fire deaths or fires in specific nonresidential occupancies. For example, North Carolina and Pennsylvania were not participating in NFIRS during the 1990s. National estimates based on NFIRS and the NFPA survey showed no fatalities in college dormitories or fraternity houses in the five-year period from 1993 through 1997, yet we knew from our Fire Incident Data Organization (FIDO) (see next section) that two fires in these properties had claimed five lives in each state. NFPA was aware of six other fatal fires in these properties during that time.[20] However, statistical projections can be footnoted, but not adjusted, on the basis of anecdotal data. Similarly, a fire with an unusually large dollar loss or number of casualties can also skew the data when projections are made.

These problems are not unique to fire data and are typical of any type of data collection effort. Even the U.S. Census Bureau considered using statistical projections to control for areas where undercounting was expected to be a problem.

OTHER SOURCES OF DATA

NFIRS and NFPA's annual fire department experience survey provide national estimates of fires reported to local fire departments. Other sources are needed to provide more detailed narrative accounts, international data, and arrest and injury data.

NFPA's Fire Incident Data Organization (FIDO)

NFPA designed and maintains the Fire Incident Data Organization (FIDO) to provide examples and details of specific types of fires. News clips, the Internet, word of mouth, and other sources

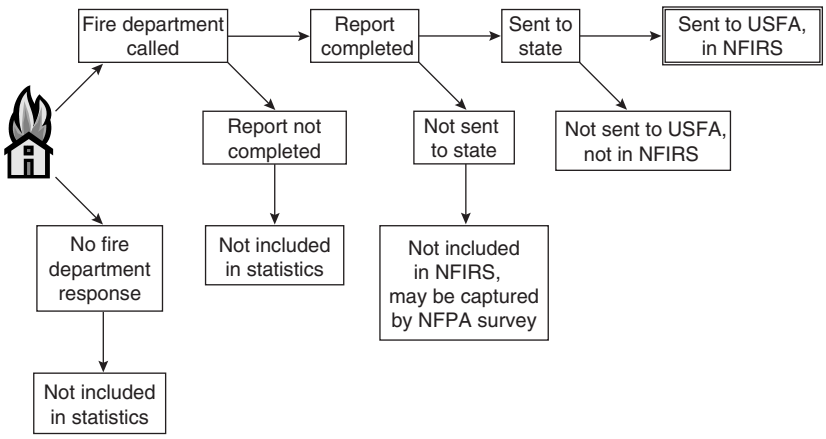

FIGURE 3.3.2 How a Fire Gets Counted

are used to identify fires of interest. Additional information is then sought from fire departments, insurance companies, and other federal and state safety agencies. FIDO is the source for the fires profiled in *NFPA Journal*'s "Firewatch" column. Because every effort, including surveying state fire marshals' offices, is made to track down reports of multiple death fires, large loss incidents, and fire fighter fatalities, we are confident of the completeness of the data and use FIDO as the source for these reports. Unsolicited fire department reports of fires with lessons learned are very welcome.

Most of the fires in FIDO are more serious than the usual. They show what can happen, not what is likely to happen. Anecdotal data such as FIDO cannot be the basis for statistical analysis. Incidents in FIDO have been entered by using codes very similar to the older versions of NFIRS, but additional fields have been added to capture other significant issues. NFPA does not release identifying information about a specific fire without the fire department's permission.

Uniform Crime Reporting System (UCR)

The Uniform Crime Reporting System (UCR) of the Federal Bureau of Investigation (FBI) collects standardized reports about crimes and offenders from nearly 17,000 law enforcement agencies around the country. Most contributing agencies are local police departments, but other agencies, including state fire marshals' offices, also make arrests. Agencies protecting about 94 percent of the U.S. population submit reports each year, but some agencies submit less than 12 months of data in a given year. As with NFIRS, UCR has a goal of complete participation.[21]

The UCR data provide information about the ages and genders of the arrestees. The FBI regularly publishes crime statistics in the Crime in the United States series.

Consumer Product Safety Commission (CPSC) Data

National Electronic Injury Surveillance System (NEISS). Through its National Electronic Injury Surveillance System (NEISS), the U.S. Consumer Product Safety Commission (CPSC) tracks injuries that were treated in a selected sample of emergency rooms. This information has been used to develop projections of injuries caused by products and to identify unsafe products or practices when using the products. Together with the Centers for Disease Control's (CDC's) National Center for Injury Prevention and Control, they have been expanding the scope of NEISS to include all types of injuries. Originally, only injuries involving consumer products were included, but in 2000, the system expanded to include all injuries treated at emergency rooms. Historically, it has been difficult to find information about nonfatal injuries. NEISS fills some of that void. Users may query the NEISS database directly from http://www.cpsc.gov/library/neiss.html. It is also possible to preview up to 30 cases that meet the search criteria or download the whole file. Although identifying information is removed to protect confidentiality, the comments provide very helpful information in understanding the injury scenarios.

Death Certificate File. The CPSC also maintains a death certificate database about deaths associated with consumer products. Victim data are removed before these data are released. Additional information may be obtained on the website for the National Injury Information Clearinghouse at http://www.cpsc.gov/about/clrnghse.html.

Phone: (301) 504-7921
Fax: (301) 504-0025

Other CPSC Data. CPSC's In-Depth Investigations (INDP) file contains summaries of investigations into product-related injuries or events. The agency's Injury/Potential Injury Incident File (IPII) contains summaries of product-related reports to the CPSC, newspaper accounts, letters, and medical examiners' reports. Although not incident based, CPSC's searchable database of recalls is a valuable tool for fire investigators.

Injury Facts

The National Safety Council compiles reports about deaths caused by unintentional injuries. *Injury Facts* (formerly *Accident Facts*) is published annually. This report provides data on death causes by age, state, home, vehicle or work, and long-term trends. A similar report, *International Accident Facts,* is updated less often but provides international comparisons from up to 50 countries.

International Fire Data Collection Organizations

NFPA is aware of two organizations engaged in collecting international fire data. Because each country collects data independently and has their own criteria for what is collected, it is difficult to make accurate comparisons.

World Fire Statistics Centre. The Geneva Association sponsors the World Fire Statistics Centre. Each year, the Centre collects data from about 20 nations on fire deaths, direct property damage, indirect fire losses, costs of fire-fighting organizations, costs of fire insurance administration, and costs of fire protection to buildings. When applicable, the data are presented as a percentage of the gross domestic product (GDP) or as per capita rates. Its annual report is presented each year to the U.N. Committee on Human Settlements. The October 2005 report noted that the European Union Fire Safety Network had been established the previous year, aiming to "interchange news, views, and statistics on fire safety matters. . . ."[22]

CTIF. The International Technical Committee for the Prevention and Extinction of Fire (CTIF) was formed in Russia in 1995. Its 2005 report[23] contains information collected from more than 50 countries, almost one-third of the world's countries with about two-thirds of the world's population. They collect information on the number of fires, structure fires, vehicle fires, arsons, false calls, and fire department staffing and equipment. They also have data from many of the world's largest cities. Their data include many of the former Soviet republics and other countries from Eastern Europe as well as elsewhere.

International Fire Data Collection

In some countries, fire data collection is a government function; in others, it is done by the insurance industry. Definitions vary from country to country, so comparisons should be made with caution.

Canada. In Canada, as in the United States, the system is three-tiered. Local fire departments report their data to the provinces. However, the provinces report the totals, not the incidents themselves, to the Human Resources and Social Development Canada (HRSDC). The Council of Canadian Fire Marshals and Fire Commissioners produces annual reports. These reports are available at http://www.ccfmfc.ca/stats/statsReports_e.html. A workshop to improve fire statistics and explore the possibility of establishing a national fire data center was held at the National Research Council of Canada in April 2005. The presentations are available online at http://irc.nrc-cnrc.gc.ca/fr/firestatisticsworkshop/nrc_fire_stats_workshop_april_2005_introduction.pdf.

Australia. The Australian Incident Reporting System (AIRS), used by most of the Australian fire service, uses a data classification standard based on the U.S. NFIRS system. However, the participating services have made their own modifications to some elements of the system.

Sweden. In Sweden, the insurance industry collects fire data. Only fire deaths are reported to the government. When the insurance industry collects the data, it is likely that fires in uninsured properties or fires that do not trigger a claim will be underreported.

United Kingdom. Fire brigades (departments) in the United Kingdom report their fires directly to the Office of the Deputy Prime Minister in London. In addition, the British Crime Survey includes questions about fire experience and provides some information about fires that were never reported. The national government manages these databases. However, the government does not collect dollar loss information; that task is left to the insurance industry. The British fire databases are described in *Fire Statistics: A User Guide for Research.*[24]

Japan. Fire departments in Japan also report their fires directly to a national government office.

SUMMARY

The data provided by NFIRS and other detailed national and international databases make it possible to monitor progress in fire prevention and protection. Almost all of the data come originally from fire services. Researchers must remember that completing incident reports is a small part of a fire officer's responsibilities and certainly not why someone joined the fire service. However, most fire officers understand that statistics can help them to manage a department more effectively, prepare and defend a budget proposal, and determine what types of fire problems their community faces.

Data collection will improve as the fire service uses the data itself and better understands the role of the data it provides in decisions elsewhere. Fire data analysis is more accurate when the analysts understand the system used and the conditions under which the data were collected.

When a fire officer completes an incident report, he or she is contributing data to a huge research effort in addition to preparing a local record of the event. NFIRS provides the ability to collect many specific details about a wide variety of incidents. NFIRS 5.0 provides the means for fire departments to document more of the concerns and activities of today's fire service. Modern computer technology makes it easier to complete and process the reports. When incident reports are compiled, the local department, the state, and the country can analyze the data to identify trends, new problems, progress solving old ones, and the effectiveness of different protective features. Between one-third and one-half of the fires reported to municipal fire departments are reported to NFIRS each year.

Projections about the total numbers of fires, fire casualties, direct property damage, and fire department calls are made from NFPA's annual fire department experience survey. Because it is smaller in scope, the results are available more quickly. Each fall, *NFPA Journal* runs *Fire Loss in the United States During . . .* for the previous year. This report is also posted on NFPA's website, free to all visitors. The sample-based survey collects summary data and lacks most of the detail collected by NFIRS. However, national estimates of specific fire problems can be obtained by developing scaling ratios from the relationship of the NFIRS totals to the totals from the NFPA survey.

Most of what we know about a country's fire experience, both in the United States and elsewhere, is based on reports filed by a fire officer. These reports are a small fraction of their responsibilities, but the data provided are critical to policy makers, regulators, life safety educators, inventors, the media, and others.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire data collection and databases discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 901, *Uniform Coding for Fire Protection,* 1976 and 1981 editions

NFPA 901, *Standard Classifications for Incident Reporting and Fire Protection Data,* 2006 edition

Chapter 4

Use of Fire Incident Data and Statistics

Revised by
Marty Ahrens ❑ Patricia Frazier ❑ Gayle Kelch

Chapter Contents

Using Data to Characterize the Fire Problem
Basic Tools for NFIRS Analysis
Data Source Issues
Approaches to Fire Data Analysis
Using Data in Program and Strategy Analysis
Comparing Estimates Using Different Databases or Analytic Approaches

Key Terms

Fire Incident Data Organization (FIDO), fire incident record, fire problem, National Electronic Injury Surveillance System (NEISS), National Fire Incident Reporting System (NFIRS), United States Fire Administration (USFA)

The previous chapter, Section 3, Chapter 3, "Fire Data Collection and Databases," provided a description of the sources used for analyses of fire experienced in the real world, as opposed to laboratory studies. In the United States, the key database for such analyses is the National Fire Incident Reporting System (NFIRS). Responsible data analysis requires the analyst to understand what is and is not included in the data and the impact of system upgrades on the data. The text in this chapter will be more meaningful if readers have a working knowledge of NFIRS or have at least read the previous chapter. Changes to NFIRS have generally been adopted gradually as different states incorporate them. Version 5.0, first introduced in 1999, was the most significant change. It is important to examine whether any trend shifts could be due to changes in NFIRS rather than the actual fire experience.

This chapter explores how data source issues impact the analysis process. Particular attention is paid to reporting policies and practices, differences between NFIRS 5.0 and earlier versions of NFIRS, and to issues that arise with data converted from the older NFIRS versions. Several approaches to fire data analysis are also described, including top-down and topic-driven analysis. This portion includes discussions of analysis by specific data elements; analysis of incidents with unknown or missing data; issues faced when working with small data sets; location-based fire data analysis; and rates and measures of risk, trend analysis, and data used for program and strategy analysis. The chapter concludes with a discussion of issues encountered when using data from different databases or analytic approaches.

Those familiar with the state of fire incident data prior to the late 1970s will realize that it is remarkable to see how much the quantity and quality of fire data available for analysis have grown. In the early 1970s, even the best fire departments typically had fire incident records only in narrative form. Neither the method of storage (in file cabinets, by incident number) nor the method of description (phrases selected by fire officers, without standardized coded descriptions or even a standard list of characteristics to be documented) facilitated analysis of the community's leading fire problems. At the state level, very few states had any fire incident database. At the national level, the National Fire Protection Association (NFPA) prepared estimates of U.S. incidents, deaths, injuries, and losses from its annual survey and provided analyses of fire causes and other detailed factors from its Fire Incident Data Organization (FIDO) anecdotal database. The Fire Reporting Committee of NFPA had developed NFPA 901, *Uniform Coding for Fire Protection* (now *Standard Classifications for Incident Reporting and Fire Protection Data*),[1] a standard fire incident reporting format, but few fire departments were using it.

In 1977, NFPA modified its survey techniques to take account of modern statistical design principles and, in the process, greatly improved estimates of the size of the national fire problem. Also in the 1970s, the new National Fire Prevention and Control Administration (now the U.S. Fire

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Administration [USFA], which is now part of the Department of Homeland Security) launched the National Fire Incident Reporting System (NFIRS). Based on NFPA 901, the NFIRS system provided the framework for a large-scale, truly national fire incident database. Since 1980, NFIRS has had the participation, in whole or in part, of the majority of states. In 2003, more than 18,000 fire departments participated in NFIRS,[2] reporting a total of more than 930,000 fires.[3] This represents 59 percent of the estimated total of fires reported to local fire departments. (As sources of the principal fire databases, NFPA and USFA also have helped each other over the years, with USFA providing financial support and technical suggestions on NFPA databases and NFPA providing developmental work and analysis services on NFIRS for USFA.)

A parallel development has enlarged the capacity for analysis of the newly generated fire incident data. The advent of powerful personal computers and the increasing affordability and flexibility of computer power in general have made it increasingly possible for the fire service and other fire data users to perform meaningful analyses. Most readers of this handbook now have access to valid national or local databases in forms suitable for analysis and to the equipment and skills required to analyze that data. See Table 3.4.1 for a sample of the many potential data users and uses.

TABLE 3.4.1 Typical Users and Uses of Fire Experience Results

User	*Use*
Fire protection engineers	Supporting data needs of performance-based codes and standards Defining and quantifying fire scenarios Estimating probabilities of fire incidence and fire protection performance Evaluating fire protection alternatives
Technical fire safety standards committees	Supporting data needs of performance-based codes and standards Identifying needs for standards Keeping standards current Monitoring the performance of standards Analyzing the benefits and costs of standards
Local and state fire service	Showing value of proposed fire safety and fire protection programs and legislation Targeting fire prevention and suppression programs Backing up budget requests Enacting and enforcing fire codes Developing community fire safety education program Monitoring progress
Fire protection planners at national and state levels	Showing value of proposed fire safety and fire protection programs and legislation Comparing fire to other problems competing for resources Planning the most effective deployment of resources to make the greatest impact on the fire problem Monitoring fire protection progress
Communicators/educators	Reporting of fire problems Educating for fire safety
Committees developing fire fighter safety standards, individuals, fire departments working to improve fire fighter safety	Identifying reasons for fire fighter deaths and injuries Developing safety and training programs Designing protective equipment
Researchers	Establishing fire safety research priorities Designing research programs
Insurers	Loss prevention Risk selection and underwriting
Industry	Worker safety Loss prevention
Product developers	Identifying needed products and markets Modifying products to improve fire safety
Building designers, architects, managers	Ensuring a fire-safe design
Legislators, regulators, enforcers, courts	Effective and equitable fire safety laws and regulations

For related topics see the following chapters in Section 3: Chapter 2, "Fire Loss Investigation"; Chapter 3, "Fire Data Collection and Databases"; and Chapter 5, "Introduction to Fire Modeling."

USING DATA TO CHARACTERIZE THE FIRE PROBLEM

Table 3.4.2 lists 10 major findings on the nature of the fire problem that have emerged from analyses of the past decades. Many of these analyses could not have been conducted without the new and refined databases that emerged in the late 1970s. This list is not arranged in any order of priority, nor is it necessarily a list of what everyone would consider the 10 most important data-based findings. The list does, however, illustrate the ability of data and analysis to identify emerging problems, describe those problems in ways that can help the design of corresponding programs, and track the impact of those programs.

BASIC TOOLS FOR NFIRS ANALYSIS

Before attempting to analyze fire data, it is important to have the right tools and an understanding of what is in and not in the data. The following items will be needed in some or all circumstances.

NFIRS 5.0 Complete Reference Guide

The coding manual for Version 5.0 of NFIRS may be downloaded from http://www.nfirs.fema.gov/documentation/reference. Because many—if not most—of the people completing reports in NFIRS 5.0 are entering the data using pull-down menus instead of a coding manual, the analyst should check the data dictionary in the *NFIRS Version 5.0 Design Documentation* manual to see the code descriptions viewed by the people completing the form. The longer definitions found in the *NFIRS 5.0 Complete Reference Guide* (CRG) provide greater specificity about what should and should not be included in a specific code. People who use computer look-ups may miss these distinctions. The analyst should be guided by the definitions used by the fire service, the people who provide the data.

NFIRS Version 5.0 Design Documentation

Those working with the national NFIRS database from years in which data were collected in Version 4.1 and converted to Version 5.0 (1999 through at least 2004) will want to be familiar with the coding system and definitions used in the older system and how such data were converted to the Version 5.0 system. The codes used with Version 4.1 may be downloaded from http://www.usfa.fema.gov/nfirs/tools. The *NFIRS Version 5.0 Design Documentation* manual contains conversion tables, record layouts, edit checks, and the data dictionary. The data dictionary contains the standard codes plus codes used only for conversion of older data. These conversion-only codes are not listed in the *NFIRS 5.0 Complete Reference Guide,* so that users will not consider them valid when completing new reports. However, they are essential to analysts working with a database that contains any converted data. This document may be downloaded from http://www.nfirs.fema.gov/documentation/design.htm. Conversion tables and Version 5.0 forms may also be downloaded separately from the same site.

Anyone who is working with the national fire database or who wishes to use national numbers in his or her own analysis should be familiar with the article "The National Estimates Approach to U.S. Fire Statistics" by Hall and Harwood.[16] A free copy of this article may be obtained from NFPA's One-Stop Data Shop [Tel: (617) 984-7450; e-mail: osds@nfpa.org]. The results of NFPA's annual survey of fire department experience can be found in Mike Karter's report *Fire Loss in the United States,*[17] an abbreviated form of which is published each fall in the *NFPA Journal*®. This information is also available from NFPA's One-Stop Data Shop and on NFPA's website at http://www.nfpa.org.

Version 4.1 Coding Manual

Codes for the incident report, civilian casualty report, and fire fighter casualty report are available from the USFA and may be downloaded from the website at http://www.usfa.fema.gov/nfirs/tools. National data for 1998 and earlier were collected and released according to this coding structure. If the NFIRS 5.0 database contains converted data, it is important to know how the data were collected originally.

DATA SOURCE ISSUES

NFIRS is not a complete census of reported fires. When people are interested in the size of the national fire problem, they must look beyond NFIRS. Because NFIRS at the national level is not a complete census and not a random sample, it cannot by itself answer questions such as "How many fires were reported last year?" or "How many people died as a result of last year's fires?" NFPA's annual survey of fire department experience, described in the preceding chapter, is based on a stratified random sample. This allows projections to be made on the "big picture" numbers of fires, residential or home fires, fire deaths, and fire injuries. When the NFIRS totals are compared to the results of the survey, scaling ratios are derived that can be applied to NFIRS to develop estimates of the national fire problem. The procedures are described in Hall and Harwood.[16]

Reporting Policies and Practices

Voluntary State Participation in NFIRS. Each state may set its own requirements. Some states require all runs to be reported, some only require fires, some have a dollar loss threshold, and, in some states, reporting is voluntary.

Different communities within each state may have different practices or interpretations of the requirements. NFIRS was designed to capture fires reported to fire departments. If the fire department did not respond, no NFIRS report was generated. When fire reporting is voluntary or based on loss criteria, there may be differences in deciding which fires are worth reporting or should be reported.

Influence of Reporting Requirements on NFIRS Data. Different states have different reporting requirements for NFIRS.

TABLE 3.4.2 Ten Major U.S. Data-Based Findings of Recent Years

1. U.S. and Canadian fire death rates were, in the 1970s and 1980s, among the highest in the developed world. The gap has been steadily closing. In the late 1970s, U.S. fire death rates were double the rates in the United Kingdom, Japan, and Sweden. In the mid-1980s, U.S. fire death rates were roughly 50 percent higher. In the early 1990s, U.S. fire death rates were only one-fourth to one-third higher. By the late 1990s and early twenty-first century, the U.S. fire death rate was lower than the fire death rate in Japan and sometimes lower than in Sweden. The U.S. fire death rate has been higher than Canada's fire death rate since the mid-1980s, although the trend lines are similar.[4]

2. Within the United States, the states of the Old South still tend to have the highest fire death rates, but the gap is closing; for some years, the South has not been the highest region. In the early 1980s, fire death rates in the South were typically around 50 percent higher than those in the Northeast and North Central regions and double the rates in the West. Excluding the events of September 11, 2001, in 1997 to 2001, the South's fire death rates have averaged one-fifth higher than the rates in the North Central and Northeast regions. The West continues to do substantially better than any other region, having an average death rate half that of the South.[5]

3. Seven (28%) of the 25 U.S. fires with the largest property loss (adjusted for inflation) were wildland fires. NFPA maintains a list of the 25 costliest fires and explosions of all time, based on loss values adjusted for inflation. The September 11, 2001, attack on the World Trade Center in New York City heads the list with an estimated direct property loss of almost $36 billion in 2004 dollars. The 1906 San Francisco earthquake fire caused losses estimated at $350 million at the time, or more than $7 billion in 2004 dollars. Seven of the 25 costliest fires occurred in the 10-year period from 1996 through 2005.[6]

4. Rural areas have a higher rate of reported fires and fire deaths than do larger communities. During the 5-year period of 1997 to 2001 (excluding the events of September 11, 2001), rural communities with populations under 2500 had an average fire death rate of 30.9 per million population. This rate was at least twice that found in most other population intervals with the exception of communities with populations of 2500 to 5000, which had a rate of 18.4 fire deaths per million population. Communities with populations under 2500 averaged 12.0 reported fires per 1000 population, twice that of all population intervals except 2500–5000 (8.3) and 5,000–10,000 (6.9). These communities also have the highest per capita rate of reported fires.[7]

5. Sprinklers are a reliable and effective means of reducing loss of life and property from fire. In reported fires large enough to operate sprinklers, the sprinklers failed to operate in only 7 percent of the fires in which they were present in the fire area. In two-thirds of the failures, the system had been shut off before the fire. These statistics are based on NFIRS Version 5.0 data reported in 1999 to 2002. Due to the lack of a code for unknown automatic suppression system presence in NFIRS Version 5.0 until 2004, older data are used to demonstrate the lifesaving effectiveness of this equipment. The death rate in 1989–1998 residential fires with this equipment was 78 percent lower than in fires that lacked this protection.[8]

6. Home smoke alarms are nearly universal, but many aspects of the national use of home smoke alarms still need attention. According to a 2004 Fire Prevention Week telephone survey done for the NFPA, 96 percent of U.S. homes had at least one smoke alarm, a remarkable change from 30 years earlier when almost no one had these devices. The small portion of homes without smoke alarms accounted for 55 percent of the home fire deaths reported in 1999 to 2002.[9]

In 1992, the U.S. Consumer Product Safety Commission (CPSC) studied smoke alarms in all types of homes—not just those that had fires—and found that in 20 percent of the households with at least one smoke alarm present, none were operational.[10] Smoke alarms were present and operating in only 52 percent of reported home fires, assuming that no working smoke alarms were present in confined fires in which the device did not alert occupants. In 2004, only 23 percent of households had escape plans that they had rehearsed, so the extra warning time provided by detectors may often be wasted in real fires.[11]

7. Playing with fire, principally matches and lighters, is still the leading cause of fire death among preschoolers. The U.S. Consumer Product Safety Commission's requirement for child-resistant lighters took effect in 1994. Fire-play deaths involving lighters and matches have since declined sharply.[12]

8. Juvenile firesetters became even more dominant as the leading share of the arson problem. In the early 1980s, juveniles (those under age 18) typically accounted for around 40 percent of those arrested for arson, according to data from the Federal Bureau of Investigation's Uniform Crime Reports. Since 1994, roughly 50 percent of those arrested were under 18. During the same time, there was a growing recognition that many of the child-playing fires involved psychological or environmental problems similar to those common among juvenile firesetters classified as arsonists. These findings supported greatly expanded programmatic attention to the juvenile firesetter problem, which was reflected in fire safety initiatives in the late twentieth and early twenty-first centuries.[13]

9. The number of reported home candle fires stabilized from 2001 to 2002, after rising 15 percent from 2000 to 2001. Candle fires generally declined in the 1980s, hitting their lowest point in 1990. They started climbing again in 1991. The year 2002 was the first since 1995 that has not seen a new high. Partly because total home fires have declined so much since 1980 and partly because candle fires have increased in recent years, the share of fires started by candles has jumped from 1 percent in the early 1980s to 5 percent in 2001 and 2002.[14]

10. From 1995 through 2004, 44 percent of the on-duty fire fighter fatalities, on average, resulted from sudden cardiac death. Forty-four percent of the cardiac victims had a history of heart-related conditions. Another 31 percent had arteriosclerotic heat disease, but the victims may not have been aware of the condition. Thirty-five percent of the victims suffered cardiac symptoms during fireground operations; 25 percent were stricken while responding to or returning from an alarm. The median age of cardiac victims was 52. Volunteer fire fighters accounted for the vast majority of cardiac fire fighter fatalities over 60 years of age.[15]

These differing requirements impact the data in ways that cannot fully be controlled. States may differ not only in what reporting they require but also in what incident types they will accept. These differences pose larger issues with NFIRS 5.0 as the USFA now accepts all types of incidents in its database. For example, in older versions of NFIRS data, it was possible to identify fires in which smoke alarms and sprinklers operated. With the expanded incident types of 5.0, it is now possible to identify incidents in which smoke alarms or sprinklers were unintentionally activated. This would help in cost/benefit analyses. However, if several states are not routinely capturing nonfire incidents, the projection or estimation rules will need to compensate for that fact, or the number of unintentional activations will appear artificially low.

Even when complete reporting is required, a dislike of paperwork has occasionally influenced how incidents were coded. In the past, fire officers had to complete the full form for structure fires but provide nothing or only basic information for smoke scares. This may have resulted in some minor fires being called "smoke scares" or in some fires not reported at all.

These problems may have resulted in the undercounting of some minor incidents. Even on the NFPA fire experience survey, the fire department can only report incidents it has documented. Consequently, minor fires and nonfire incidents may not be documented if the state does not require the department to do so.

Many departments understand that they need to know the nature of their fire problems and activities and, therefore, document all incidents regardless of what is required. NFIRS software programs facilitate documenting and reporting by making the process easier. However, there is no systematic way to control for underreporting or changes in reporting practices.

Comparing Data from Different Jurisdictions. Any comparison of fire department experience across jurisdictions must begin with a detailed evaluation of each jurisdiction's reporting practices and policies. Because of the variations described earlier, results may be misleading.

To avoid misleading results, each jurisdiction's reporting practices and policies should be reconciled with one another. If the study is to use existing data, then a data set of common assumptions may be constructed through inclusion/exclusion of specific types of incidents. For example, if a jurisdiction that reports all incidents wishes to compare itself with another jurisdiction that employs threshold reporting, then the all-incident department may exclude incidents that would not have been reported by the threshold reporting department for comparison purposes.

Similar issues pertain to location-based analysis outlined later in this chapter. Intercity comparisons should only be made when each entity adheres to similar geocoding data quality standards. If Department A maintains a 95 percent valid location rate for all incidents, and Departments B and C are only at 80 percent, there will be a bias toward higher location-specific rates for Department A's reporting areas than the others for comparison purposes. Although this might not greatly affect percentage distribution of types of fires (unless there is a bias among nongeocoded incidents), rates of fires per capita would be affected.

Optional NFIRS 5.0 Modules. Version 5.0 requires the use of five modules under specific circumstances: Basic, Fire, Structure Fire, Civilian Fire Casualty, and Fire Service Casualty. The other modules, including EMS (emergency medical services), Hazmat (hazardous materials), Wildland Fire, Arson, Juvenile Firesetter, Apparatus or Resources, Personnel, and Supplemental, may or may not be required or even accepted at the state or local level. According to NFIRS, either the Fire Module or the Wildland Fire Module may be used for grass, crop, and wildland fires.

NFIRS 5.0 Wildland Fire Module. Although it might seem logical to assume that the number of wildland forms received by NFIRS equals the number of wildland fires in the reporting areas, it is not the case. Departments using earlier versions of NFIRS will not use the Wildland Fire Module. According to the NFIRS 5.0 CRG, "The purpose of the Wildland Fire Module is to document *reportable* (emphasis added) wildland fires." A reportable wildland fire is defined as "any fire involving vegetative fuels that occurs in the wildland or urban-wildland interface areas, including those which threaten or consume structures."[18] This module may—depending on state or local policy—be used for brush, forest, or grass fires; fires on cultivated land; or unauthorized, controlled, or prescribed burning. Normally, only hostile fires are counted as fires. This means that Wildland Fire Module reports may be present for incidents that are not counted as part of the fire problem. It is generally good practice to restrict queries by incident types.

Some states, such as Kansas, encourage the use of the Wildland Fire Module for all grass fires. Some of these fires would not normally be considered wildland.[19]

Cause Categories in the NFIRS 5.0 Wildland Fire Module. The fields in the Wildland Fire and Fire Modules overlap, but there are differences in the broad cause categories (Table 3.4.3). Although the Wildland Fire Module was designed to document reportable wildland fires, local and state authorities may require or encourage its use with fires of specific incident types that have not reached the status of what would normally be called "wildland fires." If an analysis of NFIRS 5.0 data of intentionally set fires is based only on the causes from the Fire Module, incendiary fires documented on the Wildland Fire Module will be omitted.

Although similar, the cause "Failure of equipment or heat source" on the Fire Module and the cause "Equipment" on the Wildland Fire Module are not exactly equivalent. If a lantern placed on the ground ignited some leaves or pine needles, the equipment played a role, and "equipment" might reasonably be listed as the cause. However, if the Fire Module was completed instead, "Unintentional" would probably be the more appropriate code because the equipment did not really fail, except in terms of not protecting against likely misuse. "Equipment" on the Wildland Fire Module includes equipment that was operating properly as well as defective equipment. Consequently, the "Equipment" causes on the two modules cannot confidently be combined.

Impact of Abbreviated Reporting. With the older versions of NFIRS, some states allowed abbreviated reporting of the so-called no-loss outside fires—the brush, rubbish, or grass fires

TABLE 3.4.3 Cause of Ignition Codes in Fire and Wildland Fire Modules

Fire Module Cause	*Wildland Fire Cause*
1. Intentional	1. Natural source
2. Unintentional	2. Equipment
3. Failure of equipment or heat source	3. Smoking
4. Act of nature	4. Open/outdoor fire
5. Cause under investigation	5. Debris/vegetation burn
O. Other	6. Structure (exposure)
U. Cause undetermined after investigation	7. Incendiary
	8. Misuse of fire
	O. Other
	U. Undetermined

Source: Adapted from NFIRS-2, Fire Module, Revision 0/01/05 and NFIRS-8 Wildland Fire Module, Revision 01/01/04.

and the outside trash, rubbish, or waste fires. Abbreviated reporting generally captured dispatch-type information and the occupancy class or fixed property use. Ignition factor was requested but often left blank or coded as undetermined because cause investigation was not a priority in these incidents. For analysis, the uncollected fields were treated as "unknowns."

Abbreviated Reporting and the Analysis of Structure Fires. Abbreviated reporting for structure fires was generally not allowed in the older versions of NFIRS. Items such as area of origin, fire causal factors, and alarm and sprinkler performance were always required fields. Version 5.0, however, allows for abbreviated reporting of certain confined structure fires (and outside rubbish fires), including fires confined to the chimney, incinerator, trash receptacles, or fuel burner, or confined cooking fires. In NFIRS 5.0, confined structure fires are defined as small fire incidents that are generally confined to noncombustible containers and where flame damage does not spread beyond the container. Losses, such as property and contents losses, and deaths and injuries rarely occur as a result of such fires. In fact, deaths are not an expected result of confined fires.

With the introduction of Version 5.0, it was believed that causal factors were so similar for confined fire incidents that it was redundant to ask for completion of the Fire and Structure Fire Modules. When fires from the older NFIRS versions are converted, data from the Fire and Structure Fire Modules will be present for these types of fires. However, the older incidents do not have the specific confined fires incident-type codes.

Abbreviated reporting may not be allowed in some jurisdictions. In those jurisdictions, it may be a requirement that the NFIRS Fire Module and Structure Fire Module also be completed for confined fires resulting in more detailed information being reported for small fires. For the data analyst, this inconsistency has posed interesting challenges regarding assumptions about the distribution of unknowns. In 2002, approximately 20 percent of confined fire incident reports provided data beyond that of the Basic Module. Some national analysts have opted to disregard the fact that these incidents have additional information and to simply treat these fires as abbreviated, confined fires.

The USFA has investigated the topic of confined fire incidents in a report entitled *Confined Structure Fires.*[20] From this report, it was determined that structures other than buildings as well as fires that incur damages beyond their noncombustible containers are being included as confined fires. According to the NFIRS 5.0 CRG, the confined fire incident types are to be used only for fires in buildings that are confined to noncombustible containers when there is no flame damage beyond the noncombustible container.[21] The CRG also notes that "contained, no-loss fires are simply reported using only the Basic Module."[22] From USFA's analysis, it is clear that the container itself is often damaged, implying that it may be beneficial to modify the NFIRS reporting requirement to change "no-loss" to "low-loss" and define a reasonable loss threshold.

The *Confined Structure Fires* report also suggests that the confined fire incident types should not be used to code fire incidents resulting in deaths, property loss, or high content losses. Instead, it should be required that more detailed information be provided through the completion of the Fire and Structure Fire Modules. Training on the proper NFIRS conventions and requirements as well as tighter data entry controls are tools that may be explored as avenues to achieve more consistent data quality. To download a copy of the report, please visit: http://www.usfa.fema.gov/downloads/pdf/publications/confined-structure-fires.pdf.

With the advent of abbreviated reporting in Version 5.0, fire data analysts have recognized the need for new analytic approaches. Several national analysts have decided to analyze the nonconfined fires separately, including the confined fires only after any unknown data were allocated across the nonconfined fires. This approach is especially needed in the analysis area of the presence and effectiveness of smoke alarms. Further investigations into the appropriate methodologies for smoke alarm analyses are currently being pursued.

Possibility of Artificial Increase in Fires. The ease of recording abbreviated fire incidents may lead to an artificially created statistical increase in these types of incidents and in their share of the total fire problem. It will be necessary to carefully examine the breakdown of incident types to determine if the increase is real or a result of the new reporting system. Some states continue to accept older versions of NFIRS from at least some of their departments. This means that system-driven changes in the data will continue for a number of years. However, USFA is currently exploring the possibility of sunsetting NFIRS Version 4.1.

Number of Expected Entries per Data Element. Analysts working with Version 5.0 data need to understand which combinations of data elements must be completed under which circumstances. Certain data elements allow multiple entries. For example, two entries are allowed for factors contributing to ignition. Depending on how the file is structured, it may be necessary to query multiple fields for one data element. This issue also exists for other data elements such as actions taken, human factors, on-site materials, and fire suppression factors. Because only the Basic Module is required for specific confined structure fires and outside rubbish fires, data collected from the Fire Module (or Structure Fire Module, as appropriate) are not captured for all fires.

NFIRS Versions and Converted Data

Analyses are cleaner when working with data collected in only one version of NFIRS. However, it is not possible for trend analyses or for analysts who must work with data collected in two or more systems. The differences between Versions 3, 4.0, and 4.1 were not that extreme. A few new fields, such as the number of stories, were added to Version 4.0. The fire fighter casualty report was also added and required conversion of fire fighter injury reports collected on the old injury report. In Versions 4.0 and 4.1, the original injury report was used for civilian and non–fire fighter injuries only. None of the fields in the fire incident report required conversion. Version 4.1 added the Hazardous Material Module but did not change any of the elements on the other forms. With the advent of NFIRS 5.0 and its new coding scheme and data structure, the issue of converted data becomes prominent. The proportion of native 5.0 data has steadily increased since the introduction of NFIRS 5.0 in 1999. Table 3.4.4 shows NFIRS data reporting by version for 1999 to 2003. As more native NFIRS Version 5.0 data become available each year, some analysts choose to use only native NFIRS Version 5.0 data in fire data analyses.

TABLE 3.4.4 Data Collection Version of NFIRS, 1999–2003

Year	*NFIRS 4.1 Percentage*	*Native NFIRS 5.0 Percentage*
1999	93	7
2000	79	21
2001	52	48
2002	32	68
2003	18	82

Comparing Version 5.0 with Older Versions of NFIRS. The structure and the coding system of NFIRS 5.0 are significantly different from those of Versions 3, 4.0, and 4.1. Conversion tables were developed, but the conversion is not one-to-one. Code definitions differ between the systems, and conversions are often not exact. For some analyses, it would be prudent to exclude converted data.

Data collected in the older versions during the transition years are converted to the Version 5.0 format. The version in which the data were collected is recorded, enabling analysts to include or exclude the older data.

Structure and Vehicle Fires. Most analysts agree that structure fires include all the fires in the 110 and 120 series, including fires in or on structures and fires in mobile properties used as fixed structures. It is important to note that not all structure fires are building fires—structure fires also include such items as bridges, towers, tanks, and so on. Table 3.4.5 shows the categories of structure fires in Version 5.0 of NFIRS and the modules required. Vehicle fires are captured in the 130 series in Version 5.0.

Residential Fires. Residential properties are identified by the 400 series in Version 5.0 of NFIRS. NFPA and some other organizations separate homes from other residential properties. Homes include one- and two-family dwellings, manufactured housing, and apartments. These are identified by property use codes 419 (detached one- and two-family dwellings, including manufactured homes, mobile homes not in transit, and duplexes) and 429 (multifamily dwellings, including

TABLE 3.4.5 Version 5.0 Structure Fires and Required Modules

Code	*Description*	*Comments*
110	Conversion code only for older structure fires (Situation Found 11), excluding those with mobile property used as a structure	Associated data will be converted or incomplete
111	Building fire	Basic, Fire, and Structure Fire Modules
112	Fires in structures other than buildings	Basic, Fire, and part of Structure Fire Modules
113	Cooking fire, confined to container	Abbreviated report okay
114	Chimney or flue fire, confined to chimney or flue	Abbreviated report okay
115	Incinerator overload or malfunction	Abbreviated report okay
116	Fuel burner/boiler malfunction, fire confined	Abbreviated report okay
117	Commercial compactor fire, confined to rubbish	Abbreviated report okay
118	Trash or rubbish fire, contained	Abbreviated report okay, but full report encouraged when fire may have been intentionally set
121	Fire in mobile home used as fixed residence	Basic, Fire, and Structure Fire Modules
122	Fire in motor home, camper, recreational vehicle (used as fixed structure)	Basic, Fire, and Structure Fire Modules
123	Fire in portable building with a fixed location	Basic, Fire, and Structure Fire Modules
120	Fire in mobile property used as a fixed structure, other	Basic, Fire, and Structure Fire Modules

Source: *Incident Type/Module Rules* by USFA and *National Fire Incident Reporting System Version 5.0 Design Documentation Specification,* Release 2001.2, July 2001.

apartments, condominiums, townhouses, row houses, and tenements).

Outside and Other Fires. Outside and other fires were said to include outside fires involving property of value; brush, tree, grass, or forest fires; outside rubbish or trash fires; explosions with no after-fire; outside spills or leaks with ensuing fire; unclassified fires; and unknown-type fires (situation found 12, 14, 15, 16, 17, 19, and 10, respectively). Version 5.0 codes capture similar incidents with more specific codes for various types of natural vegetation fires, outside rubbish fires, special outside fires, cultivated vegetation or crop fires, and unclassified fires (incident type 140–173, and 100). In Version 5.0, an explosion that does not result in a fire (incident type 240s series) is no longer grouped with fires or counted as a fire.

Incendiary, Suspicious, and Intentional Fires. For statistical purposes, analysts generally grouped ignition factors for incendiary and suspicious from older versions of NFIRS together as arson, much to the chagrin of many fire investigators who concur with NFPA 921, *Guide for Fire and Explosion Investigations,* which does not consider suspicious to be a valid cause. Although there is broad consensus that "suspicious" is never a valid final cause determination after investigation, it was considered appropriate for fires that are likely to never be fully investigated or for reports that may not have been updated after an investigation. Version 5.0 added a new field, "Cause," to the Fire Module (see Table 3.4.3). Intentional nonwildland fires are identified in this field. The choices of *incendiary* and *suspicious* have been dropped from the Fire Module in Version 5.0.

The ignition factors of incendiary and suspicious both convert to the cause of intentional, so the distinction between the two is lost. Incendiary and suspicious both imply an illegal act; "intentional" does not carry that implication as strongly. For example, a crisis-type juvenile firesetter may be below the age of legal responsibility but may intentionally start a fire.

Smoke Alarm Information. Analyzing smoke alarm data is considerably more complicated with Version 5.0 of NFIRS than it was in the past. Detailed information on smoke alarm presence and operation is not collected for confined or contained fires, which comprise 13 percent of the reported home fires in 1999 to 2002. The percentage of these fires will increase as more of the data is originally collected in Version 5.0. Because the confined or contained fires are almost all minor, many of the minor fires are removed from the pool of data with details on smoke alarm effectiveness. The only information captured for these confined fires concerns whether the detection equipment did or did not alert occupants. Information on whether detection equipment was present, whether it operated, and whether occupants were present is generally not collected for these incidents.

If the detection equipment in a confined fire was coded as "alerted occupants," for this analysis it was assumed that a smoke alarm was present and operated. When this equipment did not alert occupants, it was assumed to have not operated or to not have been present. This approach was used to create Table 3.4.6.[23] Because a fire may be discovered before a smoke alarm operates, a smoke alarm may operate in the absence of occupants, or a confined fire may have been too small to activate detection equipment, "smoke alarm alerted occupants in confined fire" should be considered a lower bound of operating smoke alarms whereas "smoke alarms did not alert occupants in confined fire" should be considered the upper bound of possible fires with no working smoke alarms. Again, due to conversion issues, it is advisable to use data collected originally in Version 5.0 only.

Automatic Extinguishing Systems. Analyses of the effectiveness and reliability of automatic extinguishing systems should control for whether the system was actually in the fire area. Ex-

TABLE 3.4.6 Smoke Alarm Status in Homes, Version 5.0 Data Only, 1999–2002 Annual Averages

Smoke Alarm Status	*Percentage of Fires*	*Percentage of Civilian Deaths*	*Death Rate per 100 Fires*	*Percentage of Civilian Injuries*	*Injury Rate per 100 Fires*
Smoke alarm operated in nonconfined fire	25	26	0.7	41	6.9
Smoke alarm alerted occupants in confined fire	18	0	0.0	5	1.2
Subtotal—operating smoke alarm	43	26	0.4	46	4.5
Smoke alarm present but failed to operate in nonconfined fire	9	19	1.5	17	8.1
No smoke alarm present in nonconfined fire	32	55	1.2	31	4.0
Smoke alarm did not alert occupants in confined fire	11	0	0.0	4	1.7
Subtotal—no operating smoke alarm	52	74	1.0	52	4.2
Fire too small to operate in nonconfined fire	5	0	0.0	2	1.8
Total	100	100	0.7	100	4.2

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire.

Source: NFIRS and NFPA survey.

cluding fires with no reasons or unknown reasons, in 47 percent of the fires in which the system failed to operate, the reason given was "Fire not in area protected by system." The additional detail collected in Version 5.0 provides valuable information about types of systems, heads operating, and effectiveness. Unfortunately, a code for presence undetermined was not included in Version 5.0 until 2004.[24] If fire fighters were unsure if such a system was present, they were instructed to code it as "not present." The conversion from older versions has also been problematic. Consequently, statistical comparisons of the life and property savings with and without these systems have been limited to data collected prior to 1999 and will be updated after the 2004 data are released.

Equipment Involved in Ignition. The equipment involved in ignition field has been expanded to three characters, with a corresponding increase in number of choices. A separate field indicates if the equipment was portable or stationary. When working with data that include incidents collected in older versions, it is important to remember that specific equipment that was first identified separately in Version 5.0 will be undercounted. The sheer number of codes makes some form of grouping desirable; grouping can also compensate for the different code choices in the two systems. Limiting analysis to Version 5.0 data can provide the appropriate percentages for specific types of equipment.

APPROACHES TO FIRE DATA ANALYSIS

The discussion to this point has focused on how the data and the data collection system impact analysis. The remainder of the chapter will focus on approaches to fire data analysis.

Top-Down and Topic-Driven Analysis

Most characterizations of the fire problem begin with some measures of the problem's size. Why? Implicit in these measurements is the idea that fire is a problem big enough to justify concern and attention. Each year, fire kills thousands of people, injures tens of thousands more, and destroys billions of dollars of property. When the fire community wishes to pursue a program that requires the cooperation of others, that community must first attract attention. The big numbers on fire—incidents, deaths, injuries, and property damage—accomplish this goal.

Top-down analysis is an approach that begins with a summary of the big numbers and then subdivides the totals into their major parts. A top-down analysis might begin with the number of runs. Several types of subsections are possible, including types of runs (i.e., fires, EMS, false calls, etc.). These subsections may be broken down further: for example, separate profiles can be created for each time period, occupancy class, or fire cause. At the local level this breakdown might also include profiles by station or company. A top-down look at U.S. fire department runs over the past 25 years reveals a steady drop in fire calls but an increase in EMS calls and false alarms. Although the decrease in fires is encouraging, the total of reported fires and false alarms has averaged about 3.6 million since 1980. The combined total has not fallen below this average since 1993.[25] These statistics are shown in Figure 3.4.1. Fire departments cannot presume a call is a false alarm and must respond as they would to a fire. If only the statistics for fires were examined, this pattern would be missed.

The top-down approach provides the broadest perspective on the overall fire problem or a fire department's activity. It differs from topic-driven analysis, which begins with interest in certain issues involving only certain types of fires. For example,

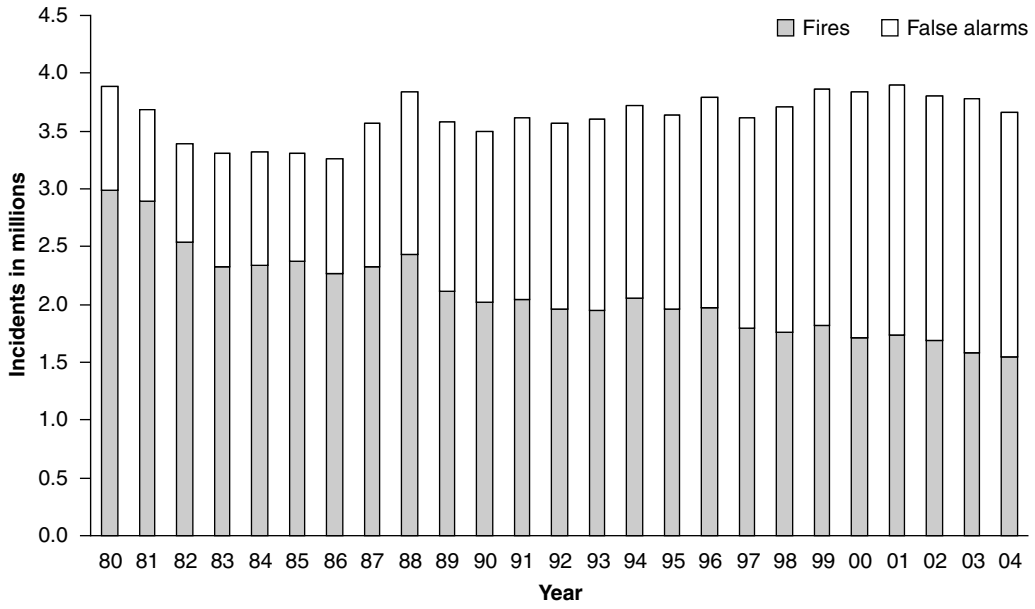

FIGURE 3.4.1 Reported Fires and False Alarms, 1980–2004 (Source: The U.S. Fire Problem Overview Report: Leading Causes and Other Patterns and Trends)

a top-down analysis of fires in residences might identify smoking materials as the leading factor in civilian fatalities in homes, accounting for roughly one-fourth of the fires for which the cause was reported. On the other hand, a topic-driven analysis focused on smoking-material fires—for example, a study of the likely impact of a self-extinguishing cigarette or of a public education program aimed at smokers—would involve more than just homes. Although both topic-driven and top-down analyses might be interested in the role of smoking-related fires in home fire deaths, topic-driven analysis might also be interested in the involvement of smoking materials in nonhome fire fatalities or in property damage in home fires. Even though smoking-related fires do not account for the largest shares of the latter two problems (intentional causes lead in both cases), they are still part of the overall smoking-related fire problem; any change that affects the smoking-related fire problem may affect all smoking-related fires.

In a top-down analysis, the basic rule is to look for the biggest parts of the problem. Why bother subdividing the problem? Resources usually are too limited to permit an attack on the whole problem and choices must be made. At times, however, important pieces of information are missed if only totals are examined. For example, home structure fires account for only one-quarter of reported fires but four-fifths of all fire deaths. The use of data to identify the largest manageable parts of the problem is the first step in making those choices. Whereas totals are used to show the overall size of the problem, percentages are used to indicate the largest parts.

Use of percentages to identify the largest parts of the fire problem is not as easy as it sounds. Judgment is involved in selecting the categories for which percentages will be calculated. For example, suppose an analysis showed the biggest subgroup of a particular occupancy group's fire problem consisted of fires involving electrical short circuits. This finding does not fit well into most strategies for attacking the fire problem. If one is going to examine every piece of equipment that could be subject to short circuits, one might as well also check for other electrical faults in that equipment. The available strategy may dictate a broader category, covering fires involving all electrical equipment faults. Or maybe it is easier to design strategies around particular types of electrical equipment (e.g., fixed wiring, heating systems, ranges, and ovens) and address all fires involving such equipment, whether the equipment or the user was at fault.

Take another example. Which of the following findings is more useful: (1) 34 percent of all reported home fires begin in the kitchen; or (2) 28 percent of reported home fires involve cooking equipment?[26] The latter finding identifies a smaller part of the problem and uses a completely different categorization (area of origin vs. equipment involved in ignition), but it locates the problem much more specifically. In a kitchen, there could be dozens of fire hazards to check out; most homes have only a few types of cooking equipment.

Finally, suppose a categorization includes equipment involvement, material ignited, and the human elements that brought them together. Such a categorization will produce detailed scenarios, but the "leading" category might account for only 2 to 4 percent of all fires. It would be necessary to develop strategies for several dozen scenarios to make any noticeable impact on the total fire problem. If that is so, it may make more sense to select scenarios that fit together logically and can be addressed by variations of the same strategy (i.e., use of less specific categories) than to select several dozen distinct scenarios and tackle each one separately. To put it another way, the scenario technique of analyzing several fire characteristics simultaneously is most useful as a second-stage analysis, performed after one characteristic has been used to establish basic clustering.

Therefore, in selecting categories for calculating percentages, it is important to match the structure of the categories to the structure of the strategies available to attack the fire problem. Remember that the size of the problem being attacked is no more or less important than the anticipated leverage on the problem; for example, a 7 percent reduction in a problem that causes 500 deaths a year is worth just as much as a 70 percent reduction in a problem that causes 50 deaths a year. (This is discussed at greater length later in this chapter under the heading "Using Data in Program and Strategy Analysis.") So be sure when you pick out the biggest parts of the problem that they collectively account for a sizable share of the total, but also remember that some parts of the problem may be much more preventable than others.

Figures 3.4.2 and 3.4.3 illustrate the effective use of percentages (presented in Figure 3.4.3 through the display of numbers) to describe patterns in the 2004 fire fighter fatality problem. (These figures also illustrate the effective use of graphics to summarize numerical data in a more comprehensible manner.) Figure 3.4.2 shows that only 28 percent of the fire fighter fatalities resulted from fireground duties. Response/return from alarm, which should involve only controllable dangers and relatively little risk, accounts for 34 percent of all fire fighter deaths. Figure 3.4.3 shows that deaths from heart attacks ac-

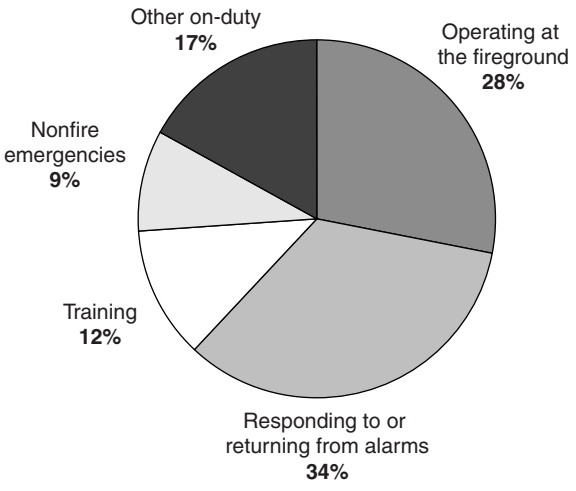

FIGURE 3.4.2 Fire Fighter Fatalities in 2004 by Type of Duty (Source: P. R. LeBlanc and R. F. Fahy, *Full Report: Firefighter Fatalities in the United States,* National Fire Protection Association, Quincy, MA, 2005)

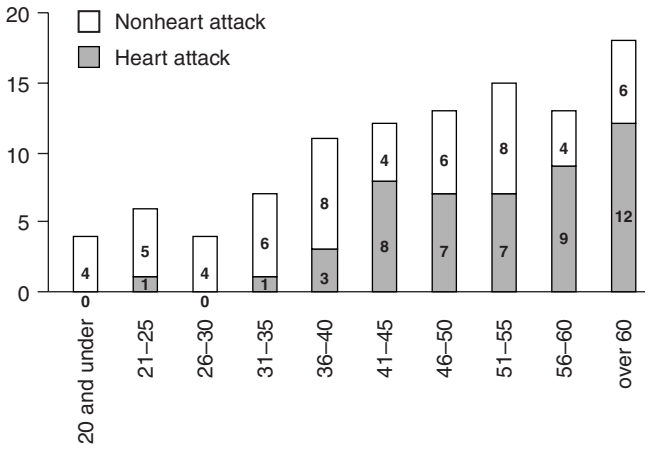

FIGURE 3.4.3 On Duty Fire Fighter Fatalities in 2004 by Age and Cause of Death (Source: P. R. LeBlanc and R. F. Fahy, *Full Report: Firefighter Fatalities in the United States,* National Fire Protection Association, Quincy, MA, 2005)

count for two-thirds of the fatalities in the two oldest age-groups but only a small share of the fire fighter fatalities in those 35 or younger.[27] Such patterns have direct implications for targeting of physical fitness programs.

Analysis by Fire Cause and Property Type

The dimensions most frequently chosen for top-down and topic-driven analyses are fire cause and property type, because most fire prevention strategies are structured along those lines. "Analysis by cause" actually refers to a variety of analyses addressed to different aspects of the causal factors. The question of how to categorize, already discussed in general terms, becomes especially difficult in analyses of cause-related information.

Even the question of how to refer to cause-based descriptions can be a problem. For example, suppose one observes that roughly one-fourth of all civilian fire fatalities in homes with fire cause reported were smoking related. Does this mean that cigarettes (the principal smoking material involved) were to blame for all those deaths? Not necessarily. If the smokers in question had been careful not to smoke in bed and always to place cigarettes in sturdy ashtrays, few of the deaths would have occurred. Or if the upholstered furniture, bedding, mattresses, and pillows that are the first items ignited in most fatal smoking-related fires had been more ignition resistant, many or most of the deaths would have been avoided. If the cigarettes used had been designed to self-extinguish more quickly, many or most of the deaths might have been prevented. A decision on which dimension to use in categorizing fire causes—the source of heat, items ignited, or the behaviors that brought them together—should be made in a way that supports analyses of workable prevention strategies. Assessments of blame are tasks for lawyers or philosophers; they do not help in the search for ways to reduce fire problems.

NFIRS contains six fire-cause-related elements of information: (1) a general cause category (intentional, unintentional, failure of equipment or heat source, or act of nature); (2) the heat source; (3) equipment involved in ignition, if any; (4) the item first ignited (e.g., chair, floor covering, structural beam); (5) type of material ignited (e.g., wood, plastic, fabric); and (6) factors contributing to ignition—the human or equipment failures that brought together the ignition heat and ignited material. Together, these six dimensions and their subsections can define billions of distinct fire-cause categories, a clearly unworkable partitioning of the problem. In the face of all this detail, several approaches have been developed to extract major patterns. These approaches include the following:

- Emphasis on intentional versus not intentional
- Emphasis on equipment
- Emphasis on behavior
- Emphasis on heat source
- Emphasis on item ignited
- Emphasis on leading causes summarized from multiple data elements

Table 3.4.7 shows how different approaches can affect the description of leading causes of home structure fires reported during 1999 to 2002. Note that confined fires are included as entries in each table. In future years, these fires are expected to account for an even larger share of the incidents. The percentages include a proportional share of fires with unknown data. This allocation will be discussed later in the section. It is important to remember that each of these data elements contributes to a fire scenario and that they often overlap. For example, some "playing with fire" incidents are intentional; most "playing with fire" incidents involve matches or lighters, but candles, cigarettes, and cooking equipment may also be factors.[28]

In the single-digit cause codes used in NFIRS 5.0, a distinction is made between "cause under investigation" and "cause undetermined after investigation." Both are considered unknown for analysis purposes, although it is possible that many incidents of "cause under investigation" are intentional. In the absence of causal information, "cause under investigation" seems the best choice.

A report by the U.S. General Accounting Office (GAO) raised a number of issues about the analysis of fire statistics concerning upholstered furniture.[29] Because of that report, the U.S. Consumer Product Safety Commission (CPSC) has excluded fires in which the ignition factor was incendiary or suspicious in older versions of NFIRS or intentional in Version 5.0. For its analyses, NFPA generally includes these fires but performs further analyses when necessary to identify causes or the number of intentional fires associated with a particular product.

Analyzing by One Data Element. Any one of the causal dimensions can be used to describe the fires. Because the coding structure used for many data elements is generally grouped into "decades" and "centuries," one can often use the first digit alone to create 10 categories, or two digits to create nearly 100 categories for each dimension. This approach often proves frustrating, however, because the structure of the coding elements often does not coincide with the issues to be analyzed.

Scenario Groupings. A third approach has been to use scenarios based on two or three of the causal dimensions. This

TABLE 3.4.7 Leading Causes of Structure Fires in Homes with Different Emphases, 1999–2002 Annual Averages

Description of Cause	*Percentages*	
Emphasis on Intentional Versus Nonintentional Based on Cause of Ignition		
Unintentional	47	Note that all known causes other than intentional could be described as unintentional.
Failure of equipment or heat source	25	
Intentional	9	An intentional fire may not be arson in the legal sense.
Unclassified	3	
Act of nature	2	
Confined fire	13	A causal determination cannot be inferred for some types of confined fires, particularly rubbish fires.
Emphasis on Equipment Based on Equipment Involved in Ignition, with Some Subgrouping Done by NFPA		
No equipment involved	39	
Range or cooking surface	14	More often than not, the equipment involved in ignition was used improperly.
Confined cooking fire	8	One can infer that some type of cooking equipment was involved in confined cooking fires; the type of cooking equipment is unknown.
Fixed wiring, switch, or outlet	4	
Clothes dryer or washer	4	
Oven or rotisserie	3	
Fireplace or chimney	3	
Confined chimney fire	3	One can infer that some type of chimney was involved in confined chimney fires.
Emphasis on Behavior Based on Factor Contributing to Ignition Originally Collected in Version 5.0 of NFIRS		
Short circuit or other electrical malfunction	18	
Heat source too close to combustibles	12	
Abandoned or discarded materials or products	8	This often refers to smoking materials.
Confined cooking fire	8	
Equipment unattended	7	
Unclassified misuse of material or product	6	
Unclassified factor contributed to ignition	6	
Exposure fire	5	
Unclassified mechanical failure or malfunction	4	
Playing with heat source	4	
Confined chimney fire	3	
Emphasis on Heat Source		
Radiated or conducted heat from operating equipment	27	Equipment power source is a separate field.
Arcing	12	
Confined cooking fire	8	Although the exact heat source is generally not captured for confined fires, some heat sources can largely be ruled out for the confined equipment fires.
Unclassified heat from powered equipment	7	
Smoking materials	7	Statistics on open flame and smoking materials, including matches, lighters, and candles, include a proportional share of fires in which the heat source was coded as "heat from other open flame or smoking material."
Candle	5	
Spark, ember, or flame from operating equipment	5	
Unclassified hot or smoldering object	4	
Match	4	
Unclassified heat source	3	
Lighter	3	
Confined chimney fire	3	

TABLE 3.4.7 Continued

Description of Cause	*Percentages*	
Emphasis on Item First Ignited		
Cooking materials, including food	16	
Confined cooking fire	8	It seems reasonable to infer that confined cooking fires began with food or cooking materials.
Structural member or framing	8	
Electrical wire or cable insulation	6	
Mattress or bedding	5	NFPA generally groups mattresses and bedding together because they function as one system.
Rubbish, trash, or waste	5	
Unclassified	4	
Exterior wall covering or finish	4	
Interior wall covering, excluding drapes	4	
Clothing	3	
Confined chimney fire	3	One could also infer that these confined chimney fires started with creosote.
Flammable or combustible liquid or gas, filter, or piping	3	This also represents a grouping of codes as some of the specific choices were not available in earlier versions of NFIRS.
Multiple items first ignited	3	
Upholstered furniture or vehicle seat	3	
Multidimensional Summary of Causes from Different Data Elements		
Cooking equipment fire	28	Note that subcategories can be nested below the main category.
Identified cooking equipment	20	Identified cooking equipment and heating equipment include fires with unclassified kitchen and cooking equipment and unclassified heating and air-conditioning equipment.
Confined cooking fire	8	
Heating equipment	14	
Identified heating equipment	11	
Confined chimney or flue fire	3	
Confined fuel burner or boiler malfunction or fire	1	
Intentional	9	
Electrical distribution or lighting equipment	9	
Smoking materials	7	
Candle	5	
Exposure to other fire	4	
Playing with heat source	4	
Clothes dryer or washer	4	

Note: Percentages represent national estimates of fires reported to U.S. municipal fire departments and, therefore, exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections.

Source: NFIRS and NFPA survey.

approach avoids the tendency, in the one-dimensional scenario, for major problems to be mixed together or disguised. The use of even two dimensions from NFIRS, however—or the use of three dimensions with the first digit only, where appropriate—can create thousands of cause categories, and again one is faced with the likelihood that even the largest parts of the total will not represent a very large share of the total.

Broad Cause Categories. The fourth approach has been to use a small number of major, easily recognizable categories based on the causal data elements but not necessarily grouped along the lines laid out in the NFIRS coding structure. Historically, the most widely used scheme based on this approach was a set of 13 categories developed at the USFA. This scheme used a hierarchical process to sort fires into categories. Priorities were established to assign each fire to one of the specific cause categories. For example, an incendiary fire started by a cigarette was counted as incendiary and not counted as caused by smoking materials. If cooking equipment were involved in a fire with heat source of radiated heat, the fire was counted as caused by cooking equipment. Fires resulting from radiant heat that did not fit into other cause categories were counted as exposures. When some type of equipment is said to be involved in ignition or the cause of fire, it means that the equipment provided the heat to ignite the fire. More often than not, human error was involved. Unattended cooking is a far more frequent cause of cooking equipment fires than defective equipment.[30]

Criticisms of this or any other hierarchical sorting approach focus on the reasonableness of the sorting priorities and the usefulness of the categories produced. If a fire is caused by a child playing with cigarettes, should that be categorized as a child playing with fire or a smoking-related fire? A revised cause hierarchy was developed for the transition years of Version 5.0 of NFIRS. As larger shares of the data were originally collected in Version 5.0, it became increasingly clear that the new hierarchy was no longer as effective. NFPA has started to produce tables showing a summary of the leading causes extracted from multiple data elements. However, these causes are not all mutually exclusive and some double counting does occur. Table 3.4.8 shows the leading causes of structure fires in homes during 1999 to 2002.[31]

Top-Down Refinement Along Causal Factors. Another approach, which can be used as a refinement of any of the others, applies the top-down approach to one dimension. Table 3.4.9 shows this approach applied to item first ignited in 1999–2002 home structure fires, including confined structure fires. Inferences were made about the item first ignited in these confined fires (organic materials for confined cooking fires; general materials for contained trash fires, confined incinerator fires, and confined commercial compactor fires; and liquids, gases, filters, or piping for confined fuel burner or boiler fires). Sums were calculated for the broad categories—organic materials, structural component or finish, general materials, and so on. Specific items within each category are shown if they accounted for at least 1 percent of the fires. This approach can be used with

TABLE 3.4.8 Leading Causes of Structure Fires in Homes, 1999–2002 Annual Averages

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*		*Civilian Deaths per 100 Fires*	*Average Dollar Loss per Fire*
Cooking equipment fire	105,400	(28%)	270	(9%)	4,230	(28%)	519	(10%)	0.3	4,900
Identified cooking equipment	75,600	(20%)	270	(9%)	3,750	(25%)	509	(9%)	0.4	6,700
Confined cooking fire	29,800	(8%)	0	(0%)	470	(3%)	10	(0%)	0.0	300
Heating equipment	53,700	(14%)	320	(11%)	1,270	(8%)	637	(12%)	0.6	11,900
Identified heating equipment	40,300	(11%)	320	(11%)	1,240	(8%)	628	(12%)	0.8	15,600
Confined chimney or flue fire	10,600	(3%)	0	(0%)	10	(0%)	7	(0%)	0.0	600
Confined fuel burner or boiler malfunction or fire	2,900	(1%)	0	(0%)	10	(0%)	2	(0%)	0.0	500
Intentional	34,400	(9%)	550	(19%)	1,500	(10%)	738	(14%)	1.6	21,500
Electrical distribution or lighting equipment	32,400	(9%)	220	(8%)	960	(6%)	679	(13%)	0.7	21,000
Smoking materials	24,800	(7%)	850	(29%)	1,900	(12%)	455	(8%)	3.4	18,300
Candle	18,200	(5%)	160	(5%)	1,640	(11%)	392	(7%)	0.9	21,500
Exposure to other fire	15,800	(4%)	30	(1%)	90	(1%)	319	(6%)	0.2	20,200
Playing with heat source	14,000	(4%)	220	(8%)	1,360	(9%)	249	(5%)	1.6	17,800
Clothes dryer or washer	13,400	(4%)	10	(0%)	280	(2%)	98	(2%)	0.1	7,300

Note: These are the leading causes, obtained from the following list: intentional (from the NFIRS field "cause"); playing with fire (from factor contributing to ignition); confined heating (including confined chimney and confined fuel burner or boiler fires), confined cooking, and contained trash or rubbish from incident type; identified heating, identified cooking, clothes dryer or washer, torch (including burner and soldering iron), electrical distribution and lighting equipment, medical equipment, and electronic, office, or entertainment equipment (from equipment involved in ignition); smoking materials, candles, lightning, and spontaneous combustion or chemical reaction(from heat source), and mobile property involved (from mobile property involved in ignition). The statistics on smoking materials and candles include a proportional share of fires in which the heat source was heat from an unclassified open flame or smoking material. Exposure fires include fires with an exposure number greater than zero, as well as fires identified by heat source or factor contributing to ignition when no equipment was involved in ignition and the fires were not intentionally set. Because contained trash or rubbish fires are a scenario without causal information, they are shown at the bottom of the table if they account for at least 2 percent of the fires. Causal information is not routinely collected for these incidents. The same fire can be listed under multiple causes, based on multiple data elements.

These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest ten, and direct property damage is rounded to the nearest million. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey.

TABLE 3.4.9 Structure Fires in Homes by Item First Ignited, 1999–2002 Annual Averages

Item First Ignited	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Organic materials	93,700	(25%)	150	(5%)	3,650	(24%)	355	(7%)
Cooking materials, including food	59,600	(16%)	140	(5%)	3,110	(20%)	296	(6%)
Confined cooking fire	29,800	(8%)	0	(0%)	470	(3%)	10	(0%)
Light vegetation, including grass	2,000	(1%)	0	(0%)	20	(0%)	25	(0%)
Structural component or finish	87,700	(24%)	580	(20%)	2,090	(14%)	2,219	(41%)
Structural member or framing	29,300	(8%)	210	(7%)	610	(4%)	917	(17%)
Exterior wall covering or finish	14,900	(4%)	30	(1%)	190	(1%)	281	(5%)
Interior wall covering, excluding drapes	13,100	(4%)	140	(5%)	510	(3%)	321	(6%)
Floor covering, rug, carpet, or mat	8,100	(2%)	110	(4%)	350	(2%)	159	(3%)
Insulation within structural area	5,200	(1%)	10	(0%)	90	(1%)	71	(1%)
Exterior roof covering or finish	3,700	(1%)	0	(0%)	40	(0%)	118	(2%)
Exterior trim, including doors	3,400	(1%)	10	(0%)	40	(0%)	51	(1%)
Interior ceiling cover or finish	2,500	(1%)	10	(0%)	60	(0%)	56	(1%)
Unclassified structural component or finish	7,500	(2%)	60	(2%)	200	(1%)	245	(5%)
General materials	78,500	(21%)	400	(14%)	1,750	(11%)	923	(17%)
Electrical wire or cable insulation	23,500	(6%)	90	(3%)	480	(3%)	297	(6%)
Rubbish, trash, or waste	17,400	(5%)	50	(2%)	360	(2%)	135	(3%)
Confined chimney fire	10,600	(3%)	0	(0%)	10	(0%)	7	(0%)
Multiple items first ignited	10,500	(3%)	190	(6%)	480	(3%)	350	(6%)
Magazine, newspaper, or writing paper	4,600	(1%)	60	(2%)	230	(2%)	71	(1%)
Contained trash or rubbish fire	4,600	(1%)	0	(0%)	20	(0%)	1	(0%)
Dust, fiber, lint, sawdust, or excelsior	4,300	(1%)	0	(0%)	70	(0%)	26	(0%)
Soft goods or wearing apparel	42,400	(11%)	710	(24%)	3,430	(22%)	683	(13%)
Mattress or bedding	18,000	(5%)	410	(14%)	2,000	(13%)	358	(7%)
Clothing	13,000	(3%)	200	(7%)	780	(5%)	160	(3%)
Curtains, blinds, drapes, or tapestry	3,600	(1%)	20	(1%)	280	(2%)	57	(1%)
Linen other than bedding	3,400	(1%)	20	(1%)	140	(1%)	33	(1%)
Unclassified soft goods or wearing apparel	3,900	(1%)	60	(2%)	200	(1%)	66	(1%)
Furniture or utensils	30,300	(8%)	770	(26%)	2,360	(15%)	634	(12%)
Upholstered furniture or vehicle seat	10,200	(3%)	560	(19%)	1,130	(7%)	283	(5%)
Cabinetry, including built-in	6,900	(2%)	40	(1%)	400	(3%)	136	(3%)
Appliance housing or casing	4,900	(1%)	20	(1%)	180	(1%)	50	(1%)
Unclassified furniture or utensils	6,000	(2%)	130	(5%)	530	(3%)	136	(3%)
Liquid, gas, filter, or piping	13,400	(4%)	170	(6%)	1,000	(7%)	246	(5%)
Flammable or combustible liquid or gas, filter, or piping	10,500	(3%)	170	(6%)	980	(6%)	244	(5%)
Confined fuel burner or boiler fire	2,900	(1%)	0	(0%)	10	(0%)	2	(0%)
Storage supplies	6,500	(2%)	40	(1%)	260	(2%)	90	(2%)
Box, carton, bag, basket, or barrel	4,300	(1%)	30	(1%)	190	(1%)	64	(1%)
Adornment, recreational material, or signs	3,800	(1%)	30	(1%)	220	(1%)	63	(1%)
Unclassified	16,700	(4%)	120	(4%)	550	(4%)	171	(3%)
Total	372,900	(100%)	2,960	(100%)	15,300	(100%)	5,383	(100%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest ten, and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation. Nonconfined and noncontained structure fires in which the item first ignited was unknown or not reported have been allocated proportionally among fires with known item first ignited. Totals may not equal sums due to rounding errors.

Source: NFIRS and NFPA survey.

any data element or element combination structured to provide greater or lesser detail, including property use (occupancy), heat source, equipment involved in ignition, area of origin, and factor contributing to ignition. Individuals interested in fires in home properties may be interested in all of these properties, or they may prefer to focus on fires in one- and two-family dwellings and to omit apartments. Nesting represents the top-down approach at its best—it provides usable levels of detail without sacrificing an overview of the largest parts of the total.

Handling Fires with Unknown or Unreported Data

Another matter to consider when analyzing fire data is how to handle incidents for which some data were unknown or unreported. A sizable share of fires is reported with missing or incomplete information. In the nonconfined home structure fires in Table 3.4.9, the item first ignited was undetermined or not reported in 21 percent of the nonconfined fires, 39 percent of the civilian deaths, 18 percent of the civilian fire injuries, and 30 percent of the direct property damage. Severe fires, particularly those that result in fatalities or unusually large losses, tend to have larger shares of unknown data. A calculation of percentages based only on cases with known data implicitly assumes (in the absence of contrary evidence) that the profile of the fires reported with unknown or missing data would look the same (if the data were known) as the profile of the fires reported with known causes. This assumption was made for Table 3.4.9.

Why is it desirable to allocate unknowns? Suppose two neighboring states have relative profiles that look the same, except that fire deaths due to unknown data appear as 14 percent in one state and 43 percent in the other. Table 3.4.10 shows the results. State B seems to be doing better than State A with respect to every known cause, but if unknowns are allocated, both states have the same problems to the same degree. If it is necessary or desirable to compare two groups, differences in the proportions of the unknowns need to be taken into consideration.

Why is it difficult to allocate unknowns? There are many reasons. One reason is that no one particular method of allocating the unknowns has been shown to be the "best." Fire data analysts have generally chosen to allocate unknowns over known data, as it is a simple solution to this potentially difficult problem. And, in the absence of another methodology, it has been generally accepted as reasonable. A study underway by the USFA to investigate the causes of unknown-cause fatal fires may shed light on the validity of this method of allocation. Moreover, this methodology is not without its detractions as some fire data analysts maintain that there is often enough information provided by the data to make other equally reasonable assumptions on how to allocate the unknown: time of day, size of fire, and property type are examples of data items that can be used to allocate the unknown across causes. Regardless of the method of allocation, it is the analyst's responsibility to both specify the allocation scheme and support the rationale behind it.

TABLE 3.4.10 The Problem of Comparisons with Unallocated Unknown Cause Fires

	Percentage of Home Fires	
Cause	*State A*	*State B*
Intentional	9	6
Unintentional	50	33
Failure of equipment or heat source	21	14
Act of nature	3	2
Other	3	2
Undetermined, under investigation, or not reported	14	43

Handling Fires with Unknown Causal Factors. As mentioned previously, NFIRS does not require causal information for certain types of confined structure fires and for outdoor rubbish fires. Table 3.4.11 shows the numbers and percentages of confined fires by incident type for the years 1999 to 2003. The percentage of structure fires that are confined increased from 2.8 percent in 1999 to 34.2 percent in 2003. A large portion of the increase is attributed to the increase of fire departments reporting incidents using NFIRS Version 5.0. In the future when all departments are reporting incidents using only NFIRS Version 5.0, it is expected that the percentages of structure fires that are confined each year will eventually plateau. The number of confined fires is large enough that they cannot be ignored.

Although these incidents generally lack causal data, some information can reasonably be inferred based on the incident types. NFPA had initially inferred information for several data elements, treating the inferred values as "known." This approach had problems. No other scenario was without unknown data. Treating them as known and adding a proportional share of the completely unknown data to them resulted in artificially large estimates. In addition, analysis of confined fires with causal data showed more variation than expected. Many analysts now use a three-step process for structure fire data that are not collected for confined fires. First, unknown data are allocated proportionally across the known nonconfined data. Second, the confined fire categories are added to the list of categories (individually or as a group) in each data element. And, third, percentages are calculated based on the total of confined and nonconfined fires.

A further observation on allocation is offered: Causal information can be more difficult to obtain in the largest fires, as more of the evidence of fire origin is destroyed. Known-cause fires indicate that cause profiles are different for larger versus smaller fires. For example, Table 3.4.8 shows that intentionally set fires, fires started by candles, and electrical distribution or lighting equipment fires result in the largest average property loss per fire, and fires started by smoking materials, intentional fires, and fires started by someone (usually a child) playing with a heat source result in the highest rates of civilian fire death per 100 fires. Therefore, if unknowns are to be allocated, the allocation ideally should take into account the cause profiles for fires of comparable size. This isue is another fire data analysis issue around which no consensus has yet formed. The ideal solution would be to find ways to reduce the rate of unknowns, but there also may be better ways to arrive at estimates in the face of the unknowns that do exist.

In the single-digit cause codes used in NFIRS 5.0, a distinction is made between "cause under investigation" and "cause undetermined after investigation." For analysis purposes, both of these may be considered unknown.

Allocating Partial Unknowns. Many data elements have categories that can be considered "partial unknowns." Equipment involved in ignition codes includes choices such as "other heating or air-conditioning equipment"; "other electrical distribution, lighting, or power transfer equipment"; "other kitchen and cooking equipment," and so on. Some of these "other" entries are true "others" with no appropriate code choice. The "other" codes tend to also include fires for which incomplete information was known. A fire official may have known that a cooking or heating appliance was involved in the ignition but be uncertain about the exact type of equipment. If these "others" are not allocated proportionally among the equipment category, the share of each equipment involved would be undercounted. Proportional allocation of these "other" codes may result in a somewhat inflated estimate. Some analyses include the allocation of these partial unknowns. NFPA now routinely uses this approach with heat source code 60, "other open flame or smoking material." Without this secondary allocation, intentional overtakes smoking materials as the leading cause of home fire deaths. Prior to Version 5.0, open flame and smoking materials were in separate categories. The trend line seems more consistent with this approach, but it is also clear that some incidents were allocated that were, in fact, unclassified or "other."

The data element, "factor contributing to ignition," has a code for "none." This code seems to be used as an alternative to "undetermined." For this multiple-entry field, NFPA treats "none," "undetermined," and "not reported" as unknowns. Because multiple entries are allowed, the scaling ratio to allocate unknowns is total/(total-none-undetermined-not reported). The known values are multiplied by this ratio to obtain allocated estimates. The nested Table 3.4.12 shows this approach used for highway vehicle fires. Due to conversion issues, it is advisable to use only data collected originally in Version 5.0 when working with this data element. When this approach is used with structure fires, nonconfined fires should be analyzed separately from the confined fires.

"Skip patterns" or blanks in nonrequired data elements also pose challenges when allocating unknowns. Factor contributing to ignition is not required for intentional fires but is sometimes completed. Type of material ignited is not required when organic or general materials (item first ignited codes 70–99) were the items first ignited, but information may be entered. To allocate unknown data across the type of material ignited in nonconfined structure fires, NFPA calculated the scaling ratio as (total – fires with organic item or general item first ignited and no type of material ignited reported)/(total – fires with type of material ignited reported undetermined or not reported – fires with organic item or general item first ignited and no type of material ignited reported).

Extreme Values. Any discussion of total fire fatalities and fire losses that encompass 2001 must indicate whether the events of September 11, 2001, are included. If included in an analysis of office building fires, losses from other causes would seem insignificant. Many analysts elect to exclude incidents with exceptionally large losses from the calculations but discuss them in the text and notes. NFPA's tables usually include this statement in the notes: "Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire." With projections, an extreme value is multiplied.

Coding Inconsistencies and Errors. The quality of any analysis is dependent on the quality of the data used. Sometimes analysts decide to exclude values that seem obviously inconsistent or unlikely. An analysis of response times might exclude any response times longer than an hour. An analysis of upholstered furniture might exclude fires in which the item first ignited was upholstered furniture, but the type of material first ignited was paper or gasoline. The type of material first ignited is intended to provide more detail about the item first ignited.

TABLE 3.4.11 Confined Structure Fires Reported to NFIRS by Incident Type, 1999–2003

	1999 Fires		2000 Fires		2001 Fires		2002 Fires		2003 Fires	
Incident Type	*Number*	*Percent*	*Number*	*Percent*	*Number*	*Percent*	*Number*	*Percent*	*Number*	*Percent*
113 Cooking	804	0.9	5,049	3.0	18,576	9.8	29,706	14.2	56,453	20.4
114 Chimney/Flue	467	0.5	2,113	1.3	5,654	3.0	8,638	4.1	12,006	4.3
115 Incinerator	8	0.0	70	0.0	211	0.1	284	0.1	492	0.2
116 Fuel burner	109	0.1	387	0.2	1,923	1.0	3,226	1.5	8,909	3.2
117 Commercial compactor	33	0.0	63	0.0	221	0.1	246	0.1	1,174	0.4
118 Trash/rubbish	1,012	1.2	2,854	1.7	6,998	3.7	9,906	4.7	15,889	5.7
Total confined fires	2,433	2.8	10,536	6.3	33,583	17.7	52,006	24.9	94,923	34.2
All other structure fires	84,207	97.2	155,587	93.7	156,061	82.3	156,797	75.1	182,435	65.8
Total structure fires	86,640	100.0	166,123	100.0	189,644	100.0	208,803	100.0	277,358	100.0

Note: Percentages may not sum to 100 percent due to rounding.
Source: NFIRS 1999–2003.

TABLE 3.4.12 Highway Vehicle Fires, by Factor Contributing to Ignition Grouping, 1999–2002, Fires Reported to U.S. Fire Departments in NFIRS Version 5.0

Factor Contributing to Ignition	*Percentage of Fires*	*Percentage of Civilian Deaths*	*Percentage of Civilian Injuries*	*Percentage of Direct Property Damage*
Mechanical failure or malfunction	**48**	**9**	**34**	**37**
Leak or break	13	6	15	11
Backfire	6	1	7	3
Worn out	4	0	2	2
Unclassified or unknown-type mechanical failure or malfunction	24	2	10	21
Electrical failure or malfunction	**23**	**2**	**12**	**22**
Unspecified short-circuit arc	7	0	4	6
Short-circuit arc from defective or worn insulation	4	0	2	3
Short-circuit arc from mechanical damage	2	1	2	1
Arc or spark from operating equipment	1	1	1	1
Unclassified or unknown-type electrical failure or malfunction	9	1	3	9
Misuse of material or product	**11**	**16**	**25**	**11**
Flammable liquid or gas spilled	2	4	5	2
Heat source too close to combustibles	2	2	5	3
Abandoned or discarded material	2	2	2	2
Unclassified or unknown-type misuse of material or product	2	4	6	2
Flammable liquid used to kindle fire	1	2	1	1
Cutting or welding too close to combustibles	1	0	1	0
Improper fueling technique	1	1	3	0
Operational deficiency	**7**	**61**	**20**	**13**
Collision, knock down, run over, or roll over	3	57	13	8
Equipment not being operated properly	1	2	3	1
Failure to clean	1	0	0	0
Unclassified or unknown-type operational deficiency	2	1	3	1
Fire spread or control	**6**	**5**	**4**	**11**
Exposure fire	6	3	3	11
Design, manufacturing, or installation deficiency	**1**	**0**	**1**	**2**
Installation deficiency	1	0	1	0
Natural condition	**0**	**1**	**1**	**1**
Unclassified factor contributed	**6**	**12**	**7**	**10**

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. More than one factor contributing to ignition could be entered. Fires, in which the factor contributing to ignition was undetermined, not reported, or coded as "none" were allocated proportionally among fires with known factor contributing to ignition. Although this field is not required for fires that were coded as intentionally set or attributed to a cause of "other," the share of incidents with unreported data (fires, 17%; deaths, 22%; injuries, 10%; property damage, 27%) or fires with "none" (fires, 28%; deaths, 16%; injuries, 19%; property damage, 27%) generally exceeded those for undetermined (fires, 11%; deaths, 11%; injuries, 10%; property damage, 13%) suggesting that this type of allocation would be most appropriate. Except for the group headings, only factors contributing that accounted for at least 1 percent of the fires are shown. Groups are shown in descending order, and within groups, factors exceeding 1 percent are also shown in descending order. Unclassified type factors are shown last. Group sums include all factors within the group, even when the factors were under 1 percent and, consequently, not shown.

Source: NFIRS and NFPA survey.

It is important to remember that the NFIRS report generally serves as the fire department report of an incident. From a purely descriptive sense, the inconsistent coding may better serve the fire department's needs. It is also important to remember that errors seldom go in one direction only. To get a fair picture of a product's fire experience, if one omits the fires that seem to have been incorrectly included, one should also add the fires that were incorrectly excluded.

Analysis of Small Data Sets

A problem can arise in the size of the database available for analyses aimed at particular property uses. In 2004, according to NFPA, all nonresidential structures combined accounted for 115,500 fires, 80 civilian deaths, 1350 civilian injuries, and $2.4 billion in property damage.[32] Typically, roughly half to two-thirds of all fires are represented in the NFIRS, which has individual incident reports and can be used to analyze patterns by specific property use. For some property uses, the number of reported fires is low enough to make detailed analysis difficult or, in some cases, pointless. Often information is needed about some part of, or problem in, a particular occupancy, such as prison cells, hospital operating rooms, auditorium areas in theaters, or school hallways. In some cases, it may be possible to include other similar occupancies or related causal factors to expand the pool of incidents. It may be prudent to provide a less detailed analysis. In other cases, it may be more appropriate to extend the length of time studied.

Some fluctuations occur normally; one large incident can artificially inflate the casualties or dollar loss. It may seem logical to use the number of fire deaths as a measure of success for a public fire education program. However, the numbers at the state and local level are generally not big enough to do so with confidence. To minimize the year-to-year variability, NFPA produces annual averages for most analyses. The USFA also uses multiyear data in its analyses for the same reason.

Introduction to Location-Based Fire Data Analysis

As mentioned earlier in this chapter, the increase in computing power has enabled sophisticated analysis of fire incident data at the local level in ways that would have been impractical, if not impossible, just a few years ago. One of the most exciting new approaches now accessible to many jurisdictions is the use of geographical information systems (GIS) for location-based analysis.

Previous efforts at a more targeted, location-based description of the fire situation have centered on fire station or district-level groupings of data. However, this tends to blur differences among neighborhoods of differing characteristics. By geocoding fire incident data, one is able to examine groups of incidents at the census tract (approximately 500–3500 people), block group, or even block levels.

What is meant by geocoding data? For our purposes, geocoding is the process of assigning an absolute location to a fire incident report. This information could be as simple as street address or zip code or as detailed as high-resolution latitude/longitude. This location can then be associated with a variety of other location-based data sets, including census tracts, fire districts, or political boundaries.

The process of geocoding incidents is fairly straightforward. For most structure fires, simply an accurately entered address will be all the information needed for processing with off-the-shelf geocoding software. The software will assign any of a number of attributes to the incident, including latitude/longitude and census tract/block group data. The types of data could include demographics such as age distribution, race/ethnicity, education level, income, residential occupancy rates, and information on the housing stock. Once this has been accomplished, the number of fires, types of fires, casualties, and any other type of incident that is collected can be identified for each census area.

Grouping these data at various levels paints different pictures of a city's fire experience. Combined with the all-incident reporting of NFIRS 5.0, location-based, rather than fire station–based, reporting may be of great interest. With well-scrubbed data, local analysis as fine as the census track/block group may be possible.

By doing this, area-specific trends and issues can be identified. Are false alarms a problem in a neighborhood? Is one area of the city experiencing a higher rate of arson? What is the expected rate of fire for a particular city? How does it vary across the city? How do neighborhoods of certain demographic attributes compare with other neighborhoods within the city and even across different cities?

It is possible to identify high densities of at-risk populations, such as the very young and very old. Limited prevention resources can be targeted at the areas where they will do the most good instead of a broad approach to public education.

Although many of these issues are intuitively obvious, in the current arena of backing dollars with facts, it is imperative that the fire service quantify the needs for its services, both for response and prevention. This approach makes it possible to say more than "Arson is a problem in poor areas of the city." The data could justify or refute statements such as "People in these sections of the city are at twice the risk for residential arson as the rest of the city."

For this approach to work, it is necessary to implement and maintain quality control procedures when entering location data. Some departments have location data (latitude/longitude) automatically associated with each dispatch. This method simplifies matters greatly and facilitates analysis of nonstructure incidents for which there might not be suitable address data.

Resources necessary for location-based fire data analysis include the following:

- Good-quality fire incident data
- Census data
- GIS application
- Locally produced data sets
- Good PC/spreadsheet-type skills

Many municipalities have GIS shops already working in offices such as transportation, planning, and zoning. It may be possible to dovetail fire-location-based analysis with existing GIS efforts. Otherwise, a reasonably literate computer user can be trained on introductory-level GIS skills in a relatively short time.

Rates and Measures of Fire Risk

The use of rates is another means to provide a context or make comparisons across groups or time. A rate is a ratio consisting of a measure of the size of a fire problem divided by a measure of the size of the group affected by that problem.

In 2004, the United States suffered 13 civilian fire deaths per million population. That is a rate consisting of the estimated number of civilian fire deaths (3900) divided by the estimated resident population, or number of people who live in the United States (293,655,000), divided by 1 million. In 2004, the average fire-related property loss in rural communities was $82 per person per year.[32] That is a ratio consisting of the total property damage in rural communities divided by the number of people living in those communities.

Rates provide measures of fire risk. They can be used, therefore, in any analysis where the size of the group affected by a problem may change. For example, as has been said, the United States suffered 13 civilian fire deaths per million population in 2004. Because the total population growth adds almost 3 million people to the population each year, the number of civilian fire fatalities will be about 33 deaths higher each year unless increased fire safety lowers the rate.

NFPA estimates that annual fire deaths fell 40 percent from 1980 through 2004. During the same time, the resident population grew 29 percent. The resulting change in deaths per million population was a decrease of 54 percent. Increased fire safety may be best measured by the decline in the fire death rate, as this rate takes into account both changes in the absolute number of fire deaths and changes in the population.

Risk measures do the best job of bringing the fire problem down to a personal level. Rural communities do not account for a majority of the country's fire deaths, but they have by far the highest fire death rates compared to communities of larger size.[32] Person for person, their citizens are in the most danger from fire. People 65 years of age or older face twice the risk of dying in a fire as do members of the general population.[33] An individual wants to know his or her own risk, not the risk to an average American. Barring that, he or she wants to know the risk for people as much like him or her as possible. Risk measured for specifically defined groups provides that information.

Risk measured by rates is of particular interest if there is the potential for large-scale shifts from one group to another of substantially higher or lower risk. In the early 1980s, analysts determined that solid-fueled heating devices, principally wood-burning stoves, accounted for an unusually high risk; that is, there was a high ratio of fires involving those devices divided by homes using those devices.[34] At the time, it appeared that the generation-long decline in use of these devices was about to be reversed, under the pressure of higher prices for oil and natural gas. This was an ideal opportunity to use data to guide action; at a time when decisions were being made, most people did not know the unusual dangers posed by their choices. As an example of risk moving in the other direction, analysts using fire incident data from the early growth years of smoke-alarm usage were able to demonstrate that the rate of deaths per home fire was just over half as great for homes with smoke alarms as for homes without them.[35] Here again, decisions with substantial impact on risk were being made regarding equipment; therefore, it was possible to get people's attention and encourage the move toward smoke alarms.

Getting Information Needed to Calculate Rates. For some analyses, it may be difficult or impossible to obtain the information needed to construct the appropriate rate. One example is an analysis comparing the dangers of fire fighting with risks of other professions. The ratio should be number of on-duty fire service deaths to number of hours of exposure by fire fighters. The latter number cannot be easily calculated, however, because no one has national statistics on how many hours volunteer fire fighters serve. Also, differences in workweek need to be considered for career fire service personnel.

Another example is a comparison of fire fatality risks in homes versus those in hotels. Numbers of persons cannot be used for both, because length of stay is obviously much shorter for hotels than for homes. Numbers of units might work better if one could obtain those data and if occupancy rates could be addressed by a single parameter estimate. The problems of selecting the right denominator and obtaining data for it usually can be solved to some degree of acceptability, but the process is often complex and challenging.

Another problem in constructing rates can occur if the group of interest is defined too narrowly. A household, for example, might like to be able to calculate a risk index that reflects its smoking and drinking habits, its number of children, the ages of its members, its types of equipment and how they are fueled or powered, and many other characteristics. Today this would pose an insoluble problem. There are not enough data to calculate the numbers of households with all those characteristics (so there can be no denominator), and the list of descriptors defines a class so narrow that the number of fires experienced by households of that precise type would be very small and subject to considerable statistical uncertainty. One could separately measure the effects of some of these characteristics and then combine the results, but such a calculation would involve modeling assumptions that are already known to be false. Considerable statistical modeling and research will be needed to make progress on questions of this type.

Risk of Fires by Occupancy. Many analyses focus on fires or incidents in specific types of occupancies (i.e., homes, health care, educational, manufacturing, etc.). By combining NFIRS data with the NFPA survey, an estimate for the number of fires in these occupancies can be obtained. These sources do not, however, reveal anything about the risk of fires in these occupancies. A denominator, based on the number of units or establishments, is required to calculate risk. NFIRS users from outside the fire service may be more familiar with the North American Industry Classification System (NAICS) codes, released in 1997 and updated in 2002, or the older Standard Industrial Classification (SIC) codes.[36] Data on the number of establishments of a certain occupancy type would most likely be collected according to the NAICS codes. Table 3.4.13 shows the sectors that are included. Each sector is further divided into subsectors, industry groups, the NAICS industry, and the national industry.

Challenges abound when two data sources are combined, and the users must remember the differences in original goals for each of the data sources. The property use codes in NFIRS describe the setting the fire department encountered; the NAICS codes describe businesses or related entities. Consequently, many of the codes will not line up neatly with each other, particularly when one business has multiple property uses, such as a parking lot, storage shed, and an office building.

TABLE 3.4.13 NAICS Codes Compared to NFIRS Property Use Codes

NAICS Sector	*NAICS Name*	*NFIRS Code*	*NFIRS Property Use*
11	Agriculture, forestry, fishing, and hunting	655	Crop or orchard
		659	Livestock production
		669	Forest, timberland, woodland
21	Mining	679	Mine or quarry
22	Utilities	610	Other energy production plant
		614	Steam or heat generating plant
		615	Electric generating plant
		642	Electrical distribution
		647	Water utility
		640	Other utility or distribution system
23	NA	NNN	None
31	Manufacturing	700[a]	Manufacturing or processing[a]
		984	Industrial plant yard area not used for storage
42	Wholesale trade		No separate category for wholesale—see retail
44–45	Retail trade	500[a]	Other mercantile or business[a]
		511	Convenience store
		519	Food and beverage sales
		529	Textile or wearing apparel sales
		539[a]	Household goods, sales, repairs[a]
		549	Specialty shop
		559	Recreational stores
		569[a]	Sale of specialized professional supplies, art supplies, home maintenance services[a]
		571	Service or gas station
		579[a]	Motor vehicle or boat sales, services, or repair[a]
		581	Department or discount store
		580	Other general retail
48–49	Transportation and warehousing	171	Airport passenger terminal or heliport
		173	Bus station
		174	Rapid transit station
		170	Other passenger terminal
		596[a]	Post office or mailing firm[a]
		644	Gas distribution or pipeline
		645	Flammable liquid distribution or pipeline
		816	Grain elevator or silo
		819	Livestock or poultry storage
		839	Refrigerated storage
		849[a]	Outside storage tank[a]
		891	Warehouse
		899[a]	Residential or self-storage units[a]
		800[a]	Other storage[a]
		921	Bridge or trestle
	Transportation and warehousing *(continued)*	922	Tunnel
		941[a]	Open waters, including ports[a]
		972	Aircraft runway
		973	Aircraft taxiway
		974	Aircraft loading area
		982	Pipeline, powerline, or other utility right-of-way[a]
51	Information	151	Library
		183	Movie theater
		185	Radio or television studio
		186	Film or movie production studio
		180[a]	Other studio or theater
		635	Computer center, including computer laboratories
		639	Communications center
		700[a]	Manufacturing (e.g., printing and publishing)
52	Finance and insurance	592[a]	Bank, including ATMs when not part of other structure[a]
		599[a]	Business office[a]
53	Real estate and rental and leasing	599[a]	Business office[a]
			See also Retail section 500–580[a]
54	Professional, scientific, and technical services	593[a]	Veterinary or research office
		599	Business office[a]
		629[a]	Laboratory or science laboratory
55	Management of companies and enterprises	592[a]	Bank, including ATMs when not part of other structure[a]
		599[a]	Business office[a]
56	Administrative and support services	599[a]	Business office[a]
		648	Sanitation utility
		919	Dump or sanitary landfill
61	Educational services	213	Elementary school, including kindergarten
		215	Middle, junior, and high school
		210	Other nonadult school
		241	Adult education center or college classroom
		200[a]	Other educational
62	Health care and social assistance	211	Preschool, not in same facility with other grades
		254	Day care in commercial property
		255	Day care in residential property, licensed
		256	Day care in residential property, unlicensed

(continued)

TABLE 3.4.13 Continued

NAICS Sector	*NAICS Name*	*NFIRS Code*	*NFIRS Property Use*
	Health care and social assistance *(continued)*	200[a]	Other educational[a]
		311	Licensed nursing homes
		321	24-hour mental retardation/ development disability facility
		322	24-hour alcohol or substance abuse center
		323	Mental institution
		331	Medical or psychiatric hospital
		332	Hospice
		341	Clinic or clinic-type infirmary
		342	Doctor, dentist, or oral surgeon's office
		343	Hemodialysis unit
		340	Other clinic, doctor's office, or hemodialysis unit
		300[a]	Other health care, detention, or correction[a]
		459	Residential board and care, long-term care, or halfway house
		629[a]	Laboratory or science laboratory
71	Arts, entertainment, and recreation	111	Bowling establishment
		112	Billiard center or pool hall
		113	Electronic amusement center
		114	Indoor or outdoor ice rinks
		115	Indoor or outdoor roller skating rinks
		116	Swimming facility
		110	Other fixed use recreation place
		121	Ballroom or gymnasium
		122	Large open hall without fixed seats, including convention halls, exhibit halls, and field houses
		123	Fixed seating in large area, including ball parks, stadiums, grandstands, and race tracks
		124	Playground or outdoor area with fixed equipment
		129	Indoor or outdoor amusement center, excluding video arcades
		120	Variable use amusement or recreation place
		141	Athletic club
		142	Clubhouse associated with country club
		143	Yacht club
		144	Casino, gambling club, or bingo hall
	Arts, entertainment, and recreation *(continued)*	140	Other club
		152	Museum or art gallery, planetarium, or aquarium
		154	Memorial structure, monument, or statue
		181	Legitimate theater
		182	Auditorium or concert hall
		180[a]	Other studio or theater[a]
		937	Beach
		938[a]	Graded and cared for plot of land, including parks, cemeteries, golf courses, and residential yards[a]
72	Accommodation and food services	161	Restaurant or cafeteria
		162	Bar, nightclub, tavern, or pub
		160	Other eating or drinking place
		439	Rooming or boarding house
		449	Hotel or motel
		462	Sorority or fraternity
		464	Barracks, dormitory
		460	Other dormitory-type residence
		935	Campsite with utilities
81	Other services (except public administration)	131	Church, temple, mosque, or other religious facility
		134	Funeral parlor or crematorium
		130	Other place of worship or funeral parlor
		419[b]	Detached one- or two-family dwelling[b]
		429[b]	Multifamily dwelling[b]
		539[a]	Household goods, sales, repairs[a]
		557	Personal service, including barber and beauty shops
		564	Laundry or dry-cleaning, including self-service facilities
		569[a]	Sales of specialized professional supplies, art supplies, home maintenance services, including linen supply services[a]
		579[a]	Motor vehicle or boat sales, services, or repair[a]
		700[a]	Manufacturing (such as photo finishing)[a]
		881[b]	Residential vehicle storage[b]

TABLE 3.4.13 Continued

NAICS Name	*NAICS Name*	*NFIRS Code*	*NFIRS Property Use*
	Other services (except public administration) *(continued)*	882[b]	General vehicle parking garage[b]
		880[b]	Other vehicle storage[b]
		965[b]	Vehicle parking area[b]
92	Public administration	155	Courthouse or courtroom
		150	Other public or government
		361	Jail or prison (not juvenile)
		363	Reformatory or juvenile detention center
		365	Police station
		300[a]	Other health care, detention, or correction[a]
		631	Defense or military installation
		888	Fire station

Note: NFIRS property uses that did not have an obvious conversion are not included in this table.
[a]May be found in more than one NAICS category.
[b]NAICS tracks economic entities. Private households are counted when they employ others; parking facilities are counted when they charge for the service.
Source: *NFIRS 5.0 Reference Guide;* North American Industry Classification System, United States, 2002.

Analysts calculating risk trends by occupancy will need to remember that the older SIC code data have been converted to the extent possible. With conversions in both the numerator and denominator, analysts should proceed cautiously.

Using Data to Identify Trends

Although most of the analyses described previously provide a "snapshot" of the fire problem, some questions need a "moving picture." Is a part of the fire problem getting better or worse? Is the character of the fire problem changing? If changes are occurring, do they track with corresponding changes in product use, property use, fire service practices, fire prevention activities, codes and regulations, or other elements of the environment? (For this last question, one may need a full-fledged strategy or program analysis, as described later in this chapter, under "Using Data in Program and Strategy Analysis.")

All trend analyses must address the question of whether or not the past is a consistent guide to the present, let alone the future. It would be nice to be able to say that a trend indicates whether fire risk is going up or coming down. However, a simple trend calculation may not provide this information if the base of comparison has been shifting during the years covered. For example, start with a calculation of the number of fire deaths per year in manufactured homes. If the number dropped over time, that might mean that manufactured homes were becoming safer or it might mean that fewer people were choosing to live in manufactured homes. A trend calculation based on the number of fire deaths per million people living in manufactured homes would factor out the latter possibility and do a better job of showing whether manufactured homes were becoming safer. This is an example of how rates (discussed earlier) are also effective measures when examining trends.

Another problem in trend calculations might be a shift in the sampling technique used to create the database. Suppose that while analyzing fire deaths per million population, as in the previous paragraph, another state was added to the database in the middle of the trend period. The increase in the number of persons would not by itself bias the results because, all other things being equal, numbers of deaths and persons would rise together. But all other things may not be equal. If that state has an unusually large percentage of households living in manufactured homes, it could exert a sizable influence on the result. Similarly, any major differences in climate, income, educational levels, and other such factors could have an impact. There would be no way to know how much of any change was due to changes in manufactured home fire safety and how much was due to the addition of a new state to the database.

As mentioned previously, trend analysis involving data collected by NFIRS 5.0 and earlier versions may be misleading. The change from SIC codes to the NAICS codes affects some of the establishment counts. These changes necessitate extreme caution in occupancy class risk analysis.

Trends in Fire Fatalities and the Protection of Life. Figure 3.4.4 shows the trend in NFPA's estimates of civilian fire deaths, starting with 1977 when the NFPA survey was upgraded. The National Safety Council (NSC) has been using a consistent estimating procedure based on state health department records of death certificates for a longer period. Its definition has, however, in the past included nonfire burn deaths and still excludes some fire deaths, most notably those involving vehicle accidents, arson, or self-immolations. Their longer trend line (Figure 3.4.5) shows an even longer decline, although there were periods of backsliding. Figure 3.4.6 shows the generally steady decline in the rate of fire deaths per million population from both sources.[37] Although the fire death definitions used by NFPA and the NSC vary slightly, the two trend lines are quite similar. The death certificate data shown by the NSC indicate that unintentional fire deaths in 2004 were roughly three-fifths (56%) lower than in 1913, whereas the 2004 fire death rate was 86 percent lower than the 1913 rate. Although these percentages should be considered rough estimates because of the definitional changes, the percentages show both the dramatic drop in fire deaths and how different progress can appear if measured by actual numbers or by rates.

Table 3.4.14 shows another approach to tracking by way of the deadliest of the big fires. Not being a graph, it lacks visual impact. Instead, the sense of progress is stated more subtly, as the table shows how much less severe the worst fires of the decade had become until the past 15 years. Figure 3.4.7 shows this relationship graphically with death counts from each of the three fires marked.

By focusing on specific fires, Table 3.4.14 can also serve as an introduction to the kind of extended discussion of turning-point fires (i.e., incidents that triggered changes in our approach

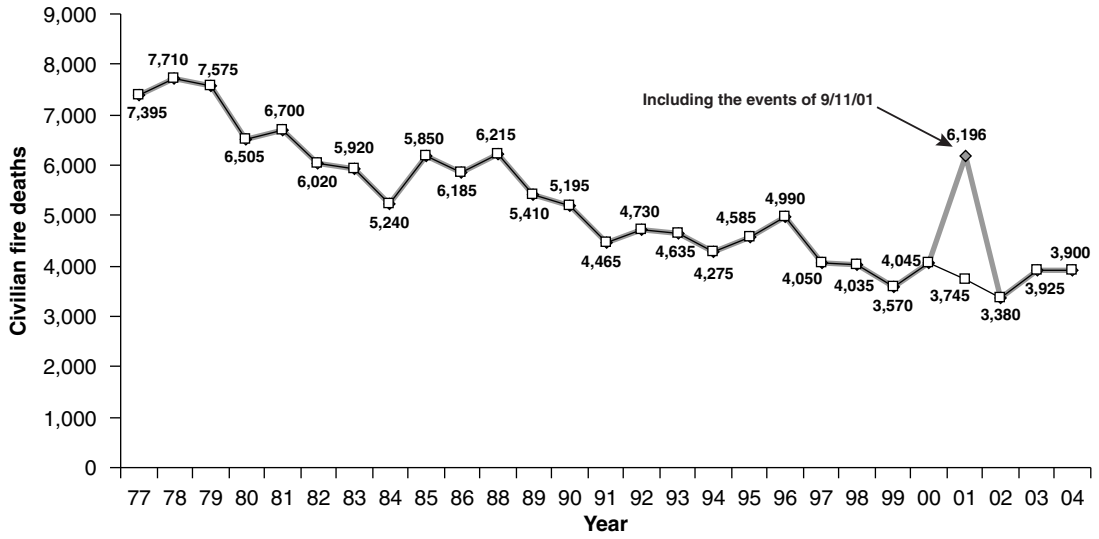

FIGURE 3.4.4 National Estimates of Civilian Fire Deaths (Source: NFPA National Experience Survey)

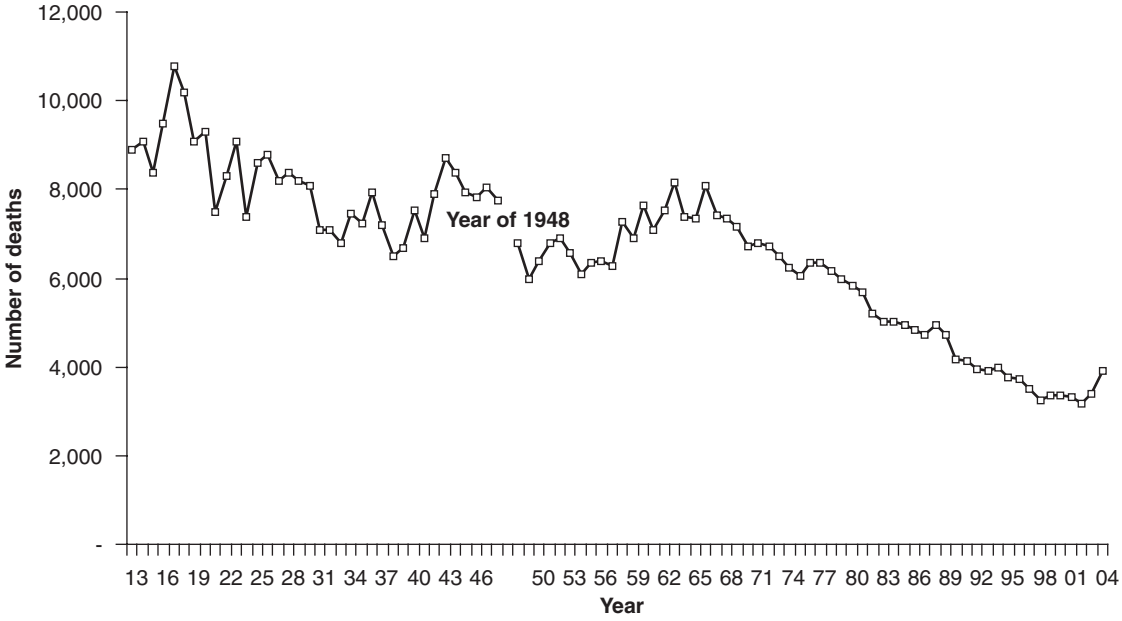

FIGURE 3.4.5 Unintentional Injury Fire Deaths per Year (Death Certificate Data), 1913–2004. Note: Two figures are given for 1948 to reflect old and new methodologies. These are reflected by a break in the graph. Other methodology changes occurred in 1958 and 1968, but different numbers were not provided. (Source: National Safety Council analysis of death certificate data, pp. 42–43[37])

to fire safety that significantly and permanently altered our loss experience, provided in Section 3, Chapter 1, "An Overview of the Fire Problem and Fire Protection"). From a statistical standpoint, it is striking that in almost every decade the deadliest fires tend to include fires that are not building fires, ranging from the ship fires at the start of the century to the airline fires at the end of the century, with forest fires and mine fires occurring throughout the century.

The purpose of statistics is to answer important questions that will help indicate what is needed for fire safety. An interest in major fires is justified by the view that fire codes and standards ought to be able to prevent any really large incidents from occurring. This view is what leads to the phenomenon of one bad fire leading by itself to a set of code changes, because it only takes one fire of sufficient severity to indicate that an objective as stringent as preventing all very large fires has not been met.

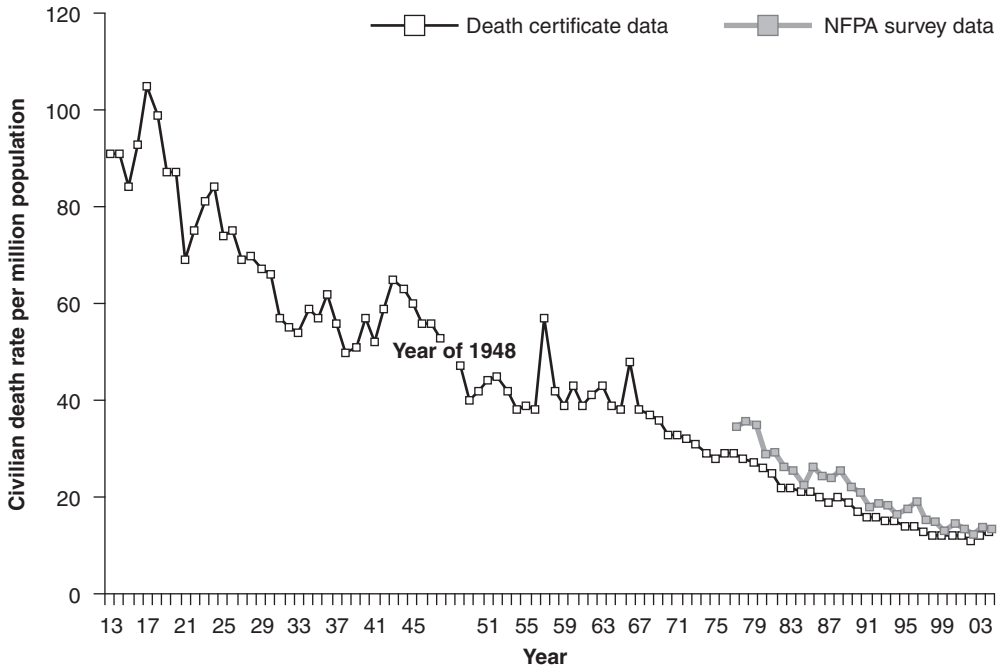

FIGURE 3.4.6 Fire Death Rates per Million Population. Note: Two figures are given for 1948 to reflect old and new methodologies. These are reflected by a break in the graph. Other methodology changes occurred in 1958 and 1968, but different numbers were not provided. Events of September 11, 2001, are not included in this graph. (Source: National Safety Council analysis of death certificate data[29] and NFPA National Fire Experience Survey, pp. 44–45)

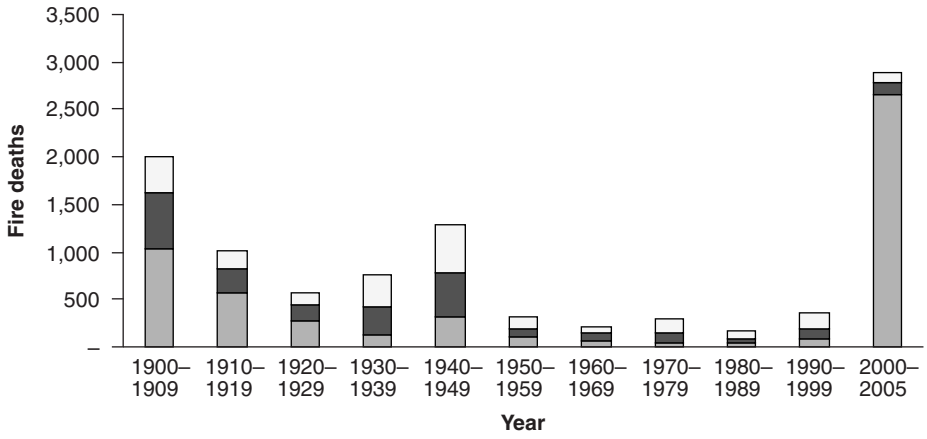

FIGURE 3.4.7 Sum of Fire Deaths from Three Largest U.S. Fatal Fires per Decade (Sources: NFPA archive files; NFPA Fire Incident Data Organization; NFPA 1984 *Fire Almanac;* J. Cornell, *The Great International Disaster Book,* Pocket Books, New York, 1976)

This sequence of events is especially likely to occur if the one bad fire occurs in a place or under circumstances never previously associated with really bad fires, because, in that case, the one bad fire will serve as a sign to many that a particular class of properties, equipment, or activities is not as safe as everyone thought it was.

Because this kind of logic is so common and seems so plausible, it is useful to introduce some cautions. First, fire protection engineering may be thought of as deterministic solutions for a probabilistic world. To put it another way, risk can never be reduced to zero, and it is important that realistic fire safety designs recognize that even the most determined enforcement of

TABLE 3.4.14 Deadliest U.S. Fires and Explosions of the Past Century, Since 1900

Fire	*Number Killed*
2000–2005	
1. World Trade Center, New York, NY (September 11, 2001)	2666
2. Pentagon, Arlington, VA (September 11, 2001)	125
3. Station Nightclub fire, West Warwick, RI (February 20, 2003)	100
1990–1999	
1. Alfred P. Murrah Federal Building, Oklahoma City, OK (April 19, 1995)	168
2. ValuJet Airlines DC-9 passenger jet, Miami, FL (Everglades) (May 11, 1996)	110
3. Happy Land Social Club, New York, NY (March 25, 1990)	87
1980–1989	
1. MGM Grand Hotel, Las Vegas, NV (November 21, 1980)	85
2. Galaxy Airlines #203, Reno, NV (January 21, 1985)	42
3. United Airlines #232, Sioux City, IA (July 19, 1989)	38
1970–1979	
1. Beverly Hills Supper Club, Southgate, KY (May 28, 1977)	165
2. Silver mine, Kellogg, ID (May 2, 1972)	91
3. Capital International chartered airliner, Anchorage, AK (November 28, 1970)	47
1960–1969	
1. Coal mine, Farmington, WV (November 20, 1968)	78
2. Indiana State Fairgrounds Coliseum, Indianapolis, IN (October 10, 1963)	75
3. Golden Age Nursing Home, Fitchville Township, OH (November 23, 1963)	63
1950–1959	
1. Coal mine, West Frankfort, IL (December 21, 1951)	119
2. USS *Bennington* aircraft carrier, off RI coast (May 26, 1954)	103
3. Our Lady of the Angels Grade School, Chicago, IL (December 1, 1958)	95
1940–1949	
1. Cocoanut Grove Nightclub, Boston, MA (November 28, 1942)	492
2. SS *Grandcamp* and Monsanto Chemical Plant, Texas City, TX (April 16, 1947)	468
3. Munitions ships and depot, Port Chicago, CA (July 17, 1944)	322
Plus 5 other incidents that each killed at least 100 people	
1930–1939	
1. Ohio State Penitentiary, Columbus, OH (April 21, 1930)	320
2. Consolidated School, New London, TX (March 18, 1937)	294
3. SS *Morro Castle,* off NJ coast (September 8, 1934)	135
1920–1929	
1. Coal mine, Mather, PA (May 19,1928)	273
2. Coal mine, Castle Gate, UT (March 8, 1924)	171
3. Cleveland Clinic, Cleveland, OH (May 15, 1929)	125
Plus 2 other incidents that each killed at least 100 people	
1910–1919	
1. Forest fire, northern MN (October 12, 1918)	559
2. Coal mine, Dawson, NM (October 22, 1913)	263
3. Aetna Chemical Company, Oakdale, PA (May 18, 1918)	193
Plus 7 other incidents that each killed at least 100 people	
1900–1909	
1. SS *General Slocum* steamship, New York, NY (June 15, 1904)	1030
2. Iroquois Theater, Chicago, IL (December 30, 1903)	602
3. Coal mine, Monongha, WV (December 6, 1907)	361
Plus 13 other incidents that each killed at least 100 people	

Source: NFPA archive files; NFPA Fire Incident Data Organization (FIDO); NFPA 1984 *Fire Almanac;* J. Cornell, *The Great International Disaster Book,* Pocket Books, New York, 1976.

the most stringent requirements will not eliminate all possibility of a serious fire.

Second, most fire deaths and other fire losses do not occur in big fires or even in the kinds of places and situations where big fires occur. Big multiple-death fires occur in high-occupancy places, such as large office complexes, hotels, or nightclubs, whereas most fire deaths occur in low-occupancy places, such as dwellings or individual apartment units, and occur as single-fatality fires. Big multiple-death vehicle fires may involve high-occupancy vehicles such as commercial airliners or large ships, whereas most vehicle fire deaths occur in small private vehicles such as cars and trucks.

Finally, it should be obvious from a casual glance at the deadliest fires in the past few decades that the problem often is not that the codes are not tough enough but rather that the adoption is not universal or the enforcement is not effective.

Event-driven changes in fire codes primarily involve the fire community. However, getting those changes adopted into law and backing the law with strong enforcement programs require the cooperation of elected officials and the public, most of whom are concerned about many subjects in addition to fire. Recognizing this, some fire chiefs have prepared legal packages targeted at particular problems in advance, holding them in reserve until a major fire provides the visibility and sense of urgency required for adoption.

In view of this strategy, it is worth noting that "newsworthiness" is not always synonymous with incident severity. Two examples will suffice. The third most deadly fire of the 1960–1969 decade was the Golden Age Nursing Home fire, which killed 63 persons; it occurred, however, on the day after President John F. Kennedy was assassinated. This coincidence of timing sharply reduced the visibility of the fire. By contrast, the 1937 *Hindenburg* zeppelin fire killed "only" 36 persons, a death toll barely a fourth the size of even the third-largest fire of that decade and only one-eighth the size of the New London, Texas, school fire in the same year. The zeppelin fire, however, was broadcast "live" and occurred in full view of newsreel cameras and, therefore, it was probably the most widely heard and seen fatal U.S. fire until the *Challenger* space shuttle explosion in 1986. The *Hindenburg* fire meant the end of the rigid-airship industry.

These examples also have a lesson for analysis of trends in fire deaths, injuries, or incidents. For fires as severe as those discussed in the last few paragraphs, only decade-by-decade comparisons suffice to separate real trends from random ups and downs. For total U.S. civilian fire deaths, year-to-year tracking is generally meaningful. For a single large city, however, year-to-year tracking of fire deaths will be subject to considerable statistical noise; for town and rural areas, there is no good way to track fatality trends except as part of a larger aggregation, such as the state or the rural portion of the entire region.

Trends in Property Damage Due to Fire. The first fire protection standards promulgated by NFPA were directed principally at property protection, reflecting the association's founding by men in the business of insuring property against loss due to fire. Assessments of the success of strategies for property protection are more difficult than for life protection, however, because data on fire damage are subject to several gaps and quirks that do not affect data on fire deaths. Although all indicators of fire—incidents, deaths, injuries, and property damage—are clouded by the absence of information on fires not reported to local fire departments, property damage is the only indicator of severity that is left unreported in a significant minority of reported fires. Estimates of property damage involve more guesswork than estimates of people killed or injured. Some very-large-loss fires are never reported to local fire departments, because the affected firms are able to handle them with on-site resources. No comparable omissions occur among multiple-death fires.

Trend analysis must take into account the effect of inflation. Table 3.4.15 shows NFPA's estimates for total national property damage due to fire during 1994 to 2004, both as published and as recalculated in terms of 2004 dollars, using the U.S. Bureau of Labor Statistics' consumer price index to remove the effects of inflation.[38] Without adjusting for inflation, the direct property damage resulting from fire in 2004 was 20 percent higher than that reported in 1994. After adjusting for inflation, the 2004 property losses were actually 6 percent lower than were reported in 1994. Also significant is the effect of changes in the number of fires, because total damage figures involve the total number of fires and the average dollar loss per fire. The average loss per fire, unadjusted, was 58 percent higher in 2004 than in 1994; the average 2004 loss was only 24 percent higher after adjusting for inflation.

This inflation makes it difficult to compare large-loss experience over several years. In the early 1930s, the NFPA defined a large-loss fire as one involving at least $250,000 in direct property damage. In 1978, a large-loss fire was redefined as one involving at least $500,000, and in the early 1980s the amount became at least $1,000,000 in direct property damage. Each minimum represented the cutoff point for the largest several hundred fires of its time. In the late 1980s, it was decided to shift the large-loss study to a more detailed treatment of a smaller number of fires and, therefore, the threshold was raised to $5,000,000.

Table 3.4.16 lists the costliest fires in U.S. history, sorted by loss in 2004 dollars. Note that the unadjusted losses for four of the top 10 fires—the San Francisco Earthquake and Fire in 1906 (#2), the Great Chicago Fire of 1871 (#3), the Great Boston Fire of 1872 (#5), the Baltimore Conflagration of 1904 (#9)—were below the threshold for inclusion in 2004 dollars. In studying the table, one might note that 12 of the 25 fires on the list occurred since 1990, 7 of the 25 were wildland or forest fires, and 6 of the 25 were in California.

Difficulties in comparison become more pronounced when points even further back in history are considered. The 1947 chemical plant fire in Texas City, Texas, had a reported loss of $67 million. Using the consumer price index, that translates into $567 million in 2004. The 1906 earthquake and fire in San Francisco had a reported loss of $350 million. That means $7.3 billion today—or more than half the loss attributed to all reported fires in the United States in a typical year. At this point, comparisons can become very sensitive to assumptions. Was the property lost in the Texas City fire sufficiently similar to the items covered by the consumer price index? Or should a more industry-specific price index be used? Were the estimates of loss

TABLE 3.4.15 U.S. Trends in Property Damage Due to Fire, 1994–2004

Year	Fires	Direct Property Damage (in Billions of Dollars)		Average Loss per Fire	
		As Reported	*In 2004 Dollars*	*As Reported*	*In 2004 Dollars*
1994	2,054,500	8.2	10.4	4,000	5,100
1995	1,965,500	8.9	11.0	4,500	5,600
1996	1,975,000	9.4	11.3	4,800	5,700
1997	1,795,000	8.5	10.0	4,700	5,600
1998	1,755,500	8.6	10.0	4,900	5,700
1999	1,823,000	10.0	11.3	5,500	6,200
2000	1,708,000	11.2	12.3	6,600	7,200
2001	1,734,500				
w/ 9/11/01		44.0	46.9	25,400	27,100
w/o 9/11/01		10.6	11.3	6,100	6,500
2002	1,687,500	10.3	10.8	6,100	6,400
2003	1,584,500				
w/ So. CA wildfires		12.3	12.6	7,800	8,000
w/o So. CA wildfires		10.3	10.5	6,500	6,700
2004	1,550,500	9.8	9.8	6,300	6,300

for the San Francisco fire made to the nearest $10 million or even the nearest $50 million? Then the 2004 version of that loss might be accurate to only the nearest $200 million or $1 billion, which would mean its range of uncertainty would be higher than the total loss of almost any recent fire.[38–40]

The lesson here is that trend analysis of loss figures can be very tricky and needs to be done with an eye toward the effects of inflation and population growth (which also affect trends in numbers of fires, deaths, and injuries). Keep in mind that loss trends have a tendency to look bad even if real progress is being made.

USING DATA IN PROGRAM AND STRATEGY ANALYSIS

Earlier in this chapter, techniques were described for using data to analyze the present (size and characteristics of the fire problem) and the past (trends in the size and nature of the fire problem). Program and strategy analysis is the most decision-relevant use of data because it tries to project the future and, in particular, the ways in which the future will be different if a particular program or strategy is or is not adopted.

The most fundamental question to be answered in using data for program or strategy analysis is whether past fire experience is a good guide to future fire problems. Sometimes it is; sometimes it is not. However, intelligent use of data with other sources of information is an essential part of the best possible projection of the future. After all, what will we use if not data? Models are tied to reality by validation, which is based on experience of the past. Expert judgment is formed, at least in part, by the experience of the past. The issue is not whether to use the past as a guide; it is how best to characterize the important changes that will occur in the future.

Often the most important aspect of the future will be a different mix of the elements already in place in the present. For example, home smoke-alarm usage has grown at a phenomenal rate in the past 25 years, with most of the growth occurring in or after 1976. Fire incident data from the early years of growth in alarm usage showed that smoke alarms reduce by nearly half the risk (measured by the number of deaths per 1000 fires) that a person will die if he or she has a fire. At that point, there were uncertainties about the applicability of this finding to the future. Would the lifesaving impact of smoke alarms remain the same when the devices were installed in poorer households with less-educated occupants?[41]

The answer turned out to be yes, although there was some erosion in the estimated benefit from smoke alarms that coincided with adverse trends in the estimated fraction of smoke alarms that were operational. But the form of the question shows how data can be used intelligently to try to project the future. Start with the future predicted by a simple projection of recent trends. Using judgment, creativity, and brainstorming, try to identify what aspects of the present environment might be changing in ways that would modify the simple projection. Try to obtain data on the speed of those changes. Try to analyze the fire data in hand to determine the sensitivity of your conclusions to those changes. Combine these results to produce a revised projection.

Most analyses to date have found that environmental changes relevant to fire occur slowly and so produce relatively modest changes in what are called baseline projections (i.e., projections of the size and character of the fire problem if no new strategies are adopted). For example, the average age of the U.S. population is rising. This means a drop in the percentage of the population in the high-death-rate years of infancy, a rise in the percentage in the high-death-rate elderly years, and other shifts along the age spectrum. By the end of the century

TABLE 3.4.16 The 25 Largest Fire Losses in U.S. History

	Loss in Year Fire Occurred (in Dollars)	*Adjusted Loss (in 2004 Dollars)*
1. The World Trade Center New York City, New York September 11, 2001	33.4 billion	35.6 billion
2. San Francisco Earthquake and Fire San Francisco, California April 18, 1906	350 million	7.3 billion
3. Great Chicago Fire Chicago, Illinois October 8–9, 1871	168 million	2.6 billion
4. Oakland Fire Storm (wildland/urban interface) Oakland, California October 20, 1991	1.5 billion	2.1 billion
5. Great Boston Fire Boston, Massachusetts November 9, 1872	75 million	1.2 billion
6. Polyolefin Plant Pasadena, Texas October 23, 1989	750 million	1.1 billion
7. Wildland Fire (wildland/urban interface) Los Alamos, New Mexico May 4, 2000	1.0 billion	1.1 billion
8. Wildland Fire (Cedar) Julian, California October 25, 2003	1.1 billion	1.1 billion
9. Baltimore Conflagration Baltimore, Maryland February 7, 1904	50 million	1.0 billion
10. Wildland Fire (Old) San Bernardino, California October 25, 2003	975 million	1.0 billion
11. Los Angeles Civil Disturbance Los Angeles, California April 29–May 1, 1992	567 million	763 million
12. Power Plant (auto manufacturing complex) Dearborn, Michigan February 1, 1999	650 million	736 million
13. "Laguna Beach Fire" (wildland/urban interface) Orange County, California October 27, 1993	528 million	689 million
14. Textile Mill Methuen, Massachusetts December 11, 1995	500 million	619 million
15. USS *Lafayette* (formerly SS *Normandie* ocean liner) New York, New York February 9, 1942	53 million	613 million
16. SS *Grandcamp* and Chemical Co. Plant Texas City, Texas April 16, 1947	67 million	567 million
17. Petroleum Refinery Norco, Louisiana May 5, 1988	330 million	526 million
18. Cargo Plane In-Flight Fire Near Newburgh, New York September 5, 1996	395 million	475 million
19. Great Fire of New York New York, New York December 16, 1835	26 million	474 million
20. Wildland Fire Florida May–June 1998	395 million	456 million
21. One Meridian Plaza (high-rise office building) Philadelphia, Pennsylvania February 23, 1991	325 million	450 million
22. Forest Fire Cloquet, Minnesota October 12, 1918	35 million	437 million
23. *Apollo* Spacecraft Cabin Cape Kennedy, Florida January 27, 1967	75 million	424 million
24. Chemical Company Plant Pampa, Texas November 14, 1987	215 million	357 million
25. Nuclear Power Plant Near Decatur, Alabama March 22, 1975	100 million	351 million

Note: Loss estimates are from NFPA records and are adjusted to 2004 dollars by using the consumer price index, including Census Bureau estimates for historical times. The list is limited to fires that have a reliable dollar-loss estimate and that occur in or over the United States.

the cumulative effect will be large, but on a year-to-year basis it produces only a small, predicted change in the national fire death rate.

An analysis of the projected impact of a strategy or program involves the following five steps:

1. Identify the part of the fire problem that the strategy can affect and measure the size of that problem. For example, a change in the flame resistance of upholstered-furniture-covering materials would affect only fires involving those materials. Keep in mind the need to address both fires that begin

with upholstered furniture and fires that begin elsewhere and become severe primarily because of spread to upholstered furniture. A change to self-extinguishing cigarettes would affect only fires whose form of heat of ignition was cigarettes, and so on.

2. Estimate the likely percentage reduction in this target fire problem if the strategy or program were adopted, and prepare estimates for each of the measures of fire severity (deaths, injuries, property loss) because the impact probably will be different for each measure. If the strategy or program is already in use (as was true for smoke alarms), then fire incident data analysis may produce these estimates. If the strategy or program is not in use or is in very limited use, as is true for home sprinklers, then some combination of modeling, laboratory tests, and expert judgment will be needed to produce the estimates. In either case, it makes sense to develop a range of estimates from optimistic to pessimistic.

3. Estimate how much of the target population will adopt the program or strategy and how quickly. This typically is a marketing question, and the results can be surprising. Most analyses of the growth in smoke alarm coverage were too pessimistic on both how much and how fast. At the same time, most analyses were too optimistic about the installation of smoke alarms in homes most likely to have fires. Although 96 percent of U.S. households called in a 2004 Fire Prevention Week survey done for NFPA reported having at least one smoke alarm, no smoke alarms were present in roughly one-third of the nonconfined home fires reported in 1999 to 2002. Additionally, smoke alarms did not alert the occupants in 11 percent of the reported confined home fires. It is assumed that in the majority of this number, either no smoke alarm was present or it did not operate.[42] This discrepancy is not unusual for strategies that work through the marketplace. The first purchasers tend to be more affluent and better educated; these people traditionally have lower fire rates than the rest of the population do. Also, speed of adoption will reflect the normal life of a product. Changes in cigarettes can be implemented for all cigarettes in months, whereas changes in the upholstered furniture ignited by cigarettes may take decades to work their way through the whole population.

4. Estimate how often the strategy will be defeated in practice. For example, what proportion of home smoke alarms will have had the batteries removed, disconnected, or not replaced on schedule? Note that if the method in step (2) involved the use of actual fire incident data, the estimate already may include the effects of defeating or attenuation. (The latter is a term that does not have the connotation of deliberate sabotage that *defeating* may have for some people.)

5. Combine the measures of fire problem size from step (1) and the percentages from steps (2) through (4) to produce estimates of the net percentage reduction in the fire problem and of the new size of the fire problem. With these results, decide how valuable this strategy or program would be and whether to press for its adoption. In some forums, this decision will require a parallel calculation of the cost of the strategy or program, followed by some kind of comparison of the costs and loss reductions.

The important point is the use of analysis to narrow the target of a program or strategy in order to maximize impact and conserve scarce program resources. Another consideration in analysis is the need to identify clearly which of many important objectives are to be given priority. For example, is it more important to reduce the fire loss actually being suffered, thereby targeting properties where most loss now occurs? Or is it more important to reduce the potential for catastrophic fire loss, thereby targeting properties with sizable numbers of lives or property value at risk, even if their actual loss has been relatively small? Also, is it most important to reduce numbers of fires, numbers of deaths and injuries, or numbers of dollars in direct property loss? In home fires, for example, a focus on fires might mean targeting cooking and heating-related fires, a focus on deaths might mean targeting smoking-related fires, and a focus on property loss might mean targeting intentional fires.

Finally, remember that tracking analysis continues to be useful even after a decision has been made and a strategy or program has been implemented. As noted earlier, most of the estimates used in an analysis involve uncertainty; therefore, it may be useful to see whether the future unfolds as projected. If not, some further refinements in the design of a strategy or program may be warranted. Even early termination of a program might be indicated.

COMPARING ESTIMATES USING DIFFERENT DATABASES OR ANALYTIC APPROACHES

The previous chapter, "Fire Data Collection and Databases," details how NFIRS, the NFPA fire experience survey, NFPA's Fire Incident Data Organization (FIDO), and other databases not exclusively dedicated to fire, such as the death certificate database, collect and categorize fires.

Occasionally a situation arises for which two different numbers exist, derived from different sources or different analytical approaches. For nonanalysts who may not know the source of either number, such a situation can prove frustrating and can encourage a cynical attitude about the arbitrariness of all fire statistics. Even analysts familiar with the sources of both numbers may have difficulty pinning down the precise reasons for any discrepancies and deciding how important the differences are and which number is best. It is very important, therefore, for all data users—and others who expect to confront arguments based on fire statistics—to understand how and why estimates can differ. For the most part, variations involve the ways different data sources and estimates deal with the inevitable gaps in coverage that affect all sources of fire incident information.

No fire database can possibly capture all instances of unwanted fires. Few databases—and none discussed in this section—cover fires that are not reported to fire departments. (Special studies, such as one done on residential fires for the CPSC in 1984[43] and the British Crime Survey's regular reports on domestic fires,[44] do provide some estimates of the size and composition of the unreported fire problem.) No fire database even captures all the fires reported to fire departments, but some databases, notably the NFPA survey, are built on sam-

ples designed to be representative of all municipal or local fire departments.

By their nature, fire databases are biased in favor of "failures" rather than "successes." The fire that is controlled so quickly that it does not need to be reported to a fire department is not captured by the databases that cover reported fires. Analyses of the impact of devices and procedures that provide early detection or suppression also need to allow for the phenomenon of missing "success" stories. Moreover, anecdotal databases such as FIDO, which provide the most detail on building features and their performance, tend to be limited to the largest of the reported fires.

There is also the issue of quality control for a database. For databases with limited depth of detail (e.g., the NFPA survey) or limited breadth of coverage (e.g., FIDO, which is confined mostly to large fires), it is possible to invest considerable effort in ensuring that each report is as complete and accurate as possible. Follow-up calls can be used to fill gaps and check possible odd answers. For a database with the depth and breadth of NFIRS, however, the same level of quality control effort has not been possible. Consequently, NFIRS is missing more entries and has more that are dubious. The trade-off between data quality and data quantity is never easy; an analyst needs to be aware of the strength and dependability of the sources before conducting an analysis.

Different sources provide different estimates of fire deaths and injuries. The CPSC's National Electronic Injury Surveillance System (NEISS) obtains estimates of the number of injuries treated at hospital emergency rooms. According to NEISS estimates, more than 48,000 nonarson civilian fire injuries were seen at hospital emergency rooms from July 1, 2002, through June 30, 2003. More than 21,000, but still less than half, of these injuries occurred at fires attended by the fire service.[45] This is higher than NFPA's estimates of civilian fire injuries reported to U.S. fire departments. In some cases, private individuals or nonfire ambulance companies may transport patients without notifying the fire service.

The fire death statistics, discussed earlier, provide another example of differing results based on different data classifications using different definitions. NFPA's estimates are sample-based statistical projections derived from the fire department survey. Fire deaths from all types of fires, including arson, self-immolations, and vehicle fires, are included. In the death certificate database, fire deaths resulting from these three causes might be classified as homicide, suicide, and vehicle accidents, respectively. In NFPA's report on fire deaths by state,[46] the National Safety Council's analysis of the death certificate database was used because of the more complete and consistent coding done with death certificates. As mentioned earlier, the National Safety Council's definition of unintentional fire deaths excludes some fire deaths, most notably those involving vehicle accidents, arson, or self-immolations. Because of these differences, discrepancies will occur. However, the trends and patterns are consistent.

Analysis decisions on matters such as how to combine codes or categories, which codes should be considered unknowns and allocated, and how extreme values are handled will impact the results obtained. Such decisions should be clearly documented.

SUMMARY

Analysis of national NFIRS data has been in transition for the past several years as an increasingly large share of each year's data is originally collected in Version 5.0. NFIRS 5.0 is significantly different from earlier versions in its structure and in much of the data collected. The NFIRS database for 1999 through at least 2004 contains a mixture of data from different versions. Trend analyses need to compensate for the changes in the data itself. The data users—fire service, insurers, industry planners, educators, and policy makers—still need the same types of information they had in the past as well as the new information that is now available. Analysts must be sensitive to the differences introduced by changes in the data collection system, but the principles of analysis remain the same.

This chapter has illustrated several techniques for analysis with data collected by NFIRS and other incident data. These techniques include the selection of appropriate data elements for consideration, the combination of data elements, dealing with unknown or missing data, trend analysis, and determining when and how risk of fire can be calculated. Geocoding and the use of other databases with NFIRS are also discussed.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire incident data discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 901, *Standard Classifications for Incident Reporting and Fire Protection Data*
NFPA 921, *Guide for Fire and Explosion Investigations*

SECTION 3

Chapter 5

Introduction to Fire Modeling

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Douglas J. Carpenter ❑ John M. Watts, Jr.

Chapter Contents

Types of Fire Models
Zone Fire Models
Computational Fluid Dynamics (CFD) Models
Probabilistic Fire Models
Fire Modeling Trends

Key Terms

computational fluid dynamics (CFD) model, computer fire model, deterministic model, field model, fire model, lumped-mass model, mathematical fire model, Navier-Stokes equations, network model, physical fire model, probabilistic model, simulation model, statistical model, validation, zone fire model

Modeling is an inherent part of research in science and engineering, and its application to fire is as old as scientific research into fire behavior itself. The first book devoted solely to modeling in fire research was published in 1959.[1] Modern fire research, coupled with the ever-increasing power of computers, has given rise to highly complex models that can only be implemented as computer fire models. Although computer fire models have popularized fire modeling, these computer-based models do not differ substantially from earlier fire models; they are simply more complex and possess greater capabilities.

Computer models are simply computer programs that implement a mathematical model simulating a process or phenomenon. Computer models have been used for some time in the design and analysis of fire protection systems, like sprinkler or gaseous agent suppression systems. Computer models, commonly known as design programs, have become the industry's standard method for designing water supply, automatic sprinkler systems, and gaseous agent systems. These programs perform large numbers of tedious and lengthy calculations and provide the user with accurate, cost-optimized designs in a fraction of the time required by manual procedures.

In addition to the design of fire protection systems, computer models may be used to evaluate the effects of fire on people and property. These computer fire models can provide a faster and more accurate estimate of the impact of a fire and the measures used to prevent or control the fire than many of the methods previously used. Although manual calculation methods provide good estimates of specific fire effects (e.g., prediction of time to flashover), they are not well suited for comprehensive analyses involving the time-dependent interactions of multiple physical and chemical processes present in developing fires.

Perhaps the most important attribute of computer fire models is their ability to predict the relevant fire behavior within their stated limitations. The predictive capability of a model depends on both the underlying scientific understanding of the processes being modeled and the translation of that understanding into a calculation methodology. There remain substantial shortcomings in the scientific understanding of fire and related processes. However, our current level of understanding supports the development of calculations with enhanced predictability. It is not necessary to understand a phenomenon fully in the pure scientific context in order to exploit a lower level of understanding for design and practice purposes. In fact, current models take great advantage of "imperfect" knowledge to yield useful results.

In recent years, increasing attention has been given to the development and use of computer fire models. They have been used by engineers and architects, building officials, the fire service, investigators, building and fire code developers, materials and systems manufacturers, fire researchers,

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and educators. The importance of modeling in its application to fire safety design has been recognized and has grown over the decades; with this widespread application comes a critical need for detailed understanding of the applicability of models to specific problems. There are ongoing issues with the application of modeling to problems for which the selected model is neither appropriate nor validated. The key challenge in the expanded use of modeling is to limit the application to appropriate and validated modeling tools.

The state of the art in computer fire modeling is changing rapidly. Understanding of the processes involved in fire growth is improving and, thus, the technical basis for the models is improving. The capabilities, documentation, and support for a given model can change significantly over a short period of time. In addition, computer technology itself (both software and hardware) is advancing rapidly. In the past, a large mainframe computer was required to use most of the computer fire models. Today, the models can be run on personal computers. Rather than providing an exhaustive discussion of the rapidly changing state-of-the-art computer models, the following discussion will focus on the general capabilities of each of the model types and brief summaries of representative models of each type.

See also Section 3, Chapter 6, "Applying Models to Fire Protection Engineering Problems and Fire Investigations"; Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations"; and Section 3, Chapter 11, "Overview of Performance-Based Fire Protection Design."

TYPES OF FIRE MODELS

The wide range of types of fire models is illustrated in Figure 3.5.1. Models can be classified into two broad types: (1) physical models and (2) mathematical models. Physical models attempt to reproduce fire phenomena in a simplified physical situation. Scale models are a widespread form of modeling, as full-scale experiments are expensive, difficult, and sometimes wholly infeasible. Insights can often be gained by studying fire phenomena at reduced physical scale. Mathematical models are sets of equations that describe the behavior of a physical system. Often the goal of physical models is to uncover laws governing the behavior of physical/chemical systems. The resulting mathematical model can then be used to predict the behavior of real physical systems. Thus, physical and mathematical models are interrelated and complementary.

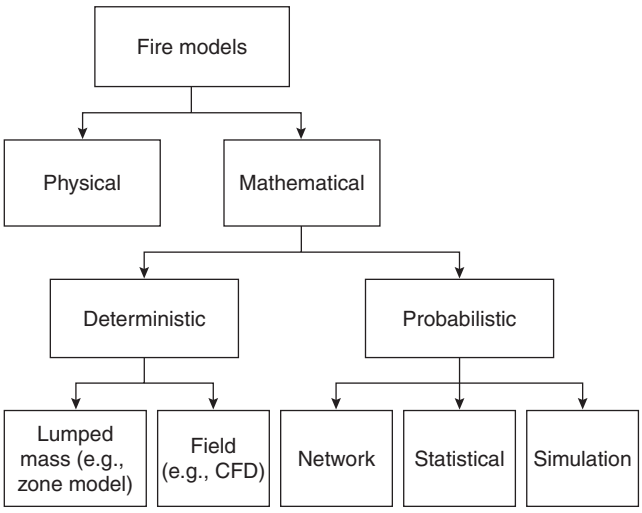

FIGURE 3.5.1 Classifications of Types of Fire Models

Mathematical Models

Mathematical models can be further classified into two classes: (1) *deterministic models* and (2) *probabilistic models.* Probabilistic models attempt to deal with the random nature of fire behavior, whereas deterministic models presume no random variation and, therefore, provide a fixed and precisely reproducible result associated with fire growth and behavior. Both approaches are valuable in understanding fire. Indeed, some probabilistic models include some deterministic modeling algorithms. In most modeling situations, the variability and multiplicity of conditions and scenarios require some form of probabilistic treatment. This may take the form of multiple deterministic modeling runs reflecting the range of conditions and scenarios, or it may explicitly include probabilistic treatment via a risk model.

Deterministic Mathematical Fire Models. Deterministic fire models can range from simple one-line correlations of data to highly complex models requiring weeks of computing time using dozens of computers. The unifying aspect of these models is that the course of a fire is fixed by the variables that establish the environment in which it occurs. The physical conditions that determine the progress and outcome of the fire are called the fire scenario. The fire scenario includes fuels involved, arrangement of the fuels, characteristics of the building and its fire protection systems, location of the ignition, location and capabilities of occupants, and any other variables that affect the fire's outcome. Thus, for all deterministic fire models, formulation of the fire scenario is of critical importance.

An example of a simple mathematical model is an equation describing the relationship shown in Figure 3.5.2.

$$L/D = 0.2(Q^{2/5}/D)$$

where L is the average flame height in meters, D is the diameter of the fire in meters, and Q is the heat release rate in kW. This equation is the result of applying Froude modeling principles. Other equations are available that are applicable at even lower values of L/D.

At the other end of the scale of complexity are models that describe the behavior of fire in one or more rooms (i.e., compartment fire models). These models may be complex because they include many physical/chemical processes or because a few processes are modeled in great detail. These complex models can be further classified into two classes: (1) *lumped-mass models* and (2) *field models.*

The most identifiable lumped-mass model is the *zone fire model.* In this type of modeling a compartment is idealized as containing one or more fire sources and the fire environment

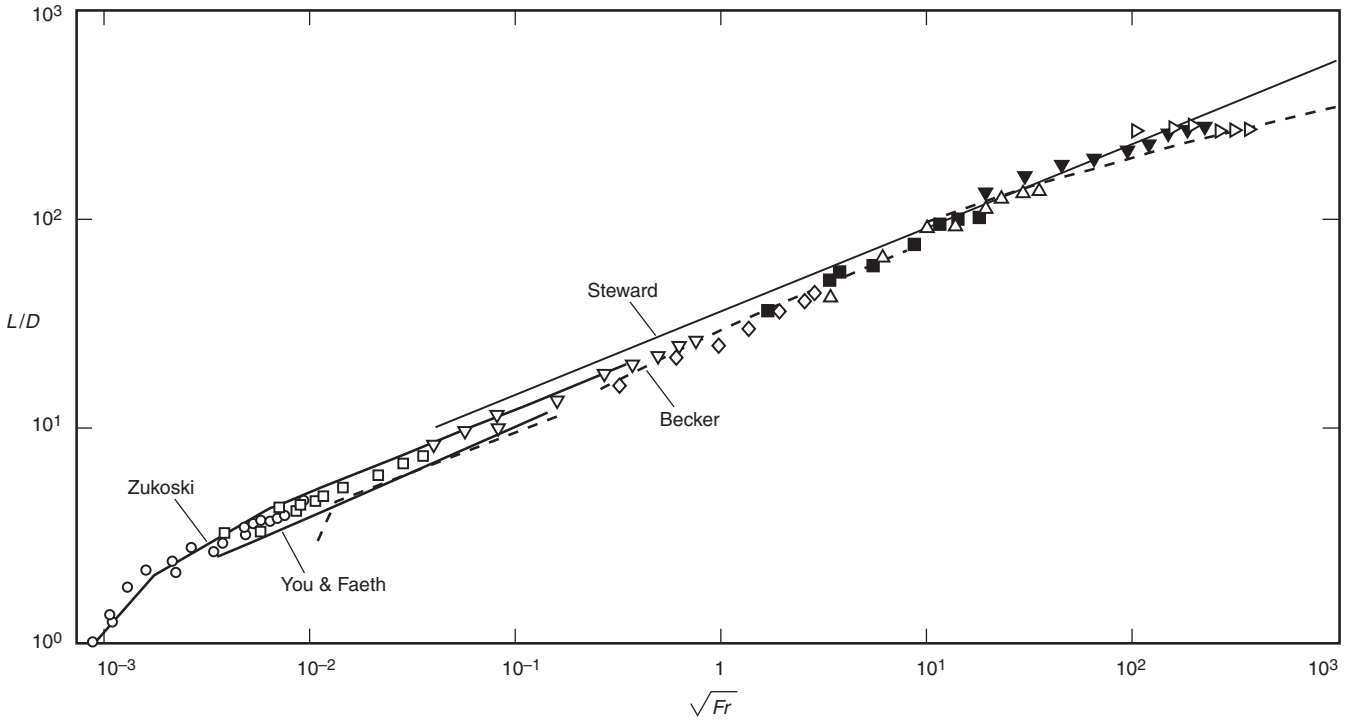

FIGURE 3.5.2 Flame-Height Correlation Model Based on Froude Modeling (Source: McCaffrey[2])

is modeled as one or two discrete volumes or zones. In single-zone models, the fire environment is characterized by a single average temperature and compartment-wide average smoke and gas concentrations. In two-zone models, the fire environment is modeled as an upper layer and a lower layer, each layer characterized by the average temperature and smoke and gas concentrations. These models can incorporate our empirical knowledge of fire phenomena and the calculations focus on the interaction of objects, such as fire sources and layers through equations describing conservation of mass and energy. These models are relatively simple so that very large buildings can be modeled using these techniques.

The most identifiable field model is the *computational fluid dynamics (CFD) model.* The key aspect of field models is the modeling of the structure of objects rather than simply the interaction of objects. So, in a CFD model the structure of the fire environment in terms of temperature and concentrations is spatially resolved throughout the compartment rather than being treated as average quantities as they are in zone models. Because the detailed structure is calculated based on detailed fluid mechanics equations, the CFD solution is more fundamentally based than zone models. However, because our fundamental knowledge of many fire phenomena is absent or at least very limited, the fire phenomena that can be modeled via CFD are also limited. Thus, the choice of model types involves trade-offs in capabilities that must be weighed when facing a specific modeling problem.

Probabilistic Fire Models. Probabilistic fire models can be categorized into three classes: (1) network, (2) statistical, and (3) simulation. Each of these deals with the uncertainties associated with fire growth processes. Network models are fire growth models in which the transition from one fire stage to another and the effectiveness of fire suppression systems, manual fire fighting, passive fire protection, and so on are governed by user-assigned probabilities that are based on historical data, engineering evaluations, or both. In some cases, these probabilities are single values, and in other models, the probabilities are time dependent. Statistical models represent the probability of an occurrence as it is determined from historical data. A classic example of a statistical model is the occurrence of fire alarms. Fire alarms are random events that are, within certain constraints, uniform in nature. That is, a fire or fire alarm might occur at any time with equal probability. Clearly, one of the constraints on this behavior is that the time of day must be controlled. It is well known that fires are a function of the time of day, and so one must restrict attention to a single time of day. Such a statistical model can be very useful in fire protection resource planning. Simulation methods try out different sets of conditions to see how they affect the outcome. Probabilities are often used to weigh outcomes for each set of conditions and produce an overall expected outcome. Simulation models may predict outcomes for a given set of conditions by using other physical, probabilistic, or deterministic models. In the latter case, simulation models regard fires as deterministic once the fire is fully defined. However, the inputs to the models are assumed to follow probabilistic models. Thus, the inputs to the deterministic model are treated as random variables. Such variables might include which furniture item is ignited or how far open the door is when the fire starts. A large series of runs is performed by

selecting inputs from the probabilistic models, and the range and frequency of different outcomes are examined. Such modeling combines elements of both probabilistic and deterministic models. Probabilistic models are taking on increased importance in the fire community in the assessment of risk. Various risk-based methods are under continuing development, most notably in Australia and Canada. These have been applied to building classes, individual buildings, and ships.

Physical Fire Models

Physical models attempt to reproduce fire phenomena in a simplified physical situation. The simplification can involve the scope of the model or the physical scale of the model. Even full-scale fire models are simplifications of the actual scenarios in which the experimenter seeks to include the important aspects of the scenario without introducing unimportant details or aspects. These unimportant details are removed because of the costs of being fully realistic and also because the experimenter seeks to provide findings with some generality. The design of such physical models is critical to the ultimate applicability of the findings.

Scale Modeling. Scale modeling does not simply mean conducting experiments at reduced physical scale. Reducing the linear dimensions of a physical situation and conducting experiments with the reduced-scale model is not sufficient. In addition to geometric scaling, it is necessary to maintain mechanical, thermal, and chemical similarity in the reduced-scale model. The scaling laws required to maintain these similarities can be determined from dimensional analysis or from the fundamental equations describing the physical/chemical phenomena. Like full-scale physical models, reduced-scale models also include simplifications of the physical arrangement to those elements of importance to the goal of the modeling effort.

The most widespread physical scaling laws in fire are known as "Froude modeling," which is applicable to buoyant flows associated with fires. Froude modeling requires that the ratio of buoyant forces to inertia forces be maintained. The Froude number, *Fr,* can be expressed as

$$Fr \sim Q^{2/5}/D \sim V/\sqrt{D}$$

where Q is the fire heat release rate, D the physical scale of the experiment, and V the characteristic velocity of the flowing medium. Thus, if a half-scale experiment is to be performed, the heat release must be reduced to 18 percent of the full-scale heat release in order to maintain the same Fr number and ensure that the flow velocities scale in the half-scale and full-scale models. The velocities themselves scale as the square root of the scale at constant Fr.

Froude modeling has been used successfully to understand plume flows, ceiling jet flows, and flame heights. Flame-height correlation models based on Froude modeling have been successful over a wide range of physical scales. An example is shown in Figure 3.5.2 , which was developed by McCaffrey.[2] The flame height to fire source diameter, L/D, is shown as a function of the $\sqrt{Fr}$. This flame height correlation based on Froude modeling has been successful over 12 orders of magnitude of Froude number, an amazingly wide range of applicability for any correlation or model.

Because different fire phenomena scale differently, it is not generally possible to study complex fires on a small scale. These differences in scale limit the use of scale modeling principles. It is notably difficult to scale convective flows and radiation at the same time. Thus, Froude modeling cannot be applied readily to fire problems where radiation is important, for instance.

Scale modeling using Froude scaling laws has been most successful in addressing smoke movement issues. Two techniques have found important applications: (1) reduced-scale gas-phase modeling and (2) saltwater modeling. The principles of these modeling techniques have been reviewed by Quintiere.[3] Saltwater modeling uses the discharge of high-density saltwater into freshwater as an inverse simulation of buoyant flows. This technique has been used successfully in both single compartments and multiple-compartment enclosures. The use of scale modeling in the design of smoke management systems is embraced by NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces.*

Non–Scale Modeling. Physical modeling does not always involve major reductions in physical scale. Physical models may simply seek to simplify complex phenomena into a manageable and understandable problem. Examples of this type of physical modeling can be found as far back as the ASTM E119 fire resistance test. The ASTM E119 time-temperature curve shown in Figure 3.5.3 was selected as a representative time-temperature curve for testing structural assemblies. The E119 fire resistance test is a form of physical modeling. The furnace environment is intended to model the fire environment experienced by structural members in a fire. The portions of the building structure exposed in an E119 furnace are intended to model the fire behavior of the

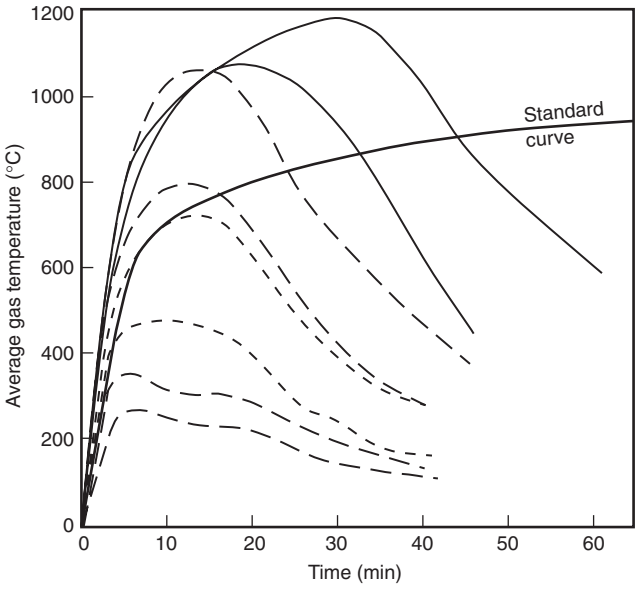

FIGURE 3.5.3 Representative Time-Temperature Curve (Source: ASTM E119)

building structure in a fire. No single time-temperature exposure can represent all fires, and testing portions of building structures does not fully represent the behavior of the structure, but the results of the simplified E119 test are useful nonetheless. Over the decades the value and the limitations of this widespread physical model have been learned.

In addition to physical models of systems, physical models of material behavior or response are available. The most identifiable example of such a physical model is the cone calorimeter.[4] This test method provides a well-controlled and well-known heating environment to which a material is exposed. The response of the material in terms of time to ignition, mass loss rate, heat release rate, smoke production, and gas generation rates are measured. This provides material data that can be employed as a relative measure of the fire performance of a material or can be used as inputs to mathematical fire models.

All standard fire tests are physical models of fire behavior. The adequacy of these physical models varies widely. There is a trend in the development of modern fire test methods to consider explicitly the adequacy of the test method as a physical model of actual fire behavior and response to fire.

Surveys have been conducted that provide a summary of the available fire models.[5,6] The most widely used lumped-mass models are known as zone models, whereas the most widely used field models are CFD models. These widely used model types are discussed in more detail in the following sections.

ZONE FIRE MODELS

Fire environment in a room is quite complex. Major insights into fire behavior have been achieved by a simple conceptual construct called zone modeling. In essence, a zone model assumes that the compartment may be idealized as consisting of uniform conditions in single or multiple regions or zones. In a two-zone model, these regions are (1) an upper region, filled with hot combustion gases, and (2) a lower region, filled with cooler, more nearly ambient air. Each region or zone is idealized to have uniform temperatures and gas concentrations. The plane dividing the two zones is the hot layer interface that may move vertically during a fire. Figure 3.5.4 shows a comparison of the temperature profile in a room fire with the idealized zone model equivalent. In one case, the zone model concept matches reality quite well; in the other, differences are clearly seen. Gas concentrations are idealized in the same way.

The two-zone model concept simplifies the room fire thermal environment to two temperatures and an interface height rather than a three-dimensional temperature field. Major simplifications are realized both mathematically and computationally. These simplifications have made many fire problems tractable and have allowed significant progress to be made.

In addition to two-zone models, there is widespread use of single-zone models in large buildings or ships. These models represent a large building with each compartment as a zone and model the movement of smoke between compartments throughout the structure. These models are designed to model complex ventilation systems that two-zone models have great difficulty modeling reliably. Smoke management systems in large buildings are routinely designed using such models. These models are also being developed to include many of the fire phenomena included in two-zone models with the goal of allowing modeling of the spread of smoke, heat, and fire through a complex building or ship.[7]

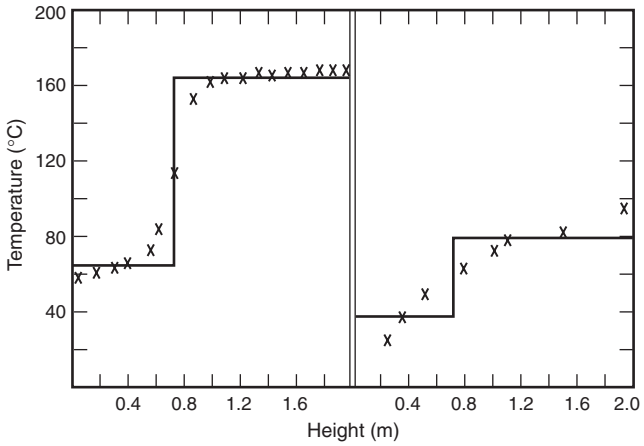

FIGURE 3.5.4 Comparison of the Temperature Profile in a Room Fire with the Idealized Zone Model Equivalent

Of course, in all zone models additional components are needed to specify fully the fire environment. Vent flows, plume entrainment, heat transfer, and combustion models are needed. Even if each of the component submodels is fairly simple, the result when coupled together is a complex model requiring computers for efficient, practical calculations.

Zone models by definition will always be approximate. The key is whether the predictions are "close enough" to yield significant insight for the situation under study. Zone modeling yields useful insight into many fire problems. There is a reasonable amount of validation test data available for comparison to models with one or with up to six compartments with length scales of 10 ft (3.05 m) connected via a corridor and modest (less than 1055 Btu/sec [1000 kW]), well-characterized fire. An excellent summary of the underlying assumptions of zone modeling is given by Quintiere.[8]

The following discussions attempt to briefly describe the current status and near-term possibilities for modeling some important phenomena. No one model is assumed; rather, the discussion summarizes the integrated capability of common zone models.

Ignition

Both piloted and unpiloted ignition due to radiative heating can be approximated. Small-scale ignition test data can be used.[4]

Burning Behavior

The burning behavior of a single fuel item cannot currently be predicted. The treatment of this obviously important subphenomenon in models is done through empirical correlations and/or large-scale test data. Approximations using small-scale tests

are possible. A more fundamental treatment is currently available for modeling the fire growth on interior finishes,[9] but these have yet to be generalized to other combustible objects found in compartments. Empirical methods, small-scale and large-scale data, and "design basis" fire assumptions will continue to form the basis of most zone models.

Flame Spread

Flame spread modeling on interior surfaces has recently been a very active area of model development. Flame spread models use the inputs from small-scale tests, such as the cone calorimeter and the LIFT apparatus, to predict the spread of flame and heat release rate in wall and corner fires. These models are beginning to be incorporated as submodels into zone fire models.[9] It is expected that the concepts developed in this work will be used in tackling the more difficult problems of flame spread and heat release rate prediction for individual fuel items.

Compartment Effects

Energy Balance. Zone-type approximations are being improved with the inclusion of plumes or ceiling jets as subzones. Heating of a ceiling in the vicinity of a flame or plume can be calculated. Enhanced radiation levels can be estimated, but it is not generally possible to predict the effect on the behavior of burning materials throughout the volume of a compartment fire.

Walls and Corners. Current methods used in most zone models to approximate the impact of walls and corners on plumes, flame heights, and ceiling jets are limited. Most available zone models do not include the full scope of our understanding of plumes in corners or against walls that is available in the *SFPE Handbook of Fire Protection Engineering.*[10]

Oxygen Starvation. The role of oxygen concentration is currently treated by use of heuristics involving a minimum oxygen concentration required for burning.

Multiple Room Fire and Smoke Spread

There are several models that treat smoke spread through multiple compartments using either a one-zone or two-zone approximation. Depending on the problem under analysis, this approach may yield acceptable results. The available validation data for multiple-room scenarios are limited.

Fire spread is currently limited to remote ignition of remote objects by heating from flames and the hot layer. Fire spread to multiple compartments is in principle predictable, though most zone models do not predict room-to-room fire spread.

Forced Ventilation

Several two-zone models have attempted to treat forced ventilation under simple vent configurations. There appear to be major unresolved technical issues in modeling forced ventilation in multicompartment two-zone models, which preclude effective modeling for many cases. Single-zone models are able to model complex forced ventilation systems.

Postflashover Predictions

The onset of flashover in a compartment poses a difficult prediction problem. Major unresolved technical problems include prediction of a radiation-enhanced burning rate; prediction of CO production in underventilated conditions; ignition of hot layers; burning at vents; and flame spread down corridors.[11,12]

There is one area where postflashover fires are well characterized. The prediction of temperature as a function of time for calculating the fire resistance of a structure is well developed. Design approaches using postflashover models are accepted alternatives to prescriptive fire resistance requirements in several countries. However, these successes are in single-zone models. Two-zone models, such as CFAST, tend to overpredict temperatures in postflashover compartment fires, especially for large vent openings.[11] The model is capable of producing predicted layer temperatures in excess of any experimentally measured layer temperature found in the literature.

Detection System Activation

Procedures exist for estimating the response of ceiling-mounted heat detectors via heating by a plume or ceiling jet. These calculations have been relatively well established for flat, smooth ceilings, with more limited validation for compartments with high ceiling heights or nonsmooth, nonflat ceilings.

Methods also exist for estimating smoke detector response to flaming fires.[13] The use of these models has been limited by the unavailability of the detector-specific parameters. Calculation methods exist for detector activation where a layer has formed. No procedures currently exist for estimating the activation of detectors in situations where the detector responds before a well-developed plume or ceiling jet forms or where mechanical ventilation appreciably perturbs the flow. Incremental progress is expected in this area in the near and moderate term.

Suppression Modeling

Fire suppression with a total-flooding gas system and with a water mist system has been successfully modeled.[14,15] Although there is research in modeling the suppression of fires by sprinklers,[16] no generally applicable design or analysis procedures are expected in the near future.

Fire Effects Modeling

Heat Damage. If the temperature threshold of a piece of equipment or material is known, standard heat transfer calculations can be used in conjunction with fire models to estimate the time dependence or degree of damage.

Smoke Damage. Estimates of smoke damage that reflect the sensitivity of the equipment exposed and type of smoke or fire involved are not generally available. Such calculations involve uncertainties associated with cold smoke transport and deposition, prediction of smoke production and properties, wide variability of smoke properties, and sensitivity of equipment to this wide variation of smoke types.

Human Interaction

Visibility. Limited experimental data on visibility combined with small-scale, constant-yield smoke concentration and optical property measurements enable rough estimates of human visibility in smoke. Using the results of computer models for smoke, layer depth, and smoke properties, approximate visibility estimates can be made.

Temperature/Radiation. Effects of heat and radiation can be estimated using empirical human tenability data.

Toxicity. Toxic effects of CO, CO_2, HCN, and oxygen depletion can be reasonably predicted using N-gas modeling approaches.[17] The effects of gases such as HCl, HF, or HBr can be estimated, but with a lower level of confidence. Bioassay methods can be used to screen for so-called paper-toxicant fire products where their existence is suspected.

The legitimate application of models to problems outside of the relatively narrow ranges discussed previously is possible and occurs frequently. If the results of the calculations do not require great accuracy (e.g., ±50%), the important physics of the problem is reflected in the model, and/or the results are used for approximate comparative purposes, these tools can be used in a much broader range of problems.

Overview of Selected Zone Models

ASET. ASET (Available Safe Egress Time) is a program for calculating the temperature and position of the hot smoke layer in a single room with closed doors and windows.[18] ASET can be used to determine the time to the onset of hazardous conditions for both people and property. The required program inputs are the heat loss fractions, the height of the fuel above the floor, criteria for hazard and detection, the room ceiling height, the room floor area, a heat release rate, and a species generation rate of the fire (optional). The program outputs are the temperature, thickness, and (optional) species concentration of the hot smoke layer as a function of time and the time to hazard and detection. ASET can examine multiple cases in a single run. ASET-B is a compact version of ASET designed to run on personal computers. Species concentrations and time to hazard and detection calculated by ASET are not calculated in the compact ASET-B version.

CFAST. CFAST (Consolidated Model of Fire Growth and Smoke Transport) is a multiroom fire model that predicts the conditions resulting from a user-specified fire within a structure.[12] The required program inputs are the geometrical data describing the rooms and connections; the thermophysical properties of the ceiling, walls, and floors; the fire as a rate of mass loss; and the generation rates of the products of combustion. The program outputs are the temperature, species concentrations, and thickness of the hot upper layer and the cooler lower layer in each compartment. Also given are surface temperatures, heat transfer, and mass flow rates. CFAST has very limited mechanical ventilation capabilities and can accommodate multiple fires, sprinklers, and detectors. FAST provides the data-editing and reporting tools for the CFAST model.

LAVENT. LAVENT (Link-Actuated VENT) is a two-zone model developed to simulate the environment and the response of sprinkler links in compartment fires with draft curtains and fusible-link-actuated ceiling vents.[19] The model used to calculate the heating of the fusible links includes the effects of the ceiling jet and the upper layer of hot gases beneath the ceiling. The required program inputs are the geometrical data describing the compartment, the thermophysical properties of the ceiling, the fire elevation, the time-dependent energy release rate of the fire, the fire diameter or energy release rate per area of the fire, the ceiling vent area, the fusible-link response time index (RTI) and fuse temperature, the fusible-link positions along the ceiling, the link assignment to each ceiling vent, and the ambient temperature. A maximum of five ceiling vents and ten fusible links are permitted in the compartment. The program outputs are the temperature, mass and height of the hot upper layer, the temperature of each link, the ceiling jet temperature and velocity at each link, the radial temperature distribution along the interior surface of the ceiling, the radial distribution of the heat flux to the interior and exterior surfaces of the ceiling, the fuse time of each link, and the vent area that has been opened.

CONTAM. CONTAM[20] is a single-zone model originally designed to track the movement of nonfire contaminants through a building. In includes extensive HVAC system model components and includes stack effect flows. Fire smoke sources can be modeled, though the temperatures in the building are set solely by the user, rather than being calculated as is done in most fire models. This modeling approach has been applied to the tallest buildings in the world to evaluate the potential for smoke movement and to design smoke management systems. Calculations are quite rapid, even for the largest buildings.

FSSIM. FSSIM[7] is a single-zone model originally designed for fire hazard analysis of ships. It includes most of the features of the popular two-zone models but within a single-zone fire environment description. It includes extensive HVAC system model components, stack effect, prediction of compartment temperatures, smoke and gas concentrations, as well as compartment-to-compartment fire spread, detection, and suppression. It has been applied to ships and buildings with several thousand compartments. Calculations are slower than CONTAM but still much faster than two-zone models and CFD models.

COMPUTATIONAL FLUID DYNAMICS (CFD) MODELS

Computational fluid dynamics (CFD) models avoid the simplifications inherent in zone models. The physical aspects of any fluid flow are governed by three fundamental principles: (1) mass is conserved; (2) Newton's second law [force = (mass) × (acceleration)]; and (3) energy is conserved. These fundamental principles can be expressed as generalized mathematical equations in the form of integral or partial differential equations and are generally referred to as the Navier-Stokes equations. Anderson[21] provides an excellent discussion of the governing equations for those who have no prior knowledge of CFD.

The Navier-Stokes equations are a coupled system of nonlinear partial differential equations and are difficult to solve analytically. To date, there is no general closed-form solution for the fully turbulent, time-dependant Navier-Stokes equations. Thus, the solution to these equations requires appropriate numerical methods. CFD is the technique of replacing the integrals and partial derivatives with discretized algebraic forms, which are solved to obtain numeric values at discrete points in time and/or space. Using an appropriate solving technique, the CFD model solves the fundamental equations of mass, momentum, and energy at each grid point in the computational domain that has been divided into a number of grid points that produce small elements. Imagine an enclosure filled with a three-dimensional grid of tiny cubes; a CFD model will calculate the physical conditions in each cube as a function of time. The CFD model program uses an iterative solver to calculate the physical changes in the cube at the current time step as a result of physical changes in the surrounding cubes from the previous time step. Depending on the size of the cubes, this model permits the user to determine the conditions (e.g., temperature, velocity, gas concentrations) at almost any point in the computational field.

CFD programs require substantial computational effort. More importantly, they require sophisticated users due to the complexity of defining initial and boundary conditions. CFD modeling programs have direct and immediate potential application to problems driven largely by fluid mechanics. Such problems include far-field smoke flow, details of flow and heat transfer to complex geometries, and impact of fixed ventilation flows on buoyancy-driven flows. Although the general problem of flame spread cannot yet be predicted with existing CFD models, significant progress has been made. At this time, modeling of combustion and the resulting heat fluxes seem to be the most difficult aspect of the problem. Applications of CFD models to fire problems have included aircraft terminals and atria, air-supported structures, power plants, aircraft cabins, tunnels, hospital wards, high-rack storage, and shopping malls.[22–30]

CFD and Turbulence Modeling

For turbulent and time-dependent flows, the generation and decay of turbulent energy within the fluid flow must be included in the model. The turbulent transport process cannot be calculated with an exact method in practical applications since the governing equations cannot account for turbulence at length scales smaller than the length scale of the computational cells; thus, it must be approximated. Various approaches for the modeling of turbulence using the CFD technique are described next.

Direct Numerical Simulation (DNS). By definition, DNS captures all of the relevant scales of turbulent motion, so no model is needed for the smallest scales. This approach is extremely computationally expensive, if not intractable, for complex problems on modern computing machines, hence, the need for models to represent the smallest scales of fluid motion that are less than the scale of the computational domain.

Reynolds-Averaged Navier-Stokes (RANS). RANS is the oldest approach for simulation of turbulent flows. In this approach, transport equations are solved for time averaged flow variables along with (zero, one, two, or more) transport equations for turbulence variables such as turbulent kinetic energy and its dissipation rate. All RANS models make the assumption that the time-varying velocity components can be represented by the sum of a mean and a fluctuating component. These equations are averaged over a time scale. This methodology is appropriate only when capturing unsteady flow behavior occurring over time scales at least an order of magnitude larger than the scales of the turbulent fluctuations. This modeling approach is not generally the most suitable for buoyant flows, which most often dominate in fire problems.

Large Eddy Simulations (LES). LES is a technique in which the smaller eddies are filtered and are modeled using a subgrid scale model, whereas the larger energy-carrying eddies are directly simulated. LES modeling involves resolving the time and space variations of the largest of the turbulent structures or eddies. With this approach the time averaging of the large eddies is not introduced, so transient behavior can be captured more faithfully. This method generally requires a more refined mesh than a RANS model but a far coarser mesh than a DNS solution.

CFD model calculations can be executed on desktop personal computers or a network of processors. From a practical standpoint, more extensive model domains may require multiple computer processors configured for parallel processing. Figure 3.5.5 shows an example of a CFD model prediction for the gas velocity in a compartment fire. The figure shows the cross section of a compartment with the door to the right of center and a fire near the floor to the left. The arrows represent the predicted gas velocity with the arrows pointing in the direction of gas flow and the speed of the flow indicated by the length of the arrows. The prediction shows air entering the lower level of the compartment to the right, rising in the fire, and flowing under the soffit as it leaves the compartment.

Overview of Selected CFD Models

Fire Dynamics Simulator (FDS). FDS allows for "Direct Numerical Simulation" or "Large Eddy Simulations (LES)" of fire effects.[31,32] The LES approach most readily lends itself to solving the types of fire problems typically found in fire engineering design and forensic applications. LES uses a low Mach number approximation for the Navier-Stokes equations and a formulation of the complex governing equations to provide a very efficient solution. Under the LES mode, the user inputs the parameters of the fire in terms of heat release rate and species generation. Although FDS includes algorithms for flame spread, burning rate, and suppression, these have not been developed and validated so as to allow their application to problems in these areas. FDS calculates the temperature, pressure, species concentrations, and flow field in relation to the prescribed fire. FDS provides for calculating the activation of heat detectors and sprinklers. In addition, the sprinklers can dispense droplets, which yield evaporative cooling and prewetting. The model supports prediction of multiple sprinkler activations. FDS also has the built-in capability of predicting the response of smoke detectors[31] based on the work of Desouza et al.[33] The major

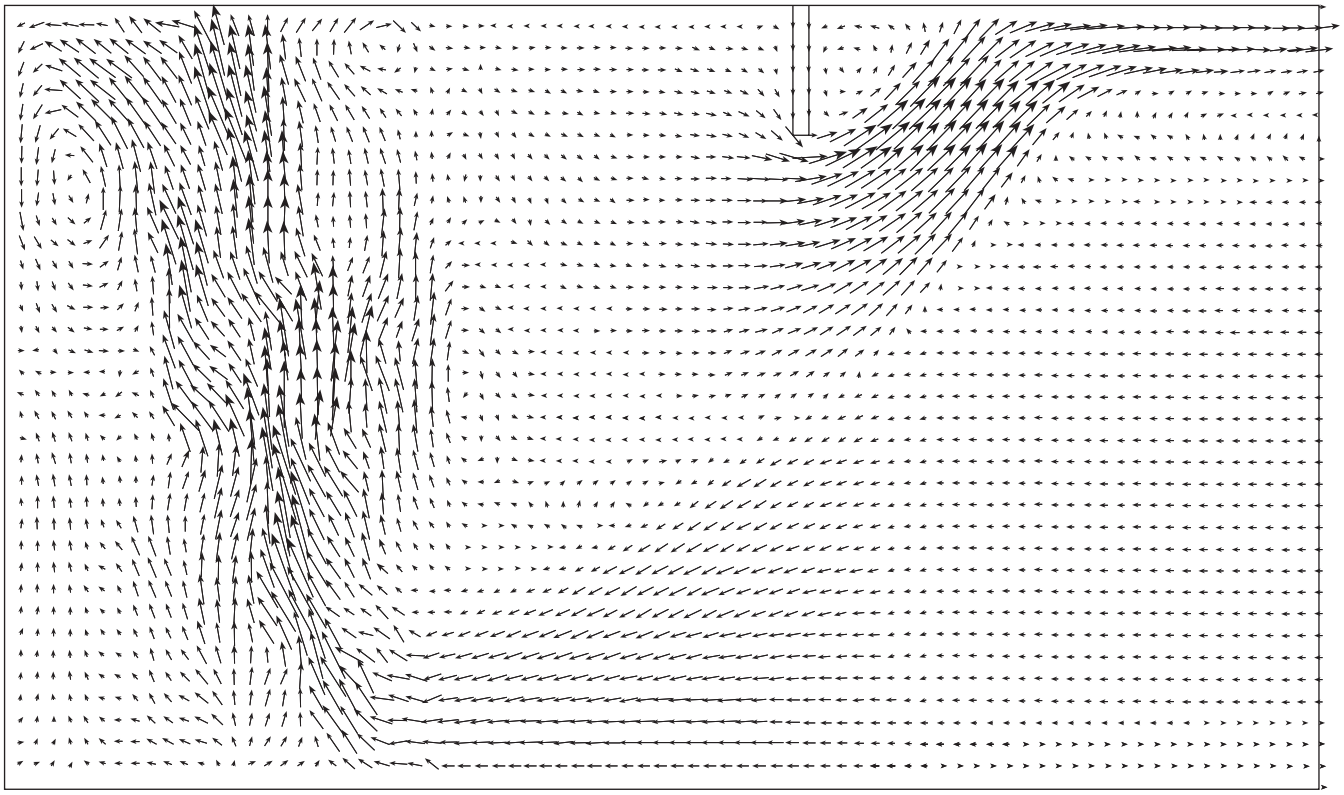

FIGURE 3.5.5 CFD Model Prediction of Gas Velocity in a Compartment Fire

geometric limitation of FDS is its exclusive use of rectilinear computational meshes, which effectively limits the model to "stair stepped" approximations for curved or sloped geometries. Although there are commercial CFD packages that allow better definition of realistic geometries, these are much less efficient and there has been limited validation of commercial CFD codes for use in fire applications. Heat transfer is treated as one-dimensional and is calculated by using thermally thin or thermally thick elements, but heat is not conducted through wall portions to other parts of the domain. The model also supports heat-activated vents that "open," allowing flow through the vent. Smokeview[34] is the companion software that is designed to visualize the numerical predictions generated by FDS.

Reynolds Averaged Navier-Stokes (RANS) Models. There are many commercially available CFD models. These general-purpose CFD models are designed to solve a wide range of flow phenomena including steady and transient, laminar and turbulent, and incompressible and compressible. Model features include heat transfer (convection, conduction, and radiation), mass transfer and chemical reaction (including combustion), porous media, scalar transport equations, discrete particle transport, multiple fluid streams, and multiphase flows. Commercial codes include graphical user interfaces (GUI) to aid the user in mesh generation, variable input, and postprocessing of results. These codes allow for body-fitted coordinates, structured and unstructured grids, as well as adaptive and moving grids. Output displays of variables include perspective views, contour mapping, vector diagrams, particle tracks, and gradients. The most widely used commercially available and general-purpose CFD codes for the simulation of combustion and fire include STAR*CD, Fluent, and CFX.

Special-Purpose Models

Fire Dynamics Tools (FDT). FDT is a suite of spreadsheets developed by the Nuclear Regulator Agency to support first-order field evaluations of potential hazards in commercial nuclear power plants. Calculations range from simple correlations to models to predict heat detector operation and the heating of bare steel.[35] The spreadsheets are available online at http://www.nrc.gov.

DETACT. DETACT-T2 (DETector ACTuation-Time squared) is a program for calculating the actuation time of thermal devices below unconfined ceilings.[36] It can be used to predict the actuation time of fixed-temperature and rate-of-rise heat detectors and of sprinkler heads subject to a user-specified fire that grows as the square of time. DETACT-T2 assumes that the thermal device is located in a relatively large area; that is, only the fire ceiling flow heats the device, and there is no heating from the accumulated hot gases in the room. The required program inputs are the ambient temperature, the response time index (RTI) for the device, the activation and rate-of-rise temperatures of the device, the height of the ceiling above the fuel, the device spacing, and the fire growth rate. The program outputs are the

time to device activation and the heat release rate at activation. DETACT-QS is a program for calculating the actuation time of thermal devices below unconfined ceilings.[37] It can be used to predict the actuation time of fixed-temperature heat detectors and sprinkler heads subject to a user-specified fire. DETACT-QS assumes that the thermal device is located in a relatively large area; that is, there is no accumulated hot gas layer in the room so only the fire ceiling flow heats the detection device. The required program inputs are the height of the ceiling above the fuel, the distance of the thermal device from the axis of the fire, the actuation temperature of the thermal device, the response time index (RTI) for the device, and the rate of heat release of the fire. The program outputs are the ceiling gas temperature at the device location and the device temperature both as a function of time and the time required for device actuation.

PROBABILISTIC FIRE MODELS

Because it plays such a big part in daily life, most people have some idea of what probability is about. They know it involves weighing the chances, or likelihood, that something will take place. They often hear, or make statements, such as, "It is likely a fire will start there"; "We have a better chance of controlling the fire if we can ventilate"; "Sprinklers have a very good probability of success." Such statements refer to situations in which the outcome is not certain but in which one has some degree of confidence that the statement will be correct. The theory of probability provides a mathematical framework for such statements.

Occurrence of fires, aspects of fighting fires, and sprinkler performance are repetitive operations, repeated often under similar circumstances. The percentage of times a certain outcome occurs, under the same conditions, will always remain approximately unchanged, only rarely deviating significantly from some average figure. It can, therefore, be said that this average figure is a characteristic measure of the given repetitive operation under prescribed conditions. Knowledge of such measures is very important as it enables us not only to describe the outcome of repetitive operations that have already occurred but also to predict the outcome in the future. There are more sophisticated definitions of probability that vary according to application. Detailed treatment can be found in the *SFPE Handbook of Fire Protection Engineering*[38] and in basic texts on probability.[39,40]

Applying probability to fire problems, the assignment of measures and the analysis of logical possibilities may, at times, depend on masses of data that are best obtained, analyzed, and interpreted by professional statisticians. At other times, the task depends more on qualitative knowledge and judgment of facts with which the fire protection professional is most familiar and is, therefore, the person best qualified to assign measures and analyze logical possibilities. Often a combination of objective fact and subjective judgment is the best source of information in assigning probabilities.[41]

Dealing with Uncertainty

Fire protection has significant uncertainty associated with most decisions. The concept of safety itself is one of uncertainty. There is no such thing as absolute safety; therefore, human activities will always and unavoidably involve risks. The concept of fire is also uncertain. Unwanted combustion is the least predictable common physical phenomenon. Reliability of manufactured, or fabricated, systems for suppression and confinement is another source of uncertainty. Reliability analysis is itself a concentrated area of study that uses probabilistic models such as fault trees to quantify the time-dependent failure of a system.[42]

Having a measure for probability is important to be able to deal with situations involving chance or uncertainty. There are many cases, when knowing the probabilities of certain events, it is useful to find the probabilities of more complicated ones. It would be inconvenient to search for a particular method of solution for each new problem of this sort that is encountered. Science tries to form general rules, the knowledge of which would readily permit one to solve mechanically, or almost mechanically, individual problems that are similar to one another. In the area of repetitive phenomena, the science that formulates such general rules is called probability. Probability theory is a branch of mathematics and, therefore, involves precise reasoning and uses formulas, tables, diagrams, and so on as its tools.

Types of Probabilistic Fire Models

Probabilistic models recognize variables as having a degree of randomness, which is more realistic than simple deterministic models and is especially useful when evaluating fire risk, since risk, by definition, includes the uncertainty of loss. There are many forms of probabilistic models. Complex models may involve both deterministic and probabilistic components. When a probabilistic model is a function of time, it is commonly referred to as a *stochastic model.* In this section we introduce three types of probabilistic models that can be used independently or as part of a more comprehensive fire risk analysis. They are networks, statistical models, and simulation.

Network Models

A network model is a graphic representation of paths, or routes, by which objects, energy, information, or logic may flow, or move, from one point to another. Network models are useful for minimizing the time or distance of travel from point to point and have many applications in solving complex problems. The connected points in a network are called nodes. The connections themselves are called links, arcs, or branches. The simplest network is two nodes connected by a single link (Figure 3.5.6).

A path is a sequence of links connecting two nodes and usually passing through other nodes. In driving from Los Angeles to New York, for instance, one might go through Denver and St. Louis. The cities could be considered nodes and the roads

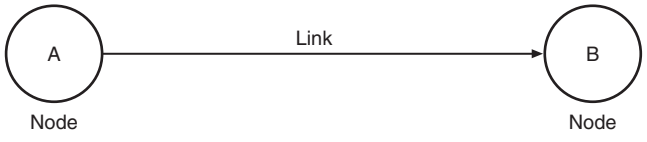

FIGURE 3.5.6 Network Components

between them links. Then one path from Los Angeles to New York would consist of the links connecting the intermediate cities. A significant advantage of a graphic model like a network is the qualitative representation of the structure of the problem or system. Such a diagram functions as a visual aid to help convey an intuitive understanding of the process for obtaining and using probabilities.

The term *tree* is used to describe a special type of network in which there is only one path connecting any two nodes. The simplest probability model, and one of the most powerful, is the event tree. Event trees model the sequence of possible states of a system and of corresponding events that lead to those states. Nodes represent events, and the links between them show how one event leads to another. Figure 3.5.7 shows a simple event tree. The tree proceeds chronologically, left to right, showing events as they occur in time.

By assigning probabilities to the outcome of each event, the tree can be used to calculate the probability of the consequences. For example, given that a fire occurs, consider the example likelihood of events as shown in Table 3.5.1.

Assuming the events are independent, the probabilities along each path are multiplied. Thus, looking at the outcome represented by the uppermost path, "Very large consequence," the probability of this path is

$$(1 - 0.7)(1 - 0.9)(1 - 0.8) = (0.3)(0.1)(0.2) = 0.006$$

Subsequently, the example probabilities for each consequence can be estimated as shown in Table 3.5.2.

Using this model, one can examine conditions such as the effect of a smoke detector to assist occupants in the discovery of a fire, the impact of automatic suppression, and the need to alert the fire department.

Other types of network models applicable to fire protection problems include fault trees,[42,43] evacuation diagrams, and system dynamics. Network models have been used in a wide variety of fire safety applications.[44,45] These model forms and others are explained more fully in textbooks on the subject.[46,47]

Statistical Models

The fields of probability and statistics are closely linked. Most statistical concepts, such as sampling protocol and hypothesis testing, have their basis in probability theory. Statistical modeling involves the description of random phenomena by an appropriate probability distribution.

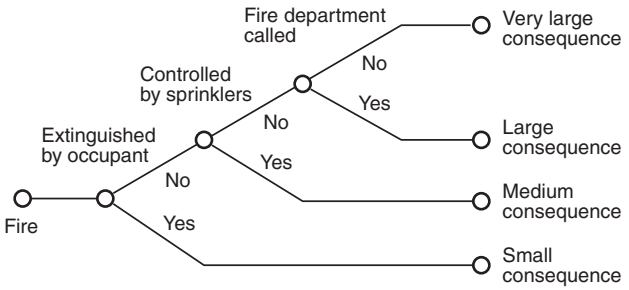

FIGURE 3.5.7 Event Tree

TABLE 3.5.1 Example Likelihood of Events

Event	*Probability of Success*
Extinguished by occupant	0.7
Controlled by sprinklers	0.9
Fire department called	0.8

TABLE 3.5.2 Example Probability of Consequences

Consequence	*Probability*
Very large	0.006
Large	0.024
Medium	0.270
Small	0.700

A probability distribution may be thought of as a mathematical function that defines the probability of an event. For example, the probability distribution that describes the roll of a die is

$$P(x) = 1/6$$

where $x = 1, 2, 3, 4, 5,$ or 6. All the possible outcomes, 1 through 6, have an equal probability of 1/6, which is called a uniform distribution. Another example of a uniform distribution is the outcome of a spin of a roulette wheel, which can be modeled mathematically as $P(n) = 0.0263158$. This equation indicates that the probability of any possible outcome, n (the numbers 1 through 36 plus 0 and 00), is 1/38 or 0.0263158. All models have underlying assumptions. In the roulette model, a perfectly fair wheel is assumed. If one chooses not to accept this assumption, then it becomes necessary to collect a lot of statistical information about the roulette wheel to calculate the individual probability of each outcome.

In addition to the uniform distribution where each outcome has the same probability, there are many other probability distributions used to describe many different types of random events. An example using historical data on fire calls is shown in Table 3.5.3. The first column shows the number of calls that might be received in any one day, and the second column shows the number of days with that many calls. The data are from a 4-month period consisting of a total of 443 calls in 123 days.[48]

Charting the data, as shown in Figure 3.5.8, reveals a trend. The frequency starts out low, increases rapidly, decreases rapidly, and then tails off toward higher numbers of calls. If more data were collected, this trend would be "smoother." A Poisson distribution can mathematically describe the shape of this trend.

The Poisson distribution is widely used to describe random events having a large opportunity to occur but a small likelihood that any one of these opportunities will actually result in an occurrence. This accurately fits the description of fire incidents.

TABLE 3.5.3 Number of Days Having a Specified Number of Calls for Service[48]

Number of Calls for Service per Day (n)	*Number of Days Having* (n) *Public Service Calls*
0	6
1	8
2	24
3	22
4	31
5	14
6	7
7	8
8	0
9	0
10	1
11	0

Mathematically, the probability of k fire alarms occurring over the period s is given by

$$P(k) = \frac{(\lambda s)^k}{k!} e^{-\lambda s}$$

where λ is the mean frequency of fire alarms. This statistical model describes the probability of a given number of alarms, k, occurring during a specified period of time, s.

Other probability distributions used to model aspects of fire protection include the familiar normal distribution and the less familiar lognormal distribution. The normal distribution (Figure 3.5.9) finds wide application in describing biological phenomena, such as human height and IQ. It also applies to characteristics such as shoulder width and walking speed to exits.

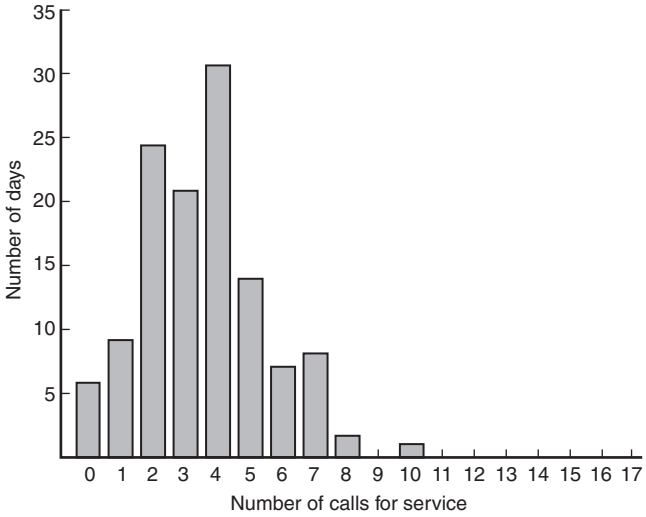

FIGURE 3.5.8 Distribution of Public Service Calls (Source: National Institute of Standards and Technology)

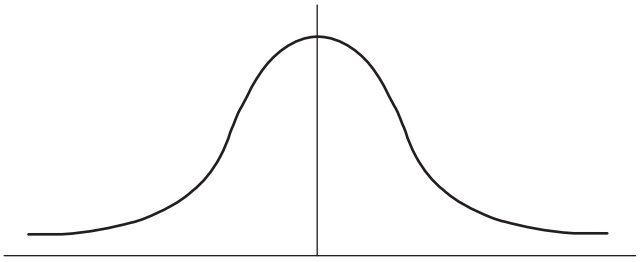

FIGURE 3.5.9 Normal Distribution

The lognormal distribution (Figure 3.5.10) is skewed like the Poisson distribution. It has been shown to describe fire load in offices.[49]

The exponential distribution is often used as a model of fire growth,[50] and the extreme value distribution is used to characterize fire loss.[51] More sophisticated statistical models use principles of the probability theory to combine probability distributions of two or more random variables.[52,53]

The event tree model in Figure 3.5.7 assumed that the probability of each event is the output of a simple binomial distribution similar to tossing a coin [$P(x) = ½$] but, in this case, the outcomes are not equiprobable. Data might show that the likelihood of a fire being extinguished by the occupant is a function of the time of day, for example, when the occupant is home and alert. A statistical model of this probability could be incorporated into the calculation of the consequences in the network.

More details of statistical modeling can be found in basic texts[39,40] and in the *SFPE Handbook of Fire Protection Engineering*.[54]

Simulation Models

Often the relevant variables in a decision problem are too numerous or the interactions too complex to be handled mathematically. One way to deal with such problems is by computer simulation. Simulation models try out different sets of conditions to see how they affect the outcome. In a flight simulator, an airplane pilot tries various maneuvers to see which work and which do not without risking life or the loss of an airplane. The

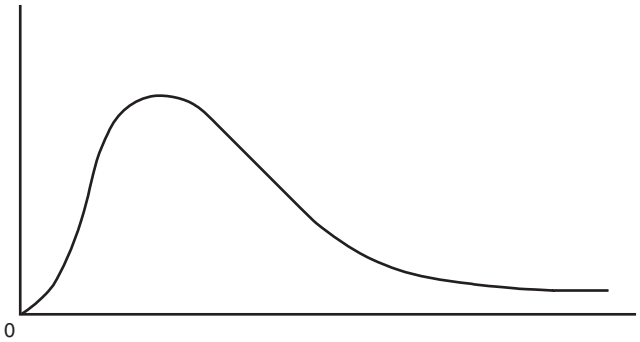

FIGURE 3.5.10 Lognormal Distribution

operation of an airplane is "simulated" by the electromechanical training device. Although there are many types of simulation, the most common form of computer simulation of systems and events is Monte Carlo.

Monte Carlo simulation uses mathematical models to predict the range of outcomes from probabilistic situations by condensing time (or some other variable). For example, a year of activity can be simulated in a few seconds of computer time. Considering the roulette wheel, letting the computer select a random number from 1 to 38 would simulate a spin of the wheel. Using the computer, the wheel can be "spun" thousands of times in a fraction of a second.

The roulette wheel analogy can be used to describe a computer simulation of fire scenarios. First, the wheel is divided like a pie chart so that a likely ignition source, such as smoking materials, has a big slice covering several numbers and a less likely ignition source, such as spontaneous combustion, has fewer or only one number. Then spinning the wheel simulates the first part of an ignition sequence, the heat source. Next, a second wheel is divided according to the most common materials first ignited. Spinning the second wheel will complete the ignition simulation. A refinement would be to provide a different second wheel for each heat source, thereby modeling the observed situation that some materials are more likely to be ignited by some heat sources than by others.

Subsequent stages of fire growth can also be included in the simulation. Fire development could be represented by a state transition model, a type of model that describes a progression from one defined state to another. In a fire, these "transitions" are determined by parameters, or variables of the fire area, such as flame spread, fire load, ventilation, and so on. Now, more roulette wheels should be added to represent these varying state transitions and to allow the computer to "spin" all these wheels hundreds of times. To calculate the resulting probabilities analytically would be intractable. This is a typical application of Monte Carlo simulation and there are several computer simulation packages that facilitate such modeling of probabilistic events.

Consider again the event tree in Figure 3.5.7. If each of the events in the tree has a complex statistical model of probability, then the calculation of consequence probabilities can become thorny. However, the nodes can be modeled individually and input to a computer simulation to estimate results. Many probabilistic models use a network to describe the framework, statistical models of events, and Monte Carlo simulation to provide resulting values.

Because of the flexibility of simulation modeling and the complex nature of fire problems, there is a wide range of applications. One area where simulation is used extensively is in the modeling of building evacuation.[55] Computer simulations of emergency egress range from simple travel time models to detailed representations of human decision making. Other applications include fire growth and development,[56,57] emergency response,[58,59] and those described in the *SFPE Handbook of Fire Protection Engineering*.[60]

Probabilistic models have many forms. The three categories discussed previously range from graphical network models with visual impact, through abstract mathematical representation of statistical models, to computer simulations that repeat possibilities enough times that they turn into probabilities. The important message is that the uncertain, probabilistic nature of fire can be modeled.

FIRE MODELING TRENDS

Having briefly discussed the current and near-term capabilities of models to predict fire effects, we will now focus on observable trends and the possibilities for the future of modeling.

Hardware

The past decade has witnessed a revolution in computing capacity available to individual users. Such prior technological advancement has made it relatively safe to forecast that more powerful, easy-to-use computer hardware will continue to evolve, which has eliminated most computational speed problems with respect to zone models. Although the computational requirements of CFD models have been reduced, computational speed will continue to be a challenge as more complex submodels are introduced into these codes to more accurately model the complex nature of fire phenomenon.

Developments in hardware should also appreciably extend the range and utility of these calculation methods, perhaps into the real-time world of the fire incident commander. The use of these models in conjunction with interactive video training and simulation will likely result in "fire simulators" becoming widely available to fire departments.[61]

Longer-term hardware developments in the area of intelligent sensors integrated with software derived from fire modeling may revolutionize fire detection. The "smart" building will include fire protection.

Application and Use

Although current applications are somewhat limited in terms of routine use, the trend has been for a relatively rapid increase in the application of models across all aspects of fire protection. Application and use of fire modeling include performance-based fire safety design, postfire reconstruction, fire risk assessment, and extrapolation of small-scale testing.

Performance-Based Fire Safety Design. There is currently widespread use of modeling in the design and evaluation of the fire safety of buildings and facilities. Computer models and other analytical tools have not, however, been formally integrated into fire protection engineering design practice. Application of fire modeling often arises in the context of "code equivalency" or the "performance-based" approach to fire safety. There are relatively few fire safety problems for which direct comparison or equivalency based on the prediction of fire growth or smoke spread alone is possible. There are almost always probabilistic, risk, economic, and political factors involved. Computer models are still helpful, however, given the almost nascent state of development, in that they provide the ability to approximately compare expected fire conditions across a range of scenarios. The potential impact of various intervention strategies can also

be evaluated in a relatively crude fashion. A major question exists on the application of these models in fire safety design relative to building codes and fire safety standards. The primary determinants in this area will likely be the degree to which relatively prescriptive codes and standards can be harmonized with more performance-based design and engineering methods. This process is, of course, more complicated than it sounds, given the legal, social, and political realities under which buildings are approved.

Postfire Reconstruction. The problem of postfire reconstruction lends itself readily to modeling tools. Several case studies of "reconstructed" fire incidents using computer models have been published.[62–68] Such case studies generally demonstrate how a computer model used as part of a more general engineering analysis is a powerful tool. One lesson of these case studies is that the state of the art is not such that one sets up a reasonable input file and the computer describes how the fire evolved. Rather, the models are more appropriately used to evaluate in approximate terms the time sequence of the event or to establish in more detail the reasonableness of one or another ignition growth and spread scenario. These programs are also used to pose "what if" questions related to the contribution of a particular material, furnishing item, or other factor versus one of greater or lesser combustibility, energy release rate, and so on. Most modeling applications occur today and have occurred in the recent past in fire litigation circumstances. Most of these applications are never published.

Fire Risk Assessment. Applications outside of litigation are often associated with the evaluation of the fire hazard posed by a product or material.[69–73] Modeling received a major boost in the context of predicting the "toxic hazard" posed by materials. The combination of deterministic models with risk assessment methods into integrated hazard assessment schemes has begun.[74,75] The method enables one to integrate ignition, flammability, and toxicity properties with the end use of the material under varying scenarios to estimate the outcome. As always, the quality of these applications is driven by the methods, data, approximations, and assumptions that are used. Additional applications that reflect the increasing use of models for a range of applications can be found in work by Peacock and Bukowski,[73] Bengston and Hagglund,[76] and Hagglund and Wickstrom.[77] An additional prerequisite for the general use of modeling in building design is the need to deal with the inherently probabilistic nature of fire events and the reliability of various construction features and fire safety systems. Several generic approaches have been suggested to integrate deterministic modeling with probabilistic problems.[78–83] This challenge also poses the greatest opportunity. The tremendous potential of this significant technological advance for improved fire safety will be recognized and exploited.

Extrapolation of Small-Scale Tests. The development of small-scale fire test methods, which in principle enables the extrapolation of the results to real fires, was essential to the development of modeling. Some of these test methods have been standardized by ASTM and NFPA. The input data required by models, which describe the burning behavior, energy release rate, smoke properties, and combustion gas yields of materials, come largely from these small-scale test methods. It is expected that the availability of these data for a wider range of products and materials will increase. The availability will accelerate dramatically if these relevant test methods are referenced in buildings codes and fire standards in lieu of or in conjunction with more traditional methods. Since models form the basis for extrapolating this flammability data to full-scale performance, increased use of models in this context is expected. In many ways, this particular class of applications may be ideal for the direct integration of modeling into building design standards.

Clearly, the use of models in postfire reconstruction will continue, and their application to special facilities and problems not directly dealt with in codes and standards will also increase. Although zone models have been the tool of choice due to the inherent simplicity and practicality, the application of CFD to fire problems has been and will continue to dramatically increase. This expanded use of CFD in the fire protection community has followed the release and further development of Fire Dynamics Simulator (FDS)[31,32] by the National Institute for Standards and Technology. To date, the most extensive use of CFD in fire is in the prediction of smoke movement, especially in large, complex open spaces like atria.

Although there are significant limitations in the treatment of important physics in widely used models, the primary difficulties arise in the overall context of the model's use. Appropriate selection of expected or worst-case input parameters, consensus on the safety factors or margins of safety to be applied, and, more fundamentally, the lack of clear design objectives remain important areas of concern. Significant differences in the results of modeling analyses of fire safety appear to arise more from these external factors than from the limitations of any particular model.

Validation

Although progress has been made, the predictive capability of computer models is limited since models rely on approximations for naturally occurring phenomena. That is, there is some level of uncertainty in the predicted results. Validation is the process of measuring the level of uncertainty of the model's predictions. It is clear that ongoing research and development efforts aimed at resolving some of these uncertainties will result in improved predictive capability. The use of heuristics to aid in simplifying particularly difficult problems will continue. Confidence in the capabilities of models will increase with improved validation and careful use.

The use of approximations also yields limitations with respect to the application to a specific scenario. It is not known with confidence to what limits these models can be applied. These issues involved in the evaluation of fire models have begun to receive attention in the technical fire community.

ASTM has developed guides to documenting and evaluating fire models,[84,85] and SFPE has begun to take on the task of providing guidance documents on the use of fire models.[86] ISO TC 92/SC 4 is also developing guidance on validation and verification of models. The U.S. Nuclear Regulatory Commission has

begun the process of evaluating and validating models within the room of fire origin.[87] Although these efforts are first steps, they reflect recognition of the need within the fire community to understand the applicability, limitations, and accuracy of fire models that are being used in hazard analysis and design.

Numerous validation studies of computer fire models have been undertaken. Surveys of fire models have been conducted that include reference to validation studies.[5,6] Most validation studies have been undertaken for relatively small (approximately 100 ft^2 [9.3 m^2]) compartments with well-defined fire sources (cribs, pool fires, or gas burners).

It is arguable that complete validation of any fire model is an impractical objective. It is unlikely given funding and prioritization realities that any significant systematic and complete validation will ever be performed on any model. Thus, models will be evaluated and the results accepted in a relatively slowly evolving time frame. The obligation that this lack of independent validation places on users and approving authorities is obvious. Particular attention must be paid to using these programs within their stated limits and, perhaps more importantly, to searching out experimental data for cases similar to the problem being evaluated. The dearth of complete validation studies should not be taken as rationale for rejecting the use or results of a model in any particular case. The validation picture could improve dramatically if it became clear that the lack thereof was a significant barrier to more widespread use.

Although validation of more complex models is an arduous task, papers have begun to appear in the literature in which experimental data and CFD model predictions are computed. Evaluation of CFD results for a particular application poses particular challenges. The sheer quantity of output data, the importance of the computational grid size, and subtleties in the internal model treatment of important physics require substantial effort to critically evaluate and ensure reliability of the results.

Acceptance

A decade of continued progress in modeling, with the increase in the number of published application studies in the *NFPA Journal* and other widely read fire literature, has led to greater acceptance of performance-based designs (which may include the use of fire models) by authorities having jurisdiction (AHJ). The trend in greater acceptance of predicted results in resolving fire safety issues is highlighted by the development of guidelines for peer review of performance-based design[88] when the engineering rigor is beyond the technical capabilities of the AHJ. This trend will continue and likely accelerate. Progress related to integration of these methods into the design of facilities is more problematic.

SUMMARY

Computer models are simply computer programs that implement a mathematical model simulating a process or phenomenon. Computer models have been used for some time in the design and analysis of fire protection systems. Models can be classified into two broad classes: (1) physical models and (2) mathematical models. Physical models attempt to reproduce fire phenomena in a simplified physical situation. Mathematical models are sets of equations that describe the behavior of a physical system. Mathematical models can be further classified into two classes: (1) deterministic models and (2) probabilistic models.

Deterministic models are sets of equations that describe the behavior of a physical system. The resulting mathematical model can then be used to predict the behavior of real physical systems. Probabilistic models attempt to deal with the random nature of fire behavior, whereas deterministic models presume that, given a well-defined physical situation, fire growth and behavior are entirely determined. This chapter presents information on deterministic and probabilistic models of fire behavior and relevant aspects of fire protection. This chapter discusses the most widely used types of models and provides a brief introduction to probability theory, including information on evaluating and assigning probability.

The development of fire models is a very active area. The preceding review is intended to offer the reader a perspective on what is currently available. The reader should also recognize that the information in this chapter is not exhaustive. Papers listed in the reference section provide additional information on the topic. Before using any fire model, the user should be aware of the underlying fire science and fire protection engineering principles assumptions and limitations for that model. The brief descriptions provided in this chapter should not be used as the basis for the selection of a model for a particular application. Further, the range of validity for an individual computer fire model is difficult to determine and is the topic of a significant amount of continuing research. Before using any model, the user should study the comparisons of model predictions with experimental data to aid in determining if the use of the model is appropriate.

Fire modeling is an old and well-developed field, though much remains to be done. Physical and mathematical models have made important contributions to fire safety and it is no longer a question of whether modeling will be used in the solution of fire safety problems but rather to what extent. The degree to which scientifically based engineering models can impact fire safety will be driven largely by their application to design practice and requires some integration with building codes and fire safety standards. Without such integration, incremental progress in predictive capability and applications can be expected. If fire safety engineering methods and codes are successfully integrated, the forecast will be one of rapid revolutionary change in all aspects of modeling as well as building design.

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Chapter 6

Applying Models to Fire Protection Engineering Problems and Fire Investigations

Revised by
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Definition of Fire Models
Types of Models
Model Applications
Computer Modeling in Fire Investigation
Considerations for Selecting and Using Fire Models

Key Terms

computational fluid dynamics (CFD) model, computer fire model, failure analysis, field model, *Fire Dynamics Simulator,* fire model, fire reconstruction, *FPETool,* hazard, heat release rate, performance-based design, sensitivity analysis, t^2 fire, zone model

Starting in the 1980s, computerized fire models were developed and applied to fire safety problems. In general, these models estimate changes (such as open or closed doors) to a building or space within a building and its environment (such as temperature or visibility), based on user input data for an assumed fire in that structure. For the most part, these models do not model the fire directly but use the input data selected by the user to predict the impact of the selected fire or the enclosure. A more extensive discussion of computer fire models and their elements is covered in other chapters in this section. The purpose of this chapter is briefly to advise the user on some of the types of applications where modeling can be of assistance and provide some guidance for users to establish criteria for selection of the model chosen and the input data used.

As an outgrowth of the major advances in understanding the dynamics of fire and its effects on the operation of fire protection devices, workers in the field have developed a number of predictive models. These models range from prediction of upper-layer gas temperature in a compartment fire[1,2] and the time of sprinkler head operation[3,4] to human response to the heat and toxic species produced.[5] Many of the models have, in turn, been assembled into larger consolidated models and hazard assessment tools[6–11] that provide a wide capability for the calculation and assessment of the predicted effects of fire using today's state-of-the-art personal computers.

See Section 3, Chapter 7, "Fire Hazard Analysis Techniques"; Section 3, Chapter 11, "Overview of Performance-Based Fire Protection Design."

DEFINITION OF FIRE MODELS

The term *model* can be applied to many physical and mathematical procedures designed to simulate reality. For the purpose of this chapter, *fire models* are defined as mathematical procedures developed to estimate the change in the environment of a space (such as a room or compartment) or building caused by a fire that varies in intensity and/or area of involvement with time. Many of these models predict the temperature of the smoke layer produced by that fire. Most fire growth models also predict the depth of the smoke layer. In addition, many models predict other variables such as the oxygen, carbon monoxide, carbon dioxide, and other gas species concentrations in

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the smoke; the rate of flow of smoke, gases, and unburned fuel from one space to another; and the temperatures of the walls, ceiling, floor, and air not yet drawn into the fire. Some models also predict the time of smoke and heat detector activation (including sprinkler heads) and the effects of opening or closing doors, breakage of windows, or other physical events that take place during a fire. Some models are limited to the room of fire involvement, others can track the flow of fire products through a series of rooms, and a few follow the spread of fire outside the room of origin.

Typically, the models involve the simultaneous solution of two or more differential equations. The more sophisticated models involve the simultaneous solution of such equations for many variables and use sophisticated techniques to obtain the results. The range of complexity and sophistication is wide, but all models follow the basic conservation principles of mass, energy, and momentum.

TYPES OF MODELS

As discussed more thoroughly in Section 3, Chapter 5, "Introduction to Fire Modeling," prediction models can generally be classed into the categories of zone models that solve the basic conservation equation for distinct regions (control volumes), and computational fluid dynamics (CFD) or field models that solve the fundamental equations of mass, momentum, and energy in a space that has been divided into a grid of small-volume cells.

Fire Dynamics Calculation Tools

The most commonly used class of models are fire dynamics calculation tools. This class of models typically calculate single values based on given input. Examples of these types of models calculate the flame height of a fire or calculate the heat release rate required to produce flashover in a compartment. Fire dynamics calculation tools are typically based on empirical correlations or on solutions of specific engineering scenarios. Fire dynamics calculation tools are popular because they provide simplified solutions of what are often complicated equations with many input variables. They also provide credible solutions because they have typically gone through a peer-review process through either publication or critical scientific review.

Fire dynamics calculation tools first became popular with the introduction of *FPETool,* published by the National Institute of Standards and Technology (NIST). The publication of *FPETool* by a governmental entity provided credibility to common fire dynamics calculations that had previously been considered unsubstantiated or poorly documented by some authorities having jurisdiction (AHJs). *FPETool* combined a variety of calculation tools and a zone model with an easy-to-use interface. The state-of-the-art fire dynamics calculation tools have been compiled by the U.S. Nuclear Regulatory Commission (NRC) and are based on spreadsheet solutions for the fire dynamics formulae.[12]

Zone Models

Most of the fire growth models in common use are *zone models.* These usually divide each room into two spaces or zones: (1) an upper zone that contains the hot gases produced by the fire and (2) a lower zone that contains a space beneath the upper zone that is the source of the air for combustion. Zone sizes change during the course of the fire. The upper zone can expand to occupy virtually all the space in the room. In zone models, any changes to the conditions in the upper layer occur instantly throughout the layer. Calculations from zone models are typically completed in minutes using desktop computers.

Computational Fluid Dynamics (CFD) Models

In the past, CFD models usually required large-capacity computer workstations or mainframe computers. Advances in memory space and operating speed now allow CFD models to run off high-end PCs. In addition, reductions in cost of high-speed networking equipment and more general operating system support of clustering approaches allows for parallel processing in typical engineering office environments. Small compartments and simple geometries can now be run in a few hours, whereas large complicated problems may take days or weeks. By dividing the space into many small cells (frequently hundreds of thousands or millions), CFD models can examine much greater detail than zone models. For example, CFD can represent the actual variation in thickness and temperature gradients in the upper layer and depict flows around obstructions and through openings. If such detail is needed, it is often necessary to use the sophistication of a CFD model. In general, however, CFD models are much more expensive to use, require more time to set up and run, and often require a high level of expertise to make the decisions required in setting up the problem and interpreting the output produced by the model. The use of CFD models in fire protection applications, however, is increasing. CFD models are particularly well suited for situations where the space or fuel configuration is irregular, turbulence is a critical element, or very fine detail is sought. CFD is particularly valuable in complex smoke management system evaluation and design.

Predictive Capability of Models

The reality of accidental fire is more varied and complex than can be exactly described by any existing collection of equations and data. Users should not expect that the model will produce an exact duplication of reality. Rather, the results of models should be considered as engineering estimates, valid to the degree that the physical relationships being calculated are those that actually dominate the situation and that the data entered into the model is accurate. Figures 3.6.1 through 3.6.6 demonstrate the type of approximation that should be expected. In Figure 3.6.1, four different models and one simple correlation were used in an attempt to reproduce the results from a well-documented test of a fire in a room.* In Figure 3.6.1, the curve using the letter x to indicate

*The fire test used for this comparison is test PRC17W4-¼. This was one of a series of compartment fire tests conducted under the sponsorship of the Product Research Committee. Test PRC17W4-¼ was conducted in a room 2.18 m^2 and 2.41 m high. The room had a single vent opening 0.19 m wide and 2 m high. The fuel for this test consisted of four wood cribs having a total weight of approximately 14 kg located near the center of the room[13] (1 ft = 0.305 m; 1 ft^2 = 0.0929 m^2; and 1 lb = 0.4536 kg).

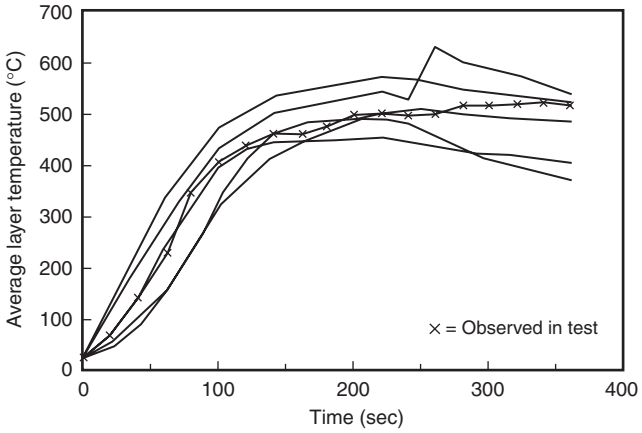

FIGURE 3.6.1 Predicted Layer Temperature by Zone Models versus Test Measurements (°F = 9/5°C + 32)

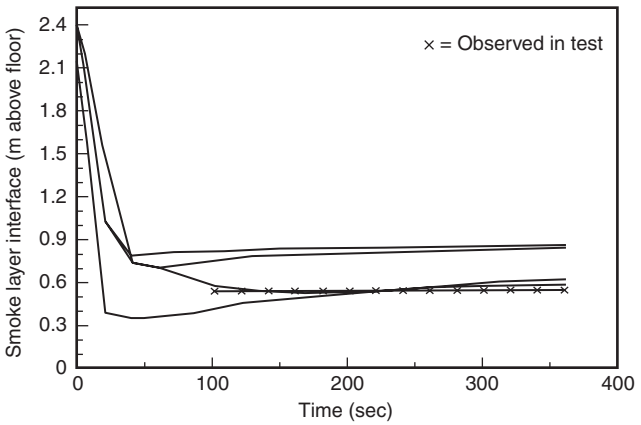

FIGURE 3.6.4 Prediction of Smoke Layer by Zone Models versus Test Measurements (1 m = 3.28 ft)

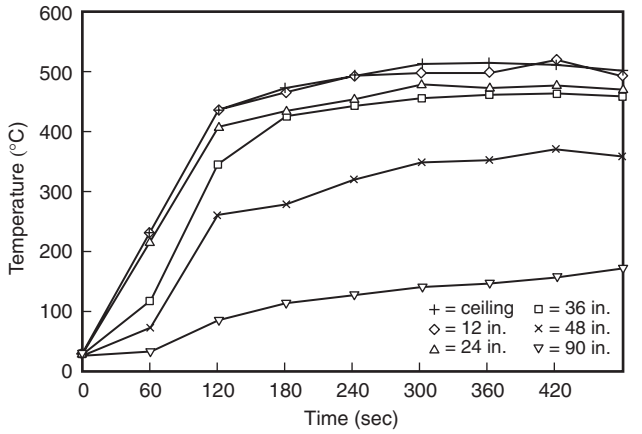

FIGURE 3.6.2 Actual Temperature Plots at Various Distances Below Ceiling (°F = 9/5°C + 32; 1 in. = 25.4 mm)

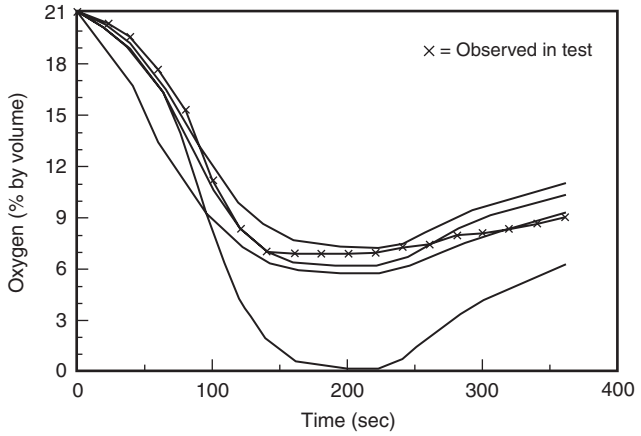

FIGURE 3.6.5 Prediction of Oxygen Concentration by Zone Models versus Test Measurements

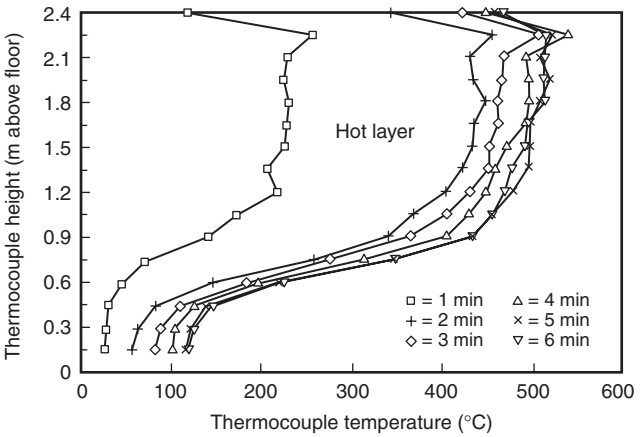

FIGURE 3.6.3 Actual Temperature Profile at 1-Min Intervals, Showing Hot Layer ("Zone") (°F = 9/5°C + 32; 1 m = 3.28 ft)

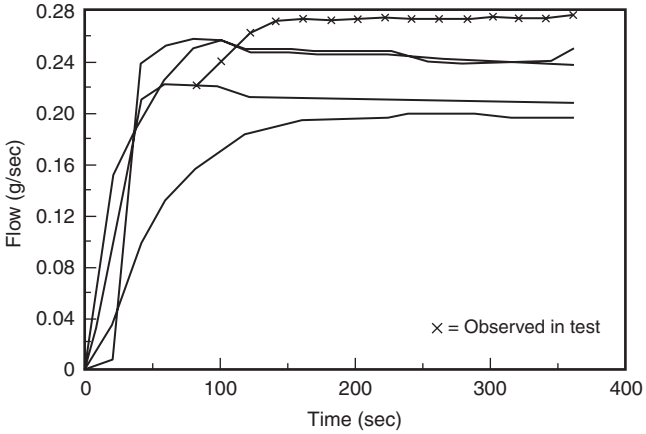

FIGURE 3.6.6 Prediction of Mass Flow Through Vents by Zone Models versus Test Measurements (1 g/sec = .0022 lb/sec)

data points plots the average upper layer temperature computed from thermocouple readings during the test. The other curves graph the predictions by the various models. The complexity of the models varied widely in this exercise. The simplest model was a single correlation equation, whereas the most complex involved the coordination of almost a hundred variables. In the case of this test, the most sophisticated model was the most accurate, but other much less sophisticated models grouped in the same range. Figure 3.6.2 is a reproduction of the actual data obtained in the burn test. Figure 3.6.2 reports the actual measured temperatures detected by a thermocouple tree near the center of the room but away from the fire plume. Every third thermocouple is plotted. Each of the lines depicts the temperature recorded by one of the thermocouples. The thermocouples were mounted with one near the ceiling and the others at 6 in. (0.15 m) intervals, with the bottom thermocouple located about 6 in. (0.15 m) above the floor. Figure 3.6.3 plots the same information as Figure 3.6.2, but rearranges the data to show the temperature profile from floor to ceiling at 1-minute intervals through the first 6 minutes of the test.

All of the models used to produce the results in Figure 3.6.1 are classed as zone models; that is, they predicted a single "upper layer" (smoke) temperature. As shown in Figures 3.6.2 and 3.6.3, an upper layer or "zone" of hot fire gases with an approximately equal temperature did exist. Although the type of approximation produced by these models is often more accurate than previous methods of estimation, the results must still be recognized as an engineering approximation. Figure 3.6.4 plots the smoke layer interface calculated by the models with that observed by the investigators. Figure 3.6.5 compares the oxygen concentration measured in the smoke in the test to concentrations calculated by the models. Figure 3.6.6 compares the measured mass flow through the vent opening with the same flow as calculated by the models. These four measures (i.e., temperature, smoke layer interface, oxygen concentration, and mass flow through the vent opening) were chosen to represent the full range of model outputs.

When using models for fire engineering or forensic investigation applications, it is important to be aware of the differences between actual and predicted fire effects as demonstrated above. The literature contains many model validation studies comparing full-scale fire test results with model predictions.[13–20] If, for example, a model overpredicts the temperature of the hot gas layer at the ceiling, the estimated time of a heat detector operation would be faster than the actual response. This would give the impression of earlier warning than would occur in reality. If the time to failure of a fire-rated ceiling was being evaluated, the failure would be predicted to occur earlier than would be expected to occur in the actual conditions.

MODEL APPLICATIONS

In the broadest sense, a fire model can be applied as a tool in the solution of any fire protection problem where the fire-produced conditions inside a building or space or the response of fire protection devices in that space are needed as input to the decision. The following are some typical examples of application classes.

Predicting a Hazard

In this case, *hazard* is defined as the expected fire-produced conditions. To start, a set of circumstances that represents a specific scenario, such as the maximum expected fire, is postulated. All of the conditions are fixed and the model is run to make a prediction of the rise in smoke (upper layer) temperature, the volume or depth of that smoke, the response of fire protection devices, the onset of serious conditions such as flashover, smoke gases or toxicity, or other items of concern. Often, this type of analysis searches for the most serious case and is used to answer questions such as, "How serious are the fire-produced conditions that can occur in this space?" Answering this question requires quantification of the conditions given a particular fire scenario, which is the role of a fire model. Frequently, a number of scenarios will have to be run to establish the most serious case. For example, consider an analysis of the hazard of a hotel room that contains a type of bed that fire tests indicate will grow, if ignited, at a moderate rate, eventually reaching a fire size of 2 megawatts (MW); a chair having a very fast fire-growth rate if ignited but a maximum rate of energy of less than 1 MW; and a number of pieces of furniture that would not be expected to be points of ignition but could join a fire at a later state. Discovery of the worst case might require a series of computer runs in which the ignition source was placed first on the bed and then on the chair, runs where the distance between the bed and the chair were varied, runs with the door open and the door closed, and other possible variations.

Sensitivity Analysis

In all of the above examples, it is frequently necessary to answer the question, "What if a change were made?" Models provide excellent tools for such parametric or sensitivity studies. Most frequently, the changes would involve the change of a material (construction, finish, furnishings), a change of an arrangement (door opened or closed, air conditioner on or off, spacing variations between fuel packages), or the presence or absence of a protection system such as smoke detectors or sprinklers. Variations in design parameters of fire protection systems can also be evaluated, such as detector or sprinkler spacing or sprinkler operating temperature and response time index (RTI). Using the example of the hotel room, typical questions might include the change in hazard or risk that would occur should the mattress be changed from a moderate-burning mattress to one that is fast burning or one that is treated to burn at a very slow rate. A similar question might relate to the use of a combustible wall material. In the case of a fire analysis, questions might relate to the difference in the situation had there been an ordinary versus a fast-response sprinkler in the space or had the door been equipped with a door closer. A first-order approximation of the contribution of an item of furnishing or a material can be made by exercising the model with and without that material present and noting the differences.

Reconstruction of a Fire

Fire models can be useful in reconstructing incidents that occur during a fire or testing suggested hypotheses or fire

cause scenarios. Ideally, there will be enough physical evidence, data available on conditions at the time of the fire, and reliable witness statements to produce all of the information necessary as input to run the selected model. In actual practice, only part of the necessary information is usually available, and running the model may in itself involve assumptions as to what the conditions were most likely to have been. Often, running the model will help demonstrate which assumptions are plausible and which are not. In the case of the example of the hotel room, the comparison of the known data to the various scenarios may demonstrate that giving the unknown data the values used in the calculation (assumptions) could not be correct as the model results do not agree with the consequences that actually occurred. In some cases, a single dominant fire scenario will emerge. The use of computer modeling in fire reconstruction and failure analysis is of particular interest to many fire protection practitioners, and papers have begun to appear in the literature.[14,15] This topic is discussed in more detail below.

Computer Modeling in Performance-Based Fire Protection Design

The application of computer fire models to performance-based design requires that the user understand the limitations and intended uses of the models selected. Several sources are available to provide guidance.[21,22] Valuable guidance can also be found in published case studies of performance-based designs found in the literature.

COMPUTER MODELING IN FIRE INVESTIGATION

Among the applications that have evolved for computer modeling has been the analysis of actual fire incidents after the fact to determine the most likely fire scenario or group of scenarios that could have produced the end result—a process called *fire reconstruction* or *failure analysis*. (See Section 3, Chapter 2, "Fire Loss Investigation.") Often, reconstruction includes an analysis of the role played by building fire protection features and how the fire might have progressed had additional fire protection measures been present, particularly when none existed at the time of the fire. *Failure analysis*[23] involves identification of the primary and contributing factors that caused the loss. Examples of factors that may result in failure include design, material or equipment selection, maintenance, and postconstruction modifications. Traditionally, these activities have been carried out by field investigators, based on physical evidence, witness statements, and the investigator's knowledge and experience, but with limited analytical tools.

Application to Reconstruction and Failure Analysis

One of the early attempts at application of the emerging analytical tools was carried out by Fleming,[24] who focused on the role that sprinklers might have played had they been present in the Haunted Castle of the Great Adventure Six Flags Amusement Park, Jackson Township, New Jersey. Fleming employed a combination of modeling and results of a variety of full-scale tests of manufactured home and compartment fires in reaching his conclusions. Since that time, a number of analyses have been carried out of major fires using progressively more sophisticated tools and approaches[25–32] in fire reconstruction and failure analysis modeling.

Because each fire incident will be different, there will be no "standard" set of models and techniques to apply. The purpose of this section is to outline the process of collecting the necessary data and setting up the modeling "experiments." The reader is encouraged to study the referenced reports as examples for specific fires.

Before a modeling effort can begin, a great deal of information needs to be obtained about the incident, beginning with an accurate layout of the building at the time of the fire. One also needs to know about the location and position of doors and windows, the type of heating, ventilating, and air-conditioning (HVAC) system, and the size and location of stairways and other vertical openings between floors. Although it may not be possible, a visit to the scene is valuable. Photos of the building during and after the fire should be studied if available. Often, news videos can be obtained.

Information needs to be gathered about the materials of construction, including the interior finishes and the furnishings and their distribution. Sources for this information include building occupants or their relatives, building owners or managers, contractors, interior decorators, or others who may have been involved in the construction, renovation, or operation of the building.

Figure 3.6.7 is a form that may prove helpful in gathering the type of data needed to use compartment models or similar analytical methods.

Where there are fire victims, important information, such as location and severity of burn injuries or blood chemistry, can be obtained from hospital or autopsy reports.

Because fire growth and the effect of fire on the building and its systems and occupants is largely time dependent, it is essential to obtain as much information as possible regarding the timing of events leading up to ignition (prefire events), during the fire (transfire events), and after the fire (postfire events).[23]

The best way to organize this information is through the use of timelines or event sequences. Benchmark events, those for which the time is known and not merely relative to a known event, are important to establish. If there are only a few events, a single timeline may suffice; otherwise, multiple timelines or event sequences[33] on the same scale may be useful. The timelines are then used for comparison with the results of the modeling experiments.

Once the data have been gathered and organized, a modeling plan should be developed based on the objectives of the study. The objective may be to assess the validity of a given hypothesis for the origin and cause of a fire or to develop new alternative hypotheses. In this case, the following questions are to be answered:

- Would the fuels, fire location, ventilation conditions, and building and occupant characteristics hypothesized result in the actual fire conditions?

Data for Compartment Fire Modeling

Room Number _____ Use _____

Size (use diagrams if possible) Wall/Floor/Ceiling Construction

Length _____ _____

Width _____ _____

Height _____ _____

Lining Materials (that represent over 10 percent of room lining)
(Include thickness, density, and other material characteristics, if known)

Wall Material	Percent of walls or area involved
_____	_____
_____	_____
_____	_____

Ceiling Material

_____	_____
_____	_____

Floor or Floor Covering Material

_____	_____
_____	_____

Doors, windows, and other openings [Enter all heights as distance above floor. If door sill is at floor enter zero (0).]

Opening	To	Top	Sill	Width	Changed During Fire (How?)*
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____

Heating, ventilating, and air conditioning (HVAC). Include air flows from HVAC systems. Give rates and positions of supply and return or exhaust in this room. Also sizes and types of ducts/diffusers.

_____

_____

_____

Tightness of walls, closed windows, door fits, etc. (Unless fit is very loose, classify fit as tight, average, or loose. If fit is very loose try to get size, number, and location of cracks, etc.)

Doors _____

Windows _____

Inside walls _____

Exterior walls _____

*For example: "window broke at 10:33" or "door was closed until opened by escaping occupant, then left open—Exact time 10:30."

FIGURE 3.6.7 A Sample Compartment Fire Modeling Data Form

- Which scenarios, given the range of available fuels, possible ventilation conditions, and building characteristics, could result in the actual fire conditions?

Another objective might be to determine whether or not someone might have been injured had a detector been in use. In this case, the question to be answered could be posed as follows:

For the set of scenarios that could result in the actual fire conditions, what conditions would the potential victim be exposed to, given the range of initial locations of the victim relative to the fire, the conditions at the time of operation of the detector, and the actions and route taken during an escape attempt?

Using the questions as a guide, a list of scenarios to be modeled and the associated variable can be prepared and perhaps arrayed as a "test matrix." For the detector case above, the matrix could be multidimensional and very large. The matrix can be pruned by eliminating highly unlikely scenarios and by starting with the most conservative scenarios, that is, those that place the occupant at greatest risk. See the following scenarios, for example:

- Fire remote from the detector
- Fire between occupant and detector
- Occupant impaired
- Fuel has highest heat release rate

Once the matrix has been developed, it will probably be noted that there are not enough facts to provide all the needed model inputs. If the initial fuel package is furniture, and the construction materials and design characteristics are not known, a database for several items that bound the actual item might be used. If the characteristics are known, an exemplar might be tested. If nothing is known about door position, this becomes a variable, as would the starting position of victims.

Most models are driven by a heat release curve (Figure 3.6.8) input by the user. The user may apply one of several "standard" fires (slow, medium, fast, or ultrafast[34]) or develop a curve more specific to the fire under investigation. These "standard" fires assume the fire grows as a function of time squared (t^2) modified by a specific factor for slow, medium, fast, and ultrafast results. The closer the rate of the heat release curve is to the actual occurrence, the more accurate the results. If "standard" t^2 fires are used, it is incumbent on the user to justify their appropriateness. Developing a case-specific heat release curve is one of the more difficult tasks in a reconstruction. One begins with the first item ignited, if this is known. If the first item is not known, part of the reconstruction will be to experiment with several possible "first items." Next, the ignition of nearby items is determined and the heat release curve(s) added to that of the first item, making adjustments for the radiation effects from the burning first item, as necessary. It has been shown[35] that the developing hot layer in a compartment fire increases the burning rate of items before the onset of flashover. Adjustments must be made to reflect this phenomenon.[26] Considerable data and reference material on heat-release rates for a variety of items and materials are available to assist in the development of case-specific heat release curves.[36,37]

Once a fire curve has been developed, one way to prune the matrix is to plan a set of experiments to test the sensitivity of

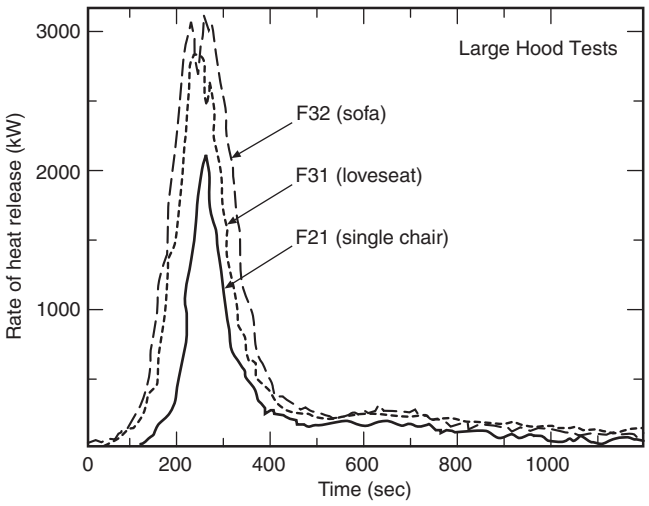

FIGURE 3.6.8 Typical Upholstered Chair Heat Release Rates (Source: Philip J. DiNenno et al. (Eds.), *SFPE Handbook of Fire Protection Engineering,* 2nd ed., National Fire Protection Association, Quincy, MA, 1995. Fig. 3-1.6)

the results to the unknowns. If, for example, the HVAC has little or no effect on the time to flashover, it may be ignored, but it may have a major effect on tenability in an area remote from the fire, in which case HVAC would need to be included. Keeping detailed records of the modeling experiments is important. It is very easy to "check a few things out" at the keyboard and not remember what the results were. Keep a "lab" notebook, which is increasingly done with a computer spreadsheet that relates the fire scenarios examined with results and run file names. It is suggested that a file-naming convention be used that tracks the scenario number as well as the key variables.

It is clear that many, many runs will be necessary for even the most straightforward analysis. It is not the intent of this chapter to thoroughly examine all aspects of modeling for fire construction and failure analysis. However, the following guidelines should be observed:

1. *Know the limitations of the models used.* ASET,[2] for example, assumes a vent flush with the floor to relieve pressure, but this is only a mathematical provision for consistency with the solved equations and the data is questionable after flashover. ASET also requires that the user assign a heat loss factor within a specified range to the space being evaluated. Most models do not consider the effect of radiation from the upper layer on the heat release of the burning items.[18] Heat detector models may not include the transit time for heated gas to reach the sensor. This can be a consideration for low-heat output fires (weak plumes) or high ceilings. The importance of transport time may be evaluated using a technique proposed by Mowrer.[38]
2. *Use more than one model.* For example, different models use different correlations for plumes[39] and for preflashover layer temperature.[40]
3. Where possible, check the model against actual experiments[41] or test data collected under similar conditions.

4. Use ranges of values for variables to which the model is sensitive, unless the value is known to be correct. For example, the heat of combustion of materials with generic names such as "polyurethane" can vary from product to product. Modeling with both upper and lower bounds will give a range of results that brackets the problem.
5. *Consider the ambient conditions.* For example, the hot layer formed under a metal deck roof on a blistering hot day will delay the transport of smoke to a detector. If the model being used for detector operation relies on temperature rise above ambient, the "ambient" used should be that of the hot layer, not the temperature lower in the compartment or outside the building. When there are open windows, the effects of wind should be considered in modeling the effects of low-energy fires (i.e., smoldering or small flaming fires).

Consistent with the development of fire models at NIST, the most recent addition to the models is the CFD model, *Fire Dynamics Simulator*[42] (FDS). It has found extensive use both in fire protection design and reconstruction. The model's increased detail in fluid dynamics has allowed its use in complex situations for which fire dynamics calculations or zone models would provide little, if any, additional insight into the scenario that occurred. NIST has used FDS to address conditions and fire development in reconstructions such as the Cherry Hill fire,[43] involving multiple fire fighter deaths, and the World Trade Center attack.[44]

Cautions on the Use of Computer Models in Fire Reconstruction and Failure Analysis

One should always keep in mind that there are some situations where a real-world fire is so complicated that the use of models at the present level of sophistication to analyze the entire event may not be valid. However, parts of the event, particularly the early stage of growth within the compartment or on the floor of origin, may be studied.

The use of fire models for forensic applications is expanding. For fire models to gain credibility in the forensic arena, they must be applied with care, keeping in mind their limitations.

CONSIDERATIONS FOR SELECTING AND USING FIRE MODELS

Models and Engineering Tools

Fire models are engineering tools. Like engineering handbooks, they arc available to all persons, regardless of competence. Unlike engineering handbooks, however, many models have been made user-friendly and can be executed by persons who may not understand their capabilities, limitations, or the impact of the choices made in setting up the problems. When decisions produced by a model impact on the safety of life and property, one of the two following cases must hold:

1. Users must understand what the model is doing and how it is achieving the results, thereby treating it as an engineering tool. In such cases, the users are as responsible for the results as they would be had they gone to the engineering handbooks and extracted the equations themselves. Engineers are encouraged to use models, understand them, and become fluent with them. They will become an excellent tool under their control, or
2. Users must ascertain the limits to which the model has been demonstrated as rational and restrain their use within these bounds. If the occasion necessitates exceeding these bounds, the user should obtain the advice and/or service of individuals competent to examine the model and determine its appropriateness for the use desired.

User Inputs

Many models require that the user provide inputs beyond a simple description of the space and its contents. Some of these inputs can greatly affect the result. The user may or may not have the data available or an understanding of the impact of his or her decision. Some models provide information to assist users; others do not. It is important that users exercise the model, find the variables required, and ensure that they can properly assign these before using the model. An important thing to remember is that many models include default values for the variables. A default value is one that has been included in the model and will be used by the model unless changed by the user. Usually, the values are ones felt to be reasonable by the model developer. However, they may or may not be appropriate for the case involved. The user must examine and responsibly accept or alter the default values as is appropriate for the case at hand.

Level of Sophistication Needed

The sophistication or detail of a model may or may not be related to its accuracy for the case involved. A general principle is to use the simplest model that meets the user's needs for the type and quality of information desired and the information required to run the model. Many of the more sophisticated models provide masses of detail that are not available in the simpler version. Conversely, some of the very simple models omit important fire phenomena. The balance between ensuring that the necessary phenomena are modeled and maintaining the sophistication of the model is best achieved by frequent use and examination of the models of interest.

Review and Adjustment

Finally, many computer fire models undergo regular review and possible adjustments. Users should try to stay abreast of updates, revisions, or other changes to models they use. They should be wary of models that are not being maintained and adjusted as needed by a competent organization.

SUMMARY

Fire growth models are tools used to solve fire protection problems. This chapter provides general guidance on the types of applications in which computerized fire growth models might

be useful. For example, fire models may be used to predict a hazard, to reconstruct a fire, or to analyze how changing the parameters of a fire might affect its outcome.

This chapter also provides specific information on the predictive capability of models and on types of models, including fire dynamics calculation tools, zone models, and CFD models.

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Chapter 7

Fire Hazard Analysis Techniques

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Chapter Contents

Performing a Fire Hazard Analysis
Developing Fire Scenarios and Design Fire Scenarios
Quantification of Design Fire Scenarios
Prediction of Hazards

Key Terms

bounding condition, design fire curve, design fire scenario, fire hazard analysis, fire model, fire scenario, performance-based design, *t*-squared fire

Available methods to estimate the potential impact of fire can be divided into two categories: risk-based and hazard-based. Both types of methods estimate the potential consequences of possible events. Risk-based methods also analyze the likelihood of scenarios occurring, whereas hazard-based methods do not. Fire risk analysis is described more fully in Section 3, Chapter 8, "Fire Risk Analysis." Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations," provides simple fire growth calculation methods.

The goal of a fire hazards analysis (FHA) is to determine the expected outcome of a specific set of conditions called a fire *scenario.* The scenario includes details of the room dimensions, contents, and materials of construction; arrangement of rooms in the building; sources of combustion air; position of doors; numbers, locations, and characteristics of occupants; and any other details that have an effect on the outcome of interest. This outcome determination can be made by expert judgment, by probabilistic methods using data from past incidents, or by deterministic means such as fire models. "Fire models" include empirical correlations, computer programs, full-scale and reduced-scale models, and other physical models. The trend today is to use models whenever possible, supplemented if necessary by expert judgment. Although probabilistic methods are widely used in risk analysis, they find little direct application in modern hazard analyses. Probabilistic models are discussed in Section 3, Chapter 5, "Introduction to Fire Modeling." Typically, when the potential impact of fire is estimated, a hazard basis is used. When probabilities or frequencies are considered, it is usually in the context of determining whether or not a scenario is sufficiently likely to warrant further analysis.

Hazard analysis can be used for one of two purposes. One is to determine the hazards that are present in an existing or planned facility. The other use is for design, where trial design strategies are evaluated to determine whether they achieve a set of fire safety goals. Hazard analysis can be thought of as a component of risk analysis. That is, a risk analysis is a set of hazard analyses that have been weighted by their likelihood of occurrence. The total risk is then the sum of all of the weighted hazard values. In the insurance and industrial sectors, risk assessments generally target monetary losses, since these dictate insurance rates or provide the incentive for expenditures on protection. In the nuclear power industry, probabilistic risk assessment has been the basis for safety regulation. Here the risk of a release of radioactive material to the environment is commonly examined, ranging from a leak of contaminated water to a core meltdown.

Available fire hazard calculation methods range from relatively simple equations that can be performed with a hand calculator to complex methods that require powerful computers, and many methods that fall between.

See also Section 2, Chapter 1, "Physics and Chemistry of Fire"; Section 3, Chapter 4, "Use of Fire Incident Data and Statistics"; Section 3, Chapter 5, "Introduction to Fire Modeling"; Section 3, Chapter 8, "Fire Risk Analysis"; Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations";

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Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety"; and Section 3, Chapter 11, "Overview of Performance-Based Fire Protection Design."

PERFORMING A FIRE HAZARD ANALYSIS

Steps of a Fire Hazard Analysis

Performing an FHA is a fairly straightforward engineering analysis. The steps include the following:

1. Selecting a target outcome
2. Determining the scenario(s) of concern that could result in that outcome
3. Selecting an appropriate method(s) for prediction of growth rate of fire effects
4. Calculating the time needed for occupants to move to a safe place
5. Analyzing the impact of exposure of occupants or property to the effects of the fire
6. Examining the uncertainty in the hazard analysis
7. Documentation of the fire hazard analysis process, including the basis for selection of models and input data

Fire hazard analysis can also be used as part of the performance-based design process. For more information on performance-based design, see Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety," and Section 3, Chapter 11, "Overview of Performance-Based Fire Protection Design."

Selecting a Target Outcome

The target outcome most often specified is avoidance of occupant fatalities in a building. Another might be to ensure that fire fighters are provided with protected areas from which to fight fires in high-rise buildings. The U.S. Department of Energy (DOE) requires that FHAs be performed for all DOE facilities.[1] Their objectives for such FHAs, as stated in DOE 5480.7A, include the following:

- Minimizing the potential for the occurrence of fire
- No release of radiological or other hazardous material to threaten health, safety, or the environment
- An acceptable degree of life safety to be provided for DOE and contractor personnel and no undue hazards to the public from fire
- Critical process control or safety systems are not damaged by fire
- Vital programs are not delayed by fire (mission continuity)
- Property damage does not exceed acceptable levels (e.g., $150 million per incident)

An insurance company might want to limit the maximum probable loss to that on which the insurance rate paid by the customer is based; a manufacturer might want to avoid failures to meet orders to avoid erosion of its customer base; and some businesses might want to guard their public image of providing safe and comfortable accommodations. Any combination of these outcomes could be selected as appropriate for an FHA.

DEVELOPING FIRE SCENARIOS AND DESIGN FIRE SCENARIOS

Fire Scenario and Design Fire Scenario Defined

Determining the fire source is one of the most important parts of performing a fire hazard analysis. To determine the fire source, a design fire scenario must be developed. A *fire scenario* is a set of conditions that defines the development of fire and the spread of combustion products. Fire scenarios comprise three sets of features: building characteristics, occupant characteristics, and fire characteristics. Building characteristics describe the building features that could affect fire development and the spread of combustion products. Occupant characteristics describe the state(s) of occupants at the time of the fire. Fire characteristics describe the ignition and growth of the fire. A *design fire scenario* is a set of conditions that defines the critical factors for determining the outcomes for trial fire protection designs of new buildings or modifications to existing buildings.[2] Design fire scenarios are the fire scenarios that are selected to analyze a trial design. They are generally a subset of the fire scenarios.

The design fire scenario is based on a fire that has a reasonable likelihood of developing from a series of events. Fire scenarios need to be based on reality and should be developed accordingly. For example, the occupancy, the purpose for which the design is being developed, the fuel load, potential changes in the property, the presence of sprinklers and fire detection, the presence of alarm and notification systems, and smoke management should be considered. Design fire scenarios differ by occupancy and should be based on reasonably expected fires and worst-case fires. Although this chapter deals with hazard-based approaches, some risk must be included in the analysis when developing design fire scenarios. For instance, if a fire may be technically plausible but is extremely unlikely, that scenario may not be necessary to include in the design fire scenarios.

Determining the Scenario(s) of Concern

Records of past fires, either for the specific building or for similar buildings or class of occupancy, can be of substantial help in identifying conditions to be avoided. Statistical data from NFPA or from the National Fire Incident Reporting System (NFIRS) on ignition sources, first items ignited, rooms of origin, and the like can provide valuable insight into the important factors contributing to fires in the occupancy of interest. (See also Section 3, Chapter 4, "Use of Fire Incident Data and Statistics.") Anecdotal accounts of individual incidents are interesting but might not represent the major part of the problem to be analyzed.

Murphy's Law ("if anything can go wrong, it will") applies to major fire disasters; that is, significant fires seem to involve a series of failures that set the stage for the event. Therefore, it is important to examine the consequences of things not going according to plan. In DOE-required FHAs, one part of the analysis is to assume both that automatic systems fail and that the fire department does not respond. This is used to determine a worst-case loss and to establish the real value of these systems. The 2006 edition of NFPA *101*®, *Life Safety Code*®, includes a performance-based design option containing a basic set of design fire scenarios. Scenario 8 is a common fire that starts while

either the fire alarm system or the sprinkler system (in turn) is rendered ineffective. Given the normal high reliability of these systems, it is not required for the performance objectives to be met fully under these conditions, but stakeholders should feel that the resulting losses are not catastrophic or otherwise unacceptably severe. In a risk assessment, the consequences of such failures would be weighted by the probability of failure and added into the total risk. In a hazard analysis, the objective is hazard avoidance, so the contribution of low probability events is more subjective. Scenarios must be translated into design fires for fire growth analysis and occupant evacuation calculation. See the discussion in the Quantification of Design Fire Scenarios section later in this chapter.

NFPA *101* Design Fire Scenarios

NFPA *101* provides eight design fire scenarios that should be considered in the development of a performance-based design. Briefly, these design fire scenarios are as follows:

1. An occupancy-specific design fire scenario that is representative of a typical fire for the occupancy
2. An ultrafast-developing fire in the primary means of egress, with interior doors open at the start of the fire (for a discussion of fire development, see Section 2, Chapter 4, "Dynamics of Compartment Fire Growth")
3. A fire that starts in a normally unoccupied room that may endanger large numbers of occupants
4. A fire that originates in a concealed wall or ceiling space adjacent to a large occupied room
5. A slowly developing fire, shielded from fire protection systems, in close proximity to a high-occupancy area
6. The most severe fire resulting from the largest possible fuel load characteristic of the normal operation of the building
7. An outside exposure fire
8. A fire originating in ordinary combustibles with each passive or active fire protection system individually rendered ineffective; this scenario is not required where it can be shown that the level of reliability and the design performance in the absence of the system are acceptable to the authority having jurisdiction (AHJ)

Although only eight scenarios are listed in the performance option of NFPA *101,* more than eight scenarios will be developed and analyzed. For most building designs, for example, there will usually be far more than a single scenario that is representative of a typical fire in a given occupancy.

Applying NFPA *101* Design Fire Scenarios

For a typical building, what happens when each of these eight general scenarios is applied to what might occur as a reasonable design fire in that building? For the purposes of this illustration, a multistory hotel building with some meeting rooms on lower floors is considered. The following fires might be used as design fires in meeting the eight-scenario criteria of NFPA *101:*

1. A typical fire based on the occupancy might include a patron smoking in bed, or a sterno-initiated fire in a meeting room or restaurant area.
2. An ultrafast fire in a primary means of egress would likely mean a flammable liquid fire in the corridor near one of the exit doors.
3. Fire in a normally unoccupied room would likely include a fire in a janitor's closet, started by oily rags or ignition of some cleaning fluid.
4. Fire in a concealed space, particularly if the hotel were of combustible construction, might occur in the drop ceiling above the bathroom. This would likely be an electrical fire.
5. A shielded fire near occupied space might be in a maid's cart or under a display table in a meeting room.
6. The most severe fire from the largest fuel load typical to the building might occur during remodeling or might occur due to storage of furniture in one room or storage of chairs in a meeting room.
7. The outside exposure fire could include other buildings, skylights in the roof of a low-rise building nearby, or a wildland fire. This fire would be specific to the occupancy and building being considered.
8. Failure of a system would need to include looking at rated walls, rated floors, as well as sprinkler and fire alarm systems. When looking at these systems, one should consider what might fail rather than failure of the entire system. For instance, failure of a sprinkler system might mean failure of the entire water supply or it might mean failure of a single sprinkler to react when expected. By providing redundancy into water supply and fire pumps, and monitoring main valves, failures could be limited as a part of this evaluation.

Bounding Conditions

During development of the fire scenarios and design fire scenarios, the allowable future changes in the facility must also be considered. The extent of the changes that are considered by the design become bounding conditions for the analysis and subsequent use of the building. One can expect that a design fire scenario is not exactly what will happen and that the building as originally designed and anticipated will not remain exactly as analyzed. Therefore, as one develops design fire scenarios and one calculates the expected fire response, some amount of change in those scenarios must also be considered.

When conducting a hazard analysis, it is important to consider the types of changes that may occur. If the hazard analysis only considered a specific set of initial conditions, then it would be necessary to revise the fire hazard analysis any time changes were made in the future. The range of changes that will be considered by the hazard analysis is a judgment call between the designers and the owner.

For example, a hotel room floor might become a meeting room floor; a meeting room area might become an exposition center; occupant loads could be greater than expected or calculated; movable walls could create simultaneous use when nonsimultaneous use was expected; or the space between a ballroom ceiling and the floor above might be used for storage. All of these events are reasonably foreseeable, but some may fall outside of the bounding conditions. Bounding conditions must be clearly identified because changes in the building may occur.

Other situations that might occur on a more general basis, for any occupancy, include the response of a fire department and cutbacks in fire department funding or unwanted alarms causing deactivation of a system. Some of these bounding assumptions can be addressed specifically—for instance, maximum fuel load or occupant characteristics.

Implied Risk

Although this chapter addresses fire hazard analysis, there is some implied risk in any such analysis. The primary risk factors involved are included in the design fire development. The design fires described for the hotel building did not include such accidents as gasoline tanker trucks crashing into the side of the building or bombs ignited at the base of the building. There is always the risk that these events could happen, but the engineer must evaluate the likelihood of these events. For example, buildings are typically not designed to survive the impact and ensuing fire of a missile strike. If this were to occur, achievement of the design goals and objectives might not be expected. Similarly, it is conceivable that simultaneous fires could occur, although prescriptive building codes such as NFPA *101* explicitly exclude such an event. These might be limitations described in the fire strategy report to clarify what is covered and what is not.

When proposing to exclude a scenario from further consideration, it is important to ensure that stakeholders understand the implications of excluding the scenario. For example, if the fire scenario associated with a gasoline tanker truck crashing into the side of the building is dismissed, and the building is located on a highway leading to a major oil refinery, stakeholders would need to understand and accept that if a gasoline tanker truck did crash into the side of the building, goals and objectives might not be met.

Data Sources

In developing design fire scenarios, it is useful to have data on which to base future quantification. Members of the NFPA *Life Safety Code* Technical Committees developed the design fire scenarios based on statistical analyses prepared by the NFPA Fire Analysis and Research Division and also on past fires that have occurred in different occupancy types.

The NFPA One Stop Data Shop provides much information regarding fire statistics and results. Other sources addressing typical fires in occupancies include Factory Mutual data, state or local jurisdiction data for various occupancies, the National Fire Incident Reporting System, or past fire history published in the *NFPA Journal.* Other possibilities include fire test results (many of which can be found on the National Institute of Standards and Technology Fire Internet site), manufacturers' data regarding specific fire performance of materials, or listings of materials by recognized test labs. It can be reasonably expected that the amount of data to develop a design fire will not be sufficient to exactly predict what will happen in all cases.

Overall Example

The following example develops scenarios for a large exhibit hall at a convention center and describes some of the work that might be done using the scenarios that have been developed.

The first step is to investigate potential fires that might occur so that the design fire scenarios can be chosen. Based on the scenarios from NFPA *101,* the scenarios examined for a typical convention center might be as follows:

1. The occupancy-specific design fire scenario might include a fire in an exhibit booth or a fire in auditorium seating.
2. The ultrafast fire might involve a fire in a plastic boat display located near the main exit.
3. A fire in a normally unoccupied room could occur in the storage of stacked chairs in an exhibit hall next to the exhibit hall being considered. There could be a show in one exhibit hall with large numbers of people, and the adjacent hall might be used as temporary storage during that event.
4. A fire in a concealed space is unlikely in Type 1 construction but could occur in electrical or insulation areas.
5. A shielded fire could occur in the plastic boat previously mentioned or in a covered exhibit space. More and more jurisdictions are requiring automatic sprinklers in covered exhibit spaces, but that is not yet universal.
6. The most severe fire to be considered would likely be the boat fire previously mentioned.
7. An outside exposure fire would typically not be considered for this occupancy because convention centers are generally surrounded by parking lots and other open areas. However, if the loading dock is considered outside, the scenario might involve fire in a truck waiting to unload at the convention center.
8. A typical fire with failure might include failure of the sprinkler or fire alarm system or perhaps failure of the smoke control system.

If the purpose of the example is to perform an egress analysis, the worst-case fire may be all that is necessary for evaluation. The worst-case fire would likely be the shielded boat fire at peak rate of heat release. To quantify the fire, users might look at the fuel load and estimate the rate of burning, they might look at plastic fires and extrapolate, they might look at fast or ultrafast fires and assume the fire peaks at the estimated sprinkler response time, they might assume the fire is shielded on the inside of the boat and so not have the fire peak at the estimated sprinkler response time, or they might specify sprinklers inside the boat and limit the fire size. The user would likely try a combination of these factors to see the effects.

Once the fire scenario is developed, smoke-filling calculations can be performed to determine the clear height of a smoke layer over time. Those calculations would be compared to the timed evacuation analysis. Both calculations would likely start without suppression or smoke control to see whether the evacuation can occur without those two systems. If so, the analysis is simplified.

Finally, the user would identify bounding conditions via a sensitivity analysis. For instance, is the size of the boat important? How about the materials of the boat? Has the fuel been removed from the boat? If smoke control is necessary to make the design work, that smoke control needs to be identified as a critical system. Similarly, the occupant load, the exit sizes, the number of disabled persons, and the availability of an alarm system as well as its audibility must all be considered in the sensitivity analyses.

Once all of these factors have been considered and dealt with, the hazard-based analysis is complete. The documentation of the analysis is the next important part and cannot be omitted from any fire hazard analysis. The assumptions, bounding conditions, scenarios considered, and limitations should be identified to the AHJs, the owner, and other interested parties. See Section 3, Chapter 11, "Overview of Performance-Based Fire Protection Design," for more details on documentation requirements.

QUANTIFICATION OF DESIGN FIRE SCENARIOS

Quantification of design fire scenarios involves two steps. The first step is to develop the design fire curve for the design fire scenario or portion of the design fire scenario of interest. The design fire curve represents the heat release rate over time for the fire in question. Once the design fire curve is estimated, the second step, predicting the fire effects, is then possible.

The purpose of the design fire is similar to the assumed loading in a structural analysis—that is, to answer the question of whether the design will perform as intended under the assumed challenge. Keeping in mind that the greatest challenge is not necessarily the largest fire (especially in a sprinklered building), it is helpful to think of design fires in terms of their growth phase, steady-burning phase, and decay phase (Figure 3.7.1).

Design Fire Curves

The design fire curve is a description of the intensity (heat release rate) of a fire as a function of time. The design fire curve can be divided into four phases: ignition, growth, steady-burning, and decay. Because there is not a single framework for developing the entire design fire curve, each step is typically developed separately and then brought together as a single curve.

It is not always necessary to quantify each phase of a design fire curve, depending on the goals of the analysis. For example, to predict when a fire detection or suppression system would activate, it might only be necessary to quantify the growth phase. For sizing a smoke control system, only the maximum heat release rate might be needed. A structural analysis might need the peak burning rate and the duration of peak burning. Performing an evacuation analysis might require quantification of the growth and fully developed stages.

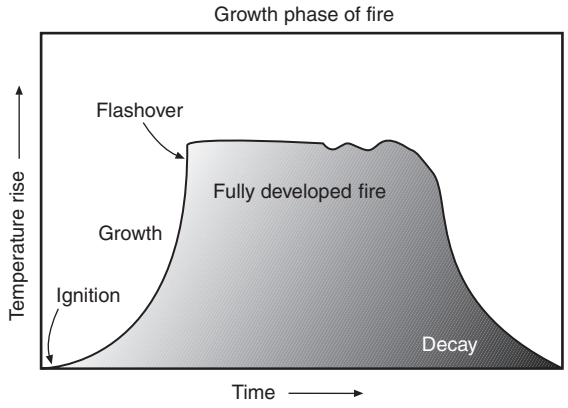

FIGURE 3.7.1 Design Fire Structure

Ignition. The design fire curve starts at ignition. A simple approach to developing a design fire curve is to assume that an ignition source of sufficient intensity is available to instantaneously ignite the initial fuel package to establish burning. However, if the heat transfer to a combustible object or the temperature of the object is known, calculations can be performed to predict whether the object will ignite. Calculations to determine whether ignition occurs depend on the state of the fuel: solid, liquid, or gas.

Ignition can be divided into two categories: piloted and nonpiloted. In the case of piloted ignition, a "pilot" such as a spark or flame initiates flaming. For nonpiloted ignition, flaming occurs spontaneously as a result of heating in the absence of flame or spark.[3] Except for piloted ignition of gases and liquids that are at a temperature above their flashpoint, all materials must first be heated before ignition can take place.[3]

Solids. With the exception of smoldering combustion, for a solid to ignite it must first be heated sufficiently to release flammable vapors. Flammable vapors can be given off either by pyrolysis or by melting and subsequent vaporization. Pyrolysis occurs when a material is heated and decomposes, releasing vapors known as *pyrolyzates.* Unlike melting and vaporization, in which no molecular changes occur, the vapors given off are different from the material that was originally heated.[4] The process of pyrolysis can be viewed as "thermal cracking," in which larger molecules are broken into smaller molecules.

Piloted ignition occurs if the concentration of pyrolysis gases is above the lower flammable limit and a "pilot" is present. For nonpiloted ignition to occur, the pyrolysis gases must be at a concentration above the lower flammable limit and they must be above their autoignition temperature. Because of this, it requires less energy for piloted ignition to occur than for nonpiloted ignition.[4]

Methods of predicting ignition of solid materials exposed to thermal radiation differ depending on whether a solid is thermally thin or thermally thick. A thermally thick material is one in which a temperature rise will not be perceived on the unexposed surface when the material is heated. Wood is a typical example of a thermally thick material, whereas sheet metal is a good example of a thermally thin material.

An engineering guide[4] published by the Society of Fire Protection Engineers (SFPE) focusing on piloted ignition contains six methods for predicting the piloted ignition of solid materials under radiant exposure as follows.

For thermally thin materials, the method of Mikkola and Wichman can be used:

$$t_{ig} = \rho L_0 c \frac{(T_{ig} - T_0)}{(\dot{q}''_r - \dot{q}''_{crit})} \quad (1)$$

where

T_{ig} = Ignition temperature (°C)

T_0 = Initial temperature (°C)

t_{ig} = Time to ignition (sec)

ρ = Density of the material (kg/m^3)

c = Specific heat of the material (kJ/kg·C)

L_0 = Thickness of the material (m)

$\dot{q}''_r$ = External heat flux (kW/m^2)

$\dot{q}''_{crit}$ = Critical heat flux for ignition (kW/m^2)

For thermally thick materials, the following methods can be used:

- Mikkola and Wichman

$$t_{ig} = \frac{\pi}{4} k\rho c \frac{(T_{ig} - T_0)^2}{(\dot{q}''_r - \dot{q}''_{crit})^2} \quad (2)$$

where k is thermal conductivity (W/m·K).

- Tewarson

$$t_{ig} = \frac{\pi}{4} \frac{(TRP)^2}{(\dot{q}''_r - \dot{q}''_{min})^2} \quad (3)$$

where TRP is thermal response parameter (kW·sec$^{1/2}$/m^2) and $\dot{q}''_{min}$ is minimum heat flux for ignition (kW/m^2).

- Quintiere and Harkleroad

$$t_{ig} = \left(\frac{\dot{q}''_{min}}{b \cdot \dot{q}''_r}\right)^2 \qquad \text{for } t \le t_m \quad (4)$$

where b is a constant related to $k\rho c$ (sec$^{-1/2}$) and t_m is characteristic time to reach thermal equilibrium (sec).

- Janssens

$$t_{ig} = 0.563 \left(\frac{k\rho c}{h_{ig}^2}\right) \left(\frac{\dot{q}''_r}{\dot{q}''_{crit}} - 1\right)^{-1.83} \quad (5)$$

where h_{ig} is heat transfer coefficient at ignition, which incorporates both the radiative and convective components (W/m^2·C).

- Toal, Silcock, and Shields

$$t_{ig} = \frac{(FTP_n)}{(\dot{q}''_r - \dot{q}''_{crit})^n} \quad (6)$$

where FTP_n is flux time product and n is flux time product index is greater than or equal to 1.

See SFPE's engineering guide[4] for additional information on applying these methods as well as the appropriateness of these methods for different situations.

Liquids. For a liquid to ignite, it must be at a temperature that is equal to or greater than its flashpoint. NFPA 30, *Flammable and Combustible Liquids Code,* defines flashpoint as "the minimum temperature of a liquid at which sufficient vapor is given off to form an ignitable mixture with air, near the surface of the liquid or within the vessel used."

A number of test methods can be used to measure the flashpoint of a liquid. Flashpoint is not a physical property and is instead a model of physical phenomena associated with vaporization of a sufficient quantity of fuel to establish a gaseous mixture that is at the lower flammable limit at a distance above the fuel surface and therefore can change with the test method employed.[3]

Ignition of a liquid at its flashpoint is analogous to piloted ignition of a solid, in that for ignition to occur, a pilot must be present. The analogy for nonpiloted ignition of liquids would be ignition at the autoignition temperature. Values for flashpoints and autoignition temperatures for some common materials can be found in NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas.*

Gases. For ignition of a flammable gas to occur, it must be mixed with a sufficient quantity of oxygen for a reaction to take place. Concentrations where this occurs are represented by a flammability range, which corresponds to gas/air concentrations that are at or above the lower flammable limit and not exceeding the upper flammable limit. Flammability limits for a variety of gases can be found in NFPA 497.

For mixtures of flammable gases, Le Chatelier's principle can be used to determine the lower flammable limit.[3] Le Chatelier's law states that

$$L_m = \frac{100}{\sum_i \frac{P_i}{L_i}} \quad (7)$$

where

L_m = Lower flammability limit of the mixture

P_i = Volume fraction of gas i

L_i = Lower flammable limit of gas i

For more information, see Section 6, Chapter 10, "Gases."

Fire Growth. Following ignition, a fire might grow as it develops on the first item ignited or spreads to additional items. To determine whether spread would occur to adjacent items, the problem can be approached from the perspective of whether or not these items would ignite. For growth involving a single item, the fire could spread to unignited portions of the item. This could either lead to the entire item burning, or earlier ignited portions might burn out before the fire spreads to involve the entire item, such that the entire item is never fully involved.

Prediction of Fire Effects

The primary importance of the appropriate selection of the design fire's growth is in obtaining a realistic prediction of detector and sprinkler activation, time to start of evacuation, and time to initial exposure of occupants. In 1972, Heskestad first proposed that for the early fire growth period the assumption that fires grow according to a power law relation works well and is supported by experimental data.[5] He suggested fires of the form

$$Q = \alpha t^n \quad (8)$$

where

Q = Rate of heat release (kW)

α = Fire intensity coefficient (kW/sec^n)

t = Time (sec)

n = 1, 2, 3

Later, it was shown that for most flaming fires (except flammable liquids and some others) $n = 2$, the so-called *t*-squared growth rate.[6] A set of specific *t*-squared fires labeled slow, medium, and fast, with fire intensity coefficients such that the fires reached 1000 Btu/sec (1055 kW) in 600, 300, and 150 seconds, respectively, were proposed for design of fire detection systems.[7] Later, these specific growth curves and a fourth called "ultrafast,"[8] which reaches 1055 kW in 75 seconds, gained favor in general fire protection applications.

This set of *t*-squared growth curves is shown in Figure 3.7.2. The slow curve is appropriate for fires involving thick, solid objects (e.g., solid wood table, bedroom dresser, or cabinet). The medium growth curve is typical of solid fuels of lower density (e.g., upholstered furniture and mattresses). Fast fires are thin, combustible items (e.g., paper, cardboard boxes, draperies). Ultrafast fires are some flammable liquids, some older types of upholstered furniture and mattresses, or materials containing other highly volatile fuels.

These *t*-squared curves represent fire growth starting with a reasonably large, flaming ignition source. With small sources, there is an incubation period before established flaming, which can influence the response of smoke detectors. During this incubation period, the fire may not significantly grow in size, although smoke would still be produced in quantities potentially sufficient to activate smoke detectors.

This specific set of fire growth curves has been incorporated into several design methods, such as that for the design of fire detection systems in *NFPA 72®, National Fire Alarm Code®*. They are also referenced as appropriate design fires in several international methods for performing alternative design analyses in Australia and Japan and in a product fire risk analysis method published in this country.[9] Although in the Australian methodology the selection of growth curve is related to the fuel load (mass of combustible material per unit floor area), this is not justified, since the growth rate is related to the form, arrangement, and type of material and not simply its quantity. Consider

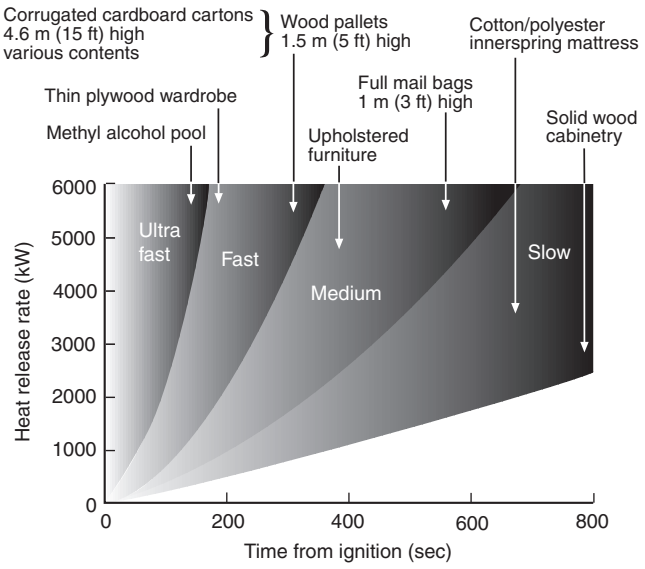

FIGURE 3.7.2 Set of *t*-Squared Growth Curves

22 lb (10 kg) of wood arranged in a solid cube, as sticks arranged in a crib, and as a layer of sawdust (Figure 3.7.3). These three arrangements would have significantly different growth rates although representing identical fuel loads.

Steady Burning. Where a fire scenario involves a fire in an enclosure, fire growth might continue until all the combustible items within the room are involved. Once this occurs, the rate of burning is influenced by one of two factors: (1) the available ventilation or (2) the available fuel. Calculation of fire temperatures within the room is easily accomplished by use of simple algebraic equations. Although computer models are frequently used in hazard analyses, they are generally no more accurate (and indeed may be less accurate) than simple hand calculations for prediction of temperature and burning rate during fully developed burning.[10] For example, for postflashover fires, hand calculation methods are generally used to estimate compartment temperatures.[11]

SFPE's engineering guide[11] on fire exposures of structural elements provides calculation methods for predicting fire temperatures and burning rates in fully developed compartment fires. Some of these methods are based on an assumption of ventilation-limited burning, and others model fuel-controlled conditions. For most cases, the method developed by Law was found to provide bounding predictions when the "Ψ" factor was not used and the predicted burning duration was increased by a factor of 1.4.

Law's method is as follows:

$$T = T_{gm}(1 - e^{-0.05\Psi})(^{\circ}C) \tag{9}$$

$$T_{gm} = 6000 \left(\frac{1 - e^{-0.1 \frac{A}{A_o\sqrt{H_o}}}}{\sqrt{\frac{A}{A_o\sqrt{H_o}}}} \right) (^{\circ}C)$$

$$\dot{m}_f = 0.18 A_o \sqrt{H_o} \left(\frac{W}{D}\right) \left(1 - e^{-0.036 \frac{A}{A_o\sqrt{H_o}}}\right) (kg/sec)$$

where

T_{gm} = Maximum compartment temperature (°C)

A = Surface area of interior of enclosure (m^2)

A_o = Area of ventilation opening (m^2)

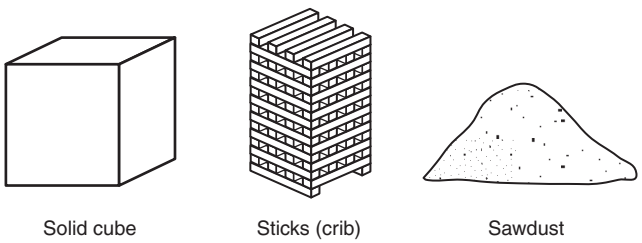

FIGURE 3.7.3 Dependence of Fire Growth on Fuel Form and Arrangements

H_o = Height of ventilation opening (m)

$$\Psi = \frac{m_f}{\sqrt{A \times A_o}}$$

m_f = Mass of fuel (kg)

$\dot{m}_f$ = Mass burning rate of fuel (kg/sec)

W = Width of wall containing ventilation opening (m)

D = Depth of compartment (m)

Law reports that the correlation for predicting burning rate is valid for

$$\frac{\dot{m}_f}{A_o\sqrt{H_o}}\left(\frac{D}{W}\right)^{1/2} < 60$$

In some cases, it may only be desired to predict whether flashover is possible for a given fire scenario involving a fire in an enclosure. In such cases, the approach described in the section Prediction of Flashover can be used.[12]

Decay. All fires eventually decrease in size. A fire can decay for one of three reasons: consumption of available fuel, oxygen depletion, or suppression. Because the hazards posed during the decay phase are typically insignificant in comparison to the hazards posed during the fully developed phase, decay is typically omitted from analysis. An exception is in calculations involving structural fire resistance of concrete or insulated steel. Where test data are available, they might include decay.

If decay occurs due to the exhaustion of fuel, Table 3.7.1 shows the expected temperature change as fuel is depleted.[11] For fires with a predicted duration of less than 60 minutes, a decay rate of 10°C/min can be used. In other case, a decay rate of 7°C/min can be used.

Decay could also occur in the event that a sprinkler system is present and activated. A simple assumption is that the fire immediately goes out, but this is not conservative. A National Institute of Standards and Technology (NIST) study documents a (conservative) exponential diminution in burning rate under the application of water from a sprinkler (Figure 3.7.4).[13] Since the combustion efficiency is affected by the application of water, the use of values for soot and gas yields appropriate for post-flashover burning would represent the conservative approach in the absence of experimental data.

Prediction of Flashover. Flashover occurs when a fire grows to such a size that it involves all combustible items within an enclosed room. Although occurrence of flashover is not a hazard in itself, flashover would affect the occurrence of other hazards as described in the next section. Several correlations are available to predict the minimum heat release rate necessary for flashover

TABLE 3.7.1 Rate of Decrease in Temperature

Temperature Decay (°C/min)	*Restrictions*
10	Duration < 60 minutes
7	Duration > 60 minutes

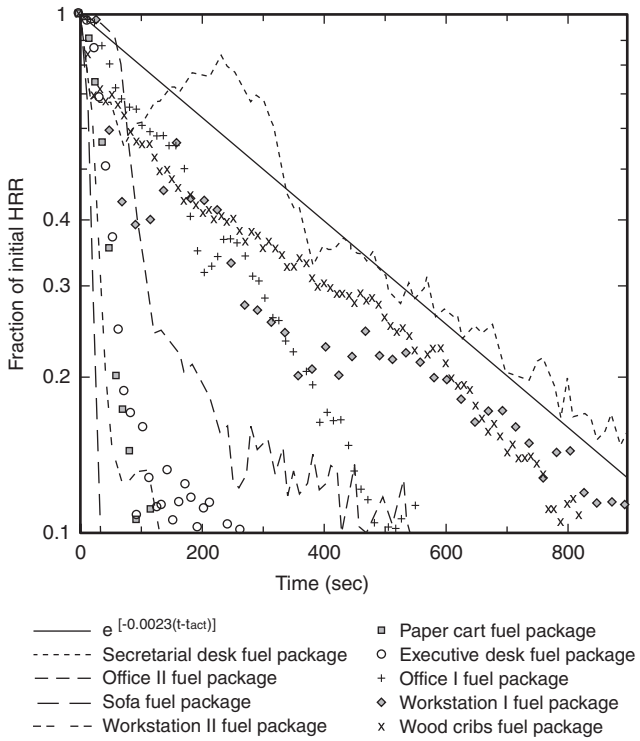

FIGURE 3.7.4 Decay Rates for Various Fuels

to occur in a room. The time at which flashover occurs can be estimated by determining when the fire is predicted to reach this minimum size. The following methods can be used to predict the minimum heat release rate necessary for flashover.[12]

- Method of Babrauskas

$$\dot{Q} = 750A_o\sqrt{H_o} \quad (9)$$

where

$\dot{Q}$ = Minimum heat release rate required for flashover (kW)

A_o = Area of opening into compartment (m^2)

H_o = Height of opening into compartment (m)

- Method of McCaffrey, Quintiere, and Harkleroad

$$\dot{Q} = 610(h_k A_T A_o \sqrt{H_o})^{1/2} \quad (10)$$

where

$$h_k = \frac{k}{\delta}$$

k = Thermal conductivity of compartment surface (kW/m·K)

δ = Thickness of compartment surface (m)

A_T = Total area of compartment surfaces (m^2)

- Method of Thomas

$$\dot{Q} = 7.8A_T + 378A_o\sqrt{H_o} \quad (11)$$

where the variables are as defined above.

PREDICTION OF HAZARDS

Fire is a dynamic process of interacting physics and chemistry, so predicting what is likely to happen under a given set of circumstances is daunting. The simplest predictive methods are algebraic equations. Computer models are used to automate fire hazard calculations and are particularly useful where many repeated calculations must be performed.

Simple Fire Hazard Calculations

Once the design fire curve has been developed, it is then possible to predict the hazards that would result. The types of hazards that might be of interest include the following:

- Radiant heat flux, which affects the potential for ignition of materials or thermal injury to people
- Smoke production, which dictates the volume of smoke produced
- Fire plume and ceiling jet temperatures and velocities, which could cause weakening of exposed structural elements
- Species production, which affects the rate at which an untenable environment could be created
- Depth of upper layer, which can be used as a surrogate for an untenable environment

As was the case with the stages of design fire curves, it is not always necessary to quantify all of the hazards that result from a design fire scenario. The hazards that are quantified are a function of the goals of the analysis. For example, if the purpose of the analysis is to determine whether a thermally activated detection or suppression system activates, only the plume and ceiling jet temperatures and velocities might be determined. For analysis of a smoke control system, only the smoke production rate might be determined. A structural analysis might only require calculation of the heat transfer to the structure. An evacuation analysis might require quantification of all of the hazards listed.

Radiant Heat Flux. Radiant heat flux is a measure of the rate of radiative heat transfer per unit area. An example of radiant heat transfer is the heating that can be felt from exposure to the sun on a hot day (although the intensity of thermal radiation in sunlight is too small to be of concern from a fire standpoint). The radiant heat flux from a single burning item can be predicted as a function of the distance from the item in accordance with Equation 18 of Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations." For radiant heat fluxes resulting from fire gases, such as in a compartment fire, the radiant heat flux can be calculated if the gas temperature and the temperature of the target object are known by applying the following equation:

$$\dot{Q}_r = \varepsilon\sigma(T_1^4 - T_2^4) \tag{12}$$

where

$\dot{Q}_r$ = Rate of radiant heat transfer (kW)

ε = Emissivity of gas (0–1) (—)

σ = Stephan-Boltzmann constant (5.67×10^{-11} kW/m^2·K^4)

T_1 = Temperature of gas (K)

T_2 = Temperature of target (K)

The equation is only applicable for instantaneous calculations, as the temperature of the target will rise as a function of the thermal radiation that it receives.

Smoke Production. When calculating smoke production rates, *smoke* is usually defined as the products of combustion and the air entrained into the fire plume. Therefore, the amount of smoke produced is a function of the height above the fire. Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations," provides a number of equations that can be used to predict smoke production.

Fire Plumes and Ceiling Jet Temperatures and Velocities. A fire will produce a plume of hot gas that will rise and contact the ceiling of a compartment, forming a ceiling jet. The temperature and velocity of a plume can be calculated as described in Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations." Similarly, the temperature and velocity of a ceiling jet can be calculated in accordance with the following equations:[14]

$$\text{For } 0.18 \geq \frac{r}{H} \qquad \Delta T = \frac{16.9\dot{Q}^{2/3}}{H^{5/3}} \tag{13}$$

$$\text{For } \frac{r}{H} > 0.18 \qquad \Delta T = \frac{5.38(\dot{Q}/r)^{2/3}}{H} \tag{14}$$

$$\text{For } 0.15 \geq \frac{r}{H} \qquad U = 0.96\left(\frac{\dot{Q}}{H}\right)^{1/3} \tag{15}$$

$$\text{For } \frac{r}{H} > 0.15 \qquad U = \frac{0.195\dot{Q}^{1/3}H^{1/2}}{(r/H)^{5/6}} \tag{16}$$

where

ΔT = Temperature rise over ambient (°C)

U = Ceiling jet velocity (m/sec)

H = Height above fire (m)

r = Horizontal distance from fire centerline (m)

$\dot{Q}$ = Total heat release rate (kW)

When using these equations, it must be cautioned that they are only valid for horizontal, unobstructed ceilings where there is no smoke layer present. In cases where a layer forms, higher temperature rises can be expected.

Species Production. Fires can create a number of products of combustion that can be toxic or corrosive, including carbon dioxide (CO_2), water vapor (H_2O), carbon monoxide (CO), and many others that vary with the fuel and burning conditions. Species production rates can be calculated from the following equation:[15]

$$\dot{G}_j = y_j\frac{\dot{Q}}{\Delta H_c} \tag{17}$$

where

$\dot{G}_j$ = Smoke production rate of species j (kg/sec)

y_j = Yield fraction of species j (–)

$\dot{Q}$ = Heat release rate (kW)

ΔH_c = Heat of combustion of fuel (kJ/kg)

Yield fractions for several fuels are available in the *SFPE Handbook of Fire Protection Engineering*.[15]

Depth of Upper Layer. As smoke is produced in a compartment, it forms a layer that descends as a function of time. This is analogous to filling a bowl of water. Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations," provides an equation that can be used to estimate the velocity of descent of the smoke layer. However, when applying this equation, it should be noted that the mass production rate of smoke is not constant, since as the layer descends, the smoke production rate decreases due to the reduced vertical distance available to entrain air into the plume. (See the equations for predicting smoke production rate in the same chapter.)

Toxicity. Toxic gases produced by a fire can incapacitate or kill people who are exposed to them. A commonly used approach to determine whether the fire-induced environment is potentially harmful to people exposed is the "fractional effective dose" (FED) model developed by Purser.[16] This can be expressed as follows:

$$F_{IN} = [(F_{I_{CO}} + F_{I_{CN}} + FLC_{irr}) \times V\mathrm{CO}_2 + FED_{I_O}] \quad \text{or } F_{I_{CO_2}} \tag{18}$$

where

F_{IN} = Fraction of an incapacitating dose of all asphyxiating gases

$F_{I_{CO}}$ = Fraction of an incapacitating dose of CO

$F_{I_{CN}}$ = Fraction of an incapacitating dose of HCN

FLC_{irr} = Fraction of irritant dose

$V\mathrm{CO}_2$ = Multiplication factor for CO_2-induced hyperventilation

FED_{I_O} = Fraction of an incapacitating dose of low-oxygen hypoxia

$F_{I_{CO_2}}$ = Fraction of an incapacitating dose of CO_2

Purser gives the following equations for calculation of the individual fractional effective doses:[16]

$$F_{I_{CO}} = \frac{8.2925 \times 10^{-4} \times [\mathrm{CO}]^{1.036}}{30} \tag{19}$$

where [CO] is the concentration of CO, expressed in parts per million.

$$F_{I_{CN}} = \frac{\exp(\mathrm{CN}/43)}{220} \tag{20}$$

where

CN = The concentration of HCN in parts per million added to the concentration of other nitriles minus the concentration of NO_2

FLC_{irr} = The fraction of the incapacitating dose from all incapacitating products (HCl, HBr, etc.)

$V\mathrm{CO}_2 = \exp\left(\frac{[\mathrm{CO}_2]}{5}\right)$, where $[CO_2]$ is the concentration of carbon dioxide in percent

$FED_{I_O} = \{\exp[8.13 - 0.54(20.9 - [O_2])]\}^{-1}$, where $[O_2]$ is the concentration of oxygen in percent

$F_{I_{CO_2}} = \{\exp[6.1623 - 0.5189[CO_2]]\}^{-1}$, where $[CO_2]$ is the concentration of CO_2 in percent

It should be noted that the equations for FED and the components of FED are based on a one minute exposure. For exposures to constant concentrations of fire products, the FED can be determined by multiplying the value determined using the previous equations by the exposure time in minutes. For exposures where the concentrations vary with time, the total FED can be calculated by discretizing the exposure (determining the average exposure at each one minute interval and summing the FED determined for each one minute interval).

It should be noted when applying the previous correlations that some populations are more susceptible than others to fire products (e.g., asthmatics, the old, and the young). Additionally, no single FED value for design has been widely agreed on even for "average" populations. A report by the National Institute of Standards and Technology investigates this subject in detail.[17]

Egress Calculations. Evacuation calculations are sometimes simple enough to be done by hand. The most thorough presentation on this subject (and the one that is most often used in alternative design analysis) is that of Nelson and Mowrer.[18] See also Section 4, Chapter 2, "Calculation Methods for Egress Prediction."

Simple Analytical Solution Techniques

Simple computer programs and spreadsheets can be used to perform simple fire hazard calculations. In the case of the equations listed previously or referenced in other chapters, this is a relatively straightforward task. However, many fires and fire effects are not steady state. An example is smoke filling within an enclosure. The smoke production rate is a function of the smoke layer height, so the rate of smoke layer descent is not constant. In such instances, spreadsheets can be used to develop solutions to differential equations for which developing an exact solution is nontrivial.

For a differential equation of the following form:

$$\frac{dy}{dt} = f(y, t) \tag{21}$$

where the initial value $y(t = 0)$ is y_0.

The Euler method is a numerical technique for solving differential equations of this form, and can be stated as

$$y_{n+1} = y_n + hf(y_n, t_n) \tag{22}$$

where

y_n = Value of equation y at time step n

y_{n+1} = Value of equation y at time step $n + 1$

h = Time step size

This process can be iterated over the desired length of time to obtain the desired solution. Since the Euler method determines the value of equation y at time step $n + 1$ based on the value at time step n and the slope of the tangent to y at time step n, errors can be introduced based on the nonlinearity of equation y. There are methods available to reduce this error, such as the improved Euler method.

However, another method of reducing the error is to reduce the size of the time step, recognizing that as the size of the time step approaches zero, the difference between the predicted value of y and the actual value of y also approaches zero. The computational power offered by modern computers allows very small time steps to be used and to still get a solution rapidly.

It should be noted that the default for many spreadsheets is to not permit iterative calculations. (The spreadsheet views the "circular reference" as an error.) Spreadsheets for which this is the case would need to be configured to allow iteration. The spreadsheet's user's manual or help function can be consulted for assistance.

EXAMPLE. *Thermal detector response can be used to illustrate application of the Euler method to a fire protection problem.* This example uses an algorithm similar to that used by the computer fire model DETACT-QS[19] to predict the time to activation of a thermal detector for a heat release rate that follows a power law curve. Two calculations will be performed. First, the instantaneous ceiling jet velocities are calculated in accordance with Equations 13 through 16. A quasi-steady assumption is made, which means that transport delays from the fire to the detector are ignored. Then, based on the temperature and velocity of the ceiling jet and the thermal response characteristics of the sensor (response time index), the temperature change at the detector will be calculated. See Section 16, "Water-Based Fire Suppression Equipment" for more information. The change in temperature of the detector can be expressed as[20]

$$\frac{dT_d}{dt} = \frac{\sqrt{U_g}(T_g - T_d)}{RTI} \tag{23}$$

where

T_d = Temperature of detector (°C)

U_g = Ceiling jet velocity at detector (m/sec)

T_g = Ceiling jet temperature at detector (°C)

t = Time (sec)

RTI = Detector response time index ($m^{1/2} \times sec^{1/2}$)

A Euler solution to this expression can be expressed as

$$T_{d_{n+1}} + T_{d_n} + \Delta t \frac{\sqrt{U_g}(T_g - T_{d_n})}{RTI} \tag{24}$$

where

$T_{d_{n+1}}$ = Temperature of detector at time step $n + 1$ (°C)

T_{d_n} = Temperature of detector at time step n (°C)

Δt = Size of time step (sec)

Equation 24 could easily be programmed into a spreadsheet or simple computer program, along with the ceiling jet temperature and velocity correlations expressed in Equations 13 through 16, to calculate U_g and T_g. It is also necessary to include a method of calculating the heat release rate at each time step.

The following example illustrates the use of this method in estimating thermal detector response. A heat detector is located on a 3 m high ceiling, 2 m away from a fire located on the floor with a constant heat release rate of 1000 kW. The room has an ambient temperature of 20°C and is sufficiently large that a smoke layer will not form quickly. The heat detector has a temperature rating of 75°C and an RTI of 50 $m^{½}sec^{½}$. When would the detector operate? Using Equation 24 and Equations 13 through 16, the solutions in Table 3.7.2 are obtained when different time steps are used.

Computer Models

Fire Models. A survey[21] documented available models and calculation methods that could be applied to FHA. The key to determining which are appropriate to a given situation and which are not is a thorough understanding of the assumptions and limitations of the individual model or calculation and how these relate to the situation being analyzed. Single-room models are appropriate where the conditions of interest are limited to a single, enclosed space. Where the area of interest involves more than one space, and especially where the area of interest extends beyond a single floor, multiple-compartment models should be used. This is because the interconnected spaces interact to influence fire development and flows.

Many single-compartment models assume that the lower layer remains at ambient conditions (e.g., ASET).[22] Since there is little mixing between layers in a room (unless there are mechanical systems), these models are appropriate. However, significant mixing can occur in doorways, so multiple-compartment models should allow the lower layer to be contaminated by energy and mass (Figure 3.7.5).

The model should include the limitation of burning by available oxygen. This is straightforward to implement (based on the oxygen consumption principle) and is crucial to obtaining an accurate prediction for ventilation-controlled burning. For multiple-compartment models, it is equally important for the model to track unburned fuel and allow it to burn when it encounters sufficient oxygen and temperature. Without these features, the model concentrates the combustion in the room of origin, overpredicting conditions there and underpredicting conditions in other spaces.

TABLE 3.7.2 Time Step(s) Predicted Activation Time(s)

Time Step(s)	*Predicted Activation Time(s)*
1	24.000
0.1	24.200
0.01	24.230
0.001	24.229

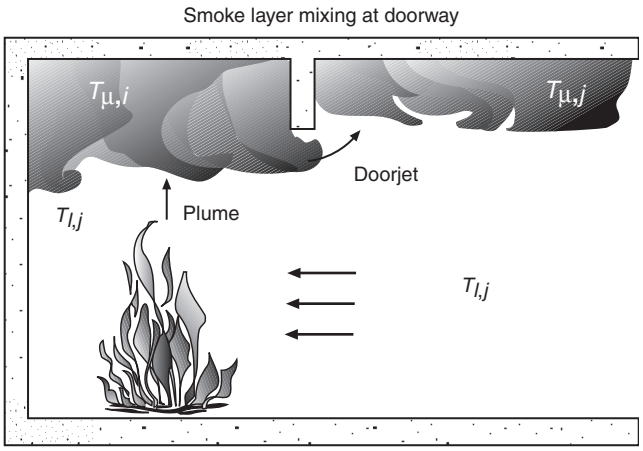

FIGURE 3.7.5 Assumption of Zone Models That Fire Gases Collect in Internally Uniform Layers

Heat transfer calculations take up a lot of computer time, so many models take a shortcut. The most common is the use of a constant "heat loss fraction," which is user-selectable (e.g., ASET or CCFM[23]). The problem is that heat loss can vary during the course of the fire.

Another problem can occur in tall spaces, for example, atria. The major source of gas expansion and energy and mass dilution is entrainment of ambient air into the fire plume. It can be argued that in a very tall plume, this entrainment is constrained. However, most models do not include this constraint, which can lead to an underestimate of the temperature and smoke density and an overestimate of the layer volume and filling rate—the combination of which may give predictions of available safe egress times that are either greater or less than the correct value. In the model CFAST,[24] this constraint is implemented by stopping entrainment when the plume temperature drops to within 1°C of the temperature just outside the plume, where buoyancy ceases.

Documentation. Only models that are rigorously documented should be allowed in any application involving public health, safety, or welfare, such as in code enforcement or litigation. This means that the model should be supplied with a technical reference guide that includes a detailed description of the included physics and chemistry, with proper literature references; a listing of all assumptions and limitations of the model; and estimates of the accuracy of the resulting predictions, based on comparisons to experimental data. Public exposure and review of the exact basis for a model's calculations, internal constants, and assumptions are necessary for it to have credibility in a regulatory application.

ASTM publishes a *Standard Guide for Documenting Computer Software for Fire Models,* ASTM E1472-05.[25] Documentation for any model used in a regulatory application should comply with this guide. Although it may not be necessary for the full source code to be available, the method of implementing key calculations in the code and details of the numerical solver used should be included. This documentation should be freely available to any user of the model, and a copy should be supplied with the analysis as an important supporting document.

Input Data. Even if the model is correct, the results can be seriously in error if the data that are input to the model do not represent the condition being analyzed. The FHA should include a listing of all data values used, their source (i.e., what apparatus or test method was employed and what organization ran the test and published the data), and some discussion of the uncertainty of the data and its result on the conclusions. The National Institute of Standards and Technology's (NIST) website contains a section of well-documented data for use in calculations, called *Fire on the Web* (http://fire.nist.gov). A much larger database, called FASTDATA, is available from NIST on a CD-ROM (see the URL above for information). (See also the subsection entitled "Accounting for Uncertainty" later in this chapter.)

Egress Models. The prediction of the time needed by the building occupants to evacuate to a safe area can be performed and compared to the predicted available safe egress time. Whether the evacuation calculation is done by model or hand calculation, it must account for several crucial factors. First, unless the occupants see the actual fire, time is required for detection and notification *before* the evacuation process can begin. Next, unless the information is compelling (such as seeing the actual fire), it takes time for people to decide to take action. The action they choose may or may not be evacuation. Finally, the movement begins. All of these factors require time, and that is the critical factor. No matter how the calculation is done, *all* of the factors must be included in the analysis to obtain a complete picture. An excellent discussion of this topic is found in SFPE's *Engineering Guide—Human Behavior in Fire.*[26]

The process of emergency evacuation of people follows the general concepts of traffic flow. A number of models perform such calculations and may be appropriate for use in certain occupancies. Most of these models do not account for behavior and the interaction of people (providing assistance) during the event. The literature reports incidents of providing assistance to disabled persons, again especially in office settings.[27] If such behavior is expected, it should be included, as it can result in significant delays in evacuating a building.

Crowded conditions, as well as smoke density, can result in reduced walking speeds.[28] A person's walking speed decreases in dense smoke until he or she moves as if blindfolded (Figure 3.7.6). Care should be exercised in using models relative to how they select the path (usually the *shortest* path) that the person travels. Some models are *optimization* calculations that give the best possible performance.

Analyzing the Impact of Exposure

In most cases, the exposure will be to people, and the methods used to assess the impacts of exposure of people to heat and combustion gases involve the application of combustion toxicology models. The HAZARD I software package contains the only toxicological computer model, called TENAB,[29] that is based on research at NIST on lethality to rats and by Purser on incapacitation of monkeys. TENAB accounts for the variation

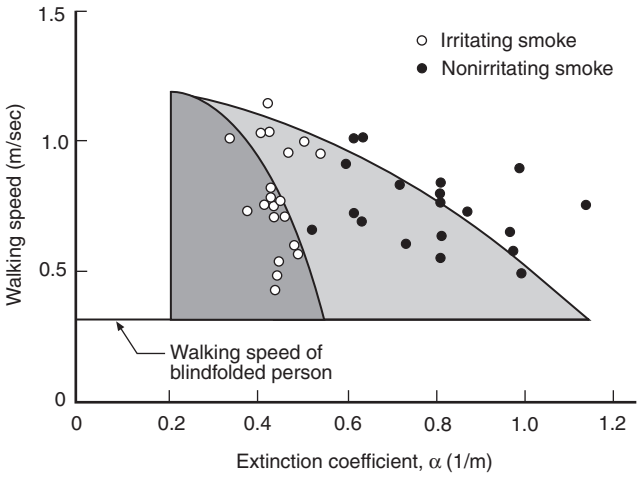

FIGURE 3.7.6 Reduced Walking Speeds Resulting from Crowded Conditions and Smoke Density

in exposure to combustion products as people move through a building, by reading the concentrations from the fire model in the occupied space during the time the person is in that space. If the person moves into a space with a lower concentration of carbon monoxide, the accumulated dose can decrease. Details such as these ensure that the results are reasonable.

Assessing the impact of exposure to sensitive equipment is more difficult, since little data exist in the literature on the effects of smoke exposure on such equipment. Of particular importance here is the existence of acid gases in smoke, which are corrosive and especially harmful to electronics. Fuels containing chlorine (e.g., polyvinyl chlorides) have been studied. However, unless the equipment is close to the fire, acid gases, especially HCl, deposit on the walls and lower the concentration to which the equipment may be exposed. CFAST in the HAZARD I package contains a routine that models this process and the associated diminution of HCl concentration.

Accounting for Uncertainty

Uncertainty analysis refers to dealing with the unknowns and variation inherent in any prediction. In the calculations, this uncertainty is derived from assumptions in the models and from the representativeness of the input data. In evacuation calculations, there is the added variability of any population of real people. In building designs and codes, the classic method of treating uncertainty is with safety factors. A sufficient safety factor is applied such that, if all of the uncertainty resulted in error in the same direction, the result would still provide an acceptable solution. In the prediction of fire development/filling time, the intent is to select design fires that provide a *worst likely* scenario. Thus a safety factor is not needed here, unless assumptions or data are used to which the predicted result is very sensitive.

The FHA report should include a discussion of uncertainty. This discussion should address the representativeness of the data used and the sensitivity of the results to data and assumptions made. If the sensitivity is not readily apparent, a sensitivity analysis (i.e., varying the data to the limits and seeing whether the conclusions change) should be performed. This is also a good time to justify the appropriateness of the model or calculation method. For more information, see Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety."

Final Review

If a model or calculation produces a result that seems counterintuitive, there is probably something wrong. Cases have been seen in which the model clearly produced a wrong answer (e.g., the temperature predicted approached the surface temperature of the sun), and there have been others in which it initially looked wrong but was not (e.g., a *dropping* temperature in a space adjacent to a room with a growing fire was caused by cold air from outdoors being drawn in an open door). Conversely, if the result is consistent with logic, sense, and experience, it is probably correct. This is also a good time to consider whether the analysis addressed all of the important scenarios and likely events. Were all the assumptions justified and were uncertainties addressed sufficiently to provide a comfort level similar to that obtained when the plan review shows that all code requirements have been met?

SUMMARY

Quantitative fire hazard analysis is becoming the fundamental tool of modern fire safety engineering practice and is the enabling technology for the transition to performance-based codes and standards. (For more information on performance-based codes, see Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety.") The tools and techniques described in this chapter provide an introduction to this topic and the motivation for fire protection engineers to learn more about the proper application of this technology.

Predicted fire hazards are a function of the design fire scenarios analyzed. Therefore, when performing a fire hazard analysis, it is important to select design fire scenarios that are challenging enough to represent a realistic "worst case," but not so challenging that the likelihood of occurrence is too remote.

There are many fire hazard calculations that can be performed with a hand calculator, a simple spreadsheet, or a computer program. In some cases, these simple methods would not be sufficient, for example, in cases where compartment geometry is complex, where it is desired to optimize cost/benefit, or where predicted hazard values are very close to acceptable limits. However, even in these types of cases, simple methods can be used for initial predictions or as a reality check of results from more complex models.

In any engineering analysis, it is incumbent on the user to understand the application and limitation of any methods used. This chapter has outlined a number of simple fire hazard calculation methods, but the applicability and limitations of the methods were not included. Users are referred to the documents referenced in the text for information regarding the applications and limitations of any of the methods included in this chapter.

ACKNOWLEDGMENT

James R. Quiter, P.E., wrote portions of the discussion of design fire scenarios, which originally appeared in the "Simple Fire Hazard Calculations" chapter in the 19th edition of this handbook.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire hazard analysis techniques discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 72®, National Fire Alarm Code®
NFPA *101®, Life Safety Code®*
NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*

Chapter 8

Fire Risk Analysis

John R. Hall, Jr. ■ John M. Watts, Jr.

Chapter Contents

Overview of Fire Analysis
General Approaches to Risk Evaluation
Analysis Frameworks

Key Terms

acceptable risk, consequence analysis, cost-benefit analysis, cost-effectiveness evaluation, event tree, fault tree, fire hazard, fire risk analysis, hazard analysis, probability analysis, risk estimation, risk evaluation, scenario cluster, scenario structure

Fire risk analysis is the most comprehensive form of analysis that can be applied to any fire safety choice. It looks at all the types of fires that may be affected by the choice, for example, of product, of building design, or of anything potentially affecting fire safety, not just one fire or a few selected fires. It provides a flexible framework for estimating the impact of any type of fire safety program or strategy in terms of actual reductions in losses—deaths, injuries, and property damage—and in terms that can be compared to the costs of those programs and strategies. There is no other method as well suited for the analysis of strategic options affecting large numbers of properties and their occupants. Product development, related research and marketing, and regulatory decisions can benefit from fire risk analysis, as can any program to manage and oversee fire safety from a financial point of view.

Also see Section 3, Chapter 4, "Use of Fire Incident Data and Statistics."

OVERVIEW OF FIRE ANALYSIS

Fire Risk Analysis Defined

Fire risk analysis supports risk reduction decisions by (1) identifying and grouping every type of unwanted fire that can lead to adverse consequences, (2) characterizing the severity of those consequences, and (3) characterizing the likelihood of those types or groups of fires. Fire types are called *scenarios*, and scenario characterization normally begins with hazard identification. *Fire hazard* is any condition with the potential to create (fire-related) harm. When that potential is quantified as to severity, this is *consequence analysis*, whereas the characterization of likelihood is called *probability analysis*.

The term *fire risk analysis* has sometimes been used to refer to an exercise of listing locations under the jurisdiction of the analyst that present the greatest potential for fire damage or for demand on fire suppression resources. Such an exercise lacks most or all of the key elements of a true fire risk analysis.

Other commonly used analysis approaches present subtler problems. Fire protection engineers often focus on alternative means for dealing with fires after fire has begun. It might seem natural to construct a fire risk analysis that takes established burning as given but measures the probability of performance for all building features and systems that operate after the fire. Assuming that it makes sense to write off fire prevention, there still will be a need to address explicitly different types of initial fires. A fast, accelerant-driven fire or an initial explosion will challenge the built-in fire protection in different ways than an ordinary flaming or smoldering fire. A concealed-space fire will present different problems than a fire in a room, and both will differ from fires that start in a means of egress. If each of these fires is analyzed separately, if the analysis leans on physics and chemistry, and if the focus is on preventing major fire extent as an either-or proposition, then the subject is more properly termed a *hazard analysis.* Although the terminology is not standardized, hazard analysis is best used to describe analyses that do not treat most probabilities explicitly, particularly probabilities of ignition and probabilities of occupant characteristics and behaviors. *Risk analysis* should be reserved for analyses that address all relevant probabilities.

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Fire Risk Assessment Process

A number of documents have recently emerged to support the application of fire risk analysis:

- *SFPE Engineering Guide to Application of Risk Assessment in Fire Protection Design*[1]
- NFPA 551, *Guide for the Evaluation of Fire Risk Assessments*[2]
- ISO/TS 16732, *Fire Safety Engineering—Guidance on Fire Risk Assessment*[3]
- ASTM E1776, *Standard Guide for Development of Fire-Risk-Assessment Standards*[4]

Figure 3.8.1 provides a simple overview of the risk estimation calculations at the heart of fire risk analysis. However, there are important steps not shown in this figure.

Figure 3.8.2 embeds this calculation sequence in the larger fire risk assessment process, with its critically important additional steps of (1) setting goals, objectives, and criteria; (2) developing scenarios from identified hazards and analyzing each one; and (3) comparing calculated risk to selected criteria to determine risk acceptability. A more detailed version of Figure 3.8.2 is used as the defining structure for the *SFPE Engineering Guide to Application of Risk Assessment in Fire Protection Design*, and a similar figure is given in ISO TS 16732.

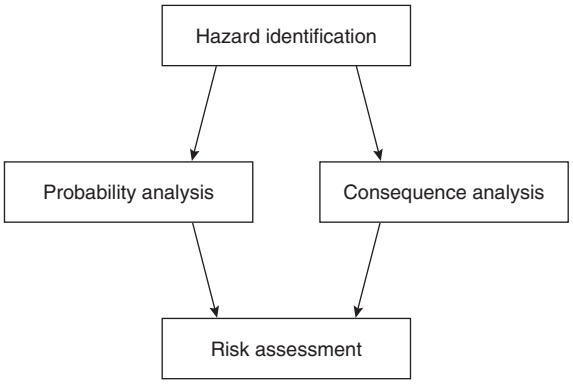

FIGURE 3.8.1 Risk Estimation Process

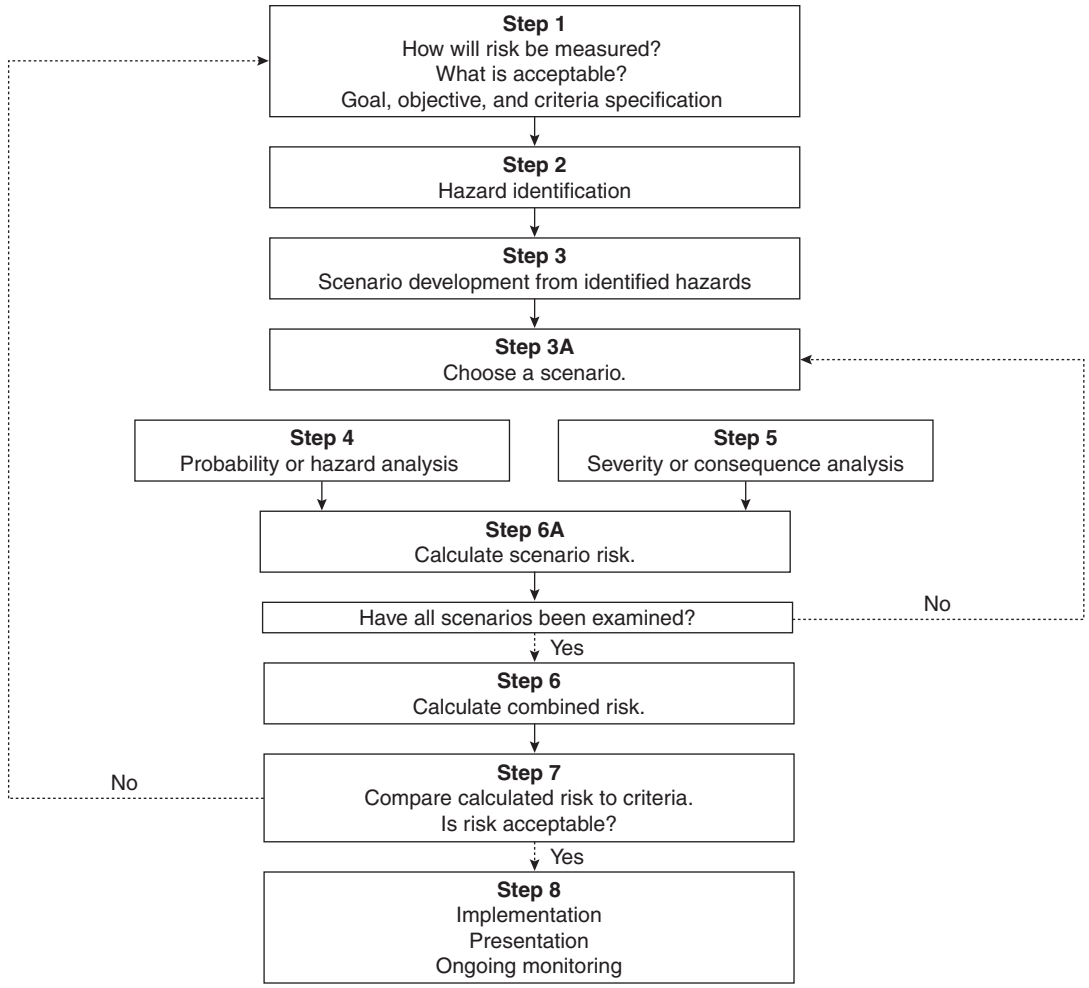

FIGURE 3.8.2 Risk Assessment Process

Figure 3.8.2 also shows the need to state, in terms suitable for analysis, the design or other decision that will be the subject of the fire risk analysis. The format and level of detail required for this specification of the decision are dictated by the models and their input data needs. Every input variable and parameter must correspond to (1) some specification of the design or other decision, (2) some defining element of the scenario, or (3) some additional assumption about the environment in which fire will occur and challenge the building, its occupants, or other setting.

If the proposed change involves the installation of new built-in smoke detection systems, for example, specifications for the systems would be needed. If the systems were available in two or more versions (e.g., ionization and photoelectric smoke detectors), the probability of each version being used should be estimated (e.g., from data on usage patterns or projected shares of market). Probabilities also would be needed for the variations in status of a system (e.g., fully operational, operational but blocked in one room, turned off, or removed). These specifications dictate precisely what fire protection and fire-related features would be in place to influence the course of fire if one occurs.

If the proposed change involves training staff or educating occupants, similar questions would be asked: What are the specifics of the program(s)? What is the likelihood that each version of the program would be used? If fire occurs, what would be the status of the program (e.g., everyone was trained and acted accordingly, some missed the training, some forgot, some panicked)?

It is sometimes useful to separate the parts of the decision model into those characteristics that were selected by a building owner or manager (e.g., a sprinkler was installed) and those that came into play after the selection (e.g., the sprinkler was installed incorrectly). The latter parts are those factors that are hardest to control, either because they require continued alertness (e.g., without scheduled testing and maintenance, a sprinkler system's reliability will decrease) or because they are not directly under the control of the building owner or manager (e.g., a manager can order a sprinkler system but has to work through others to make sure it is installed properly).

Neither the implementation model nor the larger decision model needs every bit of information on the proposed changes. The models need only those details that will affect the likelihood of having a fire, the development of that fire, or the reactions of people and property to the fire. For example, some factors will incapacitate the system so that the fire will develop as if no system were present, and that is all the information needed. Some factors will degrade system performance but still permit some impact on fire development; it may be possible to model such reduced impact as simple modifications to the impact expected if the system were fully functional.

Goals, Objectives, and Criteria

Goals, objectives, and criteria are the logical and mathematical representations by which value judgments are made about risk acceptability. As value judgments, they are not purely scientific constructs and are not governed solely, or even primarily, by engineering judgment, science, and empirical evidence. Instead, a process must be developed that will involve stakeholders and produce goals, objectives, and criteria that can be supported, or at least accepted, by all affected and interested parties. See the *SFPE Engineering Guide to Application of Risk Assessment in Fire Protection Design* for more details.

Specification of the criterion is not only a matter of deciding what kind of harm—such as deaths, injuries, property damage, or business interruption—is of concern. Sometimes, the most appropriate measure is not a simple count of how much harm is of concern.

For example, suppose harm to people is clearly of concern. Are all kinds of injuries of concern or only fatal injuries? Are injuries of concern if they are not discovered until hours or days after the fire? Are injuries of concern if they are never recognized as such, as can be the case for some symptoms of carbon monoxide poisoning? Are all injuries or deadly events of equal concern, regardless of how many people are injured or killed? Or is a count of the number of injuries and deaths more appropriate?

Are all injuries relevant, or are people disproportionately, or even exclusively, concerned about injuries in fire that can be attributed to the actions or deficiencies of strangers? Is there any level of user misuse—or of other contributions to ignition or to the degree of harm that followed—that would disqualify the resulting injuries from being counted, or being fully counted, in the severity measure of a risk analysis of a product or building?

Suppose the scale was dollars of damage. A severity measure of the number of dollars of damage would set the stage for a risk analysis on expected loss or average loss, the most common approach. Alternatively, one could set the severity measure equal to 1 if damage exceeded $100,000,000 and 0 otherwise. This would set the stage for a risk analysis focusing on large losses, which might be more useful for an insurance company that worries less about ordinary claims than about a single loss so large that the company cannot cover it.

Fire risk analysis can sometimes be separated into (1) *risk estimation,* the estimation and analysis of the measures of severity and probability and their associated uncertainties, and (2) *risk evaluation,* the additional steps required to decide on the importance of a particular value of risk or a change in risk. A fire risk analysis that includes risk evaluation may be called a *fire risk assessment* to underline the fact that the analysis will support value judgments. Risk evaluation involves comparison of the estimated risk to criteria derived from the safety goals and objectives.

GENERAL APPROACHES TO RISK EVALUATION

Cost-Benefit and Cost-Effectiveness Analyses

Risk evaluation should be familiar to anyone who has had to make business decisions because it essentially involves using analysis to determine whether you will get what you pay for. The most common approach to risk evaluation is *cost-benefit analysis,* a technique in which all benefits of risk reduction are

translated into monetary equivalents. This technique permits a proposed new product or fire suppression system to be assessed in terms of its net profit or loss, total cost plus loss, or ratio of profit to loss. In such a context, "profit" means saved lives, avoided injuries, and reduced property damage, all combined in one monetary scale, and "loss" means the cost—both initial and ongoing—of the new product or system. A variation is *cost-effectiveness analysis,* in which the benefits of risk reduction are translated into a single nonmonetary scale. For example, it is possible to derive the cost per life saved for a new system or product.

Cost-benefit and cost-effectiveness analyses require the explicit estimation or derivation of some controversial parameters. Examples include the value of reduced risk of death or injury and the discount rate by which future consequences are compared to present consequences (both discussed in more detail later in this chapter). Because these parameters are controversial, risk evaluation sometimes uses methods that downplay the role of these parameters.

Acceptable Risk

Acceptable risk is a term that is used when the method of risk evaluation involves treating risk as a constraint. This method may seem attractive because it refuses to consider costs until or unless a sufficient degree of fire safety has been provided. In an acceptable risk approach, a certain level of risk is defined as acceptable; then all alternatives meeting that level are evaluated strictly on the basis of cost.

This approach can produce unsatisfactory results. If risk is greater than the acceptable level by even a small fraction, no cost is too great to reach acceptable risk. If risk is already acceptably low, not a nickel more should be spent, no matter how much more fire safety could be purchased for very little money. This means that the selected level of acceptable risk is often set with an eye toward affordability and may be reset if technology changes. In effect, this makes the acceptable risk approach a kind of backdoor cost-benefit analysis and runs counter to most approaches to decision making in business.

When acceptable risk is not defined in terms of affordable risk, it is often defined in terms of (1) historically acceptable risk (i.e., anything in use for a long time is all right), which may be overturned if public understanding of the magnitude of the risk changes dramatically, or (2) unavoidable risk, such as the use of background radiation levels as a guide for acceptable exposure to medical X-rays. In fire protection, acceptable risk has sometimes been inferred from provisions of NFPA codes and standards. The most extreme version of an acceptable risk approach is a minimum risk approach, in which cost is not considered unless all feasible safety improvements have been made.

A logical complement to the acceptable risk approach would be an acceptable cost approach, in which the greatest risk reduction available within the fixed cost budget (but no more) would be sought. Although this approach is rarely mentioned in the literature, it almost certainly describes the way some decisions are made.

Note that the acceptable risk and acceptable cost approaches both can be very sensitive to the initial selection of a single key parameter. If these approaches are used, it is necessary to conduct a sensitivity analysis to see how conclusions would be changed if the reference level of acceptable risk or acceptable cost were different. Sensitivity analysis of key parameters is essential to all other forms of risk analysis as well and is one way in which the uncertainty surrounding estimates can be addressed systematically.

Assumptions in Fire Risk Analysis

In any fire risk analysis, there will be a certain set of assumptions about key conditions in the environment of interest: some or all of the buildings have sprinklers or detectors, some or all of the mattresses were built to a certain ignition-resistance standard, some or all of the occupants have been regularly trained in fire-safe behavior, and so forth.

Fire risk analysis refers to a systematic examination of how measures of fire risk change as the assumptions change. It may be done in conjunction with a parallel examination of changes in costs. On the one hand, if no smoke alarm is present, a household can expect to experience fires with a certain probability, and these fires will have a certain expected severity in terms of deaths, injuries, and property damage. On the other hand, if a smoke alarm is present, the household will pay purchase and maintenance costs that are not paid by the household without smoke alarms, but the smoke alarm household can expect on average to achieve lower severities of losses—and in particular, fewer deaths per fire. Risk analysis is used to quantify the expected size of the reductions in deaths, injuries, and damage. One can then determine whether these risk reductions are great enough to justify the cost. This is an analysis of cost versus risk reduction benefits in which the risk portion is measured explicitly.

Hazard Identification

The topmost box in Figure 3.8.1 and step 2 in Figure 3.8.2 refer to hazard identification. Typical buildings and processes have many fire hazards. Since each hazard represents a potential loss, it is important to identify them. In most cases fire hazards are identified on the basis of intuition and experience. At best, the experience of several persons would be combined to assess a given situation in order to fully identify all the potential hazards.

Fire Safety Checklist. The most common approach to hazard identification is some form of checklist. A traditional fire safety checklist is a list of specific items used to identify known types of hazards, design deficiencies, and potential fires associated with specific buildings, equipment, and operations. Usually, the identified items are compared to appropriate NFPA standards. Using checklists requires three simple steps: (1) identify or develop an appropriate checklist, (2) conduct a survey of the premises, and (3) document the results.

There are many forms of fire safety checklists in the literature, procedural standards, consensus codes, and industry guidelines. For example, *Uniform Fire Code™ Handbook* has checklists appropriate to different occupancies.[5] If no specific, relevant checklist is available, then information available from

authoritative references can be used to generate an appropriate checklist.

A dilemma in developing a checklist is determining the number of items to be checked. Checklists can become very large as various components are included. It can be very time-consuming for the user if large lists must be examined, especially if individual items on the checklist are so specific as to require the inspection of a large number of details. Determinations need to be made regarding which requirements should be included and which requirements should be excluded from the lists.

The checklist is completed based on observations from site visits, system documentation, interviews with operating personnel, and personal perceptions. The person using the checklist will need to determine whether or not the criteria in the list are met. If they are not met, the hazard should be identified and recommendations made.

Documentation usually consists of a summary of noted deficiencies and specific recommendations for fire safety improvement with appropriate explanations. The report should contain a copy of the checklist. The thoroughness of the analysis will depend on the level of detail of the checklist developed.

Extent of Fire Hazard Identification. The extent of fire hazard identification for any given situation will depend on several factors:

- Prior knowledge or experience with an activity
- The size and complexity of the facility, operation, process, or equipment
- The overall potential for loss
- The resources available to make the hazard identification and review

However desirable it may be to identify all fire hazards before a loss occurs, it may not be practicable to make highly sophisticated and expensive studies to locate every possible hazard. The process must be cost-effective within the context of the overall operation. Although the need to identify, evaluate, and control hazards is continuous, the costs involved must be balanced against the other demands on financial resources.

Scenarios

In general, the fire risk analyst will specify a *scenario structure,* which is a set of classification rules for dividing the range of possible fires into a manageable number of relatively homogenous groups, called *scenario clusters*. Then probabilities can be calculated or estimated for each scenario cluster, and a severity measure can be calculated or estimated for the average fire in each scenario, possibly by detailed examination of a typical or representative fire from each scenario.

Concern over computational burden is one reason why analysts sometimes conduct fire risk analyses using a very small number of scenarios (e.g., only three alternatives for where and how fire begins). There may also be concern over the shakiness of the available data and a desire to minimize the number of different terms supported by expert judgments.

In a situation like that, it is essential to understand what is being implicitly assumed by the use of a stripped-down scenario structure. One way or another, the scenarios that are modeled explicitly are being treated as representative of the far larger number of scenarios that are not modeled explicitly. If only a few scenarios are modeled explicitly, then each one is implicitly required to be representative of a much larger and more varied collection of other scenarios. There may be no good evidence to support this assumption. Is it better, for example, to examine the different types of flaming fires individually or to assume that they all behave like a burning wood crib ignited by a lighter? The variability and uncertainty are there either way; the only choice is how much to examine explicitly and how much to handle by assumption.

ANALYSIS FRAMEWORKS

Table 3.8.1, taken from NFPA 551, provides an overview of different analysis frameworks in which both probability and consequence may be treated qualitatively or quantitatively. Also in Table 3.8.1 is reference to the embedding of fire risk analysis in a larger cost-benefit context. Figure 3.8.3 is an expanded generic flow chart for such a cost-benefit framework.

Of the several approaches listed in Table 3.8.1, the simplest approach is the fully qualitative approach, which is illustrated in Figure 3.8.4 and Tables 3.8.2 and 3.8.3, all taken from the annex of NFPA 551.

For quantitative approaches, the three principal analytical approaches are (1) fault or success trees, (2) event trees, and (3) probability weights applied to consequence estimates derived from conventional fire protection engineering models or data.

Fault Tree

The most familiar fault or success tree, though unquantified as published, is the Fire Safety Concepts Tree, as shown in NFPA 550, *Guide to the Fire Safety Concepts Tree*. Fault or success trees are organized to deliver a probability of failure or success, respectively, as the outcome measure. For this reason, such trees are most useful in estimating probabilities—such as the probability of ignition—for use in a larger model with a different format.

The advantages of fault tree analysis (FTA) include, but are not limited to, the following:

- Fault trees provide the logic of how fires start and develop in a graphic format that is easy to understand.
- Fault trees show how different features, systems, and elements interact or act independently to affect fire ignition and development.
- It is easy to compute probabilities from a fault tree.

The disadvantages of FTA include, but are not limited to, the following:

- A fault tree explores only those faults and conditions that lead to a single specified event.
- It may be difficult to identify all contributing factors.
- The fault tree can become very large.

The Probability Analysis oval in Figure 3.8.3 would be a good place for use of fault or success trees.

TABLE 3.8.1 Categories of FRA Methods

Category	*Definition*	*Type of Output**	*Examples*
Qualitative method	Treats both likelihood and consequences qualitatively	Tabulations of outcome and relative likelihood of various fire scenarios and how they are affected by various protection options	What-if analyses Risk matrices Risk indices Fire safety concepts tree
Semiquantitative likelihood method	Treats likelihood quantitatively and consequences qualitatively	Determination of frequency of occurrence of different types of fires and/or fires with different types of protection	Actuarial/loss statistical analyses Stand-alone event tree analyses
Semiquantitative consequence method	Treats consequences quantitatively and likelihood qualitatively	Deterministic fire model outputs with qualitative representation of likelihood	Enclosure fire models for worst credible fire scenarios
Quantitative method	Combines quantitative estimates of likelihood and consequences	1. Determination of loss expectancy OR 2. Determination of probability of flashover OR 3. Determination of probability of fatalities in other rooms or floors of building OR 4. Plot of frequency versus number of fatalities OR 5. Plot of frequency versus size of loss OR 6. Determination of likelihood of injuries, fatalities, property damage, and business interruption OR 7. Determination of individual risk (to building occupants) and of societal risk (to entire population)	FRAs to determine probability of reactor core melt due to fire at a nuclear power plant Event tree analysis combined with fire models
Cost-benefit risk methods	Include determination of costs of alternative approaches to limit consequences and/or likelihoods	1. Determination of costs required to achieve various levels of risk reduction OR 2. Determination of "optimum" level of fire protection based on minimizing "overall risk" or some other risk criterion	Computational models that incorporate probability, consequences, and cost data in an integrated manner

*Types of output listed are representative rather than all-inclusive.
Source: Table 5.1.2.1, NFPA 551.

TABLE 3.8.2 Probability Levels

Probability	*Description*
Frequent	Likely to occur frequently, experienced ($p > 0.1$)
Probable	Will occur several times during system life ($p > 0.001$)
Occasional	Unlikely to occur in a given system operation ($p > 10^{-6}$)
Remote	So improbable, may be assumed this hazard will not be experienced ($p < 10^{-6}$)
Improbable	Probability of occurrence not distinguishable from zero ($p \sim 0.0$)

Source: Table A.5.2.5(a), NFPA 551.

Event Trees

Event trees, as the name suggests, represent fires as a sequence of events. An event may correspond to a change in the size or character of the fire, a change in the status or performance of various active systems or passive features, or a change in the status or behavior of occupants or first responders.

An event tree is a visual representation of all the events that can occur in a system. As the number of events increases, the picture fans out like the branches of a tree. The goal of an event tree is to determine the probability of an event based on the outcomes of each event in the chronological sequence of events leading up to it. The event tree displays the sequences of events involving success and/or failure of the system components. By analyzing all possible outcomes, one can determine the percentage of outcomes that lead to the desired result. To

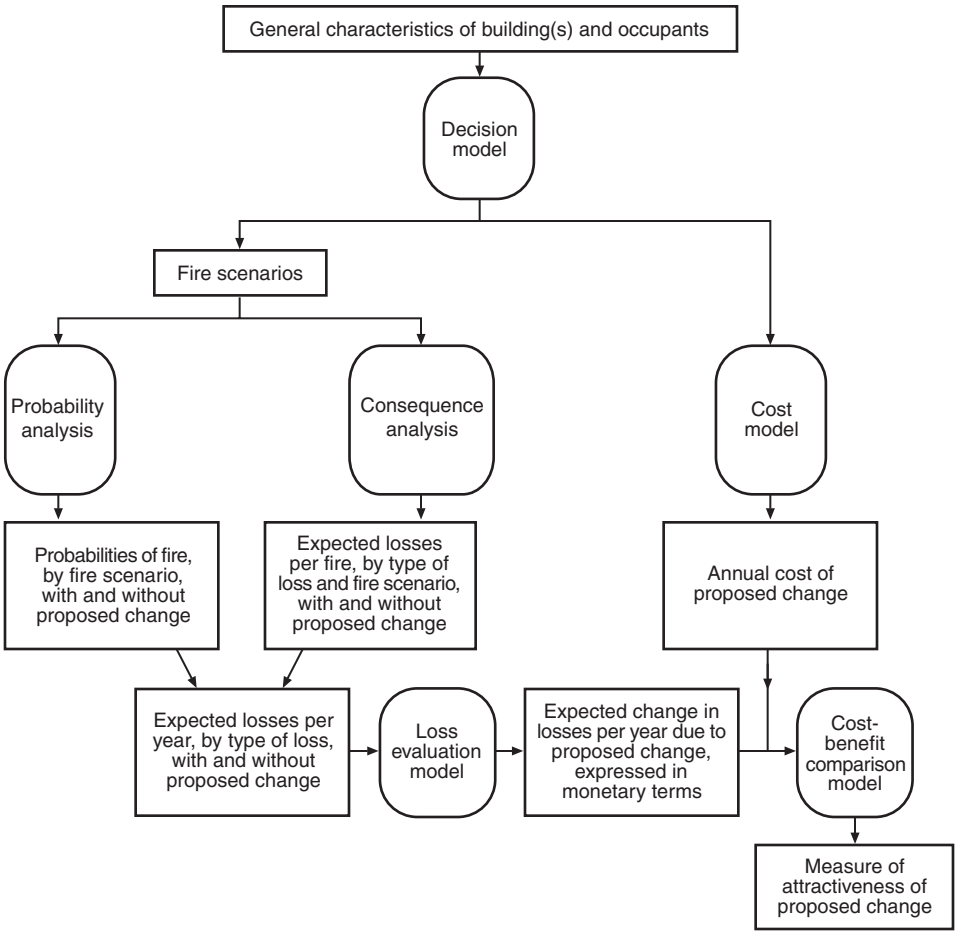

FIGURE 3.8.3 A Risk Analysis Conceptual Framework

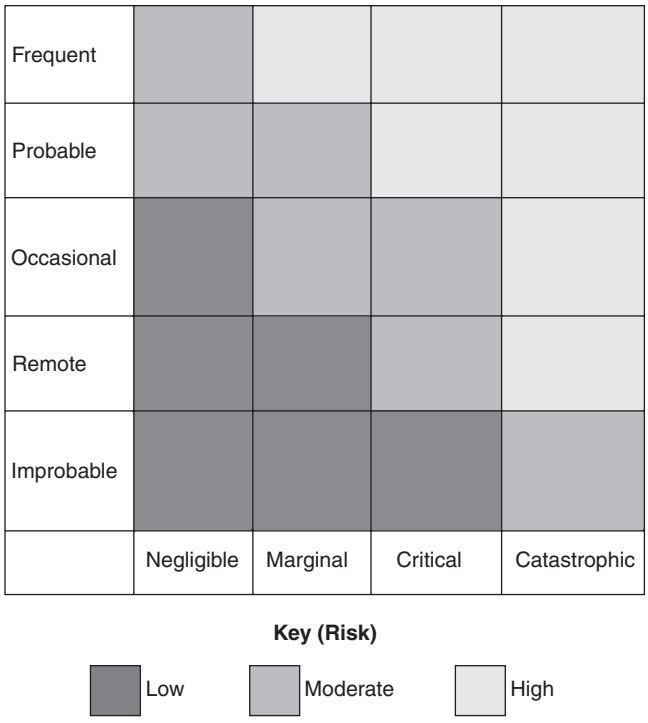

FIGURE 3.8.4 Risk Matrix (Source: Figure A.5.2.5, NFPA 551)

TABLE 3.8.3 Severity Categories

Severity	*Impact*
Negligible	The impact of loss will be so minor that it would have no discernible effect on the facility or its operations.
Marginal	The loss will have impact on the facility, which may have to suspend some operations briefly. Some monetary investments may be necessary to restore the facility to full operations. Minor personal injury may be involved.
Critical	The loss will have a high impact on the facility, which may have to suspend operations. Significant monetary investments may be necessary to restore to full operations. Personal injury and possible deaths may be involved.
Catastrophic	The fire will produce death or multiple deaths or injuries, or the impact on operations will be disastrous, resulting in long-term or permanent closing. The facility would cease to operate immediately after the fire occurred.

Source: Table A.5.2.5(b), NFPA 551.

make a model as complete as possible, the tree must represent all possible events as accurately as possible.

The initiating event, which is generally a fire, is what starts the sequence of events detailed in the event tree. All subsequent events stem from the initiating event.

As a simplistic example, an event tree can be constructed to analyze the possible outcomes of a fire. The system has two strategic components designed to handle this event: manual intervention by staff and an automatic suppression system. If the fire is too large to be controlled by staff, it will be mostly contained by the suppression system. If the suppression system fails as well, the loss is unacceptable. The event tree shown in Figure 3.8.5 can be constructed to model these events.

More events can be added to this tree, such as the detection and alarm system that alerts staff or the event that the fire department will respond to help control major fires. The event tree can grow significantly as more events are taken into consideration. For very large trees, there are techniques for reducing the necessary number of branches. In many applications a truncated or reduced event tree is sufficient. Figure 3.8.6 is an example of a more detailed event tree.

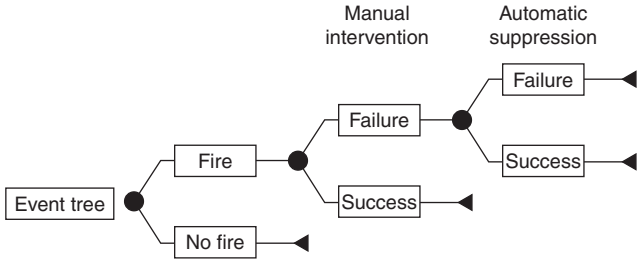

FIGURE 3.8.5 Simplified Event Tree

Event trees show all possible event options and chance events with a branching structure. They proceed chronologically, left to right, showing events as they occur in time. All outcomes along with the values and probabilities associated with them can be shown directly on the tree. There is very little ambiguity as to the possible outcomes and events the tree represents; any node gives all possible outcomes resulting from the node and the events that follow.

The advantages of event tree analysis (ETA) include, but are not limited to, the following:

- Event trees are easy to draw once the sequence of events is established.
- Event trees are easy to understand.
- It is easy to compute probabilities from an event tree.

The disadvantages of ETA include, but are not limited to, the following:

- It may be difficult to identify all consequences.
- The event tree can become very large.

ETA is a comprehensive tool for modeling all possible outcomes of a sequence of events. Event trees are used to model the selected fire scenarios. They provide a framework for the

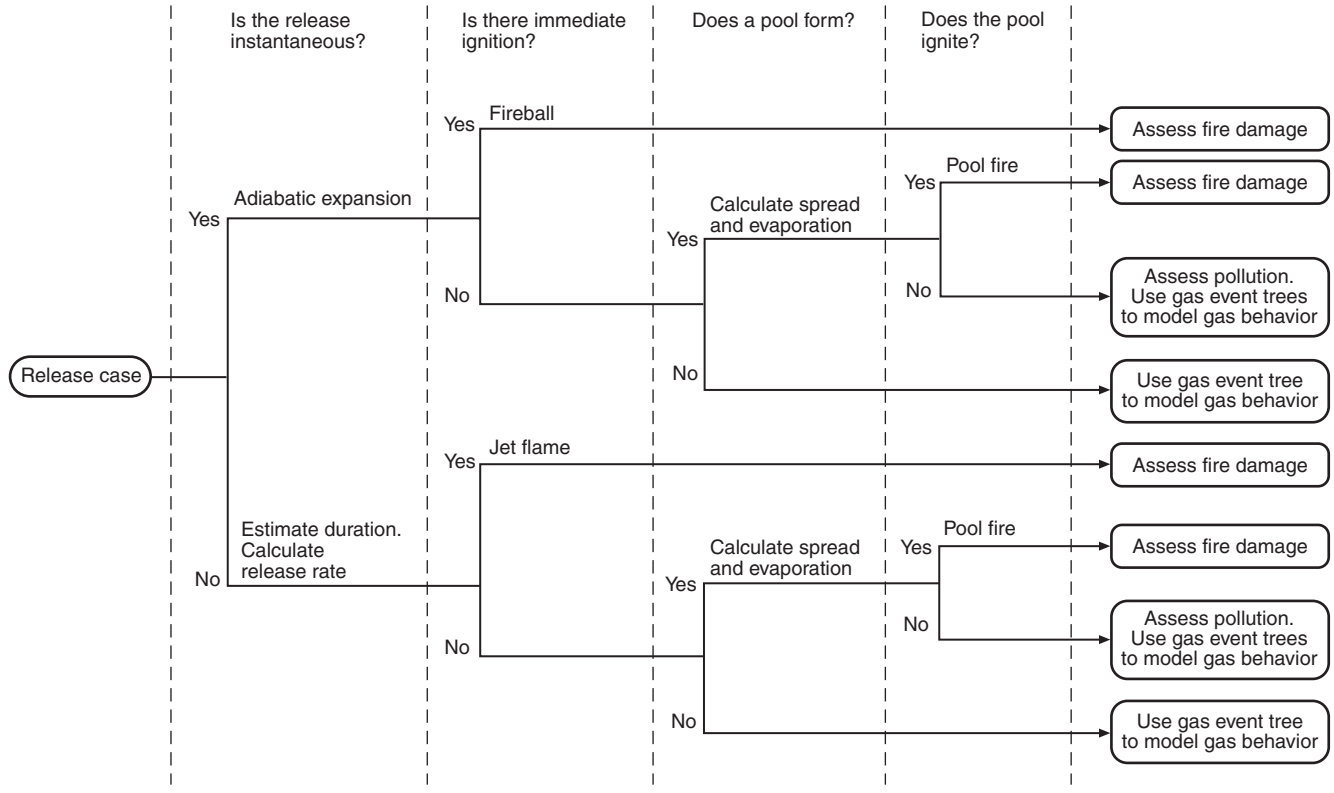

FIGURE 3.8.6 Flammable Liquid Event Tree (Source: Center for Chemical Process Safety[6])

utilization of probability data associated with the events that make up the fire scenario.

An event tree is a risk-analysis format appropriate to the Consequence Analysis oval in Figure 3.8.3. Alternatively, one can use deterministic fire protection engineering models—possibly in combination with probabilistic models for reliability or human behavior—to produce estimates of consequence for a defined scenario.

Probability Weights

Once the event tree is constructed, the frequency or probability of each outcome, or consequence, can be determined. In the example above, the calculations are done to determine the likelihood or frequency of the system incurring major destruction from failure of both strategies (consequence 1), partial damage with successful activation of the suppression system (consequence 2), and minimal damage with successful manual intervention (consequence 3). The probability of occurrence of each path is the product of the given event probabilities since they all must occur for the given outcome to occur. The total for each outcome is then the summation of all the probabilities leading to that outcome.

SUMMARY

Fire risk analysis (assessment) is a comprehensive evaluation approach that permits examination of all the types of fires that can challenge a design or other decision, including the likelihood and consequences associated with each fire type (or scenario). Recently published standards provide more detailed guidance on different aspects of fire risk analysis. This chapter has provided a brief overview of what is entailed in fire risk analysis and the methods available for performing such analysis.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on methods and concepts of fire risk analysis discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 550, *Guide to the Fire Safety Concepts Tree*
NFPA 551, *Guide for the Evaluation of Fire Risk Assessments*

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SECTION 3

Chapter 9

Closed Form Enclosure Fire Calculations

Edward K. Budnick ❑ Sean P. Hunt ❑ Mark T. Wright

Chapter Contents

Enclosure Fires
Energy Release Rate Estimates
Quantification of Fire Hazards
Enclosure Fire Effects
Comprehensive Example Application

Key Terms

axisymmetric fire, closed form equation, enclosure fire, energy release rate, fire growth rate, fire plume, flashover, heat flux, heat release rate (HRR), ignition temperature, liquid fuel fire, pool fire, preflashover, smoke exhaust rate, smoke filling rate, steady-state fire

As part of a fire protection analysis, it is often desirable to estimate the burning characteristics of selected fuels and their effects in enclosures. Also important for many analyses is the estimation of when fire protection devices such as heat detectors or automatic fire sprinklers will activate for specific fire conditions. Closed form equations are available, based principally on experimental correlations, which permit the user to estimate these effects for simple configurations and arrangements.

In this chapter, a brief introduction to enclosure fires is presented, along with equations that can be evaluated using hand calculators to provide estimates of particular effects. The equations presented are well documented and are widely used for such estimates. However, the user is cautioned that most of the equations were developed based on data from experiments that were conducted for very specific, and sometimes idealized, conditions. Therefore, caution is necessary when applying these equations to situations that may exceed the test parameters on which they are based.

The methods presented in this chapter are intended to be used in evaluating fire conditions in enclosures during the preflashover fire growth phase of a compartment fire. (See Section 2, Chapter 4, "Dynamics of Compartment Fire Growth.") The methods do not apply to fully developed room fires and postflashover conditions but some methods are provided that may be used to predict whether or not such conditions would occur. In addition, these calculations apply only to the room of fire origin and to a single burning fuel package, such as a single item or a contiguous grouping of combustibles like an upholstered chair and ottoman or a bookcase full of books. More advanced approaches are available for fully developed fire conditions, multiple rooms, and multiple fuel package fires, but they are beyond the scope of this chapter; see Section 3, Chapter 5, "Introduction to Fire Modeling" for additional information.

The topics covered in this chapter are grouped into the following four categories:

- Enclosure fires
- Energy release rate estimates
- Quantification of potential hazards from a fire
- Enclosure fire effects

Material properties, such as the heat of combustion and the heat release rate, are listed in Section 6, Chapter 17, "Tables and Charts." For additional information on material properties or the topics introduced in this chapter, refer to relevant chapters in Section 3 of the *SFPE Handbook of Fire Protection Engineering.*[1]

All calculations in this chapter are presented in SI units. For U.S. customary units, see Table 3.9.1.

If T_K is the temperature in degrees Kelvin, then the same temperature in degrees Celsius or centigrade ($T_{°C}$) is given by $T_{°C} = T_K + 273.15$. The same temperature in degrees Fahrenheit ($T_{°F}$) is given by $T_{°F} = 1.8T_{°C} + 32$.

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TABLE 3.9.1 Conversion Factors

To Convert from SI Units	*To U.S. Customary Units*	*Multiply By*
Kilograms	Pounds (avdp.)	2.2046226
Kilojoules	Btu	0.9486080
Kilowatts	Btu/hour	3414.9900000
Meters	Feet	3.2808399

See also Section 2, Chapter 1, "Physics and Chemistry of Fire"; Section 2, Chapter 2, "Physics of Fire Configuration"; Section 2, Chapter 4, "Dynamics of Compartment Fire Growth"; and Section 6, Chapter 17, "Tables and Charts."

ENCLOSURE FIRES

Enclosure Fire Defined

Enclosure fires represent a general class of unwanted fires that are characterized by boundaries that confine or restrict the flow of combustion products from the fire. Examples include room fires, attic fires, crawl-space fires, atrium fires, and so on. Enclosure fire effects are often characterized by a time-temperature profile or a transient energy release rate; countless scenarios are possible ranging from a smoldering cigarette that self-extinguishes to a postflashover fully developed fire environment that breaches the boundaries and results in fire spread and/or structural collapse. Figure 3.9.1 depicts the development of an idealized enclosure fire in terms of both the compartment temperature and the energy release rate.[2,3]

Phases of an Enclosure Fire

Four distinct phases are shown; however, one or more phases may be absent in any given enclosure fire. The incipient phase may include smoldering combustion, electrical arcing, or radiant heating of a combustible material. This phase may be very short or prolonged and typically does not result in the development of hazardous conditions per se. An incipient fire may progress into a growing flaming fire. During this phase, the energy release rate and the compartment temperature are both increasing with time; the fire typically remains confined to a single fuel package or a group of fuel packages initially involved by direct interaction with the fire and is defined as a fuel-controlled fire. When the enclosure temperature is sufficiently high, the radiant energy from the flame or combustion products may be sufficient to cause fuel surfaces other than those already burning to undergo chemical reactions yielding flammable vapors (i.e., pyrolize); an accumulation and rapid ignition of these combustible vapors often results in an instability that is typically described as flashover.[2] When flashover occurs, the energy release rate in the compartment usually increases to a level supported by the room ventilation, provided sufficient fuel is available, representing the beginning of the steady-state or fully developed postflashover compartment fire. If sufficient fuel is available such that the ventilation controls the fire size, then this stage of the fire is defined as a ventilation-controlled, fully developed enclosure fire. In the absence of structural collapse, fire spread to adjacent areas, or manual or automatic intervention, the fully developed compartment fire will eventually transition into a decay phase once sufficient fuel has been consumed and less becomes available for combustion.

The methodologies presented in this chapter are focused on predicting potential hazards and possible fire effects arising during the fire growth phase for simple fuel arrangements and

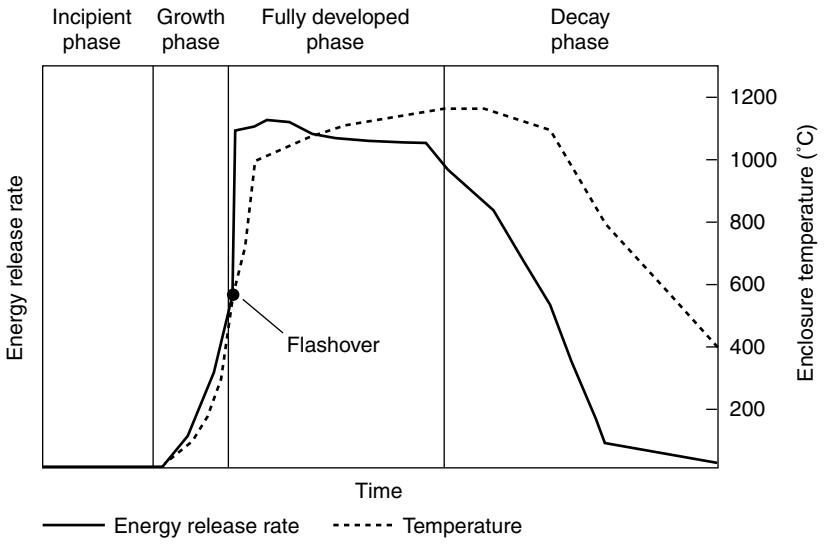

FIGURE 3.9.1 Enclosure Fire Development

enclosure geometries. The *SFPE Engineering Guide for Fire Exposures to Structural Elements*[4] as well as various chapters in Section 3 of the *SFPE Handbook of Fire Protection Engineering*[1] provide information for calculating fire hazards associated with more complex fully developed enclosure fires and interactions between the space and the development of the fire.

ENERGY RELEASE RATE ESTIMATES

Energy Release Rate Defined

Calculation procedures for fire effects in enclosures require knowledge of the *energy release rate* of the burning fuel. The term *energy release rate* is frequently used interchangeably with *heat release rate,* and it is usually expressed in units of kilowatts (kW) and symbolized by $\dot{Q}$. The energy release rate is also thermodynamically equivalent to power. The heat released by the fire oxidation process is transferred to the surroundings by convection through the heated combustion products and by thermal radiation from the heated combustion products capable of emitting thermal radiation. The convective component of the heat release rate is symbolized by $\dot{Q}_c$ and the radiant component by $\dot{Q}_r$. The sum of the convective and radiant components is equal to the total heat release rate, $\dot{Q}_T$ or just $\dot{Q}$. The radiant fraction is given by $\chi_r = \frac{\dot{Q}_r}{\dot{Q}_T}$ and is typically between 0.2 and 0.4.[1]

Currently, no broadly accepted methods exist for prediction of energy release rates based solely on basic measurements of material properties. Recent efforts in this area show promise.[5] However, it is expected that generalized methods will not be available for some time. In addition, in any enclosure fire, the actual rate of heat release is dependent not just on the burning fuel but also on the fire environment (i.e., enclosure geometry and ventilation, the manner in which the fuel is volatilized, the efficiency of the vapor combustion, and other physical and chemical effects). Therefore, for the immediate future one must rely on available laboratory test data for the specific or similar fuels. Such laboratory data may include small-scale burning properties as would be obtained in the cone calorimeter, full-scale open burning characteristics as would be obtained in a furniture calorimeter, or room burns as would be obtained from an ISO 9705 test. It is important for the data to correspond with the application considered or correlation used. Section 3 of the *SFPE Handbook of Fire Protection Engineering*[1] provides additional information on such considerations.

Knowledge of the complete energy release rate history may be required for many situations. This is particularly desirable when the fuel package exhibits unsteady or transient burning in which the mass loss rate varies with time as shown in Figure 3.9.2. The mass loss rate for unsteady fires may increase, decrease, or fluctuate with time depending on the fuel and the exposure boundary conditions. For those cases where only limiting conditions or worst-case analysis is required, it may be reasonable to assume that the fuel is burning at a constant rate representing the peak rate, which simplifies the calculation considerably.

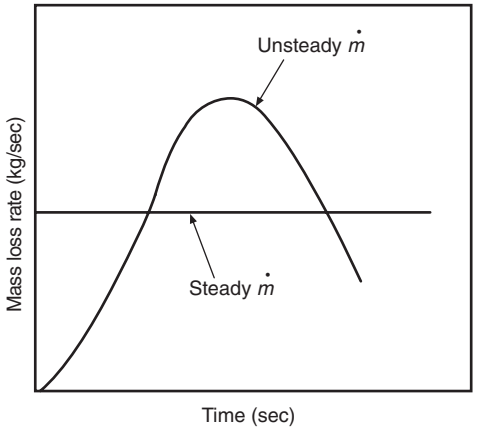

FIGURE 3.9.2 Steady and Unsteady Burning Rates

Procedures for Estimating Energy Release Rate

Several simple procedures are presented here for estimating the energy release rate from certain fuel packages burning in enclosures. A more rigorous treatment of energy release rates is available for selected material types such as wood cribs, wood and plastic slabs, and liquid pool fires where experimental correlations have been established. Section 3, Chapter 1, in the *SFPE Handbook of Fire Protection Engineering*[6] provides a detailed discussion of the prediction of burning rates from various materials. Detailed discussions and data for energy release rates for specific fuels are also available elsewhere.[7–10]

It should be recognized that most enclosure fires of interest do not exhibit constant energy release rates. Rather, as illustrated in Figure 3.9.2 for selected items of furniture, the mass loss rate and, therefore, the energy release rate vary over time. Depending on the detail required, one might select a constant mass loss rate, such as a peak value or an average value, as the basis for analysis.

In the absence of specific test data for a fuel package, a reasonable estimate of the potential energy release rate from the burning fuel package may be made based on test data for similar items. Figure 3.9.3 depicts the order of magnitude for the energy release rate for common fuel packages and burning objects.[11,12] Some fuel packages such as wastebaskets, chairs, and beds exhibit a large range of potential energy release rates. Very low energy release rates were noted in some tests due to the configuration or materials, thus resulting in a large span. Given the simplicity of the calculations, it may be prudent in many cases to select an upper bound value for the type of fuel package under consideration where postulating a larger fire is conservative.

Maximum Enclosure Fire Size

Calculating the maximum enclosure fire size is useful for establishing an upper bound for the energy release rate from a single fuel package within a space. This information can be used in combination with other data to determine whether or not a fire

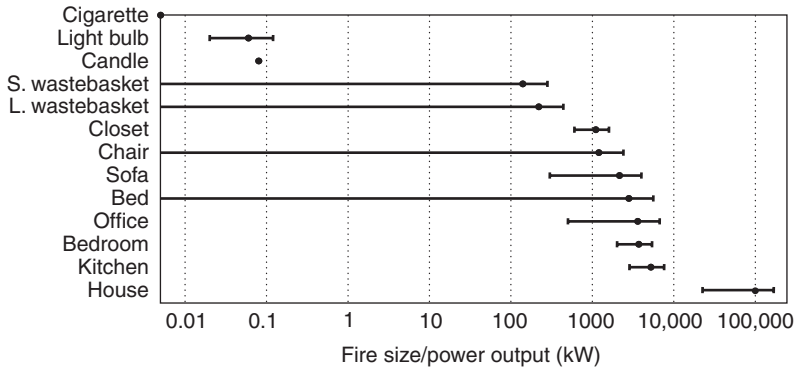

FIGURE 3.9.3 Maximum Fire Sizes for Common Combustible Objects (Sources: NUREG 1805, "Fire Dynamics Tools (FDTs)"[11]; ASTM STP 614, *Fire Standards and Safety*[12])

could become large enough to actuate detection or automatic fire suppression devices and for assessing whether or not flashover conditions could develop. This information also provides a means of establishing the reasonableness for an assumed fuel package fire size.

The maximum fire size within enclosures having a single vertical opening such as an open door or window and combustible contents dominated by wood-based materials may be estimated using the following equation:[13]

$$\dot{Q}_m = 1500 A_o \sqrt{H_o} \qquad (1)$$

where

$\dot{Q}_m$ = Maximum total energy release rate (kJ/sec or kW)

A_o = Total opening area (m^2)

H_o = Opening height (m)

The opening height is the distance between the top of the opening and the bottom of the opening. When there are two or more openings, the total opening area is the sum of each individual area and the opening height is usually assumed equal to a weighted average. Because the height appears in both the area and height terms, the most severe ventilation combination is not necessarily the largest. A sensitivity analysis may be performed in which different openings are assumed closed in order to identify the most adverse opening combination.

Equation 1 assumes that only air flowing into an opening supports the combustion process. This assumption may not be valid in large spaces where the initial enclosure air volume could support a larger fire prior to the development of ventilation-limited conditions. The amount of combustion that the initial air volume could support may be estimated using the following equation derived from a constant energy release rate of 3000 kJ/kg air:[13]

$$\dot{Q}_{air,i} = \frac{3600 \cdot V}{t_b} \qquad (2)$$

where

$\dot{Q}_{air,i}$ = Total fire size (i.e., energy release rate) supported by the initial air volume in an enclosure (kJ/sec or kW)

V = Compartment volume (m^3)

t_b = Time period (sec)

Equation 2 assumes that all oxygen in the enclosure is available for consumption. The maximum fire size that could be supported in a space prior to the development of ventilation-limited conditions over a time period specified by t_b is, thus, the sum of Equations 1 and 2, assuming that all oxygen within the space supports combustion and that the airflows into the compartment can be approximated by Equation 1. The approach is an upper bound; if greater accuracy or resolution is required for a particular application, then a computer fire model analysis would be necessary. The time period should be equal to the time period over which the effects are considered.

EXAMPLE 1. Estimate the maximum sustainable fire size that could be supported in a compartment that is 10.0 m × 5.0 m × 3.0 m tall with a single door opening measuring 0.9 m wide × 2.1 m tall. What could the maximum fire size be within the first minute? What could the maximum fire size be if there is an open window measuring 0.5 m wide × 0.5 m tall that has a sill 1.0 m above the floor?

SOLUTION 1. The maximum fire size may be computed directly from Equation 1 substituting the area of the opening and the height of the opening A_o and H_o. The opening area is 2.1 m × 0.9 m or 1.89 m^2; thus, the maximum sustainable fire size in this space is $1500(1.89)\sqrt{(2.1)}$ or approximately 4110 kW. If a 0.5 m × 0.5 m window is included, the total opening area A_o increases to 2.14 m^2. The opening height is determined from the weighted average height of the door and window. The door area is 2.1 m × 0.9 m or 1.89 m^2 and the window area is 0.5 m × 0.5 m or 0.25 m^2. Since the door height is 2.1 m and the window height is 0.5 m, the weighted average is equal to 0.5 m × .25 m^2/2.14 m^2 + 2.1 m × 1.89 m^2/2.14 m^2 or 1.91 $m^{1/2}$. The maximum sustainable fire size, as computed using Equation 1, is then 4440 kW.

The maximum sustainable fire size that could develop in this compartment within the first minute, before ventilation-limited conditions have developed, may be estimated using Equations 1 and 2. Enclosure fires where ventilation-limited conditions have

been reached are ventilation-controlled fires, as previously described in the subsection titled Enclosure Fires. The maximum fire size based only on airflows through the opening is 4110 kW; the maximum fire size that the initial oxygen volume in a compartment could support over a 1-minute time scale may be computed from Equation 2 as follows:

$$\dot{Q}_{air,i} = \frac{3600 \cdot V}{t_b} = \frac{3600 \cdot (10)(5)(3)}{60} = 9000 \text{ kW}$$

The maximum fire size over the first minute could thus be about 4110 kW + 9000 kW or about 13,110 kW, assuming complete combustion using all available oxygen. Large initial fire sizes that are supported by the initial oxygen mass within an enclosure would typically only be a factor for fires involving fuels that could support a very rapid fire growth rate such as flammable liquids. Typical Class A combustible materials (solids) have a slower growth rate such that the time scale would be large and the fire size supported by the initial compartment volume would be small in comparison to the fire size supported by the airflow through the openings.

Liquid Fuel Pool or Spill Fires

The energy release rate from liquid fuel fires is a function of the energy release rate per unit area for the specific liquid and the exposed surface area of the pool or spill and can be expressed by

$$\dot{Q}_m = \dot{q}'' \cdot A \tag{3}$$

where

$\dot{Q}_m$ = Maximum total energy release rate from the liquid fuel fire (kJ/sec or kW)

$\dot{q}''$ = Energy release rate per unit area for the specific fuel (kJ/sec·m^2 or kW/m^2)

A = Exposed liquid fuel surface area (m^2)

The energy release rate per unit area is a function of the liquid fuel type, the spill area, and the spill depth.[8,14] The maximum energy release rate per unit area for a given fuel occurs when the emissive power of the flames is maximized (i.e., the radiant transmissivity through the flames approaches zero such that all radiation from the direction of the flames originates from the fire process). Confined fuel fires would represent liquid fuel fires in containers or curbed areas. A liquid fuel fire having a diameter greater than about 0.2–1.0 m is typically treated as optically thick.[2,14] Unconfined fuel spills where the liquid is free to spread and the liquid depth is a function only of the liquid and surface tension properties have been shown to burn at a reduced energy release rate relative to an equivalent diameter confined liquid pool.[14] The reduction in the energy release rate is generally on the order of ⅘ (80%) and is attributed to thermal losses from the liquid and flames into the surface under the fuel. Unconfined liquid spill depths vary with spill volume and surface type; for concrete surfaces the unconfined liquid spill depth is about 2.8 mm or less. It is reasonable to assume that pools that are deeper than 2.8 mm are confined.

Table 3.9.2 summarizes the energy release rate per unit area for common liquid fuels in either confined or unconfined configurations. It is often conservative to assume a maximum energy release rate; thus, values for optically thick confined liquid fuel fires would be appropriate. It should be cautioned that there may be instances where it is not conservative to maximize the energy release rate, for example, when considering the actuation of fire detectors or automatic fire suppression devices. Detailed discussions on estimating the energy release rate in liquid fuel fires is available in the *SFPE Handbook of Fire Protection Engineering* (Section 2, Chapter 15,[6] and Section 3, Chapter 1[14]) as well as other sources.[2,7,8,15,16]

TABLE 3.9.2 Energy Release Rates per Unit Area for Optically Thick Liquid Fuel Fires[6,8,14]

	Energy Release Rate per Unit Area (kW/m^2)	
Fuel	*Confined Liquid Fire*	*Unconfined Liquid Fire*
Gasoline	2400	480
Kerosene	1680	340
Diesel	1950	390
Transformer oil	1790	360
Fuel oil, heavy	1390	280

The duration of a pool fire may be computed using the total mass of fuel available for combustion, the fire size, and the fuel heat of combustion as follows:

$$t_{FD} = \frac{M\Delta H_c}{\dot{Q}_m} \tag{4}$$

where

t_{FD} = Fire duration (seconds)

M = Mass of fuel (kg)

ΔH_c = Fuel heat of combustion (kJ/kg), a fuel-specific material property

$\dot{Q}_m$ = Maximum total energy release rate from the liquid fuel fire (kJ/sec or kW)

The duration of a liquid fuel fire is sometimes computed using a regression rate, or a liquid depth recession velocity, and the total liquid depth rather than the mass of fuel available; that is, $dt_{FD} = \delta/\dot{y}$, where δ is the spill depth (m) and $\dot{y}$ is the regression rate (m/sec). Caution is necessary to ensure that the regression rate data correspond to the heat release rate data to ensure mass is conserved.

By noting that the mass is equal to the product of the density and the volume and that the burning duration is independent of the source fire area, it can be shown that the regression rate approach to computing the fire duration and Equation 4 are the same.

EXAMPLE 2. A transformer leaks transformer oil into a curbed confined region having a surface area of 5 m^2, forming a deep pool. The total mass of oil is 50 kg and the heat of combustion is 40,000 kJ/kg. Estimate the maximum energy release rate and fire duration from the transformer oil if it were to ignite. What would the energy release rate and fire duration be if the

transformer oil formed a 5 m^2 pool on a flat, unconfined concrete surface through a continuous leak ignoring any liquid spreading time over the concrete surface?

SOLUTION 2. The transformer oil liquid pool fire size may be computed using Equation 3 and data in Table 3.9.2. In the case of a deep or curbed liquid pool, the plan area is 5 m^2 and the total energy release rate per unit area is 1790 kW/m^2. The total energy release rate is, thus, $\dot{Q}_m = \dot{q}'' \cdot A = (1790)(5) = 8950$ MW. The fire duration is computed from Equation 4 where the mass is 50 kg, the heat of combustion is 40,000 kJ/kg, and the total fire size is 8950 kW or (50)(40,000)/(8950) = 223 seconds. If the liquid pool is formed on an unconfined concrete surface, the energy release rate would be less due in part to thermal losses to the substrate: $\dot{Q}_m = \dot{q}'' \cdot A = (360)(5) = 1800$ MW. The fire duration is also computed from Equation 4 where the total fire size is now 1800 kW or (50)(40,000)/(1800) = 1110 seconds. Note that an unconfined liquid fuel will tend to form a larger pool surface area than a confined fuel spill for a given volume of liquid but the burning rate is reduced substantially. For a continuous leak scenario involving a fixed volume of liquid, the duration increases by a factor of five.

Growing Fires

Most methods presented in this chapter assume a steady or approximately steady heat release rate for the fire. There may be circumstances where it is of interest to estimate the time to reach a hazardous condition or to reach a minimum fire size necessary for fire detector or automatic fire suppression device actuation. In this case, knowledge of the fire growth rate history is necessary. The energy release rate for growing fires in solid fuels is often characterized by a relationship where the fire grows as a function of the square of time (t^2), expressed as[15]

$$\dot{Q}(t) = \alpha t^2 \tag{5}$$

where

$\dot{Q}(t)$ = Total energy release rate (kJ/sec or kW)

t = Time (sec)

α = Fire growth rate constant (kJ/sec^3 or kW/sec^2)

The fire growth rate constant (α) relates to the speed at which the fire grows and has been characterized as "slow," "medium," "fast," and "ultrafast." (See Section 2, Chapter 4, "Dynamics of Compartment Fire Growth.") Common fire growth rate constant values are shown in Table 3.9.3. The fire growth rate constant for specific fuel packages and fuel package arrangements is normally obtained from test data. Section 3, Chapter 1, in the *SFPE Handbook of Fire Protection Engineering*[15] and Appendix B of *NFPA 72®*, *National Fire Alarm Code®*, provide growth constants for a variety of fuel packages and fuel package configurations. Other fire growth rate constant data sources are available.[2,10]

EXAMPLE 3. Estimate the energy release rate in a fuel package array consisting of paper products densely packed in cartons and stacked 6.1 m high 1, 2, and 3 minutes after ignition.

TABLE 3.9.3 Fire Growth Rate Constants

Growth Rate	*Growth Rate Constant (kJ/sec^3 or kW/sec^2)*
Slow	0.0029
Medium	0.0117
Fast	0.0469
Ultrafast	0.1876

SOLUTION 3. A growing fire is expected in such a fuel package array. Appendix B in *NFPA 72* indicates that the growth rate would correspond to a slow t-squared profile up to about 8 minutes. As such, Equation 5 may be used to estimate the energy release rate at specific times before 8 minutes. The growth constant for a slow-growing t-squared fire is 0.0029 kW/sec^2; the energy release rate is then computed using Equation 5 as follows:

$$\dot{Q}(t) = \alpha t^2 = (0.0029)t^2$$

where the time t is in seconds. Thus, 1 minute after ignition the fire size is 10 kW; 2 minutes after ignition it is 42 kW; and 3 minutes after ignition it is 94 kW.

QUANTIFICATION OF FIRE HAZARDS

Fire hazards are defined for the purposes of this chapter as conditions within an enclosure that arise as a direct result of the fire. These conditions are characterized by a temperature increase and/or an exposure heat flux that could cause harm to occupants, impede occupant egress, damage contents or the structure, cause flashover conditions to develop, or actuate detection/suppression devices.

Flashover

A critical point in room fire growth is an event often referred to as *flashover,* the event generally associated with rapid transition in fire behavior from localized burning of fuel to involvement of all the combustibles in the enclosure.

Experimental work indicates that this transition can occur when upper room gas temperatures are between 400 and 600°C, which roughly coincides with an incident heat flux of about 20 kW/m^2 to unignited combustible material located in the enclosure.[3,12,17] Using a value of 932°F (500°C) for the transition to flashover, the heat release rate necessary to cause flashover may be estimated for a naturally ventilated enclosure with a single opening using the following equation:[3]

$$\dot{Q}_{fo} = 610[(k/\delta)A_s A_o \sqrt{H_o}]^{1/2} \tag{6}$$

where

$\dot{Q}_{fo}$ = Total heat release rate at flashover (kJ/sec or kW)

k = Thermal conductivity of enclosure material (kW/m·°C)

δ = Enclosure material thickness (m)

A_s = Total enclosure surface area excluding the opening area (m^2)

A_o = Opening area (m^2)

H_o = Opening height (m)

Equation 6 assumes that an enclosure has been heated thoroughly before flashover such that heat losses to the enclosure boundaries are roughly constant. It is also assumed that the openings are fixed (i.e., the opening does not increase in size) and are not smaller than a typical window or door. Other calculation methods, including computer fire models, are available for estimating flashover potential where boundary heat losses are not steady or where the ventilation conditions are not characteristic of a typical window or door.[3,18–20]

EXAMPLE 4. Would a 500 kW fire lead to the development of flashover conditions inside a space that is 4 m wide, 3 m long, and 3 m tall and has a single opening that is 0.9 m wide and 2.1 m tall? Assume the compartment boundaries are 1.6-cm-thick gypsum having a thermal conductivity of 0.00018 kW/m·°C.

SOLUTION 4. Equation 6 may be used to compute the minimum fire size necessary to cause flashover conditions in the space. All parameters are specified except the internal surface area A_s, which is computed directly from the compartment and opening dimensions as follows: $A_s = 2 \times (L \times W + L \times H + W \times H) - A_o$ where L is the compartment length (m), W is the compartment width (m), H is the compartment height (m), and A_o is the opening area (m^2). The internal surface area is $A_s = 2 \times (4 \times 3 + 4 \times 3 + 3 \times 3) - (2.1 \times 0.9) = 64.1$ m^2. The minimum fire size that could cause flashover is then

$$\dot{Q}_{fo} = 610[(k/\delta)A_s A_o \sqrt{H_o}\,]^{1/2}$$
$$= 610[(0.00018/0.016) \times (64.1) \times (1.9)\sqrt{2.1}\,]^{1/2}$$
$$= 860 \text{ kW}$$

Since 860 kW is greater than 500 kW, it may be inferred that a 500 kW fire would not cause flashover in the space.

Preflashover Compartment Temperature

Knowledge of the preflashover compartment temperature may be useful for predicting when a space becomes hazardous to occupants, estimating when contents may be damaged, or assessing the potential for automatic suppression or heat detection devices to actuate. In most cases, the preflashover compartment temperature is best determined using computer fire models due to the growing fire terms, boundary heat losses, and changes in ventilation that normally occur during a fire.

Although it is recognized that the enclosure gas temperature varies within the compartment, Equation 7 is based on the assumption that an average upper-layer temperature and an average lower-layer, or ambient, temperature reasonably approximate temperature conditions in the enclosure. Several researchers have developed correlations for predicting temperature rise in developing enclosure fires where the energy release rate is constant and there is a single opening. McCaffrey et al. suggest the following expression for naturally ventilated fires in a compartment with a single opening and relatively homogeneous boundary materials, based on a correlation of enclosure fire experiments:[21]

$$\Delta T = 6.85\left(\frac{\dot{Q}^2}{h_k A_s A_o \sqrt{H_o}}\right)^{1/3} \tag{7}$$

where

ΔT = Temperature rise of gas layer in the compartment above ambient (°C)

$\dot{Q}$ = Total energy release rate (kJ/sec or kW)

h_k = Effective enclosure conductance (kW/m·°C) , a measure of the capacity of the boundary to conduct heat out of the enclosure (see Equations 8 and 9)

A_s = Opening area (m^2)

A_o = Opening height (m)

H_o = Total surface area of enclosure interior excluding the opening area (m^2)

Equation 7 applies to enclosures that are naturally ventilated (doors or windows only). For the case of completely forced ventilation conditions, a correlation for enclosure temperature rise has been developed by Foote et al.[16] The temperature rise in enclosures having multiple materials may be estimated by performing a summation of $h_k A_s$ for each material surface in the enclosure, where A_s represents the exposed surface area of a single material within the enclosure. The effective enclosure conductance is determined from the following assuming that the material properties do not vary with temperature (i.e., constant material properties):

$$h_k = \left(\frac{k\rho c_p}{t}\right)^{1/2} \qquad t \le t_p \tag{8}$$

and

$$h_k = \left(\frac{k}{\delta}\right) \qquad t > t_p \tag{9}$$

where

h_k = Effective enclosure conductance (kW/m^2·°C)

k = Thermal conductivity of enclosure surface material (kW/m·°C)

ρ = Density of enclosure materials (kg/m^3)

c_p = Specific heat of enclosure material (kJ/kg·°C)

t = Time (sec)

t_p = Thermal penetration time (sec), which is the time required for the unexposed surface temperature to begin increasing as a result of the thermal boundary conditions on the exposed surface

δ = Enclosure material thickness (m)

The material properties for most materials vary with temperature, especially the heat capacity and the thermal conductivity. However, given the uncertainty associated with other

parameters such as the fire size, the flashover temperature, and the ventilation conditions, assuming constant material properties provides a reasonable result.

The thermal penetration time can be computed from the material properties and thickness of the boundary material, assuming constant material properties, using the following equation:

$$t_p = \frac{\rho c_p}{k}\left(\frac{\delta}{2}\right)^2 \tag{10}$$

where

t_p = Thermal penetration time (sec)

ρ = Density of enclosure materials (kg/m^3)

c_p = Specific heat of enclosure material (kJ/kg·°C)

δ = Enclosure material thickness (m)

k = Thermal conductivity of enclosure surface material (kW/m·°C)

Appendix B of the *SFPE Handbook of Fire Protection Engineering*[1] provides thermophysical property data that may be used to estimate the thermal penetration time and the enclosure conductance. Table 3.9.4 summarizes density, specific heat, and thermal conductivity data for several common building materials. The values in Table 3.9.4 are reasonable for the classes of materials cited but material properties can vary widely, even among specific types of materials, and they should, therefore, be researched carefully for the application at hand.

EXAMPLE 5. Estimate the temperature after 5 minutes in a space that is 4 m wide, 3 m long, and 3 m tall and has a single opening that is 0.9 m wide and 2.1 m tall. Assume a constant fire size of 500 kW, compartment boundaries that are 1.6-cm-thick gypsum having a thermal conductivity of 0.00018 kW/(m·°C), a specific heat of 1.1 kJ/(kg·°C), and a density of 960 kg/m^3. Note that this is the same space containing the same fire as that used for Example 4.

SOLUTION 5. The solution requires three steps: first, compute the thermal penetration time using Equation 10; next compute the effective enclosure conductance using either Equation 8 or Equation 9, depending on the thermal penetration time; and, finally, estimate the enclosure gas temperature using Equation 7.

Step 1. The thermal penetration time is computed directly from Equation 10 using the material properties and dimension provided:

$$t_p = \frac{\rho c_p}{k}\left(\frac{\delta}{2}\right)^2 = \frac{(1.1)\cdot(960)}{0.00018}\left(\frac{0.016}{2}\right)^2$$

$$= 375 \text{ seconds} = 6.3 \text{ minutes}$$

Step 2. Since the thermal penetration time is greater than 5 minutes, Equation 8 must be used to determine the effective enclosure conductance:

$$h_k = \left(\frac{k\rho c_p}{t}\right)^{1/2} = \left[\frac{(0.00018)\cdot(960)\cdot(1.1)}{300}\right]^{1/2} = 0.025 \text{ kW/m·°C}$$

Step 3. The enclosure gas temperature rise is computed using Equation 7:

$$\Delta T = 6.85\left(\frac{\dot{Q}^2}{h_k A_s A_o \sqrt{H_o}}\right)^{1/3}$$

$$= 6.85\left[\frac{500^2}{(0.025)\cdot(64.1)\cdot(1.9)\sqrt{2.1}}\right]^{1/3} = 263°\text{C}$$

If the ambient temperature is 20°C, then the gas temperature after 5 minutes would be 263°C + 20°C or 283°C. Note that this is well below the temperature threshold of 400 to 600°C for flashover as described in the preceding section.

Other calculation methods, including computer fire models, are available for estimating the preflashover compartment temperature when the fire size is variable, the ventilation conditions are not characteristic of a typical window or door, or they are mechanically forced and possibly vary with time.[3,18–20] For detailed discussions of methods that address multiple vents as well as forced ventilation, the reader is referred to DiNenno,[1] Foote et al.,[22] and Deal and Beyler.[23]

Flame Height

The flame height is a means of directly assessing the potential for a fire to spread to other fuel packages or cause structural damage. Figure 3.9.4 depicts an idealized fuel package and the relevant features when quantifying the potential hazards. The experimentally determined "mean" flame heights have been correlated by several researchers.

TABLE 3.9.4 Constant Temperature Thermophysical Properties for Some Common Building Materials[1]

Material	*Temperature for Properties (°C)*	*Thermal Conductivity (kW/m·°C)*	*Heat Capacity (kJ/kg·°C)*	*Density (kg/m³)*
Steel	20	0.043	0.43	7800
Gypsum	20	0.00018	1.10	960
Cement	23	0.00137	0.88	1900–2300
Wood (oak)	30	0.000166	2.40	540
Glass	20	0.00078	0.84	2700
Insulation (glass wool)	23	0.000038	0.70	24

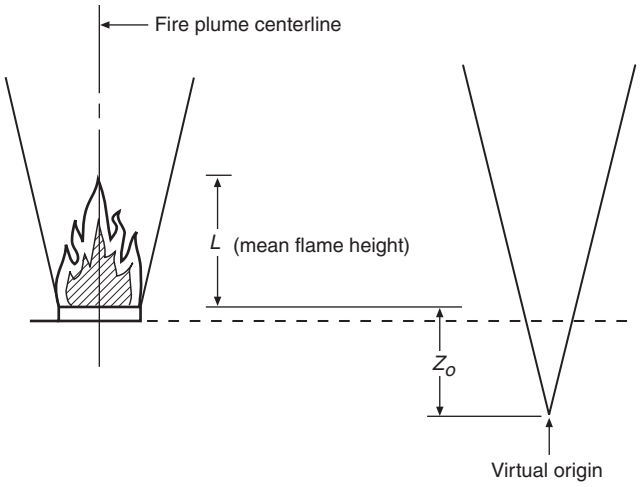

FIGURE 3.9.4 Flame and Fire Plume Characteristics

Axisymmetric Fires

Axisymmetric source fires are fires with circular plan areas. Rectangular source fires with small aspect ratios (~1) are also treated as axisymmetric source fires whereas rectangular source fires with large aspect ratios are treated as line or one-dimensional source fires. The distinction arises because of the manner in which the thermal plume develops and is related to the shape of the plume that develops as well as the plume ambient air entrainment characteristics. Correlations are available (Yokoi,[24] for example) for source fires that are neither axisymmetric nor one-dimensional, but these are beyond the scope of this section and are not addressed further.

A simple form of the developed correlation for flame heights for pool or horizontal burning fuels is based on only the diameter and heat release rate of the fire. Figure 3.9.5 provides a graphical version of the relationship.

The equation on which Figure 3.9.5 is based is as follows:

$$L = -1.02D + 0.23\dot{Q}^{2/5} \tag{11}$$

where

L = Average flame height (m)

D = Diameter of fire source (m)

$\dot{Q}$ = Total energy release rate of the fire (kJ/sec or kW)

This flame height equation is valid for Standard Temperature and Pressure (STP) conditions (101,325 Pa and 15°C). The buoyancy forces within the plume above a given fire source may vary with different ambient temperature and pressure; a more general version of Equation 11 was developed by Heskestad[25] and is found in Section 2, Chapter 1, of the *SFPE Handbook of Fire Protection Engineering.*[26]

For noncircular fuel packages, an effective fire diameter can be estimated by

$$D = 2\left(\frac{A_f}{\pi}\right)^{1/2} \tag{12}$$

which can also be expressed as

$$D = 2\sqrt{\frac{A_f}{\pi}}$$

where

D = Effective fire diameter (m)

A_f = Area of the fire (m^2)

Since flames are unsteady, the average flame height L is generally taken to be the height above the fire source where the flame tip is observed to be at or above this point 50 percent of the time. Equation 11 is considered suitable for pool fires or

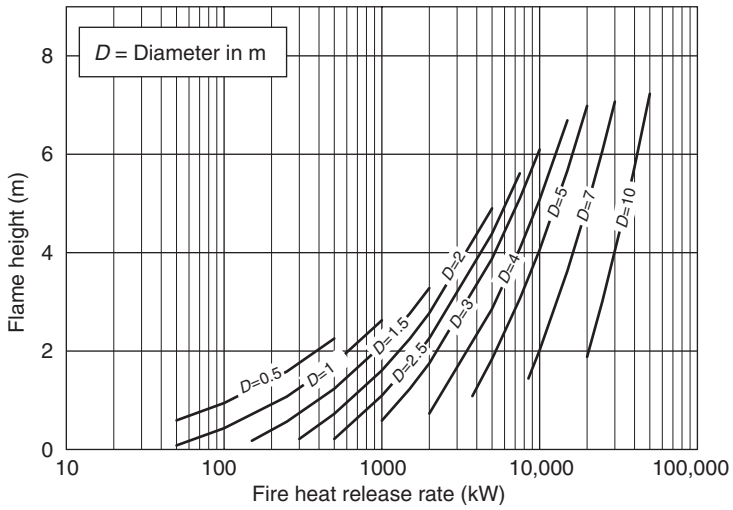

FIGURE 3.9.5 Flame Heights for Steady Fires with Various Diameters Plotted Using Equation 11

for horizontal surface burning. It should be noted that this correlation will produce negative values for L at small heat release rates. The available experimental data indicate that the most reliable region of application is where $\dot{Q}^{2/5}/D$ is greater than 16.5. For more detail on flame height calculations, the reader is referred to Beyler[27] and Section 2, Chapter 1, of the *SFPE Handbook of Fire Protection Engineering*.[26]

EXAMPLE 6. Consider a short stack of wooden pallets (1.2 m × 1.2 m) burning at a heat release rate of 900 kW. What is the height of the resulting flame?

SOLUTION 6. In order to determine the flame height, the heat release rate (given) and diameter are needed. In this case, an effective diameter is calculated using Equation 12:

$$D = 2\sqrt{\frac{(1.2 \times 1.2)}{\pi}} = 1.35 \text{ m}$$

Using the given heat release rate and effective diameter in Equation 11 provides an estimate of the mean flame height:

$$L = -1.02(1.35) + 0.23(900)^{2/5} = 2.1 \text{ m}$$

Alternatively, Figure 3.9.5 could be used to directly determine the flame height after calculation of the effective diameter. To do this, locate on the horizontal axis (i.e., the x-axis) the value 900 kW; next move vertically up from this location to the line with the diameter nearest 1.35 m, which is 1.5 m. A minor interpolation is necessary to account for the difference in actual and plotted diameters; since the next lowest diameter plotted is 1.0 m, a point somewhat between the 1.0 m and 1.5 m lines, somewhat closer to the 1.5 m line, is desired. Once found, the flame height is read by moving horizontally to the vertical or y-axis. A flame height just above 2.0 m is then read.

Wall and Line Fires

Equations have also been developed for elongated fires that are either (1) against a wall so that air is entrained (i.e., drawn in) from one side only (i.e., wall fires) or (2) sufficiently in the open so that air is entrained along both of the longitudinal sides (i.e., line fires).[28] In these equations, the flame height is based on the rate of heat release per meter of length of the fire source. The flame height for wall fires is[29]

$$L = 0.034(\dot{Q}')^{2/3} \tag{13}$$

and the flame height for a line fire is[29]

$$L = 0.017(\dot{Q}')^{2/3} \tag{14}$$

where

L = Flame height (m)

$\dot{Q}'$ = Length of total heat release per meter length of the fire source (kW/m)

EXAMPLE 7. Compare the flame height from a 100 kW/m wall fire and a 100 kW/m line fire.

SOLUTION 7. Equation 13 may be used directly to compute the line fire flame height: $L = 0.034(\dot{Q}')^{2/3} = 0.034(100)^{2/3} = 0.73$ m. Likewise, Equation 14 may be used directly to compute the wall fire flame height: $L = 0.017(\dot{Q}')^{2/3} = 0.017(100)^{2/3} = 0.37$ m. Thus, for a given heat input per unit length, the wall fire flame height is one-half the line fire flame height.

Thermal Plumes

The plume centerline temperature and velocity are parameters that are useful for determining the exposure to objects that are located within the fire plume, above the tops of flames, and below the ceiling. For detector response at the ceiling level, Alpert's plume and ceiling jet correlations are more commonly applied (see section on thermal detector response).

The plume centerline excess temperature and velocity at elevations above the mean flame height can be estimated from the following simplified equations[30] (see Figure 3.9.4):

$$T_{plume,cl} = \frac{18.8\dot{Q}^{2/3}}{(h - Z_o)^{5/3}} + T_\infty \tag{15}$$

$$U_{plume,cl} = \frac{0.77\dot{Q}^{1/3}}{(h - Z_o)^{1/3}} \tag{16}$$

where

$T_{plume,cl}$ = Centerline plume gas temperature above the fire (°C)

$U_{plume,cl}$ = Centerline plume gas velocity above the fire (m/sec)

$\dot{Q}$ = Total fire energy release rate (kJ/sec or kW)

h = Distance above fuel surface (m)

Z_o = Position of the virtual origin (m), Equation 15

T_∞ = Ambient temperature (°C)

Equations 15 and 16 assume that the convective fraction of the total heat release rate is 0.65 and the fire is in a location with standard atmospheric conditions (i.e., the pressure is 101,325 Pa and the temperature is 15°C). A convective fraction of 0.65 to 0.7 is fairly typical for common combustible materials,[27,31] but it is fuel specific and can vary from about 0.5 to almost 1.0.[31] A conservative computation would assume a convective fraction of 1.0. Data for specific fuels may be measured from small-scale tests such as the Cone Calorimeter or may be tabulated as in Sections 3–4 of the *SFPE Handbook of Fire Protection Engineering*.[31] Equations 15 and 16 are derived from more general equations presented in Heskestad.[13] If the convective fraction of the heat release rate is known to be other than 0.65, the value of $\dot{Q}$ in Equations 16 and 17 should be substituted with $[(x/0.65)\dot{Q}]$. In this substitution, x is the alternate convective fraction. Equations 16 and 17 are also only valid at heights above the mean flame height L.

Although methods exist to calculate excess temperature and velocities at locations other than along the plume centerline, the highest confidence is placed on centerline estimates. The reader is referred to Heskestad,[26] Beyler,[27] and Heskestad[30] for detailed discussions of noncenterline temperature and velocity estimates.

Calculation of the Virtual Origin

In order to estimate the plume centerline mean temperature and velocity (see next section), it is necessary to determine the virtual origin of the source fire. The virtual origin is the hypothetical location or elevation associated with substitution of a point source fire for the actual fire in question (see Figure 3.9.4). The consideration of a virtual origin is most important for evaluating centerline conditions near the fire. As the distance above the fire increases, the impact of the discrepancy that results from neglecting the virtual origin decreases. It is common practice to ignore virtual source considerations for calculations where the distance above the fire is many times the diameter of the fire. For centerline elevations near the fire, however, a more accurate estimate of the position of the virtual source is necessary. The following expression, limited to pool fires and horizontal burning, provides an estimate of the location of the virtual origin:[25]

$$Z_o = -1.02D + 0.083\dot{Q}^{2/5} \qquad (17)$$

where

Z_o = Location of virtual fire origin (m)

D = Diameter of fire source (m)

$\dot{Q}$ = Total energy release rate of the fire (kJ/sec or kW)

The intent of the virtual source computation is to find the location where a point source would produce an equivalent thermal plume to be consistent with the strong plume equation derivation. Because of variations in the source fire strength and the fire diameter, this equivalent point source location may be at, above, or below the base of the burning fuel. Typically, the point source is located below fires with a low energy release rate per unit area because the plume width is wide, thereby requiring a long entrainment distance from a point heat source having the same power to be equivalent. Conversely, fires with a high unit energy release rate may have the virtual origin located above the fire base because the plume width is narrow; thus, a short entrainment distance is required for a point source having the same power to be equivalent. Figure 3.9.6 can be used to directly determine the height of the virtual origin when the diameter and heat release rate are known in the same manner as Figure 3.9.5 can be used to estimate the flame height. Refer to Example 7 for additional details on the use of these figures.

EXAMPLE 8. A 500 kW fire is burning on the floor of a large, open industrial facility with a ceiling height of 10 m. The fire is underneath a power cable tray, which is 7 m above the floor. Assume that the fire diameter is approximately 1 m, the interior ambient temperature is 20°C, and the failure temperature of the power cables is 200°C. Will the cables potentially sustain damage from the fire?

SOLUTION 8. The first step in solving this problem is to determine the location of the virtual origin of the fire. Using Equation 17,

$$Z_o = -1.02(1) + 0.083(500)^{2/5} = -0.02 \text{ m}$$

With the location of the virtual origin known, the plume centerline temperature at a height of 7 m can be determined from Equation 15:

$$T_{plume,cl} = \frac{18.8(500)^{2/3}}{[7 - (-0.02)]^{5/3}} + 20 = 66°\text{C}$$

In this case, the plume above the fire would not be hot enough to damage the power cables in the tray above the fire.

Radiant Heat Flux

For many fires, it is of interest to estimate the radiation transmitted from a burning fuel package array to a target located at a distance from the fire. Knowledge of the incident radiant heat flux at a specific location is useful for assessing the likelihood

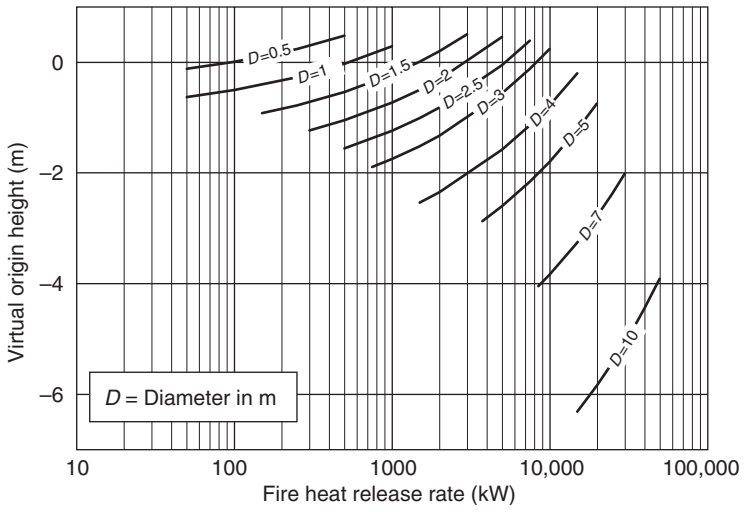

FIGURE 3.9.6 Virtual Origins for Steady Fires with Various Diameters

of fire propagation, presenting a hazard to occupants, impeding egress, or causing damage to enclosure contents. Fairly sophisticated methods and models for such estimates exist in the literature.[32,33] These methods are derived primarily from correlations of experimental flammable liquid pool fire data. The simplified methods provided here are to be used primarily as screening methods.

Lawson and Quintiere Method. Lawson and Quintiere[34] developed a simple hemispheric point source type model based on correlations of available experimental data (see Figure 3.9.4). Experimental evidence suggests that such methods are reasonably accurate provided the predicted heat flux is less than about 5 kW/m^2.[32] The following expression was developed, based on these correlations, to estimate the radiant heat flux from a fire to a target positioned normal to the radial distance:

$$\dot{q}''_r = \frac{\chi_r \dot{Q}}{4\pi R_o^2} \tag{18}$$

where

$\dot{q}''_r$ = Incident radiation on the target (kW/m^2)

χ_r = Radiative fraction

$\dot{Q}$ = Total energy release rate (kJ/sec or kW)

R_o = Distance from center of fire base to the target (m)

The radiative fraction varies from 0.2 to 0.4, depending on the fuel type and pool diameter.[31] The radiative fraction for most common materials is between 0.3 and 0.35, but, like the convective component of the heat release rate, it may vary from about 0 to 0.5 or more.[31] The radiative fraction for may be measured from small-scale fire tests such as the cone calorimeter; other sources for this parameter include tabulated data such as that provided by Tewarson.[31]

The experimental measurements relied on indicate that Equation 18 has good accuracy for

$$\frac{R}{R_o} > 4 \tag{19}$$

where

R = Radius of the base of the fire (m)

R_o = Distance from center of fire to the target (m)

At values of R/R_o less than 4, the methods tend to underpredict the incident heat flux.

Recent investigations have found that a safety factor of two should be applied to a point source model similar to the Lawson and Quintiere method.[32] Because the two approaches reflect the same type of thermal radiation model, a safety factor of two should be applied to the Lawson and Quintiere method as well.

Point source type methods assume that the pool fire is circular or nearly circular. The point source configuration factor assumption is more appropriate at larger distances from the fire, that is, where the ratio of the distance from the pool center to the pool diameter (L/D as defined in Equation 20 below) is greater than 2.5. This is in addition to meeting the constraint imposed by Equation 19. At closer locations, these methods tend to underpredict the incident heat flux. Because this method is limited to prediction of incident heat fluxes at or below 5 kW/m^2 (due to limited data), it is not suitable for use in estimating the potential for ignition of combustibles. However, reasonable estimates of lower heat fluxes associated with damage to electronics or other thermally sensitive equipment as well as the onset of burns can be expected.

Shokri and Beyler Correlation. An alternative approach to the Lawson and Quintiere method is the Shokri and Beyler correlation,[32] which was developed from large-scale pool fire data. This simple correlation can be used to estimate the heat flux to a vertically oriented surface (i.e., target) at ground level. The incident heat flux is given by

$$\dot{q}''_r = 15.4\left(\frac{L}{D}\right)^{-1.59} \tag{20}$$

where

$\dot{q}''_r$ = Incident radiation on the target or surface of interest (kW/m^2)

D = Diameter of the pool fire (m)

L = Distance from the center of the pool fire to the target (m)

Noncircular pool fires with length to width ratios of approximately 1 (e.g., square surfaces) can be evaluated based on the use of an equivalent diameter D_e rather than an actual diameter D. D_e is given by

$$D_e = \sqrt{\frac{4A}{\pi}} \tag{21}$$

where A is the surface area of the noncircular pool (m^2).

This correlation is based largely on liquid fuels that have pool diameters ranging from 1 m to 50 m and that produce luminous flames. Further, the data used were limited to values of L/D that were greater than the range of 0.7 to 15.0. Use of this correlation for L/D values less than 0.7 could underpredict the estimates of radiant heat flux.

This correlation provides realistic predictions of incident heat flux levels. When using the method of Shokri and Beyler, it is recommended that a safety factor of two be applied for general design applications.[32,35]

EXAMPLE 9. Compute the maximum radiant flux incident on a target surface 5 m from the edge of a 2000 kW pool fire confined to a 1 m^2 curbed area. Use both the Lawson and Quintiere method and the method of Shokri and Beyler.

SOLUTION 9. Per Equation 19, the maximum heat flux at the target surface may be computed using the Lawson and Quintiere method provided R/R_o is greater than 4, where R is the fire radius and R_o is the distance between the center of the fire and the target (target separation distance). The fire radius is 0.5 m and the target separation distance is 5.5 m (5.0 m from the fire edge plus 0.5 m from the fire edge to the fire center, i.e., the radius). R/R_o is thus 11, meeting the constraint imposed by Equation 19. Thus, the maximum incident heat flux computed using the

Lawson and Quintiere method is determined using Equation 18 as follows:

$$\dot{q}''_r = \frac{\chi_r \dot{Q}}{4\pi R_o^2} = \frac{(0.4)(2000)}{4\pi(5.5)^2} = 2.1 \text{ kW/m}^2$$

where the radiative fraction χ_r is conservatively assumed to be 0.4 since the maximum incident heat flux is the desired result. A safety factor of two is recommended for this method; thus, the maximum incident heat flux at the target location is predicted to be 4.2 kW/m^2.

The maximum heat flux at the target surface may be computed using the method of Shokri and Beyler provided *L/D* is between 0.7 and 15.0 where *L* is the target separation and *D* is the fire diameter. The target separation is 5.5 m and the fire diameter is 1.0 m; thus, *L/D* is equal to 5.5 m and the method of Shokri and Beyler is applicable. The radiant heat flux is readily computed using Equation 21 as follows:

$$\dot{q}''_r = 15.4\left(\frac{L}{D}\right)^{-1.59} = 15.4\left(\frac{5.5}{1}\right)^{-1.59} = 1.02 \text{ kW/m}^2$$

A safety factor of two is recommended for this method; thus, the maximum incident heat flux at the target location is predicted to be 2.0 kW/m^2, or about one-half that predicted by the Lawson and Quintiere method.

Enclosure Smoke Filling

The smoke accumulation and descent of a smoke layer within an enclosure represents a means by which to establish occupant immersion. When occupants are immersed in a smoke layer, the ability to egress is impeded and it becomes more difficult to enter an area to perform rescue and suppression activities. Smoke from a fire begins to fill an enclosure as it accumulates below the ceiling. The rate of smoke filling depends on the rate of smoke production and the size and location of vents as well as any forced ventilation or extraction rate in an area. The minimum smoke layer elevation may be computed if the smoke production rate and the vent mass flow are known. This information may also be used to establish a minimum mechanical exhaust rate necessary to maintain a smoke layer at a desired elevation, typically above occupants.

Detailed discussions on smoke filling and smoke venting calculations may be found in NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces,* and in the *SFPE Handbook of Fire Protection Engineering.*[36–39]

Smoke Production Rate

The rate of smoke-filled gas produced by a fire is nearly equal to the rate of air entrained into the rising fire plume; therefore, the mass production rate of smoke-filled gas can be estimated as equal to the mass flow rate of gas in the fire plume. This mass flow rate into a plume above the visible flame height may be estimated using the following expression developed by Zukoski:[40]

$$\dot{m}_s = 0.065 \dot{Q}^{1/3} Y^{5/3} \tag{22}$$

where

$\dot{m}_s$ = Rate of smoke-filled gas production (kg/sec)

$\dot{Q}$ = Total energy release rate (kJ/sec or kW)

Y = Distance from the virtual point source for the fire to the bottom of the smoke layer (m)

The elevation of the virtual point source may be calculated using Equation 15. Figure 3.9.7 provides graphical results of Equation 22 as a function of the fire size for different smoke layer elevations. Clearly, Figure 3.9.7 demonstrates that the production rate is a strong function of the smoke layer elevation above the virtual origin elevation.

Equation 22 is valid only when the smoke layer height is above the flame height. McCaffrey[41] has investigated gas

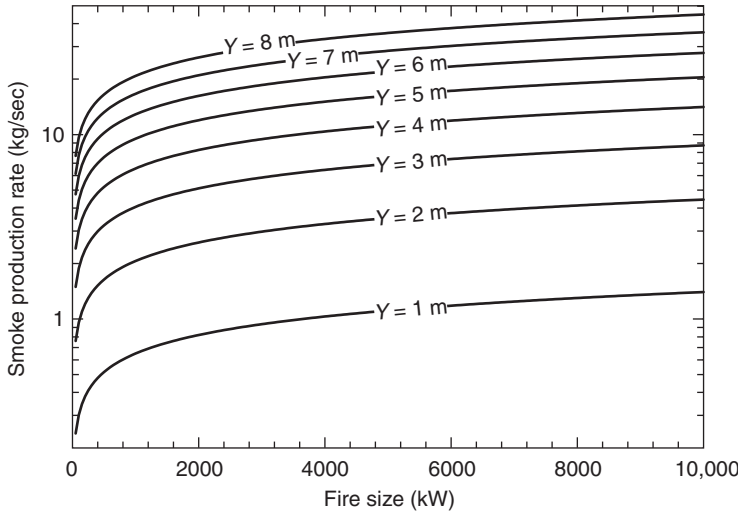

FIGURE 3.9.7 Smoke Production Rates for Steady Fires with Various Distances from the Virtual Origin

temperatures and velocity distributions in the flame region. Alternative methods are also presented by Butcher and Parnell.[42]

EXAMPLE 10. Compute the smoke production rate from a 1 m^2 Class A combustible material fire having a heat release rate per unit area of 400 kW/m^2 and a diameter of 1.1 m if the smoke layer is to be maintained at 1.8 m above the floor. What is the smoke production rate if the smoke layer is to be maintained 3.1 m above the floor?

SOLUTION 10. Equation 22 may be used to assess the smoke production rate for the source fire. The fire size is equal to the fire area multiplied by the heat release rate per unit area or 400 $kW/m^2 \times 1\ m^2 = 400$ kW. The virtual origin must first be computed using Equation 17: $Z_o = -1.02D + 0.083\dot{Q}^{0.4}$, which is equal to –0.21 m for a 400 kW source fire having a diameter of 1 m. Equation 22 may now be used directly to compute the smoke production rate for a smoke layer: $\dot{m}_s = 0.065\dot{Q}^{1/3}Y^{5/3}$. For a smoke layer maintained 1.8 m above the floor, Y is equal to 1.8 m plus 0.21 m or 2.01 m, since the virtual source is located *below* the fire base (i.e., Z_o is negative). In this case, the smoke production rate is $0.065 \times (400^{1/3}) \times (2.01^{5/3})$ or 1.53 kg/sec. Similarly, for a smoke layer maintained 3.1 m above the floor, Y is equal to 3.31 m and the smoke production rate is equal to $0.065 \times (400^{1/3}) \times (3.31^{5/3})$ or 3.52 kg/sec. Note that the smoke production rate more than doubles when the height at which the smoke layer is maintained is increased by 70 percent, or in this case about 1.3 m.

Volumetric Smoke Exhaust Rate

The minimum exhaust rate necessary to maintain the smoke layer elevation at a fixed height above the virtual origin may be estimated using Equation 22 and the estimated preflashover compartment temperature as follows:

$$\dot{V}_m = 0.065\left(\frac{T+273}{352}\right)\dot{Q}^{1/3}Y^{5/3} \qquad (23)$$

where

$\dot{V}_m$ = Minimum volumetric flow rate (m^3/sec) necessary to maintain smoke layer at an elevation Y (m) above the virtual origin

$\dot{Q}$ = Total energy release rate (kJ/sec or kW)

T = Compartment gas temperature (°C)

Equation 23 only applies to situations where the exhaust is taken only from the smoke layer and the smoke layer elevation is greater than the flame height. The reader can consult NFPA 92B or the *SFPE Handbook of Fire Protection Engineering*[38,39] for more complicated arrangements and applications.

EXAMPLE 11. Compute the volumetric flow rates necessary to maintain a smoke layer above 1.8 m inside a compartment having a 3000 kW source fire. Assume gas layer temperatures of 100°C, 200°C, and 300°C and an ambient temperature of 20°C.

SOLUTION 11. Equation 23 may be used to assess the layer height under this condition:

$$\dot{V}_m = 0.065\left(\frac{T+273}{352}\right)\dot{Q}^{1/3}Y^{5/3}$$

$$= 0.065\left(\frac{T+273}{352}\right)(3000)^{1/3}(1.8)^{5/3}$$

$$= 0.0071(T+273)\ m^3/sec$$

Thus, for a 100°C compartment temperature, the minimum exhaust flow rate would be 2.6 m^3/sec; for a 200°C compartment temperature, the minimum exhaust flow rate would be 3.4 m^3/sec; and for a 300°C compartment temperature, the minimum exhaust flow rate would be 4.1 m^3/sec. This calculation is useful to provide a quick estimate of the adequacy of the ventilation to maintain habitable conditions within a space. More detailed computation methods should be used if a greater resolution is required or when designing smoke exhaust systems.

ENCLOSURE FIRE EFFECTS

Enclosure Fire Effects Defined

Enclosure fire effects are defined in the context of this chapter as those changes or consequences that may occur as a direct result of a fire in the enclosure. These consequences are typically brought about by exposure to one or more specific fire hazards such as temperature increase, incident heat flux, or flashover. Fire effects considered in this section include ignition of adjacent solid fuel packages and actuation of detection and suppression devices. Typically, to assess such effects a knowledge of the fire size or growth profile and the hazard variable(s) that cause the effect is required. These elements have been presented in previous sections of this chapter.

Ignition of Solid Fuel Packages

The potential for a fire to ignite nearby solid fuel packages provides insight into the likelihood for fire spread within an enclosure. Conversely, separation distances between fuel packages could be established based on the requirement that one burning fuel package not cause a second fuel package to ignite.

Ignition is a complex phenomenon, dependent on physical and chemical properties of the materials, the environment in which the material exists, and the source(s) of heat exposing the material. A quantitative description of the physical and chemical processes associated with ignition of heated solids can be found in Kanury[5] and Babrauskas.[43] Solutions for ignition of solids are developed by Kanury[5] for specific applications.

Nelson and Forssell[44] developed an approach for prediction of ignition of solids that relies on material properties and data from a cone calorimeter or similar heat release rate test. The ignition time (t_{ign}) for a material exposed to a constant heat flux, as in the cone calorimeter, is estimated using empirical correlations and available test data.

For "thermally thick" materials, that is, materials that have sufficient thickness such that the time to ignition is less than the thermal penetration time through the solid, a "trial and error" fit is used to estimate the ignition time. Such an approach is outside the scope of this chapter; therefore, the reader is referred

to Kanury,[5] Babrausksas,[43] and Nelson and Forssell[44] for a detailed discussion of this approach.

A somewhat less complicated problem involves estimates of ignition time for "thermally thin" materials. These are solids that are so thin or so highly conductive that temperature gradients are essentially nonexistent within the material slab, and the temperature of the material is dependent only on the exposure time to the source of heating such as a fabric curtain or a sheet of paper. Under such conditions the heating can be treated as a bulk heating process, using the following expression where convective losses are assumed to be zero:[5]

$$t_{ign} = \frac{\rho_s c_s V_S (T_{ign} - T_S)}{\dot{q}''_{net} A_S} \qquad (24)$$

where

t_{ign} = Time to ignition (sec)

ρ_s = Density of the solid (kg/m^3)

c_s = Heat capacity of the solid (kJ/kg·°C)

V_S = Solid volume (m^3)

T_{ign} = Solid ignition temperature (°C)

T_S = Initial solid temperature (°C)

$\dot{q}''_{net}$ = Net absorbed heat flux at the solid surface (kW/m^2)

A_S = Exposed surface area of solid (m^2)

The ignition temperature for several common materials is listed in Table 3.9.5. Additional information is provided by Babrauskas,[43] Quintiere,[15] and Quintiere.[45] For the purposes of a screening analysis, the incident heat flux may be assumed for the net absorbed heat flux. If more accuracy is desired, a thermal balance at the solid surface is necessary as described by Lattimer,[46] Drysdale,[13] Tien et al.,[47] and Atrea.[48]

Caution is recommended in using the formulas provided here for estimating ignition times. As stated earlier, ignition is a complex phenomenon and the limitations associated with the use of these expressions are important. The reader is encouraged to review the more detailed discussions in Kanury,[5] Babrauskas,[43] and Nelson and Forssell.[44]

In cases where a separation distance is established, it is often appropriate to use a critical ignition heat flux as a basis for the separation distance. The critical ignition heat flux is the minimum heat flux at which a solid could ignite given the presence of a pilot such as a burning ember or a spark. These values are experimentally determined and material specific. Table 3.9.5 summarizes the critical ignition heat flux for common solid combustible materials. Additional information is provided by Babrauskas,[43] Quintiere,[15] Quintiere,[45] Babrauskas et al.,[7] and Drysdale.[13]

TABLE 3.9.5 Ignition Temperature and Critical Ignition Heat Fluxes for Common Materials[15]

Material	*Ignition Temperature (°C)*	*Critical Ignition Heat Flux (kW/m²)*
Plywood	390	16
Plywood (FR)	620	44
PMMA	278–378	9–15
Polycarbonate	528	30
Polystyrene	630	46
Hardboard	298–400	10–17
Carpet	300–465	10–23

EXAMPLE 12. Estimate the ignition time for a 1-mm-thick PVC laminate initially at 20°C that is exposed to an incident heat flux of 50 kW/m^2. Assume the flux is uniformly distributed over the surface, that the heat capacity is 0.84 kJ/kg·°C, that the density is 1450 kg/m^3, and that the ignition temperature is 220°C, typical properties for PVC as found in the *SFPE Handbook of Fire Protection Engineering*[1] and other sources.[49]

SOLUTION 12. Because the material is a thin laminate, Equation 24 is applicable. Also, since the exposure is uniform over the surface, V_s/A_s is equal to the material thickness, where V_s is the material volume (m^3) and A_s is the exposed surface area (m^2). It is also conservatively assumed that the net heat absorbed at the surface is equal to the incident heat flux, or 50 kW/m^2. In this case, the ignition time may be estimated as:

$$t_{ign} = \frac{\rho_s c_s V_S (T_{ign} - T_S)}{\dot{q}''_{net} A_S} = (0.001)\frac{(1450)(0.84)(220 - 20)}{(50.0)} = 5 \text{ sec}$$

Note that in Equation 24, V_s/A_s is replaced with the material thickness, which is 0.001 m for this example.

Thermal Detector and Automatic Fire Sprinkler Response

Plume and ceiling jet temperatures and velocities are parameters that are necessary for the evaluation of the potential for ceiling detectors to activate or to estimate their activation time. The methods in this section are appropriate for automatic fire sprinklers or fixed-temperature heat detectors. For exposure to objects within the fire plume, mean centerline plume parameters are more appropriate (see section on the plume centerline temperature and velocity).

A simplified plume temperature correlation for a steady-state fire is as follows:

$$T_{m(plume)} = 16.9\frac{\dot{Q}^{2/3}}{h_{ceil}^{5/3}} + T_\infty \qquad \text{for } r/h_{ceil} \le 0.18 \qquad (25)$$

where

$T_{m(plume)}$ = Centerline plume gas temperature above the fire (°C)

$\dot{Q}$ = Total heat release rate (kW)

h_{ceil} = Distance from the fuel surface to the ceiling (m)

T_∞ = Ambient temperature (°C)

r = Radial distance from the axis of the fire (m)

Based on cases where the hot gases have begun to spread under a ceiling located above the fire, Equation 25 also applies for a small radial distance, *r,* from the impingement point on the ceiling (Figure 3.9.8).

Over this distance, up to $r/h = 0.18$, where the gas is turning to flow outward under the ceiling, the highest temperature in the flow remains equal to the value at the impingement point directly over the fire. At greater distances from the axis of the fire, a ceiling jet temperature correlation is more appropriate. This correlation takes into account the actual distance from the impingement point:

$$T_{m(jet)} = 5.38\frac{(\dot{Q}/r)^{2/3}}{h_{ceil}} + T_\infty \qquad \text{for } r/h_{ceil} > 0.18 \qquad (26)$$

where

$T_{m(jet)}$ = Maximum ceiling jet temperature at position r (°C)

$\dot{Q}$ = Total heat release rate (kW)

r = Distance from the fire (m)

h_{ceil} = Distance from the fuel surface to the ceiling (m)

T_∞ = Ambient temperature (°C)

Correlations are also available for maximum velocities in the ceiling jet flow under a ceiling. As with the temperature correlations, there are two regions: (1) one close to the impingement point where velocities are nearly constant and (2) the other farther away where velocities vary with radial position. The two correlations are expressed as follows:

$$U_{m(plume)} = 0.096\left(\frac{\dot{Q}}{h_{ceil}}\right)^{1/3} \qquad \text{for } r/h < 0.15 \qquad (27)$$

$$U_{m(jet)} = 0.195\left(\frac{\dot{Q}^{1/3}h_{ceil}^{1/2}}{r^{5/6}}\right) \qquad \text{for } r/h_{ceil} \geq 0.15 \qquad (28)$$

where

$U_{m(plume)}$ = Maximum ceiling jet gas velocity near the plume impingement point (m/sec)

$U_{m(jet)}$ = Maximum ceiling jet gas velocity (m/sec)

$\dot{Q}$ = Total heat release rate (kW)

h_{ceil} = Distance from the fuel surface to the ceiling (m)

r = Radial distance from the fire (m)

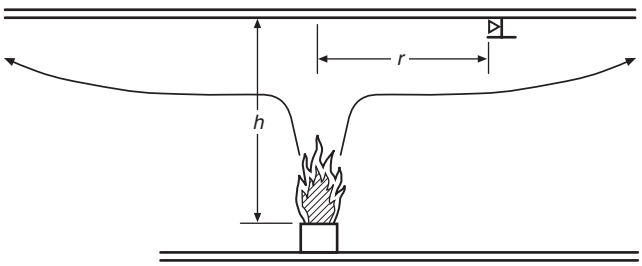

FIGURE 3.9.8 Parameters *h* and *r* Both Related to Calculation of Sprinkler or Heat Detector Actuation Time

Equations 25 and 26 can be used to determine whether the temperature of the fire-driven gas flow past a detection device is high enough to operate the device. However, more information is needed to calculate the amount of time needed to heat the detector or automatic fire sprinkler-sensing element to the operating temperature. Often, these elements are made of metal, such as the ordinary solder-type fusible link used in the link and lever automatic fire sprinklers, or they are liquid-filled glass vials, such as those used in bulb-type automatic fire sprinklers. Both of these sensing elements require some time to absorb the heat transferred from the hot gas flowing around the device.

For steady fires, the time required to heat the sensing element of a thermal detection or suppression device from room temperature to operation temperature is given by

$$t_{\text{operation}} = \frac{\text{RTI}}{\sqrt{U_m}}\log_e\left(\frac{T_m - T_\infty}{T_m - T_{\text{operation}}}\right) \qquad (29)$$

where

$t_{\text{operation}}$ = Activation time of the detector (sec)

RTI = Response time index of the detector ($m^{1/2}\cdot sec^{1/2}$)

$T_{\text{operation}}$ = Activation temperature of the thermal element/detector (°C)

T_m = Exposure temperature (°C)

T_∞ = Initial ambient temperature (°C)

The RTI is a measure of the ease of heating thermal elements in heat detectors and automatic fire sprinklers. The larger the RTI value, the greater the lag in heating the sensing element for a given fire exposure. RTI values for automatic fire sprinklers have been measured[50] in the range of 15 $m^{1/2}\cdot sec^{1/2}$ to 400 $m^{1/2}\cdot sec^{1/2}$. NFPA 13, *Standard for the Installation of Sprinkler Systems,* defines standard response sprinklers as those having an RTI greater than or equal to 80 $m^{1/2}\cdot sec^{1/2}$, and fast response sprinklers as those having an RTI less than or equal to 50 $m^{1/2}\cdot sec^{1/2}$.

For the case of fixed-temperature detectors, the minimum total heat release rate, $\dot{Q}$, needed to operate a fixed-temperature detection or suppression device at the ceiling can be estimated by rearranging Equations 25 and 26, solving for $\dot{Q}$ with T_m set equal to the activation temperature of the thermal device. In this form, Equations 25 and 26 become

$$\dot{Q} = 0.014(T_{\text{operation}} - T_\infty)^{3/2}(h_{ceil})^{5/2} \qquad \text{for } r/h_{ceil} \leq 0.18 \qquad (30)$$

$$\dot{Q} = 0.08(T_{\text{operation}} - T_\infty)^{3/2}(h_{ceil})^{3/2}(r) \qquad \text{for } r/h_{ceil} > 0.18 \qquad (31)$$

where

$\dot{Q}$ = Total heat release rate (kW)

$T_{\text{operation}}$ = Activation temperature of the thermal element/detector (°C)

T_∞ = Initial ambient temperature (°C)

r = Radial distance from the fire (m)

h_{ceil} = Distance from the fuel surface to the ceiling (m)

A common practice when estimating thermal detector response is to assume that the fire is centrally located between evenly spaced heat detectors or automatic fire sprinklers on the ceiling. This assumption normally maximizes the estimated response time of a detector in a space completely covered by detectors. The following equation can be used to calculate r, based on the spacing of detectors:

$$r = \sqrt{\left(\frac{a}{2}\right)^2 + \left(\frac{b}{2}\right)^2} \tag{32}$$

where

r = Radial distance from fire (m)

a = Spacing in one direction (m)

b = Spacing in the direction perpendicular to a (m)

See Figure 3.9.9.

EXAMPLE 13. An 1800 kW wood pallet fire is burning in a space with a ceiling height of 4.0 m. The fire is centrally located between four automatic fire sprinklers spaced at 4.5 m. The automatic fire sprinklers are standard response with an activation temperature of 74°C and an RTI of 80 $m^{1/2}\cdot sec^{1/2}$. The ambient temperature in the space is 20°C. How long will it take for the fire to activate an automatic fire sprinkler? What is the minimum heat release rate needed to activate an automatic fire sprinkler in this configuration? Assume that the sprinkler is exposed to the maximum ceiling jet temperature and velocity at a given location.

SOLUTION 13. The first step in solving this problem is to determine the radial distance r between the automatic fire sprinkler and the fire. Using Equation 32:

$$r = \sqrt{\left(\frac{4.5}{2}\right)^2 + \left(\frac{4.5}{2}\right)^2} = 3.18 \text{ m}$$

Because the ratio r/h_{ceil} is 0.8, Equations 26 and 28 are appropriate to use for determining the temperature and velocity of the ceiling jet.

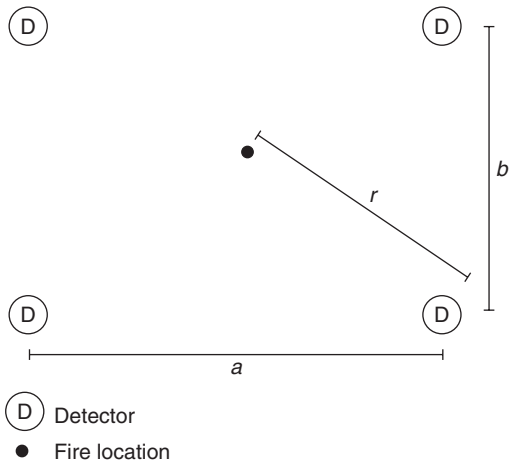

FIGURE 3.9.9 Parameters a, b, and r as They Relate to the Spacing of Detectors Described in Equation 32

$$T_{m(jet)} = 5.38\frac{(1800/3.18)^{2/3}}{4} + 20 = 112°\text{C}$$

$$U_{m(jet)} = 0.195\left[\frac{(1800)^{1/3}(4)^{1/2}}{(3.18)^{5/6}}\right] = 1.8 \text{ m/sec}$$

Equation 29 can be used to estimate the time of detection:

$$t_{\text{operation}} = \frac{80}{\sqrt{1.8}}\log_e\left(\frac{112-20}{112-74}\right) = 53 \text{ sec}$$

The minimum heat release rate needed to activate the automatic fire sprinklers in this configuration is determined from Equation 31:

$$\dot{Q} = 0.08(74-20)^{3/2}(4)^{3/2}(3.18) = 810 \text{ kW}$$

As seen in the example, the fire involving the small stack of pallets is large enough to activate the automatic fire sprinklers in this case.

The measurement of thermal lag for an automatic fire sprinkler is a topic of current research investigations and validation.[51,52] Recent progress has included means to account for the effects of heat loss due to conduction.[53] It has been found that, for cases when the gas temperature does not substantially exceed the activation temperature for the automatic fire sprinkler, significant error can occur in the prediction for activation time. In these cases, it is possible for small changes in predicted gas temperatures to result in large changes in predicted operation time.[51] In the case of constant or slowly varying gas temperatures this effect may be important where

$$\frac{T_m - T_{\text{operation}}}{T_m - T_\infty} < \frac{1}{4} \tag{33}$$

where

T_m = Exposure temperature (°C)

T_∞ = Initial ambient temperature (°C)

$T_{\text{operation}}$ = Activation temperature of the thermal element/detector (°C)

Another factor that contributes to the inaccuracy of predicted results, using Equation 29 under low gas temperatures and gas velocities and also for low RTI values, is that no means is included to account for loss of heat from sensing element, either link or glass bulb, to the automatic fire sprinkler frame and piping by conduction. Heskestad and Bill[53] and Ingason[54] have studied means to account for the effects of conduction loss and measured values for it for automatic fire sprinkler hardware. Following Heskestad and Bill,[53] Equation 29 can be modified to account for the conduction losses to the frame and piping, which are assumed to be at constant temperature equal to the initial ambient temperature (T_∞) as

$$t_{\text{operation}} = \frac{\text{RTI}}{\sqrt{U_m}\left(1 + \dfrac{C}{\sqrt{U_m}}\right)}\log_e \left[\frac{T_m - T_\infty}{T_m - T_{\text{operation}} - \dfrac{C}{\sqrt{U_m}}(T_{\text{operation}} - T_\infty)}\right] \tag{34}$$

where

$t_{operation}$ = Activation time of the detector (sec)

RTI = Response time index of the detector ($m^{1/2} \cdot sec^{1/2}$)

U_m = Ceiling jet or plume impingement gas velocity (m/sec)

C = A conduction loss parameter obtained from measurement $(m/sec)^{1/2}$

T_m = Exposure temperature (°C)

$T_{operation}$ = Activation temperature of the thermal element/detector (°C)

T_∞ = Initial ambient temperature (°C)

A realistic range of values for the conduction loss parameter is 0.5 to 1.6 $(m/sec)^{1/2}$. Using a C value of 0.9, the expected operation time for the automatic fire sprinkler in the Example 12 would increase to 139 seconds as predicted using Equation 34, which is nearly three times as slow as the prediction of 53 seconds (using Equation 29 or Equation 34 with $C = 0$). At a value of C greater than 0.94 $(m/sec)^{1/2}$, the heat loss would be great enough to prevent automatic fire sprinkler operation even though the gas temperature was sustained above the indicated operating temperature of the automatic fire sprinkler.

All calculations in use today for determining times to operation only consider the convective heating of sensing elements by the hot fire gases. The foregoing equations do not account for the additional heating of thermal elements due to conduction from the presence of a hot gas layer, nor do they account explicitly for any direct heating by radiation from the flames. Research is continuing to evaluate and improve calculations of operation for heat-activated devices, such as automatic fire sprinklers.

Automatic Fire Sprinkler Suppression

Fire suppression with water is an extremely complex physical, thermal, and chemical problem. Recently, work has been performed to aid in the design and analysis of sprinkler fire suppression experiments using fire modeling to predict the heat release rate of a fire after sprinkler operation.[55] Often, all that is needed is to gain some insight into the probable conservative bounds for time needed for suppression of fires. In that regard, a limited series of experiments has been conducted to measure the heat release rate during suppression for a series of light hazard occupancy fires involving furnishings. Data from these experiments have been correlated and bounded by a simple expression that permits hand calculations of the rate of heat release from fires during suppression by sprinklers.

Figure 3.9.10 shows the results of the measured heat release rate for furnishing and wood cribs normalized to the rate of heat release at the time of sprinkler operation. As expected, there is a wide range of behaviors. Some furnishing fires are more easily suppressed than others. The heat release rate from the sofa fire decreases rapidly—less than 10 percent of its initial value in about 20 seconds. The more complex Office I Fuel Package takes about 500 seconds to decrease by the same percentage. The regular array of wood sticks that makes up a wood crib

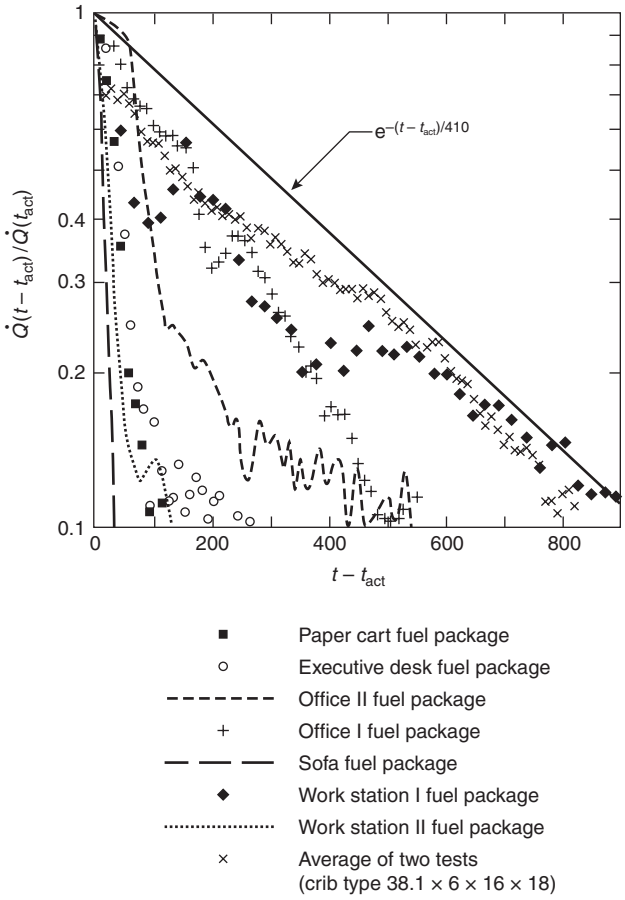

FIGURE 3.9.10 Heat Release Reduction During Suppression of Furnishing Fires with Ordinary Sprinklers. Data for spray density of 0.07 mm/sec (0.1 gal/min/ft^2). (Source: *A Sprinkler Fire Suppression Algorithm for the GSA Engineering Fire Assessment System,* NISTIR 4833)

presents both exposed and hidden burning surfaces that are difficult to extinguish. Over 800 seconds of sprinkler water spray is needed to reduce the heat release rate by 90 percent for the wood cribs tested. All of this test data were collected using a water spray density of 0.07 mm/sec.[54] This spray density is consistent with that suggested by NFPA 13 for the upper range of Light Hazard or the lower range of Ordinary Hazard I.

An upper bound for the data can be constructed by drawing a straight line of the semilog plot. This line results in an expression for the conservative bound (meaning least expected reduction in heat release rate) for suppression of a furnishing fire. This line represents the heat release rate during suppression as a decaying exponential function of time as follows:

$$\frac{\dot{Q}(t-t_{act})}{\dot{Q}(t_{act})} = \exp\left(-\frac{t-t_{act}}{t_e}\right) \qquad (35)$$

where

$\dot{Q}$ = Total heat release rate (kW or kJ/sec)

t = Time (sec)

t_{act} = Time spray suppression begins (sec)

t_e = Time constant for exponential decay (sec)

A limited experimental study of wood crib fire suppression was conducted by Walton[56] and analyzed by Evans.[57] Using the results of an earlier study[58] that showed the time to extinction of wood crib fires was proportional to the water application rate per unit of exposed surface area of the crib, the data from experiments using two different height cribs were collapsed into a single correlation. The wood crib fire suppression was analyzed in the same way as furniture fires have been analyzed previously. Although the data were scattered, as is common with suppression experiments, results[57] showed that for water spray densities varying from 0.03 mm/sec to 0.13 mm/sec, the time constant for the exponential decay in heat release rate varied as

$$t_e = 3 \cdot (m_w)^{-1.85} \tag{36}$$

where

t_e = Time constant for exponential decay (sec)

m_w = Water spray density (mm/sec)

At flow rates below the minimum, no substantial effect on heat release rate was measured.

Using Equation 36, the conservative estimate for exponential decay in heat release rate for furnishing fires suppressed with a water spray density of 0.07 mm/sec is

$$t_e = 3 \cdot (0.07)^{-1.85} = 410 \text{ sec} \tag{37}$$

where

t_e = Time constant for exponential decay (sec)

Using this time constant, the predicted values of the normalized energy release rate during suppression appear along the straight line in Figure 3.9.9. This line provides a conservative upper bound for almost all of the data as shown in Figure 3.9.9.

EXAMPLE 14. Estimate the time required for an automatic fire sprinkler having a water spray application density of 6 mm/sec to reduce an office fire fuel package having a peak energy release rate of 750 kW by 90 percent. Assume the time at which the automatic fire sprinkler actuates is 0 seconds.

SOLUTION 14: The water application flow rate is between 0.03 mm/sec and 0.13 mm/sec; thus, Equations 35 and 36 may be used to estimate the energy release rate reduction. The solution requires two steps: Equation 36 is first used to determine the exponential decay constant; Equation 35 is next used to estimate the time at which the fire size is reduced by 90 percent.

The decay constant is computed using Equation 36 directly:

$$t_e = 3 \cdot (m_w)^{-1.85} = 3 \cdot (0.06)^{-1.85} = 546 \text{ sec}$$

The time at which the fire size is reduced by 90 percent, or is equal to 10 percent of the peak value, is computed using Equation 35:

$$\frac{\dot{Q}(t - t_{act})}{\dot{Q}(t_{act})} = \exp\left(-\frac{t - t_{act}}{t_e}\right) \text{ or } 0.1 = \exp\left(-\frac{t}{546}\right)$$

rearranging:

$$t = -546 \cdot \ln(0.1) = 1260 \text{ sec} = 21 \text{ min}$$

where the inverse function of exp is the natural log.

COMPREHENSIVE EXAMPLE APPLICATION

This section provides a comprehensive example problem, drawing on several of the calculation methods described in this chapter.

EXAMPLE 15. A light manufacturing facility contains a utility room, which houses a backup diesel generator and 400 liter fuel tank that the facility uses to maintain operations during periods of city power loss. The full fuel tank has a curbed area underneath to contain any spills from the tank. The space is fully sprinklered. At some point in the past, a general-purpose workshop was placed in this space for facility support. The workshop contains typical items, including workbenches, tools, power equipment, and large trash containers. One workbench is located approximately 1.3 m from the edge of the curbed spill area, oriented such that the end of the workbench faces the curbed spill area. The ends of this workbench are made of 1.2-cm-thick plywood. An overview of this arrangement is shown in Figure 3.9.11.

A typical goal of automatic sprinkler systems is to control the fire before it spreads to a secondary fuel package. Given rupture of a pipe or of the fuel tank and a subsequent 0.2 m deep pool fire in the curbed area, is the fire likely to spread to the closest workbench prior to the activation of the automatic sprinkler system? Assume the following parameters:

- Curbed spill area dimensions: 1.4 m × 1.4 m × 0.21 m deep (ignore area occupied by tank)
- Area of plywood on workbench end: 1.0 m^2 (facing curbed area)
- Plywood density: 640 kg/m^3
- Plywood heat capacity: 2.8 kJ/(kg·°C)
- Plywood ignition temperature: 390°C
- Ceiling height: 5 m
- Sprinkler spacing 4.5 m × 4.5 m
- Sprinkler height: within maximum ceiling jet temperature and velocity
- Sprinkler operation temperature: 74°C
- Sprinkler RTI: 120 $m^{1/2}sec^{1/2}$
- Sprinkler conduction loss parameter: 0.5 $(m/sec)^{1/2}$
- The size and ventilation of the workshop are such that the heat release rate of the fire will not be limited in this case.

SOLUTION 15. This problem can be solved in three parts. The first part is determining the heat release rate of the fire. The second part is determining the potential ignition time of the workbench. The last part is determining the activation time of the automatic sprinklers.

Step 1. In order to estimate both the potential workbench ignition and the sprinkler activation time, the heat release rate of the fire must be determined. This can be accomplished using

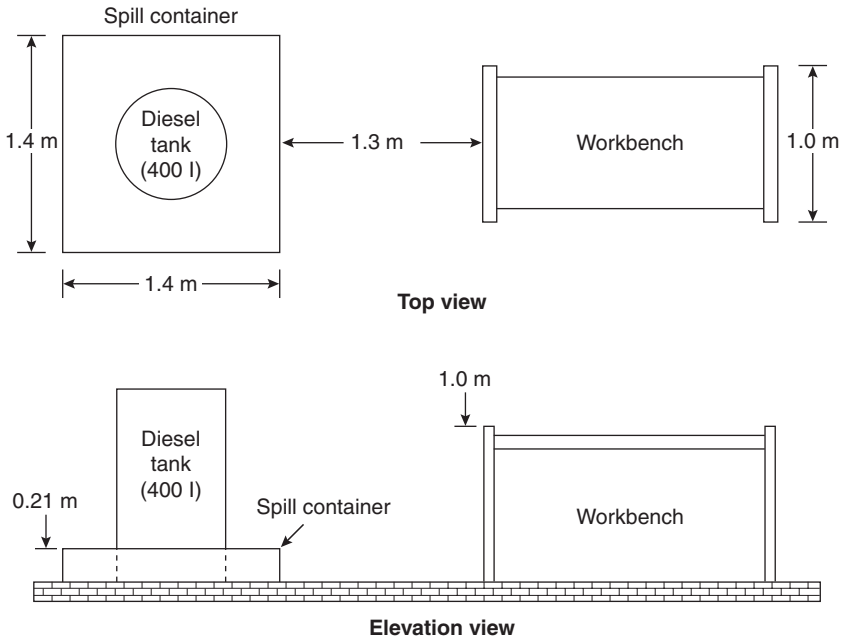

FIGURE 3.9.11 Comprehensive Example Setup

Equation 3. The value for energy release per unit area can be taken from Table 3.9.2 for a confined diesel pool: 1950 kW/m^2. The area is simply calculated from the given dimensions (1.4 m × 1.4 m = 2.0 m^2):

$$\dot{Q}_m = (1950)(2.0) = 3900 \text{ kW}$$

The effective diameter of this fire can be estimated using Equation 21:

$$D_e = \sqrt{\frac{4(2)}{\pi}} = 2.54 \text{ m}$$

Step 2. The next step is to determine the ignition time of the plywood workbench, which can be done using Equation 24. All parameters of this equation are given by the problem statement or are easily deduced, except for the net absorbed heat flux at the solid surface, $\dot{q}''_{\text{net}}$. In this case, the absorbed heat flux is conservatively estimated to be the incident flux from the fire. The incident heat flux can be calculated using Equation 20 because *L*/*D* is 0.8(2.0/2.54), which is within the valid *L*/*D* range of 0.7 to 15.0. Equation 18 is not valid because the ratio R/R_o is equal to 0.64(1.27/2.0), significantly below the minimum limit of 4.0. The resulting incident heat flux, as calculated using Equation 20, is as follows:

$$\dot{q}''_r = 15.4\left(\frac{2.0}{2.54}\right)^{-1.59} = 22.6 \text{ kW/m}^2$$

Note that the value for *L* in this equation is measured from the center of the fire to the plywood (1.3 m + ½(1.4 m) = 2.0 m). In order to be conservative, a safety factor of two is applied, resulting in an incident flux of 45.2 kW/m^2. Comparing the original and conservative incident flux values to the critical heat flux for plywood (16 kW/m^2 as shown in Table 3.9.5) indicates that the incident flux is high enough to ignite the plywood.

The ignition time is estimated by using Equation 24:

$$t_{ign} = 0.012\frac{(640)(2.8)(390-20)}{(45.2)} = 186 \text{ sec}$$

Note that the V_s/A_s term in Equation 24 is replaced with the material thickness, or 0.0127 m. Since the ambient temperature of the space or plywood is not given in this problem, it is assumed to be 20°C, which is a reasonable estimate for an interior environment.

Step 3. Prior to estimating the activation time of the automatic sprinklers, the flame height should be compared with the ceiling height. If the flames impinge on the ceiling, then the methods presented in this chapter for sprinkler activation are likely to underpredict the activation time. Using Figure 3.9.5, the flame height is estimated to be approximately 3.7 m or 3.8 m. The sprinkler activation methods in this chapter will be valid, since the flame height is less than the ceiling height of 5.0 m.

The last part of the problem is to estimate the activation time of the automatic sprinklers. The temperature and velocity of the fire gases at the detector must be determined in order to estimate the activation time. The location of the fire is conservatively chosen as equidistant from four sprinklers. Equation 32 is used to determine the radial distance between the center of the fire and the automatic sprinkler:

$$r = \sqrt{\left(\frac{4.5}{2}\right)^2 + \left(\frac{4.5}{2}\right)^2} = 3.18 \text{ m}$$

The ratio r/h_{ceil} is used to determine which temperature and velocity equations are appropriate for use. In this case, the ceiling jet correlations (Equations 26 and 28) are appropriate, since $r/h_{ceil} = 0.64$.

$$T_{m(jet)} = 5.38\frac{(3900/3.18)^{2/3}}{5.0} + 20 = 143°C$$

$$U_{m(jet)} = 0.195\left[\frac{(3900)^{1/3}(5.0)^{1/2}}{(3.18)^{5/6}}\right] = 2.62 \text{ m/sec}$$

With the temperature, velocity, and other given information, the activation time of the automatic sprinkler system can be estimated using Equation 34 since the conduction parameter is defined:

$$t_{operation} = \frac{120}{\sqrt{2.62}\left(1+\frac{0.5}{\sqrt{2.62}}\right)}\log_e \left[\frac{143-20}{143-74-\frac{0.5}{\sqrt{2.62}}(74-20)}\right] = 48 \text{ seconds}$$

Because automatic sprinklers activate (48 seconds) prior to the ignition of the plywood (186 seconds), fire spread beyond the initial pool fire is unlikely in this case.

SUMMARY

This chapter provides equations that can be evaluated using hand calculators to estimate fire conditions in enclosures. The chapter deals with fire during the preflashover fire growth period in which fire detection and automatic fire sprinklers may be activated by the fire. Means to estimate the fire size in an enclosure, flame heights, plume temperatures, radiant heat flux to targets, enclosure temperatures, smoke-filled gas production rate, ignitability of solids, and thermal fire detector and automatic fire sprinkler response are given. The methods presented were developed from systematic studies of data from experiments that were conducted for very specific, and sometimes idealized, conditions. Therefore, judgment must be used in applying the methods to particular complex fire conditions.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on closed form enclosure fire calculations discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 72®, National Fire Alarm Code®
NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*
NFPA *101®, Life Safety Code®*
NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*

SECTION 3

Chapter 10

Performance-Based Codes and Standards for Fire Safety

Milosh T. Puchovsky ❏ Morgan J. Hurley

Over the past century, the basic question concerning fire safety design for the built environment has been this: does the building comply with the detailed requirements of the code? Implied in this question is that meeting the code provides an acceptable level of safety. However, the level of safety implicit in the code was not explicitly defined. For example, how much safety, for whom, and under what conditions? How much property damage or business downtime is tolerable in the event of a fire? For what types of fires was this level of safety to be achieved?

Although code compliance remains at the center of ensuring fire and life safety in buildings, the means of achieving such compliance has taken on different forms. The traditional cookbook mentality of simply verifying prescribed code requirements is being supplemented in numerous cases by performance-based design methods. The emergence of computer fire models, design guides, and other tools, as well as a maturing fire-engineering profession, is changing the landscape.[1] The availability of these new resources prompts a host of new questions about fire safety.

Whereas traditional questions concerning fire safety design center on code compliance, new ones focus on measurement and calculation. The principal argument is that fire safety can be accomplished more effectively, and in some cases for less money, by quantifying the level of safety required and verifying that the entire fire safety package delivers that level of safety. The conventional approach of providing fire safety through the direct application of prescribed solutions embodied in traditional codes and standards might not present the best approach for all projects.

The newer approach in fire safety is commonly referred to as *performance-based design,* and its success hinges on the ability of the fire protection engineer to accomplish three overlapping tasks. The first is to effectively articulate the hazards or threats to be guarded against. Ideally this would be accomplished through some type of risk-informed analysis. The second is to quantify the point or measure at which adequate safety is provided. The third is the effective utilization of calculation or verification methods, many of which are packaged as computer models. It is these methods that embody the scientific principles that allow for the calculation of fire-related phenomena such as the spread of fire effects, the response of fire protection systems, and the reaction of building occupants, and for verifying that the hazards identified in the first task do not result in a failure to meet the specific threshold criteria established in the second task under the design solution proposed. These methods serve as the tools for engineers and other qualified professionals for evaluating fire safety solutions not prescribed by codes or standards.

Depending on the project, performance-based approaches can offer a number of advantages over traditional prescriptive-based methods. The overall intent aims at providing more effective and efficient fire safety solutions and building construction practices. By allowing greater freedom in the design process, proponents argue that the overall outcome results in an optimal level of fire safety at reduced construction costs.

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International Use of Performance-Based Regulations

Key Terms

authority having jurisdiction (AHJ), design fire, design fire scenario, functional statement, performance-based approach, performance-based design, performance objective, uncertainty

In an effort to realize these benefits, a number of nations have enacted efforts to better support performance-based design and remove barriers to its broader application.[2] The lack of quantifiable fire safety goals and hazards, as well as a tangible interface between regulations and the relevant tools and data needed to conduct performance-based design, present such barriers. A key activity across the globe, which is still ongoing, focuses on the development and implementation of performance-based building and fire codes. With few exceptions, most codes and standards were developed in a manner that did not accommodate or support the use of calculation methods and other resources. Furthermore, many current computer models were developed and distributed without an established link to the codes and standards that have dictated fire safety design over the past century. A more direct path for the application of these tools in conjunction with fire safety regulations would result in more effective use of these tools.

See also Section 1, Chapter 3, "Codes and Standards for the Built Environment"; Section 3, Chapter 7, "Fire Hazard Analysis Techniques"; and Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations."

PERFORMANCE-BASED VERSUS PRESCRIPTIVE-BASED REGULATIONS

Ideally, a performance-based code or standard explicitly states its fire safety goals and clearly defines the desired level of safety.[3] Any solution that meets or exceeds the fire safety goals would be permitted. Fire safety would be designed for a specific use or application, rather than for a generic occupancy. Means to achieve compliance with the code begin with a scientific understanding of fire safety, followed by the application of proven engineering methods.

Most fire safety codes and standards used today are considered to be prescriptive. Prescriptive-based documents provide fire safety in a generic fashion by prescribing a combination of specific requirements, such as construction materials, limiting dimensions, or protection systems, but without referring to how these measures achieve a desired level of safety or outcome. Even those documents that require measurement of performance through a fire test or calculation procedure do not explicitly state their goals or objectives in terms of the performance measures considered by the tests. In many cases, neither do they indicate how to connect the goals and objectives to the performance measured by a test. In fact, a measurable level of safety is usually neither stated nor defined as a goal or objective. Usually there is only one way of providing the specified fire safety—the prescribed way.[4]

Concerns about the reliability of systems and features, as well as other uncertainties of performance, are addressed through redundancies, often in the form of requirements for two or more independent safety provisions, each designed to be sufficient by itself to provide safety. This crude, unquantified approach to redundancy can mean excessive and costly overdesign if each of the systems and features has high reliability.

Prescriptive codes find their roots in the nineteenth century when major conflagrations created the need for specific building provisions.[4–6] Revisions to the codes resulted primarily from other significant fires that revealed deficiencies. To prevent recurrence of such disasters, changes were incorporated into the codes. However, these changes were often instituted without effectively evaluating their adequacy, excessiveness, redundancy, or conflicts with other requirements. The overall outcome has been regulations based on empiricism and experience, rather than on a scientific understanding of fire, building performance, and occupant behavior.

Many of the advances in the understanding of fire and fire safety have not been effectively incorporated into everyday fire safety practice partly because of the prescriptive nature of current codes and standards. Some argue that this lack of technology transfer has allowed fire safety to fall behind other engineering disciplines, such as structural design.

PERFORMANCE-BASED DESIGN GOALS

Fire safety is designed into buildings to achieve one or more of the fundamental fire safety goals: life safety, property protection, mission continuity, and environmental protection.[7] Presently, most fire safety design resources are expended on commercial properties, and commercial properties have performed very well in fire. For example, in 2001, there were 6196 civilian fire deaths in the United States. Excluding the 2451 of these deaths that were directly caused by the terrorist actions on September 11, there were 3745 civilian fire deaths; 3110, or 83 percent, of these deaths occurred in a home.[8]

Therefore, there is limited potential for performance-based design to improve fire safety in commercial buildings. Regardless of whether buildings are designed according to a prescriptive or a performance basis, it is not possible to achieve a risk-free environment. Application of additional resources will eventually run up against the law of diminishing returns.

However, the regulation of buildings is a balancing act of the safety requirements and the burden on society to provide those requirements. The more stringent the safety requirements, the more it costs to meet those safety requirements. Regulations are intended to identify the proper balance between the level of safety that society requires and the attendant costs of providing that level of safety.

Although the buildings to which engineering has traditionally been applied have an excellent history of fire performance, they also have an unknown safety margin. If this safety margin is too large, the extra costs associated with providing this margin have a negative impact on the economy, as the added construction costs could show up as higher costs for products and services or dissuade the construction of new or renovated buildings. Performance-based design allows the fire protection (or any other safety provision) that is provided in a building to be tailored to the characteristics of the building, the items stored within the building, and the people who would use the building.

Another advantage of performance-based design is that it allows application of the most current scientific knowledge available. Application of prescriptive-based regulations typically is accomplished with minimal reference to up-to-date engineering and scientific literature. Additionally, it takes at least three years for a code revision cycle to be completed. Therefore, one cannot be sure that the most effective job possible is being done with only the application of prescriptive-based solutions.

THE PERFORMANCE-BASED DESIGN PROCESS

General Concepts

Although many groups in many countries have independently developed their approaches to performance-based design, the underlying framework for conducting performance-based design remains relatively consistent.[7,9] Performance-based design is an iterative process that requires the completion of a series of tasks, each of which must be properly documented. The process is graphically depicted in Figures 3.10.1 and 3.10.2. Although the entire process is quite involved, the following three general concepts are employed in most performance-based design frameworks:

1. *Establish fire safety goals.* Goals indicate the overall outcome to be achieved with regard to fire. Because the desired outcomes must be quantified in some manner, goals are usually expressed as a series of requirements that begin with general statements about fire safety and conclude with measurable performance criteria (e.g., temperatures, energy levels, concentration of fire products).

2. *Specify design parameters.* Design parameters define the conditions under which the proposed fire safety goals are to be achieved. They include details and assumptions about the fire challenges (hazards) to be considered, the people and property to be protected, the characteristics of the building in question, and ultimately the proposed fire safety solution.

3. *Verify proposed solutions.* Calculation methods, computer models, and physical tests are employed to verify that the fire safety goals have been achieved for the design parameters specified. This procedure entails an iterative process in which those aspects of the design parameters pertaining to or affecting the proposed fire safety features are revised and refined until the fire safety goals are satisfied.

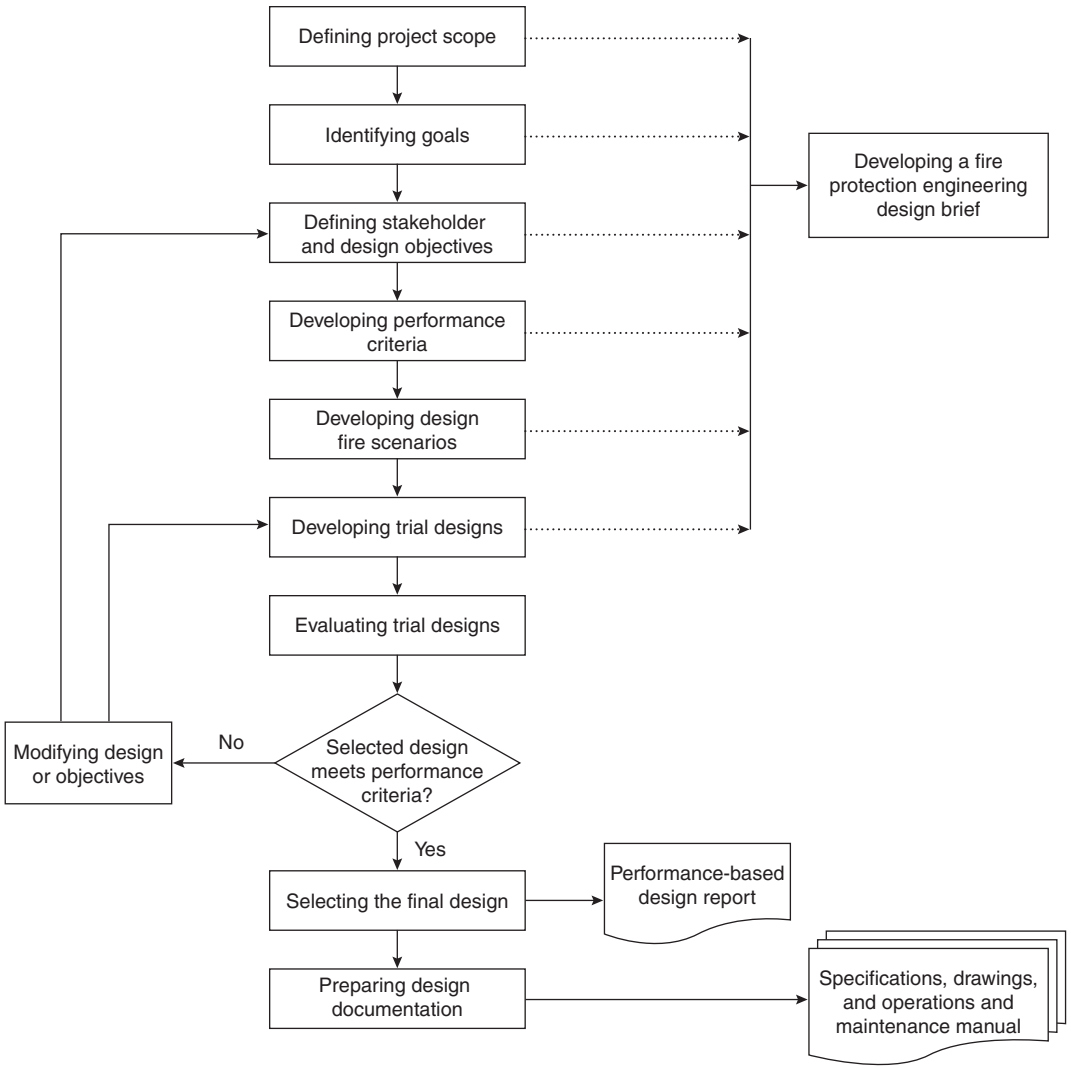

FIGURE 3.10.1 Steps in the Performance-Based Analysis and Design Procedure

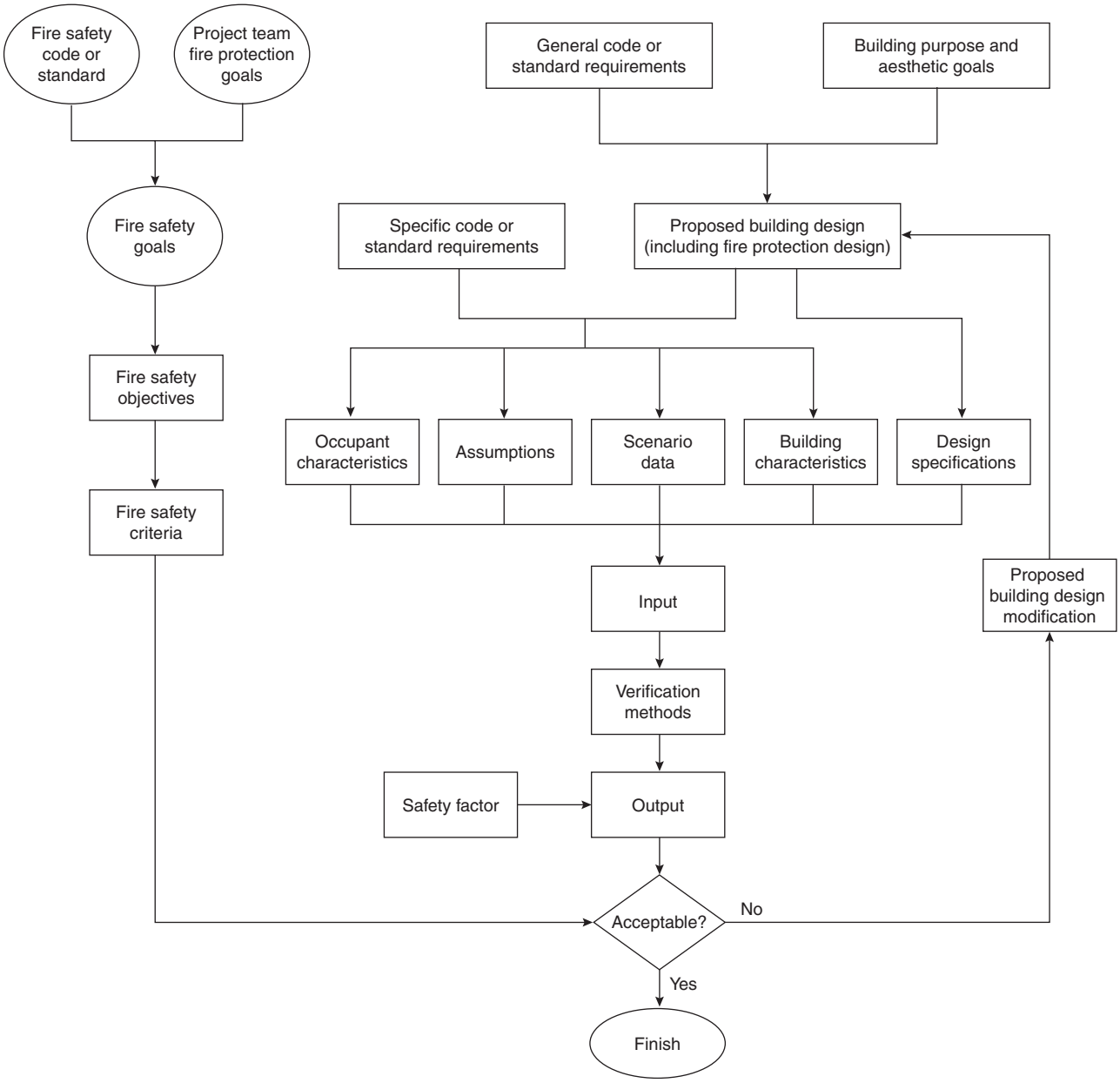

FIGURE 3.10.2 Performance-Based Design Process

Regardless of the verification method used—a computer model that calculates occupant movement, a calculation method that determines time to flashover, or a fire test that measures smoke movement—all require specific input data and knowledgeable users to produce effective results that represent reality. Input data consist of information contained within the design parameters. Those aspects of the design parameters not entered directly into the verification methods will be retained as assumptions in the design process. Depending on the method used, specific information about the fire, occupants, building, and fire protection features will be required. For example, the sprinkler/detector response model used in FPEtool would require the heat release rate of a specified fire, the horizontal and vertical distance between the sprinkler and the fire, the sprinkler's activation temperature and thermal sensitivity, and other data as input.[10]

Another example is Fire Dynamics Simulator (FDS), which can be used to predict sprinkler activation time as well as the effects of sprinkler activation on a fire compartment.[11] However, FDS requires more detailed input than does the sprinkler/detector response model in FPEtool. In order to make these predictions, FDS requires that the user input the full geometry of the space in which the sprinklers will be installed, including all obstructions and vents, as well as surface properties of all obstructions. A fire must be specified using such parameters as the heat release rate per unit area or the heat of vaporization of a fuel. Specific

sprinkler properties, including the response time index (RTI), activation temperature, operating pressure, and C-factor, as well as the sprinkler's location in the space, are input and allow FDS to predict when the sprinkler will activate. Additionally, a sprinkler's K-factor can be specified and waterflow from the sprinkler into the fire domain can be modeled.

The verification method's output will likely be produced in engineering terms such as *time, temperature,* and *heat release.* This output, in combination with the assumptions and decisions employed in the design process, will be evaluated against the performance criteria to determine whether the fire safety goals have been achieved for the design parameters specified. It is important to note that more than one verification method will likely be used to verify the various aspects of a fire safety solution.

Fire Safety Goals, Performance Objectives, and Performance Criteria

Fire Safety Goals. Fire safety goals are the overall outcomes to be achieved with regard to fire.[12,13] They should be nonspecific and expressed on a qualitative basis. Fire safety goals should be stated in terms of conditions that are intrinsically desirable and do not rely on any assumptions. Goals should be stated in language such that they can be understood by people who are not necessarily fire safety professionals. Thus, they would typically be expressed in terms of impact on people or property, business interruption, or environmental impact.

Examples of fire safety goals[7] include the following:

- Minimize fire-related injuries and prevent undue loss of life.
- Minimize fire-related damage to the building, its contents, and its historical features and attributes.
- Minimize undue loss of operations and business-related revenue due to fire-related damage.
- Limit the environmental impact of fire and fire protection measures.

Stating fire safety goals in language that can be widely understood facilitates achieving agreement and buy-in from all project stakeholders on the desired fire safety performance of a building or facility.

Performance Objectives (Functional Statements). Because they are stated in qualitative terms, goals do not provide the detail necessary to judge whether a trial design provides the desired level of fire safety. Performance objectives are intermediate measures that provide more quantitative detail than do fire safety goals. Performance objectives answer the question of "how much fire safety is desired?" Performance objectives can be described as the requirements of the fire, building, or occupants that need to be obtained in order to achieve a fire safety goal.[9] The term *functional statement* is sometimes used in place of the term *performance objective* and serves a similar purpose.

For example, a performance objective stated in terms of impact on people might be to maintain that the risk of death due to fire is not higher than the current level for similar properties or not higher than x per 100,000 people exposed. Another example of a performance objective in terms of impact on people might be to increase the likelihood that anyone capable of self-evacuation and not intimate with ignition can safely escape.

An example of a performance objective stated in terms of impact on property might be to limit fire damage to x square feet (m^2) of building space. For a particular system, such as a sprinkler system, one of the performance objectives might be to provide for a system that will aid in the detection and control of residential fires and reduce the likelihood of injury and loss of life due to fire. Objectives could also include statements that call for prevention of structural damage, no life loss in the room of fire origin, the separation of occupants from fire effects for a specified length of time, or the containment of the fire to the room of origin.

Because they are more quantitative than fire safety goals, performance objectives allow stakeholders to understand more specifically the level of fire safety that will be provided. However, objectives are still not sufficiently detailed for comparison with the output from fire models or other evaluation methods. Therefore, performance criteria are necessary.

Performance Criteria. Performance criteria can be described as performance objectives for individual products, systems, assemblies, or areas that are further quantified and stated in engineering terms.[13] Engineering terms can include *temperatures, radiant heat flux,* or *levels of exposure* to fire and products of combustion. Performance criteria provide threshold values that are treated as data for calculations used to develop a proposed solution.

For example, performance criteria for occupant survivability might be that at a distance of 5 ft (1.5 m) above the floor the following conditions are met:

1. Temperature does not exceed 150°F (65°C).
2. Instantaneous carbon monoxide concentration does not exceed 10,000 ppm.
3. Cumulative carbon monoxide concentration does not exceed 25 percent carbon monoxide hemoglobin level.
4. Oxygen concentration is maintained at 14 percent or greater.

Criteria with regard to the prevention of flashover might be:

1. Upper layer temperature does not exceed 1100°F (or the threshold might be stated as 600°C, which is roughly the same).
2. Radiant heat flux at the floor does not exceed 20 kW/m^2 (or the threshold might be stated as 1.8 $Btu/sec/ft^2$, which is roughly the same).

Characteristics of and Assumptions About Occupants, Contents, and Building Features

It is unlikely that any proposed solution, performance-based or prescriptive-based, will be able to achieve the fire safety goals for everyone and everything under all possible conditions. This situation is due primarily to limitations and uncertainty with available technology and science in combination with society's unwillingness to accept the restrictions and costs associated

with attempting to achieve zero risk. Therefore, details about who or what is intended to be protected and under what conditions need to be specified.[9]

An evaluation of the characteristics of the occupants, contents, and building features is needed. All assumptions about who or what is being protected and all other factors that could invalidate the proposed solution need to be identified as part of the design parameters. For example, a proposed solution may be valid only for occupants who are capable of self-rescue and who have an unobstructed means of egress available to them, or for occupants who are familiar with their egress routes. The effectiveness of the proposed solution for occupants who fall outside the range of these assumptions or characteristics would be much less certain.

The Fire Challenge—Fire Hazards and Scenarios

The potential for ignition and development of a fire that presents a threat to building occupants or contents exists in virtually all locations. The conditions under which these hazards exist and their likelihood of occurring in a given location need to be considered. An analysis, preferably one based on risk analysis, will identify the hazards that are intended to be protected against. The specific hazards to be guarded against need to be precisely defined through a set of fire scenarios and included in the design parameters. *Fire scenarios* specify the fire conditions under which a proposed solution is expected to meet the fire safety goals. A fire scenario can be considered as the fire load to which an occupant or building would likely be subjected. Fire scenarios pose the challenges that the fire safety solution must overcome. The fire scenario describes factors critical to the outcome of the fire, such as the ignition source, the initial fuel package, the location of initial fire development, aspects of the building arrangement, and the available fuel load. Fire scenarios describe the specifications needed for a fire test and can serve as direct input for a fire-modeling run.

As the number and type of hazards to be considered for a given project can be quite large, so can the number of potential fire scenarios. To help manage the range of possible fire scenarios, those scenarios with similar properties can be grouped into categories or clusters. Using a risk-based approach, a representative scenario from each cluster would be included as part of the design parameters.[9] For instance, the scenario that best characterizes the most severe hazard of each cluster could be used. Another possibility includes the consideration of a set of fire scenarios that includes those scenarios that are common (i.e., high probability) for the facility in question and those that are general-purpose high-challenge scenarios but less likely to occur (i.e., likely to result in rapid, early onset of severe fire conditions). An example of such a grouping of scenarios for a single-family residence is described in Table 3.10.1. (Obviously certain terms, such as *free-burning fire,* would need to be more explicitly defined.)

The design parameters for a single-family dwelling might specify, among other conditions, that the fire safety goals be met for all of the six identified fire scenarios in Table 3.10.1. Any proposed solution that demonstrates success would be permitted. For example, a residential sprinkler system designed and installed in accordance with a specific sprinkler system standard might be presented as the proposed solution. However, the sprinkler system alone might not be sufficient, as typical sprinkler systems are not intended to protect against fires in areas that are not sprinklered (high-challenge scenario no. 2) or fires that enter the dwelling from outdoors (common scenario no. 3); additional fire safety features, such as a smoke detection system and certain construction materials, might also be needed.

Design Specifications

Design specifications refer to the physical design arrangement intended to achieve the goals under the fire scenarios, assumptions, and other conditions specified. Design specifications include details about the protection systems to be employed,

TABLE 3.10.1 Possible Set of Fire Scenarios for a Single-Family Residence

Scenario	*Initial Fuel*	*Ignition Source*	*Room or Location of Fire Origin*	*Fire Type*
Common no. 1	Ordinary combustibles	Small open-flame source such as a match or cigarette lighter	Principally occupied rooms such as living room and bedroom	Free-burning fire
Common no. 2	Upholstered furniture	Cigarette	Principally occupied rooms such as living room and bedroom	Smoldering fire
Common no. 3	Ordinary combustibles	Small open-flame source such as a match or cigarette lighter	Structural area such as an attic	Free-burning combustibles
High-challenge no. 1	Ordinary combustibles	Small open-flame source such as a match or cigarette lighter	Entryway of a principally occupied room of the dwelling	Free-burning fire
High-challenge no. 2	Ordinary combustibles	Small open-flame source such as a match or cigarette lighter	Small unprotected room such as a bedroom closet	Free-burning area
High-challenge no. 3	Ordinary combustibles	Small open-flame source or cigarette	Principally occupied rooms such as living room and bedroom	Shielded room-corner fire with a substantial initial smoldering period

whether the systems are active or passive, manual or automatic. They comprise that portion of the design parameters that allow for the most design flexibility and serve as another input for a verification method, either directly or as a retained assumption. As with traditional prescriptive-based approaches, the design specifications would also identify the materials and products to be used in the design and how they are to be assembled and constructed.

Verification Methods—Calculation Methods, Computer Fire Models, Fire Tests

Calculation methods, computer fire models, and fire tests serve as tools that help verify whether the fire safety goals have been achieved for the design parameters.[14–16] Due to the complex nature of the principles involved and the numerous calculations required, models are often packaged as computer software. However, hand calculations that can model certain aspects of a fire event are available.[17,18] (See Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations," and Section 3, Chapter 7, "Fire Hazard Analysis Techniques.") All associated relevant input data, assumptions, limitations, and safety factors needed to properly implement the verification method should be provided.

It is important to note that verification methods do not provide the final solution, but rather help in the evaluation of a performance-based design. This fundamental concept is often misunderstood. The verification methods attempt to account for the physics that describe the fire phenomenon, occupant response, fire safety system performance, and their interaction, and quickly perform the necessary calculations, making performance-based design much more likely. However, the ultimate fire safety decisions lie with the designer and the authority having jurisdiction (AHJ) interpreting the methods' results.

Some fire protection engineers appear eager to apply performance-based methods and fire modeling to their projects as a means of validating non–code prescribed solutions. Currently, the majority of these approaches are used in special applications, such as in the development of unique design arrangements not addressed by current codes and standards, and to demonstrate that an alternative means of protection meets or exceeds code requirements. Although performance-based design can result in more effective solutions, preserve design vision, and reduce overall design and construction costs, it also requires increased time and effort by fire protection engineers and creates the potential for increased design costs.[12]

Although fire models can generate results with a reasonable degree of accuracy when properly employed by knowledgeable individuals, skepticism remains with regard to their routine use for designing fire safety. Overall a good deal of uneasiness exists due to the potential for misuse. Some of the reasons for this include a lack of available input data such as the fire-related properties of building materials, a lack of understanding of the model's purpose and limitations, and the improper interpretation of the model's output. These concerns are valid and efforts to resolve them continue.[19]

The increased application of performance-based design approaches and computer fire modeling warrants a higher level of scrutiny than required for prescriptive-based design. Calculation methods have limitations that may not be identified or known by their developers or users. Misuse of these methods and misinterpretation of their results can have a detrimental effect on safety and overall fire protection. Guidance is needed for users and AHJs so that they either understand or are aware of a verification method's assumptions, limitations, and proper application.[20,21] Further issues exist, as many models have not been validated to show under what conditions their results are valid, and much of the input data needed to run the models are not readily available.

Ideally, a model should be independently evaluated to demonstrate its suitability for use in the design context. At present, only one model has been independently evaluated: DETACT-QS.[22] Unfortunately, conducting a thorough evaluation of a computer fire model is quite complex and time consuming. In the absence of an independent evaluation of a model, the model user should be able to demonstrate why the model is appropriate for the proposed use. This demonstration might involve reference to the model's user's manual or other published reports or providing comparisons of model predictions to test data.

Although the development of calculation methods and fire models continues, more and improved versions are needed if a more complete performance-based design option is to be truly realized. Additional scientific research and testing are necessary for the development of new models and their input data. Existing models and methods do not provide all that is needed. However, it can be argued that fire models can become more effective once codes and standards explicitly state their fire safety goals and provide a direct connection to their application.

Uncertainty

The *SFPE Engineering Guide to Performance-Based Fire Protection* defines *uncertainty* as "the amount by which an observed or calculated value might differ from the true value."[7] Uncertainty can arise from two possible sources: epistemic and aleatory.

Epistemic uncertainty is uncertainty due to lack of (complete) knowledge. For example, it may not be possible to calculate precisely what the temperature would be in a postflashover fire due to imprecision of models and input values. It is possible to develop estimates; however, these estimates will not be exact, even if the input variables are well known. Gaining additional information or knowledge can reduce epistemic uncertainty.

Aleatory uncertainty is uncertainty due to random variation. For example, sprinklers that are manufactured may have slight variation in activation temperature and RTI. It might be known that these factors will vary by no more than a certain percentage, but it is impossible to reduce this uncertainty without changing the way the sprinklers are manufactured. Whether a coin toss will result in heads or tails is a form of aleatory uncertainty. No amount of additional research or information would reduce this uncertainty.

Uncertainty can arise from a number or sources. Performance-based designs must incorporate means of ensuring that uncertainty could not jeopardize the achievement of fire safety goals. The following techniques could be used to evaluate and address uncertainty.[7]

Safety Factors. Safety factors are frequently used in performance-based designs to deal with uncertainty or provide a margin of safety between what would be considered acceptable and unacceptable outcomes. In most cases, these safety factors are developed on an ad hoc basis, because generally few fire protection engineering methodologies provide specific safety factors.

Suppose the safety objective is for everyone to egress the building in less time than is required for fire effects such as toxic smoke to reach them. Then there are two time measures—time required for egress and time required for fire effects to reach occupied areas—and each time measure requires calculations using uncertain data, assumptions, and simplified models. A safety factor to reflect all these uncertainties could be increasing the estimated time for egress by some factor or decreasing the estimated time for fire effects to reach occupied areas by some factor, or both. Ideally, safety factors should reflect the actual magnitude of uncertainties.

Classical Uncertainty Analysis. Classical uncertainty analysis is possible in situations in which there is a large amount of measurement or test data available for a parameter. For example, wind velocity is a critical parameter in many smoke control system designs. In many cases, several years' worth of wind speed data may be available, which would enable a classical uncertainty analysis. The establishment of confidence intervals is an example application of a classical uncertainty analysis. A 50-year wind speed is another example.

Analysis Margin. Analysis margin is the difference between the estimated value of a parameter and the value used in analysis. Larger margins correspond to larger confidence that the value would not be exceeded. However, larger margins also correspond to more expensive designs, so the analysis margin should be selected carefully.

For example, consider the mass of combustibles per unit area found in an office. Field surveys and literature searches would yield a range of values. One could calculate a mean and standard deviation for this range. The mean would be the "best estimate." The best estimate value is a value that would be expected to be exceeded for half of the cases, whereas in the other half of the cases the actual value would be less.

Importance Analysis. For calculations that require multiple input variables, each input variable might not contribute equally to the uncertainty in the calculation. For example, consider Alpert's correlation for temperature rise above a fire plume:[23]

$$\Delta T = 16.9\frac{\dot{Q}^{2/3}}{H^{5/3}}$$

where

ΔT = Temperature rise above ambient (°C)
$\dot{Q}$ = Heat release rate (kW)
H = Height above base of fire (m)

When performing a calculation using this correlation, both H and $\dot{Q}$ might be subject to uncertainty, with $\dot{Q}$ most likely subject to a greater uncertainly than H. However, since $\dot{Q}$ is raised to the 2/3 power, any uncertainty in the heat release rate is reduced in its effect on the result. However, since the height above base of fire is raised to the 5/3 power, its uncertainty on the result is magnified.

Importance analysis rank orders the effect of uncertainty in each variable on the overall result. In the case of Alpert's correlation for temperature rise above a fire plume, the rank ordering would be (1) height above base of fire and (2) heat release rate.

Sensitivity Analysis. Sensitivity analysis is a technique that can be used to determine how changes in input variables affect the calculated result. A sensitivity analysis is conducted by holding all but one input variable constant while varying a single parameter and determining the effect.

The sensitivity of input variables is typically reported as a decimal, which is calculated as follows:

$$\frac{\text{Percentage change in output}}{\text{Percentage change in input}}$$

When conducting a sensitivity analysis, a base case is selected (which is usually the case of interest) and each parameter is individually varied by a percentage (e.g., 10%, 50%, etc.). If the calculated sensitivity is greater than one, then the output is more sensitive to that parameter. If the calculated sensitivity is less than one, then the output is less sensitive to that parameter. Sensitivity analysis is useful because it provides insight into the parameters that have the potential to contribute the most to the uncertainty in the calculated result.

Switchover Analysis. In a switchover analysis, the values of one or more input parameters are varied to determine which values would cause the calculated result to change from a value that would be considered acceptable (i.e., meet performance criteria) to a value that would be considered unacceptable (i.e., does not meet performance criteria).

If all foreseeable combinations of input values would not cause switchover, then the analyst can be confident in his or her conclusions. However, if some combinations of values could cause switchover, then the analyst should satisfy himself or herself that it would not be possible for a combination of factors that could cause switchover to occur.

Verification—The Role of the AHJ and Regulators

Verification is confirmation by the AHJ that a proposed solution meets the established fire safety goals under the conditions specified.[12] Verification can be thought of as a process similar to that used for the approval of traditional code prescribed solutions. However, the "cookbook" mentality associated with prescriptive-based methods is not applicable. The proposed solution developed through performance-based design cannot be easily confirmed by visual inspection for compliance with code requirements near the completion of the design process. The AHJ needs to be brought into the process early on and remain involved throughout. A different type of relationship is necessary. A solid understanding of and/or confidence level with the fire protection engineer and the engineering design concepts employed is essential.

Verification involves several steps not presently required under current prescriptive-based methods, as follows:

1. Verification that the proposed solution shows the building will meet the fire safety goals under the conditions (design parameters) established
2. Verification during construction that the building as built fits the design and data used in the proposed solution
3. Verification that the development of the proposed solution was completed by an individual or group qualified to perform such a task
4. Verification that the proposed solution implemented appropriate models, test methods, and other calculation procedures and that they were used in an appropriate manner
5. Verification that the assessment used appropriate data and that they were used in an appropriate manner

Verification confirms that the building is constructed as intended to a design that will achieve the intended goals under the conditions specified, and that the building's ability to achieve the stated goals has been demonstrated by qualified people using appropriate methods applied to correct data. SFPE recently undertook an effort to establish a more formalized approach to evaluating performance-based designs. The effect of this effort should be a more consistent approach in the verification process. More information can be found in the *SFPE Code Official's Guide to Performance-Based Design Review.*[24]

THE ROLE OF CODES AND STANDARDS IN THE PERFORMANCE-BASED DESIGN PROCESS

Value Judgments and Fire Safety Goals

When verification indicates that a proposed solution is inadequate, what can be changed to achieve success? One response might be to alter the fire safety goals. If the bar is lowered, success becomes more achievable. However, the establishment of fire safety goals represents one means by which society expresses its desires about safety. In this case society encompasses the broader community of interested parties and stakeholders who do not have a direct vested interest in the completion of a particular building project, but who require that a certain degree of safety be provided.

Goals set by society represent value judgments and cannot be compromised, even by AHJs responsible for verifying their compliance. However, other stakeholders with a more vested interest in the outcome of the project—such as the building owner, his or her financers and insurance interests, and the design and construction team—might also establish goals in excess of those embodied in building regulations. Unlike the goals of society, a degree of latitude exists for those goals set by the building owner or his or her representatives provided that they do not conflict with those of society.

Goals, whether those set by society or by the building owner, must be written in such a way that those responsible for verifying that they have been achieved can do so (i.e., the complete fire safety goal from the general statements about safety to the quantifiable performance criteria needs to be clearly stated in fire safety regulations and the project brief). This clarity is especially important, as the enforcing authority will be asked to verify a proposed solution that is based largely on the output produced by verification methods, such as computer models and calculation methods. The verification process becomes more workable when the terms used to measure the performance of a proposed solution (i.e., model output) resemble those used to quantify the fire safety goals (i.e., performance criteria).

Value Judgments and Design Parameters

The design parameters identify all the conditions about the fire, people, property, building, and protection features under which the fire safety goals are to be achieved. The severity and types of fire challenges (fire scenarios) considered as well as the condition and location of the occupants and the layout of the building affect the ability of a proposed solution to achieve the fire safety goals. If the fire scenarios encompassed within the design parameters are relatively undemanding, then a lesser degree of fire protection is necessary to achieve the fire safety goals.

A given building could be considered unsafe if it is required to meet stringent fire safety goals for a set of scenarios that does not adequately represent the associated hazards. For example, it would be less challenging for a sprinkler system in a rack storage warehouse to prevent fire spread across storage aisles if the fire load represented paper products instead of plastic commodities, as the fire challenge associated with the combustion of plastics is relatively more severe than that of paper.

A similar situation might arise if the results of an egress model indicate that building occupants will not be able to evacuate to an area of safe refuge before untenable conditions arise. Would it be acceptable to change the condition of the occupants so that their speed of movement is increased so that success could be achieved? A comparable condition would also arise if the fire safety solutions for a hotel did not consider occupants who were asleep when a fire occurred.

As in the specification of fire safety goals, the determination of the design parameters, particularly in the description of the applicable fire scenarios and character of the occupants and property, also embodies value judgments about fire safety, and therefore certain details about them need to remain fixed regardless of the specific project. The details pertaining to value judgments need to be captured by codes and standards and cannot be subject to modification by the building owner. Without securing this level of detail in building regulations, those responsible for verification would be much less certain about which conditions (fire scenarios) and what occupant characteristics the building owner must evaluate to demonstrate that the level of safety demanded by society has been achieved and remains consistent from building to building.

Value Judgments and Retained Assumptions

Although portions of the design parameters contain details that must remain fixed to meet the needs of society, they also include those details that can be modified to fit the needs of the building owner. The question about what aspects of the design parameters

need to be fixed by fire safety regulations remains. Details about the building and the potential protection features fall to the bottom of the list. After all, the intent of performance-based design is to provide for greater freedom in building design. Greater flexibility in designing fire safety in terms of the building's layout, construction materials, and protection features is the essence of performance-based design. Specifying this information in codes and standards would result in a practice no different than what has been done for the past 100 years.

Codes and standards used in conjunction with performance-based design, therefore, would not specify details about the building, but rather identify those characteristics about the building and the occupants that need to be defined by the building owner. For example, the 2006 edition of the NFPA *101*®, *Life Safety Code*®, requires details pertaining to the building's dimensions, construction materials, furnishings, spatial geometry, number and size of openings, and other facts that serve as input for specific calculation methods or models.[25]

For the most part, regulations should provide as much flexibility as possible in the layout of the building and the design of the protection features. However, there comes a point where the scale used to weigh design flexibility against practical safety considerations becomes unbalanced. It is at this point that decisions pertaining to fire safety design can impact value judgments, and this is where it becomes appropriate for codes and standards to set limits. Therefore, codes would need to further require that certain assumptions be made about any proposed solutions (design parameters). Such assumptions might include the following:

- Compliance with the fire safety goals shall not depend solely on any single safeguard.
- For life safety purposes, a minimum of two means of egress shall be provided unless it can be demonstrated that fire or smoke cannot block the occupants' egress from a single exit.
- Safeguards that comprise the proposed solution must be continuously exercised and maintained in accordance with specified requirements so that the safeguards remain properly operational for the life of the building.

Regulations and Their Impact on the Fire Challenge

The fire conditions under which the fire safety goals are to be achieved need to be specified during the design process. This clarification includes a qualitative description of the types of fires to be considered as well as a conversion of this description into quantifiable terms that can be used as input for a computer model or other evaluation method. The selection of fires to be considered embodies value judgments, as more stringent fires require more substantial safety measures that in turn raise the overall level of safety.

By providing a qualitative description of applicable fires, regulations begin to frame and scope the conditions under which a proposed solution is intended to perform. This description caps the range of potential fires to be examined and makes the design process more workable for all involved. This description also provides a reference for the AHJ when verifying a proposed solution and limits the possibilities of engineers having to prove the impossible.

Examples of the type of scenario data to be specified by regulations include the following:

- A single fire source is assumed
- An ultrafast-developing flammable liquids fire, in the primary means of escape, with interior doors open at the start of the fire
- A fire originating in a concealed wall or ceiling space adjacent to a large occupied room
- A fire starting in a normally unoccupied room that can potentially endanger a large number of occupants in a large room or other area

Because fire conditions largely depend on the characteristics of a given building, codes and standards are limited in the type of information they can provide about them. For instance, the building's operations, contents, dimensions, and so on will dictate the ignition mechanism, growth, and spread of potential fires. Additionally, because the fire conditions must be presented in quantifiable form, the final details about them need to be established by the owner through the application of pertinent data sources. As with the fire safety goals, the building owner may require that fire conditions, in addition to those specified by the regulations, be considered, and other appropriate measures would need to be implemented in this regard.

Regulations and Their Impact on Occupant and Property Characteristics

Characteristics of the occupants or property to be protected need to be specified, as they are critical in determining whether the fire safety goals can be achieved. Certain details about the occupants or property would be used as input data for computer models or be retained as key assumptions throughout the design process.

Codes and standards need to require that specific information be provided about the occupants, such as their sensibility, reactivity, mobility, and susceptibility. The building owner would need to provide specific information in this regard. However, the code might also require that specific assumptions be made about the occupants, such as the following:

- In every normally occupied room or area, at least one person shall be located at the most remote point from the exits.
- In every normally occupied room or area, the average maximum density of occupancy shall be present.

Additional details or other assumptions about the people or property exposed might be project specific, and the details about these would be the responsibility of the building owner.

Combining Performance-Based and Prescriptive Solutions

Performance-based design should not include the blind application of calculation methods and computer models. Performance-based design embodies a newer way of thinking about and

conducting fire safety design for the built environment. It is an approach that needs to be implemented from the start of a project and continued to its completion, even if all the tools and data needed for measurement and quantification are unavailable. As in the past, certain assumptions based on knowledge, judgment, experience, and existing prescriptive requirements will be needed to fill the gaps, and this information will result in a combination of prescriptive- and performance-based solutions in many cases. For example, an egress plan developed largely through performance-based design and the application of computer models is likely to rely on existing provisions for stair geometry and egress path lighting.

Another example considers the installation of sprinklers under a ceiling with varying elevations. NFPA 13, *Standard for the Installation of Sprinkler Systems,* requires that sprinklers be positioned not more than a certain distance below the ceiling to ensure that the sprinklers will activate in a timely manner.[26] However, in a ceiling that contains many changes in elevation or deep pockets, the application of the positioning rules becomes awkward as a sprinkler would be required in each pocket, and this situation could result in the installation of more sprinklers than would be needed to protect against the hazard. Computer modeling could be conducted to determine the length of time it takes for the ceiling pockets to fill with hot gases and activate the sprinklers at the lower ceiling elevation. This information could be used to determine whether sprinklers are necessary in each pocket. Although the modeling in this example might provide positioning rules that differ from NFPA 13, the other prescriptive installation rules of NFPA 13 would need to be followed unless other similar analyses are conducted.

It is worth noting that although prescriptive methods are occasionally characterized as overly burdensome, the push to performance-based design is not a result of their failure. Prescriptive methods still provide good results even though they may not be the most efficient in all cases.

PRECEDENTS FOR PERFORMANCE-BASED CODES AND STANDARDS

Although considered to be a relatively new concept, various forms of performance-based design have been performed for quite some time. Many building and fire safety codes and standards provide an option for developing an alternative means of protection or equivalency, provided the level of safety prescribed by the document is not lowered.[27,28] Obvious examples include the development of fire safety solutions for unique architectural or functional features not anticipated by building regulations, or the development of alternative means of protection to maintain the building owner's design vision. Many of the principles of performance-based design are also employed in the preparation of fire reconstructions.

Unfortunately, the application of many performance-based design approaches requires a major undertaking by both the designer and the AHJ. Most codes and standards do not serve performance-based design well. Any performance-based design attempted today must demonstrate a level of safety equivalent to the existing prescriptive standards. However, many existing codes and standards typically do not explicitly state their fire safety goals, nor do they identify the assumptions and fire scenarios under which the prescribed fire safety solution is to be effective. The task of determining what the code is intending to achieve, for whom, and under what conditions can prove to be difficult as each concerned individual typically has a differing opinion of what is intended.

To further complicate matters, most codes and standards do not reference computer models and other evaluation methods that have been demonstrated to be effective for the design and assessment of a proposed solution. Further efforts to validate models are needed. In addition, the current level of technology cannot produce the calculation methods and models that will properly address all of the relevant concerns. This situation calls for more awareness and documentation of a computer model's proper application and limitations. The overall effect is a less than ideal confidence level in performance-based design on a global level.

Once performance-based codes and their supporting design methods, tools, and data undergo a rigorous and acceptable level of standardization and evaluation, as other fire safety technologies have, they will enjoy greater acceptance overall. With the exception of a few documents, such as NFPA *101,* what primarily exist are general provisions allowing something vague called "equivalency," and a collection of experts, models, databases, and other resources that may lead to better solutions if used properly. What are needed are better definitions and procedures that allow the concerned parties to agree more explicitly on the goals against which equivalence is defined and how to demonstrate equivalence. This need is the reason NFPA initiated its development of performance-based codes and standards in 1993. Performance-based design was occurring without the presence of performance-based codes, but it was feared that an acceptable level of consistency in the application of these methods was lacking.

In the United States, a more direct call for the development of performance-based codes has recently been issued. The National Institute for Standards and Technology (NIST), through its report on the collapse of the World Trade Center towers, specifically recommends the development of performance-based standards and code provisions as an alternative to current prescriptive design methods.[29] NIST intends that such performance-based design options enable the design and retrofit of structures to resist real building fire conditions, including the building's ability to achieve the performance objective of burnout without structural or local floor collapse. Furthermore, NIST recommends the development of tools, guidelines, and test methods necessary to evaluate the fire performance of building structures as a whole system.

NFPA CODES AND STANDARDS

Although the application of performance-based methods will continue to increase, it is unlikely that performance-based approaches will entirely replace prescriptive-based methods. Prescriptive-based methods work, although their solutions might not be as effective or efficient as desired in certain situations.

It can also be said that prescriptive-based methods present a more straightforward design approach that requires less of an initial effort to implement. Last and probably most important, prescriptive-based codes are more easily enforced.

Because of the inherent advantages, NFPA codes and standards have been and will continue to be revised to include both performance-based and prescriptive-based options as appropriate.[13] In essence a dual-track approach has been advocated such that either the performance-based or prescriptive-based option could be applied to achieve the safety goals and objectives specified by the code or standard. This arrangement provides an option for either method, as one method might be better suited over the other for a certain project. The dual-track approach also connects the two design methods and supports the philosophy that performance-based options are the next level of sophistication for codes and standards. NFPA's overall approach in this regard is documented in the NFPA *Performance-Based Codes and Standards Preparation Primer.*[30]

NFPA intends to continue to revise its codes and standards to provide the necessary level of detail and standardization for the more robust application of performance-based design. A more formalized approach in codes and standards better supports the overall performance-based design and verification process by explicitly identifying the fire safety goals and by providing guidance on the establishment and use of specific fire safety criteria, assumptions, fire scenarios, and calculation methods. The overall outcome should result in more effective application and acceptance of performance-based design methods by both the design team and the AHJs. It is also anticipated that future NFPA codes and standards will provide a better direction for research efforts, improve the transfer of technology, and encourage prescriptive-based requirements to be based more on science and technology.

Since 1993, NFPA has been formally pursuing the development of performance-based codes and standards. While a number of initiatives continue, a major milestone was reached in the fall of 1999 when the NFPA membership voted to approve the 2000 edition of NFPA *101*. At that time NFPA *101* became the first code in wide use across North America to allow for and specifically address performance-based design. Specific life safety goals and objectives are stated and guidance is provided with regard to the establishment of performance criteria, fire scenarios, design assumptions, and occupant characteristics. Since then, a number of other NFPA documents have been revised to include formal performance-based design options. Some of these documents include NFPA 1, *Uniform Fire Code*™; NFPA 909, *Code for the Protection of Cultural Resource Properties—Museums, Libraries, and Places of Worship;* NFPA 914, *Code for Fire Protection of Historic Structures;* and *NFPA 5000*®, *Building Construction and Safety Code*®.

INTERNATIONAL USE OF PERFORMANCE-BASED REGULATIONS

Since the 1980s, initiatives across the globe have been effective in developing performance-based building regulations and in increasing the greater use and acceptance of performance-based design methods.[31,32] Governments and other interested parties in a number of nations have been urging the reform of their building regulations and their entire building construction industries. This has prompted the development and implementation of performance-based building regulations in a number of nations including the United Kingdom, New Zealand, Australia, the United States, and Canada. Related activities have also occurred in Japan, Norway, and Spain, among others. In some of these nations regulations have also been put forth that introduce competition and third-party review into the plans' approval process.[33] (See www.ircc.gov.au for a list of nations that have representation in the Inter-Jurisdictional Regulatory Collaboration Committee, an international consortium of officials and other professionals promoting the broader development and use of performance-based building regulations.)

The primary incentives for pursuing performance-based building regulations in some nations, such as the United Kingdom and Australia, were within the context of more global regulatory reform rather than an attempt to address specific fire safety concerns.[34] A number of government officials believed that the level of protection prescribed by traditional prescriptive building codes could be achieved by more cost-effective solutions, with the net result being increased economic growth and international competitiveness. Overall, it was thought that market forces should rule as much as possible and that regulatory interference should be minimized. New regulations were written to increase technology transfer and to promote innovation, flexibility, and deregulation with regard to building design.

Performance-based regulations in the United Kingdom and New Zealand call for simplified building codes identifying only major fire and life safety goals for an adequate and reasonable level of safety for persons within and in the vicinity of the building, and referencing design practices for achieving these goals.[35,36] The intent is to give designers more freedom to choose the methods to demonstrate compliance.

To provide guidance in achieving these goals, engineering design practices and "approved documents" have been put forth in a number of nations.[37,38] Approved documents are essentially user-friendly versions of the traditional prescriptive codes and other standards. Compliance with approved documents usually results in swift design acceptance; the use of other practices or methods typically requires more effort for acceptance. The creation of new performance-based building regulations has encouraged and promoted the development of engineering-based documents and methods for the support of performance-based design. Most notably, the Society of Fire Protection Engineers (SFPE) has initiated technical projects aimed at developing engineering design guides and other resources in this regard.

In some nations, the revised regulations have prompted the design team and the AHJ to work more as a team to identify the goals of the project and develop acceptable solutions. In certain cases, AHJs such as building and fire officials are more willing to recognize calculation methods, alternative designs, and trade-offs, as the new rules in certain countries have removed many of the constraints placed on their professional judgment. Coupled with this increased willingness is the availability of guidance materials and training programs to aid in decision making.

Examples of the application of performance-based designs have been presented at a number of conferences around the globe, one of the more recent being the SFPE's 6th International Conference on Performance-Based Codes and Fire Safety Design Methods held in Tokyo, Japan.

The International Code Council Approach

The International Code Council (ICC) has embarked on the development of a performance-based code. First published in 2000, the *International Code Council Performance Code*[39] takes a different approach than the performance-based codes and standards published by NFPA. First, unlike NFPA's performance-based codes and standards, which identify the fire safety goals and objectives and then allow for either performance-based design or the prescribed solution in a single document, the ICC's performance code is published separately. The effect of this is that a jurisdiction must separately adopt the code for it to be legally enforceable. If it is not legally adopted, it may be used as reference, but the jurisdiction may not be permitted to enforce it.

As with NFPA's performance-based codes and standards, the *International Code Council Performance Code* provides goals, objectives, and performance criteria, although the ICC uses different terminology. For example, *goals,* as defined by NFPA, are called *objectives* by ICC; *objectives* are called *functional statements;* and *performance criteria* are called *performance requirements.* However the *International Code Council Performance Code* does not specifically identify fire scenarios or explicit performance criteria. Instead, a matrix is provided that qualitatively identifies the acceptable performance as a function of the magnitude of the design event and the importance of a building (Figure 3.10.3).

Design events are classified as "small," "medium," "large," or "very large." Similarly, buildings are classified into four performance groups. Acceptable performance is classified based on the level of tolerable damage as "mild," "moderate," "high," or "severe."

The performance groups reflect the value of the building or facility to the community. Certain storage facilities might be classified as performance group I (the lowest level of importance), whereas hospitals and emergency treatment facilities would probably be classified as performance group IV. A mild impact would correspond to a minor number of mild injuries, whereas a severe impact would be a large number of significant injuries or a high probability of a fatality. A small design event might be a fire originating in a trash can, whereas a very large event might be an event such as an explosion. Decisions regarding the importance of a building, the severity of impact, and the level of tolerable damage are left to the designer and the AHJ.

Canada's Objective-Based Code

In 2005, Canada published its first "objective-based" code.[40] Canada's objective-based code is divided into three divisions, labeled A, B, and C. Division A contains performance requirements, in the form of *objectives* and *functional statements.* (The Canadian codes use similar terminology to the *International Code Council Performance Code.*) Division B contains acceptable solutions; that is, the code's prescriptive design option. Division C contains the administrative provision of the code. It is envisioned that the requirements in Division A will not change significantly with future code revisions, whereas the requirements in Division B will be revised, as is the case with most prescriptive codes.[41]

		INCREASING LEVEL OF PERFORMANCE → PERFORMANCE GROUPS			
		Performance Group I	Performance Group II	Performance Group III	Performance Group IV
Magnitude of Design Event (INCREASING MAGNITUDE OF EVENT ↑)	Very large (very rare)	Severe	Severe	High	Moderate
	Large (rare)	Severe	High	Moderate	Mild
	Medium (less frequent)	High	Moderate	Mild	Mild
	Small (frequent)	Moderate	Mild	Mild	Mild

FIGURE 3.10.3 Maximum Level of Damage to Be Tolerated Based on Performance Groups and Design Event Magnitudes (Source: Table 303.3, from the 2006 *International Code Council Performance Code for Buildings and Facilities.* Copyright 2006. Falls Church, Virginia: International Code Council, Inc. Reproduced with permission. All rights reserved. For more information go to www.iccsafe.org)

In Canada's objective-based code, each prescriptive provision is tied to an objective and functional statement. Code users would identify which portions of a building will be designed according to a performance basis and which will follow the prescriptive requirements of the code. The portions of the building that are to be designed using the prescriptive requirements of the code would have to meet the provisions in Division B, whereas portions of the building that are designed according to a performance basis would have to meet the objectives and functional statements in Division A.

The performance-based approach of Canada's objective-based code is similar in concept to using equivalency provisions contained within wholly prescriptive codes, although it is not necessary for code users to interpret the intent of prescriptive provisions. The intent is provided by the objectives and functional statements that are tied to the prescriptive provisions.

The overall concept put forth by the Canadian code has similarities in form to that of NFPA. A single regulation identifies the overall goals and objectives. Compliance can then be achieved using either the prescriptive provisions documented in the regulation or a formalized performance-based option.

SUMMARY

The performance-based design concept for fire safety continues to gain momentum across the globe. Government agencies encourage the use of engineering approaches. Fire protection engineers are increasing the application of nontraditional methods in their designs. An increasing number of code and fire officials are being asked to make decisions about fire safety designs based on performance-based approaches. Researchers continue to improve and develop new tools and data. Code developers revise codes to better address the concept. But what is performance-based design really about? Is it about minimizing the cost for fire safety in buildings and increasing design flexibility? Is it about addressing voids in current regulations? Or is it about embracing new technologies? In part, the performance-based concept encompasses all these notions. However, it must also extend beyond them.

The creation of more functional buildings at reduced cost is certainly a desirable goal. However, fire safety is about safety. Cost savings and design flexibility should be considered valued by-products in the application of performance-based design. Overall, the application of new technologies and advances in our understanding of fire safety should produce more effective and reliable fire safety solutions.

Developing regulations that better support performance-based design is only a starting point. Implementation of performance-based design into everyday practice requires more than a rewrite of existing codes and standards. Major efforts to evaluate fire models and test methods are essential, as are efforts with legal issues and education.[42] Success requires cooperation and coordination by all concerned interests.

In the end, performance-based design should provide more answers than questions about fire safety. Once a performance-based design has been implemented and the building has been built, will the building owner and the broader community feel more confident about the building's safety features? More importantly, how can they be certain?

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on performance-based codes and standards for fire safety discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 72®, National Fire Alarm Code®
NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*
NFPA *101®, Life Safety Code®*
NFPA 101A, *Guide on Alternative Approaches to Life Safety*
NFPA 301, *Code for Safety to Life from Fire on Merchant Vessels*
NFPA 550, *Guide to the Fire Safety Concepts Tree*
NFPA 551, *Guide for the Evaluation of Fire Risk Assessments*
NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*
NFPA 805, *Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants*
NFPA 909, *Code for the Protection of Cultural Resource Properties—Museums, Libraries, and Places of Worship*
NFPA 914, *Code for Fire Protection of Historic Structures*
NFPA 5000®, Building Construction and Safety Code®

SECTION 3

Chapter 11

Overview of Performance-Based Fire Protection Design

Frederick W. Mowrer ■ Eric R. Rosenbaum

Chapter Contents

Performance-Based Design Defined
Performance-Based Fire Protection Design Process
Time as a Performance-Based Design Parameter
Deterministic Hazard Versus Probabilistic Risk Assessment
Performance-Based Design Case Study
Developing Fire Scenarios and Design Fires

Key Terms

design fire scenario, deterministic hazard assessment, fire safety goals, occupant characteristics, performance-based design, probabilistic risk assessment, trial design

Engineering design is the process of selecting and orienting basic design elements to serve functional performance objectives within the constraints imposed by cost, technology, and safety. Design elements may include materials, components, products, assemblies, systems, or subsystems, depending on the application. The suitability of a design element for a particular application is determined by analysis. Different analyses use different properties or attributes of design elements to measure expected performance. Design elements selected for use must demonstrate acceptable performance based on the different analyses. In this context, all engineering design is, by definition, performance-based.

The concept of performance-based fire protection design is at least as old as the discipline of fire protection engineering. When the first sprinkler systems were developed in the mid-1800s, they were designed to meet the performance objective of automatic fire suppression in buildings with the constraints that such systems be installed at reasonable cost using technology available at the time. As with many engineered systems, these early sprinkler systems were redesigned, largely through trial and error as well as adverse loss experience, to improve their efficiency as well as their reliability. Other fire safety systems have similar development histories, as do many other engineered systems.

Although the concept of performance-based fire protection design has been around for a long time, the term *performance-based* has taken on a more specific meaning within the fire safety community in recent years. The term *performance-based* has become widely used internationally to distinguish emerging scenario-based methods of quantitative fire hazard analysis and fire risk assessment from traditional "prescriptive" regulatory approaches to fire safety. Within a performance-based design framework, desired outcomes are normally expressed in terms of specific fire safety goals, objectives, and performance criteria to be achieved. Within the traditional prescriptive framework, the analysis and design of building fire safety occur largely within the context of building code compliance, which does not explicitly demonstrate achievement of fire safety goals, objectives, or performance criteria. In a prescriptive environment, fire safety goals and objectives are generally implicit rather than explicit.

Over the past two decades, considerable progress has been made in the areas of performance-based fire protection analysis, design, and regulation. A number of guidance and regulatory documents have been published internationally that address the performance-based fire protection design process. Some of these documents include the following:

- *Comprehensive Fireproof Building Design Methods, Volume 1, Regulations for Comprehensive Design for Fire Prevention,* published by the Architectural Center of Japan in 1989[1]
- *Fire Engineering Design Guide,* first published by the Centre for Advanced Engineering at the University of Canterbury in Christchurch, New Zealand, in 1994, with the second edition published in 2001[2]

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- *Fire Engineering Guidelines,* published by the Fire Code Reform Centre in Australia in 1996[3] and the *Fire Safety Engineering Guidelines* published by the Australian Building Codes Board in 2001
- *Fire Safety Engineering in Buildings, Part 1: Guide to the Application of Fire Safety Engineering Principles,* Document DD240, published by BSI in the United Kingdom in 1997[4]
- *Fire Safety Engineering—Parts 1 through 8,* ISO/TR 13387, published by the International Organization for Standardization in Geneva, Switzerland, in 1999[5–12]
- *SFPE Engineering Guide to Performance-Based Fire Protection,* published jointly by the Society of Fire Protection Engineers and the National Fire Protection Association in the United States in 2000[13], with the second edition published in 2007
- *International Fire Engineering Guidelines,* produced in 2005 through a collaboration among the Australian Building Code Board, the Department of Building and Housing in New Zealand, the International Code Council in the United States, and the National Research Council of Canada

These documents present similar processes for the performance-based design of building fire safety. This chapter takes advantage of the processes documented in these publications to present an overview of performance-based fire protection design.

See also Section 1, Chapter 3, "Codes and Standards for the Built Environment"; Section 3, Chapter 7, "Fire Hazard Analysis Techniques"; Section 3, Chapter 8, "Fire Risk Analysis"; and Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety."

PERFORMANCE-BASED DESIGN DEFINED

Before considering the performance-based fire protection design process, it is useful to consider what distinguishes performance-based design from other design approaches. The *SFPE Engineering Guide to Performance-Based Fire Protection* (hereafter referred to as the *SFPE PBD Guide*) defines performance-based design as follows:

> An engineering approach to fire protection design based on (1) established *fire safety goals and objectives;* (2) deterministic and probabilistic analysis of *fire scenarios;* and (3) *quantitative assessment* of design alternatives against the fire safety goals and objectives *using accepted engineering tools, methodologies, and performance criteria.* [Emphasis added]

In comparison with prescriptive design, performance-based fire protection design has the following distinguishing features:

- Performance-based design is based on the specification of quantitative and physically meaningful *performance criteria* that can be used to evaluate the achievement of fire safety goals and objectives.
- Performance-based design is based on analysis of the dynamics of anticipated *fire scenarios.*
- Performance-based design is based on quantitative assessment of fire scenarios using accepted *engineering tools and methodologies,* which typically include some form of enclosure fire model.

Ultimately, the goal of performance-based fire protection design is to demonstrate, through appropriate engineering analyses, that an acceptable level of fire safety will be achieved under a comprehensive set of anticipated or foreseeable conditions of use. The adequacy and reliability of performance-based design depend in large part on the adequacy of the performance criteria selected, the comprehensiveness of the fire scenarios anticipated, and the accuracy of the engineering tools and methodologies used for analysis.

PERFORMANCE-BASED FIRE PROTECTION DESIGN PROCESS

The process of performance-based fire protection design can be considered in terms of a number of distinct steps. The *SFPE PBD Guide* outlines these steps in the flowchart illustrated in Figure 3.11.1.

Define Project Scope

The first step in the performance-based design process is to define the scope of a project. The *SFPE PBD Guide* identifies the following issues associated with defining the scope of a project:

- Constraints on the design and project schedule
- The stakeholders associated with project
- The proposed building construction and features desired by the owner or tenant
- Occupant and building characteristics
- Intended use and occupancy of the building
- Applicable codes and regulations
- The project management and delivery method

The various stakeholders must understand and agree on these issues at the outset to ensure that a performance-based design (PBD) meets their needs and interests. A stakeholder is an individual or other representative who has an interest in the successful completion of a project for financial, safety, or other reasons. Possible stakeholders include, but are not necessarily limited to, the following:

- Building owners, managers, and operations and maintenance personnel
- Tenants and other occupants
- Design team
- Construction team—construction managers, general contractors, subcontractors
- Authorities having jurisdiction (AHJ)—fire, building, insurance
- Accreditation agencies
- Emergency responders
- Peer reviewers

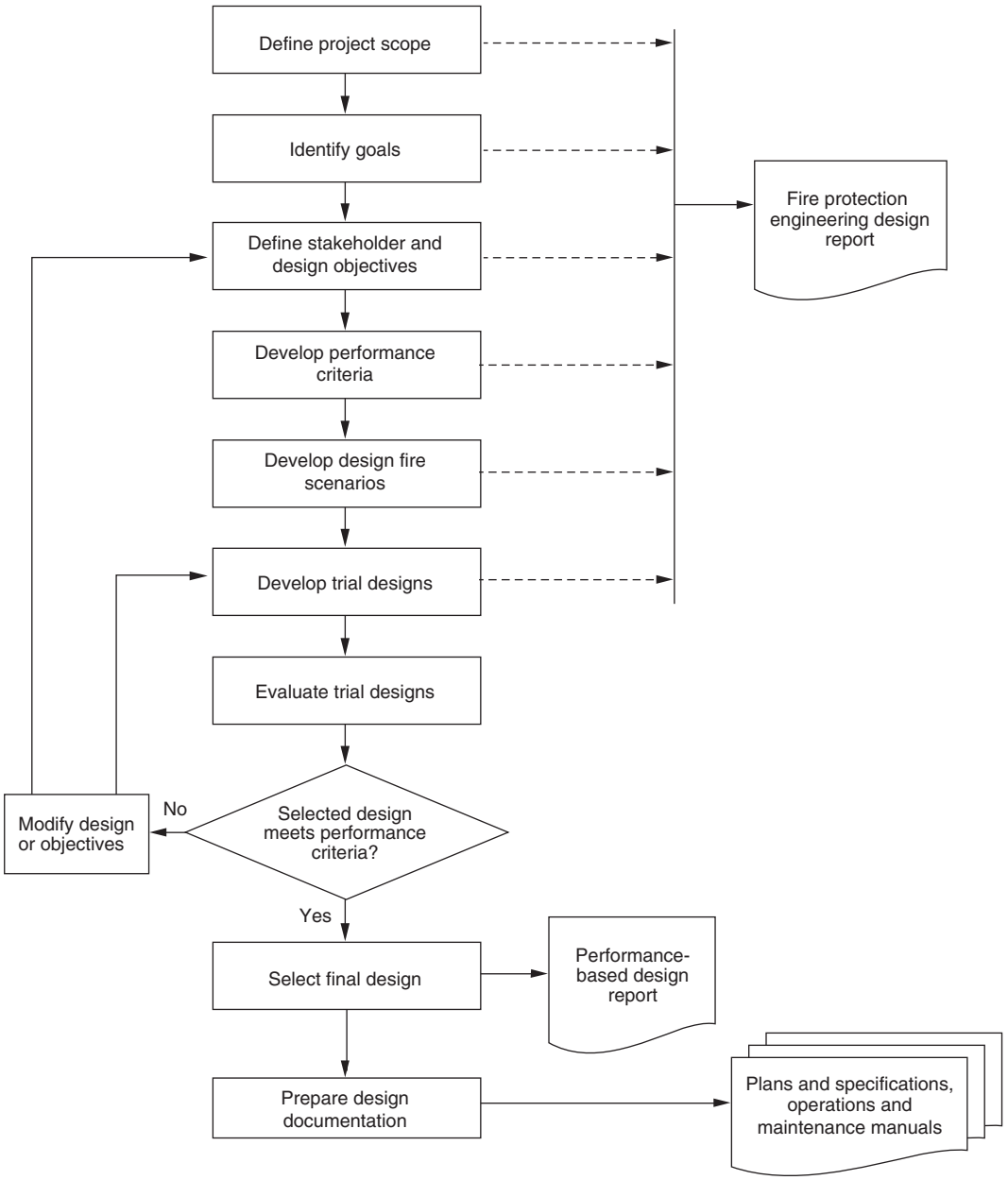

FIGURE 3.11.1 Steps in the Performance-Based Fire Protection Design Process (Source: *SFPE Engineering Guide to Performance-Based Fire Protection,* 2007, Figure 3-2)

Because the scope of many projects is limited, it is essential that the project boundaries be clearly defined and documented during this step so that all stakeholders clearly understand what will, and what will not, be addressed by the PBD. A clear definition of project scope is particularly important for the designer undertaking a PBD to avoid the potential for future misunderstandings and liabilities that might arise during the construction and use of a building.

Identify Fire Safety Goals

Once the project scope has been defined, the next step in the PBD process is for the various stakeholders to identify and for the fire protection engineer to document the fire safety goals of the design. These are the general goals to be achieved by the performance-based design. Fire safety goals may include levels of protection for people and property, or they may provide for continuity of operations, historical preservation, or environmental protection, among others. Fire protection generally has the following four interrelated fundamental fire safety goals:

1. *Provide life safety* for the public, for employees and other occupants, and for fire fighters; minimize fire-related injuries and prevent undue loss of life.
2. *Protect property,* minimizing damage to property from fire and fire protection measures (e.g., protect building,

contents, and historical features from fire and exposure to and from adjacent buildings).
3. *Provide for continuity of operations* (i.e., protect the organization's ongoing mission, production, or operating capability), minimizing undue loss of operations and business-related revenue due to fire-related damage.
4. *Limit the environmental impact* of fire and fire protection measures.

Not all of the above goals are relevant to all projects; the relevance depends on the scope of the project. One purpose of identifying fire safety goals is to help focus stakeholders on the overall fire protection concepts being developed so that all stakeholders are clear on what goals are and, of equal importance, are not being addressed by a given design. Another purpose is simply to document the fire safety goals to be achieved by the design. Although fire safety goals serve this important purpose, they do not provide sufficient detail to evaluate whether specific fire safety objectives will be achieved by a proposed design. This determination requires a more detailed description of objectives and performance criteria.

Define Stakeholder and Design Objectives and Develop Performance Criteria

The evaluation of fire safety objectives generally requires the specific stakeholder and design objectives to be defined and detailed performance criteria to be developed. Performance criteria are quantitative measures, usually in the form of threshold damage or injury levels, that reflect the intent of the design objectives. In general, some criteria address life safety whereas other criteria address damage thresholds for property. Life safety criteria generally address tenability and survivability of fire-induced atmospheres in terms of thermal effects, toxicity, and visibility through smoke. Property criteria may include thermal damage thresholds, structural integrity, smoke damage, and fire spread, among others. Some examples of fire safety goals and associated stakeholder objectives, design objectives, and performance criteria are provided in Table 3.11.1 for each of the fire safety goals described above.

Develop Design Fire Scenarios

After the performance criteria have been established, the next step in the performance-based design process is to develop design fire scenarios. In this context, a fire scenario is a set of conditions that defines the development of a fire and the spread of combustion products through a building. The fire, building, and occupant characteristics at the time of a fire need to be considered in order to define different fire scenarios because these characteristics all interact with each other and influence a fire scenario.

The fire characteristics describe the history of anticipated fire development and generally include consideration of the following:

- Ignition sources and materials first ignited
- Incipient fire development
- Flame spread and fire growth
- Flashover and fully developed fire conditions
- Fire burnout, decay, and extinction

Fire development in buildings is strongly dependent on enclosure and ventilation effects as well as on the installed fire protection features, so the building characteristics must be considered as part of the fire scenario development.

Building Characteristics. The building characteristics describe the physical features, contents, and ambient environment of a building. The building characteristics of interest for fire safety include the following:

- Architectural features, including space layout
- Structural features
- Building services and processes

TABLE 3.11.1 Examples of Fire Protection Goals, Stakeholder Objectives, Design Objectives, and Performance Criteria

Fire Protection Goals	*Stakeholder Objectives*	*Design Objectives*	*Performance Criteria*
Minimize fire-related injuries and prevent undue loss of life	No loss of life outside of the room or compartment of fire origin	Prevent flashover in the room of fire origin	COHb level not to exceed 12% Visibility greater than 23 ft (7 m)
Minimize fire-related damage to the building, its contents, and its historical features and attributes	No significant thermal damage outside of the room or compartment of fire origin	Minimize the likelihood of fire spread beyond the room of fire origin	Upper layer temperature no greater than 392°F (200°C)
Minimize undue loss of operations and business-related revenue due to fire-related damage	No process downtime exceeding 8 hours	Limit the smoke exposure to less than would result in unacceptable damage to the target	HCl no greater than 5 ppm Particulate no greater than 0.5 g/m^3
Limit environmental impacts of fire and fire protection measures	No groundwater contamination by fire suppression water runoff	Provide a suitable means for capturing fire protection water runoff	Impoundment capacity at least 1.20 times the design discharge

Source: *SFPE Engineering Guide to Performance-Based Fire Protection,* 2007, Table B-3.

- Operational characteristics
- Fire protection systems
- Emergency response characteristics
- Environmental factors

These building characteristics affect the growth and spread of fire as well as the movement of combustion products, so they need to be considered in the identification of possible fire scenarios.

With respect to fire development, the primary building features influencing a fire scenario include the following:

- Floor area and volume of the fire enclosure
- Flammability properties of room lining materials, furnishings, and other contents
- Number, type, and location of natural ventilation pathways
- Type and operating characteristics of mechanical HVAC systems
- Type and operating characteristics of automatic fire detection and suppression systems
- Thermophysical properties of enclosure boundaries and the fire endurance characteristics of enclosure boundaries and structural elements

Occupant Characteristics. Occupant activities can also influence fire development; therefore they need to be considered in the development of fire scenarios as well. Occupants can influence fire development in a number of ways, including the following:

- Occupants can accidentally or intentionally contribute to the ignition of fires.
- Occupants can open or close doors and windows to influence the potential for fire and smoke spread.
- Occupants can detect and suppress fires, particularly during the incipient stage of development.

Occupant characteristics also influence how occupants are affected by a fire and how they respond to fire-induced conditions. Some of the important characteristics influencing human behavior in fire include the following:

- Number and distribution of occupants
- Alertness, physical and mental capabilities
- Physical and physiological condition
- Role, commitment, familiarity, and social affiliation

Some of these occupant characteristics relate to the decision-making capabilities of occupants, some to their mobility, and some to their susceptibility to smoke.

Design Fire Curves. One of the most important factors to recognize and consider in the development and evaluation of fire scenarios is the transient nature of building fires. Because fire is a transient process, it affects a building and its occupants and operations in different ways at different stages. Differences of minutes or even seconds can mean the difference between the success or failure of a fire protection strategy. Consequently, in a performance-based design analysis, time is always one of the key design parameters. With respect to the development of design fire scenarios, this time dependency is normally addressed by the development of one or more design fire curves that describe the anticipated heat and smoke release rate histories of the design fire scenarios.

Design fire curves typically have some or all the stages illustrated in Figure 3.11.2. The initiating event is ignition. Following ignition, there may or may not be an incipient period of little or no growth, depending largely on the type and intensity of the ignition source and on the nature of the first fuel ignited. For example, a smoldering fire ignited by a cigarette in upholstered furniture may exhibit a relatively long incipient period, whereas a flaming fire involving the same upholstered furniture may not. Following ignition and the incipient period, if it occurs, most fires of any consequence undergo a period of growth to a maximum size. To a large extent, the rate of fire growth and the peak heat release rate distinguish relatively hazardous fire scenarios from less hazardous scenarios.

Once the fire reaches its peak heat release rate, it may continue to burn at approximately this rate for some period of time, depending on how much fuel is available to burn. This period of relatively steady burning is frequently called the fully developed stage. The final period, typically called the decay stage, occurs when the available fuel starts to become depleted. Some fires are already starting to burn out by the time they reach their peak heat release rate; these fires tend to exhibit heat release rates with distinct peaks, rather than plateaus. The area under the design fire curve represents the total energy released by the fire (see Figure 3.11.2).

In many respects, construction and quantification of design fire curves make up the most difficult, as well as the most important, aspect of the performance-based design process. Design fire curves are important because they govern the rate of hazard development as well as the ultimate magnitude of hazard development. Selection of a design fire curve that does not accurately portray the expected fire development will result in predictions of fire-induced conditions that are either too severe or too mild. This selection can result in designs that are either inadequate or uneconomical. Ideally, actual fire test data representative of the design fire scenario would be available and would be used to develop design fire curves, but in most cases such specific data are not available. In these cases, engineering judgment is needed to characterize and select appropriate design fire curves

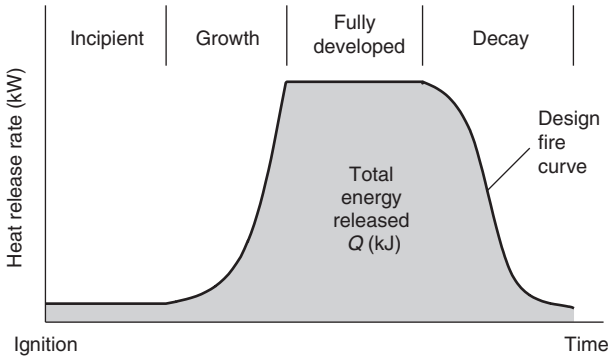

FIGURE 3.11.2 Stages of Design Fire Curves

based on the types, quantities, and configuration of available fuels, including initial and secondary fuels. It is important for all stakeholders to understand the bases for the selection of design fire curves and agree to the selection. To the extent that this selection may impose a need for administrative controls on the potential fuels within a building, these administrative controls need to be documented and enforced.

Develop and Evaluate Trial Designs

The steps of developing and evaluating trial designs are intended to consider how the various fire protection features (fire safety subsystems) will interact to provide the desired level of fire safety in a building. The fire safety subsystems considered in the *SFPE PBD Guide* include the following:

- Fire initiation and development
- Spread, control, and management of smoke
- Fire detection and notification
- Fire suppression
- Occupant behavior and egress
- Passive fire protection

These categories for fire safety subsystems are not unique; they are similar to the categories used to describe fire safety subsystems in a number of the international performance-based fire protection design guides listed at the beginning of this chapter.

Fire Initiation and Development. The fire initiation and development subsystem addresses the probability that ignition will occur as well as the rate of fire development and smoke release if ignition does occur. This subsystem is related directly to the design fire scenario and the design fire curves addressed in the previous section. Treating fire initiation and development as one of the fire safety subsystems helps to emphasize that the selection and placement of interior finishes and contents are an important part of the overall fire safety of a building. This aspect of fire protection design, controlling the fire source through product selection, is too often overlooked in favor of other fire protection strategies, such as fire detection and suppression, rather than being considered in conjunction with these other strategies.

Spread, Control, and Management of Smoke. The smoke management subsystem addresses the hazards resulting from the production and movement of smoke and the methods that can be used to control these hazards. These methods generally include the reduction of smoke generation through the control of materials that produce large quantities of smoke or by suppression, the extraction of smoke by natural or mechanical ventilation, and the containment of smoke by construction, often in combination with mechanical pressurization.

Fire Detection and Notification. The fire detection and notification subsystem addresses both the means used to detect a fire and the means used to notify building occupants and emergency responders of the presence and location of a fire. The fire detection element addresses the response of humans and automatic detection devices to the various fire signatures released during a fire.

Fire Suppression. The fire suppression subsystem addresses the means used to extinguish or control a fire. This subsystem includes automatic suppression systems, such as automatic sprinkler systems, as well as manual suppression systems, including fire department suppression operations. The impact of suppression systems and activities on fire development would be considered part of this subsystem.

Occupant Behavior and Egress. The occupant behavior and egress subsystem addresses the means used to protect occupants from the harmful effects of fire. In general, this protection means the design of an egress system that permits occupants to evacuate a building before untenable conditions develop.

Passive Fire Protection. The passive fire protection subsystem addresses the structural stability of a building as well as the fire resistance of enclosure boundaries to prevent the spread of fire between rooms of a building.

Develop Documentation

One of the most important aspects of performance-based fire protection design is documentation. Documentation is needed for the decisions made and analyses developed during the design process as well as for the duties and responsibilities of the stakeholders to ensure the ongoing conformance of the building's operation with the performance-based design basis. The *SFPE PBD Guide* identifies the following types of documentation:

- Plans and specifications
- Fire protection engineering design brief
- Performance-based design (PBD) report
- Operations and maintenance (O&M) manual

Plans and specifications are basically the same in performance-based design as in other design methods; they are intended to communicate important design information, particularly geometric data and information regarding acceptable materials and methods of construction, to the owner's representatives, to contractors, to AHJs, and to other stakeholders. The other three types of documentation are somewhat specific to performance-based design. The design brief is intended to summarize the performance criteria and analysis methods to be used to evaluate trial designs. The PBD report is intended to document thoroughly the performance-based design and its bases; the O&M manual is intended to help ensure that all the components of a PBD are in place and operating properly. Of central importance is documentation of the changes in use, occupancy, or operation of a building that should trigger a reevaluation of the building's fire safety.

TIME AS A PERFORMANCE-BASED DESIGN PARAMETER

As was noted previously, time is a key parameter in performance-based fire protection design. Most meaningful fire parameters are functions of time. For example, the physical hazards of fires are measured in terms such as fire growth rates, flame spread rates, heat release rates, smoke release rates, heat fluxes, and

burning duration—all functions of time. Similarly, the response of buildings, occupants, and fire protection systems to different fire scenarios can be considered in terms such as fire endurance periods, evacuation times, and fire detection and suppression response times. Consequently, time is an appropriate parameter to use for the quantitative evaluation of different fire scenarios and fire protection strategies.

There are two competing time scales that need to be considered, one associated with hazard development and the other with hazard mitigation. In this context, a successful fire protection strategy is one in which the time to the onset of unacceptable hazardous conditions is longer than the time to successful hazard mitigation for all relevant fire scenarios. This concept is illustrated in Figure 3.11.3.

The hazard development time scale shown in Figure 3.11.3 denotes two relevant times: $t(\dot{Q}_{crit})$ and $t(\dot{Q}_{crit})$. The first of these, $t(\dot{Q}_{crit})$, represents the time when a critical heat release rate is achieved. For example, this time might be the heat release rate needed to cause flashover of an enclosure. The second relevant time, $t(\dot{Q}_{crit})$, represents the time when a critical total quantity of heat or smoke has been released. For example, this time might be when sufficient carbon monoxide has been released to develop an untenable atmosphere. The time to critical hazard development will be based on the fire scenario and the design fire curve.

The hazard mitigation time scale shown in Figure 3.11.3 denotes three relevant times: t_{det}, t_{sup}, and t_{FR}. The detection time, t_{det}, denotes the time when a fire will be detected. The detection time will depend on the fire scenario, the design fire curve, and the types and locations of fire detection devices. The suppression time, t_{sup}, denotes the time when fire suppression is initiated. The suppression time will be equal to the detection time plus the time needed to initiate suppression once the fire is detected. For a wet-pipe sprinkler system, the suppression lag should be nil, and the suppression time will be the same as the detection time. For a dry-type sprinkler system, the suppression lag may be as much as 60 seconds for systems conforming to the requirements in NFPA 13, *Standard for the Installation of Sprinkler Systems*. For manual suppression, the suppression lag may be tens of minutes because the suppression lag includes the times needed for alarm verification and for fire department notification, response, and setup at the fire scene. The fire resistance time, t_{FR}, is the fire endurance period for the enclosure boundaries under the fire exposure conditions. For successful fire confinement, the fire resistance time must be longer than the duration of fully involved fire conditions.

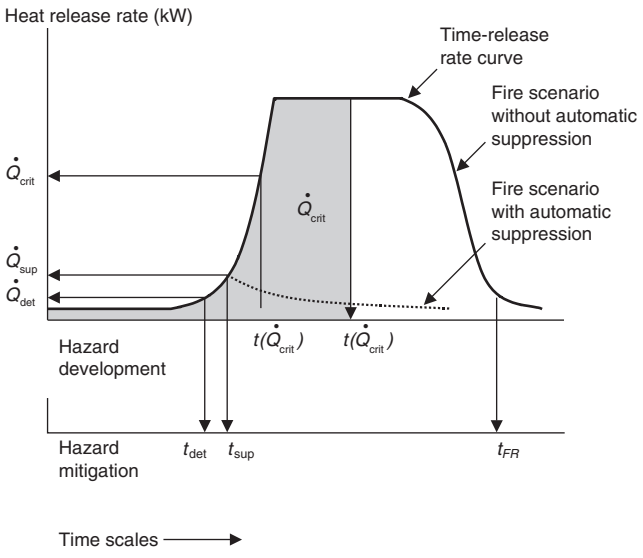

FIGURE 3.11.3 Time Scales Associated with Fire Hazard Development and Mitigation

To make practical use of this concept, the stakeholders need to agree on the performance criteria to be used and the design fire scenarios to be considered in order to evaluate when unacceptable hazard conditions are expected to develop.

All unwanted fires cause some damage and present some hazard. To permit quantitative assessment of fire mitigation strategies, a threshold level of tolerable or acceptable damage or hazard must be established. The time to the onset of unacceptable damage or hazard for a particular fire scenario depends on the following two factors:

1. The susceptibility to damage of the target being evaluated
2. The rate of development of the hazardous environment at the location of the target

If these two factors can be assessed quantitatively, they can yield either a time-dependent scale of damage or a critical time to damage onset. Damage to some targets may be related primarily to the total quantity of a fire signature, such as heat or smoke, released during a fire. This damage is represented as the area under the time-release rate curve (see Figure 3.11.3). Other targets may be damaged once a critical release rate is reached.

The relevant time scales to be compared depend on the type of fire safety analyses being performed. For life safety, the available safe egress time (ASET) must be greater than the required safe egress time (RSET). The available safe egress time is the time from ignition until the specified tenability criteria are exceeded at the location of interest. The required safe egress time is the time from ignition until the building or location of interest has been evacuated. Normally, a safety factor is added to the required safe egress time to provide for a margin of error. This concept is illustrated in Figure 3.11.4, which compares available safe egress time (ASET) and required safe egress time. Note that the required safe egress time includes a number of intermediate periods, including the time from ignition to detection, the time from detection to alarm notification, the time from alarm notification to recognition that an emergency exists, the time from recognition until movement begins, and, finally, the travel time for the exposed population to exit to a safe location. Each of these time periods needs to be evaluated through appropriate engineering analyses for each design fire scenario.

Time lines similar to the one shown in Figure 3.11.4 can be constructed to evaluate the performance of structural elements, fire barriers, and other targets that may be of interest for a particular application.

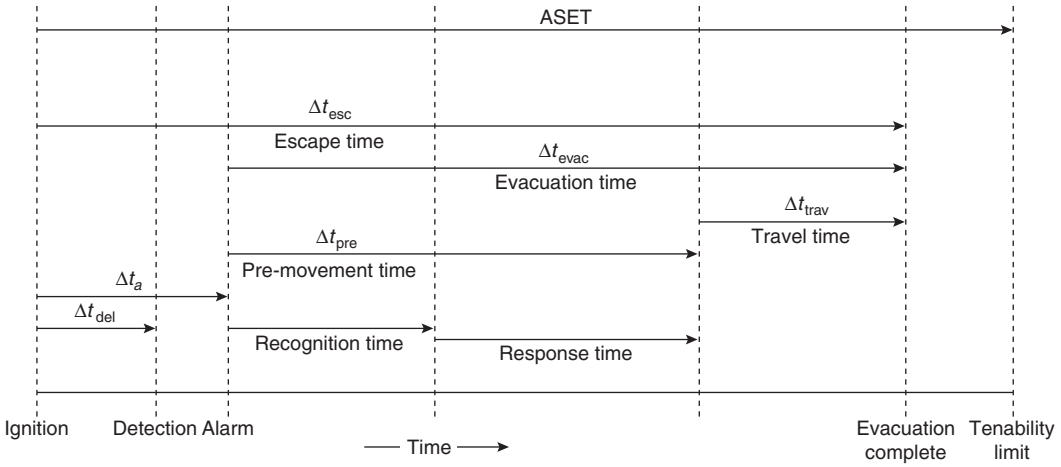

FIGURE 3.11.4 Example Time Line for Evaluation of Available Versus Required Safe Egress Times (Source: *Fire Safety Engineering in Buildings, Part 1: Guide to the Application of Fire Safety Engineering Principles,* Document DD240, BSI, 1997, Figure 2. Permission to reproduce extracts of DD240-1: 1997(E) is granted by BSI. British Standards can be obtained from BSI Customer Services, 389 Chiswick High Road, London W4 4AL. Tel: +44 (0)20 8996 9001. E-mail: cservices@bsi-global.com.)

DETERMINISTIC HAZARD VERSUS PROBABILISTIC RISK ASSESSMENT

Performance-based design is predicated on the specification of design fire scenarios and the evaluation of design alternatives. Two general approaches are available for this process: deterministic and probabilistic. Deterministic analyses consider only the consequences of specified fire scenarios, whereas probabilistic analyses consider the likelihood as well as the consequences of different fire scenarios. For example, a deterministic analysis could be used to assess the expected outcomes for a scenario with and without a properly operating sprinkler system but not the likelihood of each alternative.

Deterministic Hazard Assessment

In a deterministic analysis, a given set of input conditions always results in the same output predictions. Most fire dynamics and enclosure fire modeling calculations are deterministic. For most designs based on deterministic analysis, more than one fire scenario will be considered, even though the likelihood of the different scenarios is not explicitly addressed. For example, the performance-based option in the NFPA *101*®, *Life Safety Code*®, specifies eight required design fire scenarios without consideration of the likelihood of any of the specified scenarios.

Probabilistic Risk Assessment

In a probabilistic analysis, frequencies of occurrence are associated with design fire scenarios to yield the expected losses associated with each scenario. In this way, appropriate weights can be associated with different scenarios and different system reliabilities. A number of risk assessment tools can be used to aid the probabilistic analysis. Because time is a key parameter in fire scenarios, the event tree is a particularly useful tool for evaluating different possible outcomes at each stage of a fire scenario. The example fire event tree shown in Figure 3.11.5 illustrates the stages in fire development and typical factors that contribute to the probabilities at each stage of development.

The event tree shown in Figure 3.11.5 illustrates the concept of "defense in depth," which is widely used for building fire safety, particularly in the nuclear power industry. The defense-in-depth concept is based on the premise that the fire safety of a building should not rely exclusively on a single fire protection subsystem but should be based on a combination of subsystems in case one of the subsystems fails. The defense-in-depth concept has been used historically in building fire safety regulations, for example, through requirements for both automatic suppression and fire-resistive construction. With probabilistic assessment the costs and benefits associated with defense-in-depth applications can be appraised and optimized.

Analysis of the dynamics of different fire scenarios is not likely to differ significantly between deterministic and probabilistic approaches, but expression of performance objectives and criteria is likely to differ. For example, in a deterministic analysis the design objective may be to prevent flashover, whereas in a probabilistic analysis the design objective may be to demonstrate that the likelihood of flashover will not exceed 10^{-6}, or some other very small likelihood, per year. Conceptually, the risk-based probabilistic approach is more satisfying, but statistics are not always available to justify the probabilities needed for its application.

PERFORMANCE-BASED DESIGN CASE STUDY

The case study describes the application of performance-based design to a plan to address fire safety issues for a proposed per-

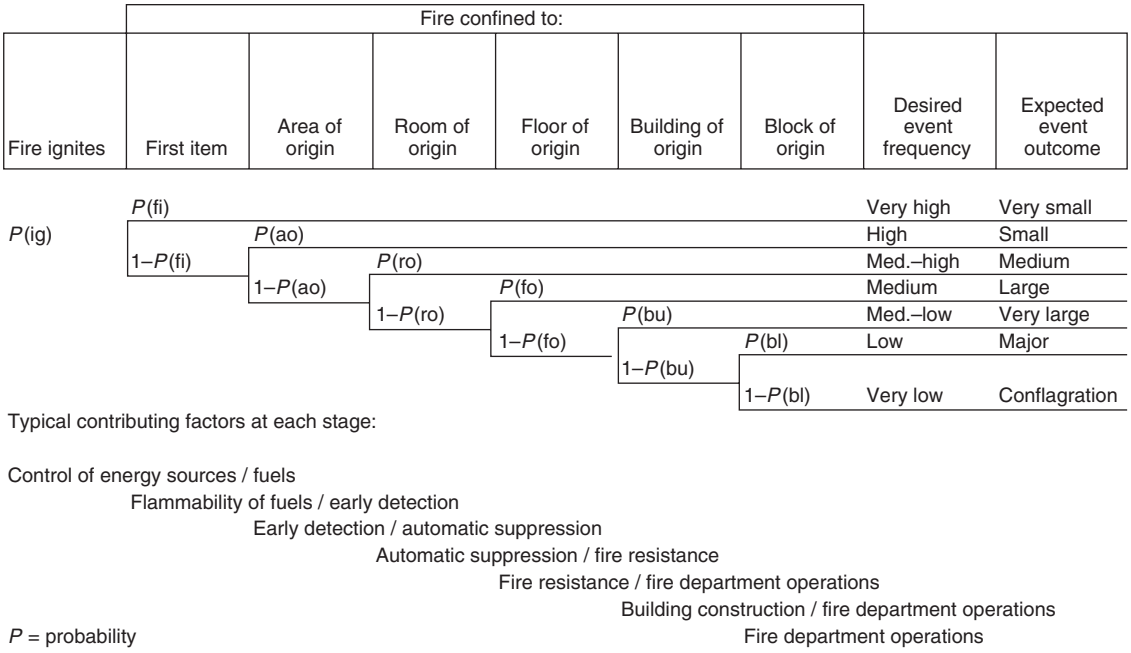

FIGURE 3.11.5 Example Fire Event Tree

forming arts center located in a large metropolitan area in the United States. The plan consisted of a comprehensive approach relative to managing a fire and exposures. As part of this fire safety plan, an alternative to smoke control for an atrium in the facility was developed.

The plan addresses fire safety by using performance-based design as documented in the *SFPE Engineering Guide to Performance-Based Fire Protection.*[13] The results of the analysis demonstrate how the *SFPE Engineering Guide* process works and provides a foundation for project stakeholders to achieve established fire safety goals.

Defining Project Scope

The example building features a large, approximately 150 ft (46 m) high, barrel-shaped glass atrium enclosing a large concert hall (more than 2000 seats) and a smaller theater (approximately 750 seats). Other uses in the building include meeting rooms, office space, and dining areas. The building is six stories high and occupies two city blocks with a footprint area of approximately 90,000 ft^2 (8360 m^2). The highest occupied level, a roof garden/terrace, is approximately 84 ft (26 m) high.

The stakeholders in the project include the owner, the authority having jurisdiction, the architect, the construction manager, the insurance company, the fire protection engineers, and other engineers responsible for designs of systems. Involvement of all of the stakeholders throughout the process is fundamental to the success of the project.

The building will be considered a mixed-use occupancy. Based on the height of the highest occupied level (i.e., the roof garden), the building was classified as a high-rise occupancy. The overall construction type of the building was determined to be protected noncombustible.

Under provisions of the applicable code, smoke control is required for all atria that connect more than two levels. The smoke control provided must maintain smoke to a minimum of 6 ft (1.8 m) above the highest level of exit access for a minimum duration of 20 minutes. Passive smoke control (i.e., no mechanical smoke control) is allowed by the code; however, an analysis must demonstrate that the smoke layer is maintained at least 6 ft (1.8 m) above the highest level of exit access for a minimum duration of 20 minutes. Therefore, the code criteria provide for safety by avoiding any smoke exposure to the occupants during an assumed exiting period. The code also allows alternative smoke control design approaches that achieve the goal of safe exiting of the building occupants. Based on the applicable code, smoke management (active, passive, or alternative) is required for the atrium of the building. An alternative approach for smoke control was developed for the proposed building that meets the intent of the code.

Identifying Goals

Goals establish the overall intent of the fire safety design. The goals were identified through discussions with stakeholders. Goals of the smoke management system include providing life safety and minimizing property damage. Compliance with the intent of the applicable code was also a goal. Unless the stakeholders agree the design meets the intent of the code, a building permit and certificate of occupancy may not be granted. These goals were modified, and other goals were developed as the project progressed. Maintaining the aesthetics of the design became a goal that all the stakeholders felt was important. Minimizing property damage by not allowing smoke to spread into surrounding areas was de-emphasized as a goal by the stakeholders.

Defining Objectives

The objectives define the engineering criteria needed to achieve the fire safety goals. Development of objectives required extensive communication among the stakeholders and an understanding of the proposed approach. The intent of the code smoke control requirements for atria is to provide for safe egress from the building and to prevent migration of smoke from or through the atrium to other areas. The stated requirements of the code require that the smoke layer be maintained above the occupants' heads. Therefore, occupants would not be exposed to smoke.

Controlling occupants' exposure to smoke is one way to provide life safety. Allowing occupants to be exposed to smoke, but limiting the concentration of combustion products in the smoke below hazardous levels is the methodology applied in this case study. A given fire size will produce varying volumes of smoke, depending approximately on the height of the space to the 5/3 power. As a result, much greater volumes of smoke are produced in tall, larger spaces than in smaller low spaces. However, the amount of particulate and energy produced is unchanged for a given fire size. A given fire size in a taller space contains a greater quantity of cool air, thus diluting the particulate-air mixture and reducing the effects of the energy input. Therefore, the relative hazard of the smoke produced by a given fire in a high ceiling space is less than that of a similar size fire in a low ceiling space. For detailed information on smoke management, see NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Areas,* and Section 18, Chapter 3, "Smoke Movement in Buildings."

The analysis for the case study building utilizes the fact that occupants may be exposed to highly diluted smoke without being exposed to a hazard. Once stakeholders understood the difference and rationale for the proposed approach—that is, allowing immersion in smoke as long as it was not a hazard—acceptance of the ideas followed. In other words, the stakeholders recognized that occupants could be exposed to smoke, but not to a hazard. A hazard to the occupants was conservatively assumed to occur if hazard criteria were exceeded prior to 20 minutes or the time calculated to egress the building, whichever is greater. The hazard criteria were based on the toxicity, temperature, and visibility within the smoke layer. The limits on toxicity were based on tolerance limits for humans established in the fire science literature. Hazards of concern included carbon monoxide and oxygen depletion. Temperature exposures were also examined. As is most often the case in this type of problem, visibility issues tend to dominate the hazard analysis.

DEVELOPING FIRE SCENARIOS AND DESIGN FIRES

The *SFPE Engineering Guide* includes the following elements as part of a design fire scenario:

- Building characteristics
- Occupant characteristics
- Fire characteristics

Building Characteristics. The case study building characteristics include a large atrium space. The atrium space is approximately 362 ft (110 m) long and 178 ft (54 m) wide. The ceiling is a glass half-cylinder that has an outer radius of 89 ft (27 m). The height of the base of the half-cylinder is about 48 ft (15 m) above the ground floor. An enclosed theater and a concert hall are located in the atrium space, but separated by fire resistance rated construction. Both the concert hall and the theater are irregular shapes and were approximated as cuboids in the analysis. The theater was assumed to be 87 ft (27 m) long, 87 ft (27 m) wide, and 85 ft (26 m) tall. The concert hall was assumed to be 130 ft (40 m) long, 192 ft (59 m) wide, and 96 ft (29 m) tall. There are five levels open to the atrium space. All of the levels potentially have floor spaces where occupants or fires can be located within the atrium. The first floor (ground floor) was located at a zero elevation, the second floor at 21 ft (6.4 m) elevation, the third floor at 32 ft (9.8 m) elevation, the fourth floor at 55 ft (18 m) elevation, and the sixth floor (i.e., roof garden on top of the theater) at 84 ft (26 m) elevation. Figure 3.11.6 illustrates the proposed building in cross-section.

Occupant Characteristics. Occupant characteristics included the number, location, and capabilities of potential occupants. This analysis was based on design occupant loads calculated using the code criteria. The occupant loads were agreed on by the stakeholders as a conservative estimate of the potential occupancy of the structure. Occupants were assumed to be characteristic of the general public capable of attending an event.

Fire Characteristics. The code identifies a specific design fire based on the occupancies of the building for the analysis of atrium smoke control systems. The baseline fire is steady-state heat release rate. Therefore, a baseline fire as required by the code was included in the analysis. In addition, other design fire scenarios included anticipated fire scenarios developed by the stakeholders. Fire scenarios included furniture, kiosks, and displays located in the atrium on all levels open to the atrium. Sprinklers are not provided in high ceiling areas where fuel loads will not be sufficient to activate the system. Spaces adjacent to the atrium and not separated by fire resistance rated con-

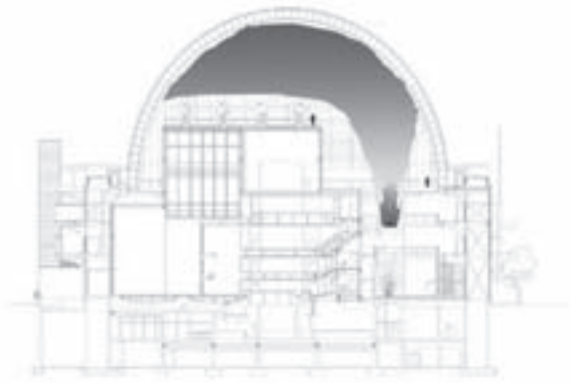

FIGURE 3.11.6 Cross Section of Proposed Performing Arts Center (Courtesy Hughes Associates Inc.)

struction have relatively low ceiling heights and are provided with automatic sprinkler protection. Therefore, fires in adjacent spaces were not evaluated. The composition of the fuel modeled in this analysis was also discussed with the stakeholders. The material properties of concern included the smoke yield, heat of combustion, and carbon monoxide yield.

Developing Trial Design

Trial designs define proposed alternative fire safety systems that address the hazard caused by the design fire scenario in order to provide the level of safety defined by the performance criteria. As the project design progressed, it became clear to all of the stakeholders that the preferred design for the smoke management system would rely on the vast size of the atrium to provide a safe haven for building occupants. This design recognized that the occupants would potentially be exposed to highly diluted smoke, and this would be acceptable. However, occupants could not be exposed to hazardous conditions. If it became apparent that relying on the size of the atrium would not provide an adequate level of safety, then alternative designs included installing a smoke exhaust at various levels in the atrium or installing a unique fire suppression system to limit fire size on the atrium floor.

Throughout the analysis, the stakeholders agreed on the approaches established. Prior to the design evaluation, an agreement on the proposed approach was recorded. The agreement consisted of documentation of meetings held to discuss the various aspects of the approach and all of the limitations and assumptions associated with the approach. All of the stakeholders understood the analysis was oriented toward establishing a fire safe approach with the first step to use the atrium volume and no emergency smoke exhaust.

Evaluating Trial Designs

Once the parameters of the evaluation had been established and agreed to by the stakeholders, the level of fire safety was evaluated. The evaluation process utilized a variety of fire models and calculations. Computer fire models were used to calculate the smoke layer properties (e.g., location, toxicity, temperature, visibility) as a function of time. Because of the limitations associated with individual modeling techniques, both zone fire models and hand calculations were used to estimate smoke layer location and composition. As further verification of the zone modeling, a smoke filling analysis was performed using computational fluid dynamics (CFD).

Due to the glass atrium construction and the potential environmental exposures, smoke stratification in the atrium was a concern. The ambient temperatures in the atrium were based on energy analysis performed by other stakeholders. The layer of hot air resulting from sun exposure to the glass roof may not allow a plume to penetrate, and, therefore, portions of the glass dome could not be utilized as a space for smoke to gather. Therefore, a smaller fire that would result in a weaker plume that would not penetrate the hot air layer might be a worse situation than a more intense fire. Stratification effects of the fire plumes were considered as part of the analysis.

A timed egress analysis was also performed to calculate the time required to evacuate the building in case of a fire. The time required to egress the building was compared to the progress and composition of the descending smoke layer to verify that tenable conditions were maintained for the duration of egress. The anticipated time to egress from the building was calculated based on a "hydraulic flow" type egress model. The basic assumption used in the hydraulic flow egress model is that the rate at which people pass through an exit component (i.e., exit flow) is based on the density of the group of persons entering the exit component. The exit flow assumption is similar in form for all types of exit components including stairs, doors, and corridors. The time to exit each floor incorporated such factors as the time to travel to an exit component, the time to wait for access to the exit component, the time to pass through the exit component, the time to descend through the building, and the time to wait in the queue before exiting the building. Several factors may delay the egress time, such as locating the exits (i.e., "way finding"), egress management activities (i.e., time for verification of alarms by building personnel), and inefficient exit use. Based on these influencing factors, a safety factor was applied to the calculated egress time.

Selecting Final Design

As a result of the evaluation, it was determined that life safety could be maintained utilizing the vast size of the atrium as a smoke reservoir. The atrium size limited the effects of a fire on the occupants of the atrium. Therefore, a large reservoir was utilized in lieu of mechanical smoke exhaust from the atrium. The evaluation demonstrated that, depending on the floor of the fire location, occupants might or might not be exposed to smoke. Where occupants were exposed to smoke, the smoke was highly diluted and did not create a hazard. Because the primary method to achieve fire safety was demonstrated to be adequate, the other trial designs were not evaluated.

One objective not addressed by the primary design was facilitating postfire operations by the fire department. The fire department's concern throughout the process was how it would clear smoke from the atrium if exhaust or openings were not provided in the glass barrel. Postfire ventilation by the fire department was facilitated by providing manually operated vents that allowed the fire department to exhaust smoke. The vents were provided high in the barrel as well as at the base of the barrel. Because of the unpredictability of the environment surrounding the building (e.g., wind and temperatures) and the low temperatures in the smoke layer, these vents were not utilized for automatic natural venting.

Because the final design did not prevent the hot upper layer's descent to floors open to the atrium, the possibility of smoke damage on floors open to the atrium exists. The stakeholders understood this limitation.

Preparing Design Documents

Documentation of the PBD process and the resulting final design was prepared and was reviewed by the stakeholders. Meetings were held to discuss the approach, assumptions, limitations and results. Limitations on fuel loads and space utilization were established in the process, and documented and approved by all of the stakeholders.

Observations

The *SFPE Engineering Guide* provides a methodology that was successfully utilized for the PBD of a smoke control system of a unique building. The performance-based design process included detailed analysis relating to the interaction of all the fire safety systems that were beyond the scope of this brief overview. Without understanding the means of egress, suppression and detection systems, and construction and other fire safety features in the structure, and without developing a comprehensive plan, a PBD may not adequately address all of the issues. The keys to the success of this process were the frequent, high-quality communications between the stakeholders and the initiation of the PBD early in the building design process. As a result of this analysis and the efforts of all the stakeholders, the fire safety goals of the project were achieved.

SUMMARY

The concept of performance-based fire protection design is not new. Fire protection engineers have been designing systems and subsystems to meet fire protection performance objectives and criteria within the constraints imposed by cost, technology, and safety for as long as such systems and subsystems have existed. In recent years, however, the term *performance-based fire protection* has taken on the more specific meaning associated with the design process outlined in this chapter. This process entails the quantitative assessment of different fire scenarios using appropriate computational methods and tools to determine whether specified performance objectives and criteria will be met by a proposed design.

The application of performance-based fire protection design demands a higher level of knowledge about building fire dynamics and fire protection system operating characteristics on the part of stakeholders than does traditional prescriptive design. Although this increased demand can impose additional costs on the design and review processes, it will also produce tangible and intangible benefits. One of these benefits is a better understanding of the expected consequences of fires in a building; another benefit, in many cases, will be reduced costs for fire protection. Whether the benefits of performance-based fire protection design will outweigh the costs depends on the particular application.

In closing this overview of performance-based fire protection design, it is important to emphasize that building fires are complex events, involving the interactions of the fire with the building and the people within the building. The range of potential interactions among the fire, the building, and the people gives rise to a large number of possible fire scenarios. It is not generally practical to evaluate every possible fire scenario, but it is important that the most significant scenarios, from either a hazard or a risk standpoint, are identified and evaluated.

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13. *SFPE Engineering Guide to Performance-Based Fire Protection,* Society of Fire Protection Engineers and National Fire Protection Association, Bethesda, MD, 2000.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on performance-based fire protection design. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*
NFPA *101®, Life Safety Code®*

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SECTION

4

Human Factors in Emergencies

Guylène Proulx

4.1 Human Behavior and Fire
4.2 Calculation Methods for Egress Prediction
4.3 Concepts of Egress Design
4.4 Techniques of Crowd Management
4.5 Strategies for Occupant Evacuation During Emergencies

Most of the *Fire Protection Handbook*® discusses, either directly or indirectly, how fire, systems, and structures behave in relationship to each other. This section focuses entirely on the role of human behavior in emergencies. More specifically, the section concentrates largely on how people discover fire and escape from fire and other emergencies. For the first time, the section also addresses the topic of crowd management, which is closely related to emergency evacuation.

Chapter 1, "Human Behavior and Fire," presents information that is as fundamental to fire protection as fire behavior. It also addresses the means by which people investigate "ambiguous threat cues" and decide that there really is a fire—namely, recognition, validation, definition, evaluation, commitment, and reassessment. Documented human behavior during several significant emergencies, including the Station Nightclub fire and events at the World Trade Center, are discussed.

Chapters 2 and 3 are particularly germane to anyone who uses or enforces NFPA *101*®, *Life Safety Code*®, or *NFPA 5000*®, *Building Construction and Safety Code*®, or who practices performance-based design. Chapter 2, "Calculation Methods for Egress Prediction," explains components of evacuation time, techniques for estimating evacuation time, and calculation methods for travel time, then discusses computer simulation and egress modeling. Chapter 3, "Concepts of Egress Design," reviews concepts that underlie the egress requirements, signage, and lighting in NFPA *101*.

Chapter 4, "Techniques of Crowd Management," is new to the *Fire Protection Handbook* and provides background information needed to fulfill the *Life Safety Code* requirement for trained crowd managers. The chapter reviews selected crowd disasters, explains the difference between crowd management and crowd control, presents a crowd disaster model, and explicates phases of crowd management.

The section closes with another new piece: Chapter 5, "Strategies for Occupant Evacuation During Emergencies." This chapter discusses occupant characteristics in the context of evacuation and compares total evacuation with the alternative strategies of defend-in-place, delayed evacuation, partial evacuation, phased evacuation, and zoned evacuation. The chapter also covers horizontal exiting, evacuation by elevator, preplanning, and nonfire emergencies.

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SECTION 4

Chapter 1

Human Behavior and Fire

John L. Bryan

Chapter Contents

Awareness of the Fire
Decision Processes of the Individual
Behavior of Occupants
Disabled or Impaired Occupants
Fire Exit Drills

Key Terms

awakening, convergence cluster, Cook County Administration Building fire, decision making model, disabled occupant, evacuation, exit drill, health care facility, hotel, human behavior, MGM Grand fire, panic behavior, Station Nightclub fire, temporal-three signal, World Trade Center

How one reacts during a fire is related to the role assumed, previous experience, education, and personality; the perceived threat of the fire situation; the physical characteristics and means of egress available within the structure; and the actions of others who are sharing the experience. Postevent analysis of behavior has described actions as adaptive or nonadaptive, participative or inhibited, and altruistic or individualistic. Detailed interview and questionnaire studies over the last half century have established that instances of nonadaptive or panic-type behavior are rare, occurring under specific conditions. Most behavior in fires is determined by information analysis, resulting in cooperative and altruistic actions.

The earliest documented studies on human behavior in the United States involved capacity counts of the velocity of pedestrian movement for the New York City design of the Hudson Terminal Building in 1901.[1] The first edition of the National Fire Protection Association's *Building Exits Code* in 1927 (which eventually evolved into NFPA *101*®, *Life Safety Code*®) was developed from evacuation studies conducted during the decade since 1917. Classical evacuation studies involving railway terminals, subway stations, theaters, department stores, and federal government office buildings with both "normal" exiting flows and "fire-drill" exiting flows were conducted in the early 1930s and published in 1935.[1]

In England, the London Transit Board and other evacuation studies were conducted.[2,3] In the United States, during the 1940s and the 1950s, there was a lack of interest in studies on human behavior in fires. Even in fires that resulted in large loss of life, such as the Cocoanut Grove fire, dedicated human behavior studies of the responses of occupants were not conducted. An exception was the interview study of selected occupants of the Arundel Park fire in 1956, which verified the process of re-entry behavior by members of family groups.[4] The most productive period for research and publications in the United States on human behavior appeared to be from 1970 through the mid-1980s. The 5 year study and report of the National Commission on Fire Prevention and Control in 1973, entitled *America Burning,* provided a federal government focus on the national fire problem.[5] This report resulted in new and enhanced federal financial support for all facets of fire research including human behavior, even though the report envisioned the role of human behavior research being primarily applicable to the educational aspects of fire prevention. During the 1970s the National Bureau of Standards, through the Center for Fire Research, and the National Fire Protection Association were the primary sources for funding studies on human behavior in fire in the United States. Thus, studies resulted in an examination and development of the methods for investigating behavior of the occupants in fire situations in both the United States and United Kingdom. Funding was also provided for the United States and Japan Natural Resource Panel on Fire Research and Safety, which included the study area of human behavior in fires.[6–14]

The emphasis of the studies during this period was on defining human behavior in fire situations, including the examination of the then popular concept of "panic behavior" and an emphasis on the study of the evacuation process as it occurred in high-rise building fires. Characteristics of human behavior individually and within groups have been determined primarily by research studies in which individuals were interviewed by fire department personnel at the scene of the fire.[7,14] It must be recognized that an individual's behavior in a fire is affected by the variables of the building in which the fire occurs and by the appearance of the fire at the time of detection. For example,

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response will vary if an individual smells smoke rather than sees flames or dark, acrid smoke completely obscuring a corridor. Variables of the fire protection provided for the building may also be critical to the individual's perception of the threat involved. Obviously, the most important individual decisions and behavior in life-threatening situations occur before the arrival of the fire department, in the early stages of the fire. Studies of health care facilities have indicated the importance of this early behavior:

> In the process of investigating these case studies we have come to believe that the period between detection of the fire and the arrival of the fire department is the most crucial lifesaving period in terms of the first compartment (the area in direct contact with the room of origin and the fire).[11]

Thus, the behavior of the individuals intimately involved with the initiation of the fire is critical not only for themselves but often for other occupants of the building. It should be recognized that the altruistic behavior observed in most fires, with occupants in the fire environment interacting in a deliberate, purposeful manner appears to be the general mode of reaction. The nonadaptive flight or panic-type behavioral reaction is apparently unusual in fires.

See also Section 4, Chapter 2, "Calculation Methods for Egress Prediction"; Section 4, Chapter 3, "Concepts of Egress Design"; and Section 20, Chapter 1, "Assessing Life Safety in Buildings."

AWARENESS OF THE FIRE

Obviously, the way an individual is alerted to the presence of a fire may determine the degree of threat perceived. With vocal alerting systems in buildings, variations in voice quality, pitch, or volume, as well as the content of the message, tend to provide threat cues.[15]

Awareness Cues

Proulx and Sime[16] in their study of evacuation drills in an underground rapid transit station found the use of directive public announcements with an alerting alarm bell most effective in creating an immediate effective evacuation. Ramachandran in his review of the research on human behavior in fires in the United Kingdom since 1969 summarized the effectiveness of alarm bells as awareness cues: "The response to fire alarm bells and sounders tends to be less than optimum. There is usually skepticism as to whether the noise indicated a fire alarm and if so, is the alarm merely a system test or drill?"[17]

Ramachandran[18] indicated that the development of "informative fire warning systems," which use a graphic display with a computer-generated message and a high-pitched alerting tone, has reduced the observed delay times in the initiation of practice evacuations. Cable[19] in his study of the response times of staff personnel to fire alarm signals in Veterans Administration hospitals found the greatest delay in response time with coded alarm bell systems. Kimura and Sime[20] in a study of the evacuation of two lecture halls by college students found that the lecturer's verbal instructions were the determining factor in students choosing to use the fire exit over the normal entrance and exit. Research literature developed from practice evacuations indicates that the use of verbal directive informative messages may be the most effective way to reduce delay in evacuation initiation.

However, note that if verbal directive messages conflict with other awareness cues, such as the odor or sight of smoke, occupants may question the credibility of the message and disregard the information. One of the few documented cases of this type of situation occurred in the South Tower of the World Trade Center on April 17, 1975. Lathrop[21] reported that the fire occurred in a trash cart in a storage area on the fifth floor, adjacent to an open stairway door that allowed smoke to infiltrate the ninth through twenty-second floors at approximately 9:04 a.m. Occupants of these floors moved into the core area of the building, and the building communications center monitoring the core lobby areas verbally directed the people in these areas to remain calm and return to their office areas at 9:10 a.m. Despite this announcement, occupants remained in the core lobby areas and became more concerned about smoke conditions. Thus, with occupants on the affected floors becoming more anxious, an evacuation message was announced at 9:16 a.m.

As Burns[22] reported, simultaneous occupant evacuations occurred in the explosion and fire of February 26, 1993, which severely affected both towers and the Vista Hotel of the World Trade Center. The explosion disrupted the Center's communications center, and the occupants, having experienced within minutes the explosion, loss of power, and smoke infiltration of the floors areas, evacuated without the established verbal directional announcements used in previous practice evacuations.

Fahy and Proulx in their questionnaire study of 382 trained fire warden personnel located in both towers of the World Trade Center at the time of the explosion and fire of February 26, 1993, found these personnel were alerted primarily in the following manner:[23]

> Respondents mentioned the following cues, either singly or in combination that something was occurring: hearing or feeling the explosion, loss or flickering of lights or telephones, smoke or dust, sirens and alarms, information from others, and people movement.

Temporal-Three Evacuation Signal

The temporal-three sound was mandated as the building evacuation signal in the 1995 edition of the National Building Code of Canada and in *NFPA 72®*, *National Fire Alarm Code®,* for all new buildings effective July 1, 1996. The temporal-three sound pattern was selected to allow the utilization of all the current types of signaling system devices. The temporal-three sound selection was a product of the Acoustical Society of America and the responsible code committees. The signal was subsequently adopted by ANSI with the standard S3.41, *Audible Emergency Evacuation Signal,* and by the International Standards Organization as ISO 8201, *Audible Emergency Evacuation Signal.* Figure 4.1.1 illustrates the temporal-three sound pattern characteristics as defined in *NFPA 72.*

It should be noted that *NFPA 72* also requires that the signal be continuous for a minimum time as follows:

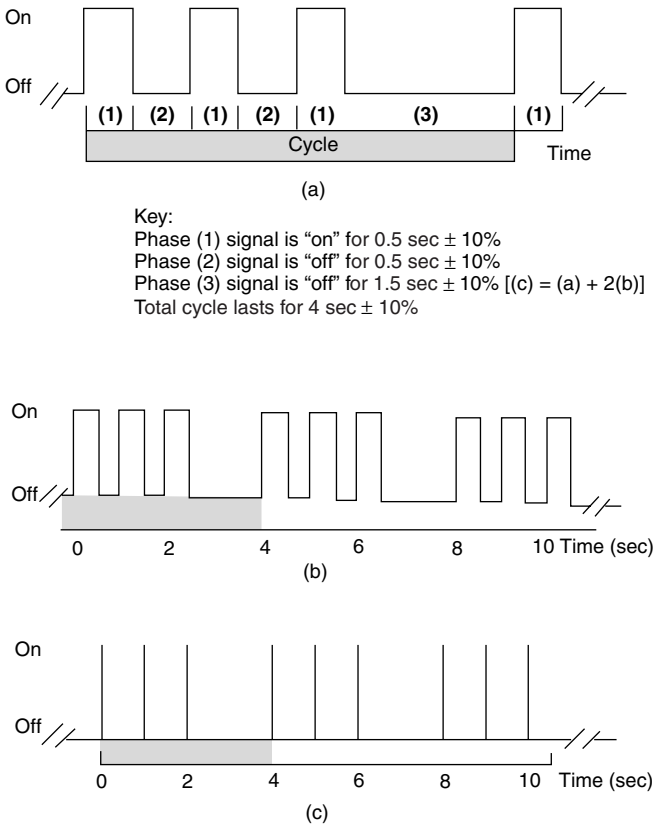

FIGURE 4.1.1 Temporal-Three Evacuation Signal (Source: *Life Safety Code Handbook,* National Fire Protection Association, Quincy, MA, 2006, p. 340)

The signal should be repeated for a period that is appropriate for the purposes of evacuation of the building, but for not less than 180 seconds.

The article by Proulx and LaRoche[24] describes the history of the selection of the temporal-three evacuation signal, but most importantly describes the details and the procedures implemented in their experimental study with 307 individuals relative to their recognition of the temporal-three sound as an emergency evacuation signal and their perceived "urgency" of the signal. The participants were provided with earphones containing the following recorded sounds: car horn, reverse alarm, buzzer, temporal-three (T-3) signal, bell, and slow whoop. The slow whoop was included due to its widespread use in the United States. The most widely utilized signaling device in Canada in institutional buildings was the bell. The presentation of the signals on each CD was varied with the temporal-three being first, third (middle), and sixth (last). The procedure in the study involved approaching the participants when they were alone and inactive in public buildings. The participant was asked to participate in a 5 minute sound recognition study. After listening to the CD each participant was asked three questions:

- Have you heard this sound before?
- What do you think this sound means?
- How urgent do you feel this sound is on a scale from 1 to 10?

Table 4.1.1 presents the results of this study.

It should be noted that of the 219 persons that indicated they had heard the temporal-three signal before, only 17 individuals or 6 percent of the participants correctly identified the signal. As indicated in this table the temporal-three signal had the least perceived urgency with a score of 3.97 on the scale of 1 to 10, with the bell and the slow whoop having the highest perceived urgency at 7.17 and 6.01. The authors of this study had the following critical conclusion concerning the temporal-three

TABLE 4.1.1 Participants' Response to Temporal-Three Signal

A. Number of Occupants Who Said They Had Heard Signal Before

Signal	*Participants (N = 307)*	*Recollection of Signal by Participants (Percentage of Participants)*
Car horn	297	97
Reverse alarm	280	91
Buzzer	249	81
T-3	219	71
Bell	177	58
Slow whoop	159	52

B. Number of Participants Who Correctly Identified Signal

Signal	*Participants (N = 307)*	*Correct Identification of Signal (Percentage of the Time)*
Car horn	302	98
Reverse alarm	218	71
Bell	155	50
Slow whoop	71	23
T-3	17	6
Buzzer	6	2

C. Perceived Urgency of Each Signal

Signal	*Urgency (as Rated by Participants on a Scale of 1 to 10, with 10 Indicating "Extremely Urgent")*
Car horn	4.93
Reverse alarm	5.60
Bell	7.17
Slow whoop	6.01
T-3	3.97
Buzzer	4.91

Source: Guylene Proulx and Chantal LaRoche, "Recollection, Identification and Perceived Urgency of the Temporal-Three Evacuation Signal," *Journal of Fire Protection Engineering,* Vol. 13, No. 1, 2003, pp. 67–82.

evacuation signal, which would apply to any emergency signal rather than an emergency communication:[24]

> The results of this study certainly dispute the assertion that the temporal content of the T-3 may be sufficiently urgent enough to trigger a general evacuation response. It is our opinion that an alarm signal, without any other cue, cannot convey a sufficient message of urgency to let people readily know that they are expected to evacuate a building. The response to the signal will still need to be learned, and probably still need to be prompted by voice communication instructions or by the behavior and directions given by staff. It cannot be expected that occupants will immediately start evacuation or relocation movement upon hearing the T-3 signal, more information will always be required to ensure occupant safe response during a fire incident in a public building.

Initial Means of Awareness

Most of the participants in residential occupancy studies were alerted initially to the fire by the odor of smoke. When the two categories "notified by family" and "notified by others" are combined, however, personal notification becomes the most frequently reported means of initial perception of fire, as indicated in Table 4.1.2.[7] The category "noise" includes noise from persons moving downstairs and through corridors, plus miscellaneous noise sources, including the breaking of glass and the arrival of fire apparatus.

Table 4.1.3 compares the means of awareness from participants of a British study[14] and those of a U.S. study.[7] The number of stimuli was reduced because the British study had fewer categories, and the U.S. responses have been adapted to the British categories. There was only one significant difference in the means of awareness between the two groups: 15 percent of the British participants became aware of the fire upon observing flame, contrasted with 8.1 percent of the U.S. participants.

Purser and Kuipers[25] studied 110 fire incidents with 210 occupants in residential buildings when the fire occurred. Table 4.1.4 presents the means of awareness for the occupants categorized with the occupant in the room of fire origin and when the occupant was not in the room of fire origin. The reader should compare the means of awareness presented in Tables 4.1.2 and 4.1.3 (1977 and 1972, respectively) with the means of awareness indicated in Table 4.1.4 of this study conducted in the early 2000s. It would appear the early means of awareness is still provided by the physical cues of the fire incident and verbal communication from other individuals.

Proulx and Fahy[26] in the study of the survivors' behavior in the terrorist aircraft attacks on the two World Trade Center towers on September 11, 2001, based on media accounts, indicated that 357 persons mentioned being alerted by the means presented in Table 4.1.5. The authors indicate the most frequent initial cue reported by 146 (69%) of the survivors in Tower 1 was building movement, feeling the building sway and tremble. The most frequent initial cue reported by 96 (66%) of the survivors in Tower 2 was the sight of fire, smoke, and debris from Tower 1. The authors note only 25 survivors (6%) who indicated building alarms in their media accounts.

A study one year later obtained information on the occupants' cues of awareness and their activities prior to movement or evacuation. The study involved 803 telephone interviews, 225 face-to-face interviews, and 5 focus group interviews with survivors and first responders, conducted by research personnel and designed and supervised by NIST.[27] In addition, the study of published data by Proulx and Fahy[26] was reviewed. The results of 440 telephone interviews indicating how survivors from World Trade Center 1 became aware of an unusual occurrence in their building are presented in Table 4.1.6. The data population of 440 consisted of approximately 55 percent of the 803 total telephone interviews of survivors from both buildings. Physical

TABLE 4.1.2 Means of Awareness of the Fire Incident (United States Studies)

Means of Awareness	*Participants*	*Percentage*
Smelled smoke	148	26.0
Notified by others	121	21.3
Noise	106	18.6
Notified by family	76	13.4
Saw smoke	52	9.1
Saw fire	46	8.1
Explosion	6	1.1
Felt heat	4	0.7
Saw/heard fire department	4	0.7
Electricity went off	4	0.7
Pet	2	0.3
Total ($N = 11$)	569	100.0

TABLE 4.1.3 Comparison of British and United States Study Results Relative to Means of Awareness of a Fire Incident

Means of Awareness	*British (Percentage, P_1)*	*U.S. (Percentage, P_2)*	$P_1 - P_2$	$SE^a_{P_1-P_2}$	CR^b
Saw flame	15.0	8.1	6.9	1.64	4.21[c]
Smelled smoke	34.0	35.1	1.1	2.27	0.48
Heard noises	9.0	11.2	2.2	1.41	1.56
Heard shouts and was told	33.0	34.7	1.7	2.25	1.20
Heard alarm	7.0	7.4	0.4	1.23	0.33
Other	2.0	2.8	0.8	0.70	1.14
Participants ($N = 6$)	2193	569			

[a]Standard error.
[b]Critical ratio.
[c]Critical ratio (CR) significant at or above the 1 percent level of confidence.

TABLE 4.1.4 How Occupants Were Alerted to Fire

Occupant in Fire Room	*Frequency*	*Occupant Not in Fire Room*	*Frequency*
Saw flame	5	Told by others	33
Heard noise	4	Heard noise	11
Told by others	2	Saw smoke	10
Smelled something	2	Smelled smoke	8
Saw smoke	2	Smelled burning	8
Saw flame and smoke	2	Heard alarm	7
Heard alarm	2	Saw flames	4
Woke up coughing	1	Saw flames and smoke	2
Smelled smoke	1	Saw sparks	2
Smelled burning	1	Woke up coughing	1
Saw sparks	1	Smelled something	1
Not known	1	Saw fire brigade	1
Heard screaming	1	Remembered chip pan	1
Felt heat	1	TV went off	1
		Heard fire brigade	1
		Saw flash	1
Total	26		93

Source: David A. Purser and Marion E. Kuipers, "Interaction Between Buildings, Fires and Occupant Behaviour Using a Relational Database Created from Incident Investigations and Interviews," *3rd International Symposium on Human Behaviour in Fire 2004,* Interscience Communications and University of Ulster, Belfast, UK, 2004, p. 451.

TABLE 4.1.5 First Cues of Event Within the Towers

First Cues	*WTC 1 (N = 212)*		*WTC 2 (N = 145)*	
Audio cues: heard explosion, crash, rumble	107	(50%)	69	(48%)
Visual cues: saw fire, incoming plane, debris, smoke	87	(41%)	96	(66%)
Building movement: felt building sway, tremble, jolt	146	(69%)	30	(21%)
Contents movement: furniture movement, ceiling falling	66	(31%)	11	(8%)
Warning from others	14	(7%)	34	(23%)
Impact	29	(14%)	1	(1%)
Smelled fumes or felt heat	12	(6%)	16	(11%)

Source: Guylene Proulx and Rita Fahy, *Analysis of Published Accounts of the World Trade Center Evacuation,* Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST NCSTAR 1-7A, National Institute of Standards and Technology, Gaithersburg, MD, Sept. 2005, p. 15.

TABLE 4.1.6 How Survivors in WTC 1 Became Aware Something Was Wrong on September 11, 2001

Cue	*Percentage (N = 440)*
Felt something (building moving, impact, shaking, swaying)	63
Heard something (boom, crash, explosion, blast, roar, rumbling)	30
Other, including saw a plane, smelled jet fuel, fell down/fell off chair, warned by someone	7

Source: NIST WTC Telephone Survey Data, in Jason D. Averill et al., *Occupant Behavior, Egress, and Emergency Communications,* Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST NCSTAR 1-7, National Institute of Standards and Technology, Gaithersburg, MD, Sept. 2005, p. 76.

cues of the aircraft striking the building consisted of 93 percent of the awareness cues to the occupants, as indicated by the following: "building moving, impact, shaking, swaying, boom, crash, explosion, blast, roar, rumbling."[27] The predominant activity of the survivors in World Trade Center 1 following their awareness of the unusual threatening cues, prior to initiating evacuation, was "Talked to Others," which would appear to be a "validation" action, as individuals were formulating their "definition" of the event, which was necessary for them to formulate their "evaluation" of a behavioral response.

The NIST telephone interviews of 363 survivors from World Trade Center 2 relating their means of awareness of an unusual occurrence in the buildings are presented in Table 4.1.7. When this table is compared with the means of awareness cues for the event in Table 4.1.6, the principal differences appear to be the cue of "Saw something (smoke or flames, plane, debris)" by 19 percent and "Warned by someone around me" by 13 percent.

TABLE 4.1.7 How Survivors in WTC 2 Became Aware Something Was Wrong on September 11, 2001

Cue	*Percentage (N = 363)*
Heard something (boom, crash, explosion, blast, roar, rumbling)	51
Saw something (smoke or flames, plane, debris)	19
Warned by someone around me	13
Felt something (building moving, impact, shaking, swaying)	11
Other, including contacted via telephone, lights flickered, news media	7

Source: NIST WTC Telephone Survey Data, in Jason D. Averill et al., *Occupant Behavior, Egress, and Emergency Communications,* Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST NCSTAR 1-7, National Institute of Standards and Technology, Gaithersburg, MD, Sept. 2005, p. 76.

It is important to realize that 81 percent of the interviewees in World Trade Center 2 indicated they were aware of the event in World Trade Center 1, having been alerted by coworkers, telephone, or news media coverage. Thus, awareness data was obtained from all of the 803 telephone interviewees.

The factors of personnel in World Tower 2 being alerted by the event in World Trade Center 1 are more clearly observable in the Proulx and Fahy study of the published accounts of survivors relative to their "first cues of events within the towers" previously presented in Table 4.1.5 for survivors from both towers.[26] The identical increase in "Warning from others" and "Visual cues, saw fire, incoming plane, debris, smoke" is verified from the published accounts. The categories of "Contents movement" and "Smelled fumes or felt heat" were not indicated in the NIST study of awareness cues and may have been a feature of the telephone interviews, which are usually more highly structured.[27]

Awakening

A study of the NFPA-recommended smoke detector noise level of 75 dBA indicates that individuals with hearing impairments, those taking sleeping pills, or those on medication may require a detector noise level exceeding 100 dBA[28] (see *NFPA 72*). Flashing or activated lights are effective fire signals in occupancies populated primarily by hearing-impaired persons.[29] The 1981 edition of NFPA *101* for the first time permitted flashing of exit signs along with activation of an audible fire alarm system.

A study of 24 male subjects designed to determine whether they were awakened by a smoke detector's audible alarm signal and could identify fire cues found that the subjects slept through the alarm signals at a signal-to-noise ratio of 10 dBA and consistently failed to identify the awakening cue or radiant heat and smoke odor cues as fire warnings.[30] Other researchers have indicated that the alarm-signal-to-noise ratio is attenuated by physical surroundings.[31] A signal passing through a ceiling or a wall may be reduced by 40 dBA, whereas a signal passing through a door may be reduced by 15 dBA; in addition, the signal could be masked by a typical residential air conditioner noise level of 55 dBA.

Due to the vulnerability of many fire victims while sleeping, the capability of a fire alarm signal to awaken sleeping individuals is a critical variable in the design and application of an alarm system. Ball and Bruck have summarized research findings in Australia relative to the auditory arousal thresholds (AATs) of individuals in sleep stages relative to voice warnings/announcements and alarm signals in the following manner:[32]

- Sleepy individuals (defined as sleep latency = 5 minutes) and alert individuals (defined as sleep latency = 10 minutes) who have been deprived of sleep do not show the usual decline in AATs across the night.
- Sleep-deprived young adults will not reliably awaken to an alarm signal.
- Both the frequency of awakenings and the intensity of a stimulus required to induce awakening are related to age, with more frequent awakenings in response to lower-stimulus intensity as age increases.
- Individual differences account for more variability in AATs than sleep stage or age.

Human voice alarms have distinctive appeal in that they convey meaning and can also directly convey emotional significance. The research has found the following:[32]

- Individuals can successfully identify the emotion being conveyed when actors deliver signal words or phrases.
- The way in which signal words are spoken determines the believability, appropriateness, and most importantly, sense of urgency being conveyed.
- An increase in pitch of voice is equated with an increase in the perceived intensity of the emotion being conveyed, whether this emotion is positive or negative.
- Human voice alarms are perceived as more urgent and intelligible, than computer synthesized voice alarms, even when the computer generated sound has been manipulated to convey urgency.
- The female voice is perceived to be more urgent than the male voice.
- The level of urgency perceived varies for different signal words with "deadly" and "danger" perceived as more urgent followed by "warning," "caution," and "note."

Ball and Bruck collected a total of 1447 responses from 163 individuals with an estimated age range of 17 to 65, composed of staff and students at Victoria University, Melbourne, Australia. The responses to the question: "What sounds would draw your attention when sleeping?" are presented in Table 4.1.8. The responses to the question: "What sounds would you feel the need to investigate upon awakening?" are presented in Table 4.1.9. As shown, the study indicated the effectiveness of a signal expressing human emotion, which agrees with research that sleeping persons will respond to emotional sounds.

TABLE 4.1.8 What Sounds Would Draw Your Attention When Sleeping?

Top Fifteen Most Frequent Responses to Question 2 (*N* = 534)

Question	*Rank*	*Sound*	*Frequency*	*Percentage of Total*
What sounds would draw your attention when sleeping?	1	Child crying or calling out	38	7.1
	2	Loud voices	24	4.5
	3	Dogs barking continuously	22	4.1
	4	Baby crying	21	3.9
	4a	Sirens	21	3.9
	6	Telephone ringing	20	3.8
	6a	Alarms	20	3.8
	8	Alarm clock	16	3.0
	9	Smoke alarm	15	2.8
	10	Loud bangs	14	2.6
	11	Any loud sounds	13	2.4
	11a	Tapping on window or door	13	2.4
	11b	Footsteps	13	2.4
	11c	Glass breaking	13	2.4
	11d	Screaming	13	2.4
	11e	Sounds that do not belong	13	2.4
Total (*N* = 534)			289	54.1

Note: Table actually includes 16 responses due to the lowest ranked sounds being nominated an equal number of times.

Source: Michelle Ball and Dorothy Bruck, "The Salience of Fire Alarm Signals for Sleeping Individuals: A Novel Approach to Signal Design," *3rd International Symposium on Human Behaviour in Fire 2004,* Interscience Communications and University of Ulster, Belfast, UK, 2004, p. 307.

TABLE 4.1.9 What Sounds Would You Feel the Need to Investigate on Awakening?

Top Fifteen Most Frequent Responses to Question 3 (*N* = 467)

Question	*Rank*	*Sound*	*Frequency*	*Percentage of Total*
What sounds would you feel the need to investigate upon awakening?	1	Child crying or calling out	31	6.6
	2	A disturbance in the house	29	6.2
	3	Sounds that do not belong	26	5.6
	4	Crying or screaming	22	4.7
	4a	Banging	22	4.7
	6	Glass breaking	21	4.5
	7	Dogs barking continuously	20	4.3
	8	Telephone ringing	18	3.9
	8a	Loud voices	18	3.9
	8b	Footsteps	18	3.9
	11	Alarm sounds	16	3.4
	12	Baby crying	15	3.2
	12a	Water dripping or rushing	15	3.2
	14	Smoke alarm	11	2.3
	14a	Door creaking or closing	11	2.3
Total (*N* = 467)			293	62.7

This set of sounds can be classified as follows:
Expressions of human emotion: sounds ranked 1, 4, 8b and 12a, giving a total of 86 responses (18.4%).
Manufactured alearting sounds: sounds ranked 8, 11 and 14, giving a total of 45 responses (9.6%).
Naturalistic alerting sounds; sounds ranked 2, 3, 4a, 6, 7, 8a, 8b, 12a, and 14a totaling 167 responses (35.8%).

Source: Michelle Ball and Dorothy Bruck, "The Salience of Fire Alarm Signals for Sleeping Individuals: A Novel Approach to Signal Design," *3rd International Symposium on Human Behaviour in Fire 2004,* Interscience Communications and University of Ulster, Belfast, UK, 2004, p. 308.

Bruck and colleagues have presented the following variables that may be significant factors in the arousal of children if the signal is significant to the children:[33]

- Ensuring the signal is not one that the child frequently hears while asleep to prevent habituation
- Increasing motivation to response through prior education/priming
- Including relevant content in the signal (e.g., using a verbal message about the fire)
- Including words with an emotional content
- Using a female voice to convey more urgency than a male voice
- Including the child's name as part of the signal

This study was conducted with children recruited by personnel at Victoria University in Melbourne, Australia. The children were all between 6 to 10 years of age. The signals were presented at the pillow of the sleeping subjects at 89 dBA ±3 dBA, with a duration of 3 minutes. Three studies were conducted. Study 1 involved a recording of the mother's voice with the message that there was a fire, they were to wake up now and go and investigate. The mother's voice message included the child's name once every 6 seconds. Study 1 also involved a female actor's recorded voice with the message of danger, there is a fire, and they must wake up now and go and investigate. All the voice messages were 30 seconds and connected to provide a 3 minute recording at 315 to 2500 Hz. In study 2 the children were exposed to a modified low-frequency temporal-three alarm at 500 to 2500 Hz. In study 3 the children were exposed to the Australian standard signal at 4000 Hz. Figure 4.1.2 presents the number of children who did or did not awaken to the four alarm signals in all three studies. Figure 4.1.3 presents the number and percentage of children who responded to the four alarm signals, with the time of the response categorized into 0–15 seconds, through 180 seconds. As indicated, the mother's voice woke 100 percent of the children, the actor's voice woke 94.4 percent, the low-frequency T-3 signal woke 96.4 percent, and the standard alarm woke 57 percent of the children. These authors suggested that alarm signals may be a critical factor, with the signals in the frequency of the human voice (2500 Hz or less) being more effective than higher-frequency signals.

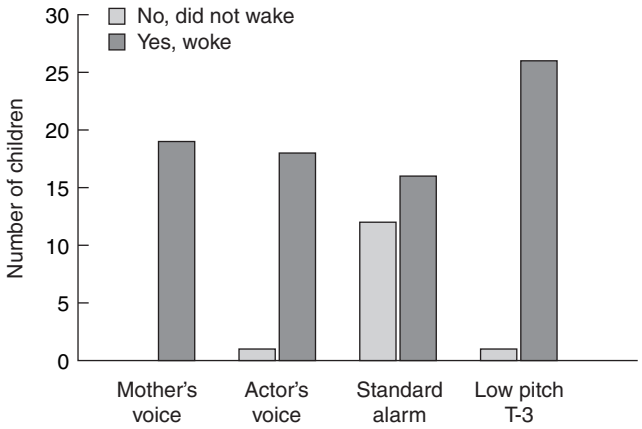

FIGURE 4.1.2 Number of Children Who Did or Did Not Awaken to the Different Alarm Signals Across All Three Studies (Source: D. Bruck et al., "The Effectiveness of Different Alarms in Waking Sleeping Children," *3rd International Symposium on Human Behaviour in Fire 2004,* Interscience Communications and University of Ulster, Belfast, UK, 2004, p. 284)

Ambiguous Threat Cues

The acknowledgment of ambiguous threat cues as signaling an emergency may be inhibited by the presence of other people. Recognition of this phenomenon resulted in an experiment involving college students (Figure 4.1.4).[34] While the students were completing a written questionnaire, the experimenter introduced smoke into the room through a small vent in the wall. If the students left the room and reported the smoke, the experiment was terminated. If the students did not report the presence

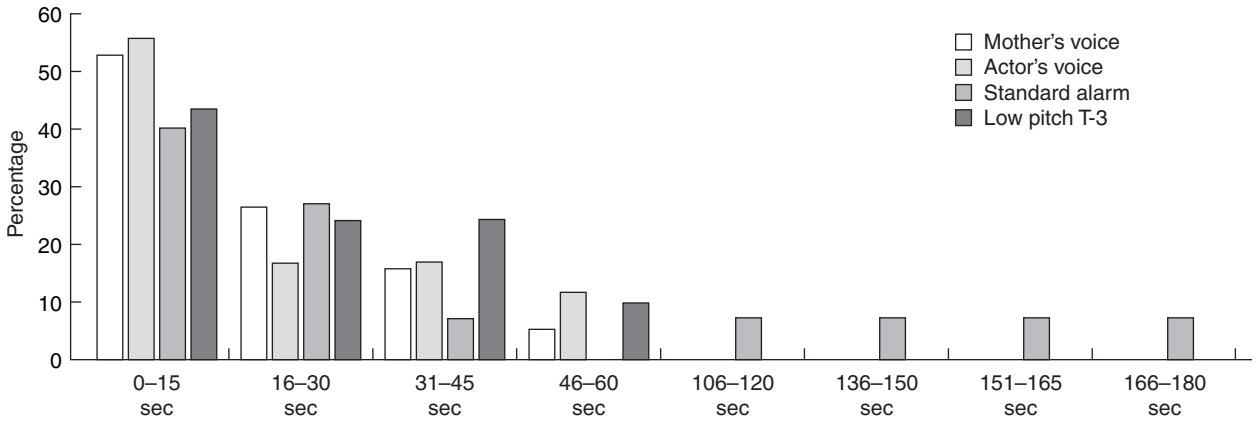

FIGURE 4.1.3 Percentage of Children Who Woke Within Different Time Categories to Different Alarm Signals (Source: D. Bruck et al., "The Effectiveness of Different Alarms in Waking Sleeping Children," *3rd International Symposium on Human Behaviour in Fire 2004,* Interscience Communications and University of Ulster, Belfast, UK, 2004, p. 285)

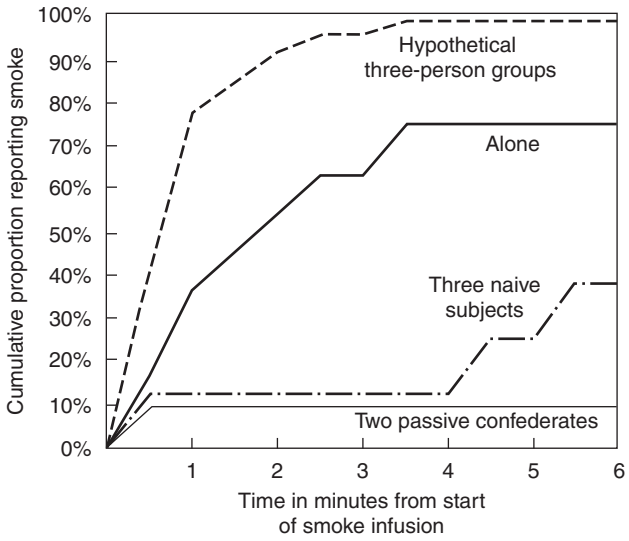

FIGURE 4.1.4 People's Inhibition of Smoke Cues (Source: B. Latane and J. M. Darley, "Group Inhibition of Bystander Intervention in Emergencies," *Journal of Personality and Social Psychology,* Vol. 10, No. 3, 1968, p. 218)

of the smoke within 6 minutes from the time they first noticed it, the experiment was considered complete. Students alone in the room reported the smoke in 75 percent of the cases. When two passive, noncommittal persons joined each student, only 10 percent of the students reported the smoke. When the experimental group consisted of three naive subjects, one individual reported the smoke in only 38 percent of the groups. Of the 24 persons involved in the eight naive-subject groups, only one reported the smoke within the first 4 minutes of the experiment. In the single-subject situation, 55 percent of the subjects reported the smoke within 2 minutes and 75 percent within 4 minutes.

The study reported that reaction to smoke was apparently delayed by the presence of other persons, with the median being 5 seconds for single subjects but 20 seconds in both the group conditions. These results undoubtedly reflect constraints that people accept regarding their behavior in public places. The performance of naive subjects in the passive-confederate situation was reported as follows:

> The other nine stayed in the waiting room as it filled up with smoke, doggedly working on their questionnaires, and waving the fumes away from their faces. They coughed, rubbed their eyes, and opened the window but did not report the smoke.[34]

It has been suggested that while trying to interpret the emergency potential of ambiguous threat cues, an individual is influenced by the reactions of others. Should these others remain passive and seem to interpret the situation as a nonemergency, the individual tends to modify his or her own interpretation according to this inhibiting social influence.[34] This behavioral experiment may help explain the reported tendency of people to disregard threat cues or interpret them as nonthreatening when they occur in places where there are many other people, such as restaurants, movie theaters, or department stores. These results may help explain the calls received by fire departments minutes or even hours after an incident is first detected. In the report of the Arundel Park fire,[4] several of the sample population indicated that when they entered the hall after observing the fire from outside the building, they warned their friends and suggested they leave but were laughed at, their warnings apparently disregarded.

Social inhibition, diffusion of responsibility, and mimicking have been indicated to be primarily responsible for the inhibition of adaptive and assistance behavior in emergencies. The inhibition of behavior in the early stages of a fire, when the cues are relatively ambiguous, may lead to nonadaptive flight behavior because the time available for evacuation has been expended. It is sometimes difficult to get the occupants of a building to evacuate because of social inhibition and diffused responsibility. The tendency to adopt cues for behavior from others is well documented in fires in restaurants, other public assembly occupancies, and hotels.

DECISION PROCESSES OF THE INDIVIDUAL

Seven processes have been identified that an individual may use in trying to structure and evaluate situational threat cues.[35] Six of these—recognition, validation, definition, evaluation, commitment, and reassessment—are presented in Figure 4.1.5. The seventh, a lattice involving the failure of successive defensives and a hierarchy of defenses, is not relevant to the decision process in fires.

Recognition

Recognition occurs when the individual perceives cues that indicate a threatening fire. The cues may be very ambiguous and

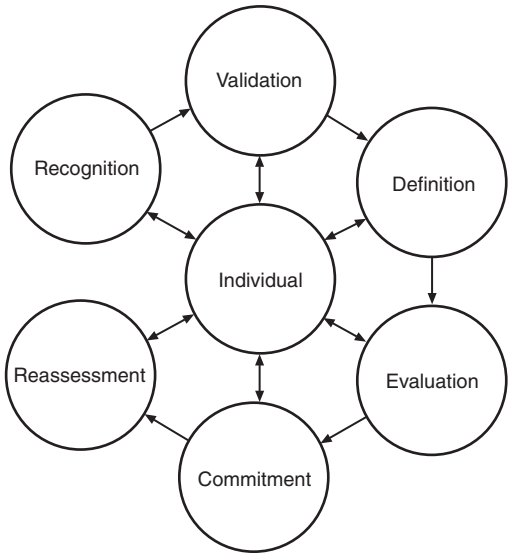

FIGURE 4.1.5 Decision Processes of the Individual in a Fire

not clearly indicative of a severe fire. However, the clues usually are continuous, with an increasing intensity due to the dynamics of flame, heat, and smoke production. It was also reported that an individual is predisposed to recognize threat cues in terms of the most probable occurrences, usually in relation to past experience and in the form of an optimistic wish. The optimistic wish aspect of the response may be a direct result of the individual's concept of his or her personal invulnerability.[35]

Threat recognition is important for fire protection. The adaptive action involved in the initiation of the fire alarm, the evacuation of building occupants, and the suppression of the fire may be delayed or postponed if individuals do not perceive the cues as indicative of a fire. The ambiguous nature of threat cues indicates that individuals who do not have specialized fire prevention or fire protection education and experience recognize only large amounts of smoke or sudden and threatening flames as indicative of a threatening fire.

Validation

Validation consists of attempts by an individual to determine the seriousness of the threat cues, usually by reassurance of the mild nature of the threat and its improbability. When the cues are significantly ambiguous, however, the individual tries to obtain additional information. In other words, the person is aware that something is happening but is not sure exactly what. This process of validation may be conducted by questioning other nearby individuals. Studies of the explosion of a fireworks plant in Houston, Texas, found that of the 139 persons interviewed, 85 individuals (or 61 percent of the population) obtained information on the source and nature of the explosion and smoke from someone they saw or from someone who telephoned and told them.[36] The presence of others during the threat recognition and validation process was found possibly to inhibit or influence the behavioral responses of the individual.

Definition

Definition essentially consists of an attempt by the individual to relate the information concerning the threat to some of the variables, such as the qualitative nature of the threat, the magnitude of deprivation of the threat, and the time context. The individual's stress and anxiety appear to be most severe before he or she has determined the situation's structure or meaning, because it is apparent that the situation requires interpretation. The individual's role (described at the end of the following section, "Evaluation") is one of the critical factors in the situation, relative to the personalization of the threat and the physical environment. The most important physical aspects in the definition process are the generation, intensity, and propagation of the smoke, flames, and thermal exposure.

Evaluation

Evaluation may be described as the cognitive and psychological activities required for the individual to respond to the threat. The individual's ability to reduce his or her stress and anxiety levels becomes the essential psychological factor. In the threat situation created by a fire, evaluation is the process involved in the decision to react by fight or flight. With evaluation, an initial decision to make an overt behavioral response is completed. Because of the time context of the generation and propagation of the fire, the mental processes up to and including the process of evaluation may have to be accomplished within several seconds.

Sime[37] emphasized the importance of the individual's perception of the time available for evacuation or to reach a refuge area as being the individual's estimation of the fire threat. He indicates that the "perceived time available" depends on the information and communication provided to the occupants concerning the fire's location and development. Variables of the physical environment are an important source of information for individuals involved in formulating adaptation, escape, or defense plans. Additional determinants may be the location of the individual relative to the egress routes, other people, the untenable effects of the fire, and the behavior of other individuals.

CASE STUDY: World Trade Center. NIST[27] in their studies of occupant behavior in the World Trade Center towers 1 and 2 provided some compilations of the activities of occupants prior to beginning their evacuation, including the following: information received and sought, the sources of help used, and the single reason to begin evacuation. Table 4.1.10 presents the activities of the occupants prior to evacuation in World Trade Center 1 and Table 4.1.11 present nine specific activities for the occupants of World Trade Center 2. A comparison of these two tables appears to indicate the occupants of World Trade Center 2 had a greater percentage of participation in the following activities: "Talked to others," "Gathered personal items," "Helped others," and "Searched for others." The percentages of occupants participating in the following activities were identical or almost identi-

TABLE 4.1.10 Activities Prior to Evacuation Reported in Telephone Survey by Survivors in WTC 1

Activities Before Evacuation	*Percentage Reporting the Activity (N = 440)*
Talked to others	70
Gathered personal items	46
Helped others	30
Searched for others	23
Talked on telephone	16
Moved between floors	8
Fought fire or smoke	6
Shut down computers	6
Continued working	3
Other activities	25

Note: Total does not add up to 100 percent because respondents may have taken multiple actions.

Source: NIST WTC Telephone Survey Data, in J. D. Averill et al., *Occupant Behavior, Egress, and Emergency Communications,* Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST NCSTAR 1-7, National Institute of Standards and Technology, Gaithersburg, MD, Sept. 2005, p. 82.

TABLE 4.1.11 Activities Prior to Evacuation Reported in Telephone Survey by Survivors in WTC 2

Activities Before Evacuation	*Percentage Reporting the Activity (N = 440)*
Talked to others	75
Gathered personal items	57
Helped others	34
Searched for others	32
Talked on telephone	16
Moved between floors	8
Shut down computers	7
Continued working	6
Fought fire or smoke	1
Other activities	20

Note: Total does not add up to 100 percent because respondents may have taken multiple actions.

Source: NIST WTC Telephone Survey Data, in J. D. Averill et al., *Occupant Behavior, Egress, and Emergency Communications,* Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST NCSTAR 1-7, National Institute of Standards and Technology, Gaithersburg, MD, Sept. 2005, p. 92.

TABLE 4.1.12 Information Received and Sought Prior to Beginning Evacuation in WTC 1

Information Type	*Information Given (N = 50) (Percentage)*	*Information Sought (N = 122) (Percentage)*
Information about what had happened	57	81
Instructions to leave	28	17
Instructions to stay	17	12
Other, including information about what to do and to receive assistance in evacuation, do not know	13	13

Note: Total does not add up to 100 percent because respondents may have observed more than one event indicative of damage.

Source: NIST WTC Telephone Survey Data, in J. D. Averill et al., *Occupant Behavior, Egress, and Emergency Communications,* Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST NCSTAR 1-7, National Institute of Standards and Technology, Gaithersburg, MD, Sept. 2005, p. 83.

cal (1% difference): "Talked on Telephone," "Moved between floors," and "Shut down computers." The only activity with a greater percentage of participation by occupants in World Trade Center 1 was the activity "Fought fire or smoke."

As can be seen from the comparison of the activities in the two tables, the rank order of the activities is identical except for the activity "Fought fire or smoke." It should be noted that World Trade Center 1 was struck by the aircraft at approximately 8:46:26 a.m. and survived 102:05 minutes, collapsing at approximately 10:28:31 a.m. World Trade Center 2 was struck at approximately 9:02:54 a.m. and survived 56:50 minutes, collapsing at approximately 9:59:04 a.m.[27]

The information received and sought by the occupants of World Trade Center 1 prior to their evacuation activity is presented in Table 4.1.12, and the identical activity for the occupants of World Trade Center 2 is presented in Table 4.1.13. A comparison of these two tables indicates the most information given and sought was "Information about what had happened." The information given and received in both towers for "Instructions to leave" was very similar, with a difference of only 2 percent in the information given. One of the greatest differences in the information given to the occupants was in the category of "Instructions to stay." In World Trade Center 1, 17 percent of the occupants were given this information, whereas in World Trade Center 2, 35 percent of the occupants were given this information, many over the building's public address system prior to the aircraft striking the second tower. An announcement is reported to have been made to occupants in World Trade Center 2 at 9:00 a.m. as follows:

> *There is a fire condition in WTC 1. WTC 2 is secure. Please return to your offices.*

At 9:02 a.m., a second announcement was reported as follows:

TABLE 4.1.13 Information Received and Sought Prior to Beginning Evacuation in WTC 2

Information Type	*Information Given (N = 77) (Percentage)*	*Information Sought (N = 64) (Percentage)*
Information about what had happened	65	92
Instructions to leave	26	17
Instructions to stay	35	13
Other, including information about what to do and to receive assistance in evacuation, do not know	10	5

Note: Total does not add up to 100 percent because respondents may have observed more than one event indicative of damage.

Source: NIST WTC Telephone Survey Data, in J. D. Averill et al., *Occupant Behavior, Egress, and Emergency Communications,* Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST NCSTAR 1-7, National Institute of Standards and Technology, Gaithersburg, MD, Sept. 2005, p. 93.

> *May I have your attention, please. The situation is in Building 1. However, if conditions on your floor warrant, you may wish to start an orderly evacuation.*[27]

Remember, as indicated previously, World Trade Center 2 was struck by the aircraft at 9:02:54 a.m. Obviously, these contradictory buildingwide announcements may have been interpreted by some occupants as instructions to stay. The sources of help or assistance used by the occupants prior to their initiation of an evacuation are presented in Table 4.1.14 for the occupants of

TABLE 4.1.14 Sources of Help Used by Occupants Prior to Beginning Their Evacuation in WTC 1

Source of Help	*Percentage (N = 87)*
Coworker	48
Police officer/fire fighter	16
Floor warden	12
Manager/supervisor	13
Other/do not know	13
Stranger	8

Note: Total does not add up to 100 percent because respondents may have received help from more than one person.

Source: NIST WTC Telephone Survey Data, in J. D. Averill et al., *Occupant Behavior, Egress, and Emergency Communications,* Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST NCSTAR 1-7, National Institute of Standards and Technology, Gaithersburg, MD, Sept. 2005, p. 84.

World Trade Center 1 and in Table 4.1.15 for the occupants of World Trade Center 2.

A comparative examination of these two tables indicates the greatest difference in the source of help is in the category of "police officer firefighter," with 16 percent of the occupants in World Trade Center 1 indicating this source of help and only 7 percent in World Trade Center 2. This difference could be a result of the difference in the initiation times of the two aircraft strikes. World Trade Center 2 was struck later, at 9:02:54 a.m., and collapsed quicker, at 9:50:04 a.m., surviving only 56:50 minutes; thus, emergency personnel had not reached as many floors in World Trade Center 2 as they had in World Trade Center 1. Proulx and Fahy[26] reported that 143 survivors reported seeing fire fighters in World Trade Center 1 and 26 reported seeing fire fighters in World Trade Center 2. The highest floor in World Trade Center 1 where survivors reported seeing fire fighters was on the 83rd floor. In World Trade Center 2 the highest floors in which fire fighters were reported seen was in the mid-level floors from the 43rd to the 76th.

TABLE 4.1.15 How Survivors Received Help Prior to Beginning Their Evacuation in WTC 2

Source of Help	*Percentage (N = 60)*
Coworker	56
Manager/supervisor	15
Floor warden	12
Other/do not know	11
Police officer/fire fighter	7
Stranger	5

Note: Total does not add up to 100 percent because respondents may have received help from more than one person.

Source: NIST WTC Telephone Survey Data, in J. D. Averill et al., *Occupant Behavior, Egress, and Emergency Communications,* Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST NCSTAR 1-7, National Institute of Standards and Technology, Gaithersburg, MD, Sept. 2005, p. 94.

TABLE 4.1.16 Single Reason Given by Survivors to Begin Their Evacuation From WTC 1

Reason	*Percentage (N = 440)*
Building movement	20
Afraid/felt danger	20
Was told to evacuate	14
Friends/coworkers evacuated	9
Saw debris	6
Saw smoke	5
Other, including saw fire, 1993 experience, saw/heard plane, people panicking, fire alarm going off	26

Source: NIST WTC Telephone Survey Data, in J. D. Averill et al., *Occupant Behavior, Egress, and Emergency Communications,* Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST NCSTAR 1-7, National Institute of Standards and Technology, Gaithersburg, MD, Sept. 2005, p. 95.

Table 4.1.16 presents the single reason given by the occupants of World Trade Center 1 to begin their evacuation, and Table 4.1.17 provides similar information for the occupants of World Trade Center 2.

A comparative examination of these two tables indicates that 26 percent of the occupants of World Trade Center 2 decided to initiate their evacuation from their observation of the fire and damage conditions of the situation following the aircraft strike in World Trade Center 1. It should be noted that an estimated 86 to 91 percent of the occupants in World Trade Center 2 initiated their evacuation before their building was struck by the aircraft.[27] The other single reasons the occupants indicated as their reason to begin evacuating which differed from occupants of World Trade Center 1 were "1993 experience (thought was a bomb)," and "WTC 2 building hit." The single reasons given by occupants of World Trade Center 1 to begin evacuating not specifically mentioned by World Trade Center 2 occupants

TABLE 4.1.17 Single Reason Given by Survivors to Begin Their Evacuation from WTC 2

Reason	*Percentage (N = 363)*
WTC 1 observations	26
Was told to evacuate	21
Afraid/felt danger	17
Friends/coworkers evacuated	11
1993 experience (thought was a bomb)	6
WTC 2 building hit	6
Other, including jet fuel, information seeking, evacuating the building, just felt like the right thing to do	7

Source: NIST WTC Telephone Survey Data, in J. D. Averill et al., *Occupant Behavior, Egress, and Emergency Communications,* Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST NCSTAR 1-7, National Institute of Standards and Technology, Gaithersburg, MD, Sept. 2005, p. 94.

were "Building movement," "Saw debris," and "Saw smoke." The single reasons given by the occupants of both towers were "Afraid/felt in danger," "Was told to evacuate," and "Friends/coworkers evacuated."

During evaluation, an individual may decide to leave the building—flight—or to use a portable fire extinguisher—fight. During this time, he or she is particularly susceptible to the actions and communications of others. Thus, the individual may mimic the behavioral reactions of observed individuals, resulting in mass adaptive or nonadaptive behavior rather than selective, individualized behavior. The following situation at an auto sales and service agency in 1971 demonstrates what may have been an instance of mimicked behavior becoming normative group behavior:[38] About 10 p.m., the fire department received an alarm from a street fire alarm box. When fire fighters arrived, the 150 ft by 200 ft (46 m by 61 m) combination one-and-two-story building of wood frame and hollow block construction was well alight and nearly 300 spectators were watching the fire in 10°F (–12°C) weather. An investigation revealed the fire had been burning for about 90 minutes before the fire department was notified.

In studies of nonadaptive group behavior, the concept that this mode of behavior depends directly on the individual's perception of the reward structure of a situation has been developed.[39] People in a building who are confronted with a fire would probably initially perceive a reward structure that would encourage cooperative and adaptive behavior; in such cases, everyone should be able to reach and proceed through the available exits. However, the reward structure perceived by some individuals more remote from the egress routes could result in competitive behavior. Such individuals would perceive that cooperative behavior would make it impossible for them to reach an exit in time to escape the fire. Once the pattern of competitive behavior is initiated, the behavior pattern of the group may become one of intense individual competition for the escape routes.

In the evaluation process, an individual's cultural influences and assumption of a particular role may be very important in formulating defense or escape plans. It is believed that an individual playing a familiar role that is also suitable for the threat situation experiences less anxiety and responds with more adaptive behavior than an individual in an unfamiliar role confronted with an unfamiliar threat.

Jones and Hewitt[40] conducted detailed interviews with 40 occupants of a 27 story office building who had evacuated the building during a fire. It should be noted the fire occurred at 9:00 p.m. when the fire management plan was not in effect due to the building's reduced occupancy. In this situation it appeared that leadership and evacuation group formation were related to the occupants' fire training and their normal roles. The investigators found that relationship of the occupancy roles and normal or emergent leadership of occupants were critical factors in successful evacuation, with the following variables:

> The social and organizational characteristics of the occupancy, including what a person knows (or believes) of the situation, whether the person is alone or part of a group, the normal roles that people hold within the occupancy, and the organizational structure or framework. One factor that appears to be related to the chosen evacuation strategy of an occupant is the presence of leadership and the form which that leadership takes.

Horiuchi, Murozaki, and Hokugo[41] reported on a questionnaire study of 458 occupants of an 8 story office building involved in a fire incident. The researchers found significant differences between occupants who were familiar with the building and occupants attending training sessions who were unfamiliar with the building, relative to their actions, selection of evacuation routes, and effectiveness in exiting. The regular occupants of the building engaged in fire-fighting actions and alerted or assisted other occupants, whereas occupants unfamiliar with the building primarily engaged in evacuation.

Commitment

Commitment consists of the mechanisms the individual uses to initiate the behavior required to fulfill defense plans conceptualized in the evaluation process. This overt response to the threat of fire results in success or failure. If the response fails, the individual immediately becomes involved in the next process of reassessment and commitment. If the action succeeds, the anxiety and stress aspects of the situation are reduced and relieved, although the severity of the general fire situation may have increased.

Reassessment

Reassessment and overcommitment are the most stressful personal processes because previous attempts to adjust to the threat have failed. Thus, more intense effort goes into the behavior and the individual tends to become less selective in the choice of response. Encountering successive failures, the individual becomes more frustrated. The possibility of injury and risk increases with a greater activity level and with less probability of success, as was demonstrated in the Arundel Park fire, discussed later in the chapter. There, the number of those who selected windows as a means of escape increased as people became involved in their second escape attempts.[4]

In analyzing the behavior of an individual involved in the processes of recognition, validation, definition, evaluation, commitment, and reassessment, it must be remembered that these are dynamic processes. They are constantly being modified in relation to their magnitude, velocity, and intensity. A person's usual psychological and physiological activities will probably be below normal during the recognition process, when he or she is concentrating on perceiving the threat cues. During the process of validation and definition of the threat, adjacent members of the threatened population communicate overtly. The period of hyperactivity appears to occur initially during the process of commitment and to become intense during the process of reassessment and recommitment. Stress increases with each successive stage, as the primary motivation of the behavior is stress reduction. Appearance, proximity, propagation, time, and toxic gases of the fire threat also tend to predispose the individual to a higher level of activity, again depending on the individual's perception of these threat variables. During the process

of reassessment and recommitment, the individual's activity level may assume the hyperactive mode of frantic activity, or it may be expressed in the catastrophic state of complete physical immobility with a loss of ability to communicate coherently. These individuals appear to perceive the threat as above their level of adaptability. The stress is too severe, and they give up completely. Thus, they cease to make any attempt at an adaptive behavior and retreat totally from the situation through the mechanism of psychological withdrawal. These behavioral dynamics are presented in Figure 4.1.6.

Decision Making Models

Conceptual Model. A conceptual model of the individual's decision processes similar to some concepts previously discussed has been developed. Instead of the six processes described, only three have been used: (1) recognition/interpretation; (2) behavior, with either action or inaction; and (3) the outcome of the action, which involves the evaluation and long-term effect of the behavior.[6] Behavior evaluation is similar to the process of reassessing the decision model. Both the recognition/interpretation concept and the behavior concept involve factors critical to the decision processes. Experience and immediate circumstances have an impact on the recognition/interpretation concept. It has been emphasized that individuals in a fire may not know right away that they are involved in a fire and may not know where, in relation to their location, the fire is developing or where egress routes are located. A concept of a heuristic (i.e., experimental or provisional) systems model is presented in Figure 4.1.7.

The conceptual model just described has been modified into one involving three phases: (1) detection of cues, (2) definition of the situation, and (3) coping behavior. In addition, tentative determinants of the behavior have been developed, which increase the probability of detection and of fire suppression.[42]

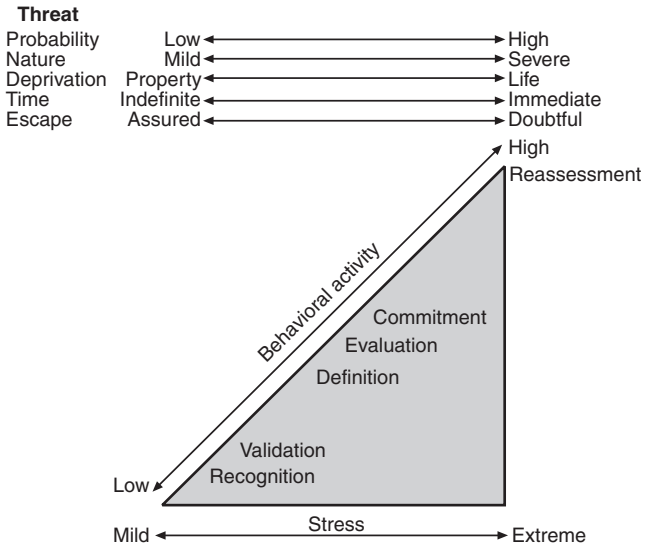

FIGURE 4.1.6 Dynamics of Behavioral Activity of the Individual

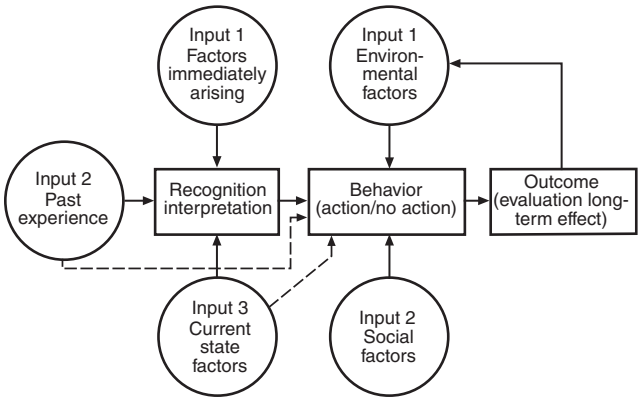

FIGURE 4.1.7 Preliminary Heuristic Systems Model of Behavior in Fires

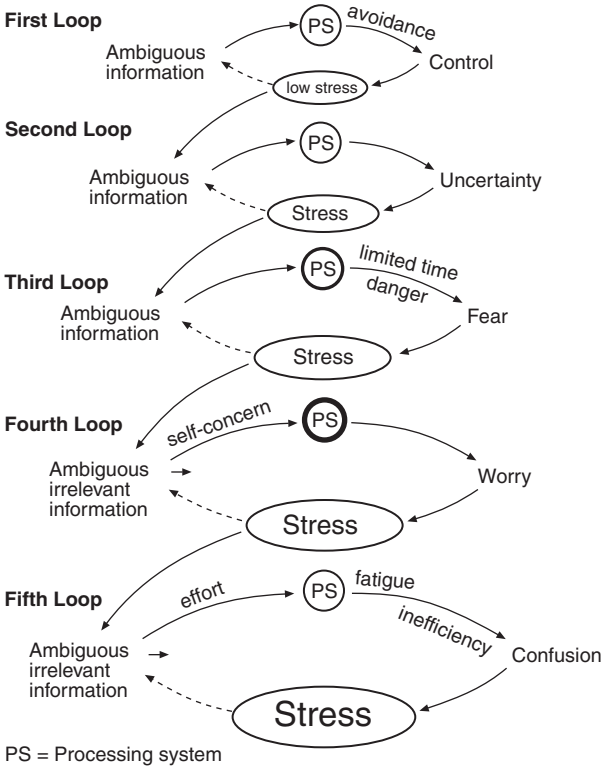

FIGURE 4.1.8 Stress Model of People in a Fire

Stress Model. Proulx[43] developed a stress model to demonstrate various levels of stress generation within an individual involved in the decision process during a fire incident. Figure 4.1.8 illustrates this stress model, which should be compared with the behavioral activity dynamics of the individual in a fire incident presented in Figures 4.1.6 and 4.1.7.

The left side of Figure 4.1.8 indicates the information the individual must process; the right side indicates the emotional state that results. Proulx describes the five loops in the stress model as follows:

1. The first loop starts with the perception of ambiguous information. This information is decoded in the processing system (PS in Figure 4.1.8) for interpretation. Given that the available information may not allow for a straightforward assessment of the situation, people will at first minimize or deny the situation. These defensive strategies of avoidance lead to an absence of reaction.

2. Although individuals may vary considerably in their appraisal of the same event, the repeated perception of ambiguous information will eventually generate a state of uncertainty, which will then induce a feeling of stress. Some time can be spent going repeatedly through the second loop.

3. The third loop is related to the interpretation of the situation as an emergency. The thicker line around the processing system expresses the pressure of the overload of information with which the person tries to deal at once. The fear felt by the person is a manifestation of a specific appraisal of the environment.

4. The fourth loop relates to the person's processing of irrelevant information and is represented by the very thick line around the processing system. This irrelevant information creates worry and more stress. The irrelevant information, created by the person, is caused by concern for his or her own performance in coping with the situation. Perceived feelings of arousal and fear, uncertainties regarding how to proceed with the problem, difficulties in interpreting what exactly is going on, and self-estimation of the efficiency of already applied actions become additional information to process.

5. The fifth loop supposes an investment of more mental effort to master the problem, momentarily reducing the pressure on the processing system, but resulting in fatigue and inefficiency manifested in a state of confusion.

Proulx indicates that definitive, valid, and directive information provided to occupants of a building in a fire incident most effectively reduces stress and thus tends to minimize response delays created in the first and second loops of the stress model.

Naturalistic Decision Model. Chubb[44] proposes that the model of the decision processes that fire department officers use in the incident command procedure be adopted as the decision process of building occupants in a fire situation. The decision model was developed from the theory of naturalistic decision making, which evolved from studies of decision makers in complex, time-critical situations. The critical variables of naturalistic decision-making theory appear to share many environmental and psychological features of fire situations involving building occupants. Chubb identified these critical variables:

- Ill-defined goals and ill-structured tasks
- Uncertainty, ambiguity, and missing data
- Shifting and competing goals
- Dynamic and continually changing conditions
- Real-time reactions to changed conditions
- Time stress
- High stakes
- Organizational goals and norms
- Experienced decision makers

Recognition-Primed Decision Model. Figure 4.1.9 illustrates the recognition-primed decision (RPD) model developed by Klein[45] from studies of fire department officers. Chubb correctly indicated this model's limitation when applied to building occupants. They lack the dynamic abilities—suitable training and previous experience—in building fires that fire officers have. Static abilities relative to building occupants' mental and physical capabilities also appear to be more varied and limited than those of fire officers. Chubb indicates that successful recognition-primed decision making depends on occupant training and practice of fire safety plans, with the decision support system in the building consisting of egress signs, emergency lighting, and vocal communication systems.

BEHAVIOR OF OCCUPANTS

A study involving 952 fires and 2193 individuals interviewed by fire department personnel at the scenes of fires in the United Kingdom found that the most frequent responses to fire involved evacuating the building, fighting or containing the fire, and alerting other individuals or the fire brigade.[14] An identical broad behavior categorization was found in a similar study, which involved interviewing 584 participants in 335 fires in the United States. Interviews were conducted by fire department personnel, who used a structured questionnaire at the scene of the fires.[7]

Purser and Kuipers[25] in their study of the 110 residential fire incidents previously discussed, also reported the sequence and frequency of people's actions as presented in Figure 4.1.10. This figure and the results of this study conducted in the early 2000s should be compared with Table 4.1.18, which concerns the first actions of participants involved in fires in Great Britain in 1971 and the United States in 1977, since the types and sequences of actions appear very similar. Table 4.1.20 also address initial responses, namely the first three actions of a U.S. population involved in fires in 1977. The authors of this report indicate the action of "investigate" was very common as a first action by 45 percent of their respondents and as a second action by 23 percent. These authors also report that actions such as "mitigate the fire," "help others," and "call for

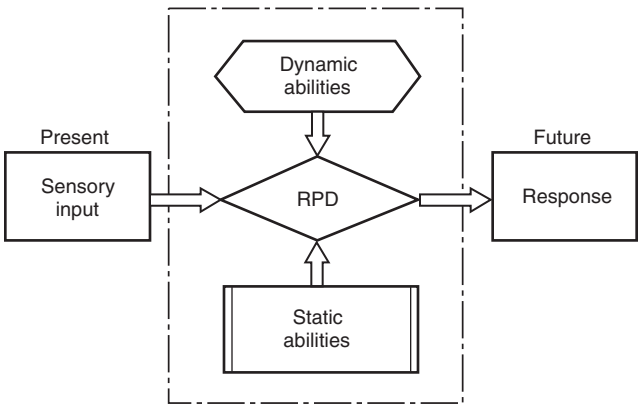

FIGURE 4.1.9 Recognition-Primed Decision Model

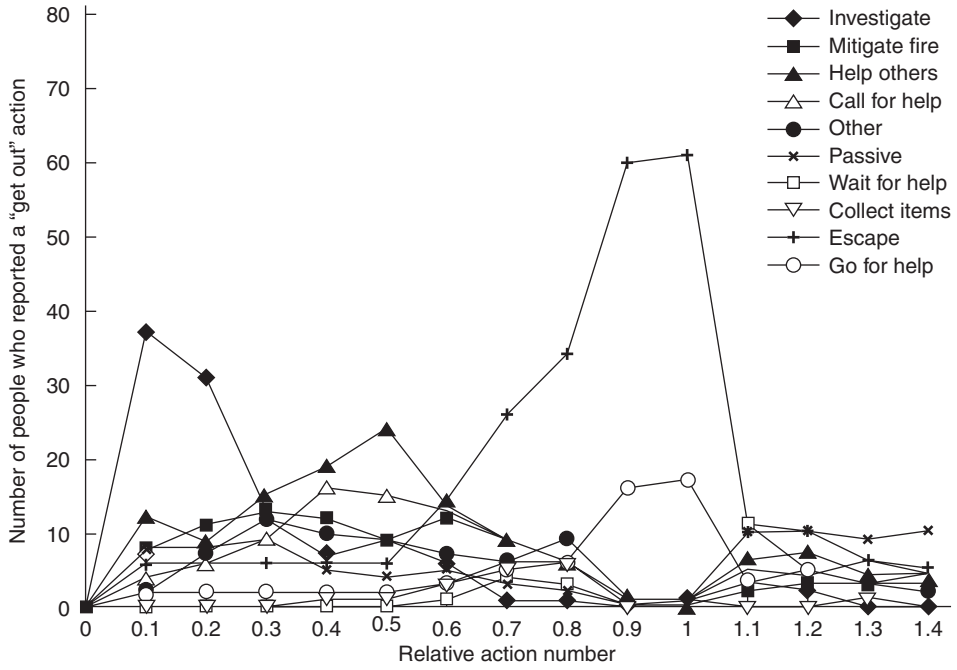

FIGURE 4.1.10 Frequency and Sequence of Actions Relative to Escape Action (Source: David A. Purser and Marion E. Kuipers, "Interaction Between Buildings, Fires and Occupant Behaviour Using a Relational Database Created from Incident Investigations and Interviews," *3rd International Symposium on Human Behaviour in Fire 2004,* Interscience Communications and University of Ulster, Belfast, UK, 2004, p. 452)

help" are in the middle of the actions sequence, and "escape" or "go for help" at the end of the usual sequence of four to five actions, although 50 percent of the occupants reported seven actions. "Call the fire brigade" was generally a fourth action, and "fight the fire" was usually occurring between the second and the sixth action. This study reported a similar cultural sequence of actions relative to the males and females found in the 1971 British study[14]and the 1977 U.S. study.[7] "Males were more likely than females to report 'investigate' or 'mitigate fire,' but less likely to report 'call or go for help' or 'remaining passive.'"

Comparison of the First Actions of British and U.S. Study Populations

Examination of initial behavioral responses to fire is presented in Table 4.1.18. Behavior of the individuals also varied by gender: males were predominantly active in fighting the fire, whereas females were predominantly concerned with alerting and helping others leave the building.

It should be noted that there were 10 statistically significant differences between the British and U.S. study populations. The U.S. study population was more likely to report five categories of first actions: "notified others," "got dressed," "got family," "left area," and "entered the building." A higher percentage of the British population reported as first actions "fought fire," "went to fire area," "closed door to fire area," "pulled fire alarm," and "turned off appliances."

Comparison of the Behavior of the British and U.S. Study Populations

The general classification of the three early actions for the British and the U.S. study populations alike were categorized as "evacuation," "re-entry," "fire fighting," "moved through smoke," and "turned back." Comparison of the two populations is presented in Table 4.1.19. There was a statistically significant difference between British and U.S. populations in every category except "moved through smoke."

Summary of the First, Second, and Third Actions of the Occupants

An interesting aspect of the U.S. study involves variation in the first, second, and third actions reported by participants. Table 4.1.20 presents the three actions for the group, totaling 584 individuals. "Notifying others" accounted for 15 percent of the first actions, but by the time of the third actions, it accounted for only 5.8 percent. A similar reduction in frequency can be observed for "searching for the fire." This activity decreases from 10.1 percent as the first action to 0.8 percent as the third action. The actions "got dressed" and "got family" also reduced in frequency with the progression from the first to the third action as time passed during the fire. In contrast, "left building," "fought fire," and "called fire department," increased in frequency from the first to the third actions.

Canter, Breaux and Sime[46] developed a decomposition diagram of the acts of 41 persons in 14 domestic fires. This study,

TABLE 4.1.18 Comparison of the First Actions of a British and U.S. Study Population

Action	*British (Percentage, P_1)*	*U.S. (Percentage, P_2)*	$P_1 - P_2$	$SE^a_{P_1-P_2}$	CR^b
Notified others	8.1	15.0	6.9	1.38	5.00[c]
Searched for fire	12.2	10.1	2.1	1.51	1.39
Called fire department	10.1	9.0	1.1	1.40	0.79
Got dressed	2.2	8.1	5.9	0.85	6.94[c]
Left building	8.0	7.6	0.4	1.27	0.31
Got family	5.4	7.6	2.2	1.11	1.98[d]
Fought fire	14.9	10.4	4.5	1.63	2.76[c]
Left area	1.8	4.3	2.5	0.70	3.57[c]
Nothing	2.1	2.7	0.6	0.69	0.87
Had others call fire department	2.8	2.2	0.6	0.76	0.79
Got personal property	1.2	2.1	0.9	0.55	1.64
Went to fire area	5.6	2.1	3.5	1.01	3.47[c]
Removed fuel	1.2	1.7	0.5	0.53	0.94
Entered building	0.1	1.6	1.5	0.30	5.00[c]
Tried to exit	1.6	1.6	0.0	0.00	0.00
Closed door to fire area	3.1	1.0	2.1	0.76	2.76[c]
Pulled fire alarm	2.7	0.9	1.8	0.70	2.57[d]
Turned off appliances	4.1	0.9	3.2	0.85	3.20[c]
Total ($N = 18$)	2193	580			

[a]Standard error.
[b]Critical ratio.
[c]Critical ratios significant at or above the 1 percent level of confidence.
[d]Critical ratios significant at or above the 5 percent level of confidence.

TABLE 4.1.19 Comparison of the Behavior of the British and U.S. Study Populations

Behavior	*British (Percentage, P_1)*	*U.S. (Percentage, P_2)*	$P_1 - P_2$	$SE^a_{P_1-P_2}$	CR^b
Evacuation	54.5	80.0	25.5	2.30	11.09[c]
Re-entry	43.0	27.9	15.1	2.30	6.51[c]
Fire fighting	14.7	22.9	8.2	1.74	4.71[c]
Moved through smoke	60.0	62.7	2.7	2.29	1.18
Turned back	26.0	18.3	7.7	2.01	3.83[c]
	2193	584			

[a]Standard error.
[b]Critical ratio.
[c]Critical ratios significant at or above the 1 percent level of confidence.

conducted in the United Kingdom, covers home fires, as do the studies by Wood[14] and Bryan[7] discussed previously. Figure 4.1.11 presents this decomposition diagram and should be compared with Tables 4.1.18 through 4.1.20. The sequence of the first, second, and third actions of the U.S. study population are generally similar to the sequence of actions in the decomposition diagram.

Summary of the First Actions of the Occupants, According to Gender

Differences between the first actions of the participants according to their gender have been examined. Table 4.1.21 presents the reported initial actions of the U.S. study population relative to the gender of the participants. Statistical differences between males and females are significant in the categories "searched for fire," "called fire department," "got family," and "got extinguishers." Male participants more frequently reported investigation and fire-fighting activities. For example, 14.9 percent of the males "searched for fire," as opposed to 6.3 percent of the females; 6.9 percent of the males "got extinguishers," as opposed to 2.8 percent of the females. Females more frequently reported warning and evacuation activities. For example, 11.4 percent of the females "called fire department" as their initial action, as opposed to 6.1 percent of the male participants. In relation to evacuation behavior, 10.4 percent of the females reported "left building" as the first action, contrasted with 4.2 percent of the male participants. The influence of cultural roles is probably indicated explicitly in the concern for other family

TABLE 4.1.20 Summary of First, Second, and Third Actions of the Occupants in the U.S. Study Population

	Action (Percentage)		
	First	*Second*	*Third*
Notified others	15.0	9.6	5.8
Searched for fire	10.1	2.4	0.8
Called fire department	9.0	14.6	12.7
Got dressed	8.1	1.8	0.3
Left building	7.6	20.9	35.9
Got family	7.6	5.9	1.4
Fought fire	4.6	5.7	11.5
Got extinguisher	4.6	5.3	1.6
Left area	4.3	2.8	1.1
Woke up	3.1	0.0	0.0
Nothing	2.7	0.0	0.0
Had others call fire department	2.2	4.0	4.1
Got personal property	2.1	3.8	0.8
Went to fire area	2.1	1.0	0.0
Removed fuel	1.7	1.0	1.1
Entered building	1.6	0.8	1.1
Tried to exit	1.6	2.4	0.5
Went to fire alarm	1.6	1.8	1.1
Telephoned others	1.2	0.6	1.1
Tried to extinguish	1.2	1.8	1.9
Closed door to fire area	1.0	0.2	0.3
Pulled fire alarm	0.9	0.6	0.5
Turned off appliances	0.9	0.6	0.3
Checked on pets	0.9	1.4	0.5
Awaited fire department arrival	0.0	1.0	3.6
Went to balcony	0.2	0.8	2.7
Removed by fire department	0.0	0.0	1.6
Opened doors/windows	0.2	0.4	1.1
Other	3.9	8.0	6.6
Total ($N = 29$)	100.0	100.0	100.0
Range	0–87	0–106	0–131
Percentage of participant population	99.3	86.6	62.9

Source: J. L. Bryan, *Smoke as a Determinant of Human Behavior in Fire Situations,* Department of Fire Protection Engineering, University of Maryland, College Park, MD, 1977.

members—11 percent of the females "got family" as the first action, whereas only 3.4 percent of males engaged in this as an initial action. It should be noted that the second and third prevalent male actions of "searched for fire" and "got extinguishers" were equated to the female actions of "called fire department" and "got family."[7] This behavior has also been observed in health care and educational facility fires.

Behavior in Hotel Fires

Fire protection of high-rise buildings and their occupants was tested severely by the MGM Grand Hotel fire in Clark County, Nevada, on November 21, 1980,[47] and by the subsequent fire at the Las Vegas Hilton Hotel on February 10, 1981.[48] Both these hotel fires resulted in injuries and fatalities among guests. NFPA conducted an intensive questionnaire study of the guests registered in the MGM Grand Hotel on the evening of November 20 and morning of November 21, 1980.[49]

The MGM Grand Hotel fire was discovered by a hotel employee who entered the unoccupied deli-restaurant located on the casino level of the hotel at approximately 7:10 a.m. on November 21, 1980. As instructed, the hotel telephone operator immediately notified the Clark County Fire Department at approximately 7:17 a.m. The telephone operators were forced from their switchboard by the smoke immediately after they had made an announcement over the public address system, at approximately 7:20 a.m., to evacuate the casino area. The fire quickly reached flashover in the deli, immediately spread from east to west through the main casino area, and extended out the west portico doors on the casino level immediately following the arrival of the first fire department personnel.

An addition to the hotel was being constructed adjacent to the west end of the building, and construction workers helped warn and evacuate guests and assisted in fire fighting. The heat and smoke rapidly extended from the casino area through the seismic joints, elevator shafts, and stairways throughout the 21 residential floors of the hotel. The heat was intense enough on the 26th floor, a top floor, to activate automatic sprinklers in the lobby adjacent to the elevator shafts.

Due to the rapid early evacuation of the telephone staff, guests were not alerted by the hotel public address system or the local fire alarm system. Guests warned early in the fire, and those already awake and dressed, were able to escape before the smoke became untenable on the upper floors. Guests alerted later remained in their rooms or moved to other rooms, usually with other occupants. The fire itself did not extend above the casino level, except in a rather minor nature, into two guest rooms on the fifth floor. The fire resulted in 85 fatalities and injured 778 guests and 7 hotel employees. Seventy-nine body locations were documented: 18 on the casino level, 25 in guest rooms, 22 in corridors and lobbies, 9 in stairways, and 5 in elevators. The victims were found on the casino level and on the 16th and floors above, with the majority between the 20th and the 25th floors.

Table 4.1.22 presents the means by which the responding participants became aware of the fire incident within the hotel. It should be noted the hotel was protected with a fire alarm system of the presignal type, with manual stations only on the guest room floors; apparently, the system was never activated on the guest room floors. An examination of Table 4.1.22 indicates that similar to the means of awareness reported for residential fire incidents in single-family homes and apartments, 169 persons reported they were alerted by the awareness cue of seeing or smelling smoke, and 193 individuals indicated they were alerted by the actions of others involving: "Notified by others, people yelling, and a knock on the door."[49] From the questionnaires came statements that individuals evacuating the floors would knock on doors and yell out as they passed through the hotel corridors, realizing there had not been an alarm activation in the hotel, with many persons in their rooms at the documented 7:17 a.m. time that the fire department received a telephone alarm. It

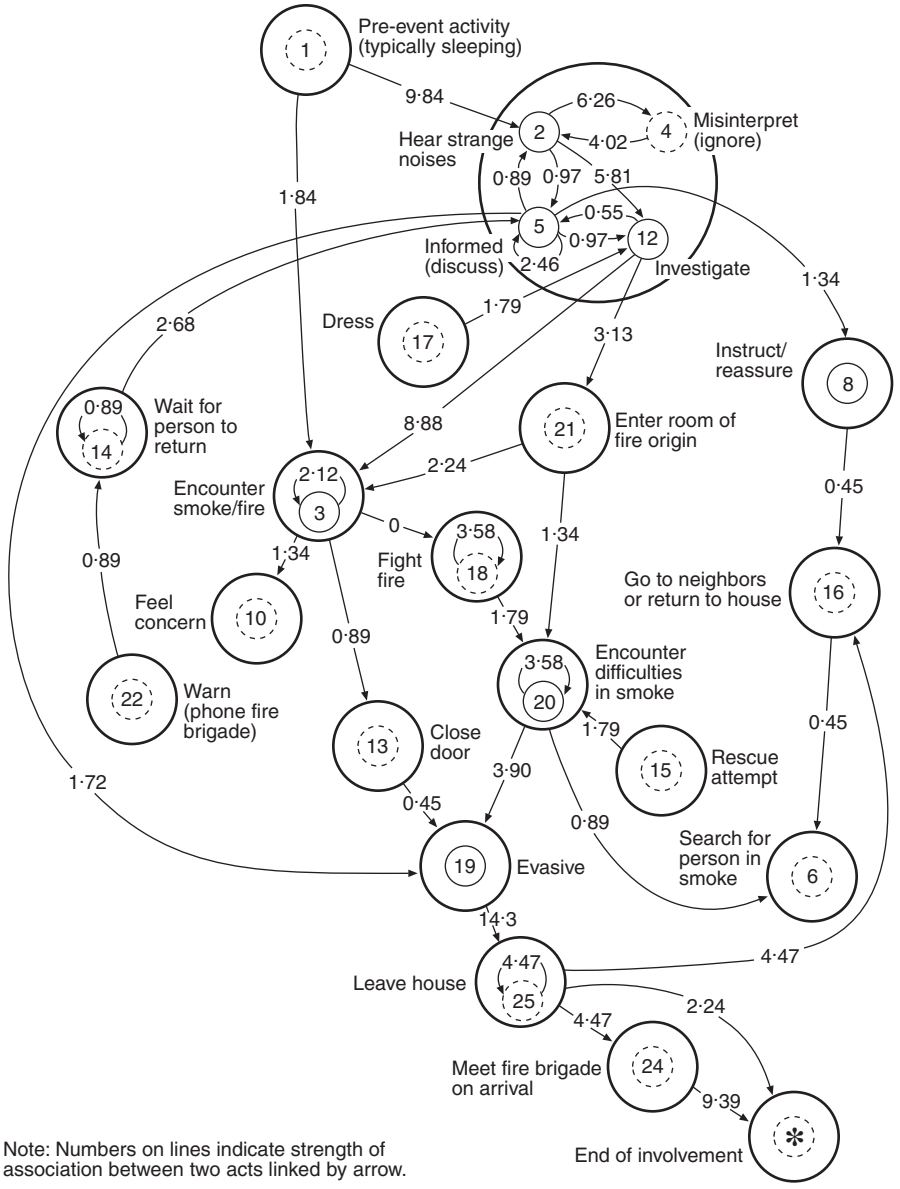

FIGURE 4.1.11 Decomposition Diagram—Domestic Fires

should also be noted that due to the extensive occupant notification actions 275 persons, or 51 percent of those reporting the time at which they became aware of the fire, indicated times between 6:30 a.m. and 7:15 a.m., all prior to the fire department notification. Figure 4.1.12 is a diagram of the guest floor of the MGM Grand Hotel that was used in the engineering study conducted by NFPA.[47]

Of the 9 victims found in the stairways, 2 were in stairway 1 at the extreme south end of the south wing on the 17th floor; 6 were between the 20th and 23rd floor in stairway 2 at the central end of the south wing; and 1 was found at the ground-floor level of stairway 4 at the extreme west end of the west wing. There are various estimates of the number of guests and fire department personnel who suffered injuries at the MGM Grand Hotel fire. Morris indicated that 619 people were taken to hospitals, and another 150 were treated at the Las Vegas Convention Center, where the survivors were transported from the hotel.[50]

The MGM Grand Hotel tragedy was a unique fire, especially from two aspects: (1) it was the second most serious hotel fire in U.S. history, surpassed only by the Winecoff Hotel fire in Atlanta, Georgia, on December 7, 1946, which killed 119; and (2) it was the first high-rise fire in the United States in which helicopters evacuated large numbers of people. About 300 were evacuated in this manner; the fire department rescued approximately 900 people by other means.

Shortly after the MGM Grand Hotel fire, NFPA prepared a 4 page, 28 item questionnaire that included the floor plan of the guest rooms. A total of 1960 questionnaires were mailed, and 554, or approximately 28 percent, of these were

TABLE 4.1.21 First Actions of the Occupants, According to Gender of Occupant

First Action	*Male (Percentage, P_1)*	*Female (Percentage, P_2)*	$P_1 - P_2$	$SE^a_{P_1-P_2}$	CR^b
Notified others	16.3	13.8	2.5	2.98	0.83
Searched for fire	14.9	6.3	8.6	2.51	3.43[c]
Called fire department	6.1	11.4	5.3	2.41	2.19[d]
Got dressed	5.8	10.1	4.3	2.30	1.87
Left building	4.2	10.4	6.2	2.22	2.79[c]
Got family	3.4	11.0	7.6	2.22	3.42[c]
Fought fire	5.8	3.8	2.0	1.77	1.13
Got extinguisher	6.9	2.8	4.1	1.77	2.31[d]
Left area	4.6	4.1	0.5	1.70	0.29
Woke up	3.8	2.5	1.3	1.45	0.90
Nothing	2.7	2.8	0.1	1.38	0.72
Had others call fire department	3.4	1.3	2.1	1.23	1.71
Got personal property	1.5	2.5	1.0	1.17	0.85
Went to fire area	1.9	2.2	0.3	1.20	0.25
Removed fuel	1.1	2.2	1.1	1.08	1.02
Entered building	2.3	0.09	1.4	1.02	1.37
Tried to exit	1.5	1.6	0.1	1.05	0.09
Went to fire alarm	1.1	0.19	0.8	1.02	0.78
Telephoned others	0.8	1.6	0.8	0.91	0.87
Tried to extinguish	1.9	0.6	1.3	0.91	1.43
Closed door to fire area	0.8	1.3	0.5	0.87	0.57
Pulled fire alarm	1.1	0.6	0.5	0.75	0.66
Turned off appliances	0.8	0.9	0.1	0.79	0.12
Checked on pets	0.8	0.9	0.1	0.79	0.12
Other	6.5	2.5	4.0	1.70	2.35[d]
Total ($N = 25$)	262	318			

[a]Standard error.
[b]Critical ratio.
[c]Critical ratios significant at or above the 1 percent level of confidence.
[d]Critical ratios significant at or above the 5 percent level of confidence.

TABLE 4.1.22 Awareness of Fire, MGM Grand

Means	*Number*	*Percentage*
Saw smoke	95	17.7
Fire apparatus	89	16.5
Smelled smoke	74	13.8
Notified by others	74	13.8
People yelling	71	13.2
Knock on door	48	8.9
Noise	40	7.4
Other	47	8.7
Total (97.1% participation)	538	100.0

Source: J. L. Bryan, *An Examination and Analysis of the Dynamics of the Human Behavior in the MGM Grand Hotel Fire,* rev. ed., National Fire Protection Association, Quincy, MA, 1983, p. 9.

returned. Of the respondents, 455 indicated a willingness to be interviewed.[51]

The age of the questionnaire population ranged from 20 to 84 years, with an average age of 45. The population consisted of 331 males and 222 females; one respondent did not indicate a gender. There were 103 guests who indicated they were alone at the time they became aware of the fire. The presence of other people, especially if they belong to the individual's primary group, appears to be a determinant of the response of many individuals in residential fires.[7] The initial five actions reported by the 554 guests, as elicited from the NFPA questionnaire study, are presented in Table 4.1.23.

Notice that the five most frequent first actions were "dressed," "opened door," "notified roommates," "dressed partially," and "looked out window." Guests reporting these actions were predominantly engaged in determining the degree of threat to themselves. Only 7.9 percent of the study population began or tried to begin their own evacuation with such actions as "attempted to exit," "went to exit," and "left room." A total of 16 individuals, or 2.9 percent of the population, initiated actions to improve the room as an area of refuge: "wet towels for face" and "put towels around door." The actions of the guests could be classified, in general, as evacuation actions or refuge processes. Actions relating to evacuation behavior appeared to be initiated early if the egress passages were clear of smoke or if the smoke was not perceived as personally threatening. If the smoke was

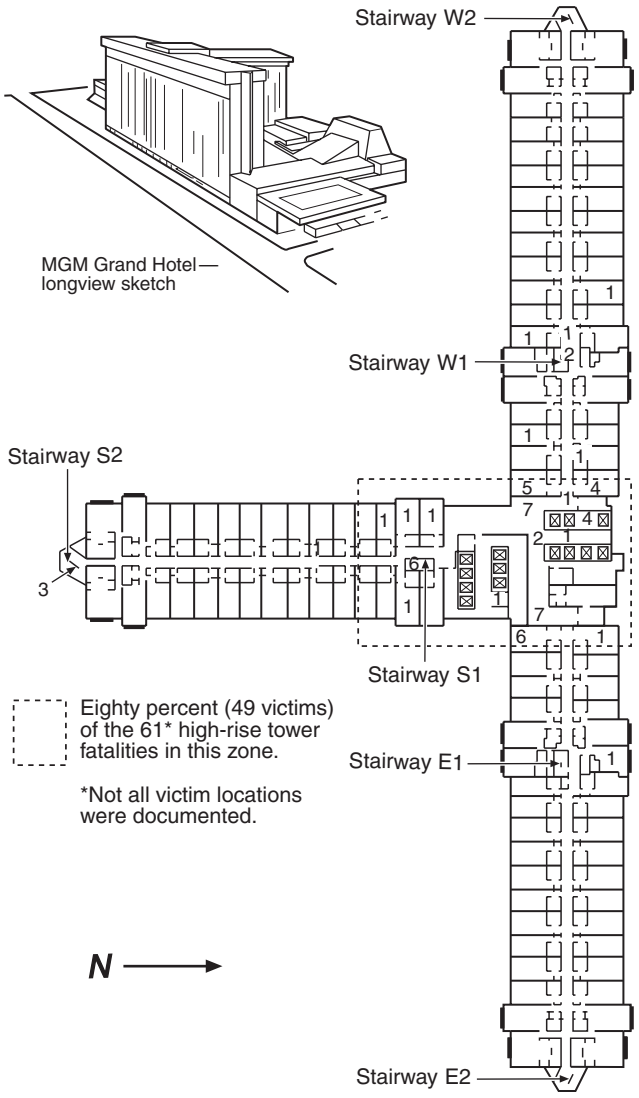

FIGURE 4.1.12 Residential Floor Diagram of the MGM Grand Hotel

heavy, however, the guests apparently decided to stay in their rooms or other rooms and to initiate actions to prevent smoke migration into the rooms of refuge.

Further examination of Table 4.1.23 shows that the five actions most frequently reported by guests as their second actions were "opened door," "dressed," "went to exit," "dressed partially," and "secured valuables." Approximately 19 percent of the study population reported dressing before initiating evacuation or refuge procedures.

The third actions of guests in the study population generally progressed to evacuation, attempted evacuation, and notification. Approximately 25 percent of this population was involved in evacuation actions, and approximately 10 percent attempted evacuations, as identified by the third actions of "attempted to exit" and "returned to room." The alerting and notification actions are identified as "notified occupants" and "notified other room."

The fourth actions of the guests in the study population indicate a progression to evacuation, attempted evacuation, and self-protection or room refuge actions. The most frequently reported fourth action was "went to exit"; approximately 16 percent of the population indicated that they did this. However, when one combines the guests involved in this action with those who "went down stairs," "went to another exit," "left hotel," and "left room," a total of 151 guests, or approximately 30 percent, were involved in evacuation as their fourth action. The process of forming convergence clusters was noted in this hotel fire. This action involved individuals clustering together in rooms they considered areas of refuge with individuals they usually characterized as strangers before the fire. The fourth actions of "went to other room" and "went to other room/others" are explicit indicators of the formation of convergence clusters.[51]

The fifth actions of the guests were primarily for self-protection and included improving the room as an area of refuge and evacuation behavior. The evacuation actions were "went downstairs," "left to exit," and "went to another exit." Involved in these evacuation actions were 175 individuals, or approximately 40 percent of the study population. Those unable to evacuate, and thus vitally concerned with refuge procedures, reported the fifth actions of "went to other room/others," "wet towels for face," "put towels around door," "broke window," "returned to room," "went to other room," "offered refuge in room," and "went to balcony." Approximately 40 percent of the fifth-action study population was involved in refuge procedures and self-protection actions.

Convergence Clusters

The phenomenon of convergence cluster formation was first noticed in a study of occupant behavior in a high-rise apartment building fire in 1979.[52] The clusters appear to involve occupants of the building who converged into specific rooms they perceived as areas of refuge. In the MGM Grand Hotel fire, guests tended to select rooms on the north side of the east and west wings and rooms on the east side of the south wing. In addition, guests reported that people had converged in the rooms with balconies and doors leading out to the balconies because of the ventilation, reduced smoke, improved visibility, and communication that the balconies offered. Guests who reported this behavior either estimated the number of persons in the room or connecting rooms, or they indicated only that "others" or "other persons" were present.[51]

Table 4.1.24 lists the rooms identified by guests as areas of refuge for numerous persons other than the original occupants. This table also presents estimates of the length of time that the clusters were maintained in the rooms—usually until the individuals were evacuated, or until the occupants were notified by fire or rescue personnel that evacuation was possible. Numbers in the two right-hand columns indicate the total number of persons in the clusters for the total number of rooms identified on the floor. The smallest number of people identified as a cluster was 3, and the largest was 53.

The greatest number of rooms used by convergence clusters and the largest population participating in convergence clusters

TABLE 4.1.23 First Five Reported Actions of Guests in the MGM Grand Hotel Fire

	Action (Percentage of Population)				
	First	*Second*	*Third*	*Fourth*	*Fifth*
Dressed	16.8	11.6	6.5	—	—
Opened door	15.9	11.7	6.7	3.4	—
Notified roommates	11.6	3.0	—	—	—
Dressed partially	10.1	7.5	4.5	—	—
Looked out of window	9.7	5.7	—	—	—
Got out of bed	4.5	—	—	—	—
Left room	4.3	5.4	8.1	2.4	2.0
Attempted to phone	3.4	3.6	—	2.8	—
Went to exit	2.5	10.3	9.5	16.1	6.7
Put towels around door	1.6	2.5	3.0	6.8	7.7
Felt door for heat	1.3	2.3	—	—	—
Wet towels for face	1.3	3.7	6.3	4.6	7.9
Got out of bath	1.1	—	—	—	—
Attempted to exit	1.1	3.0	5.8	4.3	—
Secured valuables	—	6.8	4.3	—	—
Notified other rooms	—	3.4	2.2	—	—
Returned to room	—	—	3.9	8.4	4.1
Went down stairs	—	—	3.9	5.4	21.3
Left hotel	—	—	3.4	2.6	2.0
Notified occupants	—	—	3.0	—	—
Went to another exit	—	—	—	3.6	4.8
Went to other room	—	—	—	3.6	3.6
Went to other room/others	—	—	—	3.4	8.7
Looked for exit	—	—	—	2.4	—
Broke window	—	—	—	—	4.3
Offered refuge in room	—	—	—	—	1.8
Went upstairs to roof	—	—	—	—	2.9
Went to balcony	—	—	—	—	1.8
Other	14.8	19.5	28.9	30.2	20.1
Total (percentage)	100.0	99.1	96.9	90.6	79.6
Number of guests	554	549	537	502	441

were located on the 17th floor of the hotel. No convergence clusters were identified by guests on the 6th, 21st, or 26th floors. The clusters appear to serve as an anxiety- and tension-reducing mechanisms for individuals confronted with a threatening situation. The action of "offered refuge in room," previously identified in the discussion of the fifth actions, is a positive indication of the occurrence of a convergence cluster.

In addition to the detailed human behavior study of the MGM Grand Hotel fire,[51] NFPA conducted a questionnaire study of guests' behavior in the Westchase Hilton Hotel fire in Houston, Texas, on March 6, 1982, in which 12 people died.[53,54]

Figure 4.1.13 presents the decomposition diagram for eight multiple-occupancy fires covering the actions of 96 persons.[46] These multiple occupancy fires in the United Kingdom involved hotel occupancies. A comparison of Figure 4.1.13 with Table 4.1.23 shows similarities between the five actions of the guests in the MGM Grand Hotel fire and the occupants' behavior in the British study

Guylène Proulx and her team at the National Research Council of Canada, studied human behavior in a fire in a 30 story apartment building in North York, Ontario, on January 6, 1995. The study was conducted by a mailed questionnaire sent to 349 apartments resulting in a return rate from 190 (54%) apartments. Table 4.1.25 identifies the "convergence cluster" information on this fire, identified by the researchers as "voluntary relocation." A total of 44 persons moved from one apartment to another during the fire. Of these occupants 26 (60%) changed floors before taking refuge in another apartment. Of these 26 occupants 16 (62%) indicated they had to find an area of refuge because of the smoke. It should be noted that on average occupants traveled 9 floors before accessing another apartment. It was reported that 18 (40%) of the 44 occupants involved in relocation did not change floors, only 3 of whom reported they relocated due to smoke; the remaining 15 were apparently motivated to join family members, friends, or neighbors. Of the 29 occupants who provided information on their relationship to the occupants of the relocated apartment,

TABLE 4.1.24 Summary of Rooms, Time Duration, and Number of Guests Reported in Convergence Clusters in MGM Grand Hotel Fire

				Persons	
	Floor	*Room Number(s)*	*Time (hr)*	*Number*	*Percentage*
	7	731	0.60	3	0.7
	8	827, 840	1.50–1.75	14*	3.3
	9	927	2.50	5	1.2
	10	1009A, 1025, 1034, 1060	1.00–2.00	53	12.7
	11	1129, 1115	1.50–2.00	30*	7.2
	12	1261, 1225, 1233A	2.00–3.00	53	12.7
	14	1433A, 1461A, 1451, 1416A	1.50–2.00	8*	1.9
	15	1501, 1533A, 1510	2.00–3.00	38*	9.1
	16	1643, 1625, 1633, 1629, 1627, 1615	2.00–3.50	35*	8.4
	17	1725, 1775, 1731, 1719, 1762, 1756, 1733A	2.00–2.50	84	20.1
	18	1819, 1802, 1850	2.00–3.00	20	4.8
	19	1929, 1919, 1962A, 1962, 1964, 1925	2.00–3.50	13*	3.1
	20	2027, 2013, 2030	2.50–3.50	25	6.0
	22	2213, 2221, 2229	2.00–3.00	13	3.1
	23	2329, 2314, 2342, 2331, 2308, 2340	2.50–3.25	20*	4.8
	24	2446	3.50	4	0.9
	25	2512, 2509A	3.50	*	0.0
Total	17	57		418	100.0
Range	7–25	1–7	0.60–3.50	3–84	0–20.1

*Persons indicated only as "others."

21 indicated they did not know the occupants of the relocated apartment.[55]

The classic types of nonadaptive behavior in a fire ignore adaptive actions that might facilitate the evacuation of others or limit the propagation of smoke, heat, or flame. Nonadaptive behavior ranges from the single act of leaving a room of fire origin without closing the door, thus allowing the fire to spread throughout the structure and endanger the lives of all the occupants, to the more generalized behavior of fleeing from a fire without regard for others and perhaps injuring others in what is often termed "panic."

Nonadaptive behavior may be an omission, such as forgetting to close a door, or it may involve an action that, although well meaning, results in negative consequences. When the results of behavior are extinguishing the fire and eliminating the threat, the behavior may be said to be adaptive. However, the same behavior may be ineffective because the fire was more severe than first perceived. In such cases, the time spent trying to extinguish the fire might have been used more effectively to warn others and notify the fire department. Thus, some behavior that appears to be nonadaptive really is behavior that would have seemed most adaptive if it had been successful. Injuries people suffer in relation to a fire may be cues to their nonadaptive or risk behavior.

Behavior in a High-Rise Office Building Fire

The fire in the unsprinklered 36 story Cook County Administration Building on Friday, October 17, 2003, resulted in six fatalities and a dozen people injured. Proulx and Reid conducted a human behavior study using questionnaires to gain an understanding of the existing conditions in the building prior to the fire, past training and occupant awareness of the evacuation procedure, and occupant behavior and evacuation on the day of the fire.[56] Results show that although 85 percent of the survey respondents had received fire safety training, only 20 percent understood the phased-evacuation plan. There were only around 250 building occupants still in the building at the time of the fire; half of them used an elevator to exit. Unfortunately, the combination of locked doors that prevented re-entry on floors from the stairwells and fire-fighting activity taking place from the stairwell, were contributing factors to this tragedy.

The Cook County Administration Building located at 69 West Washington in Chicago, was built in 1964. The 36 story office building housed mainly Cook County offices, as well as a few other organizations. The floor area was approximately 17,000 ft^2 (1579 m^2). The central core common to all floors contained 16 passenger elevators. There were also 2 stairwells at the southeast and northwest corners, which traveled the full length of the building. The southeast stairwell had a smoke tower using a natural ventilation shaft. The doors between the stairwell and the tenant were permanently locked from the inside; once a person entered the stairwell they had to travel the full length of the stairwell to the ground floor lobby to exit. Re-entry was not possible on any floor and no access to the roof was available. The locked doors in the stairwells did not unlock upon alarm activation or power failure; these doors could be unlocked only with a master key. The building engineer held

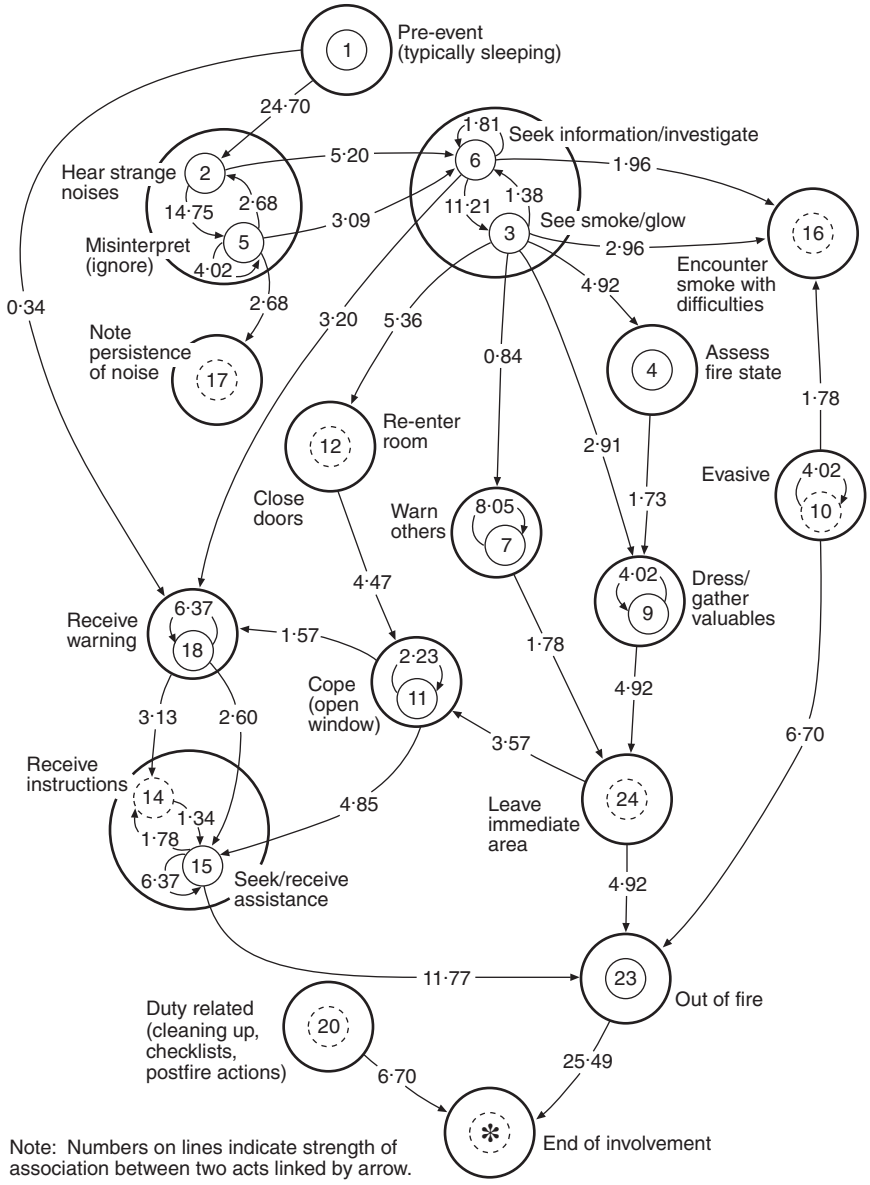

FIGURE 4.1.13 Decomposition Diagram for Multiple Occupancy Fires

one master key and another was kept in the security office on the third floor. Figure 4.1.14 illustrates the exterior of the Cook County Administration Building and the floor plan of the fire origin twelfth floor.

In total, 1862 surveys were distributed to employees. There were 551 surveys returned, which represents a return rate of 30 percent. Among the returned surveys, 462 were from occupants who worked in the building but were not present at the time of the fire. The remaining 89 responses were from occupants who were in the building at the time of the fire and provided information on their evacuation experience. The 89 surveys from respondents who were in the building at the time of the fire represented 40 percent of the occupants who were seen leaving the building on videotapes. Of these 89 respondents, 68 percent were female and 32 percent were male. The mean age of the respondents was 42.3 years (SD = 10.7). In the initial moment of the incident, the 89 respondents were evenly located throughout the building on different floors: 34 percent of the respondents were located on low-level floors, 33 percent were located on mid-level floors, and 33 percent were located on upper-level floors. This distribution of the respondents provides a very good overview of conditions throughout the building as perceived by the respondents.

Of the respondents, 38 percent first became aware of something unusual occurring by hearing a P.A. message, 28 percent became aware because they saw or heard others, 24 percent because they smelled something, and 10 percent because they saw something. Respondents were asked the time at which they

TABLE 4.1.25 Voluntary Relocation of Individuals Between Units

Location of Refuge	*Number of People in Unit (Total, or Tenant + Other)*	*Original Location of Refugee*	*Knew Tenants of Refuge Unit*	*Length of Stay (Hours)*	*Reason for Refuge*
7 SE	2 + 1	7 NE			
7 NW	4	10 NW (1 person)	No	5:30	Proximity
		14 SW (1 person)	No	6:00	Smoke
		17 SE (1 person)	No	7:00	Smoke
7 NW	4	7 SW (1 person)	No	3:00	
7 ??	1 + 1	7 NW	Yes	1:00	Confused
8 SW	approx. 10	17 SW (2 people)	No	6:00	
		24 NE (1 person)	No	6:00	Smoke
		27 SW (2 person)	No	8:00	
9 SW	1 + 15	9 SW (1 person)	Yes	6:00	Invited
		28 NE (1 person)	No	5:00	Smoke
9 NE	2 + 1	24 NW	No	5:00	Smoke
10 SE	3 + 4	10 SW (3 people)	No		Smoke
		27 ?? (1 person)			
10 SE	5	15 SW (1 person)	No	6:10	Smoke
10 NE	8	25 SE (2 people)	No	4:00	Smoke
		25 NE (1 person)	Yes	5:00	
11 SE	3 + 1	11 NE			
11 SW	1 + 1	11 NW	No	6:00	Locked out
12 NE	1 + 6	12 NE (3 people)			
		12 NW (1 person)			
		16 SW (2 people)	No	5:00	Fainted
12 SW	1 + 1	12 NW			
15 SE	2 + 1	22 SE			
16 SE	2 + 1	16 SE	No	0:30	Confused
18 SW	2 + 6	21 SE (2 people)	No	2:00–2:30	Smoke
18 NW	1 + 1	18 NE	No	5:00	Smoke
20 SW	1 + 2	29 SW	Yes	0:10	Family
22 NE	4 + 1	22 ??			
23 SE	4	28 NE (1 person)	No	2:00	Needed air
23 SE	1 + 2	23 NW	Yes	6:00	Friends
23 NE	3	17 NE (1 person)	No	1:00	Smoke
		21 NE (1 person)		3:00	
24 SE	2 + 2	24 SE	Yes	5:00	Smoke
24 NW	2 + 2	24 NW	Yes	6:00	Invited
		25 SW	No	2:00	Smoke
28 SW	1 + 5	21 NE			
		21 NW			
29 SE	2 + 3	25 NE (2 people)	No	5:00–6:00	Smoke
		30 ?? (1 person)			
29 NE	2 + 2	19 NE	No	2:30	Smoke
29 NW	1 + 1	29 NW			
30 SW	1 + 2	30 SW			
		19 SE			

Source: G. Proulx et al., *Study of the Occupants Behaviour During the 2 Forest Laneway Fire in North York, Ontario, January 6, 1995,* Internal Report No. 75, National Research Council Canada, National Fire Laboratory, Ottawa, 1995, p. 38.

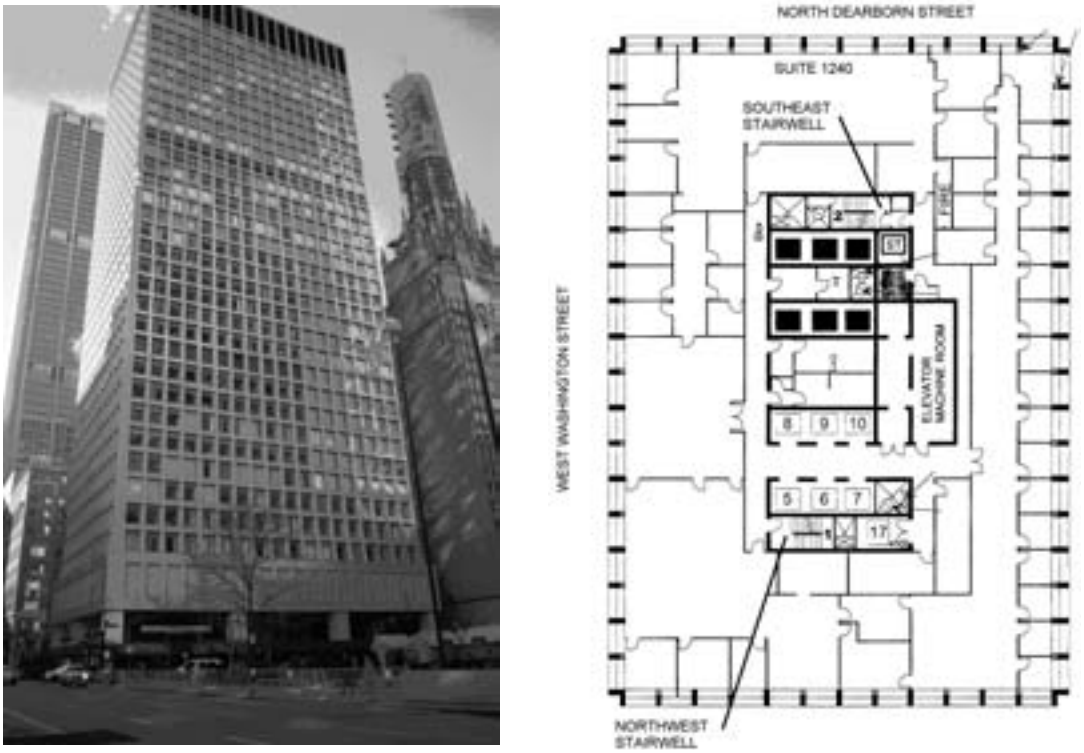

FIGURE 4.1.14 Cook County Administration Building and Twelfth Floor Plan (Source: G. Proulx and I. M. A. Reid, *Occupant Behavior and Evacuation During the Chicago Cook County Administration Building Fire,* Fire Research Program, National Research Council Canada, Ottawa, 2006, p. 4)

initially became aware that something unusual was happening. There was a marked tendency to round off the various reported times; therefore, the time analyses should be used with caution. The time reported by 25 percent was 5:00 p.m. For those who became aware of the incident via a P.A. message, the time ranged from 4:50 p.m. to 5:15 p.m., with most responses being at 5:05 p.m. Respondents were asked what they thought was happening in the initial moments. Of the 84 who responded to this question, 30 percent thought that there was a fire or emergency, 29 percent thought that there was a minor problem, 29 percent did not know what was happening, and 12 percent thought that it was a false alarm or a drill. When asked "How serious did you believe the situation to be at first?" respondents were provided with four categorized answers: "Not at all serious," "Only slightly serious," "Moderately serious," and "Extremely serious." It appears that initially, 36 percent thought that the situation was "Not at all serious," 28 percent thought that it was "Moderately serious," 22 percent thought that it was "Only slightly serious," and 14 percent thought the situation was "Extremely serious." Analysis showed that respondents' initial assessment of the situation significantly affected how serious they thought the situation was ($X^2 = 8.975$, $df = 3$, $p = 0.030$). This is shown in Figure 4.1.15.

When asked what factors motivated their decision to evacuate their floor, 88 percent of respondents provided one or more motivations for starting their evacuation. Motivations were coded under five factors as presented in Table 4.1.26. Respondents could mention one or several motivating factors, and in fact one-third of the respondents mentioned more than one factor. Overall, the most mentioned motivating factor was the perception of "fire cues," which are the smell or sight of smoke or flames. In second place was hearing one or more messages from the P.A. system, followed by being motivated to evacuate by other people. Another motivating factor was that it was time to leave for the day anyway. Finally, a small number were mo-

TABLE 4.1.26 Motivation to Start Evacuation

Motivation to Evacuate	*Respondents Who Mentioned*	*Percentage of Respondents Who Mentioned (of 78)*
Perceived fire cues	37	47.4
Heard P.A. message	24	30.8
Interaction or behavior of other occupants	21	26.9
Was leaving for the day	19	24.4
Concerned for own safety or danger	8	10.3

Source: G. Proulx and I. M. A. Reid, *Occupant Behavior and Evacuation During the Chicago Cook County Administration Building Fire,* Fire Research Program, National Research Council Canada, Ottawa, 2006, p. 12.

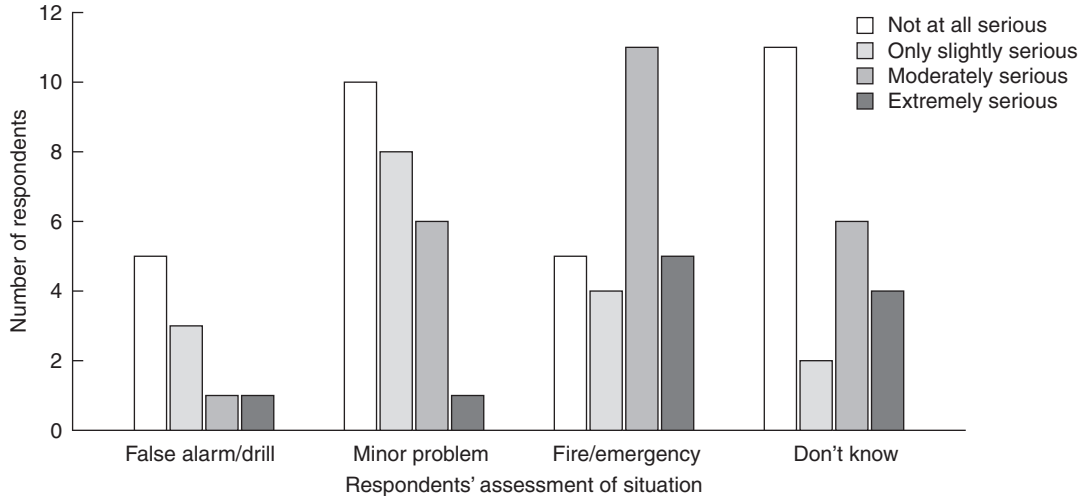

FIGURE 4.1.15 Initial Feelings About the Situation (Source: G. Proulx and I. M. A. Reid, *Occupant Behavior and Evacuation During the Chicago Cook County Administration Building Fire,* Fire Research Program, National Research Council Canada, Ottawa, 2006, p. 10)

tivated to evacuate because of a concern for their safety or the potential danger.

When asked if they left because someone told them to leave, 45 percent of the respondents gave a positive response. When asked who told them to leave, the survey provided 6 categories, as follows: 38 percent reported they were told to leave by a "Coworker," 24 percent by a "Supervisor," 22 percent by the "Message," 16 percent were told to leave by multiple persons (a combination of the above-mentioned choices), and no one reported being told to leave by a "Fire warden" or "Fire fighter." When they started to evacuate, 77 percent of the respondents were in a group of two or more. Half of the respondents waited for others before they left. Respondents were asked if they took anything with them when they left. Three categories were provided: "Personal effects," "Job-related material," and "Emergency equipment." A majority of the respondents, 71 percent, took personal effects, 7 percent took both personal effects and job-related material, 4 percent took job-related material, and 4 percent took emergency equipment when they left; 14 percent specified they took nothing. For respondents who took personal or job-related items, they took what they regularly took home for the weekend. Further, it can be seen from the security videos that most people exiting the building were wearing jackets. The approximate outside temperature at the time of the fire was 55°F (13°C). In addition, respondents from the day-care center located in the Bustle Building mentioned taking phone lists of the families of the children. Figure 4.1.16 presents the motivation of occupants to leave relative to their location in the building.

In total, 51 percent of the respondents attempted to use an elevator to evacuate. Such a high percentage of respondents attempting to use the elevator was rather unexpected considering that the building evacuation procedure and training recommended the use of stairwells and prohibited the use of elevators during a fire emergency. Further, signs located directly above the elevator call button, on every floor, indicated that "In Case of Fire, Elevators Are Out of Service." It should be noted that this information was not entirely correct, since the elevators did not have an automatic recall function and would continue to operate in a fire until manually or electronically recalled.

The high use of elevators to evacuate the building appears to be related to the time of the day; many people were leaving for the day and the weekend. Of those who mentioned that their motivation to evacuate was because they were leaving for the day, 95 percent (18 of 19 respondents) attempted to use the elevator. Of these 18 persons, most were aware that something unusual was happening; 11 had heard a P.A. message, 7 smelled

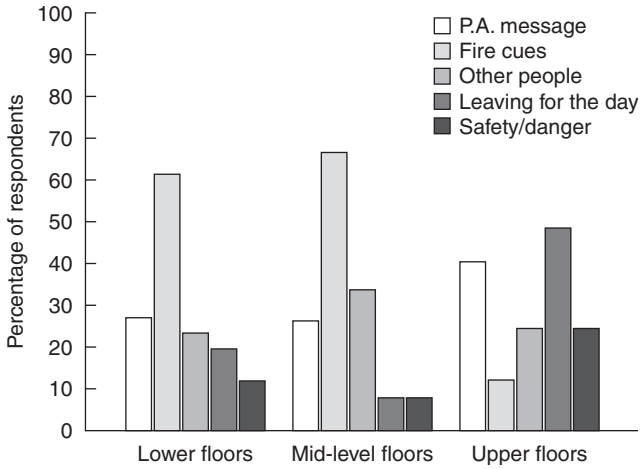

FIGURE 4.1.16 Motivation to Evacuate by Floor Level (Source: G. Proulx and I. M. A. Reid, *Occupant Behavior and Evacuation During the Chicago Cook County Administration Building Fire,* Fire Research Program, National Research Council Canada, Ottawa, 2006, p. 13)

smoke, 2 saw smoke, and 1 respondent heard a fire alarm on their floor prior to evacuating by elevator. Among the respondents that mentioned using the stairs as the appropriate evacuation procedure, 54 percent attempted to use the elevator to evacuate. Four of the individuals who reported using the stairs also mentioned that you should not use the elevator during an evacuation, but did attempt to use the elevator to evacuate. No statistical relationship was found between those attempting to use elevators and their floor level ($X^2 = 3.339$, $df = 2$, $p = 0.188$). A greater percentage, however, of those located on higher floors attempted to use the elevator; 62 percent of those located on upper floors versus 38 percent of those located on the lower floors attempted to use the elevator. Of those that used the elevator, all but one got off the elevator on the ground level floor.

Video cameras positioned on the ground floor lobby captured 223 occupants exiting the building from 5:00 p.m. until 5:35 p.m. These exiting occupants are shown as a continuous line in Figure 4.1.17. The number of occupants observed is shown on the right axis.

Also represented in Figure 4.1.17 are the exiting times of the survey respondents, calculated by adding the respondent estimated premovement time to the travel time from the time of initial awareness that something unusual was happening. The respondents exiting times range from 5:00 p.m. to 5:40 p.m., in 5 minute intervals. Exiting times are represented with bars for respondents that used the elevator or the stairs. The number of respondents is shown on the left axis.

The two sets of data presented in Figure 4.1.17, the video recordings and the respondent estimated times, show a similar pattern. It can be seen that a large proportion of the building occupants evacuated within 5 to 10 minutes of the first P.A. message issued. Initially, more occupants evacuated using the elevators whereas the stairs evacuees spread over a longer period of time.

Panic Behavior

One concept always discussed following a fire in which multiple fatalities occur, such as the Beverly Hills Supper Club fire,[57] is panic behavior. One classic definition of panic is

> a sudden and excessive feeling of alarm or fear, usually affecting a body of persons, originating in some real or supposed danger, vaguely apprehended, and leading to extravagant and injudicious efforts to secure safety.[58]

According to this definition, panic is a flight or fleeing type of behavior that involves extravagant and injudicious effort and is likely not to be limited to a single individual, but to be transmitted to and adopted by a group of people. From simulation experiments, a panic-type behavior reaction has been defined in the following manner: "A fear-induced flight behavior which is nonrational, nonadaptive, and nonsocial, which serves to reduce the escape possibilities of the group as a whole."[59]

The concept of panic is often used to explain the occurrence of multiple fatalities in fires even when there is no physical, social, or psychological evidence showing that competitive, injudicious flight behavior actually took place. The media and public officials often label various types of fire behavior as panic. The evidence accumulated from interviews with participants in the Beverly Hills Supper Club fire, and questionnaires completed by occupants, provided no evidence of the classic group-type of panic behavior with competitive flight for the exits.[60]

It has been said that panic as a concept is primarily a description rather than an explanation of behavior. The concept is used to support the introduction of requirements in fire and building laws or ordinances to provide for the fire safety of occupants. There also has been shown to be a difference between use of the concept to describe other persons' behavior in a fire and the use by someone engaged in the behavior to indicate

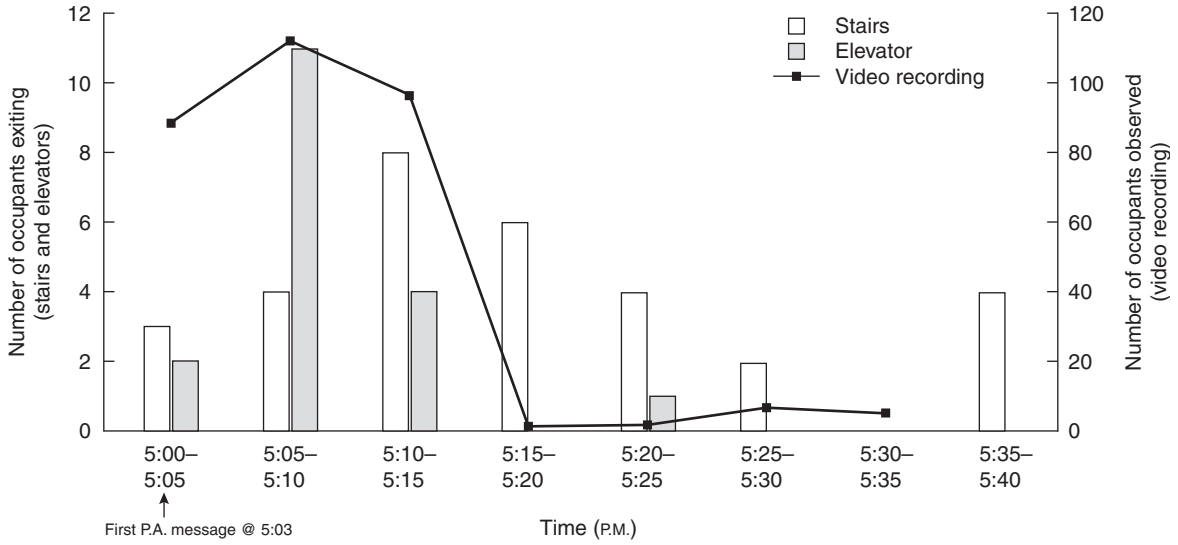

FIGURE 4.1.17 Number of Occupants Exiting the Building Between 5:00 p.m. and 5:40 p.m. (Source: G. Proulx and I. M. A. Reid, *Occupant Behavior and Evacuation During the Chicago Cook County Administration Building Fire,* Fire Research Program, National Research Council Canada, Ottawa, 2006, p. 18)

his or her own state of concern and anxiety.[61] Just because an individual identifies behavior as associated with panic does not necessarily identify the behavior as the classic panic-type response. The outcome of the behavior, as previously discussed, affects its labeling; the behavior of people in a fire is most likely to be misinterpreted when the outcome of the fire has been unfortunate.

The use of the concept of panic must be separated from use of the terms "anxiety" or "fear." The concept of self-destructive or animalistic panic responses to stimuli, such as the presence of smoke, has not been supported by the research on human behavior in fires. As has been pointed out, it is rare to have panic behavior in which the flight is characterized by competition among the participants, with resultant personal injuries.[7,14,15,60,62] In an interview study of 100 participants in single-family dwelling fires, no instances of panic behavior were found; primarily altruistic, helpful behavior was found instead.[63]

Ramachandran in his review of studies of human behavior in fires in the United Kingdom came to this conclusion about nonadaptive behavior:

> In the stress of a fire, people often act inappropriately and rarely panic or behave irrationally. Such behavior, to a large extent, is due to the fact that information initially available to people regarding the possible existence of a fire and its size and location is often ambiguous or inadequate.[17]

S. J. Blake, E. R. Galea, H. Westeng, and A. J. P. Dixon[64] conducted an analysis and review of media accounts of 250 survivors of World Trade Center towers 1 and 2 during the terrorist aircraft attacks of September 11, 2001. This study is very similar to the study previously considered by Guylène Proulx and Rita Fahy. In this study 124 survivors reported pre-evacuation behavior, 94 survivors (76%) reported one action, 19 survivors (15%) reported they left immediately with no pre-evacuation actions. The most frequent pre-evacuation action was "gather/provide information." These authors reported in their study the following account of nonadaptive behavior:[64]

> The extreme behavior action (which included the classic panic action or people behaving in an irrational manner) was only noted in 1/124 (0.8%) cases.

The Station Nightclub Fire

The most recent and one of the most deadly fires involving the occurrence of the classic type of panic behavior occurred in the Station Nightclub fire which occurred at approximately 11:09 p.m. on February 20, 2003, in West Warwick, Rhode Island.[65] This fire incident was also one of the most detailed videotaped fires since a television reporter/cameraman from station WPRI was on the premises filming when the fire was ignited by performers' pyrotechnics adjacent to highly combustible foam interior finish on the walls and the ceiling of the platform performance area. The fire resulted in 100 occupant fatalities and between 186 and 200 occupant injuries.

Figure 4.1.18 presents the interior dimensions of the club. Figure 4.1.19 presents the arrangement of the main entrance at the front of the building through which all the occupants were admitted, since the cashier's station was at the end of the entrance corridor. This area had a single door for egress indicated in the figure as 36 in. (0.9 m) in width.[65]

Although the videotape shows a crowd crush at the double exterior doors it appears from the investigation including the survivors accounts the primary crowd crush that denied access to the main exit was at the single door prior to the two main egress doors at the exterior of the building. The crowd crush occurrences at both locations had all the characteristics of the panic type of behavior defined by Schultz[59] as being a "fear-induced flight behavior which serves to reduce the escape possibilities of the group as a whole."

The investigation report provided the following analysis relative to the occupants egress behavior as follows:[65]

> The first patrons recognized the fire danger about 24 seconds after ignition of the foam; the bulk of the crowd began to evacuate shortly after that, around the time the band stopped playing (30 seconds).
>
> The rate of egress from the main entrance at the front of the building was primarily limited by the single doorway inside the vestibule, not the double doors visible from the outside.
>
> About two-thirds of the occupants appear to have attempted to leave through the single main entrance in the front of the building; many were unsuccessful.
>
> Prior to 1½ minutes into the fire, a crowd-crush occurred in the front vestibule which almost entirely disrupted the flow through the front exit. The precise event which led to the crowd-crush likely was related to the arrangement of the single interior door with merging streams of traffic and the pressure to escape the rapidly deteriorating conditions in the main area of the nightclub.
>
> Measurements of temperature, heat flux and gas species in a reconstruction of the platform area fire at NIST and computer models of the NIST experiment and the full nightclub suggest that the conditions around the platform, dance floor, sunroom and dart room would have led to severe incapacitation or death within about 1½ minutes after ignition of the foam for anyone remaining standing, and for not much longer even close to the floor.
>
> The number of building occupants at the time of the fire was reported by the *Providence Journal* to be 440.[65]

The NIST report[65] provided a total of 12 recommendations from the investigation and analysis of the Station Nightclub fire. The following recommendation addresses the human behavior factors that appeared to be critical in this fire incident:

> NIST recommends that research be conducted to better understand human behavior in emergency situations, and to predict the impact of building design on safe egress in fires and other emergencies (real or perceived) including the following:
>
> a. the impact of fire products (gases, heat, and obscuration) on occupant decisions and egress speeds

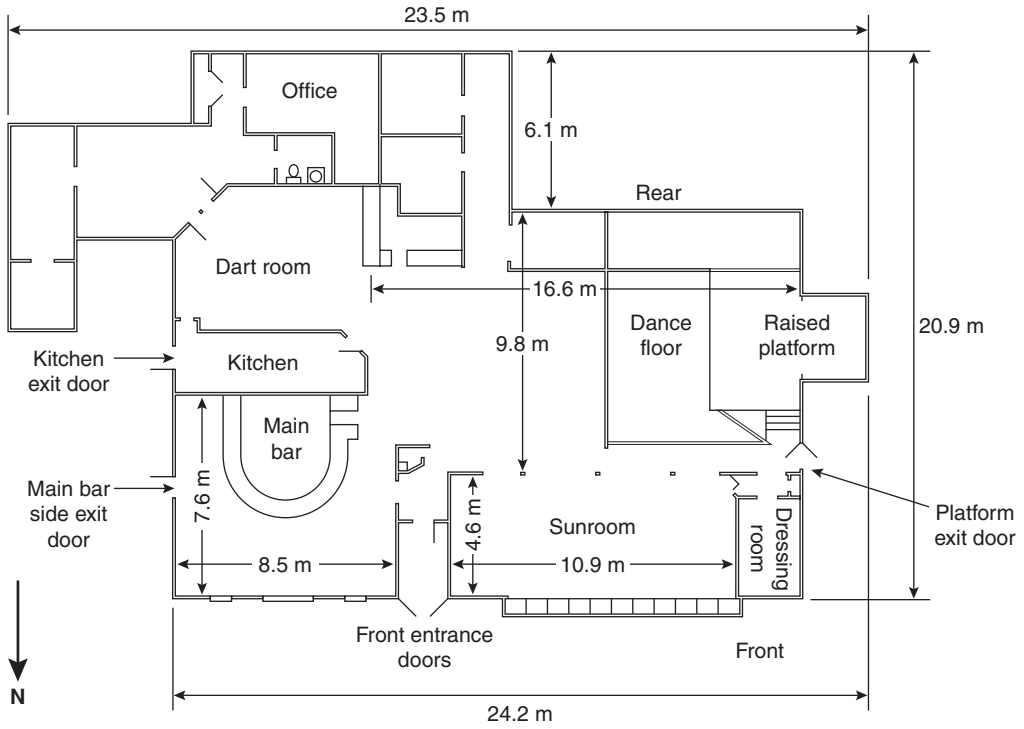

FIGURE 4.1.18 Plan View of the Station Showing Different Rooms and Exits (Source: W. L. Grosshandler, N. Bryner, D. Madrzykowski, K. Kuntz, *Report of the Technical Investigation of the Station Nightclub Fire,* NIST NCSTAR 2, National Institute of Standards and Technology, Gaithersburg, MD, 2005, p. 1-6)

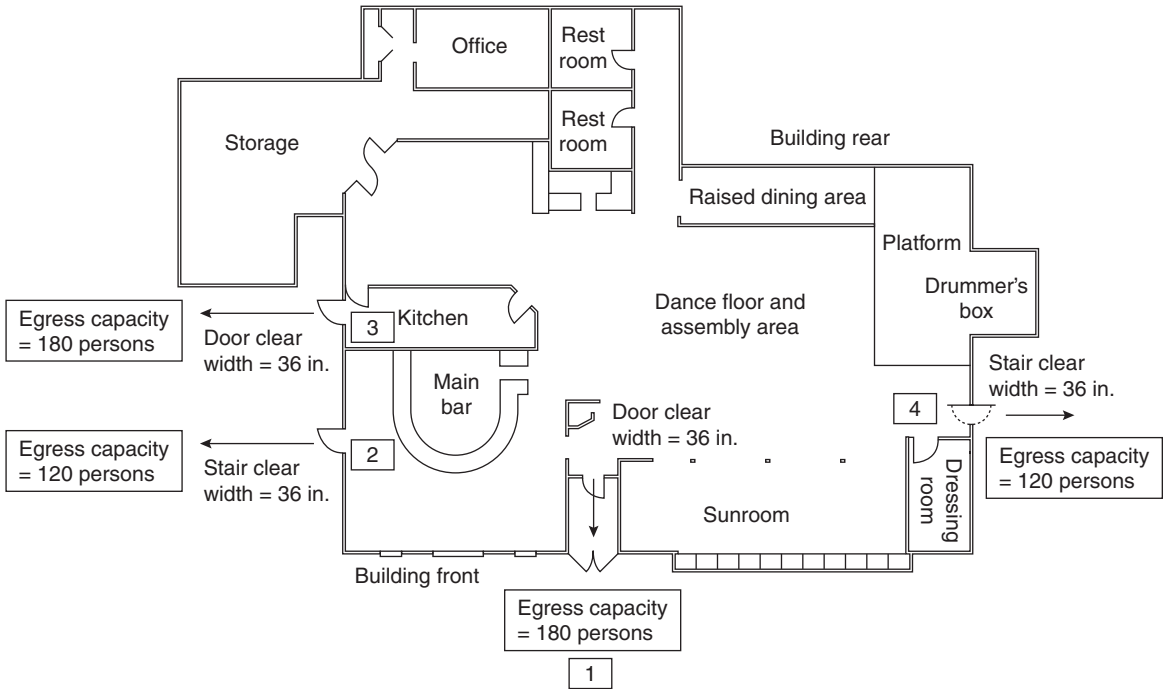

FIGURE 4.1.19 Station Nightclub Egress Capacity (Source: W. L. Grosshandler, N. Bryner, D. Madrzykowski, K. Kuntz, *Report of the Technical Investigation of the Station Nightclub Fire,* NIST NCSTAR 2, National Institute of Standards and Technology, Gaithersburg, MD, 2005, p. 7-1)

b. exit number, placement, size and signage
c. conditions leading to and mitigating crowd-crush
d. the role of crowd managers and group interactions
e. theoretical models of group behavior suitable for coupling to fire and smoke movement simulations
f. the level of safety that model codes afford occupants of buildings[65]

Re-Entry Behavior

The study of the 1956 Arundel Park fire was the first to document the phenomenon of re-entry behavior.[4] Some older codes and regulations affecting design of the means of egress appear to have been based on the assumption that pedestrian traffic only moves away from a fire and away from the area or floor of the building involved. However, the Arundel Park study indicated that approximately one-third of the survivors interviewed had re-entered the building.

Thus, it has become apparent that doors, stairways, and corridors will often be subjected to two-way movement of occupants and others. The occupant who, after leaving the building safely, turns around and re-enters is often completely aware of the fire in the building and of the specific portions of the building involved in fire and smoke propagation. Based on interviews with 61 persons, Table 4.1.27 presents the number of participants who re-entered Arundel Park during the fire. Note the reasons for the re-entry behavior and that those who re-entered were predominantly male.

The Arundel Park fire occurred in an assembly occupancy being used for a church-sponsored oyster roast, a family-type affair. Thus, the primary group cultural role of father or husband was apparently a critical variable in the re-entry behavior of the population interviewed and may have resulted in the fact that the re-entry participants were mostly male. It can reasonably be argued that re-entry behavior is not a nonadaptive behavior, since it is often used to assist or rescue persons remaining or believed to be remaining in the building. This type of behavior is often used by parents whose children are missing during a fire. The behavior is often undertaken in a rational, deliberate, and purposeful manner, without the emotional anxiety and self-doubt usually associated with nonadaptive behavior. However, re-entry behavior has been considered nonadaptive, since people going back into a burning building often hinder the efficient and effective evacuation of others through the same means of egress. The reasons elicited from participants in re-entry behavior in the Project People study[7] in the United States are presented in Table 4.1.28.

It would seem that 163 people from the total study population of 584, or 27.9 percent, engaged in re-entry behavior. The most popular reason given was to "fight fire," followed by "obtain personal property," "check on fire," "notify others," "assist fire department," and "retrieve pets." These six reasons accounted for approximately 73 percent of re-entry behavior. Table 4.1.29 compares the re-entry behavior of the British and U.S. study populations.

Note that all the reasons were significantly different, with the exception of the item "save personal effects." The re-entry reasons of the U.S. population were predominantly "save personal effects," "call fire department," "rescue pets," "notify others," "assist fire department," and "assist evacuation." The British population's re-entry reasons were predominantly "fight fire," "observe fire," "shut doors," "await fire department," and "fire not severe."

TABLE 4.1.27 Behavior of Occupants Who Re-Entered in the Arundel Park Fire, Relative to Gender and Re-Entry Reasons

Gender	*Re-Entered and Left by Same Exit*	*Re-Entered and Left by Different Exit*	*Stated Reason for Re-Entrance*
M	1		Turn off kitchen stoves
M	1	1	Tell people to leave
M	3	1	To help
M	1		Assist people
M	2	3	Find wife
M	2	2	Assist fire fighting
M & 1 F		5	No stated reason
21 M & 1 F	10	12	

TABLE 4.1.28 Reasons for Re-Entry of Occupants

	Participants	
Reason	*Number*	*Percentage*
Fight fire	36	22.2
Obtain personal property	28	17.2
Check on fire	18	11.0
Notify others	13	8.0
Assist fire department	12	7.4
Retrieve pets	12	7.4
Call fire department	9	5.5
Assist evacuation	4	2.5
To be taken to hospital	3	1.8
Turn power back on	2	1.2
Rescue from balcony	1	0.6
Help injured family member	1	0.6
Turned off gas	1	0.6
Open windows	1	0.6
Close door	1	0.6
No apparent danger	1	0.6
Entered nondanger area	1	0.6
Job responsibility	1	0.6
Due to fire	1	0.6
Told to by others	1	0.6
Not reported	16	9.8
Total ($N = 21$)	163	100.0
Range = 1–36		Percentage of participant population = 27.9

TABLE 4.1.29 Comparison of Reasons for Re-Entry Behavior of British and U.S. Study Populations

Reason	*British (Percentage, P_1)*	*U.S. (Percentage, P_2)*	$P_1 - P_2$	$SE^a_{P_1-P_2}$	CR^b
Fight fire	36.0	22.2	13.8	4.02	3.43[c]
Observe fire	19.0	11.0	8.0	3.25	2.46[d]
Save personal effects	13.0	17.2	4.2	2.91	1.44
Shut doors	10.0	0.6	9.4	2.38	3.95[c]
Await fire department	9.0	0.0	9.0	2.26	3.98[c]
Call fire department	2.0	5.5	3.5	1.32	2.65[c]
Rescue pets	2.0	7.4	5.4	1.40	3.86[c]
Fire not severe	5.0	1.2	3.8	1.74	2.18[d]
Notify others	0.0	8.0	8.0	0.92	8.69[c]
Assist fire department	0.0	7.4	7.4	0.80	8.41[c]
Assist evacuation	0.0	2.5	2.5	0.54	4.63[c]
Total ($N = 11$)	943	163			

[a]Standard error.
[b]Critical ratio.
[c]Critical ratios significant at or above the 1 percent level of confidence.
[d]Critical ratios significant at or above the 5 percent level of confidence.

Occupant Fire-Fighting Behavior

Occupants who engaged in fire-fighting behavior were predominantly male, and this behavior now appears to be a culturally determined and expected aspect of the male role. However, it should be noted that, in the Project People[7] study of 335 U.S. fires, approximately 23 percent of the study population of 584 individuals were involved in occupant fire-fighting behavior. Of these, 37.3 percent were female. Of the 134 individuals who participated in fire-fighting behavior, 50 were female and 84 male. They ranged from a 7-year-old girl to an 80-year-old man. Distribution of the participants by gender and age is presented in Table 4.1.30. A plurality of those involved in fire-fighting behavior, or approximately 30 percent of the fire-fighting behavior population, were between 28 and 37 years old. A higher proportion of males than females reported "got extinguisher" and "fought fire," and this difference is statistically significant (Table 4.1.31).

Approximately 15 percent of the male population reacted by obtaining extinguishers. Similarly, approximately 26 percent of the male population fought the fire when they became aware of it, as contrasted with approximately 10 percent of the female participants. A higher proportion of women (33%) than men (26%) notified the fire department, as indicated in Table 4.1.31, but this difference is not statistically significant.

Occupant fire-fighting behavior appears most prevalent in occupancies in which the individuals are emotionally and economically involved—that is, in their homes or where such behavior is an assigned role as a result of training.[66] At some time during the fire, 285 individuals engaged in one of the six actions defined as fire-fighting behavior and 252 individuals participated in one of the four actions defined as notifying the fire department.

In the study of residential fires in Berkeley, California, 180 persons were involved in extinguishing and fire-fighting behavior. This study surveyed a population different from that of Project People, since the 1411 Berkeley households, with 208 fires, included fires not reported to the fire department; these accounted for approximately 80 percent of the total 208 fires. The majority of the unreported fires were extinguished by the occupants alone or with the help of neighbors.[67] Six percent of these fires self-extinguished; and 52 percent were extinguished by the individual who had started the fire. Thus, it appears that only the fires in the Project People study that were judged uncontrollable by the occupants resulted in notification to the fire department.

TABLE 4.1.30 Age and Gender of the Occupants Engaged in Fire-Fighting Behavior

	Participants	
	Number	*Percentage*
Gender		
Male	84	62.7
Female	50	37.3
Total	134	100.0
Age		
7–17	8	5.9
18–27	31	23.1
28–37	41	30.6
38–47	27	20.1
48–57	16	11.9
58–67	2	1.5
68–80	3	2.2
Unknown	6	4.7
Total	134	100.0
	Percentage of participant population = 22.9	

TABLE 4.1.31 Gender Differences of the Occupants Engaging in Fire Fighting and Notifying the Fire Department

Action	*Male (Percentage, P_1)*	*Female (Percentage, P_2)*	$P_1 - P_2$	$SE^a_{P_1-P_2}$	CR^b
Searched for fire	17.2	9.1	8.1	4.23	1.91
Got extinguisher	15.6	6.0	9.6	3.95	2.43[d]
Fought fire	25.6	9.7	15.9	4.83	3.29[c]
Removed fuel	3.4	3.1	0.3	2.17	0.14
Tried to extinguish	5.3	2.8	2.5	2.49	1.00
Went to fire area	3.1	2.8	0.3	2.07	0.14
Total	70.2	33.5	36.7	6.01	6.11[c]
Number interviewed	184	101			
Called fire department	25.6	33.0	7.4	5.83	1.27
Had others call fire department	9.2	7.5	1.7	3.27	0.52
Went to fire alarm	3.8	3.8	0.0	0.0	0.0
Pulled fire alarm	1.9	1.6	0.3	1.65	0.18
Total	40.5	45.9	9.4	6.31	0.85
Number interviewed	106	146			

[a]Standard error.
[b]Critical ratio.
[c]Critical ratios significant at or above the 1 percent level of confidence.
[d]Critical ratios significant at or above the 5 percent level of confidence.

Similarly, approximately 85 percent of the fires in the National Fire Prevention and Control Administration National Household Survey[68] were not reported to the fire department.

In the Project People study, 107 of the 584 participants did not leave the building voluntarily after becoming aware of the fire. Their reasons for staying in the building are presented in Table 4.1.32.[7]

Fifty-two of the participants, or approximately 49 percent of the population, who stayed in the building reported that they remained because they wished to engage in fire control or fire-fighting activities. The other most frequent reasons were to notify others of the fire or because the occupant's way out of the building was blocked by smoke.

TABLE 4.1.32 Reasons Elicited from Occupants for Not Leaving the Fire Building

	Participants	
Reason	*Number*	*Percentage*
Fight fire	52	48.7
Notify others	7	6.5
Blocked by smoke	7	6.5
Blocked by fire	5	4.7
Overcome by smoke	5	4.7
Search for fire	3	2.8
Needed help	2	1.9
Secure property	2	1.9
Afraid of fire spread	2	1.9
No fire in area	1	0.9
Help others	1	0.9
Does not know	1	0.9
No response to fire department	1	0.9
Home	1	0.9
Return to area	1	0.9
Not reported	16	15.0
Total ($N = 15$)	107	100.0
Range = 1–52	Percentage of participant population = 15.6	

Occupant Movement through Smoke

Often related to fire-fighting behavior, and a definite component of evacuation behavior in many fires,[7,14] is the movement of occupants through smoke. The principal variables influencing an occupant's decision to move through smoke appear to be recognition of the location of the exit and thus of the travel distance, the appearance of the smoke, the smoke density, and the presence or absence of heat.[52–54] To achieve evacuation, occupants have moved through smoke, even for extended distances under conditions of extremely limited visibility at personal risk, and sometimes have been forced to turn back without completing the evacuation.[52,53]

Jin and Yamada[69] reported on a study involving 31 subjects (14 males and 17 females) traveling a maximum distance of 34.5 ft (10.5 m) in a corridor while exposed to smoke from smoldering cedar crib chips. The smoke extinction coefficient varied from

0.1 to 1.2 (m^{-1}). Subjects were also exposed to increasing heat from radiant heaters at the end of the corridor, where the mean temperature was 82°C. At five points in the corridor the subjects stopped and were asked mental arithmetic questions. Both walking speed in the corridor and mental arithmetic capability decreased as smoke density and radiant heat exposure increased.

Fahy and Proulx[23] in their questionnaire study of 382 employees in the 1993 World Trade Center explosion and fire found that 94 percent of the respondents in WTC 1 and 70 percent of the respondents in WTC 2 moved through smoke. In addition, the study reported that approximately 75 percent of these individuals turned back during their evacuation because of smoke, crowding, locked doors, breathing difficulty, fear, and poor visibility. It was also reported that some occupants continued to move through smoke, even when they perceived the smoke to be worsening and believed that they may have been moving toward the fire.

Proulx and Fahy[26] in their study of the media reports of occupant behavior in the World Trade Center terrorist aircraft attack of September 11, 2001, indicated that in WTC 1, 74 occupants (55%) reported "smoke" was the most frequent adverse condition; thus, it may be assumed they may have traversed through smoke conditions at some time in their evacuation. In WTC 2, 25 persons (44%) indicated "smoke" was an adverse condition, also implying some movement through smoke. Although smoke was reported as the most frequent adverse condition in WTC 1, in WTC 2 the most frequent adverse condition was "debris or collapse of a wall, ceiling or floor."

Table 4.1.33 compares the distance moved through smoke for the 1316 persons in the British study and the 322 persons in the U.S. study.

Reports by 60 percent of the British study population and 62.7 percent of the Project People participants indicated that they moved through smoke. It is thus apparent that building occupants will move through smoke in an evacuation process. An important variable may be the smoke density or the visibility distance of the occupants during the evacuation process.

Table 4.1.34 presents the visibility distance reported by the British and U.S. occupants as they moved through smoke while evacuating a building fire. They reported their movement through smoke under relatively high smoke density conditions, with visibility under 12 ft (3.7 m) for 64 percent of the British population and for 47.6 percent of the U.S. population.

Visibility distance for the British and U.S. populations at the time participants were forced to turn back is presented in Table 4.1.35. Comparison with Table 4.1.34 reveals that very few participants turned back when they could see more than 31 ft (9.4 m). The greater percentage of participants turned back at shorter visibility distances. When the visibility distance was below 12 ft (3.7 m), 91 percent of the British study population and 76.4 percent of the U.S. study population turned back (see Table 4.1.35).

Proulx[70] in the study of occupant response to a fire in a 25 story high-rise apartment building had 137 questionnaires returned, with 68 percent of the occupants over 60 years of age. Of the occupants, 114, or 83 percent, attempted to evacuate during the fire and 96, or 84 percent, of those attempting to evacuate moved through smoke. Of those moving through smoke, 45 percent indicated they could see "nothing at all" or "little," and 30 percent said they could see 12 to 15 m in the corridor. Of the 114 occupants who attempted to evacuate, 61, or 54 percent, were successful and 53, or 46 percent, were unsuccessful due to the smoke conditions in the stairs or corridors. Relative to the 53 unsuccessful occupants, 29, or 55 percent, returned to their own apartments and 24, or 45 percent, sought refuge in other apartments.

Heskestad and Pederson[71] have reported on five large "escape through smoke" experiments involving more than 300 persons with various way-guidance systems. In all of these ex-

TABLE 4.1.33 Comparison of the Distance Moved Through Smoke for British and U.S. Populations

Distance Moved (ft)	*British (Percentage, P_1)*	*U.S. (Percentage, P_2)*	$P_1 - P_2$	$SE^a_{P_1-P_2}$	CR^b
0–2	3.0	2.3	0.7	1.02	0.69
3–6	18.0	8.4	9.6	2.23	4.30[c]
7–12	30.0	17.1	12.9	2.71	4.76[c]
13–30	19.0	45.5	26.5	2.62	10.11[c]
31–36	5.0	2.0	3.0	1.25	2.40[d]
37–45	4.0	4.1	0.1	1.19	0.08
46–60	5.0	11.0	6.0	1.47	4.08[c]
60+	15.0	9.6	5.4	2.10	2.57[d]
Number interviewed	1316	322			

[a]Standard error.
[b]Critical ratio.
[c]Critical ratios significant at or above the 1 percent level of confidence.
[d]Critical ratios significant at or above the 5 percent level of confidence.

TABLE 4.1.34 Comparison of the Visibility Distance for the British and U.S. Populations When Moving Through Smoke

Visibility Distance (ft)	*British (Percentage, P_1)*	*U.S. (Percentage, P_2)*	$P_1 - P_2$	$SE^a_{P_1-P_2}$	CR^b
0–2	12.0	10.2	1.8	1.99	0.90
3–6	25.0	17.2	7.8	2.65	2.94[c]
7–12	27.0	20.2	6.8	2.73	2.49[d]
13–30	11.0	31.7	21.7	2.24	9.69[c]
31–36	3.0	2.2	0.8	1.03	0.78
37–45	3.0	3.7	0.7	1.08	0.65
46–60	3.0	7.4	4.4	1.21	3.64[c]
60+	17.0	7.4	9.6	2.24	4.20[c]
Number interviewed	1316	322			

[a]Standard error.
[b]Critical ratio.
[c]Critical ratios significant at or above the 1 percent level of confidence.
[d]Critical ratios significant at or above the 5 percent level of confidence.

TABLE 4.1.35 Comparison of the Visibility Distance for the British and U.S. Populations Relative to Turn-Back Behavior

Visibility Distance (ft)	*British (Percentage, P_1)*	*U.S. (Percentage, P_2)*	$P_1 - P_2$	$SE^a_{P_1-P_2}$	CR^b
0–2	29.0	31.8	2.8	5.31	0.53
3–6	37.0	22.3	14.7	5.57	2.64[c]
7–12	25.0	22.3	2.7	5.02	0.54
13–30	6.0	17.6	11.6	3.07	3.78[c]
31–36	0.5	1.2	0.7	0.90	0.77
37–45	1.0	0.0	1.0	1.10	0.91
46–60	0.5	4.7	4.2	1.16	3.62[c]
60+	1.0	0.0	1.0	1.10	0.91
Number interviewed	570	85			

[a]Standard error.
[b]Critical ratio.
[c]Critical ratios significant at or above the 1 percent level of confidence.

periments, visibility was less than 3 m due to the induced smoke conditions. Two of the experiments involved the test situation modeled on a ship staircase and a ship or hotel corridor. One of these experiments involved an emergency training mock-up, one experiment used a corridor in a health care facility, and one experiment used portions of a passenger ferry. Variables measured during the experiments were the time for occupants to travel through the experimental facility with the number of incorrect decisions made during the travel. These experiments found that tactile and audible way-guidance systems appear to be as suitable as the visible systems in assisting movement by individuals through smoke.

Jin[72] has reported on numerous studies involving the effectiveness of guidance sign systems with human subjects in smoke environments. Improvements resulting from these experiments include a pictorial exit sign, flashing exit lights, and a flashing row of lights at floor level indicating the direction of egress travel. The flashing row of lights was effective in a smoke level of 1.01/m with the spacing of the lights at 0.5 m.

DISABLED OR IMPAIRED OCCUPANTS

Fire problems involving occupancies designed for permanently or temporarily disabled persons, such as nursing homes and hospitals, appear to be matched on the basis of building design, adequate staff training, and ability to protect the occupants in place until evacuation is possible. An extensive study of human behavior in health care facilities[66] indicated that the nursing staff performed their professional roles for their patients even when they were at risk.

The few fires studied involving disabled persons in occupancies other than health care facilities have primarily been in residential occupancies. In two of these cases, handicapped individuals were helped by other occupants to evacuate successfully. One instance involved a wheelchair user[51] and the other a blind person.[73]

Types of Impairment

Disabled people may have a variety of limitations that increase their risk in a fire: sensory problems, such as deafness and blindness; mobility problems that may entail the need for a wheelchair; and intellectual problems, such as mental retardation. Many handicapped persons with mobility problems also are concerned about their personal risk in high-rise office and residential buildings where the use of elevators is not allowed in a fire. In such situations, adequate areas of refuge must be provided for disabled, as well as able-bodied, occupants.[74]

In their reports of the explosion and fire in the World Trade Center on February 26, 1993, Isner and Klem[75,76] indicated that when the explosion occurred at approximately 12:18 p.m., normal power was lost and the emergency generators failed about 20 minutes later; all remaining power to the World Trade Center complex was disconnected at approximately 1:32 p.m. Thus, the simultaneous evacuations of both able and disabled occupants from towers 1 and 2 were conducted in darkness with varying smoke conditions in the stairways. These simultaneous evacuations may have involved the largest number of occupants and the longest evacuation times of any fire-induced evacuations of buildings in the United States.

Juillet,[77] in one of the first documented studies of this type, reported on the interview study of 27 occupants with disabilities evacuated from one of the two towers in the World Trade Center during the explosion and fire of February 26, 1993. The impairments of the interviewees included 14 with mobility impairments, 3 with sight or hearing impairments, 3 who were pregnant, 2 with cardiac conditions, and 7 with respiratory conditions. Juillet[78] indicated that the total disability population in both towers at the time of the incident was believed to be between 100 and 200 persons, approximately 100 of whom had been previously identified. The average evacuation time of the 27 study participants was 3.34 hours, with evacuation times reportedly ranging from 40 minutes to over 9 hours. The predominant means of evacuation was through the stairs with assistance from other evacuees or emergency personnel. The altruistic behavior seen in many fires involving large populations[51,53,77] appeared to have been exhibited in this fire in relation to the disabled occupants as reported by Juillet.

> However, in the absence of communications by authorities, they gladly accepted assistance—from colleagues and even from complete strangers—in evacuating. These caring groups of people who assisted the disabled protected their "charges" until they were safely evacuated and moved away from the building.[78]

The Fire Safety Engineering Research and Technology (SERT) Centre at the University of Ulster has completed the most extensive and detailed analytical and experimental studies of the evacuation capabilities of impaired individuals. Boyce, Shields, and Silcock conducted a series of studies in Northern Ireland to determine the number and characteristics of impaired persons who may be expected to frequent public buildings and

to determine the capabilities of these persons to complete an evacuation. The initial study determined the number and types of impaired persons expected to occupy public assembly occupancies.[79] This study found that 12 percent of the mobile population of Northern Ireland out in public are impaired persons and 2 percent of these impaired persons require assistance. Table 4.1.36 presents the number of impaired adults and children by their degree of mobility expressed as a percentage of the total mobile population.[80]

Table 4.1.37 illustrates the impaired persons in public who have experienced mobility difficulties as percentages of the total mobile population. Table 4.1.38 indicates the involvement of impaired persons in social and recreational occupancies relative to their degree of mobility.

Additional data presented in this study involved the frequency with which impaired persons go out in public. The prevalence of the type of impairment among the impaired population attending theaters, concert halls, motion picture theaters, sports stadiums, leisure centers, hotels, and lodging occupancies was reported. In addition, data was presented relative to the types of impairment among impaired adults who live in communal facilities and go out for meals and drinks and for adults who are employed. The perceived value of this information and data relative to the application of performance codes was stated in the following manner:

> The information provided in this analysis has important implications for characterizing building occupan-

TABLE 4.1.36 Number of Disabled Adults and Children Who Go Out by Degree of Mobility, Expressed as Percentages of the Total Mobile Population (Able-Bodied People and Mobile Disabled People), N. Ireland

	Adults			Children			Total (Adults and Children)		
Disability	*Unassisted*	*Assisted*	*Total*	*Unassisted*	*Assisted*	*Total*	*Unassisted*	*Assisted*	*Total*
Locomotion	6.00	1.60	7.60	0.20	0.10	0.30	6.20	1.70	7.90
Wheelchair users	0.05	0.09	0.14	—	—	—	0.05	0.09	0.14
Zimmer/rollator user	0.13			—	—	—	0.13		
Walking stick/crutch	1.27	1.52	6.91	—	—	—	1.27	1.52	6.91
No aid	3.99			—	—	—	3.99		
Reaching and stretching	1.80	0.80	2.60	0.00	0.00	0.00	1.80	0.80	2.60
Dexterity	2.20	0.90	3.00	0.10	0.00	0.10	2.20	0.90	3.10
Seeing	2.00	0.90	2.90	0.04	0.04	0.20	2.10	0.90	3.00
Blind	0.02	0.05	0.06	0.00	0.00	0.00	0.02	0.05	0.07
Hearing	4.20	0.80	5.00	0.10	0.10	0.20	4.30	0.90	5.20
Deaf	0.10	0.10	0.10	0.00	—	0.00	0.10	0.10	0.10
Mental or behavioral	2.00	0.70	2.70	0.30	0.20	0.50	2.30	0.90	3.20

Note: Percentages for each disability do not sum to percent provided of the mobile population since many individuals have more than one disability. Percentages for wheelchair users and walking aid users do not sum to total since some data is missing.

Source: K. E. Boyce, T. J. Shields, and G. W. H. Silcock, "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Prevalence, Type, and Mobility of Disabled People," *Fire Technology,* Vol. 35, No. 1, 1999, p. 41.

TABLE 4.1.37 Number of Disabled Adults Who Go Out and Experience Difficulty, Expressed as Percentages of Total Mobile Population of N. Ireland

	Go Out Unassisted Degree of Difficulty			Assisted Degree of Difficulty			Total Degree of Difficulty		
Action	*Some*	*Great*	*Impossible*	*Some*	*Great*	*Impossible*	*Some*	*Great*	*Impossible*
Go up and down stairs	2.4	1.10	0.20	0.2	0.60	0.20	2.59	1.69	0.43
Climb outside steps	1.5	0.80	0.20	0.3	0.40	0.20	1.81	1.14	0.40
Cross door saddles	0.1	0.10	0.03	0.2	0.10	0.01	0.32	0.13	0.04
Go through doors	0.1	0.03	0.01	0.1	—	0.01	0.15	0.03	0.02
Turn door knobs	0.3	0.10	0.03	0.2	0.07	0.05	0.43	0.13	0.08

Note: Since these percentages are based on adults only, the actual percentages of the mobile population in N. Ireland who experience difficulty may be higher.

Source: K. E. Boyce, T. J. Shields, and G. W. H. Silcock, "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Prevalence, Type, and Mobility of Disabled People," *Fire Technology,* Vol. 35, No. 1, 1999, p. 42.

TABLE 4.1.38 Extent of Involvement of Disabled Adults and Children in Various Social and Recreational Activities by Degree of Mobility, N. Ireland

	Adults			Children			Total (Adults and Children)		
Activity	*Unassisted*	*Assisted*	*Total*	*Unassisted*	*Assisted*	*Total*	*Unassisted*	*Assisted*	*All*
Participates in theatre, i.e., opera, musicals, ballet, cinema	9,756 (6.5)	2,514 (9.6)	12,270 (7.0)	1,028 (14.0)	387 (7.3)	1,415 (11.3)	10,784 (6.9)	2,901 (9.5)	13,685 (7.3)
Goes shopping*	1,532 (58.5)	2,233 (40.0)	3,765 (40.1)	153 (81.0)	53 (28.0)	206 (75.7)	2,235 (79.6)	1,330 (23.5)	3,565 (42.1)
Participates in indoor sport/ spectates sport	13,161 (8.9)	1,006 (4.0)	14,167 (8.1)	3,205 (44.0)	1,084 (20.5)	4,289 (3.4)	16,366 (10.5)	2,090 (6.8)	18,456 (9.9)
Attends ordinary social club	8,052 (5.4)	898 (3.6)	8,950 (5.1)	— —	— —	— —	8,052 (5.4)	898 (3.6)	8,950 (5.1)
Stayed in hotel/ other holiday accommodation	40,220 (27.0)	4,437 (17.6)	44,657 (25.6)	— —	— —	— —	40,220 (25.7)	4,437 (14.5)	44,657 (23.9)
Goes out for meals/drinks*	1,318 (50.3)	2,032 (36.4)	3,350 (40.9)	— —	— —	— —	1,277 (45.5)	2,032 (35.8)	3,350 (39.6)
Is employed	18,896 (12.7)	229 (0.9)	19,125 (11.0)	— —	— —	— —	18,896 (12.1)	229 (0.7)	19,125 (10.2)
Attends ordinary school	350 (0.2)	0 (0.0)	350 (0.2)	0 (0.0)	0 (0.0)	0 (0.0)	350 (0.2)	0 (0.0)	350 (0.2)
Attends college for further education	316 (0.2)	0 (0.0)	316 (0.2)	0 (0.0)	0 (0.0)	0 (0.0)	316 (0.2)	0 (0.0)	316 (0.2)

*Asked of disabled persons living in communal establishments only.

Source: K. E. Boyce, T. J. Shields, and G. W. H. Silcock, "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Prevalence, Type, and Mobility of Disabled People," *Fire Technology,* Vol. 35, No. 1, 1999, p. 44.

cies. It establishes that public buildings are frequented by a significant number of disabled people and that the nature of their disabilities and how well they can be expected to evacuate without assistance during an emergency will be a function of the use of the building or part of the building. Characterizing buildings and characterizing occupants as required by performance-based codes, are not mutually exclusive activities, a fact that has not yet percolated through the design professions.[80]

Movement by People with Disabilities

The second study by Boyce, Shields, and Silcock[81] involved experimental observations and measurement of the movement of impaired persons on a horizontal corridor, inclined ramps, and stairs. Observations included the velocity of movement, rest periods required, assistance required, and the physical aids used relative to their degree of mobility impairment. There were 107 persons (54 males and 53 females, ages 20 to 85) who completed the horizontal corridor without assistance. The velocity of this population relative to their mobility impairment is presented in Table 4.1.39. Sixteen of the manual wheelchair users needed assistance to traverse the 50 m corridor at the 90° turn, 8 m from the starting point. Only 34 individuals were capable of participating in the stair movement studies involving ascent and descent travel, 30 without assistance and 4 with assistance, including three blind persons.

In general the movement velocity was slightly faster in descent travel on ramps, whereas on the stairs the ascent movement was faster, as indicated in a comparison of Table 4.1.40 and Table 4.1.41.

These authors indicated the following findings from these experiments:

> The abilities of disabled people cover a wide spectrum with respect to movement on horizontal and inclined planes. Given the significant differences in the capabilities of those using different mobility aids and the inherent differences in their spatial requirements, it is suggested that, for evacuation and modeling purposes, they be considered separately.
>
> Escape times are usually determined from characteristic travel speeds coupled with premovement times. From this study it is apparent that, for some disabled people, it may also be necessary to include periods of rest and time to negotiate changes in direction. This paper's findings should help designers derive characteristic times for disabled people traversing any typical escape route.

TABLE 4.1.39 Speed (m/sec) on Horizontal by Presence/Absence of Locomotion Disability and Walking Aid—Unassisted Ambulant, N. Ireland

Subject Group	*Mean (m/sec)*	*Standard Deviation (m/sec)*	*Range (m/sec)*	*Interquartile Range (m/sec)*
All disabled (n = 107)	1.00	0.42	0.10–1.77	0.71–1.28
With locomotion disability (n = 101)	0.80	0.37	0.10–1.68	0.57–1.02
No aid (n = 52)	0.95	0.32	0.24–1.68	0.70–1.02
Crutches (n = 6)	0.94	0.30	0.63–1.35	0.67–1.24
Walking stick (n = 33)	0.81	0.38	0.26–1.60	0.49–1.08
Walking frame or Rollator (n = 10)	0.57	0.29	0.10–1.02	0.34–0.83
Without locomotion disability (n = 6)	1.25	0.32	0.82–1.77	1.05–1.34

Source: K. E. Boyce, T. J. Shields, and G. W. H. Silcock, "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and on an Incline," *Fire Technology,* Vol. 35, No. 1, 1999, p. 54.

TABLE 4.1.40 Speed (m/sec) on Stairs (Ascent) by Presence/Absence of Locomotion Disability—Unassisted Ambulant, N. Ireland

Subject Group	*Mean (m/sec)*	*Standard Deviation (m/sec)*	*Range (m/sec)*	*Interquartile Range (m/sec)*
With locomotion disability (n = 30)	0.38	0.14	0.13–0.62	0.26–0.52
No aid (n = 19)	0.43	0.13	0.14–0.62	0.35–0.55
Crutches (n = 1)	0.22	—	0.13–0.31	0.26–0.45
Walking stick (n = 9)	0.35	0.11	0.18–0.49	
Rollator (n = 1)	0.14	—	—	—
Without disability (n = 8)	0.70	0.24	0.55–0.82	0.55–0.78

Source: K. E. Boyce, T. J. Shields, and G. W. H. Silcock, "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and on an Incline," *Fire Technology,* Vol. 35, No. 1, 1999, p. 64.

TABLE 4.1.41 Speed (m/sec) on Stairs (Descent) by Presence/Absence of Locomotion Disability—Unassisted Ambulant, N. Ireland

Subject Group	*Mean (m/sec)*	*Standard Deviation (m/sec)*	*Range (m/sec)*	*Interquartile Range (m/sec)*
With locomotion disability (n = 30)	0.33	0.16	0.11–0.70	0.22–0.45
No aid (n = 19)	0.36	0.14	0.13–0.70	0.20–0.47
Crutches (n = 1)	0.22	—	—	—
Walking stick (n = 9)	0.32	0.12	0.11–0.49	0.24–0.46
Rollator (n = 1)	0.16	—	—	—
Without disability (n = 8)	0.70	0.26	0.45–1.10	0.53–0.90

Source: K. E. Boyce, T. J. Shields, and G. W. H. Silcock, "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and on an Incline," *Fire Technology,* Vol. 35, No. 1, 1999, p. 65.

The detailed observations made during the movement studies suggest that, in designing accessible escape routes, more attention needs to be focused on the real, rather than the perceived needs of disabled people. Consideration should be given to the nature and position of support systems such as handrails, and the positioning of doors in escape routes, since these will influence the progress and the flight behaviors of some disabled occupants.[82]

Door Operation and Egress

The third study by Boyce, Shields, and Silcock[83] was an experimental study of door operation and egress with 104 mobility-impaired

persons (54 male and 50 female, ages 25 to 85). Impairments of the participants involved 5 using crutches, 28 using a walking stick, 8 using a walker, and 63 using no mobility aids. The time to negotiate a standard single-leaf door with a clear width opening of 750 mm for these individuals is presented in Table 4.1.42 with the type of door operation and the closer force on the door leaf.

In addition to mobility impairments, other critical impairments for this action involved 45 persons with a minor reaching and stretching impairment and 58 persons with a dexterity impairment. Table 4.1.43 presents the failure rates and the time to negotiate the door for the seven manual wheelchair users. The manual wheelchair users in general took more time to push the door open than to pull the door open. It also took these wheelchair users three to four times longer than the mobility-impaired persons to negotiate the door.

Signage

The fourth study by Boyce, Shields, and Silcock[84] was an experimental study to determine the ability of impaired persons

TABLE 4.1.42 Time (sec) to Negotiate Door for Each Door Setting by Mobility Aid—Ambulant Disabled, N. Ireland

	No Aid ($N = 63$)			Crutch Users ($N = 5$)		Walking Stick Users ($N = 28$)			Walking Frame/ Rollator Users ($N = 8$)	
Closing Force (N)	*Mean (sec)*	*Standard Deviation (sec)*	*Range*	*Mean (sec)*	*Range*	*Mean (sec)*	*Standard Deviation (sec)*	*Range*	*Mean (sec)*	*Range*
Push										
21	3.0	0.8	1.7–4.5	3.7	3.6–3.8	3.7	1.5	2.3–7.4	7.9	2.0–12.8
30	3.5	2.2	1.9–15.0	3.0	2.5–3.2	3.8	1.5	2.5–7.3	6.3	2.2–10.5
42	3.7	1.5	1.6–10.2	3.8	2.9–5.2	4.0	1.6	2.3–7.5	5.2	2.1–10.3
51	4.1	2.4	1.0–14.3	3.6	3.1–3.9	4.3	2.4	1.5–10.7	7.9	2.0–14.3
60	4.0	1.9	1.3–13.0	3.8	3.6–4.1	3.7	1.5	1.7–7.9	5.2	2.0–10.3
70	4.3	2.0	1.7–11.2	3.9	3.3–4.6	4.6	2.1	2.5–11.1	6.2	1.7–11.2
Pull										
21	3.3	1.5	1.5–7.6	2.8	2.2–4.0	3.6	1.4	1.8–7.6	5.7	2.0–8.2
30	3.2	1.0	1.5–5.2	—	—	3.2	0.9	1.8–4.9	5.2	4.3–6.0
42	3.7	1.8	1.4–12.6	4.0	2.9–6.3	3.9	1.4	1.9–6.8	4.7	2.6–6.9
51	3.8	1.6	1.5–10.2	3.6	2.5–4.6	4.6	2.2	1.5–9.5	6.3	2.5–11.2
60	4.1	1.9	1.5–11.4	3.6	2.7–4.7	4.1	1.7	1.4–7.4	8.9	1.9–17.0
70	4.6	2.2	1.5–12.6	4.6	2.6–4.7	4.9	2.3	2.1–9.7	3.2	1.9–6.7

Source: K. E. Boyce, T. J. Shields, and G. W. H. Silcock, "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People to Negotiate Doors," *Fire Technology,* Vol. 35, No. 1, 1999, p. 73.

TABLE 4.1.43 Percentage of Failure and Time (sec) to Negotiate Door for Each Door Setting—Manual Wheelchair Users, N. Ireland

Closing Force Leading Edge (N)	*Number of Failures (Percentage)*	*Number Successful (Percentage)*	*Mean (sec)*	*Median (sec)*	*Range*
Push ($N = 7$)					
30	1 (14.3)	6 (85.7)	13.1	7.4	3.6–39.0
42	1 (14.3)	6 (85.7)	13.3	10.7	3.6–36.0
51	2 (28.6)	5 (71.4)	10.0	7.4	3.6–20.5
60	2 (28.6)	5 (71.4)	10.5	10.5	3.5–17.4
70	2 (28.6)	5 (71.4)	11.6	6.7	3.6–26.3
Pull ($N = 7$)					
30	2 (28.6)	5 (71.4)	13.5	11.3	3.7–34.0
42	3 (42.9)	4 (57.1)	12.8	6.8	3.8–34.0
51	3 (42.9)	4 (57.1)	10.5	7.0	3.8–24.0
60	5 (71.4)	2 (28.6)	4.2	4.2	2.8–4.6
70	5 (71.4)	2 (28.6)	4.3	4.3	3.7–5.0

Source: K. E. Boyce, T. J. Shields, and G. W. H. Silcock, "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People to Negotiate Doors," *Fire Technology,* Vol. 35, No. 1, 1999, p. 74.

to locate and read three types of exit signs: nonilluminated, internally illuminated, and light-emitting diode (LED) signs. The signs were placed in a clear atmosphere in a room 2.3 m from the floor with a maximum viewing distance of 85 m. The distance from which participants were able to read the exit signs was measured, presented in Table 4.1.44. A total of 118 impaired persons participated in this study, including 25 persons with a sight impairment. The LED signs appeared to be the most visible and legible by the impaired persons with and without a sight impairment.

In a related study, Shields[85] observed that wheelchair users and mobile participants did not impede each other in evacuation progress and wheelchair persons did not impede each other. Mobility-impaired persons with walkers did impede wheelchair users.

Elevator Use

Klote, Alvord, Levin, and Groner[86] examined the design considerations needed to use elevators in tall buildings for the evacuation of disabled occupants. In the World Trade Center explosion and fire of 1993, the loss of power in both towers (including emergency power) trapped occupants in elevators in both buildings.

Burns[22] indicated WTC 1 had 99 elevator cars, many of them occupied. When one 6 ft × 8 ft (1.8 m × 2.4 m) car was opened, nine occupants were found unconscious. It was estimated that they had been exposed to the smoke in the shaft for approximately 2 hours at the ninth floor. Sherwood[87] reported that one 9 ft × 12 ft (2.7 m × 3.6 m) elevator car was stuck for 6 hours at the 41st floor of WTC 2 with 72 occupants (62 elementary schoolchildren and 10 adults).

NFPA *101* in the 1991 edition permitted the use of elevators with fire-fighter service from areas of refuge, which are also specified in this handbook. In 1997 the *Life Safety Code* permitted the use of a fire-fighter service elevator with special features to be used as a second means of egress from towers, along with specifications on the occupant load of the tower, the provision of automatic sprinklers, the egress arrangement, and capacity.

In the 1970s Pauls studied a number of evacuation drills in high-rise office buildings in Canada, which indicated that approximately 3 percent of the occupants were unable to use the stairs due to permanent or temporary conditions limiting their mobility.[88] The study population included occupants with heart conditions and individuals recovering from surgery, other illnesses, and accidents.

FIRE EXIT DRILLS

Determining when and what area to evacuate is probably the most important decision in a fire emergency. Any area at all affected by heat, flame, or smoke should be evacuated; in case of doubt, the entire building should be evacuated. Well-marked exits do not ensure life safety during an evacuation. Exit drills are necessary so that occupants will know how to make an efficient and orderly escape according to NFPA *101,* which contains detailed information on exit drills in individual occupancies.

Exit Drill Requirements and Procedures

Exit drills are required in schools, board-and-care facilities, and health care facilities, and are common in industries with high hazards. Employee training and drills are required in assembly, hotel, mercantile, and large business occupancies. Some form of exit drill should be conducted wherever or whenever possible to avoid confusion and ensure the evacuation of all occupants during a fire.[89] Personnel should be assigned to check exits for availability, search for stragglers, count occupants once they are outside the fire area, and control re-entry into the building before it is safe.

This re-entry behavior for rescue purposes of persons involved in fires should be noted. In a study of 335 fire incidents involving 584 persons, it was found that 163 persons, approxi-

TABLE 4.1.44 Distance (m) at Which Subjects Can Read Exit Signs by Presence/Absence of Seeing Disability, N. Ireland

Type of Sign and Subject Group	*Mean (m)*	*Median (m)*	*Standard Deviation (m)*	*Range (m)*	*Interquartile Range (m)*
Nonilluminated exit sign					
All disabled (N = 105)	13.3	15.0	3.1	1.0–15.0	12.0–15.0
With seeing disability (N = 25)	11.4	12.0	4.0	1.0–15.0	9.7–15.0
Without seeing disability (N = 80)	13.7	15.0	2.7	6.0–15.0	15.0–15.0
Illuminated exit sign					
All disabled (N = 118)	14.2	15.0	2.7	1.0–15.0	15.0–15.0
With seeing disability (N = 25)	12.9	15.0	4.6	1.0–15.0	15.0–15.0
Without seeing disability (N = 93)	14.5	15.0	1.8	6.0–15.0	15.0–15.0
LED sign					
All disabled (N = 83)	14.6	15.0	1.6	5.0–15.0	15.0–15.0
With seeing disability (N = 23)	14.0	15.0	2.6	5.0–15.0	15.0–15.0
Without seeing disability (N = 60)	14.7	15.0	1.2	7.0–15.0	15.0–15.0

Source: K. E. Boyce, T. J. Shields, and G. W. H. Silcock, "Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of People with Disabilities to Read and Locate Signs," *Fire Technology,* Vol. 35, No. 1, 1999, p. 83.

mately 28 percent of the study population, re-entered the fire buildings following evacuation.[7] Approximately 10.5 percent of those persons who re-entered the buildings did so to alert or assist other persons.

The fire loss prevention and control management staff are responsible for planning exit drills. Plans should be discussed with both middle and line management to ensure understanding and cooperation. If there is no fire loss prevention and control manager, the plant, facility, or building manager should assume this responsibility or assign it to a staff member. After each exit drill, a meeting of the responsible managers should be held to evaluate the success of the drill and to solve any problems that may have arisen.

All employees should recognize the evacuation signal and know the exit route they are to follow.[90] On hearing the signal, they should shut off equipment and report to a predetermined assembly point. Primary and alternative routes should be established, and all employees should be trained to use either route.[90,91]

The problem with audible evacuation signals is the conditioning of the population within the occupancy to ignore the signal due to numerous false alarms. An investigation of an apartment building fire found that the alarm system actuation to initiate evacuation behavior was ignored by many of the building occupants due to the conditioning effect of numerous prior false alarms; 44 percent of the building occupants believed the alarm signal was a false alarm.[92]

When employees are assembled, the manager or supervisor of each area should account for all personnel. Missing employees should be immediately reported to the fire loss prevention and control manager and responding fire department personnel so that search and rescue efforts can be initiated. Only trained fire-fighting search and rescue personnel with adequate protective equipment should be permitted to re-enter an evacuated area.

One significant improvement to the traditional concept of fire drills in educational occupancies was suggested by a study of fire drills conducted in such occupancies.[93] The concept of smoke drills has been established, whereby the occupants are instructed to move through the simulated smoke areas in a crouched position. Students have transferred the smoke drill concept to fire incidents in residential occupancies, with effective results. Obviously, smoke drill training may be effective in a fire and should be used where applicable.

The timing of drills depends on the nature of the operation in the facility. Generally, drills conducted a few minutes before the lunch break have been found to minimize loss of time and production. The frequency of drills should be determined by the degree of hazard present and by the complexity of shutdown or evacuation procedures.

If a facility does not maintain a security organization that is responsible for daily inspection of emergency exits and designated evacuation routes, one employee in each area should be assigned this task. Maintenance of doors, panic hardware, exit lights, and emergency illumination should be given high priority, and repairs must be made without delay.

Research has found that for multistory office buildings, a trained group of floor wardens is the most effective means of monitoring the evacuation of occupants.[89] Adequate training for floor wardens or other personnel is necessary and must be specifically developed to include the procedures of the emergency evacuation plan for the facility. The most serious problem with using building monitors is the turnover of personnel due to employee transfers, reassignments, or resignations. Effective evacuation planning and preparation should assign specific responsibilities to staff positions (rather than individuals) within an organization. This ensures continuity of performance despite personnel changes.

The evacuation signal should be familiar to all employees. Vocal alarm systems (VAS)[94,95] reduce the need for employee perception and recognition of a signal, because the system provides vocal communication to the areas designated for evacuation. NFPA *101* first recommended the use of the VAS in assembly occupancies in 1981. An evaluation of VAS systems in nine buildings found that familiarity with the system compared with initial activation without prior familiarity did not significantly affect the egress behavior of populations.[87] In addition, the investigation determined the evacuation drills were valuable because they gave floor or area wardens an opportunity to rehearse their procedures. The use of an alerting tone in the frequency range of 2000–4000 Hz for the VAS is recommended prior to the verbal announcement, which should be specific for the audience and the facility.[90,95]

Health Care Facilities Drills

Fire drills in health care institutions are usually conducted as a part of the orientation program for new employees. Later, the drills are supplemented with in-service training for the staff personnel, including the emergency procedures. Fire drills in many facilities are conducted once a month on each shift. The training for the drills typically involves instruction and practice for the staff personnel in the various means of moving nonambulatory patients, procedures for alerting the facility staff, and the method of notifying the fire department. Once or twice a year, many facilities have fire departments provide training in the operation of portable fire extinguishers. Some fire departments actually provide staff personnel with experience in the operation of extinguishers on external fires.

However, most health care facilities prefer to train their personnel. The lecture method has been used to convey the essential features of the emergency plan to employees in health care facilities.[94] However, it was also found that the emergency plan in the facility studied was too general and ambiguous. Most health care facilities adopt the philosophy that it is the staff's responsibility to ensure the safe evacuation of patients initially to an area of refuge and then to the exterior if necessary. The control of the fire is limited to preventing the spread of heat and smoke by closing doors. This protects the occupants and inhibits or restricts the propagation of smoke and heat throughout the facility. Staff personnel have effectively evacuated numerous patients during fires or have protected the patients in their rooms by closing doors.[96]

A content and time evaluation of fire drill behavior by staff in six nursing homes concluded that a training program of the most modest type can produce changes in both knowledge and

behavior of evacuation and fire emergency procedures.[94] A total of 339 nursing home staff participated in the study that matched a group of 37 persons receiving the training with a control group of 49 persons not receiving the training. The high rate of personnel turnover, which appears to be rather typical in nursing home facilities, was noted. Following the presentation of the training program, staff members were evaluated by a written knowledge test, and their behavior was observed during the conduct of a drill of the emergency plan.

The evacuation process may be considered in four sequential phases: (1) the personnel supply phase, (2) the patient preparation phase, (3) the patient removal phase, and (4) the rest and recovery phase.[97] This approach focuses on the occupants in the fire-threatened area and the patients in or adjacent to the fire area. Removing immediately threatened patients and closing doors to the room of fire origin and to adjacent patient rooms would be compatible with this four-phase approach to evacuation. A detailed report on the fire evacuation organization, training, and drills involved in a 502-bed acute-care teaching hospital with 2500 employees has been published.[98]

In 1985, NFPA *101* included a new chapter devoted to the fire protection and life safety requirements for board-and-care facilities. That chapter now requires the evaluation and classification of the population of existing facilities according to their evacuation capability.

Evaluating Fire Drill Plans

The ultimate evaluation of fire drill and emergency plans has two factors: (1) performance of the occupants in a fire, and (2) effectiveness of the behaviors used in accordance with the fire drills or the fire emergency plan. In a World Trade Center fire incident report,[21] building occupants tended to seek verification of their beliefs about the threat of fire by physical clues, primarily smoke in the occupants' area. The report also indicated public address messages were not sufficient to alleviate spontaneous evacuations when occupants saw smoke on their floor. Further, occupant evacuation was reported (9th through 22nd floors) due to the perception and concern that a valid fire threat existed. In actuality, the fire did not require such an extensive evacuation.

Successful evacuation of personnel from the two floors above and below a fire in a 28 story high-rise college dormitory has been reported.[99] To allow free evacuation flow of the occupants down the stairways and allow fire department personnel to move up the stairs, stairs have been marked for occupant and fire department movement. The fire department movement stair has a red circle, 6 in. (152 mm) in diameter on the door; it is also utilized for ventilation. The occupant stair is marked with a 6 in. (152 mm) green circle.

In the safe evacuation of 190 guests during a high-rise hotel fire, 110 guests were assisted by the fire department. The success of the evacuation was made possible by the hotel employees' fire safety education and practice of evacuation procedures.[100]

Figure 4.1.20 correlates human response to cues, decision making, and movement as variables of individual behavioral response during fires.

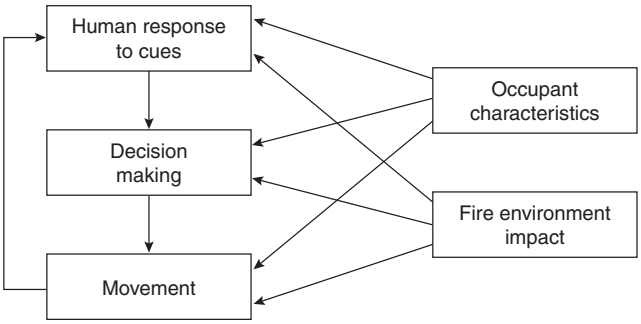

FIGURE 4.1.20 Principal Interrelationships of Human Factors (Reproduced with permission from the *Engineering Guide: Human Behavior in Fire.* Copyright 2003, Society of Fire Protection Engineers)

SUMMARY

The Society of Fire Protection Engineers *Human Behavior in Fire, Engineering Guide*[101] summarizes the variables that are related and may be determinants of an individual's behavior in a given fire. Occupant characteristics include not just individual physical, cultural, and psychological characteristics but also other factors of the occupant's primary group relative to the occupational/cultural setting of the fire. The fire environmental impact includes the evaluation of the susceptibility of the occupants to the heat, flames, smoke, and toxic gases created by the fire incident relative to the locations of the fire effects and the occupants within the confines of the building, structure, or at an unconfined fire incident.

Behavior in fires can be understood as a logical attempt to deal with a complex, rapidly changing situation in which minimal information on which to act is available. It is suggested that the goals of codes should be "reoriented to increase the likelihood of informed decisions being made by people in fires."[102] Examination of behavior in the Beverly Hills Supper Club fire led to the recommendation that "fire safety education should consider and be based on people's erroneous conceptions about distance being related to safety, and the time needed to escape from a fire emergency."[103] More than a decade of detailed systematic research on human behavior in fires has resulted in the following consensus[61] on the behavior of most persons:

> Despite the highly stressful environment, people generally respond to emergencies in a "rational," often altruistic manner, insofar as is possible within the constraints imposed on their knowledge, perceptions, and actions by the effects of the fire. In short, "instinctive panic" type reactions are not the norm.

The relationship between the physical and social environment in which behavior occurs is complex. The situation is complicated by the individual's perception of ambiguous fire cues, which is primarily influenced by the person's relevant training and previous fire experience, if any. It must be recognized that fire cues are a product of a rapidly changing dynamic process that is constantly altering the decisions of the building occupant.

This dilemma has been summarized: "What is an appropriate action at one stage may be quite inappropriate a minute later."

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on human behavior and fire discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 72®, National Fire Alarm Code®
NFPA *101®, Life Safety Code®*

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Chapter 2

Calculation Methods for Egress Prediction

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Chapter Contents

Components of Evacuation Time
Estimating Evacuation Time
Calculation Methods for Travel Time
Computer Simulation and Modeling of Egress Design

Key Terms

delay time, disabled occupants, egress, evacuation, evacuation time, occupant characteristics, pre-evacuation activity time, reaction time, Station Nightclub fire, time to notification, travel time

The evaluation of an engineered design requires a balanced comparison of predicted fire conditions and realistic evacuation predictions. Over the past decade or so, fire safety engineers have worked with, and developed confidence in, a range of calculation methods for the prediction of fire conditions. Researchers working in the area of human behavior in fire have begun to make real progress in the collection of data necessary for this analysis and in the development of predictive tools that will be comparable to those used to predict the growth and spread of fire and its effects.

Performance building and fire codes allow designers to use innovative building materials and concepts often not encouraged or even permitted in existing prescriptive codes, which can result in more cost-effective and creative designs. But this openness to innovation requires the designer to then demonstrate that the design is safe. For a design to be shown to be "safe," the designer must demonstrate that the time needed to move people to a safe location will be less than the time predicted when fire effects will have a potentially lethal impact on any occupant.

Time available to escape (ASET) > Time needed to escape (RSET)

ASET is defined as the time interval between fire ignition and the time at which conditions become untenable and occupants are unable to move to a location of safety, and RSET is defined as the time period required for an occupant to travel from his or her initial location to a location of safety. The location of safety can be a temporary refuge or can be a location completely free from danger. Fire safety design is a two-sided problem that requires fire safety engineers and the enforcement community to have knowledge in the use of both fire models and egress and human behavior models. Currently, fire safety engineers are very well trained in predicting fire growth and the spread of fire effluents in a structure. The focus of a fire safety design appears to favor this component of the fire safety problem. But it is crucial that the complexity and importance of the egress/behavior component never be underestimated or short-changed and that a balance between both components be maintained.

For their part, building and fire officials (the enforcement community) need to evaluate designs presented in their jurisdictions that will use various computer models or other calculation methods to demonstrate both the time necessary and the time available for occupant evacuation. They may need guidance on how to judge the appropriateness of methods, data, and assumptions used in these evaluations, particularly in the egress portion of analyses.

Members of both user groups must balance the two sets of escape time calculations in order to produce a meaningful result.

See also Section 4, Chapter 1, "Human Behavior and Fire"; and Section 4, Chapter 5, "Strategies for Occupant Evacuation During Emergencies."

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COMPONENTS OF EVACUATION TIME

The *evacuation time* for an individual is the entire span of time that elapses from the ignition of the fire until the occupant emerges from the building or arrives at a location of safety. It consists of four components, all of which must be taken into consideration:

- Time to notification
- Reaction time
- Pre-evacuation activity time
- Travel or movement time

The first three components are often grouped together and referred to as "delay time" or "premovement time."

$$\begin{aligned}\text{Evacuation time} &= \text{Delay time} + \text{Travel time}\\ &= \text{Time to notification} + \text{Reaction time}\\ &\quad + \text{Pre-evacuation activity time}\\ &\quad + \text{Travel time}\end{aligned}$$

It is very important that engineers not underestimate the contribution that delay time can make to total evacuation time. Studies of evacuation drills in apartment buildings have shown that, on average, travel time makes up less than 25 percent of the average total time to evacuate.[1] In office evacuations, however, delay times can be extremely short, and the largest proportion of total evacuation time is accounted for by travel time. Therefore, the selection, estimation, or calculation of premovement times is extremely important to obtain valid results.

Time to Notification

In the evaluation of an engineered building design, evacuation time begins when ignition occurs. Some period of time, the time to notification, will elapse before conditions develop to the point where an alarm sounds or where people begin to sense the cues of the fire itself. The fire cues that reach occupants can be the sight or smell of smoke, heat, the sight of flames, the sound of glass breaking, or the sound of an alarm signal from a smoke alarm, a heat detector, or a sprinkler system. The time to notification can be modeled, or it could be estimated if necessary using expert judgment.

Fire growth and smoke transport models can be used with detector/sprinkler activation models to estimate this period of time. Some models that can be used include ASET,[2] which estimates the temperature and position of the smoke layer in the room of fire origin; DETACT,[3] which models heat detection and sprinkler activation; BREAK1,[4] which estimates time until glass breaks; or FDS (Fire Dynamics Simulator)[5], which predicts the transport of heat and smoke from a fire.*

Reaction Time

Reaction time is the time it takes an occupant to perceive the alarm or fire cue and decide to take action. For example, if a person is asleep when the smoke alarm sounds, it will take some period of time for the person to wake up, to identify the sound as the smoke alarm, and to decide to leave. There is currently no generally accepted modeling technique available for reaction time. The time used in an analysis may depend on observations (data) or expert judgment. An appropriate reaction time will depend on whether the person is awake or asleep, on his or her hearing ability, mental capacity, age (baby/child/adult), and so on. Some findings on sleep inertia in young adults awakened by smoke alarms have been published in recent years.[6] Studies have also looked at the ability of smoke alarms to awaken children and intoxicated adults.[7,8]

Pre-Evacuation Activity Time

Pre-evacuation activity time includes the time that elapses while the occupant is preparing to leave or seek refuge. Pre-evacuation activities involve all of the activities in which an occupant will engage from the time when he or she makes the decision to leave until the time he or she actually starts to travel toward an exit or an area of refuge. These activities may vary by occupancy. For example, hotel occupants might stop to pack their bags before they leave their rooms, whereas office workers may take time to shut off equipment and lock files. In an industrial setting, there may be a procedure that must be followed to safely shut down the plant's operations. To some degree, pre-evacuation activities can be reduced or eliminated through education or training. As with reaction time, there are no generally accepted modeling techniques available for pre-evacuation activity time, and the time used in an analysis may depend on observations (data) or expert judgment.

In reality, reaction time and pre-evacuation activity time are often considered together. In data collection exercises, it is generally not possible to separate the two time components, and the results will be reported as a single, combined time from notification to the time that movement toward the exit begins. Some of the data on pre-evacuation delays that have been obtained from postfire behavior studies and evacuation drills will be presented later in this chapter.

Travel Time

Travel time is the final component in the calculation of evacuation time. It is defined here as the time to move to a location of safety. There are various calculation or estimation techniques available for travel time. Some simple calculation methods can be found in FPEtool,[9] which is available from the National Institute for Standards and Technology (NIST) in the United States. These are based on some of the hand calculation methods described later in this chapter.

ESTIMATING EVACUATION TIME

For evacuation modeling, several types of data are needed, either as model inputs or as considerations for the designer in setting up an analysis of a building design. A major data category that overarches the components of evacuation is occupant factors. Occupant factors include the characteristics of the people who would be expected to populate a building, whether on a perma-

*The mention of these models does not represent or imply an endorsement of the models or the organizations that developed them.

nent or transient basis. These factors include age, agility, commitment to the task at hand, familiarity with the building, level of training in what to do in emergencies, and many others.

More specifically, to calculate evacuation time, data are needed on delay times and travel times for a range of occupancy types. What types of delays should be expected, and how long they may last, is very often a function of the characteristics of the occupants. Likewise, travel times will be impacted by the characteristics of the occupants.

Factors Related to Delay Times

Delay times, also referred to as premovement time, initial response time, or time to start, can last from a few seconds to several minutes or more. It is important to remember that during this period of delay, people might be simply ignoring available cues, or they might be engaged in pre-evacuation activities as discussed earlier. As described previously, delay time includes time to notification, reaction time, and pre-evacuation activity time.

Several factors can result in variations in delay times. These factors, which are also related to the characteristics of the occupants, include the following:

- Effectiveness of different cues
- Effectiveness or training
- Time of day, weather, and so on

Alarm devices use different sounds and, as a result, there can be confusion among building occupants as to what the sound is that they are hearing. And the alarm itself does not give people information as to what actions they should take. When building occupants hear an alarm, will they know if it is a burglar alarm or a fire alarm? Will they know if they should evacuate, or wait for further instructions? Voice communication systems, on the other hand, can convey information to building occupants and can decrease delay times by telling people what the situation is and what they are expected to do and how they should do it.

Training has been shown in studies to decrease delay times.[10] Trained building occupants can be expected to know where the closest exits are, should be able to recognize the alarm signal and know what to do, and could be expected to have shorter delay times. In buildings such as theaters and shopping centers, where the building occupants are not expected to be familiar with the alarms and exits, trained staff can reduce delay times significantly by directing occupants to the nearest exits immediately on hearing an evacuation signal.

Time of day and weather can have an impact on premovement delays. People may be reluctant to leave a building during a storm, in cold weather, or during the night. People may need extra time in winter to dress themselves and small children warmly.

Various characteristics of the occupants can also impact delay times. People with hearing impairments may not hear or interpret the sound of an alarm as quickly as people without impairments. People with mobility impairments may be slower to prepare themselves to evacuate or move to another location in the building. People who are engrossed in an activity may be too preoccupied to hear an alarm or warnings from other occupants, and then may be reluctant to leave what they are doing to take any protective actions.

Available Data on Delay Times

There are two principal sources of data on delay times: postfire survey questionnaires and videotaped observations from drills. Each method of data collection has its own advantages and disadvantages. Postfire survey questionnaires provide a method to collect information from real fires. However, it is very difficult for people to accurately estimate timelines for events in the past, particularly for traumatic events. Another problem is the subjectivity of the observations. For example, when people are asked to describe the thickness of smoke they traveled through or the duration of events, there is often a wide disparity in the descriptions among people who were in the same space at the same time. Videotaped observations allow the collection of very precise timelines, occupant densities, and travel flows in corridors and through doorways; however, the building occupants are not operating under any threat, and it is not clear to what degree observations from a fire drill will provide a good estimate of delay times or travel speeds in real fires. A third alternative method that has been mentioned recently is the use of video recordings from security cameras operating during a fire incident. Although the existence of such recordings has been mentioned, no data from the tapes have been reported yet in the literature. Some news footage of fires and evacuations in progress has been recorded in recent years. Examples include the Station Nightclub fire in Rhode Island in 2003 and the football stadium fire in Bradford (UK) in 1985.

Until behavioral models exist that can accurately predict the activities and behaviors of occupants before they begin to leave a building, it will be necessary for a designer evaluating an engineered design to provide an estimate of the duration of time those activities will require. Although a database of "accepted values" does not yet exist, there are summaries of delay times observed in several evacuation drills and actual fires available in the literature.[11]

One such summary report is based on five case studies that involved two sets of evacuation drills in apartment buildings, one set of office building drills, an actual apartment building fire and a fire in a megastructure complex.[12] The five case studies were part of an ongoing data collection project on human behavior in fire conducted at the National Research Council of Canada. These studies uncovered a broad range in the delay times that can occur and provided an indication of some of the factors that can result in delays. The times observed in these studies cannot be taken at face value as the "correct" times a designer should use, but they do provide an indication of the range of times that exists in real-life situations.

The main factor influencing delay times in the evacuation drills was the audibility of the alarm system. The evacuation drills in apartment buildings took place during two research projects and involved seven mid- and high-rise buildings. In the two mid-rise apartment buildings where the performance of the alarm systems was described as "good," the average time for occupants to begin evacuation was 2.82 minutes. For the two mid-rise apartment buildings with alarm system performance

described as "bad," the average delay time increased to 8.92 minutes.

Alarm system performance in two of the high-rise apartment buildings was described as "good," but the average delay time in those evacuations was quite different: 2.80 minutes in one and 5.32 minutes in the other. This discrepancy pointed out another factor that can significantly influence delay time—the weather. Since it was snowing at the time of one of the high-rise evacuation drills, the occupants took the time to dress warmly before leaving their apartments, adding approximately 2.50 minutes to the mean delay time. Overall in the apartment drills, the shortest average delay time for a building was 2.50 minutes and the longest was 9.70 minutes. Clearly, then, the delay time selected by a designer in the calculation of total evacuation time can greatly impact the final result and must be chosen with care.

The short delay times observed in the two office building evacuation drills demonstrated the combined effect of "good" alarms, training of occupants, and the use of fire wardens to assist in the evacuation. The delay times in the two drills averaged 0.60 minute and 1.05 minutes.

The activities most frequently reported in postdrill questionnaires were gathering valuables, getting dressed, and notifying others. To these activities, the participants in the residential drills had added: looking in the corridor, finding children, finding pets, and moving to the balcony.

A building designer must be cautious when using delay time data from evacuation drills as input to an evacuation model, as drills might underestimate the amount of time an occupant will delay. Although one might expect that occupants will move more quickly in an actual fire, it often takes longer, while the occupants attempt to sort through ambiguous cues and determine whether or not they really need to act.[13]

The postfire human behavior study provided important evidence that evacuation might take longer in an actual fire than in a drill. The fire started on the fifth floor of a 30 story building at approximately 5:00 a.m. on a winter morning. Six building occupants died in two stairwells while attempting to evacuate. The building occupants who participated in this study filled out questionnaires 2 to 3 weeks after the fire. Because of the time that elapsed between the fire and the survey, the occupants often rounded off the times they reported, but the study still provided important information on the range of time between various activities and events. Although the respondents in this study reported delays in beginning evacuation that ranged from 0 to 12 hours, close to half of the occupants attempted to leave within the first hour of becoming aware of the fire. And because no one above the fire floor who started evacuating after 5:30 a.m. was able to reach ground level on his or her own, the activities of the occupants in the first hour are of most interest. The average delay time for occupants who started to evacuate in the first hour was 10.50 minutes.

The human behavior study of the megastructure complex involved the explosion and fire that impacted the two 110 story World Trade Center towers in New York City in 1993. Building occupants had been trained, as had the occupants in the office drills mentioned previously, but in this case they were trained to wait on their respective floors for instructions. Since the emergency control center was destroyed in the explosion, the fire alarm system did not sound and no messages were transmitted. Occupants were forced to rely on ambiguous cues to alert them to the incident. Since the explosion was closer to the base on one tower, cues in that tower were somewhat less ambiguous than in the other. The delay times reported for the tower closer to the blast ranged from 0 to 4.08 hours, with a mean time of 11.03 minutes and a median time of 5.00 minutes. For the other tower, the delay times ranged from 0 to 3.08 hours, with a mean time of 25.40 minutes and a median time of 10.00 minutes.

Additional data need to be collected before a database exists that will provide precise estimates suitable for use, directly, in evacuation modeling. This set of studies illustrates, however, the variation that exists among different types of occupancies, between occupancies of the same type, and between drills and actual incidents, as well as the role of alarm effectiveness, training, and weather.

It is important to mention that the delay times described here are mean times. The distribution of delay times shown in Figure 4.2.1 is typical, with most times relatively short, but with a long tail that can stretch to infinity (representing building occupants who never leave the building during the incident). The data in Figure 4.2.1 comes from a fire drill in a one-story department store.[10] A fire safety engineer or building designer must take into consideration the actual distribution of delay times in evaluating an engineered design.

As mentioned earlier, some of the data collected has been summarized in a recent paper that proposed a database of travel speed and delay time data.[11] The delay time data from that paper can be found in Table 4.2.1.[14–25] The studies represented in this table involved hotels, office buildings, department stores, and a training facility. The user is cautioned to refer to the source documents for the full context of the experiments and incidents before applying the data to his or her application; otherwise, important differences between the evacuations that were the source of the data and the design being evaluated will be missed, and the resulting analysis could be completely invalid.

Factors Related to Travel Time

Travel time is a function of travel speed and distance to the exit and will vary among occupants. Evacuation models handle the calculation of travel time in various ways. Some evacuation models require the user to set a travel speed that will apply to all occupants throughout the evacuation, but this method does not take into account the effect of crowdedness, which will slow the travel speed of the occupants and increase their travel and total evacuation time. Another problem is that a uniform travel speed does not take into consideration the differing abilities of the building's occupants.

Travel time is to some degree a function of exit choice, because exit choice will determine travel distance. Buildings can be designed with multiple exits in the hope that people will use the closest exit in an emergency and thereby reduce their evacuation time. It has been shown time and again, however, that people tend to use the exit with which they are familiar, even if there is a closer emergency exit.[26] Without training, or instructions from trained staff, it may not be appropriate to assume that people will take the shortest route out of a building.

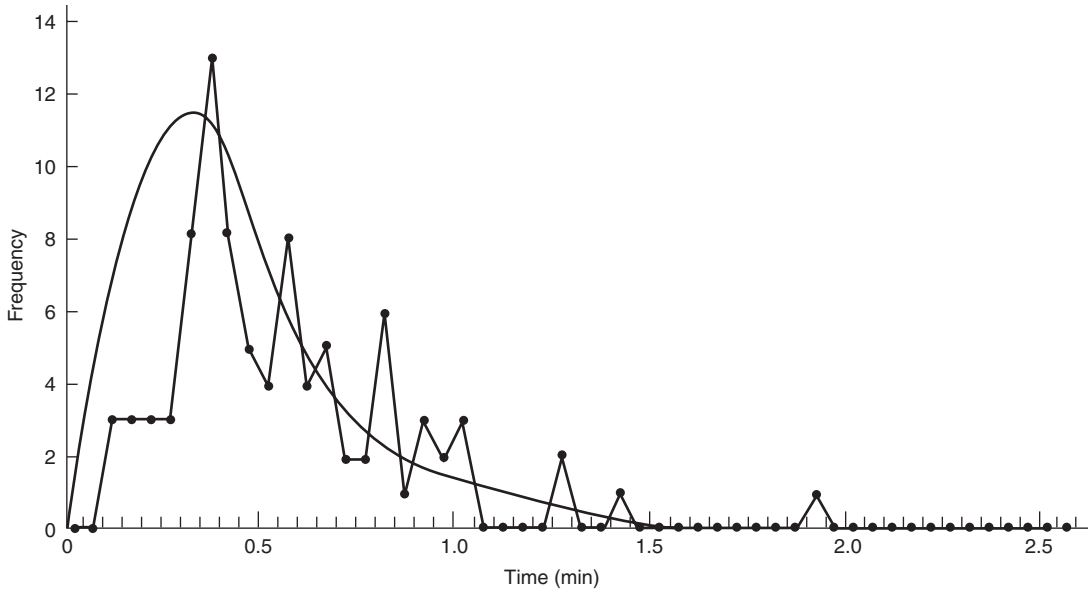

FIGURE 4.2.1 Experimental and Theoretical Premovement Times in a Department Store Evacuation

Other occupant characteristics impact both delays and travel time, but until very recently much of the necessary data to calculate their effects were not available. One important characteristic for which data have not been readily available is mobility, but a series of papers on the characterization of occupants of buildings, with particular emphasis on disabled occupants, was published in 1999. The series of papers covered the following:

- Prevalence, type, and mobility of disabled people
- Capability of disabled people to move horizontally or on an incline
- Capability of disabled people to negotiate doors
- Capability of disabled people to read and locate exit signs

The first paper documents a study that was done in Northern Ireland to estimate the number of disabled people who leave their homes and should be expected to use a variety of public buildings.[27] The study also looked at what percentage of the mobile population consists of the mobility impaired as well as to what degree those who use public places are disabled, concentrating on disabilities that would influence a person's ability to escape a fire. According to this study, almost 8 percent of the total mobile population has a mobility impairment of some sort and 0.14 percent use a wheelchair. The study also looked at the use of public buildings by people with disabilities and found that approximately 40 percent of mobility-impaired adults frequent theaters and sports facilities, almost 60 percent stay in hotels, almost 30 percent are employed, and approximately 50 percent frequent eating and drinking establishments. The paper also presents detail on the frequency of use of public spaces and degree of mobility (whether or not they require assistance). A design team should be able to calculate, using the data presented in the paper, the proportion of building occupants likely to have a mobility impairment. Other types of disabilities that impact the ability to evacuate are also detailed, including dexterity, reaching and stretching, seeing, hearing, and mental abilities.

The second paper in the series provides important data on the travel speed of a mobility-impaired population on horizontal paths, ramps, and stairs, with and without assistance.[28] For those traveling without assistance on horizontal paths, the mean speed for the mobility-impaired group was 2.62 ft/sec (0.80 m/sec), compared to 4.10 ft/sec (1.25 m/sec) for those not mobility impaired. The mean travel speed for the mobility impaired varied by type of aid required, from 1.87 ft/sec (0.57 m/sec) for walker users to 3.12 ft/sec (0.95 m/sec) for those who did not use an aid. Electric wheelchair users had a mean travel speed of 2.92 ft/sec (0.89 m/sec) whereas manual-wheelchair users had a mean speed of 2.26 ft/sec (0.69 m/sec). Travel speed data are also presented in the paper for movement on ramps, up and down stairs, and around corners. Information on the study participants' use of travel paths included observations on the amount of space used by people as they made their way along corridors or on stairs, the use of handrails, and difficulties negotiating stairway landings. An important added consideration covered in this paper is the rest time that many participants required while negotiating the 164 ft (50 m) paths and the recovery time required by those who completed the 164 ft (50 m) distance without stopping.

The third paper in the series looks at the ability of disabled people to use doors.[29] The data in the paper include the percentage of mobility-impaired participants who could not negotiate doors with various closing forces and the time needed to negotiate doors of various closing forces, overall and by type of aid used. The authors conclude in this paper that the travel times predicted for disabled building occupants must include the time needed to negotiate doors.

The fourth and final paper in the series looks at the ability of disabled people to locate and read exit signs.[30] The study

TABLE 4.2.1 Delay Times (Minutes) Derived from Actual Fires and Evacuation Exercises Reported in the Referenced Literature

Event Description	*N*	*Min*	*1st Q*	*Median*	*3rd Q*	*Max*	*Mean*	*Factors*
High-rise hotel[14]	536	0	3.3	60.0	130.9	290.0	NA*	MGM Grand Hotel fire, no alarm notification, grouped data from questionnaires
High-rise hotel[15]	47	0	2.0	5.0	17.5	120.0	NA	Westchase Hilton Hotel fire, no alarm in early stages, grouped data from questionnaires
High-rise office building[16]	85	0	2.0	5.0	10.0	245.0	11.3	World Trade Center explosion and fire, no alarm notification (building closer to explosion)
High-rise office building[16]	46	0	4.5	10.0	31.5	185.0	28.4	World Trade Center explosion and fire, no alarm notification (building further from blast)
High-rise office building[17]	107	1.0	1.0	1.0	1.0	~6.0	NA	Fire incident, no alarms, data from interviews with occupants of four floors of building (11 interviewees were trapped)
High-rise office building[18]	12	0.5	NA	1.0	NA	2.3	1.2	Unannounced drill on three floors; data for first person to reach each of four stairwell doors to wait for voice instruction; trained staff; data from video recordings
Mid-rise office building[19]	92	0	0.4	0.6	0.8	<4.0	0.6	Unannounced drill, good alarm performance; fire wardens; warm day
Mid-rise office building[19]	161	0	0.5	0.9	1.4	<5.0	1.1	Unannounced drill, good alarm performance; fire wardens; cool day
One-story department store[20,21]	95	1.0	0.2	0.3	0.5	0.9	0.4	Unannounced drill; trained staff; data here derived from grouped data for 95 participants
Three-story department store[21]	122	0.05	NA	NA	NA	1.6	0.6	Unannounced drill; trained staff; times distilled from analysis of videotapes
One-story department store[21]	122	0.07	NA	NA	NA	1.7	0.5	Unannounced drill; trained staff; times distilled from analysis of videotapes
One-story department store[21]	71	0.03	NA	NA	NA	1.0	0.4	Unannounced drill; trained staff; times distilled from analysis of videotapes
High-rise apartment building[22]	NA	0	NA	NA	NA	NA	10.5	Forest Laneway fire; for occupants who attempted to evacuate in the first hour, based on questionnaire responses
	219	0	NA	187.8	NA	720.0	190.8	Forest Laneway fire, for all occupants
High-rise apartment building[23]	33	0.3	0.8	1.3	4.4	10.2	2.8	Unannounced drill; good alarm performance
High-rise apartment building[23]	93	0.4	1.5	3.6	6.9	18.6	5.3	Unannounced drill; good alarm performance; heavy snow during drill
High-rise apartment building[17]	27	1.0	2.0	8.0	14.0	>20.0	NA	Fire incident in early morning, alarm functioned, fewer than half the occupants evacuated
Mid-rise apartment building[24]	42	0.6	1.0	1.4	3.0	>14.0	2.5	Unannounced drill; good alarm performance
Mid-rise apartment building[24]	55	>0.5	1.6	4.4	13.5	>21.0	8.4	Unannounced drill; poor alarm performance
Mid-rise apartment building[24]	77	>0.3	1.9	7.7	19.1	>24.0	9.7	Unannounced drill; poor alarm performance
Mid-rise apartment building[24]	80	>0.3	1.2	2.5	3.7	>12.0	3.1	Unannounced drill; good alarm performance
Training facility[25]	566	<0.2	0.7	1.1	1.5	>5.0	NA	Testing sleeping subjects at a training facility

*NA = Not reported.

evaluated three types of exit signs—nonilluminated signs, internally illuminated signs, and light emitting diode (LED) signs. The paper presents data on the distances required by those with and without vision disabilities to locate and read exit signs and concludes that LED signs are the most visible and legible. The study did not, however, evaluate the ability of the participants to locate and read signs in the presence of distractions such as contrasting colors and smoke.

When an engineered design is being developed for public assembly properties, the design team must consider the characteristics of a population that accurately reflects the expected user population. This set of papers describes research on disabled groups in Northern Ireland. Whether or not it is reasonable to extrapolate the results to the rest of the world, this research provides data that begin to answer critical questions about the population at risk in public places. A Japanese study of users of two new shopping centers reported similar travel speeds for people with difficulty walking.[31] This study also reported average walking speeds for various other categories of occupants as well as the proportion of building users who reported difficulties in walking and using stairs. The observed walking speeds are shown in Table 4.2.2. Walking speeds were not reported for the small number of people who used wheelchairs or walking aids, who had visual impairments, or who were injured.

Similar data must be collected for the full range of occupancy types. A great deal of data on travel speeds has been collected and reported in the literature for a long time. To put the reported data into the correct context, it is important to note the factors that can result in variations in movement speed. These include crowd density; the mobility, age, and other characteristics of the occupants; the presence of family groups; the presence of smoke; and lighting and other design features. As the density of the crowd increases, the ease and speed of movement decrease until the crowd is moving at a shuffling pace. Family groups will attempt to stay together and will move at the speed of the slowest person. The presence of smoke can slow people down, or it can cause them to change directions or ultimately to stop their evacuation. Low lighting can slow people, particularly on stairs, and the evenness of the exit path and the roughness or smoothness of the walls along the exit path can also impact travel speeds.

Additional data on travel speeds have been summarized in a recent paper.[11] The data collected include the following types of occupancies: transport terminals, apartment buildings, assembly properties, industrial buildings, and hotels. Data for both able-bodied and mobility-impaired subjects are also available. The summary data from that paper are shown in Table 4.2.3.[32–35] Again, the user is cautioned to refer to the source documents for the full context of the experiments and incidents before applying the data to his or her application.

CALCULATION METHODS FOR TRAVEL TIME

Calculating the travel time for an individual alone is a fairly straightforward exercise: travel time will be the product of travel distance and walking speed. Calculating the travel time for a crowd of occupants is more complex. There are three fundamental characteristics of crowd movement: density, speed, and flow. Density of a crowd is defined as the number of persons per unit area (e.g., 2.0 persons/m^2). Density can also be expressed

TABLE 4.2.2 Average Walking Speeds and Standard Deviation for Various Categories of Users of Two Shopping Centers[31]

User Category	*Average Walking Speed (m/sec)*	*Standard Deviation (m/sec)*	*N*
Adult with difficulty walking			
Older adult walking very slowly	0.83	0.20	21
Adult with walking disability	0.78	0.19	8
Pregnant woman	0.79	0.12	4
Adult with child, baby, or toddler	0.93	0.33	171
Adult with child and baby or toddler	0.88	0.26	25
Adult with baby or toddler	0.90	0.24	77
Adult with child	1.00	0.41	69
Older adult	0.93	0.22	155
Older adult with another person	0.88	0.23	49
Older adult walking alone	0.96	0.22	103
Able-bodied adult			
Walking with another person	0.93	0.25	314
Walking alone	1.14	0.27	446
Total	1.03	0.29	937

Source: Interscience Communications

TABLE 4.2.3 Travel Speeds Reported in the Referenced Literature

Type of Situation	*Measured Travel Speeds*				
A. Where Density Was Reportedly Not a Factor					
Transport terminals[32]	265 ft/min on walkways (1.35 m/sec)				
Average under "normal conditions"[33]	60 m/min (1.0 m/sec)				
Experiment with disabled subjects[34]					
	Min	1st Q	3rd Q	Max	Mean
On horizontal (m/sec)					
All disabled subjects	0.10	0.71	1.28	1.77	1.00
With locomotion disability	0.10	0.57	1.02	1.68	0.80
No aid	0.24	0.70	1.02	1.68	0.95
Crutches	0.63	0.67	1.24	1.35	0.94
Cane	0.26	0.49	1.08	1.60	0.81
Walker/rollator	0.10	0.34	0.83	1.02	0.57
Without locomotion disability	0.82	1.05	1.34	1.77	1.25
Unassisted wheelchair	0.85	—	—	0.93	0.89
Assisted ambulant	0.21	0.58	0.92	1.40	0.78
Assisted wheelchair	0.84	1.02	1.59	1.98	1.30
On upward incline					
All disabled	0.21	0.42	0.74	1.32	0.62
With locomotion disability	0.21	0.42	0.72	1.08	0.59
No aid	0.30	0.48	0.87	1.08	0.68
Crutches	0.35	—	—	0.53	0.46
Cane	0.21	0.38	0.70	1.05	0.52
Walker/rollator	0.30	—	—	0.42	0.35
Without locomotion disability	0.70	—	—	1.32	1.01
Unassisted wheelchair	0.70	—	—	—	—
Assisted ambulant	0.23	0.42	0.70	0.72	0.53
Assisted wheelchair	0.53	0.70	1.05	1.05	0.89
On downward incline					
All disabled	0.10	0.42	0.70	1.83	0.60
With locomotion disability	0.10	0.42	0.70	1.22	0.58
No aid	0.28	0.45	0.94	1.22	0.68
Crutches	0.42	—	—	0.53	0.47
Cane	0.18	0.35	0.70	1.04	0.51
Walker/rollator	0.10	—	—	0.52	0.36
Without locomotion disability	0.70	—	—	1.83	1.26
Unassisted wheelchair	1.05	—	—	—	—
Assisted ambulant	0.42	0.52	0.86	1.05	0.69
Assisted wheelchair	0.70	0.96	1.05	1.05	0.96
Mid-rise apartment drill[24]	0.47 m/sec on stairs (ranged from 0.34 to 1.08 m/sec among various adult age groups; one visually impaired person traveled 0.31 m/sec)				
Mid-rise apartment drill[24]	0.44 m/sec on stairs (ranged from 0.32 to 0.56 m/sec among various adult age groups)				
Mid-rise apartment drill[24]	0.41 m/sec on stairs (ranged from 0.30 to 0.47 among various adult age groups)				
High-rise apartment drill[23]	1.05 m/sec (ranged from 0.57 to 1.20 m/sec among various adult age groups)				
High-rise apartment drill[23]	0.95 m/sec (ranged from 0.56 to 1.12 m/sec among various adult age groups)				
B. Where Density Was a Factor					
Public places[32]	100–250 ft/min on walkways (0.51–1.27 m/sec) 70–150 ft/min on stairs (0.36–0.76 m/sec)				
Public places[33]	17 m/min minimum on horizontal (0.28 m/sec) 11–16 m/min down stairs (0.18–0.27 m/sec)				
Theaters and educational[33]	15–20 m/min (0.25–0.33 m/sec) max 2.33 m/sec				
Industrial buildings[33]	25–30 m/min (0.42–0.56 m/sec) max 2.33 m/sec				
Transport terminals[33]	20–25 m/min (0.33–0.83 m/sec) max 2.10 m/sec				
Descending stairs[33]	20–25 m/min (0.33–0.42 m/sec) max 1.28 m/sec				

TABLE 4.2.3 Continued

High-rise office building drill[18]	Mean Speed	Density
Stair with full lighting	0.61 m/sec	1.30 persons/m^2
Stair with reduced lighting	0.70 m/sec	1.25 persons/m^2
Stair with photoluminescent material (PLM) installation and reduced lighting	0.72 m/sec	1.00 persons/m^2
Stair with PLM only	0.57 m/sec	2.05 persons/m^2
Mid-rise office building drill[19]	0.78 m/sec down stairs	
Mid-rise office building drill[19]	0.93 m/sec down stairs	

Hotel exercise—along corridor (m/sec)[35]

	Min	1st Q	Med	3rd Q	Max	Mean
Daytime scenario 1						
Able-bodied participants	0.6	1.1	1.3	1.8	4.0	1.5
Wheelchair users	0.2	—	—	—	1.2	0.8
Walking disabled	0.1	—	—	—	—	—
Daytime scenario 2						
Able-bodied participants	0.3	0.9	1.1	1.3	1.6	1.1
Wheelchair users	0.4	—	—	—	0.7	0.6
Walking disabled	0.7	—	—	—	—	—
Nighttime scenario						
Able-bodied participants	0.5	1.1	1.3	1.7	3.8	1.5
Wheelchair users	0.5	—	—	—	0.9	0.7
Walking disabled	2.4*	—	—	—	—	—

*This person traveled at this speed for a distance of 4.9 m.

as the area per person (e.g., 0.5 m^2/person). Speed is the time rate of motion of the occupants, usually expressed in meters per second. Flow is the rate at which people pass a particular point, such as a doorway per unit of time (e.g., 2.0 persons/sec). Along with path width, the three characteristics of crowd movement are related as follows:

$$\text{Flow} = \text{Speed} \times \text{Density} \times \text{Width}$$

As mentioned in the previous section, speed is a function of density. The more people there are in a space, the more slowly they move, until eventually they reach the point where they are at a shuffling speed. Flow and density have a more complex relationship. At low densities, the rate of flow is small, as there are few people in the stream. Flow rates again are slow at high densities where there is little movement. Optimal flow is achieved at a density of approximately 2.0 persons/m^2. For details on the derivation of this value, the reader is referred to the *SFPE Handbook of Fire Protection Engineering*.[36]

There are several different approaches to calculating egress time. Flows through doors or corridors can be calculated. Walking speeds can be calculated or can be used as input to models to calculate evacuation time. These methods can be simple enough to do by hand or can be carried out by computer models that may incorporate other behavioral factors.

Empirically Based Evacuation Time Equations

Figure 4.2.2 presents a comparison of observed evacuation times for tall buildings with derived equations for the prediction of total evacuation time.[37–39] Pauls's data[39] are based on measurements obtained from 29 evacuation drills, primarily in office buildings ranging from 8 to 21 stories high. Pauls observed evacuation times varying from approximately 10 sec/story for buildings with small populations to approximately 20 sec/story for buildings with large populations. The evacuation equations

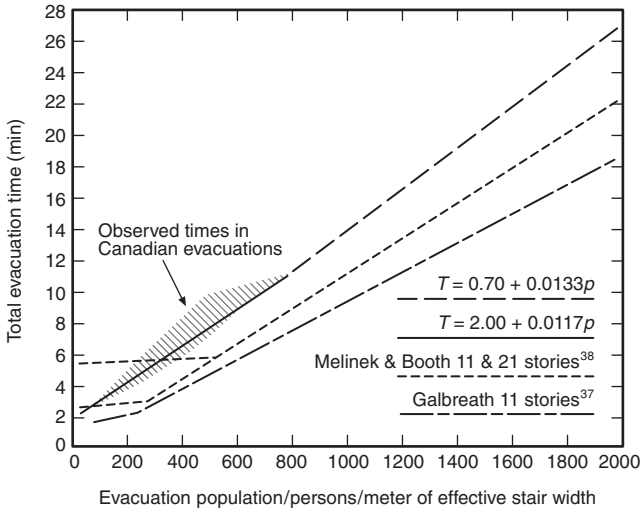

FIGURE 4.2.2 Predicted and Observed Total Evacuation Times for Tall Office Buildings

indicated in Figure 4.2.2 were developed from these observed evacuation times. The first equation,

$$T = 0.70 + 0.0133p$$

is to be applied to predict evacuation times in buildings with large populations exceeding 800 persons/m^2 of effective stair width. T is the minimum time (min) to complete an uncontrolled total evacuation by stairs, and p is the actual evacuation population/m of effective stair width, measured immediately above the discharge level of the stair.

It should be recognized that "effective stair width," as used by Pauls, is defined in the following manner:[39]

> This empirically based model describes flow as a linear function of a stair's effective width—the width remaining once the edge effects are deducted (150 mm or 6 inches from each wall boundary and 90 mm or 3.5 inches from each handrail centerline). It takes into account the propensity of people to sway laterally—especially when walking slowly in a crowd—and therefore to arrange themselves in a staggered traditional unit-width model based on presumed static dimensions of people's shoulders.

The second equation in Figure 4.2.2,

$$T = 2.00 + 0.0117p$$

is to be applied when the population/m of effective stair width is less than 800 persons.

Pauls[39] also examined the relationship between the speed of evacuation and the density on the stairs during the uncontrolled total evacuation, as indicated in Figure 4.2.3. It should be remembered that this movement would be in the vertical, downward direction.

Hydraulic Flow Calculations

The estimation of modeled evacuation time uses a series of expressions that relate data acquired from tests and observations to a hydraulic approximation of human flow.[40] Although the expressions indicate absolute relationships, there is considerable variability in the data. Figure 4.2.2 shows a typical relationship between the source data and the derived equation. The equations and relationships presented in the following paragraphs can be used independently or collectively to solve a complex egress problem. Such a coordinated collection of equations is demonstrated in the sample problem.

Effective Width, W_e. Persons moving through the exit routes of a building maintain a boundary layer clearance from walls and other stationary obstacles they pass. This clearance is needed to accommodate lateral body sway and assure balance.

Discussion of this crowd movement phenomena is found in the works of Pauls,[41] Fruin,[42] and Habicht and Braaksma.[43] The useful (effective) width of an exit path is the clear width of the path less the width of the boundary layers. Figures 4.2.4 and 4.2.5 depict effective width and boundary layer. Table 4.2.4 is a listing of boundary layer widths. The effective width of any portion of an exit route is the clear width of that portion of an exit route less the sum of the boundary layers.

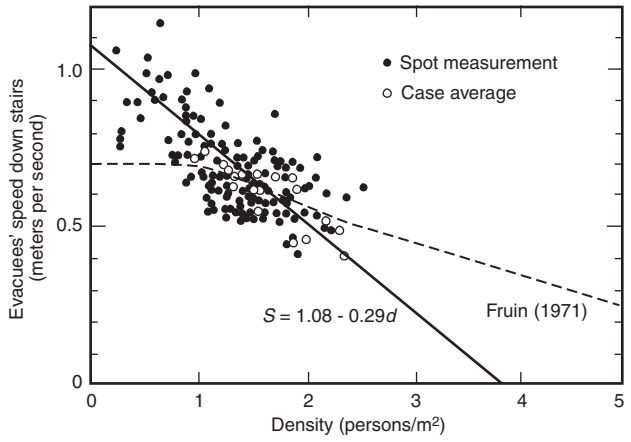

FIGURE 4.2.3 Relation Between Speed and Density on Stairs in Uncontrolled Total Evacuations

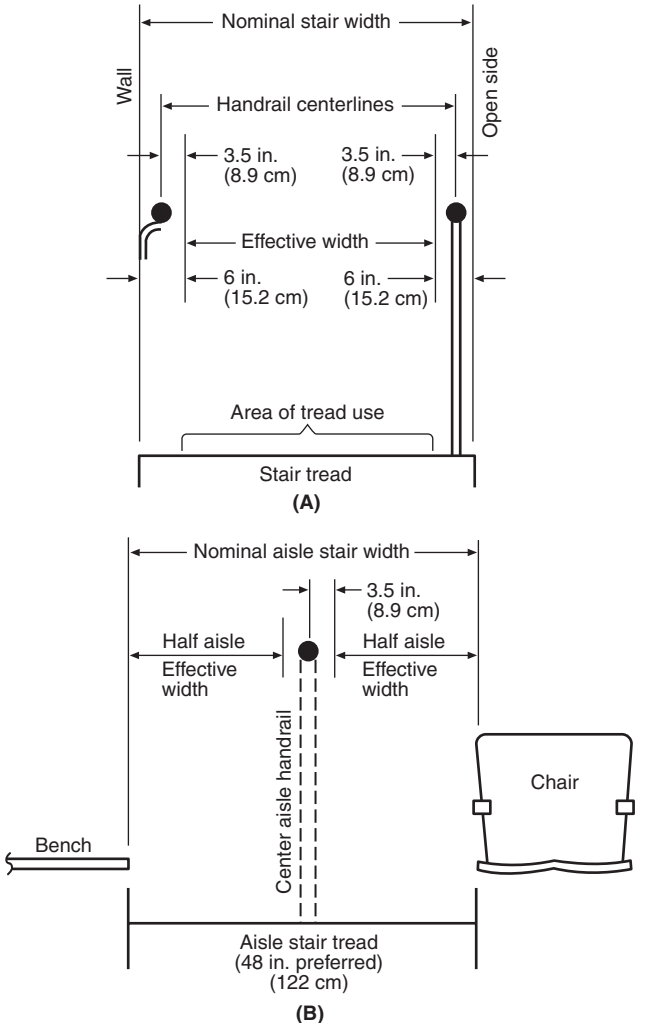

FIGURE 4.2.4 Measurements of Effective Width of Stairs in Relation to Walls, Handrails, and Seating

TABLE 4.2.4 Boundary Layer Widths

Exit Route Element	Boundary Layer *in.*	*cm*
Stairways—walls or side of tread	6.0	15
Railings, handrails*	3.5	9
Theater chairs, stadium benches	0.0	0
Corridor, ramp walls	8.0	20
Obstacles	4.0	10
Wide concourses, passageways	Up to 18	46
Door, archways	6.0	15

*Where handrails are present, use the value if it results in a lesser effective width.

Clear width is measured as follows:

1. From wall to wall in corridors or hallways
2. As the width of the treads in stairways
3. As the actual passage width of a door in its open position
4. As the space between the seats along the aisles of assembly arrangement
5. As the space between the most intruding portions of the seats (when unoccupied) in a row of seats in an assembly arrangement

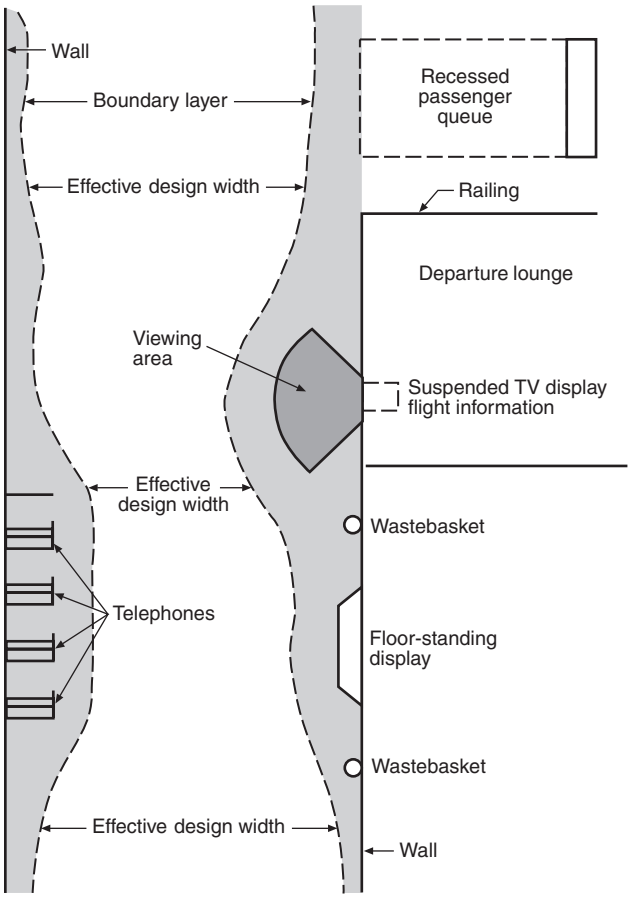

FIGURE 4.2.5 Public Corridor Effective Width

The intrusion of handrails is considered by comparing the effective width without the handrails and the effective width using a clear width from the edge of the handrail. The smaller of the two effective widths then applies. Using the values in Table 4.2.4, only handrails that protrude more than 2.5 in. (6 cm) need to be considered. Minor midbody height or lower intrusions such as panic hardware are treated in the same manner as handrails. Where an exit route becomes either wider or narrower, only that portion of the route has the appropriate greater or lesser clear width.

Density, *D*. Density is the measurement of the degree of crowding in an evacuation route and is usually expressed in persons/unit area. The calculations in this chapter are based on density expressed in persons/ft^2 (or persons/m^2).

Unless information on the dispersion of occupants indicates otherwise, the density of the first exit element (aisle, corridor, ramp, etc.) is based on all of the served occupants. This calculation will demonstrate the capacity limits of the route element and produce a value representing the maximum capacity of the element.

However, if the egressing population is widely dispersed, in terms of reaching the exit route element, the calculation is based on an appropriate time step. At each time increment, the density of the exit route is based on those who have entered the route minus those who have passed from it.

The density factors in subsequent portions of the egress system are determined by calculation. The calculation methods involved are contained in the section on transitions.

Speed of Exiting Individuals, *S*. The evacuation speed of a group is a function of the population density. The relationships presented in this section have been derived from Fruin,[42] Pauls,[41] and Predtechenskii and Milinskii.[44]

If the population density is less than about 0.05 person/ft^2 (0.54 person/m^2) of exit route (20 ft^2/person [1.85 m^2/person]), individuals will move at their own pace, independent of the speed of others. If the population density exceeds about 0.35 person/ft^2 (3.8 persons/m^2), no movement will take place until enough of the crowd has passed from the crowded area to reduce the density.

Between the density limits of 0.05 and 0.35 person/ft^2 (0.54 and 3.8 persons/m^2), the relationship between speed and density can be considered as a linear function. The equation of this function is

$$S = k - akD \tag{1}$$

where

S = Speed along the line of travel

D = Density (persons/unit area)

k = Constant, as shown in Table 4.2.5, where
- $k = k_1$ and $a = 2.86$ when calculating speed in feet per minute and density in persons per square foot
- $k = k_2$ and $a = 0.266$ when calculating speed in meters per second and density in persons per square meter

TABLE 4.2.5 Constants for Equation 2, Evacuation Speed

Exit Route Element		k_1	k_s
Corridor, Aisle, Ramp, Doorway		275	1.40
Stairs Riser (in.)	Tread (in.)		
7.5	10	196	1.00
7.0	11	212	1.08
6.5	12	229	1.16
6.5	13	242	1.23

Note: 1 in. = 25.4 mm.

Table 4.2.5 shows evacuation speed constants.

Figure 4.2.6 is a graphic representation of the relationship between speed and density. The speeds determined from Equation 2 are along the line of movement; for stairs this is along the line of the treads. Table 4.2.6 provides convenient multipliers for converting vertical rise of a stairway to a distance along the line of movement. The travel on landings must be added to the values derived from Table 4.2.6. The maximum speed occurs when the density is less than 0.05 person/ft^2 (0.54 person/m^2). These maximum speeds are listed in Table 4.2.7.

Within the range listed in Tables 4.2.5 through 4.2.7, the evacuation speed on stairs varies approximately as the square root of the ratio of tread width to tread height. There are not sufficient data to appraise the likelihood that this relationship holds outside this range.

Specific Flow, F_s. Specific flow, F_s, is the flow of evacuating persons past a point in the exit route/unit of time/unit of effective width, W_e, of the route involved. Specific flow is expressed

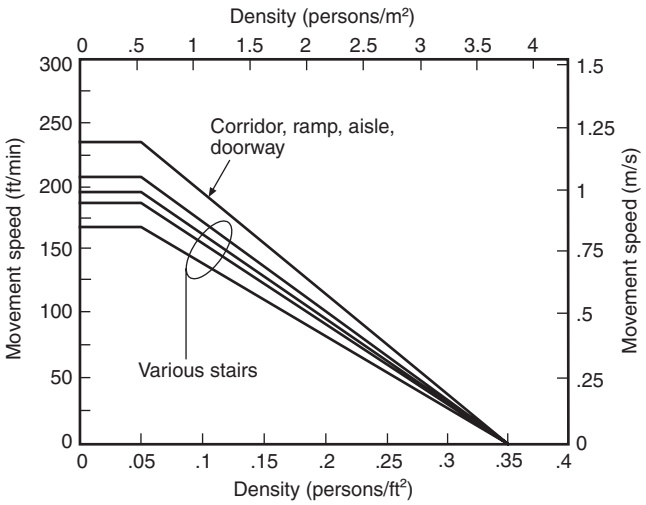

FIGURE 4.2.6 Evacuation Speed as a Function of Density. $S = k - akD$, where D = density is persons/ft^2 and k is given in Table 4.2.5. Note that speed is along line of travel.

TABLE 4.2.6 Conversion Factors for Relating Line of Travel Distance to Vertical Travel for Various Stair Configurations

Stairs Riser (in. [mm])	*Tread (in. [mm])*	*Conversion Factor*
7.5 (190)	10.0 (254)	1.66
7.0 (178)	11.0 (279)	1.85
6.5 (165)	12.0 (305)	2.08
6.5 (165)	13.0 (330)	2.22

in persons/min/ft of effective width (if the value of $k = k_2$, from Table 4.2.5) or persons/sec/m of effective width (if the value of $k = k_2$, from Table 4.2.5). The equation for specific flow is

$$F_s = SD \tag{2}$$

where

F_s = Specific flow

D = Density

S = Speed of movement

F_s is in persons/min/ft^2 when density is in persons/ft^2 and speed is in ft/min; F_s is in persons/sec/m^2 when density is in persons/m^2 and speed is in m/sec.

Combining Equations 1 and 2 produces

$$F_s = (1 - aD)kD \tag{3}$$

where k is as listed in Table 4.2.5.

The relationship of specific flow to density is shown in Figure 4.2.7. In each case the maximum specific flow occurs when the density is 0.175 person/ft^2 (1.9 persons/m^2) of exit route space. Maximum specific flows are associated with each type of exit route element; these are listed in Table 4.2.8.

Calculated Flow, F_c. The calculated flow, F_c, is the predicted flow rate of persons passing a particular point in an exit route.

The equation for actual flow is

$$F_c = F_s W_e \tag{4}$$

TABLE 4.2.7 Maximum (Unimpeded) Exit Flow Speeds

Exit Route Element		Speed—Along Line of Travel *ft/min*	*m/sec*
Corridor, Aisle, Ramp, Doorway		235	1.19
Stairs Riser (in. [mm])	Tread (in. [mm])		
7.5 (190)	10 (254)	167	0.85
7.0 (178)	11 (279)	187	0.95
6.5 (165)	12 (305)	196	1.00
6.5 (165)	13 (330)	207	1.05

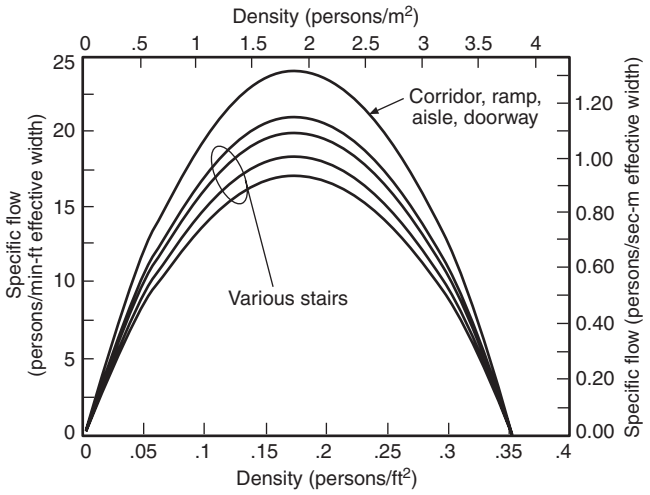

FIGURE 4.2.7 Specific Flow as a Function of Density

where

F_c = Calculated flow

F_s = Specific flow

W_e = Effective width

Combining Equations 3 and 4 produces

$$F_c = (1 - aD)kDW_e \tag{5}$$

F_c is in persons/min when $k = k_1$ (from Table 4.2.5), D is in persons/ft^2, and W_e in ft.

F_c is in persons/sec when $k = k_2$ (from Table 4.2.5), D is in persons/m^2, and W_e in m.

Time for Passage, T_p. Time for passage, T_p, that is, time for a group of persons to pass a point in an exit route, can be expressed as

$$T_p = P/F_c \tag{6}$$

TABLE 4.2.8 Maximum Specific Flow, F_{sm}

Exit Route Element	Maximum Specific Flow: *Persons/ min/ft of Effective Width*	Maximum Specific Flow: *Persons/ sec/m of Effective Width*
Corridor, Aisle, Ramp, Doorway	24.0	1.30
Stairs		
Riser (in.) / Riser (mm) / Tread (in.) / Tread (mm)		
7.5 (190) 10 (254)	17.1	0.94
7.0 (178) 11 (279)	18.5	1.01
6.5 (165) 12 (305)	20.0	1.09
6.5 (165) 13 (330)	21.2	1.16

Source: Table 3-14.5, *SFPE Handbook of Fire Protection Engineering,* 3rd edition, 2002. Courtesy Society of Fire Protection Engineers.

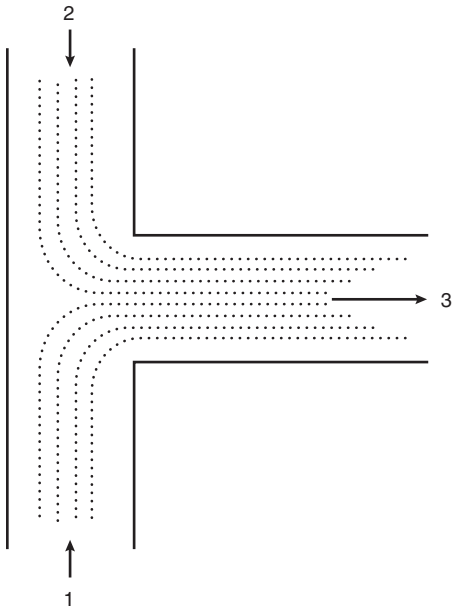

FIGURE 4.2.8 Merging Egress Flows

where T_p is time for passage (T_p is in minutes where F_c is persons/min; T_p is in seconds where F_c is persons/sec). P is population in persons.

Combining Equations 5 and 6 yields

$$T_p = P/(1 - aD)kDW_e \tag{7}$$

Transitions. Transitions are any point in the exit system where the character or dimension of a route changes or where routes merge. Typical examples of points of transition include the following:

1. *The point where two or more exit flows merge.* For example, the meeting of the flow from a cross aisle into a main aisle that serves other sources of exiting population. It is also the point of entrance into a stairway serving other floors (Figure 4.2.8).
2. *The point where a corridor enters a stairway.* There are actually two transitions: one occurs as the egress flow passes through the doorway; the other as the flow leaves the doorway and proceeds onto the stairs.
3. *Any point where an exit route becomes wider or narrower.* For example, a corridor may be narrowed for a short distance by an intruding service counter or similar element. The calculated density, D, and specific flow, F_s, differ before reaching, while passing, and after passing the intrusion (Figure 4.2.9).

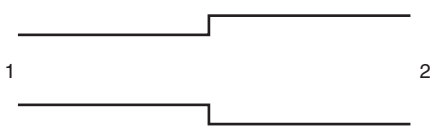

FIGURE 4.2.9 Transition in Egress Component

The following rules apply to determining the densities and flow rates following the passage of a transition point:

1. The flow after a transition point is a function, within limits, of the flow(s) entering the transition point.
2. The calculated flow, F_c, following a transition point cannot exceed the maximum specific flow, F_{sm}, for the route element involved multiplied by the effective width, W_e, of that element.
3. Within the limits of rule 2, the specific flow, F_s, of the route departing from a transition point is determined by the following equations:
   (a) For cases involving one flow into and one flow out of a transition point:

$$F_{s(\text{out})} = F_{s(\text{in})} W_{e(\text{in})} / W_{e(\text{out})} \tag{8a}$$

   where

$F_{s(\text{out})}$ = Specific flow departing from a transition point

$F_{s(\text{in})}$ = Specific flow arriving at a transition point

$W_{e(\text{in})}$ = Effective width prior to a transition point

$W_{e(\text{out})}$ = Effective width after passing a transition point

   (b) For cases involving two incoming flows and one outflow from a transition point, such as that which occurs with the merger of a flow down a stair and the entering flow at a floor:

$$F_{s(\text{out})} = \{\lfloor F_{s(\text{in})\text{-}1} W_{e(\text{in})\text{-}1} \rfloor + \lfloor F_{s(\text{in})\text{-}1} W_{e(\text{in})\text{-}2} \rfloor\} / W_{e(\text{out})} \tag{8b}$$

   where the subscripts (in-1) and (in-2) indicate the values for the two incoming flows.
   (c) For cases involving other merger geometries, the following general relationship applies:

$$\lfloor F_{s(\text{in-}1)} W_{e(\text{in-}1)} \rfloor + \cdots + \lfloor F_{s(\text{in-}n)} W_{e(\text{in-}n)} \rfloor = \lfloor F_{s(\text{out-}1)} W_{e(\text{out-}1)} \rfloor + \cdots + \lfloor F_{s(\text{out-}n)} W_{e(\text{out-}n)} \rfloor \tag{8c}$$

   where the letter n in the subscripts (in-n) and (out-n) is a number equal to the total number of routes entering (in-n) or leaving (out-n) the transition point.
4. Where the calculated specific flow, F_s, for the route(s) leaving a transition point, as derived from the equations in rule 3, exceeds the maximum specific flow, F_{sm}, a queue will form at the incoming side of the transition point. The number of persons in the queue will grow at a rate equal to the calculated flow, F_c, in the arriving route minus the calculated flow leaving the route through the transition point.
5. Where the calculated outgoing specific flow, $F_{s(\text{out})}$, is less than the maximum specific flow, F_{sm}, for that route(s), there is no way to predetermine how the incoming routes will merge. The routes may share access through the transition point equally, or there may be total dominance of one route over the other. For conservative calculations, assume that the route of interest is dominated by the other route(s). If all routes are of concern, it is necessary to conduct a series of calculations to establish the bounds on each route under each condition of dominance.

EXAMPLE: This example uses stairs of U.S. conventional size and is therefore presented in English units. Consider an office building (Figure 4.2.10) with the following features:

1. There are nine floors, 300 ft × 80 ft.
2. Floor-to-floor height is 12 ft.
3. There are two stairways, located at ends of building (no dead ends).
4. Each stair is 44 in. wide (tread width) with handrails protruding 2.5 in.
5. Stair risers are 7 in. wide; treads are 11 in. high.
6. There are two 4 ft × 8 ft landings per floor of stairway travel.
7. There is one 36 in. clear width door at each stairway entrance and exit.
8. The first floor does not exit through stairways.
9. Each floor has a single 8-ft-wide corridor extending the full length of each floor. Corridors terminate at stairway entrance doors.
10. There is a population of 300 persons/floor.

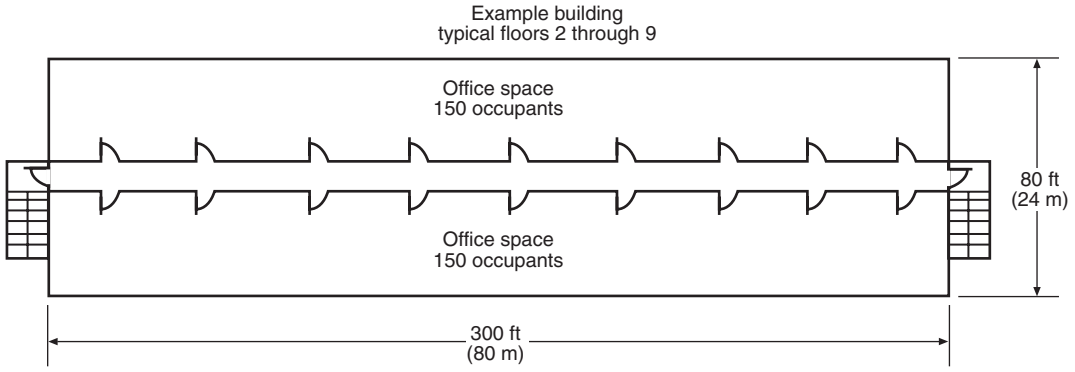

FIGURE 4.2.10 Floor Plan for Example

SOLUTION A—FIRST-ORDER APPROXIMATION

1. *Assumptions.* The prime controlling factor will be either the stairways or the door discharging from them. Queuing will occur; therefore, the specific flow, F_s, will be the maximum specific flow, F_{sm}. All occupants start egress at the same time. The population will use all facilities in the optimum balance.
2. *Estimate flow capability of a stairway.* From Table 4.2.4, the effective width, W_e, of each stairway is 44 – 12 in. = 32 in. (2.66 ft). Also, the effective width, W_e, of each door is 36 – 12 = 24 in. (2 ft). The maximum specific flow, F_{sm}, for the stairway (from Table 4.2.8) is 18.5 persons/min/ft effective width. Specific flow, F_s, equals maximum specific flow, F_{sm}. Therefore, using Equation 4, the flow from each stairway is limited to 18.5 × 2.66 = 49.2 persons/min.
3. *Estimate flow capacity through a door.* Again from Table 4.2.8, the maximum specific flow through any 36 in. door is 24 persons/min/ft effective width. Therefore, using Equation 4, the flow through any door is limited to 24 × 2 = 48 persons/min. Since the flow capacity of the doors is less than the flow capacity of the stairway served, the flow is controlled by the stairway exit doors (48 persons/stairway exit door/min).
4. *Estimate the speed of movement for estimated stairway flow.* From Equation 1, the speed of movement down the stairs is 212 – (2.86 × 212 × 0.175) = 105 ft/min. The travel distance between floors (using the conversion factor from Table 4.2.6) is 12 × 1.85 = 22.2 ft on the stair slope plus 8 ft travel on each of the two landings, for a total floor-to-floor travel distance of 22.2 + (2 × 8) = 38.2 ft. The travel time for a person moving with the flow is 38.2/105 = 0.36 min/floor.
5. *Estimate building evacuation time.* If all of the occupants in the building start evacuation at the same time, each stairway can discharge 48 persons/min. The population of 2400 persons above the first floor will require approximately 25 minutes to pass through the exit. An additional 0.36 minute travel time is required for the movement from the second floor to the exit. The total minimum evacuation time for the 2400 persons located on floors 2 through 9 is estimated at 25.4 minutes.

SOLUTION B—MORE DETAILED ANALYSIS

1. *Assumptions.* The population will use all exit facilities in the optimum balance; all occupants start egress at the same time.
2. *Estimate flow density, D, speed, S, specific flow, F_s, effective width, W_e, and initial calculated flow, F_c, typical for each floor.* Divide each floor in half to produce two exit calculation zones, each 150 ft long. Determine the density, *D,* and speed, *S,* if all occupants try to move through the corridor at the same time, that is, 150 persons moving through 150 ft of an 8-ft-wide corridor.

$$\text{Density, } D = 150 \text{ persons}/1200 \text{ ft}^2 \text{ corridor area} = 0.125 \text{ person/ft}^2$$

From Equation 1, speed, $S = k - akD$.

From Table 4.2.5, $k = 275$.

$$S = 275 - (2.86 \times 275 \times 0.125) = 177 \text{ ft/min}$$

From Equation 3, specific flow, $F_s = (1 - aD)kD$.

$$F_s = [1 - (2.86 \times 0.125)] \times 275 \times 0.125 = 22 \text{ persons/ft effective width/min}$$

From Table 4.2.8, the specific flow, F_s, is less than the maximum specific flow, F_{sm1}; therefore, F_s is used for the calculation of calculated flow.

From Table 4.2.4, the effective width of the corridor is 8 – (2 × 0.5) = 7 ft.

From Equation 5, calculated flow, $F_c = (1 - aD)kDW$

$$F_c = [1 - (2.86 \times 0.125)] \times 275 \times 0.125 \times 7 = 154 \text{ persons/min}$$

Note: At this stage in the calculation, calculated flow, F_c, is termed "initial calculated flow" for the exit route element (i.e., corridors) being evaluated because the calculated flow rate can be sustained only if the discharge (transition point) from the route can also accommodate the indicated flow rate.

3. *Estimate impact of stairway entry doors on exit flow.* Each door has a 36 in. clear width. From Table 4.2.4, effective width, W_e, is 36 – 12 = 24 in. (2 ft).

From Table 4.2.8, the maximum specific flow, F_{sm}, is 24 persons/min/ft effective width.

From Equation 8,

$$F_{s(\text{door})} = [F_{s(\text{corridor})}W_{e(\text{corridor})}]/W_{e(\text{door})}F_{s(\text{door})} = (22 \times 7)/2 = 77 \text{ persons/min/ft effective width}$$

Since F_{sm} is less than the calculated F_s, the value of F_{sm} is used. Therefore, the effective value for specific flow is 24.

From Equation 4 the initial calculated flow is $F_c = F_sW_e = 24 \times 2 = 48$ persons/min through a 36 in. door.

Since F_c for the corridor is 154 whereas F_c for the single exit door is 48, queuing is expected. The calculated rate of queue buildup will be 154 – 48 = 106 persons/min.

4. *Estimate impact of stairway on exit flow.* From Table 4.2.4, effective width, W_e, of the stairway is 44 – 12 = 32 in. (2.66 ft).

From Table 4.2.8, the maximum specific flow, F_{sm}, is 18.5 persons/ft effective width.

From Equation 8, the specific flow for the stairway, $F_{s(\text{stairway})}$, is 24 × 2/2.66 = 18.0 persons/ft effective width. In this case, F_s is less than F_{sm}, and F_s is used.

The value of 18.0 for F_s applies until the flow down the stairway merges with the flow entering from another floor.

Using Figure 4.2.6 or Equation 3 and Table 4.2.5, the density of the initial stairway flow is approximately 0.146 person/ft^2 of stairway exit route.

From Equation 1, the speed of movement during the initial stairway travel is 212 × (2.86 × 212 × 0.146) = 123 ft/min.

From Solution A, the floor-to-floor travel distance is 38.2 ft. The time required for the flow to travel one floor level is 38.2/123 = 0.31 min (19 sec).

Using Equation 4, the calculated flow, F_c, is 18.0 × 2.66 = 48 persons/min.

After 0.31 minute, 48 × 0.31 = 15 persons will be in the stairway from each floor feeding to it. If floors 2 through 9 exit all at once, there will be 15 × 8 = 120 persons in the stairway. After this time, the merging of flows between the flow in the stairway and the incoming flows at stairway entrances will control the rate of movement.

5. *Estimate impact of merger of stairway flow and stairway entry flow on exit flow.* From Equation 9, $F_{s\,(\text{out-stairway})} = \{[F_{s\,(\text{door})} \times W_{e\,(\text{door})}] + [F_{s\,(\text{in-stairway})} \times W_{e\,(\text{in-stairway})}]\}/W_{e\,(\text{out-stairway})} = [(24 \times 2) + (18 \times 2.66)]/66 = 36$ persons/ft effective width

   From Table 4.2.8, F_{sm} for the stairway is 18.5 persons/min/ft effective width. Since F_{sm} is less than the calculated F_s, the value of F_{sm} is used.

6. *Track egress flow.* Assume all persons start to evacuate at time zero. Initial flow speed is 177 ft/min. Assume that congested flow will reach the stairway in 30 seconds. At 30 seconds, flow starts through stairway doors. F_c through doors is 48 persons/min for the next 19 seconds. At 49 seconds, 120 persons are in each stairway, and 135 are waiting in a queue at each stairway entrance door.

   Note: Progress from this point on depends on which floors take dominance in entering the stairways. Any sequence of entry may occur. To set a boundary, this example estimates the result of a situation where dominance proceeds from the highest to the lowest floor.

   The remaining 135 persons waiting at each stairway entrance on the 9th floor enter through the door at the rate of 48 persons/min. The rate of flow through the stair is regulated by the 48 persons/min rate of flow of the discharge exit doors. The descent rate of the flow is 19 sec/floor.

   Thus,

at 218 sec (3.6 min)	All persons have evacuated the 9th floor.
at 237 sec (4.0 min)	The end of the flow reaches the 8th floor.
at 401 sec (6.7 min)	All persons have evacuated the 8th floor.
at 420 sec (7.0 min)	The end of the flow reaches the 7th floor.
at 584 sec (9.7 min)	All persons have evacuated the 7th floor.
at 603 sec (10.1 min)	The end of the flow reaches the 6th floor.
at 767 sec (12.8 min)	All persons have evacuated the 6th floor.
at 786 sec (13.1 min)	The end of the flow reaches the 5th floor.
at 950 sec (15.8 min)	All persons have evacuated the 5th floor.
at 969 sec (16.2 min)	The end of the flow reaches the 4th floor.
at 1133 sec (18.9 min)	All persons have evacuated the 4th floor.
at 1152 sec (19.2 min)	The end of the flow reaches the 3rd floor.
at 1316 sec (21.9 min)	All persons have evacuated the 3rd floor.
at 1335 sec (22.3 min)	The end of the flow reaches the 2nd floor.
at 1499 sec (25.0 min)	All persons have evacuated the 2nd floor.
at 1518 sec (25.3 min)	All persons have evacuated the building.

COMPUTER SIMULATION AND MODELING OF EGRESS DESIGN

Simulation modeling may be appropriate for problems that would otherwise require costly, time-consuming, and tedious manual effort; those that cannot be solved through experimentation because of high costs or unacceptable risks to human participants; and for which past experience, intuition, or available data do not provide the proper insight.[45]

Types of Evacuation Models

Three types of evacuation models are currently available:

- Single-parameter estimation models
- Movement models
- Behavioral simulation models

Single-Parameter Estimation Models. Single-parameter estimation models are generally used for simple estimates of movement times. They can be hand calculations or simple computer models (e.g., flow times based on widths of exit paths or travel times based on distances).

Movement Models. Movement models generally handle large numbers of people in a network flow. This type of model, often referred to as a hydraulic model, treats occupants like water in a pipe or ball bearings in a chute. They tend to optimize occupant behavior, with all occupants moving at the same speed, with perfect knowledge of the building's layout and exit routes. These models often do not include any delay times before occupants begin evacuation. Such models can be useful in benchmarking designs; if the calculated overall evacuation times using this type of model are insufficient for safe evacuation, then the actual evacuation time in a real fire will certainly be insufficient.

Behavioral Simulation Models. Behavioral simulation models consider more of the variables related to occupant movement and behavior. They treat occupants as individuals with unique characteristics. Occupants can move at different speeds in reaction to the conditions in their surroundings. Because they are tracked individually, their exposure and reaction to toxic conditions while evacuating can be estimated by some of these models or by tenability or toxicity models that analyze the

simulation results. This type of model allows a more realistic simulation, but there are concerns with their use related to the lack of available data that would allow the prediction of human behavior in fire. In choosing a model, the user has to understand the underlying assumptions and be sure that those assumptions are appropriate to the analysis at hand.

Computer simulation and modeling have become important tools in designing adequate means of egress under a variety of occupancy and structural conditions. Evacuation modeling has become particularly important in recent years since standards-making organizations around the world have developed performance-based options for fire protection design. The evaluation of an engineered design requires, for a range of fire scenarios, a comparison of the fire effects predicted for each scenario with the results of an evacuation model that will predict where and for how long people will be dispersed throughout a structure. The occupants' potential exposure to the effects of a fire will determine whether or not a design is acceptable.

History of Evacuation Modeling

Evacuation modeling has a long history. In one study of the critical variables for fire safety in relation to buildings used to house the elderly, the problem of fire development and evacuation as a time-structured problem was considered.[46] This study analyzed the variables related to the occurrence and spread of fire relative to the population's ability to reach an area of refuge from the effects of the fire. The study established the variables for the fire on a continuum of a "critical time" and the parameters for the survival of the occupants on a continuum of a "reaction time."

The definition adopted for critical time is the time elapsed from the start of the fire to the attainment of intolerable levels. The definition for reaction time is reported as the amount of time used by the occupant to react to the fire and to achieve safety by evacuating the fire area or by obtaining a place of refuge from the effects of the fire. Thus, within the framework of these definitions, both the parameters of the problem of the human behavior factors involved in a fire in a building and the variables of the problem are considered. This conceptualization of a critical time for fire development within a building and of the reaction time required for occupants to perceive and respond to the fire threat, either by evacuation or movement to an area of refuge, has been studied thoroughly. It resulted in multiple computer models of this essential egress behavior since Caravaty and Haviland's study in 1967.[46]

A computer model that simulated the movement of people during evacuation through the floor of fire origin was developed in the mid-1970s.[47] This Markov-based model focused on the movement of people through a fire floor from the time of alarm until their safe exit or until they became casualties of the fire. Six variables affecting their movement were identified:

1. Objective location of the threatening stimuli in time and space
2. Occupants' prior knowledge of effective egress routes
3. Occupants' perception of the location and severity of the threat
4. Occupants' perception of available alternatives
5. Occupants' threat-reducing experiences prior to the current movement decision
6. The interjection of sudden interpretations to the occupants' goal-directed behavior

A modeling technique was developed in the early 1980s that appeared to have potential for comparing the evacuation behavior of occupants assisted by trained personnel with evacuation without assistance.[48] This model determined the escape potential from an area of a building based on a deterministic approach with a computer algorithm, and it evaluated the effects of fire growth and smoke movement on occupants as they try to egress. Occupant evacuation was simulated with evaluation of the effects of the egress design, the density of the occupants in the means of egress, the congestion at door or other restrictions, and the effects of the combustion products on occupants.

The concepts of critical time and reaction time as originally formulated by Caravaty and Haviland[46] were adapted into a determination of the available safe egress time (ASET) model.[2] This model is a mathematical procedure for simulating the conditions that develop between the time of fire ignition and the onset of untenable conditions for human occupancy. It was developed to evaluate the evacuation plans and procedures within a specific building.[2] This model required input data on the physical dimensions of the building areas, the means of egress, and the specified evacuation routes with the number and location of the occupants. The model provided an estimated average evacuation time and an estimated total evacuation time.

Building network evacuation models similar to the model of O'Leary and Gratz[49] were developed that evaluate the egress environment within the building and the characteristics of the population relative to density and location.[50] The models predicted evacuation flows and times, and identified queuing problems. The model was validated with evacuation data from high-rise federal office buildings and college dormitories.

An analytical queueing network model (QNM) was also developed to be used in the analysis of a building design relative to the suitability of the egress system.[51] This model provided estimates of the evacuation times, the average queue lengths along egress routes, potential impairments, and total egress probability.

The improvement and use of computer models for evacuation analysis in the late 1980s were examined and reviewed by Watts.[52]

During the 1990s, development of evacuation models accelerated. Fahy[53] developed a FORTRAN model called EXIT89 to predict evacuation times for high-rise buildings. This evacuation model was designed to work with two of the subprograms of HAZARD I,[54] FAST, and TENAB to estimate the hazard to the occupants from the modeled fire incident. It calculates the occupants' movement along the shortest evacuation routes or user-defined "familiar" routes and the queuing of the occupants along these routes. The walking speeds in this model are derived from the occupant densities values developed by Predtechenskii and Milinskii.[44] The model has been further developed over the following decade to incorporate a range of real-life features, such as the presence of disabled occupants, premovement delays, choices in exit route selection, counterflows, and so on.[55]

In recent years, improvements in computer technology have allowed a new generation of computer models that take advantage of the power of computers today and the sophistication of newer software tools. Many of these models are analogous to the CFD models of fire development. Rather than using network-node descriptions of a building, these models describe the building space as a mesh, or grid, and use complex spatial analysis and computer-generated route-finding techniques. Rather than jump from node to node, as simulated occupants will appear to do in a network model, occupants will move from "tile" to "tile" in the grid that overlays the floor plan. This allows a more precise location of occupants throughout spaces.

The current generations of models all include the phenomena that EXIT89 sought to address. Some of the new models also include additional phenomena, but there are always tradeoffs between the completeness and detail of the models and the implied magnitude of data requirements. It is not clear that the net predictive power or accuracy is improved if simplified representations requiring limited data with moderate uncertainty are replaced by elaborate, highly sophisticated representations requiring enormous databases with large associated uncertainty and a heavy reliance on subjective estimation to compensate for a lack of field data. In short, the range of choices has expanded greatly over the past several years, but the value of simpler models has not been diminished.

Due to the variation in techniques used for modeling evacuation, it is not possible to present the equations used. For that level of detail, the reader is referred to the documentation for the particular model of interest. And, as the available list of evacuation models grows, it would not be feasible to list the models here. No truly objective comparison has been undertaken of the range of evacuation models currently available, but a brief overview of many of the currently available programs can be found in the literature.[56–59] The degree to which behavior is simulated varies extensively among available models. Care must be taken in choosing a model. The complexity of some models implies a greater predictive capability, but the scarcity of data available on behavior means that a great number of assumptions are embedded in the models, and the appropriateness of those assumptions is critical in evaluating the validity of a model's results.

Chapter 3–14 of the *SFPE Handbook of Fire Protection Engineering,* 3rd edition, "Emergency Movement," includes guidance on the selection of evacuation models. A list of questions the user should be able to answer about the model selected for analysis is provided.

SUMMARY

It is critically important in estimating the time to evacuate a building that attention be paid to more than the travel time necessary to clear spaces. The total time to evacuate a building, or to bring occupants to a location of safety, must include delay times before movement or refuge actions begin. Whether the estimates are based on data or on calculations, and regardless of whether the calculations are done by hand or by computer, a valid total evacuation time estimate cannot be estimated without consideration of time to start. The characteristics of the building occupants and of the building itself will govern the choice of appropriate delay time estimates, as well as the calculation of travel times.

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Chapter 3

Concepts of Egress Design

James K. Lathrop

Chapter Contents

Fundamentals of Design
Life Safety Code®
Influences on Egress
Definition of the Term "Means of Egress"
Capacity of Means of Egress
Egress Facilities and Arrangements
Egress Lighting and Exit Signs
Alarm Systems
Emergency Egress and Relocation Drills
Maintenance of the Means of Egress

Key Terms

egress width, exit, exit access, exit discharge, hazard of contents, human factors, *Life Safety Code*®, means of egress, movement of people, NFPA *101*®, *NFPA 5000*®, occupant load

Means of egress and their design should be based on an evaluation of a building's total fire protection system and an analysis of the population characteristics and hazards to the occupants of that building. The means of egress design should be treated as an integral part of the total system that provides reasonable life safety from fire.

This chapter covers the fundamental concepts of good egress design that are the basis for NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®. NFPA *101* governs good practices to provide life safety features in existing buildings and structures and features that can be designed as integral parts of new construction to provide reasonable safety to occupants in fires. *NFPA 5000* addresses new construction only, but covers life safety from many hazards in addition to fire. The components of good means of egress are discussed in some detail, with their functions and relationships in the total concept of proper egress design. Computer modeling and simulation to assist the egress design process also are discussed.

See also Section 4, Chapter 1, "Human Behavior and Fire"; Section 4, Chapter 2, "Calculation Methods for Egress Prediction"; Section 4, Chapter 5, "Strategies for Occupant Evacuation During Emergencies"; and Section 20, Chapter 1, "Assessing Life Safety in Buildings."

FUNDAMENTALS OF DESIGN

The approach to designing means of egress first requires a familiarity with the reactions of people in fire emergencies. These reactions can differ widely, depending on the physical and mental capabilities and conditions of building occupants. The psychological and physiological factors affecting the use of exits during emergencies are being identified and measured in research studies. Dr. John L. Bryan discusses in detail behavioral response to fire and smoke in Section 4, Chapter 1 of this book.[1]

Patterns of movement of people, singly and in crowded conditions, must also be understood. In buildings used as schools or theaters housing highly mobile occupants, for example, there are certain reproducible flow characteristics from persons exiting the buildings. These predictable flow characteristics have fostered computer simulation and modeling to aid the egress design process. However, no number of practical exit facilities can prevent injury or loss of life if the occupant egress flow is inhibited or prevented by the building itself, by personnel, or by fire and smoke conditions. An in-depth review of movement of people by Proulx can be found in Section 3, Chapter 13 of the *SFPE Handbook of Fire Protection Engineering,*[2] as well as in "Emergency Movement" by Nelson and Mowrer in Section 3, Chapter 14, of the same document.[3]

Human Factors

The design and capacity of doors, passageways, stairways, and other components in the total means of egress are related to the physical dimensions of the human body. The tendency of people to avoid bodily contact with others should be recognized as a major factor in determining the number of

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persons who will occupy a given space at any given time. Given a choice, people usually automatically establish "territories" to avoid bodily contact with others.

Studies have shown that most adult men measure less than 20.7 in. (520 mm) across at the shoulder, with no allowance for additional thicknesses of clothing.[4] A "body ellipse" concept is used to develop the design of pedestrian systems. The major axis of the body ellipse measures 24 in. (609 mm), whereas the minor axis is 18 in. (457 mm). This ellipse equals 2.3 ft^2 (0.21 m^2), which is assumed to help determine the maximum practical standing capacity of a space.

The movement of persons results in a swaying action that varies from male to female and, depending on the type of motion, varies with movement on stairs, on level surfaces, or in dense crowds. Body sway has been observed to range 1½ in. (38 mm) left and right during normal free movement. Where movement is reduced to shuffling in dense crowds and to movement on stairs, a total sway range of almost 4 in. (101 mm) has been observed. In theory, this indicates that a total width of 30 in. (762 mm) would be required to accommodate a single file of pedestrians traveling up or down stairs.[5]

Crowding people into spaces where less than 3 ft^2 (0.28 m^2) of space per person is available under nonemergency conditions may create a hazard. When the average area occupied per person is reduced to 2¾ ft (0.25 m^2) or less, contact will be unavoidable. Needless to say, under the psychological stresses imposed during a fire, such crowding and contact could contribute to crowd pressures, resulting in injuries. When a queue occurs because of an artificial, temporary situation or because of some permanent design feature, crowd control becomes difficult, and the well-being of individuals is threatened.

Factors Affecting Movement of People

There are several factors that determine how quickly people may pass through the means of egress.

In level walkways an average walking speed of 250 ft/min (1.26 m/sec) is attained under free-flow conditions, with 25 ft^2 (2.3 m^2) of space available per person. Speeds below 145 ft/min (0.73 m/sec) show shuffling, which restricts motion. Figure 4.3.1, adapted from *Research Report No. 95* of the London Transport Board,[6] shows the rate of speed reduction for space concentrations of less than 7 ft^2 (0.65 m^2) per person. Speeds of less than 145 ft/min (0.73 m/sec) result in shuffling, and, finally, a jam point is reached with one person every 2 ft^2 (0.18 m^2). The possibility of a significant nonadaptive behavior exists whenever egress movement is restricted, and the problem becomes urgent under fire exposure conditions, especially when there is more than one person every 3 ft^2 (0.28 m^2).

Calculations of flow rates using velocity (ft/min [m/sec]) and density (persons/ft^2 [m^2]) will reveal flow (persons/min/ft [persons/sec/m] of width), which increases as the pedestrian area decreases. The flow increases will continue until forward movement becomes restricted to the point that the flow begins to drop. Interestingly, observations of flow rates in one study noted the same flow rate sometimes occurred even though walking speeds of people were significantly different. Investigation revealed that the rate of decrease in speed, accompanied by an increase in density, results in uniform flow rates over a wide range of conditions.

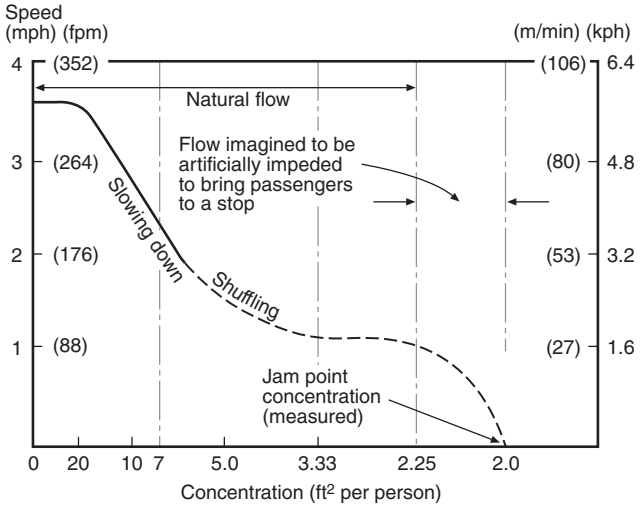


FIGURE 4.3.1 Speed in Level Passageways (SI units: 1 ft/min = 0.305 m/min; 1 ft^2 = 0.093 m^2)

A study of passageways indicates that for passageways over 4 ft (1.2 m) wide, flow rates are directly proportional to width. The London Transport Board *Research Report No. 95*[6] determined the flow rate in level passages to be 27 persons/min/ft (1.5 persons/sec/m) of width. Travel down stairways was determined at 21 persons/min/ft (1.2 persons/sec/m) of width, whereas upward travel was reduced to 19 persons/min/ft (1.1 persons/sec/m) of width. Where the width of a footway is less than 4 ft (1.2 m), the flow rate depends upon the number of possible traffic lanes. Absolute maximum flow rates occur when approximately 3 ft^2 (0.28 m^2) is occupied per person, which is applicable to both level walkways and stairs. In observed and measured evacuations, however, it has been empirically determined that the maximum flow rates down stairs in high-rise buildings occur when from 4 to 5 ft^2 of space (0.37 to 0.46 m^2) is occupied per person, as shown in Figure 4.3.2.[5] When flow in opposite directions takes place in a passageway up to the point where the two flows are of equal magnitude, there is no significant reduction in total flow below that which would be predicted on the basis of unidirectional flow in the same passageway.

Further, flow can be 50 percent greater in short passageways less than 10 ft (3.05 m) long than through a long passageway of the same width. Minor obstructions within a passageway do not appear to have a significant effect on flow. Within a 6-ft (1.82-m) wide passageway, there is no effect on flow rates when a 1 ft (0.35 m) projection is introduced. A 2 ft (0.61 m) projection resulting in a 33 percent reduction in width reduces the flow rate by approximately 10 percent. A major obstruction, though, such as that which occurs at a ticket booth or turnstile, may interrupt the movement of people and reduce flow rates.

Corners, bends, and slight grades up to 6 percent are apparently not factors in determining flow rates. A slight reduction in speed does occur, but the flow rate is maintained by an increased concentration of persons.

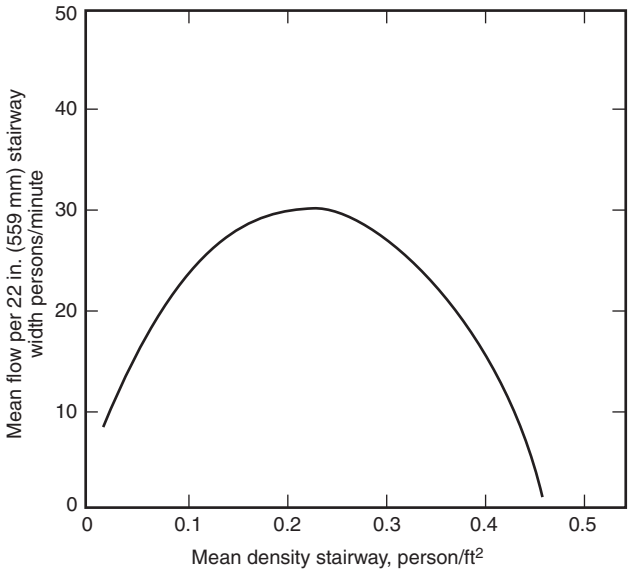


FIGURE 4.3.2 Effect of Density on Flow Down Exit Stairways in Evacuations of High-Rise Office Buildings[5] (SI units: 1 ft^2 = 0.093 m^2)

A center handrail or mullion, which may divide a passageway into narrower sections, can further reduce the capacity of the passageway. The observed capacity of a 6-ft (1.82-m) wide stairway reveals a reduction from 130 to 105 persons/min after installation of a center handrail.

Except for the very young and the very old, age does not appear to be a significant factor in determining travel speed. Studies have shown a significant reduction in walking speeds for persons over 65 years of age. Studies have further revealed that a 40 percent increase is possible in the normal walking speed, which tends to discount this factor as a major influence on flow rates.[4]

For additional information see Section 3, Chapter 13, of the *SFPE Handbook of Fire Protection Engineering*.[2]

Methods of Calculating Egress

Two major principles are used to determine the necessary egress width. They are based on anticipated population characteristics identified with a specific occupancy.

The Flow Method. This method uses the theory of evacuating a building within a specified maximum period of time. Flow rates were traditionally set at 60 persons per 22 in. (559 mm) width/min through level passageways and doorways. In older editions of NFPA *101* this 22 in. (559 mm) width was referred to as 1 "unit" of exit width. Credit was given only for whole or half units, a half unit being 12 in. (0.3 m). The unit of exit width is no longer being used in most model codes. The flow method most commonly used today is based on so much width of an egress element per person served. For example 0.2 in. (0.5 cm) per person for a door or other level egress component is what is used by the *Life Safety Code* and the *International Building Code*. Table 4.3.1 provides the capacity factors used by the *Life Safety Code*.

TABLE 4.3.1 Capacity Factors

	Stairways (Width per Person)		Level Components and Ramps (Width per Person)	
Area	*in.*	*mm*	*in.*	*mm*
Board and care	0.4	10.0	0.2	5
Health care, sprinklered	0.3	7.6	0.2	5
Health care, nonsprinklered	0.6	15.0	0.5	13
High-hazard contents	0.7	18.0	0.4	10
All others	0.3	7.6	0.2	5

Source: Table 7.3.31, NFPA *101*, 2006 edition.

Pauls's[7] effective stair width concept advocates the consideration of only the portion of the stair used in effective movement by the occupants, as observed in functional and practice evacuations. This width is established with 6 in. (150 mm) clearance from each side wall of the stair. Figure 4.3.3 illustrates the flow time in seconds relative to the effective stair width per person and the units of width.

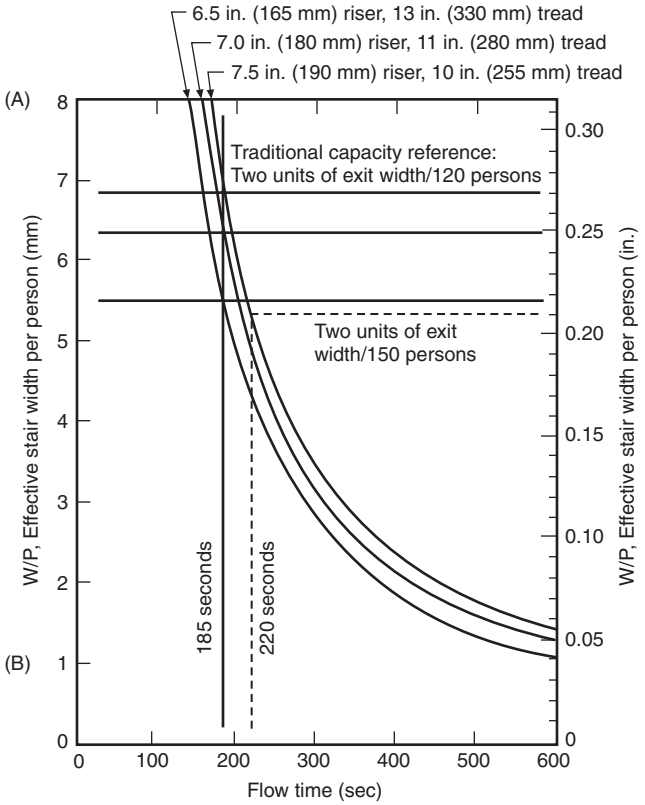


FIGURE 4.3.3 Relationship between Effective Stair Width and Units of Exit Width per Person and Flow Time for Three Stair Geometries[7]

The Capacity Method. This method is based on the theory that sufficient numbers of stairways should be provided in a building to adequately house all occupants of the building without requiring any movement, or flow, out of the stairways. In theory, assuming a stairwell provides a safe and protected area for all occupants within the protective barrier created by the stairway enclosure, evacuation of the building may then be more leisurely, permitting people to travel at a rate within their physical ability. The capacity method recognizes that evacuation from high-rise buildings is physically very demanding. Further, evacuation of a health care facility is likely to be slow. Thus, design criteria are established to permit holding occupants within exits or areas of refuge. The capacity method is not recognized in most model codes. However, codes do recognize areas of refuge. For example, the *Life Safety Code* does mandate that most health care occupancies have smoke compartments into which patients can be moved without having to evacuate the building.

Application

The capacity and flow methods may both be applied to efficient egress design, depending on specific circumstances. Where people are expected to be physically or mentally sick, aged, asleep, or incapacitated in any way, evacuation and use of the flow method can be augmented with the capacity method. Unless using a performance-based design, most model codes do not recognize the use of the capacity method alone.

There is little time between an alert and the use of an exit in assembly occupancies, and maximum flow rates that cause reductions in the area used by each person may result in reduced traffic flows. On the other hand, the staff supervision of children in an educational setting, coupled with their familiarity with the surroundings, their presumed high physical capabilities, and their experience with a program of drills should allow rapid evacuation times. Pauls has reviewed the historical and current literature relative to the principles of people movement, exit width determination, and the design of the means of egress.[8]

Design of Means of Egress

Designing a means of egress involves more than numbers, flow rates, and densities. Safe exit from a building requires a safe path of egress from the fire environment. The path is arranged for ready use in case of emergency and should be sufficient to permit all occupants to reach a safe place before they are endangered by fire, smoke, or heat. Proper egress design permits everyone to leave the fire-endangered areas in the shortest possible time with efficient exit use. If a fire is discovered in its incipient stage and the occupants are alerted promptly, effective evacuation may take place.

Maximum permitted evacuation travel distances are related to the occupant characteristics, occupant alertness, and building fire protection. The less capable people are to move, the less alert they are (such as sleeping), and the less protected a building is (such as no automatic sprinkler protection), the shorter the permissible travel distance.

Depending on the physical environment of the structure, the characteristics of the occupants, and the fire detection and alarm facilities, fire or smoke may prevent the use of one means of egress. Therefore, at least one alternative means of egress remote from the first is essential. Provision of two separate means of egress is a fundamental safeguard, except where a building or room is small and arranged so that a second exit would not provide an appreciable increase in safety. There are fewer or no advantages to separate means of egress if there is travel through a common space or use of common structural features that result in the loss of the two distinct and physically separate means of egress.

One example of a "common" structure is a multistory building where scissors stairs are used. These are two stairs enclosed within a common shaft, separated by a partition common to both stairs. Scissors stairs are sometimes used to provide the required exit capacity while minimizing the loss of valuable floor space. Where a set of scissors stairs is the only means of egress when two remote exits are required, the fundamental principle of two separate means of egress design may be violated. If the common partition between the stairs fails, it would result in the simultaneous loss of both exits during a fire, leaving no alternative means of egress. With scissors stairs, the validity of the two separate means of egress, therefore, depends on the design characteristics and construction of the common partition (Figure 4.3.4).

In some proposed egress designs, all the exits discharge through a single lobby at street level, even though this procedure results in egress travel through a common space. This design philosophy presumes that the lobby may be considered a safe area for all future egress needs during the life of the building. Where two remote means of egress are required, this type of egress design is not permitted by the *Life Safety Code* or by most model building codes.

NFPA *101* limits openings in exit enclosures to those necessary for access to the enclosure from normally occupied spaces and for egress from the enclosure. Penetration of enclosures by ducts or other utilities constitutes a point of weakness and may result in contamination of the enclosure during a fire and should not be permitted. Furthermore, it is not good practice to use exit enclosures for any purpose that could interfere with their value as exits. For example, exit stair enclosures should not be used for storage or any other use not associated with egress or areas of refuge for mobility impaired persons.

Provisions for handicapped persons is an important consideration in the design of an emergency means of egress from a building. A 32 in. (813 mm) doorway is considered the minimum width to accommodate a person in a wheelchair. Since handicapped employees or visitors may be found in all types of buildings, special life safety considerations are indicated. NFPA *101* contains several additional provisions to protect mobility-impaired individuals. It also must be noted that mobility handicaps are not the only type of handicap needing to be addressed. Hearing and sight impairments, along with certain mental disabilities, must be considered.

LIFE SAFETY CODE®

NFPA *101,* introduced in 1927 and revised and reissued in successive editions, is developed by several committees under the

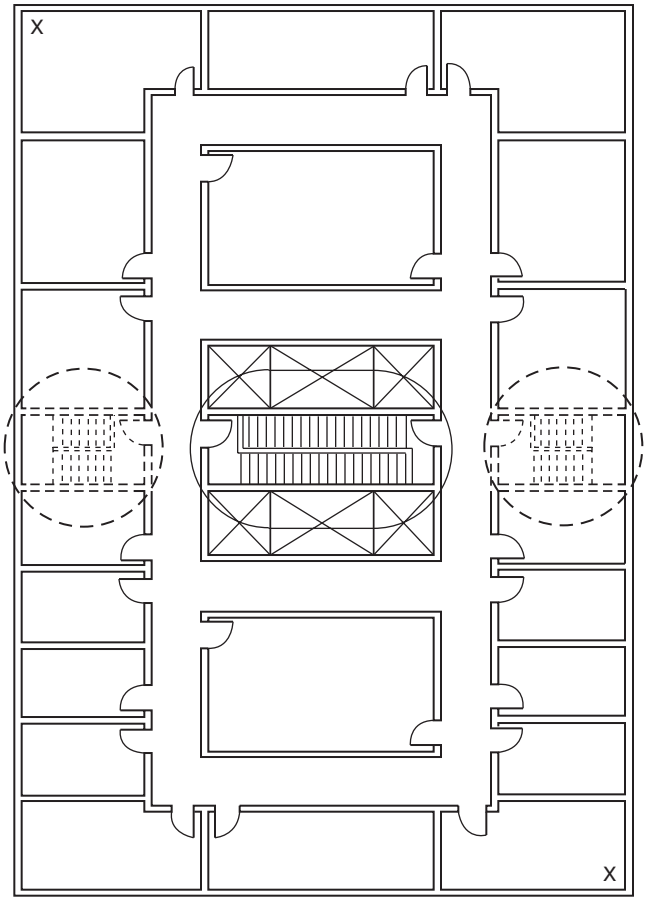


FIGURE 4.3.4 Advantages and Disadvantages of Scissors Stairs versus Conventional Stairs. This set of scissors stairs provides the same degree of remote exit doors as the circled stairs shown by dotted lines—travel distance for all occupants is the same, even if the dotted exit stairs were located at opposite corners as denoted by the cross marks. Space is saved; however, the integrity of the separation of the two scissors stairs is in question.

oversight of the Technical Correlating Committee on Safety to Life, a representative group dedicated to safety of life from fire. NFPA *101* is primarily concerned with the control of conditions that threaten the lives of individuals in building fires. This objective is different from fire protection provisions in building codes, which are concerned with the preservation of property in addition to the preservation of life. In 2000, NFPA announced its intent to write a building code. The first edition of *NFPA 5000®*, *Building Construction and Safety Code®*, was published in 2003. The provisions for means of egress in *NFPA 5000* are written by the same committees that write NFPA *101*. Because of this, the discussion here will address NFPA *101*. It is equally applicable to *NFPA 5000* when dealing with new construction.

Adequate means of egress alone are not a guarantee of life safety from fire. They do not protect an individual whose own carelessness causes a threat to life, such as setting his or her own clothes on fire. Neither do sufficient means of egress alone provide adequate protection in occupancies such as hospitals, nursing homes, prisons, assisted living facilities, and mental institutions, where occupants are confined or are physically or mentally unable to escape without effective and immediate assistance. NFPA *101* does recognize such situations and provides life safety measures, including low-flame-spread and reduced-smoke-producing materials for interior finish. In addition, automatic sprinkler and smoke management systems called for by NFPA *101* are designed to restrict the spread of fire and smoke and thus help to defend the occupants within an area of refuge until they are able to use the exits or until the fire has been extinguished.

In general, saving building occupants from a fire requires the following, all of which are identified in NFPA *101*:

1. Sufficient number of properly designed, unobstructed means of egress of adequate capacity and arrangement
2. Provision of alternative means of egress for use if one means of egress is blocked by fire, heat, or smoke
3. Protection of the means of egress against fire, heat, and smoke during the egress time determined by the occupant load, travel distance, and exit capacity
4. Subdivision of areas by proper construction to provide areas of refuge in those occupancies where total evacuation is not a primary consideration
5. Protection of vertical openings to limit the operation of fire protection equipment to a single floor
6. Provision of detection or alarm systems to alert occupants and notify the fire department in case of fire
7. Adequate illumination of the means of egress
8. Proper marking of the means of egress and the indication of directions
9. Protection of equipment or areas of unusual hazard that could produce a fire capable of endangering the egressing occupants
10. Initiation, organization, and practice of effective drill procedures
11. Provision of instructional materials and verbal alarm systems in high-density and high-life-hazard occupancies to facilitate adaptive behavior
12. Use of interior finish materials that prevent a high flame spread or dense smoke production that could endanger egressing occupants

Figure 4.3.5 illustrates some of the principles of exit safety.

NFPA *101* recognizes that full reliance cannot be placed on any single safeguard, because any single protective feature may not function due to mechanical or human failure. For this reason, redundant safeguards, any one of which will result in a reasonable level of life safety, should be provided. NFPA *101* also recommends the special protection of hazardous areas and specifies where automatic sprinkler, detection, and other protective systems are required.

NFPA *101* is used widely as a guide to good practice and as a basis for local laws or regulations. It differs from building codes since it generally provides little distinction among the different classes of building construction. However, where total

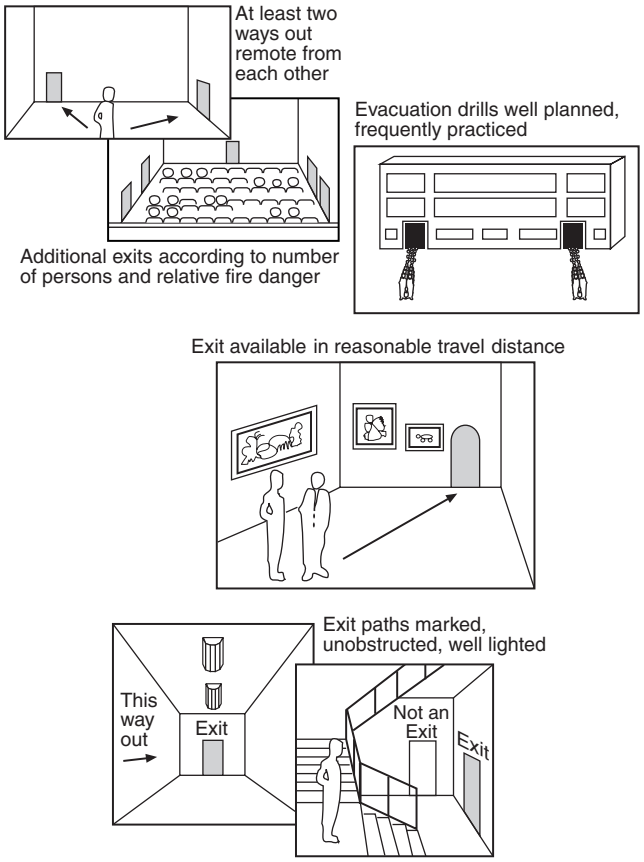


FIGURE 4.3.5 Principles of Exit Safety

evacuation of a building is not practical, due either to the occupant characteristics or the building environment, the construction type becomes an important variable and should be considered.

NFPA *101* also recognizes that all habitable buildings contain sufficient quantities of combustible contents to produce lethal quantities of smoke and heat.[9,10] In addition, casualty studies have established that the toxic properties of smoke are the principal hazard to life,[11] and this hazard is recognized in NFPA *101*.

NFPA *101* is intended to be applied to both new and existing buildings and is designed to provide a reasonable level of life safety from fire in both types of buildings. The authority having jurisdiction is given considerable latitude in achieving conformance with existing buildings. Each existing building represents a special situation that requires individual attention for the most effective and economical method of achieving a reasonable level of life safety.

The claim that buildings constructed many years ago according to all the legal requirements are sufficiently safe now should not necessarily be accepted. If the cost of reasonable life safety is judged to be prohibitive, the occupancy or the structure should be changed or prohibited because there is no justification for subjecting building occupants to an unreasonable level of peril from a fire.

There may be a variety of differing opinions as to what constitutes reasonable life safety from a fire in any given case. It is not possible to guarantee occupants 100 percent life safety from a fire; beyond certain conditions, a building becomes hazardous to the life safety of the occupants in a fire. How should the authority having jurisdiction establish the minimum conditions? NFPA *101* provides guidance for such decisions with the help of studies of major-loss-of-life fires,[12,13] fire development research,[10,14] personnel evacuation,[15–17] and human behavior.[1,18]

NFPA *101* examines the various occupancy populations according to their perceived life safety hazard, which includes psychological and sociological variables in addition to the physiological and environmental factors. These occupancy classifications are assembly, educational, day care, health care, ambulatory health care, detention/correctional, residential, residential board and care, mercantile, business, industrial, and storage. Additional provisions for special-purpose and high-rise structures are also included.

Separate and distinct means of egress provisions are made for each occupancy classification, with the various occupancy subgroups included. These classifications, based on the perceived hazard to life safety from a fire, often differ from older building code occupancy classifications. For example, mercantile and office occupancies were often grouped together in previous editions of building codes. However, there appears to be an increased hazard to life in mercantile properties, resulting from the displays of combustible merchandise, the greater density of the population, and the transient character of most of the occupants. These factors are not usually found in office and educational buildings, which have a relatively low combustibility content, a lower population density, and normally alert occupants who are in the building daily and presumably have the opportunity to familiarize themselves with the means of egress through functional use and evacuation drills.

INFLUENCES ON EGRESS

Influence of Hazard of Contents

An evaluation of the hazard of the building contents must take into account the relative probability of the ignition of combustibles, the spread of flames and heat, the probable smoke and gases expected to be generated by the fire, and the possibility of a fire-related explosion or other structural failure endangering occupants. The degree of hazard is usually determined by the flammability or toxicity of the contents and by the processes or operations conducted in the building. Most NFPA *101* requirements are based on the exposure created by contents with an ordinary hazard. Special requirements for areas with high-hazard contents usually consist of special protection systems, isolation of the hazard area via fire-rated construction, reduced travel distances, and additional means of egress.

To assist in evaluating the contents hazards, NFPA *101* establishes three classifications of contents: (1) low-, (2) ordinary-, and (3) high-hazard. They are discussed next. These should not be confused with the classifications established by NFPA 10, *Standard for Portable Fire Extinguishers,* or NFPA 13, *Standard*

for the Installation of Sprinkler Systems, nor with those established by some model building codes.

Low-Hazard Contents. These are contents of such low combustibility that no self-propagating fire can occur in them. Consequently, the only probable danger requiring the use of emergency exits will be from smoke or from fire from some external source. These are extremely unusual. The storage of sheet metal without combustible packing is one example.

Ordinary-Hazard Contents. These are contents that are liable to burn with moderate rapidity and to give off a considerable volume of smoke. This class includes most buildings and is the basis for the general requirements of NFPA *101*.

High-Hazard Contents. These are contents that are liable to burn with extreme rapidity or from which explosions are to be feared in the event of fire. Examples are occupancies in which flammable liquids or gases are handled, used, or stored; in which combustible dust explosion hazards exist; in which hazardous chemicals or explosives are stored; in which combustible fibers are processed or handled in a manner that produces combustible flyings; and similar situations.

Influence of Building Construction and Design

A building of fire-resistance-rated construction is designed to permit a burnout of contents without structural collapse. Fire-resistance-rated design does not ensure the life safety of the occupants of such buildings.[12,18] However, the ability of a structural frame to maintain building rigidity under fire exposure is important to the maintenance of the fire resistance protection of exit enclosures. Where a 2-hour fire-rated exit enclosure is required, a fire-resistance-rated structural frame capable of withstanding stresses imposed by fire for a similar period is also necessary. It is inconsistent to provide a 2 hour exit enclosure in a building with a structural frame rated at less than 1 hour, for example, unless special construction precautions are taken to prevent structural failure of the building from adversely affecting the protective construction of the exit enclosures.

The protection of vertical openings is one of the most significant factors in the design of multistory buildings, from the standpoint of life safety and exit design. Because of the natural tendency of fire to spread upward in a building, careful attention to details of design and construction are required to minimize this effect. One of the greatest hazards to life safety results from fires that start below the occupants and the means of egress, such as in basements or on the level of exit discharge. Similarly, fires in multistory buildings may result in smoke spread into enclosed exits before evacuation.[12,13,18] Conversely, escape from fires that occur above the occupants is relatively simple, provided sufficient warning is given and adequate means of egress are available.

The influence on the life safety of the occupants by the materials used in building construction depends primarily on whether the materials will propagate flame, support combustion, or create dense amounts of smoke when exposed to a fire initially involving the building contents. Some materials used as insulation, for example, could contribute to rapid flame development and dense smoke production spread. Masonry walls enclosing a wood-frame interior provide no increased occupant life safety compared with a total wood-frame structure.

Exit requirements are based on buildings of conventional design. Unusual buildings, such as those without windows or those with unopenable windows, call for special consideration. Windows provide a number of advantages in a fire. Windows allow occupants to see rescue operations in progress and allow occupants to communicate visually with rescue personnel. They also provide a means of access to the building by fire department personnel for rescue and fire fighting. Operable windows provide the additional advantage of access to fresh air, the potential ability to communicate orally with rescue personnel, and potential use for escape. Although it might be possible to break fixed windows to provide those same advantages, this poses several problems. First, falling glass presents a hazard to fire fighters outside; next, if the broken window permits smoke to enter, it cannot be closed as an operable window can; and last, depending on the type of glass and its thickness the window may be very difficult to break. Automatic sprinklers are considered a primary requirement for life safety in windowless buildings, buildings with unopenable windows, and underground structures.

Influence of Interior Finish, Furnishings, and Decorations

The rapid spread of flame over the surface of walls, ceilings, or floor coverings may prevent occupant use of the means of egress. In general, NFPA *101* limits the flame-spread index classification of interior finish materials on walls and ceilings to a maximum of 200, based on the results of tests conducted in accordance with NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials,* also known as ASTM E84. Lower ratings are prescribed for the interior finish materials used in exits and in exit access corridors. Materials classified as having a lower flame-spread index are also required in certain areas in individual occupancies. A fire-retardant coating may be used on existing interior finish materials to reduce the rate of flame spread. In areas protected with automatic sprinklers, the use of materials with higher flame-spread index classifications sometimes is permitted. Table 4.3.2 summarizes the interior finish requirements contained in NFPA *101* for the various occupancy classifications. NFPA *101* also recognizes NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth.* Any material that passes this test, based on the pass-fail criteria contained in NFPA *101,* can be used anywhere in a building.

Floor coverings are evaluated by NFPA *101,* through the use of NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source,* also known as ASTM E648. Two classes of floor coverings are established: Class I finishes, with a minimum critical radiant flux of 0.45 W/cm^2, and Class II finishes, with a minimum critical radiant flux of 0.22 W/cm^2.

Furnishings and decorations—particularly furnishings—play an increasingly important role in loss of life by fire.

TABLE 4.3.2 Interior Finish Classification Limitations

Occupancy	*Exits*	*Exit Access Corridors*	*Other Spaces*
Assembly—new			
>300 Occupant load	A	A or B	A or B
	I or II	I or II	
≤300 Occupant load	A	A or B	A, B, or C
	I or II	I or II	
Assembly—existing			
>300 Occupant load	A	A or B	A or B
≤300 Occupant load	A	A or B	A, B, or C
Educational—new	A	A or B	A or B;
	I or II	I or II	C on low partitions*
Educational—existing	A	A or B	A, B, or C
Day-care centers—new	A	A	A or B
	I or II	I or II	
Day-care centers—existing	A or B	A or B	A or B
Day-care homes—new	A or B	A or B	A, B, or C
	I or II		
Day-care homes—existing	A or B	A, B, or C	A, B, or C
Health care—new	A	A	A
	NA	B on lower portion of corridor wall*	B in small individual rooms*
	I or II	I or II	
Health care—existing	A or B	A or B	A or B
Detention and correctional—new	A or B	A or B	A, B, or C
(sprinklers mandatory)	I or II	I or II	
Detention and correctional—existing	A or B	A or B	A, B, or C
	I or II	I or II	
One- and two-family dwellings and lodging or rooming houses	A, B, or C	A, B, or C	A, B, or C
Hotels and dormitories—new	A	A or B	A, B, or C
	I or II	I or II	
Hotels and dormitories—existing	A or B	A or B	A, B, or C
	I or II*	I or II*	
Apartment buildings—new	A	A or B	A, B, or C
	I or II	I or II	
Apartment buildings—existing	A or B	A or B	A, B, or C
	I or II*	I or II*	
Residential board and care— (See Chapters 32 and 33 of NFPA *101*.)			
Mercantile—new	A or B	A or B	A or B
	I or II		
Mercantile—existing			
Class A or Class B stores	A or B	A or B	Ceilings—A or B; walls—A, B, or C
Class C stores	A, B, or C	A, B, or C	A, B, or C
Business and ambulatory health care—new	A or B	A or B	A, B, or C
	I or II		
Business and ambulatory health care—existing	A or B	A or B	A, B, or C
Industrial	A or B	A, B, or C	A, B, or C
	I or II	I or II	
Storage	A or B	A, B, or C	A, B, or C
	I or II		

Notes:
1. Class A interior wall and ceiling finish—flame spread 0–25, (new applications) smoke developed 0–450.
2. Class B interior wall and ceiling finish—flame spread 26–75, (new applications) smoke developed 0–450.
3. Class C interior wall and ceiling finish—flame spread 76–200, (new applications) smoke developed 0–450.
4. Class I interior floor finish—critical radiant flux, not less than 0.45 W/cm^2.
5. Class II interior floor finish—critical radiant flux, not more than 0.22 W/cm^2 but less than 0.45 W/cm^2.
6. Automatic sprinklers—where a complete standard system of automatic sprinklers is installed, interior wall and ceiling finish with a flame spread rating not exceeding Class C is permitted to be used in any location where Class B is required and with a rating of Class B in any location where Class A is required; similarly, Class II interior floor finish is permitted to be used in any location where Class I is required, and no critical radiant flux rating is required where Class II is required. These provisions do not apply to new detention and correctional occupancies.
7. Exposed portions of structural members complying with the requirements for heavy timber construction are permitted.

*See corresponding chapters of NFPA *101* for details.

Source: Table A.10.2.2, NFPA *101,* 2006 edition.

Decorations can be treated with a flame retardant. Furnishings, on the other hand, are difficult to control and regulate as a fire hazard, since they are not attached to, or part of, the building construction or of the interior finish materials. Furnishings are moved, refurbished, and replaced. However, there are now test procedures for measuring the combustibility of upholstered furniture and its susceptibility to ignition.[19] Two NFPA standards address furniture combustibility: NFPA 260, *Standard Methods of Test and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture;* and NFPA 261, *Standard Method of Test for Determining Resistance of Mock-Up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes.* ASTM E1590, *Standard Method for Fire Testing Mattresses,* assesses heat release of mattresses and bedding. If the *Life Safety Code* regulates upholstered furniture or mattresses, the restriction will be found in the appropriate occupancy chapter. Few occupancies have such regulations, and even those occupancies limit the restriction to new upholstered furniture and mattresses. The U.S. Consumer Products Safety Commission (CPSC) also has a standard for evaluating the ignitability of mattresses.[20] A number of fires have been documented in which severe conditions resulted from fire involvement of only a few furnishing items.[9,10,14]

Influence of Psychological and Physiological Factors on Egress

The psychological and physiological conditions of the occupants must be considered, in addition to the physical configuration factors of the building, in planning means of egress. Studies indicate people usually behave adaptively and often altruistically in the stress of a fire.[21,22] A heterogeneous collection of persons under the influence of alcohol or drugs, as may be present in an assembly occupancy, may pose a greater probability of nonadaptive group behavior, with a competitive flight, panic-type behavior the likely result. Historically, this type of nonadaptive behavior has been documented, although studies indicate that the phenomenon is rare and depends on unique, predetermined conditions involving both the population and the physical environment of the structure.[21–23]

In some cases, evacuation procedures and the creation of areas of refuge within high-rise buildings encourage occupant movement upward within the building. The effectiveness of this concept has not been completely validated in actual fires. Because of the orientation of some people toward total evacuation and escape from the building, it is possible that they may attempt to evacuate a building in the conventional "down and out" approach despite instruction to the contrary.[22] This is even more problematic since the September 11, 2001 World Trade Center disaster.

Evacuation procedures in federal high-rise office buildings, as directed by vocal alarm systems, have continually obtained the selective movement of personnel in both upward and downward directions.[15] In two serious high-rise office building fires in São Paulo, Brazil, the occupants moved upward to the roof when their downward movement was inhibited by smoke and heat.[12] In the MGM Grand Hotel fire in Las Vegas, Nevada, in November 1980, there also was upward movement in the stairways to the roof and to rooms on upper floors when downward travel was made untenable by smoke and heat.[13,21] It should be noted that rarely have successful helicopter rescues from the roof been performed. Roof-mounted structures, antennas, and similar items make close approach difficult. In a significant fire, thermal updrafts make approaching the building hazardous. Buildings properly built and maintained in accordance with codes such as the *Life Safety Code* should not need such drastic measures.

All exits need to be conspicuously marked, because people are likely to be unfamiliar with the various exits from an area under fire conditions and thus neglect alternate means of egress. It is also important that the means of egress from a building be used as a matter of daily routine, so the occupants will be familiar with their location and operation. NFPA *101* requires that the main exit of assembly occupancies, which also serves as the entrance, be sized to handle at least half of the total occupant load of the building. Some assembly occupancies are now required to have a main exit that can accommodate two-thirds of the occupant load. This is a result of the Station nightclub fire in West Warwick, Rhode Island, where 100 people died.

There are three critical parameters in the effective use of the zoned evacuation of personnel to areas of refuge within a building:[24]

1. Proper construction to provide compartmented areas that are protected from the effects of fire and smoke
2. An effective verbal alarm system giving clear and comprehensive instructions, with provision for originating on-scene instructions from the fire department[15]
3. Effective evacuation drills to familiarize the occupants with the way the system functions

It has been advocated that occupants in fire-resistant, compartmented buildings used as hotels, motels, apartments, dormitories, hospitals, and other health care facilities should stay in their rooms rather than evacuate, because the rooms are the most adequate area of refuge.[25] In general, this method has not been adopted by NFPA *101* or by model building codes. However, the concept of areas of refuge is used by NFPA *101* extensively in occupancies such as health care as well as detention and correctional facilities and also to protect occupants with mobility impairments in all occupancies. In occupancies such as health care, ambulatory health care, and detention and correctional occupancies, NFPA *101* has mandatory provisions for smoke compartmentation to limit the need to move occupants off the story of fire origin. In new construction of any occupancy, buildings that are not protected by automatic sprinklers are required to provide "accessible means of egress" which in multistoried buildings usually means areas of refuge. NFPA *101* provides various ways of providing areas of refuge. The two most common areas of refuge are oversized exit stair landings or subdivision of the story by horizontal exits or smoke barriers.

Influence of Fire Protection Equipment

It is unsuitable to rely totally on manual or automatic fire-extinguishing systems in place of adequate means of egress, because fire-extinguishing systems are subject to both human and

mechanical failure. In addition, building areas may become untenable for human occupancy before the fire-extinguishing systems are effective. Under no condition can manual or automatic fire suppression be accepted as a substitute for the provision and maintenance of proper means of egress. However, NFPA *101* does provide significant alternative methods of compliance for buildings protected by automatic sprinkler systems. In addition, automatic sprinkler systems and various automatic detection systems are often installed in existing buildings to compensate for problems with the means of egress.

Where a complete standard system is installed, automatic sprinklers are sufficiently reliable to have a major influence on life safety. In addition to providing an automatic alarm of fire, they quickly discharge water on the fire before smoke has spread dangerously. Although automatic sprinklers should never be used in place of adequate means of egress, they are recognized in various ways by NFPA *101*. When total automatic sprinkler protection is provided, NFPA *101* permits increased travel distance to exits, the use of interior finish of greater combustibility, reductions in corridor requirements, and, in some occupancies, the use of combustible construction in situations where it would otherwise be prohibited. Provisions for areas of refuge are significantly easier to comply with in buildings protected throughout by automatic sprinklers. Sprinklers are particularly valuable in dealing with problems in existing buildings.

Automatic fire detection, or fire alarm, systems are valuable in notifying building occupants of a fire so they may evacuate promptly. Automatic fire detection systems only provide a warning of fire and do nothing themselves to suppress or limit the spread of fire and smoke. An automatic fire detection system is not a substitute for adequate means of egress.

Smoke detection systems can be useful to help mitigate problems in existing buildings. They can be especially useful where earlier egress may help solve problems, such as existing excessive common paths of travel, dead ends, and travel distance.

DEFINITION OF THE TERM "MEANS OF EGRESS"

NFPA *101* and most of the U.S. model building codes use the term "means of egress." A means of egress is a continuous path of travel from any point in a building or structure to a public way that is in the open air outside at ground level. Egress consists of three separate and distinct parts:

1. *Exit access.* Portion of a means of egress that leads to the entrance of an exit.
2. *Exit.* Portion of a means of egress that is separated from the area of the building from which escape is to be made by walls, floors, doors, or other means that provide the protected path necessary for the occupants to proceed with reasonable safety to the exterior of the building. An exit may comprise vertical and horizontal means of travel, such as exterior doors, protected stairways, ramps, and exit passageways.
3. *Exit discharge.* Portion of a means of egress between the termination of the exit and a public way.

Figure 4.3.6 illustrates the relationship among these three parts of an exit in a building.

The Exit Access

The exit access may be a corridor, aisle, balcony, gallery, room, porch, or roof. The length of the exit access establishes the travel distance to an exit, an extremely important feature of a means of egress, because an occupant might be exposed to fire or smoke during the time it takes to reach an exit. The average recommended maximum travel distance is 200 ft (61 m), but this distance varies with the occupancy, depending on the fire hazard and the physical ability and alertness of the occupants (Table 4.3.3). The travel distance must be measured from the most remote point in a room or floor area to an exit.

In most cases, the travel distance can be increased if the building is completely protected with a standard supervised automatic sprinkler system.

A dead end is an extension of a corridor beyond an exit or an access to exits that forms a pocket in which occupants may be trapped. Since there is only one direction of travel to an exit from a dead end, a fire in a dead end between the exit and an occupant prevents the occupant from reaching the exit. Another problem with dead ends is that while traveling toward an exit in a smoky atmosphere, an occupant may pass by the exit and walk into the dead end. This requires return travel, which adds distance, and therefore time, to reach the exit. In good egress

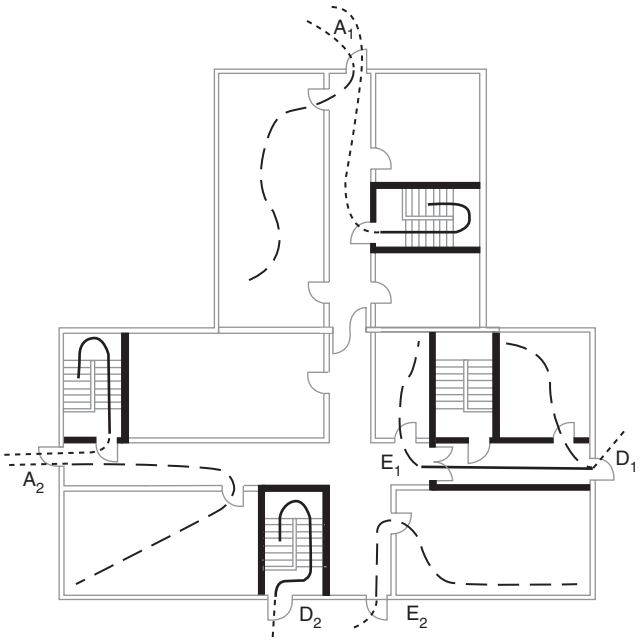


FIGURE 4.3.6 Examples of Exit Access, Exit, and Exit Discharge. To the occupant of the building on this level, the doors at A_1, A_2, E_1, and E_2 are exits. To the person emerging from the exit enclosures doors D_1 and D_2 are exit discharge doors. Exit access is denoted by dashed lines. Exit discharge is denoted by dotted lines. Solid lines are within the exit.

TABLE 4.3.3 Common Path, Dead-End, and Travel Distance Limits (by Occupancy)

	Common Path Limit		Dead-End Limit		Travel Distance Limit	
Type of Occupancy	*Unsprinklered ft (m)*	*Sprinklered ft (m)*	*Unsprinklered ft (m)*	*Sprinklered ft (m)*	*Unsprinklered ft (m)*	*Sprinklered ft (m)*
Assembly						
New	20/75 (6.1/23)[a]	20/75 (6.1/23)[a]	20 (6.1)[b]	20 (6.1)[b]	200 (61)[c]	250 (76)[c]
Existing	20/75 (6.1/23)[a]	20/75 (6.1/23)[a]	20 (6.1)[b]	20 (6.1)[b]	200 (61)[c]	250 (76)[c]
Educational						
New	75 (23)	100 (30)	20 (6.1)	50 (15)	150 (45)	200 (61)
Existing	75 (23)	100 (30)	20 (6.1)	50 (15)	150 (45)	200 (61)
Day Care						
New	75 (23)	100 (30)	20 (6.1)	50 (15)	150 (45)[d]	200 (61)[d]
Existing	75 (23)	100 (30)	20 (6.1)	50 (15)	150 (45)[d]	200 (61)[d]
Health Care						
New	NR	NR	30 (9.1)	30 (9.1)	NA	200 (61)[d]
Existing	NR	NR	NR	NR	150 (45)[d]	200 (61)[d]
Ambulatory Health Care						
New	75 (23)[e]	100 (30)[e]	20 (6.1)	50 (15)	150 (45)[d]	200 (61)[d]
Existing	75 (23)[e]	100 (30)[e]	50 (15)	50 (15)	150 (45)[d]	200 (61)[d]
Detention and Correctional						
New—use condition II, III, IV	50 (15)	100 (30)	50 (15)	50 (15)	150 (45)[d]	200 (61)[d]
New—use condition V	50 (15)	100 (30)	20 (6.1)	20 (6.1)	150 (45)[d]	200 (61)[d]
Existing—use condition II, III, IV, V	50 (15)[f]	100 (30)[f]	NR	NR	150 (45)[d]	200 (61)[d]
Residential						
One- and two-family dwellings	NR	NR	NR	NR	NR	NR
Lodging or rooming houses	NR	NR	NR	NR	NR	NR
Hotels and dormitories						
New	35 (10.7)[g,h]	50 (15)[g,h]	35 (10.7)	50 (15)	175 (53)[d,i]	325 (99)[d,i]
Existing	35 (10.7)[g]	50 (15)[g]	50 (15)	50 (15)	175 (53)[d,h]	325 (99)[d,h]
Apartments						
New	35 (10.7)[g]	50 (15)[g]	35 (10.7)	50 (15)	175 (53)[d,i]	325 (99)[d,i]
Existing	35 (10.7)[g]	50 (15)[g]	50 (15)	50 (15)	175 (53)[d,i]	325 (99)[d,i]
Board and care						
Small, new and existing	NR	NR	NR	NR	NR	NR
Large, new	NA	125 (38)[h]	NA	50 (15)	NA	325 (99)[d,i]
Large, existing	110 (33)	160 (49)	50 (15)	50 (15)	175 (53)[d,i]	325 (99)[d,i]
Mercantile						
Class A, B, C						
New	75 (23)	100 (30)	20 (6.1)	50 (15)	150 (45)	250 (76)
Existing	75 (23)	100 (30)	50 (15)	50 (15)	150 (45)	250 (76)
Open air	NR	NR	0 (0)	0 (0)	NR	NR
Mall						
New	75 (23)	100 (30)	20 (6.1)	50 (15)	150 (45)	400 (120)[j]
Existing	75 (23)	100 (30)	50 (15)	50 (15)	150 (45)	400 (120)[j]

(continued)

TABLE 4.3.3 Continued

Type of Occupancy	Common Path Limit		Dead-End Limit		Travel Distance Limit	
	Unsprinklered ft (m)	*Sprinklered ft (m)*	*Unsprinklered ft (m)*	*Sprinklered ft (m)*	*Unsprinklered ft (m)*	*Sprinklered ft (m)*
Business						
New	75 (23)[k]	100 (30)[k]	20 (6.1)	50 (15)	200 (61)	300 (91)
Existing	75 (23)[k]	100 (30)[k]	50 (15)	50 (15)	200 (61)	300 (91)
Industrial						
General	50 (15)	100 (30)	50 (15)	50 (15)	200 (61)[l]	250 (75)[m]
Special purpose	50 (15)	100 (30)	50 (15)	50 (15)	300 (91)	400 (122)
High hazard	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	75 (23)
Aircraft servicing hangars, ground floor	50 (15)[n]	100 (30)[n]	50 (15)[n]	50 (15)[n]	[a]	[a]
Aircraft servicing hangars, mezzanine floor	50 (15)[n]	75 (23)[n]	50 (15)[n]	50 (15)[n]	75 (23)	75 (23)
Storage						
Low hazard	NR	NR	NR	NR	NR	NR
Ordinary hazard	50 (15)	100 (30)	50 (15)	100 (30)	200 (61)	400 (122)
High hazard	0 (0)	0 (0)	0 (0)	0 (0)	75 (23)	100 (30)
Parking structures, open	50 (15)	50 (15)	50 (15)	50 (15)	300 (91)	400 (122)
Parking structures, enclosed	50 (15)	50 (15)	50 (15)	50 (15)	150 (45)	200 (60)
Aircraft storage hangars, ground floor	50 (15)[n]	100 (30)[n]	50 (15)[n]	50 (15)[n]	[a]	[a]
Aircraft storage hangars, mezzanine floor	50 (15)[n]	75 (23)[n]	50 (15)[n]	50 (15)[n]	75 (23)	75 (23)
Underground spaces in grain elevators	50 (15)[n]	100 (30)[n]	50 (15)[n]	100 (30)[n]	200 (61)	400 (122)

Notes:
NA = Not applicable.
NR = No requirement.
[a]For common path serving > 50 persons, 20 ft (6.1 m); for common path serving ≤ 50 persons, 75 ft (23 m).
[b]Dead-end corridors of 20 ft (6.1 m) permitted; dead-end aisles of 20 ft (6.1 m) permitted.
[c]See Chapters 12 and 13 of NFPA *101* for special considerations for smoke-protected assembly seating in arenas and stadia.
[d]This dimension is for the total travel distance, assuming incremental portions have fully utilized their permitted maximums. For travel distance within the room, and from the room exit access door to the exit, see the appropriate occupancy chapter of NFPA *101*.
[e]See business occupancies, Chapters 38 and 39 of NFPA *101*.
[f]See Chapter 23 of NFPA *101* for special considerations for existing common paths.
[g]This dimension is from the room/corridor or suite/corridor exit access door to the exit; thus, it applies to corridor common path.
[h]See the appropriate occupancy chapter of NFPA *101* for requirements for second exit access based on room area.
[i]See appropriate occupancy chapter of NFPA *101* for special travel distance considerations for exterior ways of exit access.
[j]See 36.4.4 and 37.4.4 of NFPA *101* for special travel distance considerations in covered malls considered to be pedestrian ways.
[k]See Chapters 38 and 39 of NFPA *101* for special common path considerations for single tenant spaces.
[l]See Chapters 40 and 42 of NFPA *101* for special requirements on spacing of doors in aircraft hangars.
[m]See Chapter 40 of NFPA *101* for industrial occupancy special travel distance considerations.
[n]See Chapters 40 and 42 of NFPA *101* for special requirements if high-hazard conditions exist.
Source: Table A.7.6, NFPA *101,* 2006 edition.

designs, dead-end corridors are not used. However, NFPA *101* permits dead ends in most occupancies, within reasonable limits (see Table 4.3.3). Two examples of dead-end corridors are illustrated in Figure 4.3.7.

The width of an exit access should be at least sufficient for the number of persons it must accommodate. In some occupancies, the width of the access is governed by the character of activity in the occupancy. One example is a new hospital, where patients may be moved in beds or in gurneys. The corridors in the patient areas of the hospital must be 8 ft (2.4 m) wide to allow for a bed to be wheeled out of a room and turned 90°.

A fundamental principle of exit access is the provision of a free and unobstructed way to the exits. If the access passes through a room that can be locked or through an area containing a fire hazard more severe than is typical of the occupancy, the principles of free and unobstructed exit access are violated.

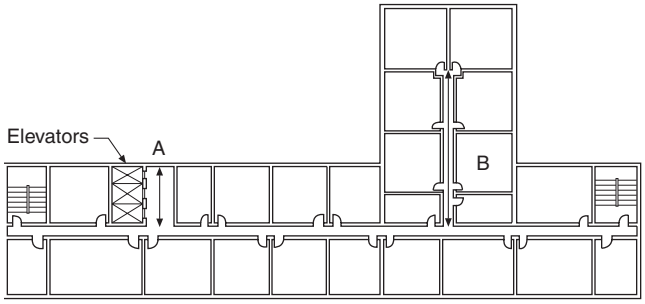


FIGURE 4.3.7 Two Examples of Dead-End Corridors. A shows an elevator lobby that has no exit at the far end, thereby forming a dead-end corridor. B is a "classic" dead-end corridor.

The floor of an exit access should be level. If this is not possible, small differences in elevation may be overcome by a ramp and large differences by stairs. Where only one or two steps are necessary to overcome differences in level in an exit access, a ramp is preferred, because people may trip in a crowded corridor and fall on the stairs if they do not see the steps or notice that those in front of them have stepped up or down.

The Exit

The types of permissible exits are doors leading directly outside at ground level or through a protected passageway to the outside at ground level, smokeproof enclosures, protected interior and outside stairs, exit passageways, enclosed ramps, and in existing buildings, enclosed escalators or moving walkways. Elevators are not accepted as exits; however, they can be used to provide a way of removing mobility-impaired individuals from areas of refuge. NFPA *101* also recognizes elevators for very limited use as a second exit for limited-access towers such as FAA control towers. Research is currently being conducted in an attempt to make elevators more usable for egress purposes. See Figures 4.3.8 and 4.3.9 for illustrations of some common types of exit arrangements.

The specific placement of exits is a matter of design judgment, given the specifications of travel distance, allowable dead ends, common path of travel, and exit capacity. NFPA *101* states

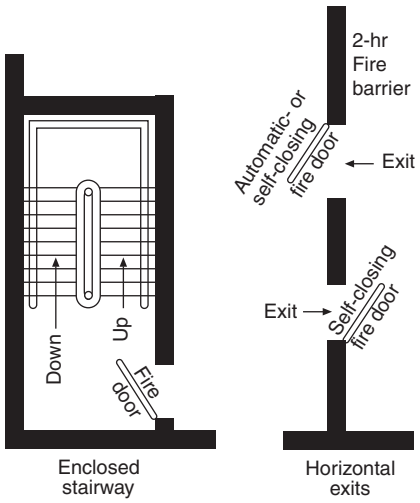


FIGURE 4.3.8 Plan Views of Types of Exits. Stair enclosure prevents a fire on any floor from trapping the persons above. A smokeproof tower is better, as it opens to the air at each floor, largely preventing the chance of smoke in the stairway. A horizontal exit provides a quick refuge and lessens the need for a hasty flight down stairs. Fire-rated doors must be arranged to be self-closing or automatic-closing by smoke detection.

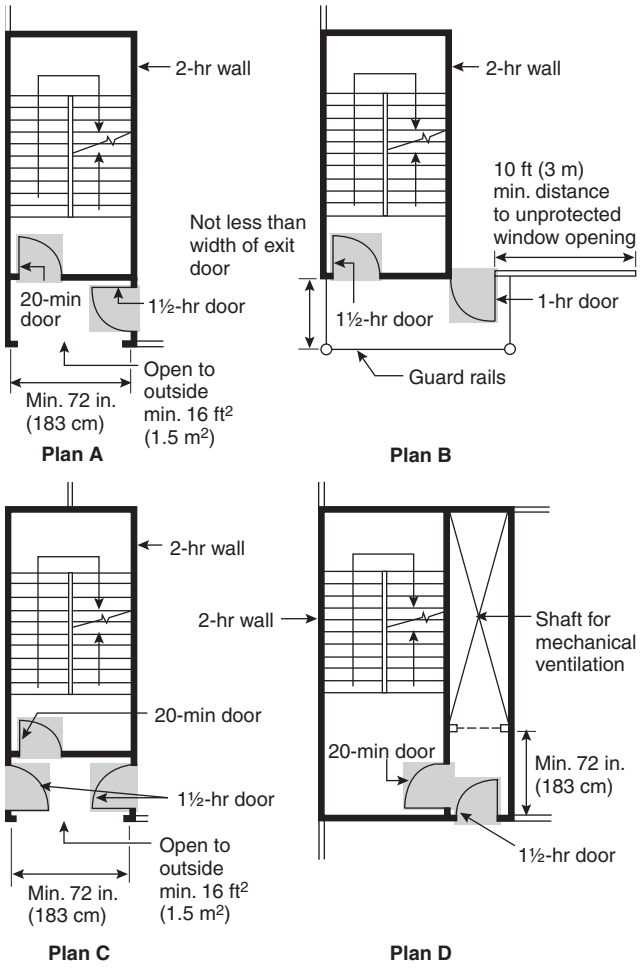


FIGURE 4.3.9 Four Variations of Smokeproof Enclosures. Plan A has an open-air vestibule opening from a corridor. Plan B shows an entrance by way of an outside balcony. Plan C could provide a stair entrance common to two areas. In Plan D, smoke and gases entering the vestibule would be exhausted by a natural or induced draft in the open air shaft. In each case, a double entrance to the stair tower with at least one side open or vented is characteristic of this type of construction. Pressurization of the stair tower in the event of fire provides an attractive alternate for tall buildings and is a means of eliminating the entrance vestibule.

that exits must be remote from each other, thus providing two separate means of egress so located that occupants can travel in either of two opposite directions to reach an exit. This concept is important when it is necessary for occupants to leave a fire or smoke-contaminated area and move toward an exit. If occupants have no choice but to enter the fire area to reach an exit, it is doubtful whether they will be able or willing to do so.

The Exit Discharge

Ideally, all exits in a building should discharge directly to the outside or through a fire-resistance-rated passageway to the outside of the building. NFPA *101* permits a maximum of 50 percent of the exit stairs to discharge onto the street floor. The obvious disadvantage of this arrangement is that if a fire occurs on the street-level floor, it is possible for people using the exit stairs discharging there to be discharged into the fire area. If any exits discharge to the street floor, NFPA *101* therefore requires that such exits discharge to a free and unobstructed way to the outside of the building, that the street floor be protected by automatic sprinklers, and that the street floor be separated from any floors below by construction having a 2 hour fire resistance rating.

Discharging an exit to the outside is not necessarily discharging to a safe place. If the exit discharges into a courtyard, an exit passageway must be provided from the courtyard through the building so that the occupants can get away from the building. If the exit discharges into a fenced yard, the occupants must be able to get out of the yard to get away from the building. If the exit discharges into an alley, the alley must be of sufficient width to accommodate the capacity of all the exits discharging into it, and any openings in the building walls bordering the alley should be protected to prevent fire exposure to the occupants proceeding through the alley.

When exit stairs from floors above the street floor continue on to floors below the street floor, occupants evacuating the building may miss the exit discharge door to the street level, continue down the stairway, and enter a floor below the level of exit discharge. Therefore, NFPA *101* requires a physical barrier or other effective means at the street floor landing to prevent evacuees from passing the level of exit discharge.

CAPACITY OF MEANS OF EGRESS

The capacity of exits is calculated using a capacity factor provided in NFPA *101*. This capacity factor is given as in./person (cm/person) and varies with the occupancy (see Table 4.3.1). The total exit capacity for each component of the means of egress, such as doors, stairs, ramps, corridors, and so on, is calculated based on its clear width. For example, one 34 in. (86 cm) clear-width door in an office occupancy would have an exit capacity of 170 persons (34 in. ÷ 0.2 in./person = 170 persons [86 cm ÷ 0.5 cm/person = 172 persons]). The reason for these variations in exit capacity factors is to establish a consistent total evacuation time in different occupancies, based on the physical ability, mental alertness, age, and sociological roles of the occupants. In occupancies where people are housed for care, the time taken to reach exits will be greater than in some other occupancies, and so the exits must be sufficiently wide to allow nonambulatory occupants to egress and to prevent any waiting to get into the exit.

Occupant Load

Occupant load, or the number of people to be expected in a building or an area within a building at any time for whom exits must be provided, is determined by the actual anticipated occupant load but not less than that number obtained by dividing the gross area of the story or the net area of a specific portion of the building by the area in ft^2 (m^2) projected for each person. The amount of floor area projected for each person varies with the occupancy (Table 4.3.4). These figures are based on actual counts of people in buildings and on reviews of architectural plans. In some situations, the maximum number of people in a building above the calculated occupant load can be determined at the design stage, in which case this number should be used in the design of the exits. A typical example is an assembly occupancy in which fixed seating is installed. Counting the number of seats provided, and calculating the standing or waiting areas by the occupant load factor, would obviously give a more accurate figure than multiplying a ft^2 (m^2)/person figure by the net floor area.

Computing Required Egress Width

To compute the minimum required egress widths from the individual floors of a building, the following steps are necessary:

1. Calculate the floor area, either net or gross, whichever is applicable.
2. Determine from NFPA *101* the estimated number of ft^2 (m^2)/person, or occupant load factor.
3. Divide the number of ft^2 (m^2)/person (occupant load factor) into the floor area to determine the minimum number of people for whom exits must be provided for that floor; use this calculated occupant load or the actual occupant load, whichever is *higher*.
4. Measure the clear width of each component in the means of egress.
5. Determine the capacity factor from NFPA *101* for each exit component for the appropriate occupancy.
6. Divide the clear width of each exit component by the capacity factor to determine the egress capacity for each component.
7. Determine the most restrictive component in each egress system.
8. Determine the total egress capacity for the story.
9. Ensure that the total egress capacity equals or exceeds the total occupant load.

In multistory buildings, the egress capacity for each story is calculated separately. In other words, the capacity of the stairs need only be wide enough to serve each floor, but it must not be less than the minimum width required by NFPA *101*. It must also be noted that the required egress capacity cannot be decreased in the direction of egress travel.

Street-floor exits may require special treatment, depending on the occupancy. Some occupancies require that street-floor

TABLE 4.3.4 Occupant Load Factor

Use	*ft² per Person*[a]	*m² per Person*[a]
Assembly Use		
Concentrated use, without fixed seating	7 net	0.65 net
Less concentrated use, without fixed seating	15 net	1.4 net
Bench-type seating	1 person/18 linear in.	1 person/455 linear mm
Fixed seating	Number of fixed seats	Number of fixed seats
Waiting spaces	See 12.1.7.2 and 13.1.7.2 (NFPA *101*)	See 12.1.7.2 and 13.1.7.2 (NFPA *101*)
Kitchens	100	9.3
Library stack areas	100	9.3
Library reading rooms	50 net	4.6 net
Swimming pools	50 (water surface)	4.6 (water surface)
Swimming pool decks	30	2.8
Exercise rooms with equipment	50	4.6
Exercise rooms without equipment	15	1.4
Stages	15 net	1.4 net
Lighting and access catwalks, galleries, gridirons	100 net	9.3 net
Casinos and similar gaming areas	11	1
Skating rinks	50	4.6
Educational Use		
Classrooms	20 net	1.9 net
Shops, laboratories, vocational rooms	50 net	4.6 net
Day-Care Use	35 net	3.3 net
Health Care Use		
Inpatient treatment departments	240	22.3
Sleeping departments	120	11.1
Ambulatory health care	100	9.3
Detention and Correctional Use	120	11.1
Residential Use		
Hotels and dormitories	200	18.6
Apartment buildings	200	18.6
Board and care, large	200	18.6
Industrial Use		
General and high-hazard industrial	100	9.3
Special-purpose industrial	NA	NA
Business Use	100	9.3
Storage Use		
In storage occupancies	NA	NA
In mercantile occupancies	300	27.9
In other than storage and mercantile occupancies	500	46.5
Mercantile Use		
Sales area on street floor[b,c]	30	2.8
Sales area on two or more street floors[c]	40	3.7
Sales area on floor below street floor[c]	30	2.8
Sales area on floors above street floor[c]	60	5.6
Floors or portions of floors used only for offices	See Business Use	See Business Use
Floors or portions of floors used only for storage, receiving, and shipping, and not open to general public	300	27.9
Mall buildings[d]	Per factors applicable to use of space[e]	Per factors applicable to use of space[e]

Notes:
NA = Not applicable. The occupant load is the maximum probable number of occupants present at any time.
[a]All factors are expressed in gross area unless marked "net."
[b]For the purpose of determining occupant load in mercantile occupancies where, due to differences in grade of streets on different sides, two or more floors directly accessible from streets (not including alleys or similar back streets) exist, each such floor is permitted to be considered a street floor. The occupant load factor is one person for each 40 ft^2 (3.7 m^2) of gross floor area of sales space.
[c]For the purpose of determining occupant load in mercantile occupancies with no street floor, as defined in 3.3.239 of NFPA *101,* but with access directly from the street by stairs or escalators, the floor at the point of entrance to the mercantile occupancy is considered the street floor.
[d]For any food court or other assembly use areas located in the mall that are not included as a portion of the gross leasable area of the mall building, the occupant load is calculated based on the occupant load factor for that use as specified in Table 7.3.1.2 of NFPA *101*. The remaining mall area is not required to be assigned an occupant load.
[e]The portions of the mall that are considered a pedestrian way and not used as gross leasable area are not required to be assessed an occupant load based on Table 7.3.1.2 of NFPA *101*. However, means of egress from a mall pedestrian way are required to be provided for an occupant load determined by dividing the gross leasable area of the mall building (not including anchor stores) by the appropriate lowest whole number occupant load factor from Figure 7.3.1.2(a) or Figure 7.3.1.2(b) of NFPA *101*.
Each individual tenant space is required to have means of egress to the outside or to the mall based on occupant loads calculated by using the appropriate occupant load factor from Table 7.3.1.2 of NFPA *101*.
Each individual anchor store is required to have means of egress independent of the mall.
Source: Table 7.3.1.2, NFPA *101,* 2006 edition.

exits be sized to handle not only the occupant load of the street floor but also the occupant load of the exits discharging to the street floor from floors above and below. In addition, in those occupancies where floors above and/or below the street floor are permitted to have unenclosed stairs and escalators connecting them with the street floor, the exits must be sufficient to provide simultaneously for all the occupants of all communicating levels and areas. In other words, all communicating levels in the same fire area are considered a single floor area for the purposes of determining the required egress capacity. This unified fire area factor can have a considerable effect on the sizing of the street-floor exits.

Should two or more exits converge into a common exit, the common exit should never be narrower than the sum of the widths of the exits converging into it.

Generally, the minimum number of exits is two. In certain limited situations, however, one exit may be permitted in some occupancies if there is a very low occupant load, low fire hazard, and a limited travel distance.

EGRESS FACILITIES AND ARRANGEMENTS

The following egress facilities are covered in NFPA *101*.

Doors

Doors should be side-hinged or pivoted swinging type and should swing in the direction of egress travel, except in small rooms. Horizontal sliding, vertical, or rolling doors are recognized for use as means of egress in some occupancies. In assembly occupancies, day-care centers, and schools, panic hardware should be installed on all egress doors equipped with latches that serve areas with an occupant load of 100 or more.

Where doors protect exit facilities, as in stairway enclosures and horizontal exits, they normally must be kept closed to limit the spread of smoke. If open, they must be closed immediately in case of fire. Although ordinary, fusible-link-operated devices to close doors in case of fire are designed to close in time to stop the spread of fire, they do not operate soon enough to stop the spread of smoke and are not permitted by NFPA *101*. At relatively low temperatures, smoke accumulation could continue and could reach untenable levels long before the fusible link melts, allowing the door to close.

Sometimes, people keep self-closing doors open with hooks or with wedges under the door. Doors also can be blocked open to provide ventilation, for the convenience of building maintenance personnel, or to avoid the accident hazard of swinging doors. The following measures have been provided in the NFPA *101* to alleviate this undesirable situation:

1. Doors that are normally kept open can be equipped with door closers and automatic hold-open devices that release the door and allow them to close when smoke detectors operate.
2. Doors that are normally closed can be equipped to open electrically or pneumatically when a person approaches the door, as long as smoke detectors are used to prevent the door from automatically opening when there is smoke in the area.
3. Doors that normally are closed can be opened and held open manually by monitors, as in schools.

Qualifications and limitations are applicable to each of these measures. One is that, in the event of electrical failure, the door must close and remain closed unless it is opened manually for egress purposes.

Another major maintenance difficulty with exit doors is the exterior door that is locked to prevent unauthorized access or for other reasons. NFPA *101* specifies that when the building is occupied, all doors must be kept unlocked in the direction of egress.

NFPA *101* allows a delayed releasing device on some egress doors, provided this is permitted by the requirements of the occupancy in question. Where the devices are allowed, the following provisions apply:

1. The building must be protected throughout by an approved and supervised automatic fire detection system or automatic sprinkler system.
2. The release devices are installed only in low- or ordinary-hazard areas.
3. The devices must unlock when the fire detection system or automatic sprinkler system operates.
4. The devices must unlock on loss of power.
5. The devices must initiate an irreversible process that will free the latch within 15 seconds whenever a force of not more than 15 lb (6.8 kg) is applied to the releasing device, and the door must not relock automatically. Operation of the releasing device must actuate a signal near the door.
6. A sign must be placed adjacent to the door that reads: PUSH UNTIL ALARM SOUNDS. DOOR CAN BE OPENED IN 15 SECONDS!
7. Emergency lighting must be provided at the door. Refer to NFPA *101* for more details and restrictions. Some of the occupancy chapters have further limitations.

NFPA *101* also provides "Access Controlled Egress Doors." The code spells out several limitations for these. One of the limitations included is that when an occupant approaches the door from the egress side, a sensor must unlock it.

Locks on a door that let people exit but not enter are satisfactory, but even this type of lock may not be satisfactory for security purposes. Possible measures to prevent unauthorized use of exit doors include the following:

1. An automatic alarm that rings when the door is opened
2. Visual supervision such as wired-glass panels, closed-circuit television, and mirrors, which may be used where appropriate
3. Automatic photographic devices to provide pictures of users

So-called exit locks, with a break-glass unit actuated by striking a handle with the hand, are not permitted by NFPA *101* unless installed in conjunction with panic bars. Otherwise, they do not comply with the NFPA *101* provision that reads: "A latch or other fastening device on a door shall be provided with a re-

leasing device having an obvious method of operation and that is readily operated under all lighting conditions."

Other types of break-glass locks and electrical controls for releasing exits from a central point are not permitted by NFPA *101*. The exception is an occupancy where controls may be necessary, as in health care or detention and correctional occupancies.

A single door in a doorway should not be less than 32 in. (813 mm) wide in new buildings and 28 in. (711 mm) in existing buildings. To prevent tripping, the floor on both sides of the door should have the same elevation for the full swing of the door.

Panic Hardware

Egress doors in assembly, day-care, and educational occupancies, such as schools or movie theaters, normally are equipped with panic hardware. Basically, panic hardware devices are designed to facilitate the release of the latching device on the door when a pressure not to exceed 15 lb (6.8 kg) is applied in the direction of exit travel. Such releasing devices are bars or panels extending not less than one-half of the width of the door and placed at a height not less than 30 in. (762 mm) or more than 44 in. (1.1 m) above the floor.

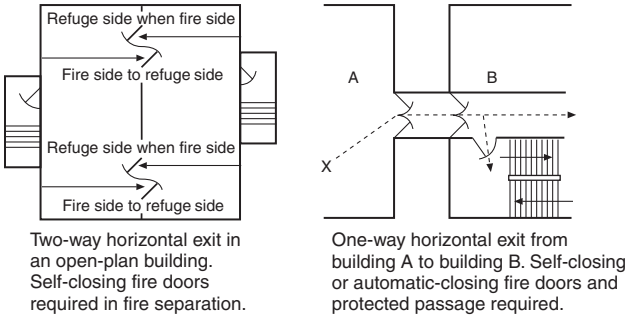
Panic hardware that has been tested and listed for use on fire-protection-rated doors is termed "fire exit hardware." If panic hardware is needed on fire-protection-rated doors, only fire exit hardware is to be used.

Panic hardware is available for use on single and double doors, with variations for rim-mounted hardware and mortise or vertical rod devices.

Horizontal Exits

A horizontal exit is a means of egress from one building to an area of refuge in another building on approximately the same level, or a means of egress through a 2 hour fire barrier to an area of refuge at approximately the same level in the same building that affords safety from fire and smoke. With a horizontal exit, it is obvious that space must be provided in the area or building of refuge for the people entering the refuge area. NFPA *101* recommends 3 ft^2 (0.28 m^2) of space per person, with the exception of health care or detention and correctional occupancies, where 6 to 30 ft^2 (0.56 to 2.79 m^2) of space is recommended. Horizontal exits cannot comprise more than one-half the total required exit capacity, except in health care facilities, where horizontal exits may comprise two-thirds of the total required exit capacity, and in detention and correctional facilities, where horizontal exits can comprise 100 percent of the total exit capacity. Horizontal exits have been applied universally in health care facilities where the evacuation of patients over stairs is slower and more difficult than taking them through a horizontal exit to a safe area of refuge. A horizontal exit arrangement within a single building and between two buildings is illustrated in Figure 4.3.10.

A swinging door in a fire wall provides a horizontal exit in one direction only. Two openings, each with a door swinging in the direction of exit travel, are needed to provide horizontal exits from both sides of the wall. Where property protection requires fire doors on both sides of the wall, a normally open, automatic, fusible-link-operated, horizontally sliding fire door may be used on one side, with a swinging fire door on the other.



Two-way horizontal exit in an open-plan building. Self-closing fire doors required in fire separation.

One-way horizontal exit from building A to building B. Self-closing or automatic-closing fire doors and protected passage required.

FIGURE 4.3.10 Types of Horizontal Exits

Stairs

Exit stairs are arranged to minimize the danger of falling, because one person falling on a stairway may result in the complete blockage of an exit. Stairs must be wide enough for two persons to descend side by side, thus maintaining a reasonable rate of evacuation, even though aged or mobility-impaired persons may slow the travel on one side. There must be no decrease in the width of the stair along the path of travel, since this may create congestion.

Steep stairs are dangerous. Stair treads must be deep enough to give good footing. NFPA *101* specifies a minimum 11 in. (279 mm) tread and a maximum 7 in. (178 mm) riser for new stairs. Landings should be provided to break up any excessively long individual flight. Continuous railings are now recommended for new stairs. New stairs more than 60 in. (1.5 m) wide should have one or more center rails. Beginning with the 2006 edition of NFPA *101,* new very tall buildings will be required to have wider stairs. If a stair serves a total of more than 2000 people there are more stringent width requirements to accommodate better flow (allowing for easier passing and for easier movement of mobility-impaired persons) as well as counter flow (allowing fire fighters with equipment up while occupants are evacuating).

Prior to 2006, two classes of stairs were permitted in NFPA *101* for existing buildings, with a single class of stairs for new stairs. There were Class A and Class B stairs for existing buildings. Starting with the 2006 edition the provisions for Class A stairs were deleted from the code and now there is one set of requirements for new and one for existing. The requirements are given in Table 4.3.5.

Stairs can serve as exit access, exit, or exit discharge. When used as an exit, they must be in an enclosure that meets exit enclosure requirements or outside the building and properly protected. Exit access stairs that connect two or more stories are vertical openings and must be protected as a vertical opening.

Stairways may be inside the building where NFPA *101* generally specifies protective enclosures. They also may be outside

TABLE 4.3.5 Requirements for New and Existing Building Stairs

	New Stairs	*Existing Stairs*
Minimum width clear of all obstructions except projections not exceeding 3½ in. (0.89 mm) at and below handrail height on each side	44 in. (1.12 m) 36 in. (0.91 m) where total occupant load of all floors served by stairways is less than 50	36 in. (0.91 m) 36 in. (0.91 m)
Maximum height of risers	7 in. (178 mm)	8 in. (203 mm)
Minimum height of risers	4 in. (102 mm)	—
Minimum tread depth	11 in. (279 mm)	9 in. (229 mm)
Minimum headroom	6 ft 8 in. (2.03 m)	6 ft 8 in. (2.03 m)
Maximum height between landings	12 ft (3.7 m)	12 ft (3.7 m)
Minimum dimension of landings in direction of travel	Stairways and intermediate landings shall continue with no decrease in width along the direction of exit travel. In new buildings every landing shall have a dimension, measured in direction of travel, equal to the width of the stair. Such dimension need not exceed 4 ft (1.22 m) when the stair has a straight run.	
Doors opening immediately on stairs, without landing at least width of door	No	No

if they comply with the requirements for exterior stairs and are arranged so that persons who fear heights will not be reluctant to use them, are not exposed to fire conditions originating in the building, and, where necessary, are shielded from snow and ice. Exterior stairs should not be confused with fire escape stairs (Figure 4.3.11). Exterior stairs as shown in the figure can be used in many types of occupancies, such as schools, motels, small professional buildings, and so on. Note that there are two means of egress, remote from each other, from the second-story balcony.

Construction details of stair enclosures involve the principles of limiting fire and smoke spread. Doors on openings from each story are essential to prevent the stairway from serving as a flue. In general, stairway enclosures should include not only the stairs, but also the path of travel from the bottom of the stairs to the exit discharge, so that occupants have a protected, enclosed passageway all the way out of the building. The stair enclosure should be of 1 hour construction when connecting three or fewer floors and of 2 hour construction when connecting four or more floors.

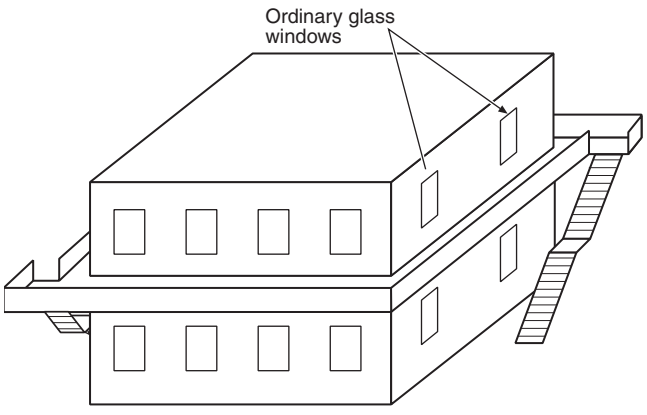


FIGURE 4.3.11 Outside Stairs Providing Direct Exits to the Outside for All Rooms in a Multistory Building. There are no interior corridors through which smoke and flame could spread.

Smokeproof Enclosures

Smokeproof enclosures provide the highest protected type of stair enclosure recommended by NFPA *101*. Access to the stair is only by balconies open to the outside air, vented vestibules, or mechanically pressurized vestibules, so that smoke, heat, and flame will not spread readily into the tower even if the doors are accidentally left open (see Figure 4.3.9).

Ramps

Ramps, enclosed and otherwise arranged like stairways, are sometimes used instead of stairways where there are large crowds and to provide both access and egress for nonambulatory persons. To be considered safe, exits ramps must have a very gradual slope.

Exit Passageways

A hallway, corridor, passage, tunnel, or underfloor or overhead passageway may be designated an exit passageway, providing it is separated and arranged according to the requirements for exits.

The use of a hallway or corridor as an exit passageway introduces some unique considerations. The use of these spaces for purposes other than exiting may violate fundamental design considerations. In an industrial situation, for example, the use of a gasoline-powered forklift in a corridor designated as an exit passageway would violate the principles of exit design.

NFPA *101* specifies that an exit enclosure should not be used for any purpose that could interfere with its value as an exit and is strictly limited by the code. Furthermore, penetration of the enclosure by ducts and other utilities may violate the protective enclosure.

Each opening in an exit enclosure introduces a point of weakness that could allow fire contaminants to spread into the exit and prevent its use. The typical corridor used as an exit with numerous door openings could result in fire contamination of the enclosure if a door fails to close and latch. The door openings in exit enclosures should be limited to those necessary for access to the enclosure from normally occupied spaces. Therefore, doors and other openings to spaces such as boiler rooms, storage spaces, trash rooms, and maintenance closets are not allowed into an exit passageway.

An exit passageway should not be confused with an exit access corridor. Exit access corridors do not have as stringent construction protection requirements as do exit passageways, because they provide access to an exit rather than being an extension and component of the exit. In Figure 4.3.6 the passage between E_1 and D_1 is an exit passageway.

Fire Escape Stairs

Fire escapes are, at best, a poor substitute for standard interior or exterior stairs. NFPA *101* only permits existing fire escapes in existing buildings; for some occupancies they are not allowed even for existing buildings. Existing fire escape stairs can be rebuilt, but new fire escapes cannot be installed on an existing building unless specifically approved by the authority having jurisdiction.

The same principles of design apply to fire escapes that apply to interior stairs, though requirements for width, pitch, and other dimensions are generally less strict. NFPA *101* gives the following criteria for fire escape stair design.

Fire escape stairs ideally extend to the street or to ground level. When sidewalks would be obstructed by permanent stairs, swinging stair sections designed to swing down under the weight of a person may be used for the lowest flight of the fire escape stairs. The area below the swinging section must be kept unobstructed so the swinging section can reach the ground. A counterweight of the type that balances on a pivot should be provided for swinging stairs; cables should not be used. Fire escapes that end on balconies above the ground level and provide no way to reach the ground, except by portable ladders or jumping, are unsafe.

Many persons who fear heights are reluctant to use fire escapes. As far as possible, design should provide a sense of security, as well as suitable railings and other details actually needed for safety. Fire escapes must be well anchored to building walls and kept painted to prevent rust.

Preferred access to fire escapes is through doors leading from the main building area or from corridors, never through rooms that may have locked doors except where every room or apartment has separate access to a fire escape. Although preferred access to fire escapes is by doors, windows may be used, in which case sills should not be too high above the floor. Windows should be of ample size, and, if insect screens are installed, they should be of a type that can be opened or removed quickly and easily. Decorative grilles or security bars should not be installed over windows that provide access to fire escapes.

Fire escapes can create a severe fire exposure to people if flames come out windows beneath them (Figure 4.3.12). The best location for fire escapes is on exterior masonry walls without exposing windows, with access to fire escape balconies by exterior fire doors. Where window openings expose fire escapes, fixed wired glass in metal sashes should be used. Where there is a complete standard automatic sprinkler system in the building, the fire exposure hazard to personnel on fire escapes is minimized.

In northern climates, outside fire escapes may be obstructed by snow and ice.

Escalators, Moving Walkways, and Elevators

In some occupancies, escalators may be recognized as egress in existing buildings. However, they are seldom installed in such a way that they would qualify as exits, and it is common to find escalator installations with unprotected floor openings. Escalators are not recognized as an acceptable component in a means of egress in new construction in any occupancy and in existing conditions in many occupancies.

Moving walkways also may be used as existing means of egress if they conform to the general requirements for ramps, if inclined, and for passageways, if level.

Elevators are not recognized as exits. However, elevators are permitted to be used, under limited conditions, to serve areas of refuge for the mobility impaired. The *Life Safety Code* also recognizes elevators, under very limited conditions, as the second exit from limited-access towers such as FAA control towers. As mentioned earlier, there is significant research being conducted in an attempt to develop ways to use elevators for egress.

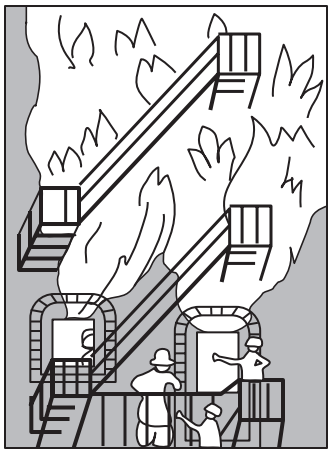


FIGURE 4.3.12 The Makeshift, Often Dangerous Aspect of Fire Escapes. Fire may make fire escapes useless as this picture, drawn from a photograph of an actual fire, shows.

Areas of Refuge

Since 1991, NFPA *101* has listed "areas of refuge" as a specific means of egress element. Although they are beneficial to all people, their primary purpose is for people with difficulty using stairs. All new buildings must address the issue of "accessible means of egress." In most new nonsprinklered multistory buildings, this will require some form of area of refuge. Figures 4.3.13 and 4.3.14 illustrate two methods for providing areas of refuge in nonsprinklered buildings.

Ropes and Ladders

Ropes and ladders generally are not recognized in codes as a substitute for standard exits from a building. This is proper since there is no excuse for permitting their use except possibly in existing one- and two-family dwellings where it is economically impractical to add a secondary means of escape. In this case, a suitable rope or chain ladder or a folding metal ladder may be suitable. However, the homeowner should recognize that aged, infirm, very young, and physically handicapped persons cannot use ladders and that, if the ladder passes near or over a window in a lower floor, flames from the window can prevent the use of the ladder.

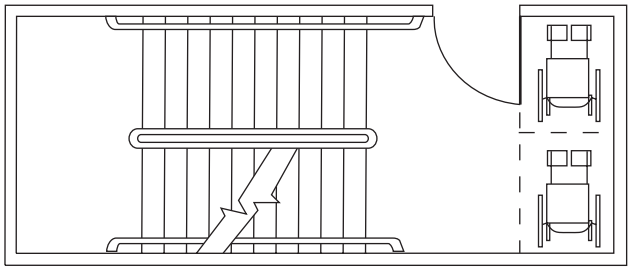


FIGURE 4.3.13 Exit Stair Used as an Area of Refuge. When stair landings are used as an area of refuge, the stairs are required to be 48 in. (122 cm) between handrails to accommodate carrying persons in wheelchairs.

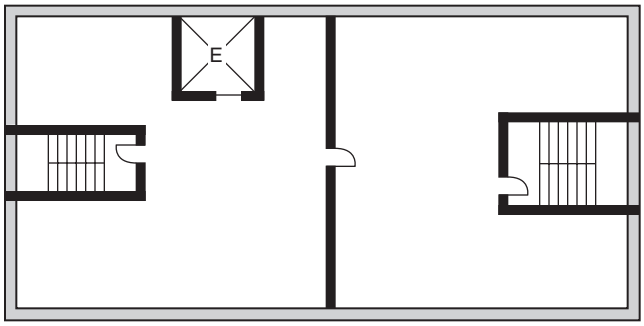


FIGURE 4.3.14 Areas of Refuge in Nonsprinklered New Construction. In this case the story is subdivided by either a horizontal exit or a 1 hour fire resistance rated smoke barrier. Each side of the barrier is an area of refuge for the other side. If the smoke barrier is used the stairs are required to be 48 in. (122 cm) between handrails to accommodate carrying persons in wheelchairs.

Windows

Windows are not exits. They may be used as access to fire escapes in existing buildings if they meet certain criteria concerning the size of window opening and the height of the sill from the floor. Windows may be considered a means of escape from certain residential occupancies.

Windows are required in school rooms subject to student occupancy, unless the building is equipped with a standard automatic sprinkler system, and in bedrooms and living areas in one- and two-family dwellings that do not have two separate means of escape. These windows are for rescue and ventilation and must meet the criteria for size of opening, method of operation, and height from the floor.

EGRESS LIGHTING AND EXIT SIGNS

Egress Lighting

In buildings where artificial lighting is provided for normal use, the illumination of the means of egress is required to ensure that occupants can evacuate the building quickly. The intensity of the illumination of the means of egress should be not less than 1 footcandle (10.77 lu/m^2) measured at the floor. It is desirable that such floor illumination be provided by lights recessed in the wall and located approximately 1 ft (30.5 cm) above the floor because such lights are then unlikely to be obscured by the smoke that might occur during a fire. In auditoriums and other places of assembly where movies or other projections are shown, NFPA *101* permits a reduction in this illumination for the period of the projection to values of not less than ⅕ footcandle (2.2 lu/m^2).

Emergency Lighting

NFPA *101* requires emergency power for illuminating the means of egress in many occupancies. For example, emergency lighting is required in assembly occupancies; in most educational buildings; in health care facilities; in detention and correctional facilities; in most hotels and apartment buildings; in Class A and B mercantiles; in business buildings based on occupant load and number of stories; in most industrial and storage buildings; and in underground or windowless structures subject to occupancy by more than 100 persons.

Well-designed emergency lighting using a source of power independent from the normal building service automatically provides the necessary illumination in the event of an interruption of power to normal lighting. The failure of the public utility or other outside electric power supply, the opening of a circuit breaker or fuse, or any manual act, including accidental opening of a switch controlling normal lighting facilities, should result in the automatic operation of the emergency lighting system.

Reliability of the exit illumination is most important. NFPA 70, *National Electrical Code*®, details requirements

for the installation of emergency lighting equipment. Battery-operated electric lights and portable lights normally are not used for primary exit illumination, but they may be used as an emergency source under the restrictions imposed by NFPA *101*. Luminescent, fluorescent, or other reflective materials are not a substitute for required illumination, because they are not normally sufficiently intense to justify recognition as exit floor illumination. However, such items are being used to supplement emergency lighting. And, as is discussed under exit signs below, code-compliant luminescent exit signs are now being manufactured.

Where electric battery-operated emergency lights are used, suitable facilities are needed to keep the batteries properly charged. Automobile-type lead storage batteries are not suitable because of their relatively short life when not subject to frequent recharge. Likewise, dry batteries have a limited life, and there is a danger that they may not be replaced when they have deteriorated.

If normal building lighting fails, well-arranged emergency lighting provides necessary floor illumination automatically, with no appreciable interruption of illumination during the changeover. Where a generator is provided, a delay of up to 10 seconds is considered tolerable. The normal procedure is to provide such emergency lighting for a minimum period of 1½ hours. Most health care occupancies have self-contained electric generating plants for emergency power supplies, not only for exit lighting but also for use in the event of failure of the public utility. Where such emergency electric facilities are provided, they may supply power for emergency exit lighting, as well as other critical areas of such buildings.

Exit Signs

All required exits and access ways must be identified by readily visible signs where the exit or the way to reach it is not immediately visible to the occupants. Directional "EXIT" signs are required in locations where the direction of travel to the nearest exit is not immediately apparent. The character of the occupancy will determine the actual need for such signs. In assembly occupancies, hotels, department stores, and other buildings with transient populations, the need for signs will be greater than in a building with permanent or semipermanent populations. Even in permanent residential-occupancy buildings, signs are needed to identify exit facilities, such as stairs, that are not used regularly during the normal occupancy of the building. It is just as important that doors, passageways, or stairs that are not exits but are so located or arranged that they may be mistaken for exits be identified by signs with the words "NO EXIT."

Signs should be so located and of such size, color, and design as to be readily visible. Care should be taken not to obscure the visibility of these signs with decorations, furnishings, or other building equipment. NFPA *101* does not make any specific requirement for sign color but requires that signs be of a distinctive color. Some local codes do specify exit sign color. NFPA *101* specifies the size of the sign, the dimensions of the letters, and the levels of illumination for externally illuminated signs. For internally illuminated signs, the code mandates compliance with UL 924, *Standard for Emergency Lighting and Power Equipment.* This performance-based standard provides methods to evaluate different types of exit signs, including luminescent signs.

Improvement in the physical marking of exits in an office occupancy with point-source, red or green strobe lights has been suggested. Placing corridor illumination on the walls close to the floor to provide effective illumination under smoke conditions, as is the practice in Japan, is a technique worthy of research.[26]

ALARM SYSTEMS

Fire alarm systems to alert occupants to leave the building are normally operated manually. The alarm-sounding devices themselves should be distinctive in pitch and tone quality from all other sounding devices, and the use of these devices should be restricted to evacuation notification. Vocal alarm systems have been developed and installed in many high-rise buildings.[14] NFPA *101* mandates voice alarm and communication systems in high-rise buildings. It is, of course, very important that all alarm system devices be distributed throughout a building so as to be heard effectively in every room above all other sounds. Visible, as well as audible, alarm devices are sometimes used in buildings. NFPA *101* permits flashing the exit signs with the activation of the fire alarm system. In new construction, visible alarms must be provided in addition to audible alarms in most instances. Advances in alarm technology, such as directional sounders, are now being used to assist people in finding the exits.

The proper maintenance of alarm systems is most important. Alarm systems should be supervised by a responsible person who will make the proper tests at specified intervals and will take charge of all alterations and additions to the systems.

EMERGENCY EGRESS AND RELOCATION DRILLS

Emergency exit and relocation drills are essential in schools and are desirable in every type of occupancy to ensure familiarity with the exits and their operation. In occupancies such as hospitals, nursing homes, hotels, and department stores, drills are usually limited to employee participation, without alarming patients, guests, or customers. Drills should be planned to get everyone out of the building or to an area of refuge in an orderly manner, as promptly as possible. Fire fighting is always secondary to life safety, and, in general, fire-fighting operations should not be started until the evacuation is completed, except in cases where trained fire departments conduct rescue and fire-fighting operations simultaneously.

Drills should be held at least once a month or more often, but not at regularly scheduled periods. Drills should occur on all shifts in an occupancy operated 24 hours a day. They should simulate typical fire conditions for the occupancy. Drills, both with and without warning, are beneficial.

School emergency egress and relocation drills are an exercise in discipline, not speed, though reasonably prompt evacuation of a building is important. Students and staff should not be permitted to stop to put on coats. No individuals should be

permitted to remain in the building, and no one should be excused from participating in the drill. The drill should include a roll call by class at designated assembly areas outside the building to make sure that no one has been left behind.

There also should be an established routine for a complete check of the entire building, including toilets, to make sure that no one has been left behind. All exits should be used in drills, but routes should be varied from drill to drill. Occasional drills should be held that simulate conditions of an exit blocked by fire or smoke. All drills should simulate the fire department notification procedure. For a more detailed discussion of fire exit drills, see Chapter 1 of this section.

MAINTENANCE OF THE MEANS OF EGRESS

The provision of a standard means of egress with adequate capacity does not guarantee the safety of the occupants in the event of an evacuation of any building. Means of egress that are not properly maintained can mean loss of life in a fire. Property managers usually assign definite responsibility for maintenance of mechanical and electrical equipment but may fail to do the same for the means of egress. As a result inspection authorities may find otherwise safe stairways used as storage for materials during peak sales or manufacturing periods. In apartment buildings, rubbish, baby carriages, and other obstructions are often found in stairway enclosures. Exit doors may be found locked or hardware in need of repair. Doors blocked open or removed from openings into stairway enclosures may permit rapid spread of smoke or hot gases throughout the building. Loose handrails and loose or slippery stair treads offer the dangerous probability that persons evacuating a building will fall in the path of others seeking escape. Maintaining the exit discharge free of the accumulation of ice and snow in climates subject to such weather is very critical. Maintaining the means of egress in safe operating condition at all times is as important to the prevention of loss of life as the proper construction of the building and the elimination of fire hazards.

SUMMARY

Providing adequate means of egress is a key fire safety issue in both new buildings and existing facilities. NFPA *101* provides in-depth coverage for providing adequate means of egress. For new construction, many of the issues are also covered in building codes, including *NFPA 5000.* This chapter only introduces the subject. To more completely understand the subject, both the NFPA *Life Safety Code® Handbook* and the *SFPE Handbook of Fire Protection Engineering* should be consulted.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on concepts of egress design discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™*
NFPA 13, *Standard for Installation of Sprinkler Systems*
NFPA 70, *National Electrical Code®*
NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA *101®*, *Life Safety Code®*
NFPA 101A, *Guide on Alternative Approaches to Life Safety*
NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 260, *Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture*
NFPA 261, *Standard Method of Test for Determining Resistance of Mock-Up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes*
NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*
NFPA 914, *Code for Fire Protection of Historic Structures*
NFPA 5000®, *Building Construction and Safety Code®*

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UL 924, *Standard for Emergency Lighting and Power Equipment*

Chapter 4

Techniques of Crowd Management

John J. Fruin

Chapter Contents

Overview of Crowd Management and Crowd Control
Crowd Disaster Model
Crowd Management Examples and Disaster Incidents
Crowd Management Phases

Key Terms

Chicago E2 nightclub incident, craze, critical occupancy, crowd control, crowd management, DuPont Plaza Hotel fire, egress, flight response, ingress, metering, pressure point, Station Nightclub fire

Crowds occur frequently for different purposes in a wide variety of venues. Entertainment and sporting events will attract thousands of spectators. Large numbers of passengers move through transportation terminals during peak periods, sometimes resulting in serious crowding when connecting services are disrupted. Major office and shopping complexes have large tenant and transient visitor occupancies. Special events such as parades and public demonstrations can attract many thousands of participants and observers. Usually these large gatherings of people occur without serious problems. Occasionally fires or other events, combined with venue or management deficiencies, precipitate a rapid concentration of people that results in multiple casualties.

This chapter defines the terms *crowd management* and *crowd control* and differentiates between the two. A crowd disaster model, patterned after the systems analysis method, forms a basis for evaluating crowd incidents. A sampling of crowd disasters, which illustrate aspects of crowd behavior, is followed by a description of the sequence of crowd management phases.

See also the following chapters with related topics: Section 4, Chapter 1, "Human Behavior and Fire"; Section 4, Chapter 2, "Calculation Methods for Egress Prediction"; Section 4, Chapter 3, "Concepts of Egress Design"; and Section 4, Chapter 5, "Strategies for Occupant Evacuation During Emergencies."

OVERVIEW OF CROWD MANAGEMENT AND CROWD CONTROL

Crowd Management and Crowd Control Defined

Crowd Management. *Crowd management* is defined as the planned movement and assembly of people.* Although the terms *crowd management* and *crowd control* are often used interchangeably, there are important differences. Crowd management involves the systematic assessment of all aspects of venue occupancy prior to use. It can be considered an adjunct to the life safety evaluation process, with greater concentration on the possibilities for extreme crowding and its potentially fatal consequences. Crowd management planning includes determination of expected number of occupants of a space, anticipated group behavior, assessment of the adequacy of assembly areas, means of both ingress and egress, processing procedures such as ticket collection and security screening, staffing requirements, and means of communication.

Crowd Control. *Crowd control* is defined as the restriction or limitation of group behavior.* Crowd control may be part of a crowd management plan or may occur as a reaction to a group problem. It can include extreme measures to enforce order, such as the use of force, threat of personal injury, or arrest. It may employ barriers that alter the space available for occupancy and patterns of group

*The definitions of crowd management and crowd control are based on composite opinions of various safety professionals who recognize the differences between the proactive preplanning of events and reactive control during the event itself.

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movement. Inappropriate or poorly managed control procedures may precipitate crowd incidents rather than prevent them. For example, reacting to a group of unruly persons at a rock concert, police herded these individuals into areas where there was no means of egress, causing some to jump off grandstands and be injured. Other crowd incidents have occurred where exit controls, or even locked exits, have prevented orderly egress. Compliance with codes does not ensure safe functioning of an extremely crowded venue.

Crowd Composition

Crowds can attract participants who come to observe and to enjoy an event peacefully, as well as predators in search of victims and people with other psychological, social, or political agendas. The crowd provides some with a cover to engage in hostile or aberrant behavior, or as an opportunity for theft, selling drugs, or solicitation.[1] As an illustration of criminal manipulation of a crowd, a team of pickpockets was observed by the author delaying train departures at a New York City transit station to purposely increase crowding in subway cars. They then boarded the train, pushed their way through the crowded car, picking pockets along the way, and fleeing at the next stop. Casualties have been caused by the failure of guard railings under crowd pressures and by the structural failure of ramps and bridges under the stress of heavy crowding, as illustrated in the railing failure noted in the Hillsborough Stadium disaster described later in this chapter.

Crowd Psychology

Psychologists have likened a crowd to a series of intermeshing behavioral cells. Each crowd cell is composed of a small group of surrounding people, with limited personal interaction and communication within it. The members of an individual cell have no broad view of what is occurring in the crowd mass. A dominant cell member may influence the behavior of others within the cell. There may be cell-to-cell communication, often with the spread of unfounded rumors and misinformation. Investigations of several major crowd incidents—for example, the Who concert described later—have shown that misinformation precipitated inappropriate reactions. Crowd situations show a lack of front-to-back communication. People in the rear of the crowd will continue to press forward, while those in front experience severe distress but are unable to communicate their plight. This situation is due in part to the differences in pedestrian densities between front and rear ranks of a crowd. Those in the rear are at densities that still permit movement, whereas those in front are immobile and under great pressure. The unpredictability of group behavior is a significant complication in crowd management planning.

Crowd Categories

Three general categories of potentially dangerous crowd situations have been identified: (1) critical occupancy, (2) flight response, and (3) craze.[2] All types of crowds, even relatively small gatherings, can quickly become dangerous if not carefully managed. For example, a number of eager young participants were injured at an Easter egg hunt when sponsors began throwing gifts out to them.

Critical Occupancy. Critical occupancy is the gradual accumulation and overloading of a pedestrian space, beginning at levels below 3 ft^2/person (0.28 m^2/person) until it reaches the plan view area of the human body of about 1.3 to 1.5 ft^2 (0.12 to 0.14 m^2). Critical occupancies can occur in transportation terminals during service disruptions, at public events, or at other venues where ingress and assembly are not controlled. Escalators, because of their continuous passenger delivery characteristic, have caused critical occupancy fatalities where the discharge end space is restricted. So-called "festival seating" events, at which there are actually no seats, aisles, or other assembly control features, can more easily result in critical occupancy conditions. In one sense, all fatal crowd incidents are the result of critical occupancy conditions, with the difference that flight and craze events involve sudden mass movement.

Flight Response. The flight response occurs where people are fleeing either from a real threat, such as a fire or explosion, or from a perceived, but otherwise nonthreatening, event. Flight responses may be labeled as panics and stampedes, but closer examination shows that rapid group movement away from the threat was a reasonable reaction. Later investigation of victim behavior may show that mutual cooperation and assistance existed within group cells, rather than the destructive nonadaptive behavior of a panic. Flight response fatalities may occur where egress facilities are overwhelmed by the sudden rush and are restricted or blocked. Flight response incidents may occur due to fire, explosions, power outages, structural failures, group altercations, police actions, severe weather such as hailstorms or tornadoes, and earthquakes.

Craze. A craze is a competitive rush to obtain some highly valued objective. Crazes may happen when spectators attempt to get closer to celebrities, gain entry into a popular event, or, more unfortunately, where food is being distributed to starving victims of a disaster. Craze fatalities can occur where ingress facilities such as doors, ticket collection, or other pedestrian movement elements in the path between the crowd and its intended objective are overwhelmed.

CROWD DISASTER MODEL

The primary elements involved in crowd disasters have been determined from personal experiences in dense crowds, studies of many major crowd incidents, and basic pedestrian traffic engineering principles. The elements provide a model for understanding the causes of crowd disasters, means of prevention, and possible mitigation of an ongoing crowd incident. The model is patterned after classic systems analysis elements of time, space, information, and energy, and modified to form the descriptive acronym FIST. The acronym itself is a useful reminder that any crowd situation is potentially dangerous. The meaning of the initial letters of the acronym is as follows:

F = *Force* of the crowd, which is sufficient to cause compressive asphyxia, bend or dislodge steel railings, and, when fully unleashed, nearly impossible to control

I = *Information* on which the crowd acts or reacts, real or perceived, true or false, any and all means of communication with the crowd, security, medical, and first responder personnel

S = *Space* involved in the crowd incident and all its related physical facilities, standing area, doors, stairs, corridors, and escalators

T = *Time* during which the crowd buildup occurs, duration of incident, scheduling, and other time-based factors such as processing rates of pedestrian facilities

Force

The physical and psychological pressures within crowds at maximum density are difficult to describe unless one has personally experienced them. When crowd density equals the area of the human body, individual control is lost as one becomes an involuntary part of the mass. The crowd mass becomes almost fluid, with shock waves propagated through it sufficient to lift people off their feet and propel them distances of 10 ft (3 m) or more. People may be literally lifted out of their shoes or have clothing torn off.

Intense crowd pressures, exacerbated by anxiety, can make it difficult to breathe. Compressive asphyxia from these pressures is the most common cause of crowd deaths, not the trampling usually reported in the press. Compressive asphyxia, a condition medically difficult to reverse, has occurred in people as others pile up on them as they fall. As evidence of the magnitude of forces involved, bent steel railings were discovered after several fatal crowd incidents (for example, in the Who concert disaster). This indicates that forces of more than 1100 lb (500 kg) occurred. The pressures are not due entirely to pushing, but are also the domino effect of people being forced off balance and leaning on those in front. It could be compared to the compression of a giant steel spring. The human shock waves that surge through the crowd are a combination of this domino effect and a collective muscular reflex to obtain breathing space. Persons falling during a crush will have others forced on top of them, pinning them down and if the pile is high enough, causing respiratory failure.

Casualties have also been caused (as indicated in the Hillsborough Stadium disaster) by the failure of guard railings under crowd pressures and structural failure of ramps and bridges under the stress of heavy crowding. Security personnel may attempt to control the crowd from the front, urging people not to push. However, this type of control can be ineffective because counterpressures in front ranks can cause falls farther back within the crowd, resulting in pileups. For example, in the Who concert, fatalities occurred about 30 ft (10 m) back from a wall, possibly indicating that those at the wall were "pushing off" and subjecting those in the fatal zone to pressure from both front and rear ranks.

Information

The lack of immediate, reliable, and authoritative information by both crowd managers and crowd participants can be a critical factor in crowd incidents. In the broad systems sense, information has many forms. It includes any and all means of communication, the sights and sounds affecting group perceptions, training and actions of personnel, signs, and even methods of ticketing. Crowd managers and control personnel require an instant and accurate view of levels of occupancy, movement, and the actions of a crowd. They must know the practical limitations and capacities of every facet of the venue. Crowd members need to be informed of the status of events and requirements for safe and orderly conduct. Tickets affect crowd behavior and movement by determining the numbers of people involved in an activity and specific points of entry, assembly, and exit. Information is considered to be one of the most important aspects of crowd management.

Space

Space encompasses all the physical facilities used for the assembly and movement of people. It includes the size and areas of standing and seating spaces, and the number and practical working capacities of corridors, ramps, stairs, doors, turnstiles, escalators, and elevators. The configuration of these facilities is also a consideration. For example, a confusing or circuitous alignment of egress facilities would be an impediment to orderly evacuation in a flight response incident, particularly if obscured by smoke or power and illumination failures. Deficiencies in the capacity and configuration of assembly and movement facilities are considered to be the primary cause of crowd disasters.

Time

Time is the duration of the crowding experience. It is a direct determinant of total movement capacity. Crowd incidents may begin with a rapid buildup of people at a point where practical capacity is exceeded and free movement is blocked. As a simple example of temporal effects, there are significant differences in the group experience during the longer ingress period before a sporting event, compared to the game end when all patrons wish to exit at once. During the exit sequence, facilities are used to near maximums, and dense crowding occurs. Time-based strategies can be used to manage the degree of crowding during some events. Major art exhibitions have reduced traffic peaking and venue crowding by time-of-arrival ticketing. These tickets stipulate a specific time block during which the ticket is valid.

Metering

Metering is a time-based crowd management and control technique used to control the arrival rate of persons at any "bottleneck" facility with limited capacity. Examples include stairs, narrow corridors, escalators, doors, ticket processing, and security screening locations. In California, a form of metering was applied by the Bay Area Rapid Transit (BART) system planners at the Oakland stadium pedestrian bridge connection to the adjacent transit station.* The bridge was purposely underdesigned so that bridge traffic flow rate equaled the passenger loading

*This information was based on a conversation with the then chief of planning design of the BART system

rate of the transit system trains. This form of crowd management avoids potentially dangerous crowding on transit platforms.

Metering must be carefully applied because it can cause waiting lines on the approaches to the metered facility. These approaches should be open and large enough to accommodate expected demands. Formalized queue lines are frequently used at the approaches to metered facilities.

Staff communication is a critical aspect of metering control. Personnel involved in metering control procedures should be in constant communication with each other and alert to any overcrowding problems and to stop movement. In the Oakland stadium example, a BART train service delay would require immediate notification of personnel at the pedestrian bridge entrance control.

CROWD MANAGEMENT EXAMPLES AND DISASTER INCIDENTS

A sampling of lethal crowd disasters in the critical occupancy, flight, and craze categories follows. Several historical lists of crowd disasters are posted on the Internet.*

Viewing Situations

Stalin's Funeral, 1953. Stalin's funeral in March 1953 is an example of a critical occupancy incident caused by ineffective crowd management and control procedures. Reportedly 3 million persons had gathered to view Stalin's body lying in state at the Hall of Columns near Moscow's Red Square. Side streets along the route to Stalin's bier were blocked by army tanks and trucks to control movement of the crowd. Police and military, some on horseback, beat people with clubs to further control the crowd, even as hundreds of people were fatally crushed against building walls and the parked tanks and trucks. This event is in sharp contrast to the management of the crowd at Pope John Paul II's lying in state.

Pope John Paul II, 2005. Approximately 4 million people came to view Pope John Paul II lying in state in April 2005. An orderly queue line was set up on the approaches to St. Peter's Cathedral, at times reaching 3 miles (5 km) in length. Some mourners waited as long as 15 hours for a few seconds of viewing. Security was a significant concern, not only because of the sheer magnitude of the crowd but also because of visiting heads of state, some unpopular, and potential terrorist acts. Thousands of security forces, taken from the ranks of police and fire departments across Italy, were called in for crowd control. At one point two large lines heading toward St. Peter's Square were gradually merged into one by alternately releasing 500 persons at a time. The entire route was observed by CCTV, and crowd status was constantly communicated to police. Approximately 18,000 people per hour viewed the pope, with ushers dividing the line in two at the bier and urging mourners to walk past quickly.

Viewing situations, whether for those described here or for museum exhibitions, have capacity limitations. The viewing frontage, or the number of observers either standing or walking, and their viewing times determine the rate of flow. The smallest picture in a museum exhibit can determine flow rates because of its limited viewing frontage. Functions such as ticket collection and security screening also restrict pedestrian traffic flow and crowd processing rates.

Sports Stadia

Hillsborough Stadium, Sheffield, England, 1989. Sports stadia have been the scenes of a number of critical occupancy crowd disasters around the world. The 1989 Hillsborough Stadium in Sheffield, England, is cited only because it is one of the most thoroughly investigated.[3] Overcrowding of a stadium terrace, lack of front-to-back communication, combined with a railing failure resulted in 96 deaths and more than 400 injured. In this incident a larger than anticipated turnout of fans for a semifinal cup event overwhelmed the turnstile processing capacity, causing a backed-up crowd outside the stadium. It was later estimated that it would have taken more than two hours to process the accumulated fans with the available turnstiles. Police decided to open the gates to the west terrace to avoid crowd rush problems that would have occurred with the start-up of the match. Detailed analysis of photographs before the railing collapse showed that average standee densities on the terrace steps were 8.4 persons per square meter (1.3 ft^2/person), varying from 7.5 persons to 10.0 persons per square meter (1.4 to 1.1 ft^2/person) in rear and front rows, respectively.

Stadia with reserved seating are less likely to experience crowd crush incidents, such as the one that occurred at Hillsborough, because this system results in balanced, predictable occupancy, and dispersed pedestrian points of entry and egress. Seat and aisle arrangements result in spectator densities of about 2 persons per m^2 (5 ft^2/person) in seated sections.

Stepped Terraces and Stairs

Stepped terraces and stairs of any type are inherently dangerous places to accumulate crowds. Several incidents that follow show the involvement of stairs in fatal crowd incidents. Stairs provide a narrow platform for standing, and any pressure from the rear can cause chain reaction falls and potentially lethal pile-ups. Stairs are often weak links in pedestrian traffic movement because of reduced capacity and difficulties in bypassing slower pedestrians.

City College of New York Gymnasium, 1991. Critical occupancy of a stair resulted in 9 deaths and 28 injured at the entrance to the City College of New York gymnasium in December 1991.[4] A celebrity basketball game, advertised on a local radio station, attracted a large crowd. The gym was quickly filled, and the code-compliant, outward-opening doors closed to prevent more entries. Police controlled the crowd on the streets

*The website for Crowd Dynamics Ltd. (http://www.crowddynamics.com) has a comprehensive list of incidents; the online encyclopedia *Wikipedia* (http://www.wikipedia.org) lists crowd disasters under the term "human stampedes"; stories on crowds by both BBC News and CNN often cite a history of incidents; http://www.crowdsafe.com is also a useful site.

outside the venue, but were unaware of what was happening inside. Those precariously queued on the stair were driven into the lower landing area, jamming into the closed doors and piling up against them.

Festival Seating Events

Festival seating events, actually general admission without the formalized control offered by reserved seats and aisles, consistently result in critical occupancy conditions. Fan exuberance combined with extreme densities in front ranks cause most of these incidents.

Pearl Jam Concert, Roskilde, Denmark, 2000. In June 2000, 9 persons were killed and more than 25 injured as the band Pearl Jam played at 1 of 7 stages in Roskilde, Denmark.[5] Roskilde is one of Europe's biggest annual outdoor music events. It was estimated that 50,000 people had congregated at the Pearl Jam venue. Band members became aware of the crush and implored the audience to step back. It is virtually impossible to reverse a crowd crush in progress by this method because those in front ranks, in the "crush zone," cannot move, while those in the rear sense no danger. Subsequent police investigation exonerated the band and music fair management and blamed actions of the crowd for the deaths. A police representative suggested changes that might have lessened the tragedy, including a shorter chain of command to stop concerts more quickly and possible better surveillance of the audience.

Security staff is relatively ineffective in festival seating events, relegated to standing around the perimeter of the audience, without direct crowd access. Persons becoming ill in a dense crowd must be "surfed" out of the venue, by being passed overhead by the audience to security personnel on the perimeter. Surfing itself can be dangerous in critical occupancy conditions if the "surfer" is dropped and then becomes a fall and pileup hazard. Some top performers contractually limit crowd controls because they want to "feel" the energy of their fans (from the stage, not in the audience). Performers will sometimes throw souvenirs such as T-shirts out into the audience, potentially inciting dangerous crowd movement; at other times last-minute cancellation of an event has led to crowd disorders. Venue owners and managers have the responsibility of controlling promoter and entertainer actions, consistent with the venue capabilities and audience safety.

Central Park, New York City.

Festival seating events in New York City's Central Park have been successfully managed for many years without serious incidents. The concert security staff use crowd barriers to create a clear center aisle approximately 12 ft (about 4 m) wide extending from the rear of the venue up to the stage. The center aisle serves multiple purposes, including observation of crowd behavior, removal of unruly persons, and provision of medical assistance if needed. Other venues have installed crowd access and safety zones along the front of the stage, with some extending the zone out into the audience in "T" and "H" configurations. These configurations require clear routes out of the crowd scene to a secure area where medical aid can be administered. Extra-large format (Jumbo-Tron) TV screens offer opportunities to quickly communicate with crowds, by showing crush conditions in the front of the venue. In indoor venues they provide an opportunity to inform spectators of exit locations, venue rules, and other safety information.

Flight Response Incidents

Flight response incidents are triggered by fires, explosions, or unusual weather events that are perceived as threatening personal safety. Misinformation has also caused flight response incidents when there is no real threat.

DuPont Plaza Hotel Fire, San Juan, Puerto Rico, 1986. The DuPont Plaza Hotel fire in San Juan, Puerto Rico, in December 1986 resulted in 98 deaths in the hotel casino.[6] The casino had a double door at the front entrance off the main lobby and a single door at the rear. The rear door was a short distance from the pool area and the nearby beach. Under normal circumstances, the casino could be evacuated in a few minutes. The fire, started by arsonists, began in a ballroom on the other side of a wide stair adjacent to the casino. Hotel staff became aware of the fire shortly after ignition and made futile attempts to extinguish it. Casino occupants were not made aware of the fire at that time. Within an estimated 12 minutes, the fire flashed over the stair and rapidly engulfed the casino. The flashover blocked the main entrance doors, leaving only the single rear door for escape. Had this door opened outward, instead of inward, many lives would have been saved because of its close proximity to the pool area. However, fleeing victims piled up against the door, jamming it shut. Virtually all the victims were found at this door (Figure 4.4.1).[7]

The incident illustrates the importance of rapid communication, and the design and maintenance of viable egress routes. The DuPont Plaza Hotel fire and a number of other hotel fires resulted in the passage of the Hotel and Motel Fire Safety Act of 1990 (PL 101-391). This law mandates that federal employees on travel must stay in public accommodations that meet certain minimum levels of safety, including (1) sleeping rooms equipped with hardwired smoke alarms in accordance with *NFPA 72®*, *National Fire Alarm Code®*, and (2) the installation of an automatic sprinkler system complying with NFPA 13, *Standard for the Installation of Sprinkler Systems,* or NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height,* as appropriate. The automatic sprinkler provision does not apply to accommodations that are three stories or less in height.

E2 Nightclub Incident, Chicago, 2003. In February 2003 a DJ dance at the E2 nightclub in Chicago resulted in 21 dead and 85 injured.[8] Occupancy estimates vary, but a fire department official stated that as many as 1500 persons were on the second floor of the popular club at the time. There was an altercation in the club and the promoter's security personnel used mace pepper spray in an attempt to quell it. The spray permeated the air causing some to choke. Rumors spread that it was a terrorist act using poison gas. The bulk of the crowd rushed toward a 54-in. (21.3-cm) wide stair that connected to the front entrance, exceeding its capacity. Critical occupancy of the stair resulted

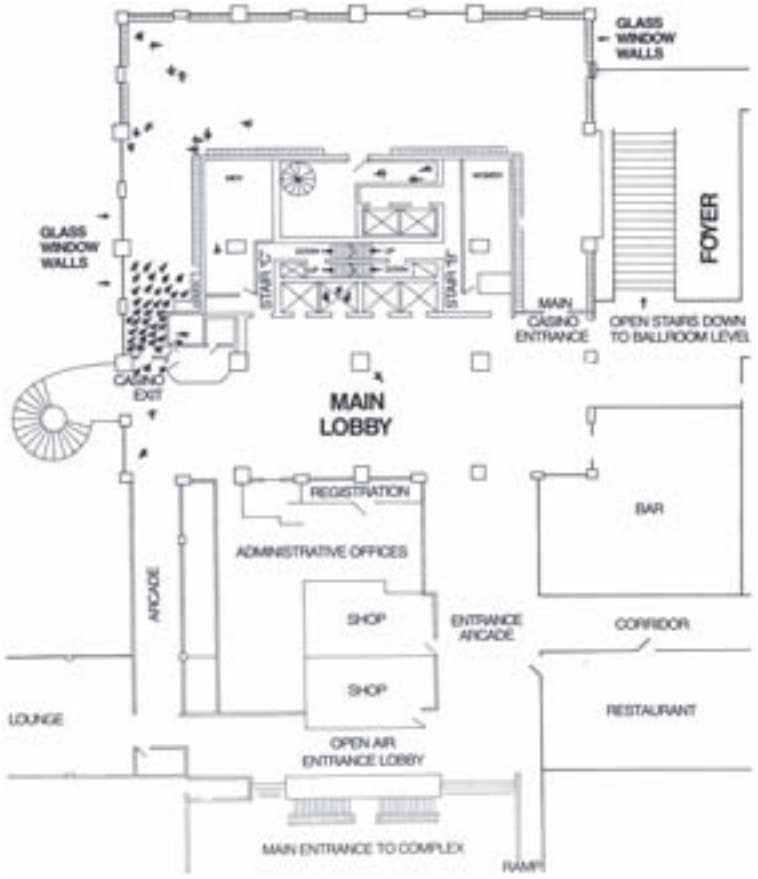

FIGURE 4.4.1 Location of DuPont Plaza Hotel Fire Fatalities on Casino Floor (Source: K. J. Thomas, "Investigation Report on the Dupont Plaza Hotel Fire, December 31, 1986, San Juan, Puerto Rico," *NFPA Investigation Report,* National Fire Protection Association, Quincy, MA, 1987)

in a pileup in the 11 ft by 12 ft (3.4 m by 3.7 m) entrance lobby below. One of the witnesses said it was not uncommon for mace to be used in clubs for control purposes. Had the rumors not spread, it is likely that only minor eye irritations and breathing discomfort would have resulted from security staff actions.

The Station Nightclub Fire, 2003. The Station Nightclub fire in West Warwick, Rhode Island, also in February 2003, resulted in 100 dead (Figure 4.4.2) and more than 180 injured.[9]

Pyrotechnics used by the heavy metal band Great White ignited soundproofing behind the stage and quickly spread. A fire official stated that the nightclub was fully involved within 3 minutes. For a brief moment some watched the fire, thinking it was part of the act, but then quickly realized the danger. Most headed for the front entrance, the typical escape route in many incidents, jamming it and blocking orderly egress. Those outside tried to extricate victims in the pileup, succeeding in rescuing some. Three other exits were functional at the time, but exit signs were obscured by smoke. There were reports of the victims attempting to aid each other in finding other exits, helping some to survive.

Quitab Minar Tower Blackout, New Delhi, India, 1981. A power failure resulted in 45 deaths, 27 of them children, in December 1981 at the Quitab Minar Tower in New Delhi, India.[10] The 800-year-old tower is a popular tourist attraction and museum. A blackout, combined with unfounded cries that the tower was falling, triggered a sudden flight of 300 to 400 people. The fatalities occurred on a narrow tower stair.

Craze Incidents

The Who Concert Disaster, Cincinnati, Ohio, 1979. The Who concert disaster in December 1979 at the Cincinnati, Ohio, Coliseum is an example of a craze.[11] A crowd of 18,000 young fans was gathered outside the Coliseum waiting to enter this general admission event. All seats were on a competitive first in–best seat basis. Many were waiting for hours with inadequate lavatory facilities. The opening of the gates was delayed until shortly before the scheduled time of the performance. The warmup band started playing, and the fans thought the concert had begun. Only two doors were open to permit entry. The crowd rush and pressures resulted in 11 deaths.

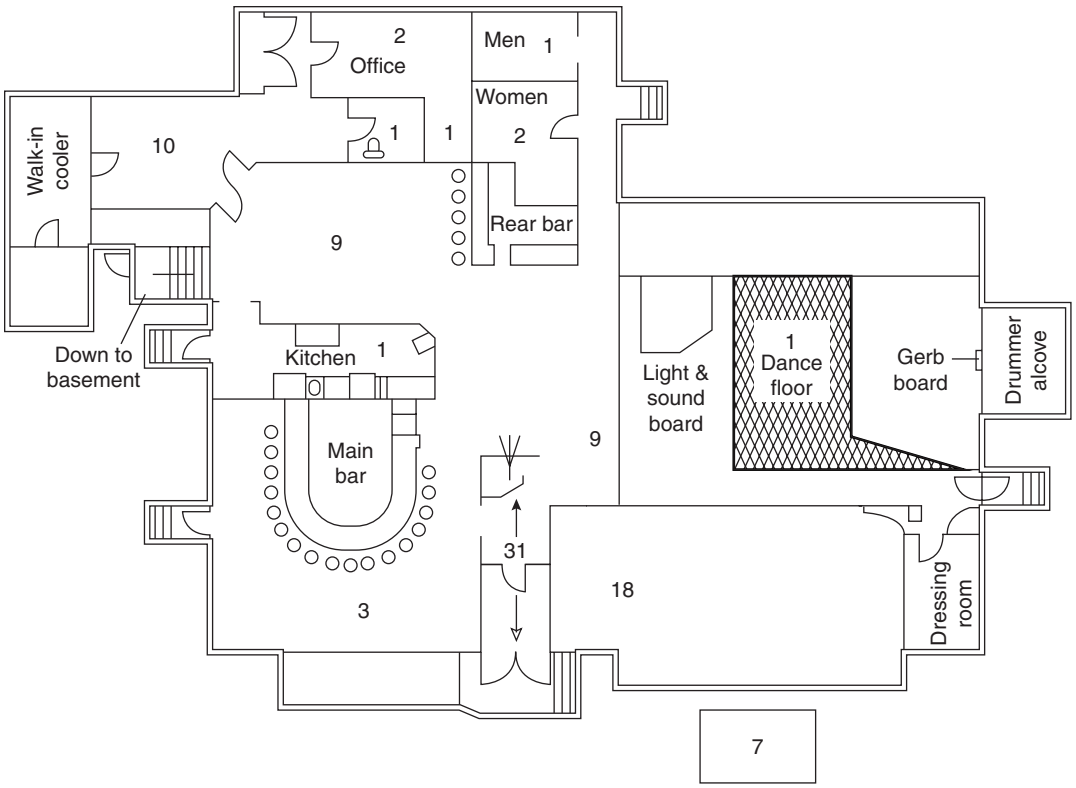

FIGURE 4.4.2 West Warwick, Rhode Island, Police Department Victim Location Diagram (Source: http://www.nist.gov/public_affairs/releases/Vol_I_NCSTAR2.pdf, Figure 5.54)

Sangju, South Korea, Concert Incident, 2005. The Who concert disaster scenario was replicated in October 2005 at a Sangju, South Korea, venue.[12] About 20,000 people had been waiting two hours for a free admission event featuring traditional Korean music popular among the elderly. The rush began when only one gate was opened, causing 11 deaths and injuring 72 others. The dead included 8 women aged 54 to 76, along with 3 boys aged 7, 12, and 14.

Minsk, Belarus, Incident, 1999. A crowd rush into a transit station in the Belarus capital, Minsk, in May 1999 killed 54 and injured more than 100.[13] About 2500 people had just left a concert when a hailstorm caused them to seek cover in the Nyamiha station. The incident happened in a tunnel leading to the station. Among those killed were 2 police officers, who died trying to control the crowd, and 42 teenage women.

Mecca, Saudi Arabia, Hajj Incidents. The vast multitudes of devout Muslims participating in Hajj at Mecca, Saudi Arabia, make it a monumental crowd management problem. More than 2 million people, the equivalent of the combined population of the cities of Boston and Philadelphia, participate in a series of symbolic rituals as part of the pilgrimage. There has been a series of crowd incidents over the years related to movement between the housing areas and the ritual site and during rituals at the site. Crowd deaths totaled 1426 in July 1990, 270 in May 1994, 180 in April 1998, 35 in March 2001, 36 in February 2003, 244 in February 2004, and 345 in January 2006.[14] After the 2004 incident, Saudi officials widened ramps leading to the ritual stoning of the devil where several crushes occurred, expanded the ritual area, added more emergency exits, and installed CCTV cameras. Reportedly, 60,000 security personnel are used for crowd control, or about 1 for every 40 pilgrims. Falling during the mass movement of pilgrims is a common cause of these incidents, with the following crowd unable to stop because of the pressures from behind.

CROWD MANAGEMENT PHASES

There are three phases in which crowd management principles should be applied: (1) venue design, (2) pre-event planning, (3) and the event itself, including ingress and egress. Crowd management objectives are to provide a safe, secure, and convenient environment, with the objective of preventing critical occupancy conditions and avoiding incidents that would precipitate sudden mass movement within the venue or to and from it.

Venue Design

Many architects and engineers give minimal attention to the movement of people in initial venue design beyond that required for compliance with local building code or permit requirements. Compliance with standards does not guarantee that a venue will function well during maximum occupancy or emergency

conditions. Designers have the responsibility of preparing the initial crowd management plan. Designing for crowd management requires that the projected maximum occupancy of a space, combined with expected behavioral factors, be correlated with the traffic processing capabilities of all corridors, stairs, ramps, escalators, elevators, and other related facilities.

Circulation "Tree" Diagram. A good management technique is to develop a circulation "tree" diagram, or schematic pedestrian traffic flow plan, to show how the expected occupancy of a space will be distributed among its various elements. For example, a circulation tree diagram for a stadium would schematically show the section capacities, aisle widths and capacities, vomitories, connecting hallways, entrance doors, numbers of turnstiles, capacities of queuing spaces, and so on. The circulation diagram is a useful tool for assessing actual venue performance under various conditions and pinpointing areas that are not performing as expected. The circulation plan can be further refined by using computer simulations of pedestrian traffic movement, queuing accumulations, and other parameters. Simulations offer the advantage of examining the performance of a venue for a wide variety of scenarios, including the impacts of extreme variations in venue occupancy; the timing of events; temporal changes in venue configuration; and number of turnstiles, doors, or other processing facilities[15,16] (Figures 4.4.3 and 4.4.4).

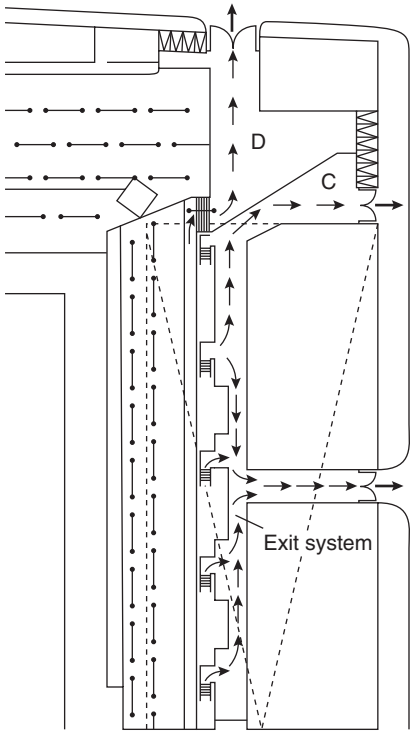

FIGURE 4.4.3 Plan on Stand (Source: Reprinted from *Engineering for Crowd Safety,* R. A. Smith and J. F. Dickie (Editors), "Strategies and Methods for Appraising Existing Stands" by M. Dickson, Figure 2, p. 3, Copyright 1993, with permission from Elsevier.)

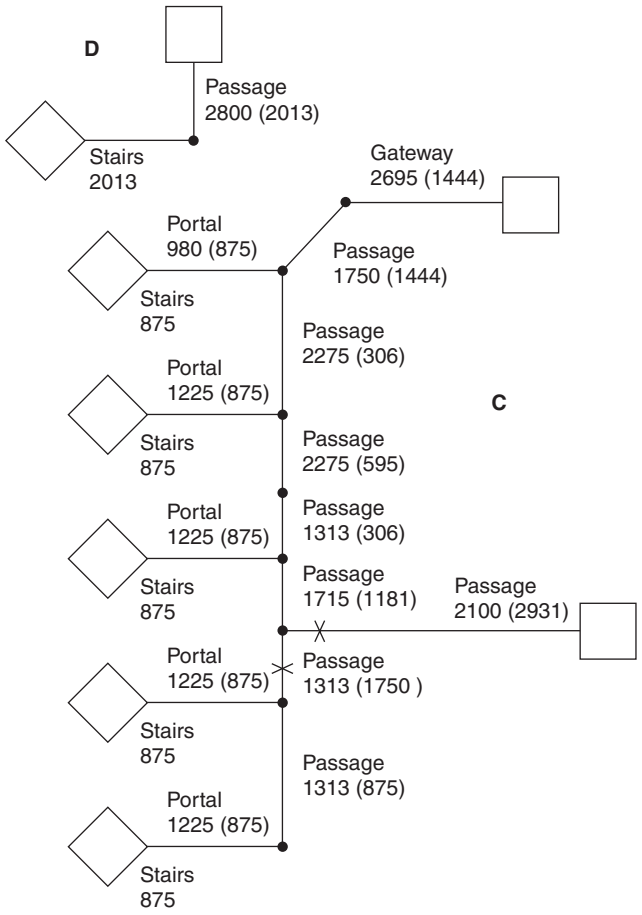

FIGURE 4.4.4 Exit System as Network (Source: Reprinted from *Engineering for Crowd Safety,* R. A. Smith and J. F. Dickie (Editors), "Strategies and Methods for Appraising Existing Stands" by M. Dickson, Figure 3, p. 3, Copyright 1993, with permission from Elsevier.)

Movement Pathways. Movement pathways should be simple and direct, and not circuitous or offset from the normal straight line of sight. Arrangements that result in unbalanced use of egress or ingress routes, dead ends, or similar confusing and irregular pathway choices, are not acceptable. Dispersed and equally balanced ingress and egress points are preferred over a single centralized location. The influence of external facilities on the volume and patterns of movement within a venue must be considered. For example, the concentration of parking or transit operations on one side of a stadium will focus internal movement toward that side, resulting in unbalanced traffic demands. Signing should be used to identify functions such as ticketing, to clarify routes within the venue and also to identify external elements such as parking and transit.

Pressure Point Hazards. Pressure point hazards along movement pathways must be avoided. Pressure points are locations where a right angle change in the normal direction of movement or a confluence of traffic streams results in crossing conflicts and accident exposure. Pressure point incidents may result in ca-

sualties where there are inadequately guarded openings to lower levels, at stair approaches, and on landings at the discharge or outlet ends of escalators. Crowd pressures at such locations may result in people being pushed over guardrails or down stairs, or in the structural failure of the guardrails.

Determining Location of Crowd Management Center. The crowd management center location and its supporting communications should be determined early in design. Real-time information about the status of crowd conditions in large assembly spaces is critical. The center should provide a maximum view of the venue, supplemented by CCTV access to blind spaces, pressure points, and major movement pathways. The crowd management center requires full communications integration with all crowd management staff; local police, fire, and emergency medical services; and any on-site radio or television media staff. Provision should be made for location of extra-large format TV screens as a multipurpose means of communication.

Backup Standby Power. Backup standby power for lighting and communications must be included in the design. The New Delhi Quitab Minar Tower blackout crowd incident is an example of the confusion that can result from a lighting and communications failure. Public address systems tied only to primary power sources would be lost during a power outage, potentially when they might be needed the most.

Emergency Medical Facilities. Emergency medical facilities sufficient to handle routine accidents as well as potentially larger crowd incidents are necessary. Lives may be unnecessarily lost in large crowd incidents due to the lack of simple equipment such as stretchers, oxygen, and defibrillators. Many venues accommodate the population equivalent of a medium-sized city, requiring that the medical center be fully equipped to provide immediate skilled response to cardiac cases, spinal injury cases, and other similar emergencies. The means of communication with local hospitals and emergency medical services, their response times and capabilities, and their ability to handle a possible mass crowd disaster should be established.

Pre-Event Planning

Operational Plan. Pre-event planning for the movement and assembly of large groups of people involves the determination of projected levels of occupancy, volumes and pathways of movement, crowd densities, anticipated crowd behaviors, and appropriate staffing. If available, the designer's crowd management plan can provide basic information about movement and assembly capabilities of the venue. The operator has the responsibility of using these data, combined with knowledge of the characteristics of the group and expected behaviors, to develop the operational plan. The ideal operating plan establishes a continuing pattern of normal crowd management that will easily shift into an emergency mode if circumstances suddenly change.

General Admission Events. General admission events should be avoided because they introduce competition within groups to obtain favorable viewing positions. Reserved seating has been combined with festival seating areas to maximize attendance at some events. This combination can result in competition by those in reserved seating to move closer to the performers in the festival viewing area. This situation can precipitate confrontations with crowd control personnel and in some venues can result in accidents as patrons attempt to enter the festival sections forcibly and unsafely.

Staffing Levels. Staffing levels for crowd management in different venues depend on group size, whether the group simply moves through a space or will both move and assemble, and the expected behaviors of the group. There are three types of security staff, with different levels of responsibility. Security staff can consist of peer, or "T-shirt" personnel, who are limited more to ushering and have limited contact with the audience; uniformed venue personnel, with the power to remove disorderly persons and hold them in custody; and police officers, with full powers of arrest and use of force if necessary. Impulsive crowd movement by groups of as few as 30 people can result in falls and other crowd-induced injuries.

Staffing in large assembly spaces depends on the configuration of the venue and the type of event. A children's parade or circus is obviously much different from a rock concert or hotly contested sports event. Security staffing for a low-risk event could be as low as 1 person per 250 patrons and for a high-risk event, 1 per 50. For instance, the 2006 edition of NFPA *101*®, *Life Safety Code*®, requires at a minimum 1 trained crowd manager for every 250 occupants for new and existing assembly occupancies.

The number of ticket collectors and others processing the entry of patrons depends on projected peak arrival demands and the procedures required. A simple pass-through gate with no information exchange required can accommodate up to 60 patrons per minute. This rate will be cut in half if the ticket processor has to read and tear the ticket. When patrons require more involved instructions or information, entry processing rates can drop to 6 per minute. In venues in which there are "stop and frisk" procedures, entry processing may be reduced further. Individuals selected for more involved security screening should be quickly moved away from the main entry stream, in a space set aside for this purpose. Airport-type security, employing metal detectors and other types of screening, may be necessary at some public gatherings.

Staff training for crowd management is of vital concern. Frequently casual labor individuals are used as peer security employees at large events, with nothing more than vague instructions about controlling certain crowd behaviors. Even permanent staff may have limited training in crowd management, recognition of potentially dangerous crowd problems, and the handling of accidents and other emergencies.

During a study of door egress rates at a 16,000 seat arena, the author observed that a number of doors were chained and locked during the event as a means of controlling gate crashing. Crowd densities during a sudden emergency egress would make it impossible for the staff to gain access to these doors to unlock them. Training should include instructions on the basics of normal and emergency crowd movement and assembly; initial

handling of accident victims, altercations, and other crowd incidents; communications procedures and use of communications equipment; avoidance of actions that would incite or trigger dangerous crowd behaviors; and conduct and demeanor during an emergency. Personnel should be provided with a pocket guide to reinforce training guidelines and communications procedures.[17]

Weather Conditions. Weather conditions are a factor in open venues in areas where tornadoes, thunderstorms, hailstorms, or other similar meteorological events are common. The crowd manager in open venues has the responsibility of keeping abreast of local area weather, particularly when severe weather is predicted. The retaining of a private meteorological service for this purpose for larger public events and venues is advisable.

The Event

Communication failures are a common component of virtually all serious crowd incidents. Accurate and timely information is necessary to assure an appropriate response to developing situations before they reach critical phases. All security personnel should be connected to the central crowd management control center via handheld radios. Public address systems should be capable of reaching all areas of the venue, and instructions should be accurately phrased and understandable. Closed-circuit TV surveillance cameras should be situated to cover all blind spots, as well as a wide view of the event venue. A staff member should be constantly monitoring the situation from a control center and be prepared to pass on information to staff on site and to provide instruction to the crowd via the public address system. Extra-large TV screens are an excellent means of audience communication, but camera personnel must be included in the communications network and must understand what to record for crowd crush or other emergency incidents. Crowd managers should know how to communicate with first responders in an emergency and what their radio frequencies are. This information could prove valuable in assuring that appropriate equipment and numbers and type of personnel are dispatched to the site.

One aspect of September 11, 2001, that has not received much attention is that there were three subway transit stations in the World Trade Center (WTC) complex and two more nearby. These stations were capable of delivering many thousands of occupants into the complex within a few short minutes. Out of all the communication failures, there was one success: the NYPD stopped all the trains from entering the WTC, avoiding even more people on the scene.

SUMMARY

Crowds occur frequently in a wide variety of venues. Occasionally, a sequence of events precipitates a rapid concentration of people that results in multiple casualties. Crowd management is a planned program for the safe movement and assembly of people. Three categories of situations that have resulted in crowd fatalities include critical occupancy, flight response, and craze. A systems model of the primary elements involved in crowd disasters are embodied in the acronym FIST, with F standing for force, I for information, S for space, and T for time. To illustrate both the three categories and the four elements involved in crowd incidents, a number of crowd disasters are described. The role of crowd management in venue design, in pre-event planning, and during events is critical to ensure a safe, secure, and convenient environment and to avoid incidents that would bring about a sudden mass movement either within the venue or to or from it.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on crowd management issues discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA 72®, National Fire Alarm Code®
NFPA *101®, Life Safety Code®*

Chapter 5

Strategies for Occupant Evacuation During Emergencies

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Key Terms

area of refuge, area of rescue assistance, defend-in-place, delayed evacuation, elevator, horizontal exiting, occupant characteristics, partial evacuation, phased evacuation, total evacuation, zoned evacuation

As children, we learned in school that when the fire alarm signal is given, whether bells, horns, or strobes, we should immediately stop what we are doing and line up to evacuate the building by the nearest exit. We learned that if that route is blocked by smoke or fire, we must use an alternate exit. The school held fire drills so that if a real fire occurred, evacuation would be fast and orderly. The school preplanned not only for a possible fire but for other events as well, such as tornadoes, earthquakes, and other natural or man-made circumstances that could affect the students and teachers. For some events, we found refuge in the building, but fire situations invariably called for immediate and total evacuation to a place of safety outside.

The common evacuation drills experienced during our school years represent a total general building evacuation; that is, everyone evacuates (general) and they evacuate to a point completely outside the building. More recently, there has been growing recognition that the considerations of occupant characteristics, authority-figure influence, and building type can make a total general building evacuation a disproportionate or even dangerous response. If the building is very large or very tall, most people may be too far away to be in danger from even a large and growing fire, and the length of travel during evacuation may pose significant risks (e.g., falls) of its own. If the occupants are restricted or nonambulatory, there may be little likelihood that total evacuation can be accomplished ahead of the growing fire.

This chapter discusses a variety of evacuation strategies that may be appropriate for various occupancies. The conditions under which any one evacuation strategy should be used depend on the nature of the building and the occupant characteristics. The following examples outline some of the basic building and occupancy considerations that may impact the selection of an appropriate evacuation strategy:

- *Assembly buildings:* large and potentially dense population of occupants subject to the threat of a single fire incident
- *Low- and mid-rise residential:* sleeping occupants in buildings of combustible construction types with a higher risk of fire spread and total fire involvement
- *High-rise residential:* sleeping occupants in buildings generally of high degree of fire-resistive construction and floor-to-floor compartmentation
- *Health care facilities:* these are facilities in which occupants can be expected to require assistance from staff and are physically not capable of relocating down stairs or to the building exterior
- *Detention/correctional facilities:* occupants who cannot be released to the public space but must be relocated in the event of fire to adjoining secured zones

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- *Multistory or large-floor-area buildings:* buildings in which total or partial evacuation is possible, depending on the nature of the building fire protection features and occupancy
- *Very tall buildings:* buildings with large occupant loads and long total evacuation times (e.g., >1 hour)
- *Buildings with occupants with disabilities:* special provisions in the form of specific refuge areas or procedures for relocating occupants with physical or mental limitations may be necessary for a wide variety of buildings and occupancies
- *Critical operations buildings:* facilities housing personnel and functions that control critical processes or operations (e.g., air traffic control tower, power plant control room) in which early evacuation of key personnel would create large risks from unattended critical processes (e.g., crash of incoming aircraft, core meltdown and release of radioactivity)

See also Section 1, Chapter 7, "Protecting Against Extreme Events"; Section 1, Chapter 8, "Emergency Management and Business Continuity"; Section 4, Chapter 3, "Concepts of Egress Design"; and Section 5, Chapter 3, "Disaster Preparedness Education."

OCCUPANT CHARACTERISTICS

The characteristics of occupants play an important role in selecting an appropriate evacuation strategy.

Consider the contrasts between two occupancy scenarios—a mid-rise office building and a low-rise nursing home. Generally, the mid-rise office building occupants are assumed to be alert, able-bodied occupants of various ages. Such occupants can be expected to comprehend emergency instructions and make decisions relative to their individual safety based on the emergency information in any fire incident. Additionally, office building occupants can readily move to the safety of exit stairs and down the stairs to the exterior of the building. These occupant characteristics are amenable to selecting a phased or total evacuation of such a mid-rise office building.

In contrast to the office building occupants is the scenario involving a low-rise nursing home facility. The occupants of such a facility exhibit characteristics that are significantly different than those of the office building occupants. First, the general population age is expected to be over 65 years, and the physical and mental capabilities are expected to be significantly diminished compared to the office building population. The presence of staff in a nursing home is a positive factor, yet it can be a difficult and ineffective undertaking for a few staff members to initiate and conduct a total evacuation of occupants in poor health and who may be sleeping. A total evacuation may, in fact, put nursing home residents at greater risk during a fire incident, given their inability to comprehend and follow instructions, slower walking speeds, and need for physical assistance if nonambulatory. Compared to the office building scenario, it is apparent that a rapid, effective total evacuation is not the best option for a nursing home scenario, and an alternative strategy to shelter nursing home residents from the effects of a fire may be better. Certainly, facility staff are expected to respond by evacuating or attempting rescue of those in near threat of the fire followed by relocating other residents to safe areas of the building.

TOTAL EVACUATION COMPARED TO ALTERNATIVE EVACUATION STRATEGIES

Total Evacuation

For most buildings, immediate and general evacuation of occupants to the street or other exterior place of safety in the event of fire is the accepted norm. This is the common practice for houses, hotels, dormitories, rooming houses, stores, restaurants, movie theaters, schools, and other low-rise structures. If a fire alarm system is installed, an automatic or manual alarm initiation starts the general evacuation signals. Where NFPA *101®*, *Life Safety Code®*, is accepted and subject to approval of the authority having jurisdiction (AHJ), a positive alarm sequence can provide a 3 minute window for investigation (2 minute delay in Residential Board and Care) before the general evacuation signal is given.

In most locations, total evacuation immediately or very soon after fire discovery is the most conservative and best response. Smaller buildings are less likely to have personnel trained to respond to and realistically evaluate the potential threat of an incipient fire. For fires in the home, the best procedure is to get everyone to safety as fast as possible, before making an attempt to fight the fire. Even calling the fire department is best done away from the home that is on fire.

Alternative Evacuation Strategies Defined

Immediate, total evacuation may not always be desirable or feasible. Health care and detention facilities may operate under conditions that prevent such evacuation, and the mechanics and time involved in totally evacuating very large or very high structures immediately following detection of a fire make delayed or phased evacuation a necessity. Several different but related concepts are recognized when immediate, total evacuation is not possible or desired.

Partial or Zoned Evacuation. Partial or zoned evacuation provides for immediate, general evacuation of the areas of the building nearest the fire incident. A partial evacuation may be appropriate when the building fire protection features assure that occupants away from the evacuation zone will be protected from the effects of the fire for a reasonable time. However, evacuation of additional zones may be necessary.

Phased Evacuation. Phased evacuation provides for immediate, general evacuation of the areas of the building nearest the fire incident with continuing, selective evacuation of all other building areas.

Delayed Evacuation. Delayed evacuation takes advantage of temporary holding places, typically known as *areas of refuge* or *areas of rescue assistance,* where occupants can remain in relative safety, albeit near the fire area, for a period of time before

evacuating the building, either by themselves or with assistance from emergency responders or others.

Defend-in-Place. The defend-in-place strategy recognizes that at times it is safer for occupants to remain in place within protected zones of a building than to evacuate the building.

Partial or Zoned Evacuation

Using a partial evacuation strategy will depend to a large extent on the building characteristics. Buildings built with distinct fire barriers, smoke separations, or horizontal exits or which have a high degree of floor-to-floor fire resistance are candidates for using a partial evacuation. These fire and/or smoke compartmentation features provide protection for those occupants outside of the affected fire area or floor. Those occupants located in the fire or smoke compartment of origin are subject to the greatest risk and, therefore, it is logical to focus on their evacuation and movement to safety (Figure 4.5.1). However, evacuating only those at immediate risk does not mean that the evacuation is completed. The circumstances of the fire incident, the nature of the occupants, and the assessment of fire conditions by the responding fire department will be factors in the decision to evacuate any additional zones.

Partial or zoned evacuation of a building may be an appropriate strategy in some facilities. A partial evacuation can avoid subjecting all occupants to a mass exodus event, which alone poses a set of risks to the occupants and can interfere with the efficient response of the fire department or other emergency responders. In all cases when a partial evacuation is the general strategy to be used, it is important that evacuation procedures address and account for additional and continued evacuation of building zones.

Phased Evacuation

Phased evacuation is total evacuation but not all at once. Occupants most likely to be affected by the fire incident are evacuated first, followed by others who are more remote from the fire incident. This is done to smooth the flow of people from the building. Everyone attempting to exit simultaneously from a high-rise building soon causes the stairways to be filled and will slow the evacuation from the portions of the building most affected by the incident.

Phased evacuation is accomplished most often by voice communication over fire alarm speakers. The initial evacuation may be done automatically as an alarm is received and can be for the fire floor and the floors immediately above and below or variations thereof. Subsequent evacuation is ordered by the fire department on a selective basis.

Delayed Evacuation and Areas of Refuge

For many buildings, a principal evacuation strategy may be generally applicable to the building population; however, there may be a small number of occupants having special needs or limitations that may require specific consideration or procedures to address needs for their safety.

In today's society local, national, and international laws as well as the general business community continue to strive to

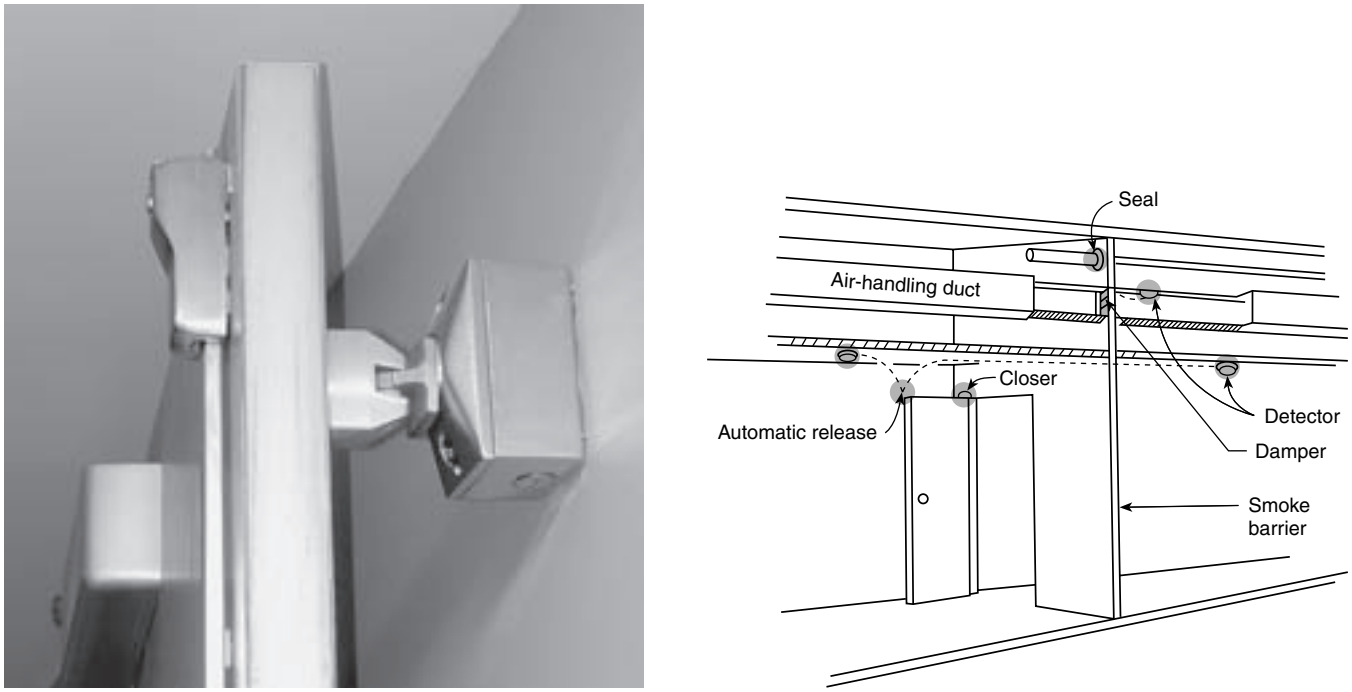

FIGURE 4.5.1 Magnetic Release for Door Barrier (left) and Typical Protective Measures for Smoke Barrier Penetrations (right) (Source: Exhibits 8.8 and 8.10, *Life Safety Code® Handbook,* 2006 edition)

provide employment, goods, and services to individuals who have a disability or impairment. Often these individuals will require special assistance in the event of a building evacuation. In the United States the Americans with Disabilities Act of 1990 (ADA) requires that policies and procedures for public accommodations address people with disabilities, which include individuals with one of the following impairments that could impact their evacuation from a building:

- *Mobility impairment:* includes slow walkers and wheelchair users
- *Visual impairment:* blind or difficulty with seeing the exit route or proceeding down stairs
- *Hearing impairment:* individuals whose deafness or limited hearing may preclude hearing and interpreting emergency evacuation instructions
- *Temporary impairment:* individuals who have been injured or are recovering from a serious medical condition
- *Medical condition:* individuals whose stamina or physical condition may inhibit their ability to egress (e.g., individuals with respiratory disorders, pregnant women)
- *Mental impairment:* individuals who may have difficulty implementing an appropriate emergency response, may become confused, or lose direction during an emergency

Depending on the nature of any given individual's disability, the level of evacuation assistance required will vary. In many cases the assistance needed may not be readily available and temporary relocation to an area of safety within a building as a delayed evacuation measure may be necessary.

NFPA *101* provides for temporary holding areas within buildings, protected from the immediate effects of a fire and, thus, allowing delayed evacuation. The definition of an area of refuge, from which evacuation can be delayed, has been expanded in recent years to include sprinklered buildings and reduced fire ratings.[1] In effect, NFPA *101* recognizes that immediate, total evacuation can be avoided where provisions are made within the structure to hold people while the situation is being assessed. By definition, an area of refuge is either (1) a story in a fully sprinklered building that has at least two accessible rooms or spaces separated from each other by smoke-resisting partitions or (2) a space within the path of travel leading to the outside, protected from other spaces by some means of separation or by virtue of its location. Two separated accessible spaces in a sprinklered building are not required for low-hazard occupancies, such as business and apartment buildings. Figure 4.5.2 illustrates a typical area of refuge.

Further explanation and expansion of the concept of an area of refuge to delay total evacuation is provided in the NFPA *101* Annex:[2]

> An area of refuge might be another building connected by a bridge or balcony, a compartment of a subdivided story, an elevator lobby, or an enlarged store-level exit stair landing. An area of refuge is accessible by means of horizontal travel or, as a minimum, via an accessible route meeting the requirements of ICC/ANSI A117.1, American National Standard for Accessible and Usable Buildings and Facilities.

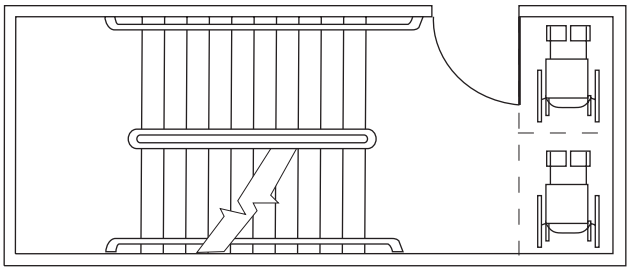

FIGURE 4.5.2 Exit Stair Used as an Area of Refuge (Source: Figure A.7.2.12.3.1, NFPA *101,* 2006 edition)

> This *Code* (NFPA *101*) recognizes any floor in a building protected throughout by an approved supervised automatic sprinkler system as an area of refuge. This recognition acknowledges the ability of a properly designed and functioning automatic sprinkler system to control a fire at its point of origin and to limit the production of toxic products to a level that is not life threatening.
>
> The requirement for separated rooms or spaces can be met on an otherwise undivided floor by enclosing the elevator lobby with ordinary glass or other simple enclosing partitions that are smoke resistant.

Defend-in-Place

As an alternative to total evacuation, a defend-in-place concept is recognized in NFPA *101*. An appendix paragraph[3] from the 1997 edition of NFPA *101* summarized the concepts that continue to be recognized under the 2006 edition of NFPA *101*.

> It is not always necessary to completely evacuate the building or structure to escape from a fire or other emergency. An area of refuge formed by horizontal exits, smoke barriers, other floors, or similar compartmentation often can serve as a place for the occupants to remain in relative safety until the emergency is over. In those occupancies where access to the exits is by way of enclosed corridors, particularly those occupancies with sleeping occupants, a single fire may block access to all exits, including horizontal exits and smoke barriers. In such cases, the occupants may achieve a greater degree of safety by remaining in their rooms.

An area of refuge becomes "defend-in-place" if fire control is achieved before it becomes necessary to order evacuation from spaces that are remote from the fire incident. The use of fire-resistive construction and fire partitions and the availability of horizontal exiting all can reduce the risk that the area of refuge will ever be sufficiently threatened that it must be abandoned for a total evacuation.

The defend-in-place concept has been used in apartment buildings of fire-resistive construction, where it can be safer to remain in the apartment than to attempt evacuation through a smoke-filled corridor and down several flights of stairs. Partitions between apartments and corridors typically have at least

1-hour fire resistance ratings, giving sufficient time for fire department response and phased evacuation as needed. Human behavior has been on several occasions cited as playing a major role in the fatalities and injuries of high-rise residential buildings in 1985 by Macdonald[4] and most recently in some detail by the works of Proulx.[5] Both authors' works have seriously questioned the appropriateness of evacuation of high-rise residential buildings, including hotels. Frequently during fires, occupants who stayed in their apartments or hotel rooms were safe and uninjured, whereas those who evacuated became casualties. Both conclude that occupants of residential high-rise buildings should use a stay-in-place approach, which then suggests a defend-in-place design philosophy.

Defend-in-place is not limited to fire-resistive construction. As stated earlier, NFPA *101* recognizes each floor of a fully sprinklered building to be a place of refuge from a fire on another floor. Thus, immediate evacuation is not necessary and evacuation may not be necessary at all. Except in rare cases, there is time for orderly, phased evacuation.

HORIZONTAL EXITING

Horizontal Exiting Defined

Evacuation from a building, as normally thought of, envisions everyone leaving the building for an exterior place of safety, either a street or a path that leads to a street. But evacuation can also be to another building, by first crossing an open space between the buildings or directly through a communicating opening in a common wall. This is horizontal exiting, and it does not have to be at ground level. Horizontal exits, whether across an open-air passageway or through a fire wall, can be on any or all levels of a multistory building. Horizontal exiting often is feasible within a building that has fire-resistive floors through the use of 2 hour fire partitions, as seen in Figure 4.5.3.

Benefits of Horizontal Exiting

Horizontal exiting can be very beneficial for defend-in-place situations where total evacuation is particularly difficult, such as health care facilities with nonambulatory patients and detention facilities that do not care to have inmates wander the streets. The space to which occupants evacuate via a horizontal exit must be large enough to house the population (in a cramped manner) and must have its own stairway or other exits leading to the exterior.

Besides the advantage cited earlier—of not having to evacuate occupants to the street or other exterior location—horizontal exiting permits same-level, faster evacuation from the location of a fire incident on upper stories of a building. The queuing delay common for stairway exiting is avoided, using the same exit widths in relation to stairways, and often horizontal exiting permits the elimination of one or more stairways, providing good financial benefit. Exiting capacity is calculated separately for each section, and credit is given for the horizontal exit (as a doorway exit) in both directions.

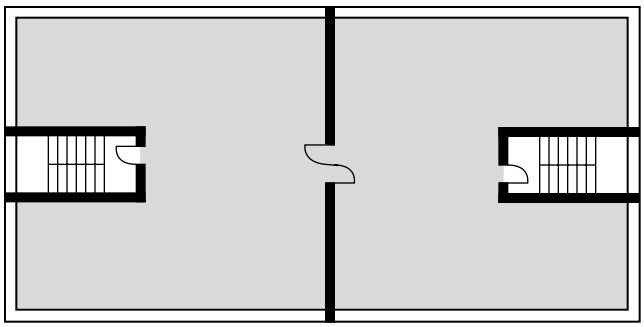

FIGURE 4.5.3 An Area of Refuge on Both Sides of the Wall Provided by a 2 Hour Fire Barrier Incorporating a Horizontal Exit (Source: Exhibit 7.70, *Life Safety Code® Handbook,* 2006 edition)

EVACUATING BY ELEVATOR

Disadvantages of Evacuating by Elevator

Following fire incidents in which people were trapped in elevators as elevators stopped at fire floors and would not allow elevator doors to close, building evacuation using elevators has become universally discouraged. The ubiquitous signage "Use Stairways in Case of Fire—Do Not Use Elevators" in elevator lobbies is the result. NFPA *101* does not accept elevators as exits (except in limited-occupancy towers) but permits them to be used for evacuation of mobility-impaired individuals.[6]

Beside the problem of the elevator being called to the fire floor by circuit malfunction, other problems with elevators during a fire have been cited,[7] including the following:

- Delays in elevators arriving may cause people to wait in an environment exposed to smoke, heat, or flames.
- Persons calling for elevators at the fire floor may expose additional persons to the fire by having a descending elevator stop at the fire floor.
- Large numbers of persons attempting to crowd into an elevator in an attempt to escape may prevent the doors from closing, trapping all at the fire floor.
- A power failure during elevator operation may cause people to be trapped between floors; emergency power can be ineffective if elevator cabling or machinery is affected.

Conditions for Elevator Evacuation

Despite the general adverse attitude, elevators can be very efficient in moving people out of upper floors of buildings, and they are almost a necessity for evacuating those unable to descend many flights of stairs unassisted. In fact, the use of elevators for emergency evacuation can be especially attractive in high-rise buildings and should focus on immediate assisted evacuation from the floor levels affected by a fire emergency. Each floor of a high-rise building can qualify as an area of refuge. Thus, limiting elevators to floors in most immediate need of evacuation can be done without endangering occupants on other floors.

To use elevators as a primary means of egress, so that they can be safely utilized for evacuation during a fire emergency, a

number of proposed requirements have been set forth by one author, a retired New York City fire officer:[8]

- The building should be fully sprinklered.
- Elevator shafts should be pressurized.
- Elevator lobbies should be enclosed and pressurized.
- Air intakes for pressurization of shafts and lobbies should be from a smoke-free source.
- Elevator lobbies should have smoke detectors.
- Elevator systems should be water resistant.
- Elevators should return to a designated level on a power failure.
- Elevators should have dedicated emergency power.
- Elevator lobbies should have direct access to a pressurized stairway.
- Elevator cabs and lobbies should have two-way communication with the fire command station.
- Elevator response during fire emergencies should be preplanned.

Whether all such conditions are needed to make elevator evacuation as safe as stairway evacuation is debatable, but several of the items are part of current code requirements. Elevator recall is common, and smoke detectors to actuate elevator recall tend to be provided for any new or retrofit elevator work. NFPA *101* allows elevators to be used for exiting from places of refuge provided the elevator is arranged for fire fighter service, power supplies are protected, and the shaft meets the requirements for a smokeproof enclosure.[9]

Fire Fighter Use of Elevators

Although not giving credit for elevators that are available for evacuation (except towers with limited occupancy), NFPA *101* recognizes elevators as a means of egress under certain conditions.[10] Under manual, in-car "fire fighter" control, elevators may be operated by trained emergency service personnel (e.g., building personnel or fire personnel) to assist in evacuation, particularly in high-rise buildings, in towers, or in deep underground spaces where travel over considerable vertical distance on stairs may require excessive physical effort. Stairways are intended to be used for the initial escape from the immediate area of danger, and elevators are permitted to be used to complete the travel to the street. Where stairway doors are locked against re-entry, as may still be permitted in existing buildings, re-entry to allow escape by elevators may not be an option. Even when emergency preplanning includes provisions for elevator evacuation, the presence of persons waiting at elevators may not be known by emergency service personnel.

Elevator systems, to be reasonably safe for emergency personnel, need basic safeguards that will also allow them to be used for controlled evacuation, and during the evacuation phase doing so necessitates primarily that elevator lobbies and shafts are kept free of smoke and heat and that power is maintained to the elevators.

A task group formed by the American Society of Mechanical Engineers (ASME A17) is conducting a hazard analysis and identifying the corrective measures to allow the use of elevators for egress of occupants as well as fire fighters. This renewed interest in the use of elevators for egress sprang from the recommendation following the NIST investigation into the World Trade Center disaster. The terrorist attacks and subsequent progressive collapse of the Twin Towers have resulted in renewed interest in being able to totally evacuate high-rise buildings if there is a fire of sufficient magnitude to threaten the structural integrity of the building.

In the early stages of a fire, smoke barriers with minimal fire resistance can provide a reasonable level of assurance against smoke filling of elevator shafts, and when elevator banks on the same level are separated by smoke or fire barriers, there is an even greater likelihood that at least one bank will be smoke-free for a considerable period of time. With a small likelihood of smoke filling and with reliable power and two-way communication between elevator lobbies and a fire command station, which also controls elevator operation, all available elevators can be dispatched to the floor needing immediate evacuation and returned nonstop to the lobby. A concept such as this will limit the number of persons who need to be evacuated by means of stairways from upper levels of high-rise buildings under most circumstances.

PREPLANNING FOR FIRE INCIDENTS

What is a "fire plan"? To some people it means a small-scale floor plan mounted on the wall in schools, hotels, and other places, showing where the fire exits are and possibly the fire extinguishers. What is really meant by the term is the preplanning document for fire emergencies. Often it is an emergency plan that covers other events as well (Figure 4.5.4). Every building, or complex of buildings, needs to preplan for emergencies—the single-family home, church, hospital, school, college campus, apartment building, or factory. When only a few people are involved, the preplanning can be informal, but for any place in which large numbers of people are present, a written plan covering fire and other emergencies is essential. NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs,* has been recommended for disaster/emergency planning by the 9/11 Commission and has been adopted by the U.S. Department of Homeland Security as the National Preparedness standard.

General Guidelines for Fire Incidents

For fire incidents, the fire plan has to cover items such as who does what in case of fire (who calls the fire department, who initiates fire evacuation signals, who checks that all rooms have been cleared, etc.). The person or persons in charge may be designated as well as floor monitors or others with special duties during fire emergencies. The plan may call for periodic fire drills and prescribe how they will be conducted. Persons or agencies to be contacted should be set forth, including emergency telephone numbers. Prefire planning should include measures to assure that routes to fire exits are clear, exit doors can be opened in an emergency, and exit signage is maintained. If delayed evacuation procedures are permitted, the plan must set forth how evacuation will be accomplished and who will be responsible for ordering evacuation following the initial evacuation from the fire incident area. If there is a fire control center in

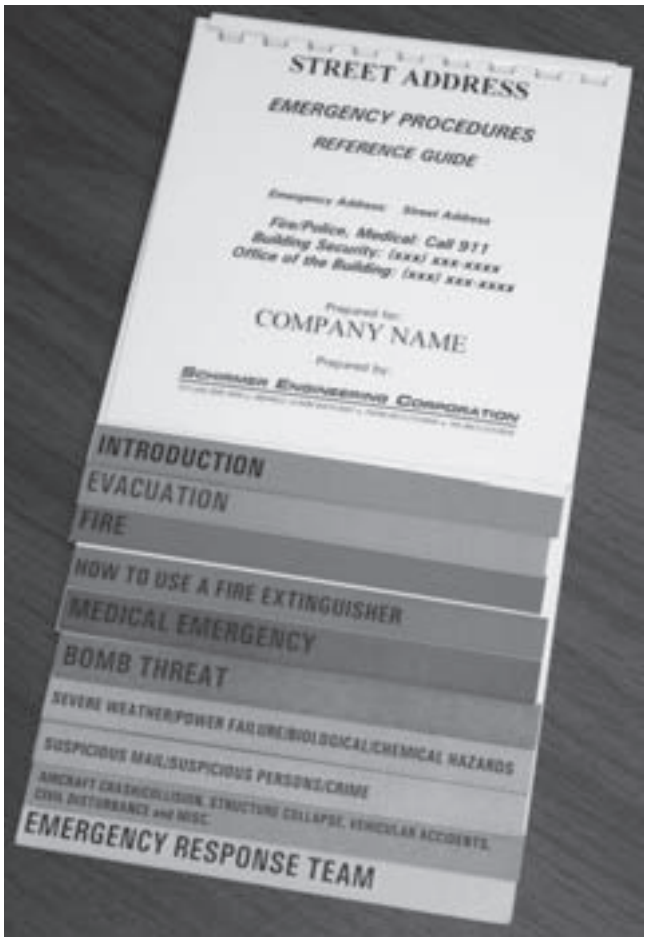

FIGURE 4.5.4 Sample Emergency Procedures Reference Guide (Courtesy Schirmer Engineering Corporation)

the building or there is two-way communication from areas of refuge, the plan must designate how communication with persons needing assistance will be accomplished and provide for the dispatch of trained personnel for rescue assistance (unless this function is clearly established to be the purview of the fire department).

Fire Drills

Periodically holding fire drills enhances the ability to safely evacuate the building under emergency conditions. Occupants become familiar with the alarm signals and know how to find designated exits. They learn the locations of alternate means of egress, such as emergency exit doors that are not normally used by building occupants. If the building has installed directional sounders, occupants familiarize themselves with their ability to guide them to the nearest exit.

School Evacuations

School Evacuations Under Terrorist Threat. Pulling a false fire alarm in a school in order to lure students outside so that they can be attacked has been tried, and it may happen again. The threat is slight, but suitable precautions should be taken when there is a viable threat, either when the school has received information of a possible terrorist attack or when local authorities have determined that there is a higher danger of such an attack. Currently, there are no good guidelines for measuring the comparative threat to the student body from fire versus terrorist attack in order to decide whether the risk to students from an assumed fire is less than the threat of killers waiting outside.

False Alarms and School Evacuations. False alarms for the purpose of disrupting classes is an ongoing problem in some schools, and the 3 minute delay prior to sounding alarm signals alluded to earlier in this chapter provides an opportunity for investigating the legitimacy of the alarm. Another successful method to reduce false alarms is to provide an approved cover over the device, which when raised sounds an audible alarm immediately, before there is an opportunity to pull the fire alarm. The *Life Safety Code* permits omitting manual fire alarm stations in schools when an automatic sprinkler system or automatic fire detectors have been provided.[11] In Chicago, schools are allowed to move manual fire alarm stations into classrooms to make them less accessible for malicious use.[12] Any of these methods can be successful in reducing the ability to initiate a false alarm solely for the purpose of achieving evacuation to an attack-vulnerable location.

Horizontal Exiting in Schools. When appropriate to the building and subject to approval of the AHJ, horizontal exiting, as previously described in this chapter, can avoid evacuation to the exterior of the building under most circumstances as long as the distance to the nearest horizontal exit from any point in the building is within the limits established by local code. Zoning of the fire alarm system is necessary so that evacuation signals sound only in the zone where the alarm was initiated. Sound preplanning and drills must be carried out to assure that all teachers and students feel comfortable with any scheme that does call for immediate evacuation to the outside upon a fire signal.

Aids to Evacuation from Fire

A number of manufacturers promote the sale of equipment or devices to help people escape from burning buildings, targeting high-rise buildings in particular. Among these items are rope ladders or similar escape devices that can be deployed from windows, escape hoods, escape suits fastened to cables, special chairs or slides for assisted evacuation on stairways, parachutes, and suspended rescue platforms. At the right place at the right time, such devices may provide for the evacuation of a few people who might otherwise be trapped. None are currently recognized by NFPA *101* or other generally accepted life safety standard.

Except for escape hoods, which can be issued to everyone in a building, none of the devices appears to provide the capacity to assist more than a minimal number of persons, and to do that they have to be located at the point at which people are trapped and from which the device is capable of reaching ground level in a safe manner. ASTM Committee E06 has established a subcommittee to develop standards for high-rise external evacuation devices to better define and evaluate device suitability.[13]

Escape hoods can provide a measure of protection from smoke and other toxic fumes, but whether they meet manufacturers' claims needs to be evaluated by independent testing under standardized conditions. Furthermore, the potential benefit of attempting to escape through otherwise intolerable smoke and heat conditions in a high-rise fire needs to be evaluated against remaining in a designated area of refuge until assisted evacuation can be provided.

Evacuation from rooftops by means of helicopters also has limited applicability and limited chances of success under the severe fire conditions under which it is most needed. Smoke, wind, and updrafts are deterrents to safe evacuation, and at best, only a few people can be rescued in this manner. Those who most require assisted evacuation may not be able to reach the rooftop, and they are better served by areas of refuge within the building.

NONFIRE EMERGENCIES

Although fire is the most common emergency consideration in buildings, other emergencies may be of greater potential threat and may require a different strategy for evacuation or no evacuation. Such emergencies include weather-related events or natural disasters, as well as man-made incidents. The following is a list of such events that may be a consideration for any given building depending on the geography, potential local building or site hazards, or building service outages:

- Earthquakes
- Tornadoes
- Hurricanes
- Flood events including heavy rain/melting snow, hurricane storm surge, tsunamis, mudslides, dam failure
- Volcanic eruptions
- Wildland or forest fires
- Building power outages
- Hazardous materials incidents

In contrast to a fire incident in a building, an event such as a tornado, earthquake, volcanic eruption, one of the flood scenarios, or a hazardous materials incident can pose an unanticipated and immediate threat to occupants in many if not most areas of a building. To escape the threat of fire in a building generally requires evacuation to the building exterior or specific fire refuge area within the building; however, the strategy for some of these events will require a different approach.

Commonsense guidance on procedures and safety measures can be found from a variety of sources. The Federal Emergency Management Agency, the National Safety Council, the American Red Cross, and the Building Owners and Managers Association International[14] provide Web-based literature and other guidance documents useful in preplanning for natural disaster and hazardous materials events. Some of the basics included in these sources follow. (See also Section 5, Chapter 3, "Disaster Preparedness Education.")

Earthquake

During an earthquake, building evacuation is not the appropriate strategy. Moving into or out of a building during an earthquake is not recommended, and occupants are best protected by relocating away from windows and glass constructions (partitions, skylights) to relative safety under desks or tables. Individuals on elevators should leave the elevator and find similar refuge as soon as possible.

Tornado

Tornado emergencies also would not require a building evacuation to the exterior; however, interior evacuation or relocation of occupants may be necessary. Occupants are best directed to seek shelter away from windows and glass, and relocate if possible to underground areas. In buildings lacking sufficient underground areas occupants should seek refuge in small rooms on the lowest floors of the building or find refuge in the most interior rooms away from doors and windows. Spaces with large-span flat roofs are most susceptible to roof collapse and should not be considered as areas of shelter. Evacuation instructions directing occupants to the designated areas of shelter in the building should be provided.

Other Natural Disasters

The impending threat from hurricanes, forest fires, volcanoes, and floods are often threats that are preceded by warnings through public information sources such as radio, television, and the Internet. Given that these events can be catastrophic to life and property, it is recommended that emergency procedures would allow for immediate building and site evacuation provided the warning time frame allows for major relocation of occupants. Procedures for such evacuations need to be in place well in advance, as the logistics may be time consuming, as in the case of buildings housing the elderly or disabled.

Hazardous Materials Incidents

Hazardous materials incidents are by nature unpredictable events that can impact the interior spaces of a building or expose a facility from an exterior location. The magnitude of a hazardous material event and the nature of the health threat can vary widely and the input of those familiar with the building hazards or expertise in hazmat incidents (e.g., fire department) is needed to develop a reasonable emergency response. Evacuation, relocation, or other protective measures may be needed. Getting the information and communicating protective measures to affected or potentially exposed building occupants are important aspects for handling any hazardous material incident.

SUMMARY

Occupant response strategies involve a number of considerations that include the building characteristics, the occupant characteristics, the criticality of building operations, and outside influences, such as weather, or in the case of schools the threat of violence. These many factors require that preplanning and procedures be established well in advance and can work to assure that occupants can be protected when an emergency scenario arises. Immediate evacuation in the event of an emergency may not be the appropriate response and the scenarios

for delayed evacuation should be reviewed and understood by building staff and occupants.

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NFPA Codes, Standards, and Recommended Practices

References to the following NFPA codes, standards, and recommended practices will provide further information on occupant evacuations during emergencies discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA *101®*, *Life Safety Code®*

NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs*

SECTION

5

Fire and Life Safety Education

Edward Kirtley

5.1 Principles and Techniques of Fire and Life Safety Education
5.2 Fire and Life Safety Education Messages
5.3 Disaster Preparedness Education
5.4 Media's Role in Fire and Life Safety Education
5.5 Reaching High-Risk Groups
5.6 Juvenile Firesetting
5.7 Using Data for Public Education Planning and Decision Making
5.8 Evaluation Techniques for Fire and Life Safety Education

Section 5 of the *Fire Protection Handbook*® addresses fire and life safety education, an activity that includes topics far beyond traditional school-based fire and burn safety programs. As the field of fire and life safety education becomes broader, it is also becoming more quantifiable, as seen in the two chapters dealing with data and evaluation. For this edition, the section includes two new chapters—one on educational messages and another on disaster preparedness education.

Chapter 1, "Principles and Techniques of Fire and Life Safety Education," applies educational fundamentals to fire and life safety education through topics such as principles of learning, the learning process, education models, and the importance of audience age and cultural background. The chapter also introduces the concept of message effectiveness.

Chapters 2 and 3 are new to the *Fire Protection Handbook*. The purpose of Chapter 2, "Fire and Life Safety Education Messages," is to expand on the concept of an appropriate fire or life safety message and to link the communication process to the effective application of a message. Sample fire safety messages developed through an NFPA demonstration project are introduced to illustrate one process of message development. Chapter 3, "Disaster Preparedness Education," provides examples of disasters and disaster-specific messages, and discusses the processes for identifying and analyzing community risks.

Chapter 4, "Media's Role in Fire and Life Safety Education," summarizes ways in which the news media and fire and life safety educators interact. Emergency scene public information and legal issues are among the chapter's contents.

Chapters 5 and 6 cover specific audiences. Chapter 5, "Reaching High-Risk Groups," presents considerations and techniques for reaching preschool children, older adults, low-income audiences, First Nations' populations, and people with disabilities. Chapter 6, "Juvenile Firesetting," outlines the characteristics of children involved in firesetting behavior, their motivation, and intervention strategies. The chapter also introduces the function of the Juvenile Firesetter Intervention Specialist (JFIS).

In its final two chapters, the section turns to the role of data and evaluation. Chapter 7, "Using Data for Public Education Planning and Decision Making," relates data to decisions that identify the major fire problems and target audiences, design an education program to address those problems with that audience, and deliver the right program to the right people. Chapter 8, "Evaluation Techniques for Fire and Life Safety Education," explains the evaluation process and highlights a hierarchy of evaluation measures.

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Chapter 1

Principles and Techniques of Fire and Life Safety Education

Edward Kirtley

Chapter Contents

Principles of Learning for Fire and Life Safety Educators
The Learning Process
Age and Learning
Effectiveness of Messages
Fire and Life Safety Education Models
Curriculum Development
Target Audience
Cultural Considerations
Other Educational Techniques

Key Terms

curriculum development, domains of learning, education, educational methodology, five-step method of instruction, information, learning, learning environment, program (education), public fire and life safety educator, social marketing, target audience

Public fire and life safety education may be defined as "comprehensive community fire and injury prevention programs designed to eliminate or mitigate situations that endanger lives, health, property, or the environment."[1] Organizations whose personnel conduct fire and life safety education programs include fire departments, state or provincial fire agencies, schools, burn prevention and treatment organizations, city health departments, and corporate safety offices. Fire and life safety educators blend and apply seven distinct areas of expertise in their professional practice: (1) principles of education, (2) education techniques, (3) methods of coalition building, (4) presentation skills, (5) working with the media, (6) education program planning, and (7) education program evaluation. This chapter focuses on principles and techniques of education.

For further information, see the following chapters in Section 5: Chapter 2, "Fire and Life Safety Education Messages"; Chapter 3, "Disaster Preparedness Education"; Chapter 4, "Media's Role in Fire and Life Safety Education"; Chapter 5, "Reaching High-Risk Groups"; Chapter 6, "Juvenile Firesetting"; Chapter 7, "Using Data for Public Education Planning and Decision Making"; and Chapter 8, "Evaluation Techniques for Fire and Life Safety Education."

PRINCIPLES OF LEARNING FOR FIRE AND LIFE SAFETY EDUCATORS

Learning Defined

The terms *learning, education,* and *information* are related, but there are important differences among these three concepts.

Learning is knowledge gained through observation and study, resulting in a change of attitude or behavior.[2] Stated another way, learning cannot take place without change.

Education is the process of training, teaching, or instructing students in new skills. Training, teaching, and instruction all deal with preparing students for some kind of action or activity, such as driving a car, operating a machine, or testing a smoke detector. "How to do" something is at the core of education.

Information is facts, knowledge, or data. Information is the raw material of the new skills of education and the change of learning. For example, a presentation for the chamber of commerce on how to develop an occupant emergency plan for the workplace is an educational activity. It teaches a skill (i.e., how to develop an occupant emergency plan). Later, when the participants actually do their plans, a change has happened; that is, learning has taken place.

A presentation to the same group about how the community's Insurance Services Office (ISO) rating is set is a public information activity. Interesting facts have been shared. But the participants

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do not have any new skills, such as how to use an ISO grading schedule.

It is important to differentiate between education and entertainment in public education. There are many programs used today in fire and life safety education that depend heavily on entertainment. Entertainment, unlike education, does not necessarily result in learning. The audience may enjoy the program and the program may result in an increase in awareness of fire safety issues, yet there is no change in behavior. This is an essential difference between an educational program and a program that focuses on entertainment. Although entertainment certainly has a place in fire safety education initiatives, it should not be confused with, nor promoted as, an educational program that results in learning (i.e., a behavior change). Note that changing a person's attitude—the way the individual feels about fire safe behavior—is an important step in changing behavior. The changed attitude is a necessary precursor to changed behavior.

Characteristics of Learning

For the practicing fire and life safety educator, the complex field of learning theory can be summarized in several points.[2]

1. Learning can be and often is a lifelong activity. Learning does not stop when school ends.
2. Changing attitude or behavior can be stressful. For example, it is uncomfortable to change a fire and life safety attitude from "My kids would never play with fire" to "I need to be more careful about where I put my cigarette lighter."
3. People learn at different rates and in different ways. How people learn is not related to intelligence.
4. Learning benefits from reinforcement. This characteristic argues against once-a-year fire and life safety education programs but is a strong argument for ongoing activity.
5. Effective learning benefits from support from the people who influence or control the students. In the workplace, supervisors should support an employee's new interest in keeping exits clear. Parents need to support a child's desire to install more smoke detectors.
6. Learning is enhanced when multiple senses are stimulated. Students need to *hear* words and *see* illustrations. Through props (such as burned items from a house fire) students *touch* and even *smell* the effects of fire. This characteristic of learning applies to adults as well as children, although great care should be taken in the use of potentially threatening props with children.
7. Learning is most effective when it is focused. In focused learning, the fire and life safety educator begins with an overview (e.g., "This morning we will learn what to do in case your clothes catch fire") and then explains the individual actions (e.g., how to "Stop, Drop, and Roll," how to cool a burn, and when to get medical attention).

Motivation and Learning[3]

Motivation is an essential step in the learning process. Educators have long realized the importance of motivation when attempting to create behavioral and attitudinal changes in the learner. Although several different models describe learner motivation, there are common elements in all the models.

First, the educator must establish a strong connection between the topic and the needs of the learner. This is commonly called the relevance of the topic. The learners must be able to see that the topic applies to their world. For fire and life safety topics the learners must understand that the risk applies to them. For example, an educator is delivering a presentation to parents (the target audience) of young children about the need for bicycle helmets. The educator must convince the parents that their children who ride bicycles, skateboards, and so on are at risk from injury if they crash without a helmet. This can be accomplished through the use of personal testimonies, injury statistics, anecdotes, or local news stories about a child being injured without a bike helmet.

Next, the educator must explain the benefit to the target audience of acting on the information. In other words, members of the target audience must believe they will benefit from changing their behavior or their beliefs about the topic. In the example above involving bicycle helmets, the parents must understand *and believe* they and their children will benefit from wearing the helmets; that is, their children will avoid a head injury from a bicycle crash. This can be accomplished with personal testimony, statistics, medical information, and so on. As with relevance, the greater the benefit for the learner the stronger the motivation to learn about the fire or life safety education topic.

A final component of motivation is the ability to act on the information, especially for adult learners. The learners must be able to take personal action with the information to be motivated to change. If they believe there is no way to act on the recommendations, they will not act. For example, consider the example of the bike helmets already discussed. Suppose that the target audience were low-income parents who could not afford bike helmets or who might not have access to them. The parents may clearly understand the need for helmets, and the benefits from them, but cannot act because of the monetary issue. In this case, the educator must provide a way for the learners to take action, for example, by providing the helmets to the children at little or no cost.

These two motivational issues must be addressed with every audience, regardless of age, if motivation for the topic is to be created. With younger children this will require a simple approach using basic language that is positive and does not frighten or intimidate the children. For adults, the educator must draw on the experiences of the audience and an understanding of their needs to create the motivation.

The Domains of Learning

Education is not based solely on fundamental human needs but is also based on audience needs. Audience needs are often described according to three domains of learning:

1. The *affective domain* involves how people feel about a situation and is the realm of values and opinions (e.g., whether or not they worry that their cigarette may have started a grass fire; whether they care about damage to wildlands).
2. The *cognitive domain* involves what people understand (e.g., how fast a grass fire is likely to grow).

3. The *psychomotor domain* deals with what people can do (e.g., how to dispose of smoking materials properly).

When developing a presentation, at least the affective and cognitive domains must be addressed during the presentation. With some behaviors and issues, information provided on the fire safety issue (cognitive domain) will result in a change in the learner's values (affective domain). In other cases, a learner's values or perception of the fire problem must be changed before the person is willing to receive information on the problem. In either situation, the affective and cognitive domains must both be addressed. If the presentation includes psychomotor skills such as crawling low under smoke, the psychomotor domain must be included in the presentation. This objective may require an opportunity for the learners to practice the skill or behavior.

Each domain can be related to specific kinds of educational needs (Table 5.1.1). As discussed later in this chapter, the domains of learning are very important to the process of writing educational objectives.

THE LEARNING PROCESS[3]

To be effective in creating behavior and attitude change in the learner, the educator must approach educational presentations with a sound understanding of how people learn—that is, the learning process (Figure 5.1.1). By understanding the learning process, educators can appropriately apply all the educational tools available to them. Although the learning process is basically the same for all audiences, the tools used will vary greatly based on the topic, the age of the learner, and amount of life experiences of the learner.

Steps

The first step in the learning process is for the learners to receive information about the topic. The information is received by learners through the senses—what they see, what they hear, and what they touch and experience. The more senses that are involved in this step the greater the likelihood that learning will occur.

Motivation. Part of this first step is also creating the initial motivation to learn about the topic. This has previously been discussed. It is important to remember that young or old, without the motivation, learning will not occur. This means the first few minutes of a presentation, when communication is initiated with the learner, are critical to the success of the overall learning experience.

TABLE 5.1.1 Education Needs and Learning Domains

Target Domain	*Audience Needs*	*Audience Situation*
Affective	Motivation	Does not value something
Cognitive	Information	Does not know something
Psychomotor	Skills	Cannot do something

Transfer to Short-Term Memory. The second step in the learning process is the transfer of the information into short-term memory (STM). STM is an area where information is initially sorted. It has a limited storage capacity, approximately six or seven bits of information or one "chunk" of information. When the information arrives in short-term memory, the learner's mind immediately begins searching for a connection with knowledge the learner already possesses that is similar to the new information. If a connection, or link, is made with existing knowledge, the information is then transferred to long-term memory. If the information is not connected, it is lost as more new information comes into STM, since STM can hold only six or seven individual bits of information.

Transfer to Long-Term Memory. The third step in the learning process is the transfer of information from STM to long-term memory (LTM). LTM is the storage area for all knowledge and skills the learner possesses. LTM is similar to a computer memory in that information is stored based on similar characteristics. These storage areas are called "cells." There may be a cell for colors, one for automobiles, one for birds, and so on. The more life experiences the learner has, the greater the number of cells that exist in LTM. As discussed above, a link must be established between the new information and a cell that already exists. If a cell does not exist, the educator must create a new cell for that type of information. This is especially important with presentations to preschool children. In all cases, the educator must actively and thoughtfully create the link for the learner through examples, stories, experiences, and so on.

Application. The fourth step in the learning process is application of new information so that transfer of learning occurs. By applying or practicing the new skills or knowledge, the learner strengthens the information in procedural memory, an element of long-term memory. Transfer of learning is the ultimate goal of the learning process. When transfer of learning occurs, learners are able to apply the new information—skills, knowledge, and attitude—to situations in their lives. Transfer of learning occurs through application of the new information or skills. In other

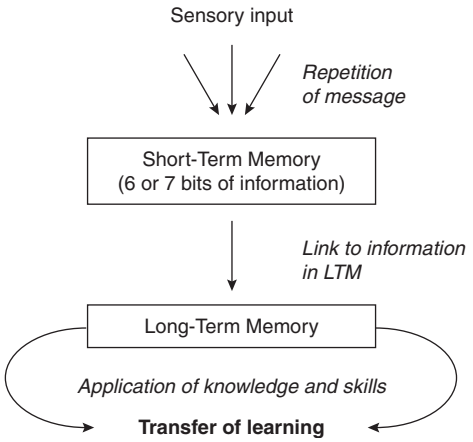

FIGURE 5.1.1 The Learning Process

words, transfer of learning occurs after the new information or skill has been practiced. For young children this means performing the behavior—for example, fire or life safety behavior—until it is mastered. For adults this can be accomplished through questions or activities and may even require actual practice with some skills, such as donning a bicycle helmet or placing a child in a car safety seat.

The amount of application required to achieve transfer of learning is determined by several factors. First, the developmental stage of the learner will influence the amount of application required. Young children can require more time for practice than will adults in most cases. Another factor is the life experience of the learner. Someone who has had experience with a fire or life safety behavior, for example, the use of a fire extinguisher, might well require less practice. Finally, the quality of the educational experience will affect the amount of application required. A high-quality experience that utilizes appropriate presentation techniques and applies learning theory will result in quicker transfer of learning.

It is important to understand that learners may know the correct action to take, but without transfer of learning, they may not be able to actually perform the action when the time comes. For example, children may know that if their clothes catch on fire, they are to "Stop, Drop, and Roll." However, if they have never applied or practiced "Stop, Drop, and Roll," they may not be able to do so if their clothes actually catch on fire.

Essential Elements

There are several essential elements from the learning process the educator should apply in every presentation to enhance transfer of learning:

1. The educator should present information so that multiple senses of the learner are used. This means adding at least visual and kinesthetic components so the learner sees, hears, and experiences the new information.

2. The educator must explain the relevance and benefit of the new information at the beginning of the presentation and reemphasize them throughout the remainder of the presentation when appropriate. The educator's job is more than just presenting good information; it also involves connecting with and, if necessary, changing the learner's personal values about fire and life safety. This approach means that the educator must overcome existing beliefs about safety, especially with learners who have extensive life experiences. This change in values can be accomplished only when the learner clearly understands the need to change (motivation), a process that begins with understanding the relevance and benefit of the new information.

3. The educator should present information in small amounts, such as six or seven bits of information or one psychomotor skill, and must then apply the information. This process of "present—apply" ensures that no information is lost between short-term and long-term memory. It also helps ensure that transfer of learning occurs.

4. The educator should create strong links between the new information or skills and the learner's current knowledge, skills, or experiences. This process is planned by the educator and is never left to chance. If that link is not created, the information or skill will be lost from short-term memory and the learning process will be stalled.

5. The educator should minimize the stress in the learning environment. This objective is especially critical for younger children. The educator should always use positive behaviors, should avoid the use of "don't," and should never scare or frighten the learners, as feeling afraid closes their minds to learning.

AGE AND LEARNING

People learn from cradle to grave. *How* people learn, on the other hand, changes throughout life. The twin factors of development stage and age determine how people learn throughout their lives. Generally, people pass through six development stages, as outlined in Table 5.1.2.[4]

Aging happens automatically, whereas psychological development happens only when the person is ready and when environmental factors (such as family, friends, school, and work situation) are right. Preschoolers, elementary school children, adolescents, adults, and seniors all learn very differently. In learning, age combines the influences of psychological/social/personal development with the effects of motor ability and communication skills. Being aware of how people learn at different ages is the first step in making sure that education programs and materials are "age appropriate."

Preschool Children

Children ages 3 to 5 grow and change more rapidly than any other fire safety audience. Some basic facts, though, will be true throughout the preschool years.

Basic Facts

1. Children ages 3 to 5 will learn fire and burn safety the same way they learn everything else—by seeing and doing.[5] What young children *do* will have a more lasting effect than what they *see*. For example, an adult will remember how to "Stop, Drop, and Roll" after seeing a demonstration. A preschool child must practice before learning happens.

2. What young children *see* is more influential than what they *hear*. A child will watch an adult find a lighter but will not remember the adult saying: "Always tell me when you find a lighter. Never touch a lighter."

3. Young children love repetition. Fire and life safety educators will need far fewer programs and activities for this group than for other audiences.

4. Young children have fewer experiences in the world than adults and, consequently, their understanding of the world around them is more limited. Using the right approaches with this audience is critical, because the wrong approach can be dangerous.

Children's Television Workshop (the producers of *Sesame Street*) studied how preschoolers would interpret fire and burn safety messages on television. Their findings also apply to nontelevised programs. Their findings include the following:[6]

TABLE 5.1.2 Developmental Stages and Implications for Education

Stage	*Characteristics*	*Educational Implications*
Stage 0, Blind trust	Develops only biologically; does not interact with surroundings	Too early for education
Stage 1, Focused on self	Responds out of fear; recognizes and begins to interact with surroundings; bases decisions on authority, obedience, and punishment	Wants to avoid the pain of burns; may fear punishment for fireplay
Stage 2, "Me and thee"	Responds out of need for personal gain; will satisfy needs of others for personal gain; bases decisions on "What's in it for me?"	Wants approval of others: for children, approval of fire fighters, teachers, and parents is important. Adults will seek approval of individuals who matter to them.
Stage 3, Group stage	Responds from a need for belonging and loyalty; accepts group rules as price for being part of the group; tries to meet group expectations	Responds to pressure from peers (whether children, adolescents, or adults) for fire safety; may respond to group pressure to be fearless
Stage 4, Group focus stage	Makes groups more abstract, does things "for the good of the order"; values social stability; accepts group rules for the good of other people	Responds to fire safety rules (such as bans on outdoor burning) and ordinances (such as smoke detector codes)
Stage 5, Interactive and independent stage	Regulates own behavior; negotiates for what the individual thinks is best	Will be fire safe only if it personally matters; may ignore rules that "don't apply to me"

1. Showing a dangerous activity, even while warning against it, is not recommended for preschoolers. *Children respond more to what they see than to what they hear.*

2. The extremely limited vocabulary of preschool children limits the fire and burn safety concepts that can be presented. "Hot" and "fire" will be understood, but "scald," "avoid," "prevent," "appliance," and "boil" are beyond preschoolers.

3. Young children have difficulty relating one event to another. "If/then" thinking or making choices (e.g., "If the door is hot, do not open it" or "Use your second way out") is simply more than many preschool children can do.

4. Young children view the world unpredictably. They may focus on one part of a program or story but ignore the rest. It is difficult for them to link the beginning and end of even the simplest story. Preschoolers do not necessarily link a problem and its solution.

Basic Techniques. Findings such as the above have very practical implications for fire and life safety educators. For example, "All fire safety messages should involve the two basic techniques by which preschoolers actually gain knowledge. By seeing an image, it is implanted; by doing, the action is learned. These two principles should guide fire safety messages for the preschool audience."[6]

Clearly, special care is needed in teaching safety to preschool children. Rather than develop their own, fire and life safety educators may prefer to rely on programs and materials such as the *Learn Not to Burn: Preschool Program*[7] and the *Sesame Street Fire Safety Resource Book.*[8]

A recent study at Oklahoma State University[9] indicates that any fire safety education message or behavior involving preschool children must address or consider three areas of development: physical skills, cognitive skills, and socioemotional skills. (The ability to relate to others and develop a healthy relationship with others in a group are examples of socioemotional skills.) Skills from all three areas must be utilized if teaching and learning are to be effective. For example, consider the behavior "crawl low under smoke." When teaching this behavior, the fire safety educator must consider if the individual child's physical development and skills allow him or her to crawl quickly through the obstacles found in most homes enroute to the exit. The child's ability to understand the behavior and the decisions necessary to perform the behavior also must be considered. A younger child of 3 or 4 years old may not be able to understand the behavior. Finally, the socioemotional development of the child must be considered. Does the child have the emotional ability to make decisions associated with the behavior, and then perform the behavior, under the stress of the fire situation?

All of these issues must be considered for every behavior taught to preschool-age children in order to ensure each individual child fully understands the expected behavior and is able to correctly make decisions and perform the behavior when required to do so in a fire situation.

Elementary School Children

The elementary school years are marked by steady physical, mental, and emotional growth. Considering physical growth, for example, "There are some marvelous happenings going on in the body, such as the shedding and erupting of teeth, the body's changing proportions. Along with the increase in height and weight, the internal organs—heart, kidneys, and liver—are increasing in their ability to function."[10]

Children ages 5 to 11 are probably the most frequent audience for fire and life safety education programs. Two strong trends in elementary education relate directly to fire and burn prevention: (1) *developmental learning* and (2) *comprehensive education.* Fire and life safety educators may need to tailor their approach and techniques to conform to these educational trends in elementary schools.

Developmental Learning.[11] University of Chicago educator Robert Havighurst identifies nine major groups of "developmental tasks" for elementary school children. Several of these tasks relate directly to fire and life safety:

1. *Physical skills.* Children become much more coordinated so that tasks that were impossible or difficult a short time ago—such as lighting a match—become possible or easy.
2. *Self-attitudes.* Children develop strong attitudes about themselves: their adequacy, personal hygiene and appearance, vulnerability, or safety.
3. *Social skills.* By elementary school age, children learn to get along with others, to make friends. Courtesy and other rules (including safety behavior) become important to them.
4. *Social roles.* Boys and girls become more interested in gender differences. Children this age are curious about—and want to follow—what society perceives as masculine and feminine roles.
5. *Academic skills.* Elementary school children learn a fantastic array of academic skills. In the mid-elementary years, abstract learning begins; speed reading, spelling, cursive writing, and higher math skills follow.
6. *Living concepts.* Concepts of everyday living (such as social, work, and civic issues) are included here.
7. *Values.* With the development of a conscience, children learn to distinguish between good and bad, right and wrong.
8. *Independence.* Between the ages of 5 and 11, children realize that adults are imperfect. As children spend more time away from their home, peers become more important.
9. *Social attitudes.* Feelings about home, religion, government, and other groups develop.

Fire and life safety programs that actually teach bigger areas, such as Havighurst's developmental tasks, have a far better chance of being taught in the classroom than a stand-alone fire safety effort. For example, consider the following:

1. Fire and life safety helps children develop positive *self-attitudes.*
2. A fire station tour teaches *social skills* (how the fire fighters live and work together), *social roles* (both men and women can be fire fighters), and *living concepts* (the fire service as a career), in addition to *self-attitudes* (learning about safety).

Comprehensive Education. An established strategy for teaching fire and life safety behaviors in schools is comprehensive education. Rather than being taught as a stand-alone subject, fire and burn safety is taught as part of a larger safety program or as part of a comprehensive health education program.

In many ways, fire and life safety education has been comprehensive education for many years. For example, for years fire departments have conducted baby-sitter programs that teach first aid and child care along with fire safety. Many fire safety educators include electrical safety, water safety, and citizen cardiopulmonary resuscitation (CPR) in their presentations. Many fire departments teach emergency response to hurricanes, earthquakes, or other natural disasters.

The National Fire Protection Association's *Risk Watch* program is an excellent example of a comprehensive education approach to fire and life safety education. *Risk Watch* addresses nine of the most critical or highest risk areas for children. The program was developed cooperatively with agencies that focus on the risk areas. The individual risk areas addressed include the following:

- Motor vehicle safety
- Fire and burn prevention
- Choking, suffocation, and strangulation prevention
- Poisoning prevention
- Falls prevention
- Firearms injury prevention
- Bike and pedestrian safety
- Water safety
- Natural disaster emergency response

Adolescents[12]

Knowing how adolescents develop and learn helps make the job of teaching them easier. Sowers[12] has observed:

> [Adolescents] live in the present and seem reluctant, even fearful, of looking too far beyond next weekend. Taking precautions in advance or being too concerned about the possible dangers that could harm them are not considered very important by most young people. This may be in part because teenagers characteristically have an "it-can't-happen-to-me" attitude, but the underlying reason may have more to do with appearing "babyish" or "nerdlike" to their friends than to any real sense of invulnerability.[12]

Of all the characteristics of adolescence, fire and life safety educators especially need to understand their developmental tasks and how adolescents learn.

Developmental Tasks. Adolescence is a bridge between childhood and adulthood. Becoming an adult is much more than going through puberty, learning how to drive, and deciding what to do after high school. Adolescence involves several developmental tasks that H. D. Thornburg listed in his landmark 1975 book, *Development in Adolescence*, as follows:

1. Develop conceptual thinking and problem-solving skills
2. Form more mature relationships with peers of both sexes
3. Achieve a masculine or feminine social role
4. Prepare for marriage and family life
5. Prepare for a career
6. Acquire a set of ethics to guide behavior
7. Develop civic competence and responsible community behavior

A major challenge for fire safety educators is to find ways to fit their message into the big picture of adolescent development. For example, a discussion about reporting who is pulling false alarms can be presented as ethics. The role of smoking in residential fire death can be taught in terms of responsibility toward others.

How Adolescents Learn. Adolescents have their own distinct learning style, especially when it comes to learning behaviors and attitudes (rather than facts). Ways that adolescents learn include the following:

1. *Direct experience.* Although direct experience with a fire or burn must be avoided, adolescents can have indirect experience with a fire or burn through fire department "ride-along" programs, serving coffee and donuts at the fire scene, or by volunteering at a burn unit or burn camp.
2. *Hypothetical projection.* Adolescents might think about how a fire would destroy their clothes or stereo or about how a burn injury would change their appearance.
3. *Role model emulation.* This involves following the attitudes and actions of role models. For example, young adolescents will observe whether their heroes smoke and how they dispose of their smoking materials.
4. *Instruction/demonstration.* This technique is particularly effective in teaching skills, such as changing a smoke detector battery or CPR.
5. *Rehearsal.* Through simulation, adolescents practice their response to emergencies.
6. *Teaching "best practice" to others.* For example, showing younger adolescents the safe use of portable fire extinguishers is a good test of how well the "teacher" can perform and gives a sense of competence.

Adults[3]

Adults as students reflect the many roles they have in life.

> They are parent, spouse, employer, employee, homeowner, renter, community worker, volunteer, child to their parents, hero to their children, and emotional and financial provider. They are expected to face the trials of the very young, the confusion of the teenager, the responsibility of adjusting to a changing world, and, somehow, balance their own desires and needs for relaxation and happiness.
>
> Adults appreciate the need for training and education for professional purposes. They also invest untold amounts of money and time in leisure activities. The task of the educator is to make fire safety just as worthy of their time, interest, and effort.[13]

When it comes to learning, adults are not simply "grown-up children." Instead, adults learn in specific ways. Although adults might not participate in formal education experiences on a regular basis, adults continue to learn in both formal and informal settings. General principles of how adults learn include the following:

1. *Adults need to know why they must learn something.* Establishing a need to know is the cornerstone of teaching adults. For the most part, adults feel that they need to know practical, nuts-and-bolts-type information. Being able to perform some task better is usually a strong motivator for the adult learner.
2. *Adults need to be self-directing.* Adults like to control their lives and make their own decisions. Similarly, adults like to control what and how they learn. In other words, adults are participatory—not passive—learners. Instructional methods that encourage participation include role play, debate, problem-solving discussion, demonstration, case discussion, coaching others, and skills-practice exercises.
3. *Adult learners bring their total life experiences into the learning environment.* Instructional methods that encourage participation take advantage of the experiences and knowledge of adult learners. However, adults may have already made up their minds about how fire safe they are—or want to be. Brainstorming exercises or group discussion may help keep minds open.
4. *Adults are task-centered learners.* Adults tend to center their learning around completing tasks, solving problems, or handling the way they live. Adults are, for example, much more interested in "writing better business letters" than in diagramming sentences or in "doing my time sheet right" than in addition.
5. *Adults have external and internal motivators to learn.* External motivators to learning include objectives such as getting promoted, getting a raise, or finding a job with better working conditions. For the most part, external motivators are visible or measurable. Internal motivators are related to the hierarchy of needs. They are usually invisible and impossible to measure.

Older Adults.[14] Older adults, senior citizens, seniors, the elderly, elders—perhaps no other group has so many names. Older adults are an important audience for fire and life safety education for two reasons: (1) older adults are the fastest-growing segment of the population, and (2) older adults have an unusually high risk of fire and burns.

When planning fire and life safety programs for older adults, remember to do the following:

1. Allow plenty of time. Like anyone else, older adults may get anxious if time appears short.
2. Count on a talkative audience and include a question-and-answer session.
3. Watch out for too much sunlight or glare in a room.
4. Darken the room, as possible, when using audiovisuals.
5. Keep the room at a steady, warm temperature.
6. Limit programs to 30 minutes.
7. Keep a low-pitched voice; speak slowly and clearly.
8. Use or design simple handouts. Avoid "busy" materials and fancy typography. Look for double-spaced materials.

For more guidance on working with older adults, see Section 5, Chapter 5, "Reaching High-Risk Groups."

EFFECTIVENESS OF MESSAGES

There has been surprisingly little research about what kinds of messages motivate people to be firesafe. The research that

does exist, though, gives clear direction to fire and life safety educators.

Negative Messages

A Study of Motivational Psychology Related to Fire Preventive Behavior in Children and Adults,[15] commissioned by the NFPA and completed in 1974, states:

> There is ample evidence that fear and threats of violence, unless continually maintained, have little long-term positive effect on behavior. People tend to tune out or suppress information which is disturbing or contrary to their belief or inclinations.
>
> People under threat or tension will seek to reduce that tension. Some will seek new information in order to act effectively. Others will block out that which is creating the tension. Therefore, fire prevention information should be directed toward positive motives which already exist within the recipient of the message.[15]

Positive Messages

The *Motivational Psychology*[15] study shifted the tone of fire and life safety education from negative to positive. Messages such as "Stop, Drop, and Roll" began replacing negative messages, such as "do not run if your clothes catch fire." The study also contributed to the development of the National Fire Protection Association's *Learn Not to Burn* programs. That study challenged the conventionally held view of the public's apathy about fire safety by concluding that people *do* care about fire safety, even though they might not know how to prevent or respond to fires. Based on interviews with people who had and had not experienced a fire, the study noted that "awareness of a fire as a powerful and potentially tragic force is not deeply buried in most people's consciousness." For both those who had and had not experienced a fire, "fire prevention awareness is increased when a person is responsible for others."

The association's research also included questions about how the public wanted fire safety information presented. The messages from the public were clear: Teach, don't preach. Do not scare us to death but make us think about fire safety. Give us information and if you can't make it interesting, at least make it short.[16]

A 1991 study by the American Red Cross about whether people took action to prepare for natural disasters after seeing slides of disasters reached conclusions that were similar to the Strother study.[15] Highlights from the American Red Cross report are as follows:

1. People remember more when they see disaster damage images in presentations.
2. Seeing disaster images does not encourage people to take action to get ready for a natural disaster.
3. Seeing disaster images discourages people from taking action.
4. After seeing disaster images, people were confused about what to do.
5. Avoiding or denying something unpleasant caused people not to take action among those who saw disaster images.
6. "Just not getting around to it" caused people not to take action among those who did not see the disaster images.[17]

FIRE AND LIFE SAFETY EDUCATION MODELS

Social Marketing[18]

Social marketing is a design approach to fire and life safety education that has begun to be used in the United States and South Africa. Social marketing has been used successfully by international health promotion agencies that work in foreign countries for many years. Social marketing applies proven commercial marketing techniques to health and safety problems that require long-term behavior change in the target audience. However, social marketing does not just rely on marketing principles for success. Principles and techniques from other disciplines such as sociology, education, psychology, and communications are incorporated into the social marketing framework. The critical element in social marketing is the paradigm that the needs and characteristics of the target audience are the basis for program decision making and design.

There are seven key concepts in social marketing. The concepts work together to bring about personal and social change in behavior resulting in reduced fire risk and risk from preventable injuries. The concepts are summarized as follows:

1. *Action is the objective.* The goal of every social marketing initiative is to change the risk behaviors of the target audience. By changing these personal behaviors and improving safety decision making, the risk from fire and injury is reduced. In social marketing awareness of the problem is not enough; the prize is the long-term change in behavior.

2. *The target audience is the focus of the initiative.* In many cases prevention experts, including fire safety educators, have designed prevention initiatives around *their perception* of the problem. Althouh this educator-centered approach has worked with white, middle-class issues, the approach has failed miserably with high risk audiences. The fire problem is based on the characteristics, norms, values, and habits of those people involved in the problem. Subsequently, the solutions must also reflect the characteristics, norms, values, and habits of those involved (i.e., the target audience).

3. *The target audience must believe the change in behavior is a positive exchange.* This concept is based on the willingness to trade one behavior, generally well established in the target audience, with a new behavior that will improve fire safety. For example, a parent or caregiver may have smoked in bed for 20 years. What does the new behavior (not smoking in bed) offer in exchange for quitting the old behavior? The fire safety educator must show that a positive exchange is possible and desired. In this example, the positive exchange is being safe from a potentially fatal bedroom fire versus the pleasure of having one last cigarette before going to sleep.

4. *The target audience is segmented into specific markets that share characteristics.* This is the opposite of the "one size fits all" approach to fire safety messages. In social marketing,

there may be several different groups identified in a single target audience. Each group has its own messages designed to change behavior. For example, a growing fire problem in the United States is the careless use of candles. There are several groups that should be targeted including teenagers and young adults who use candles for ambience, seniors who use candles for pleasant scents in the home, the poor who use candles for lighting, and so on. Each of these groups has specific reasons for using candles and each will respond to different approaches.

5. *The fire safety education campaign or initiative utilizes the four Ps of marketing: product, price, place, and promotion.* This is the traditional marketing principle that is employed by social marketing. The product involves the desired behavior, that is, what the target audience is being asked to do. Price involves what the target audience perceives it must pay, or give up, in the behavior exchange. It is critical that the price be considered from the target audience's perspective, not the perspective of the fire safety educator. Place is how the fire safety messages are disseminated to the target audience so that the messages are received and understood. Promotion is the means or strategy for convincing the target audience to take action, that is, that the exchange is worth the price of change.

6. *The competition to change the behavior is understood and addressed.* To the fire safety educator the need to change behavior is self-evident and little convincing is required. To the target audience in a social marketing initiative the need to change may not be so obvious, especially when there are competing behaviors. In short, the target audience may perceive strong reasons or justification to *not* change behavior. Consider the example of teenagers using candles. The new desired behavior is for teenagers to avoid using candles in their bedrooms. However, the norm for teenagers is to use a lot of candles when friends come over. The norm of social pressure to conform and fit in competes against the desired fire safety behavior.

7. *The initiative must be constantly monitored and be changed when needed.* The target audience and the environment in which behaviors occur are constantly changing. These changes include sociocultural norms, changes in services available to the target audience, and so on. The initiative or program must be constantly monitored to ensure the messages are correct, the four Ps still apply, behavior change is occurring, and fires and injuries are decreasing. When a change is noted, the initiative must be adjusted accordingly. Remember, the goal is *long-term* social and behavioral change resulting in lower fire and injury risk.

Health Belief Model[19,20,21]

Another useful model that is being used in the design of fire safety education programs and individual presentations is the health belief model. This model is used to explain what must occur for a person, generally an adult, to make the decision to change a safety-related behavior. In other words, the model explains what is involved in the decision making of typical adults when deciding to mount a smoke alarm in their house for the first time. The model was developed by the public health profession over many years of experience with health promotion initiatives. In 2005 the National Fire Academy incorporated the model into the fire and life safety education course *Changing American Family at Risk* because of its potentially positive impact on the success of fire safety education initiatives and programs. When presented with information on a fire and life safety behavior, a person may choose to adopt the new behavior if the following conditions are satisfied:

1. The person is aware that a problem exists due to current behavior.
2. The person understands the problem and the factors contributing to it.
3. The person believes he or she, or someone under his or her care, is personally at risk from the problem. In other words, the problem may actually happen to the person.
4. The person believes the benefits to change outweigh any barriers to do so. This belief is the same concept of the exchange in social marketing.
5. The person believes he or she is capable of successfully making the behavior change.
6. The person clearly understands what he or she must do to reduce the risk.
7. The person has an understanding and personal commitment to the reasons for changing the behavior.
8. The person has the resources and ability to successfully make the change in behavior.
9. The person receives positive feedback when the change is made.

By understanding these conditions must be present, the fire safety educator can build them into the program or presentation. For example, consider an initiative on mounting smoke alarms in the home. Based on the health belief model, the first step of the fire safety educator is to successfully inform the target audience that there is a problem; that is, they are at risk from fire or injury by not having a smoke alarm in their homes. This initial message must clearly explain the problem and the factors contributing to it.

Next, the message must be convincing *and compelling.* A message may clearly point out a problem and the need to take action *without compelling the target audience to take action.* The target audience must be compelled to take action and mount the smoke alarm. Part of this effort involves convincing the target audience that the benefits outweigh any barriers, they are capable of the behavior change, and the resources to make the change are readily available. In some cases accomplishing this goal may mean the fire department must make the smoke alarms available at no cost *or may require the department to go to the home and mount the smoke alarm.*

Once the change in behavior is made, there must be positive feedback to the person who has mounted the smoke alarm. Over the years a lack of positive feedback has been a problem with smoke alarms. For example, a fire safety presentation convinced a homeowner to go home and mount a smoke alarm. The homeowner mounted the alarm in the bedroom hallway right outside the bathroom. Every time someone took a shower the alarm sounded. The chronic false alarms were negative feedback and soon led the homeowner to remove or disable the alarm. This result could have been prevented by giving

the homeowner more explicit instruction on where to mount the smoke alarm so that false alarms would be eliminated or minimized.

CURRICULUM DEVELOPMENT

There are seven basic steps to curriculum development: (1) writing educational objectives, (2) developing a course outline, (3) developing a lesson plan, (4) selecting instructional methods, (5) choosing educational materials, (6) developing testing tools, and (7) allocating time to a subject.

Writing Educational Objectives

Educational objectives are sometimes called instructional objectives, behavioral objectives, or learning objectives. Regardless of what they are called, objectives answer the question: "What will happen as a result of the education program?"

Increasingly, objectives focus on what people can *do* after education, not on what they will *know* after education. For example, "the student will *show how to* change the battery in a home smoke detector" rather than "the student will *describe how to* change the battery in a home smoke detector," or "the student will appreciate the importance of changing the battery in a home smoke detector."

Objectives need to be realistic and measurable. Making objectives realistic is the responsibility of the educator. Making objectives measurable—so that students and programs can be evaluated—is also necessary. A standardized language and format for educational objectives help make them measurable.

Objectives are often written in a standardized format, originally developed by Robert F. Mager in his seminal book, *Preparing Instructional Objectives.*[22] This standardized format has three components:

1. The *performance* or behavior component of the objective describes what learners must be able to do to demonstrate what they have learned.
2. The *condition* component of the objective describes the conditions and resources available to the learner.
3. The *standard* or *criterion* component describes how well the action must be performed.[23]

Table 5.1.3 presents sample objectives for the affective, cognitive, and psychomotor domains of learning. Note that the affective objective deals with values (i.e., what is important). The cognitive objective covers understanding or knowledge. The psychomotor objective describes what the participant will be able to do. These three sample objectives are measurable.

Developing a Course Outline

The course outline is developed to meet the educational objectives and may be as straightforward as determining the sequence for teaching several lessons. For these instances, fire safety educators teach a single audience a single lesson and developing a course outline is not necessary.

Developing a Lesson Plan

A series of steps, known as the "five-step method of instruction," comprises the act of "teaching." The steps are (1) pretest, (2) preparation, (3) presentation, (4) application, and (5) evaluation. The steps of preparation, presentation, application, and evaluation will become part of the written lesson plan.

A lesson plan is a step-by-step guide for presenting a lesson. It outlines the material to be taught and the procedures to be followed in teaching the fire safety lesson. The lesson plan helps ensure efficient use of time and accurate coverage of the subject matter. When several fire and life safety educators are involved, the lesson plan helps ensure uniform teaching and helps avoid overlapping instruction.

The lesson plan guides how the students and educator spend their class time but does not dictate what will happen in class minute by minute. A lesson plan is *not* a script. A good lesson plan has some built-in flexibility—which is very valuable if, for example, the pretest reveals that the class already knows what the educator planned to teach but does not understand what the educator expected the class to already know.

Pretest. Pretests determine what the student/participant already knows (and doesn't know) before the fire safety education program. Pretests allow the public fire educator to customize the presentation to meet the needs of the individual participants.

In addition, pretests are useful tools for audience assessment. Some public fire educators use pretests as motivational

TABLE 5.1.3 Educational Objectives and Domains of Learning

Domain	*Sample Objective*
Affective (values, feelings, or opinions)	At the conclusion of the 30 min presentation on residential fire safety (condition), the adult participant will be able to state two factors (standard or criterion) that illustrate the importance of testing and maintaining smoke detectors (performance or behavior).
Cognitive (knowledge or understanding)	At the conclusion of the 30 min presentation on residential fire safety (condition), the adult participant will be able to describe three key steps (standard or criterion) in testing and maintaining smoke detectors (performance or behavior).
Psychomotor (skills)	At the conclusion of the 30 min presentation on residential fire safety and given a smoke detector for demonstration purposes (condition), the adult participant will be able to change the smoke detector's battery (performance or behavior) so that the detector alarms when tested (standard or criterion).

tools. Pretests can also provide students with an overview of what they will learn. Finally, pretests can serve as learning aids by providing questions for practice quizzes and by guiding individual study and review.

The most common type of pretest is the pencil-and-paper written test, although oral or performance tests are also used. Written or oral pretests are somewhat more convenient, simply because the entire class can take part in a written or oral pretest simultaneously. However, written or oral pretests do not assess psychomotor skills; for example, a score of 100 percent on a written pretest about home smoke detectors is no guarantee that the student can actually change the battery.

Generally, formal pretesting is not feasible with adult audiences and special events. Time constraints and the nature of the audience and venue make formal pretesting impractical with adult audiences and at special events. In place of a pretest a survey may be sent to the members of the audience in advance of the presentation. This requires that the educator prepare in advance and be able to compile the survey results when received. The more formal written pretests should be used with presentations and programs in schools where the learning environment is more structured.

Preparation. In everyday speech, the term *preparation* describes the necessary "homework" that educators do prior to a class or presentation. In educational use and this chapter, the term *preparation* describes how the educator prepares the student to learn.

Preparation involves developing a desire in learners for the information being presented. The educator must establish the relevance of the information, that is, how the information applies to their everyday lives. The educator must also explain the benefit of the information to the learners, that is, how this information is going to help them in their everyday lives. Both the relevance and benefit to the learner are closely tied to the learner's development and personal experiences. Regardless of the age or experiences of the learner, the preparation step must be accomplished successfully for every audience.

Presentation. Presentation is the actual delivery of instructional materials and ideas. This activity involves explaining information, using supplemental training aids, and demonstrating methods and techniques.

Application. During the application step, students use or apply what the instructor has taught. Through application, students practice new techniques and skills. Whenever possible, each student should apply new knowledge by performing the task or solving problems. For example, students could demonstrate how to report a fire, perform the "Stop, Drop, and Roll" technique, or test a smoke detector. The fire and life safety educator should supervise the application step closely, checking key points and correcting errors.

Evaluation. During evaluation or testing, the fire and life safety educator finds out whether the educational objectives have been met. Seen another way, evaluation shows whether students can perform a task independently.

Selecting Instructional Methods

Instructional methods and educational materials are the vehicles that carry the fire and life safety education message to the audience.

Fire and life safety educators have many types of instructional methods available to them. The challenge is to select the most appropriate instructional method for the educational objective.

Types of Instructional Methods. Types of instructional methods include lecture, illustration, demonstration, and discussion.

Lecture. In a lecture, the fire and life safety educator tells, talks, and explains. Today's audiences are accustomed to the fast pace, as well as the visual and audio stimulation, of television, computers, and video games. Lectures can bore the audience. For this reason, fire and life safety educators should use the lecture format sparingly—and only for short periods.

Illustration. Through the illustration method of instruction, the fire and life safety educator shows the audience something, for example, how an overloaded electrical outlet looks. Unlike a *demonstration,* illustration does not show the audience how to perform a task. The illustration method relies heavily on educational materials (such as drawings, posters, photos, slides, overhead transparencies, videotapes or films, models, and diagrams) and props. Illustration is especially helpful in combination with the lecture format.

Demonstration. The demonstration method teaches new skills. The educator actually does the task, usually explaining the task step by step. The audience may then practice the skill through drills. *Safety is always a concern with demonstrations and drills,* especially so when live fire is involved. Whenever the safety of a live demonstration is in question, use another method or material.

Discussion. Group discussion can be valuable, especially when the audience already has basic knowledge. Types of discussion are *guided discussion* (an exchange of ideas directed toward a goal), the *conference method* of discussion (in which the group directs its thinking toward solving a common problem), the *case study* (the group reviews real or hypothetical events), *role playing* (in which the group acts out various scenarios), and *brainstorming* (in which the objective is to identify as many ideas or approaches as possible).

Matching Instructional Method to Educational Objective. Selecting the most appropriate instructional method to address a specific educational objective is a critical skill for fire and life safety educators; it is a matter of using the right tool for a particular task. Table 5.1.4 presents examples of matched instructional methods and educational objectives.

Choosing Educational Materials[24]

Educational materials are any material—printed matter, audiovisual materials, or props—that the educator uses to teach new fire and life safety skills to the audience. Through materials, the

audience will actually *see* the effects of fire and burns, as well as the specific steps to take to avoid them. The materials literally give shape and color to the information and skills that the educators are teaching. Effective materials are important tools in getting and keeping the attention of the audience.

As important as they are, materials alone do not make an education program. An education program has specific measurable objectives and evaluation instruments, uses instructional methods that match the objectives, and uses materials to reach the objectives and reinforce the methods.

Materials are also important from the standpoint of resources. Next to the educator's time, materials are the most expensive item in the budget.

For these reasons, fire and life safety educators must use special care in selecting or creating their materials. Recognizing that materials are tools (rather than a program) and matching the material to the educational objective and to the audience are especially key to selecting educational materials.

Kinds of Educational Materials. The three kinds of educational materials are (1) print matter, (2) audiovisual materials, and (3) props:

1. Print materials include brochures (also called flyers or folders), posters, fact sheets, coloring books, activity sheets, display or bulletin boards, educational card or board games, and pretests/posttests.

2. The variety of audiovisual materials is expanding and now includes films and filmstrips, videotapes and audiotapes, 35 mm slides and slide-tape combinations, overhead transparencies, CDs, and computers. Flip charts and blackboards are also examples of audiovisual materials.

3. Props are artifacts or samples that the audience can see, touch, smell, or hear. A burned object from a home fire, a piece of melted glass, a manual fire alarm pull station, or a smoke detector could each be an effective prop during a fire and life safety presentation. Props are effective teaching aids because they make the subject real. Since they often involve several of the senses, props are an excellent memory aid.

Evaluating Educational Materials. There are vast differences in the quality of fire and life safety educational materials. Whether purchased commercially, borrowed or adapted from another educator, or created in-house, all educational materials should be evaluated.

At a minimum, educational materials should be evaluated before their first use and should be re-evaluated every year or so. The purpose of the follow-up evaluation is to make sure that what was acceptable initially still is.

The techniques for evaluating materials range from asking a few simple questions to sophisticated testing. The amount of evaluation needed depends on (1) how much money the fire and life safety educator is investing, (2) how many people the material is expected to reach, and (3) how long the material will be used.

The kinds of evaluation techniques for educational materials can also vary greatly. For example, qualitative approaches are fairly subjective and rely on the fire and life safety educator's experience, judgment, and interpretation. Quantitative approaches are likely to be more sophisticated and to involve formal testing. In evaluating educational materials, the key point is to evaluate all materials being considered in the same way.

Qualitative Approaches. Evaluating educational materials can be as simple as reviewing the material against a standard checklist. Questions to ask during a review include the following:

1. How well does the material match the specific educational objectives of the fire and life safety program?

2. Is the material technically accurate? Is the material produced by a reputable organization?

3. Is the information clearly understood by members of the potential audience? Answering this question can range from asking several members of the audience to describe or demonstrate skills that the material is trying to teach, to more elaborate testing.

4. Is the material age appropriate? With 3- to 4-year-old children, for example, are stories or activities limited to the 5-minute typical attention span for that age group? For guidance

TABLE 5.1.4 Matching Instructional Methods and Educational Objectives

Educational Domain	*Sample Educational Objective*	*Effective Instructional Method*
Affective (values, feelings, or opinions)	At the conclusion of the 30 min presentation on residential fire safety, the adult participant will be able to state two factors that illustrate the importance of testing and maintaining smoke detectors.	Group discussion, role play, and case study
Cognitive (knowledge or understanding)	At the conclusion of the 30 min presentation on residential fire safety, the adult participant will be able to describe three key steps in testing and maintaining smoke detectors.	Lecture, illustration, guided discussion, conference discussion, and case study
Psychomotor (skills)	At the conclusion of the 30 min presentation on residential fire safety and given a smoke detector for demonstration purposes, the adult participant will be able to change the smoke detector's battery so that the detector alarms when tested.	Illustration, demonstration and drills, and role play

in determining how age appropriate the material is, see *Developmentally Appropriate Practice in Early Childhood Programs: Serving Children from Birth Through Age Eight.*[25]

5. Is the material free of bias? Does the material reflect how people in the audience really live and work? The only way to make sure that material is bias free is to invite (and *accept*) comments from representative members of the potential audience.

These questions essentially call for "yes" or "no" responses. The Pan-Educational Institute has developed a more sophisticated approach to evaluating materials as part of its *Practical Criteria and Instruments for Selecting and Implementing Sound Fire and Burn Education Programs in School and Community.*[26] The package includes work sheets for assessing posters and stand-alone print visuals, written informational materials (brochures, stand-alone handbooks, storybooks, coloring books, and workbooks/work sheets), and audiovisual materials (media campaigns, public service announcements, and audiovisual presentations). When the scoring is done, a material is found to fit one of five categories: (1) limited quality, (2) below average quality, (3) medium quality, (4) high quality, or (5) comprehensive high quality.

Quantitative Approaches. Reading ease is a major consideration in selecting written fire and life safety education materials. A seventh- to eighth-grade reading level is typical for adults in the United States. Daily newspapers are often written at about that reading level.

Several readability indexes measure how easy a passage is to read. Commonly used indexes are a passive sentence index (a simple percentage of passive sentences within a passage), Flesch Reading Ease/Flesch Grade-Level Index, and the Gunning Fog Index.

The Flesch Index is based on a 100-word passage of the written material and counts the average number of words per sentence and the average number of syllables. With the Flesch Index, 17 words per sentence and 147 syllables per 100 words is "standard" reading ease. The Gunning Fog Index, on the other hand, combines the average sentence length and the number of difficult words (three or more syllables). Curriculum specialists with local school departments, or the education and journalism departments of universities, can help fire and life safety educators use these or other readability indexes.

These indexes can be used manually and are included in some word-processing programs. Whether the indexes are used manually or through the word processor, *the important point is to check whether sample materials are harder or easier to read than some standard that reflects the audience.* A highly precise test is not necessary, so long as the fire and life safety educator knows whether written materials are "in the ballpark" for readability.

Testing Materials. In some cases, fire and life safety educators may need to test materials before going into full production. Questions to ask when deciding to test materials include the following:

1. Could someone get hurt if the educational message is misunderstood?
2. How widely will the material be distributed?
3. How difficult or expensive will it be to change the material once it is produced?

After considering questions such as these, the NFPA *Learn Not to Burn* Foundation, now the Center for High Risk Outreach at NFPA, decided to test a planned television public service announcement (PSA). The results are published in *Pre-Production Evaluation of the "Tell a Grown-Up to Put It Away" Public Service Announcement for 3–6 Year Olds.*[27] In that test, 50 children ages 3 to 6 saw the preproduction version of a 30-second PSA twice. The children were then interviewed, one at a time, after each viewing to determine understanding. The PSA was found to be ineffective with the target audience. The test results influenced the *Learn Not to Burn* Foundation's decision not to produce the PSA.

The *Learn Not to Burn* Foundation experience offers some lessons for all fire and life safety educators. The preproduction test had a *set* interview procedure and questions—so the results compared "apples and apples." The test evaluated how well the *target* audience responded; for example, if only middle-income children had been in the study, the results would have been different. Perhaps most important, the material was tested when *changes were still possible.*

Creating or Purchasing Educational Materials. Many fire and life safety educators like to prepare their own educational materials rather than buy them (from a business or nonprofit organization) or adopt what other educators have already created. The interest in developing materials often is related to saving money ("Those other materials are too expensive for me") or the desire to give materials a "local flavor."

Before deciding to create their own materials, fire and life safety educators can use the following as a checklist:

1. How much will it really cost to develop materials (including the cost of time spent)?
2. How important is "local flavor"? How can it be added at the lowest possible cost?
3. What is the motivation to create the materials? Are locally created materials really needed and cost-effective? Or does the educator just prefer to create materials?
4. Does the fire and life safety educator have the technical knowledge, experience, and equipment to create materials?

Selecting Audiovisual Materials. Audiovisual materials range from the simple—flip charts, 35 mm slides, and overhead transparencies—to the sophisticated—films and filmstrips, videotapes and audiotapes, slide-tape combinations, and computer simulators.

Flip charts, 35 mm slides, overhead transparencies, and digital slide shows can be very effective audiovisual educational materials and can be created in-house. The key points are (1) limit the text, (2) have effective visuals in audiovisual materials, and (3) keep the visual image as simple as possible. Large-size or projected words are simply words.

Flip Charts. Flip charts are often used to record ideas from meetings and can also be used as audiovisual educational materials. Flip charts are inexpensive, easy to change, and effective with small groups. Although the paper is always white, marking pens come in a wide variety of colors. Flip charts can be reused a few times but will need to be replaced when they get torn, rumpled, or soiled.

35 mm Slides. Occasionally 35 mm slides are still used for do-it-yourself audiovisuals. They are far superior to flip charts in illustrating concepts (e.g., the extensive damage caused by a home fire), emotions (e.g., the face of a fire fighter after a rescue), and objects (e.g., the parts of a smoke detector). Slides are also easy to rearrange into different presentations, are effective with large groups, and are more durable than flip charts or overhead transparencies.

There are, though, several disadvantages with slides. The lights must be down or off, making eye contact with the audience difficult or impossible. Once the presentation has started, the flexibility to change is gone. The fan on the slide projector may be noisy.

Overhead Transparencies. "Overheads" are among the most popular teaching aids of all time—for good reason. They are inexpensive and easy to make, are durable, and can be used in rooms ranging in size from a classroom to an auditorium. They show text and line art to good advantage. The user can mark on them to underscore a point during a presentation. The lights can be on full or almost full. Overheads can be rearranged for use in several presentations.

Like flip charts and 35 mm slides, overhead transparencies do have some disadvantages. Photographs do not reproduce particularly well on transparencies. Like the slide projector, the overhead transparency projector fan may be noisy.

Digital Slide Shows. Digital slide shows have become the most common projected media used in fire safety education presentations. Digital shows are created on a computer using presentation software. The show can be saved to disk and taken to a remote site for a presentation. A presentation does require a digital projector and a computer, which may limit its use. However, small projectors are now available that allow the presentation to be loaded directly, thus eliminating the need for a separate computer.

Developing Testing Tools

Testing tools can be pencil-and-paper tests or nonwritten tests, such as practical skills tests. Some fire and life safety materials include testing instruments. Local schools may develop testing tools or help fire and life safety educators develop them. Section 5, Chapter 8, "Evaluation Techniques for Fire and Life Safety Education," covers the analysis of test results.

Allocating Time

A key part of developing a lesson plan is deciding how much time to spend on various subjects. A basic rule of thumb is to spend time on topics and drills that support the educational objective. Topics and drills that do not support the educational objective should receive little (if any) time in the lesson plan.

TARGET AUDIENCE CULTURAL CONSIDERATIONS[28]

The ethnic diversity of the communities in the United States and Canada has significantly increased. In some metropolitan areas it is not unusual to have 30 to 40 different ethnic groups represented in local schools.

Each of these ethnic groups has cultural differences that may include differences in language, lifestyle, religious beliefs, and cultural norms and values. In some cases, these differences are subtle. For example, many Hispanic immigrants are devout Catholics and their religious practices are virtually the same as those already living in the United States and Canada. In other cases, the differences can be noticeable. For example, some of the groups from Southeast Asia have very close-knit families where several generations may live in the same apartment together. This is a contrast to the typical one-family–one-dwelling American lifestyle.

In all cases, these ethnic groups are still at risk from fire and preventable injuries. In fact, some of the groups have a higher incidence of fire than the average population. Regardless of where the group comes from, or where the individuals are living, they need fire and life safety information in a manner they can understand and act on. This is the responsibility of the fire safety educator.

Learning About a Target Audience's Culture

Once an educator has determined that there is an immigrant community that has developed in the department's jurisdiction, even if it is a small group, it is time to learn more about the culture of the community. There are several methods for developing such an understanding. The most effective method is to develop a working relationship with someone from within the culture. This person does not have to be leader in the group, but he or she must be able to make a connection between both worlds. In many cases high school age young adults are the best in this area. They have been immersed in the American culture long enough to understand it, and they still have deep roots in their ethnic culture.

Another source of information is the Internet. There is probably not a single ethnic group that may locate in your community that is not already established in some other community. In other words, some other government or nonprofit agency has already crossed the bridge you are trying to cross. When you do your search, don't limit it to just fire department programs. Search public health departments, schools, social services, crime prevention, and community development agencies and programs.

A third source of information is the staff at larger universities. The campus of a large university is a home of cultural diversity and ethnic membership. Faculty and professional staff can usually put you in contact with a student from that culture.

Some student life offices may even have programs and information files that can provide you with the information you need.

Information Needed

What information is needed in order to develop and deliver education presentations that will be effective in reducing risk from fire and preventable injuries? You should ask the following six questions when gathering information on the culture:

- What are the lifestyle habits and practices of the group?
- What the social practices of the group?
- What is the community and family hierarchy?
- How does the group communicate with each other and with the rest of the community?
- What is the group's experience with emergency services and government?
- In terms of interaction and support from the rest of the community, is the group independent or interdependent?

Lifestyle Habits and Practices. Any experienced fire safety educator knows that a large portion of residential fire risk has to do with the lifestyle habits of the individual and family. When asking this question you must pay attention to any habits that may increase the risk of fire or injury. For example, if it is a cultural norm to cook food in deep skillets filled with grease, the risk of kitchen fires and burns increases. The multigenerational living habits of Southeast Asians mentioned earlier is another example of a lifestyle habit.

It is important to also look a little deeper at these habits. In some cases the habit may reflect a situation that does not represent the culture of the group but rather a situation imposed on them as new immigrants living in this country. For example, in an area that utilizes a large number of Hispanic immigrants it is common to find several families living in the same house or apartment. This situation may be from economic necessity or from a lack of available housing rather than it being part of the cultural lifestyle. Is the risk of injury by not being able to escape during a fire still increased? Yes it is—and fire safety education is still needed.

Social Practices. How do the members of the community gather to socialize? What type of recreation do they participate in? Do they tend to live in close proximity to each other, or are the members of the group scattered throughout the community? These answers will identify potential methods for meeting with the group members.

Community and Family Hierarchy. In many ethnic groups there is a specific person or group of people that makes the decisions for the entire group. Many times this person is an elder. Sometimes this elder is the oldest male living in the area. In other cultures it is the oldest woman in the family. If it is necessary to gain the trust of the group in order to have the members take some type of safety action, you must understand this hierarchy. To violate this hierarchy can be an insult not only to the leader but also to the members of the group as a whole.

Group Communication. One of the most difficult challenges with fire safety initiatives involving immigrants is reaching the group with fire safety information that *every member of the group can easily understand*. The first element of this challenge involves actually getting the information to the group. Most immigrant groups will not speak or read English at a functional level, especially the older members. In fact, some may not even read their native language. Putting a story in the local English-language newspaper probably won't have much of an impact.

But because the members of the group may not be reading the local newspaper or may not watch local television does not mean that a communication network does not exist. There is probably a very effective communication network within the group. In some communities immigrants have a native-language newspaper that is widely read. These newspapers provide information from home, pertinent local news, advertisements, and so on. These newspapers are an excellent communication medium about fire safety information. Similarly, there may be a local radio station in the native language, which is also an excellent medium to communicate information.

Having the luxury of a native-language newspaper or radio station may make your job a little easier. Unfortunately, many immigrant groups will not have any formal communication mediums such as newspapers and radio. Rather, communication is through an informal network between members of the group and generally involves person-to-person communication during social activities such as religious meetings, dances, family events, and so on. Although this medium is not as easily accessed as newspapers, it can be just as effective and in some cases more effective. It will require work on your part to identify how to access the medium and the best way to format the messages so they can be understood and acted on.

You must remember that a fire safety concept that has meaning to you, or to someone who was raised in the United States, may not make any sense whatsoever to someone who has just moved here from another country. In most Third World countries, smoke alarms are not used. A message that encourages a family to mount a smoke alarm may not make any sense and consequently will be ignored.

Creating a successful message means putting the behavior in terms that a member of the group can understand *and* can act on. For some behaviors and risk issues, this objective may require reaching the younger children who can communicate the information to the adults and seniors in the group. In other cases, the most effective strategy may be to get the endorsement of the elder or leaders in the group. You may have to use pictures or symbols if the members of the group do not read their native language. Success in this area depends heavily on how well you gather information with the questions previously mentioned. However, the communication barrier can be overcome.

Group Experience with Emergency Services and Government. The fire service has long been part of the American culture. However, in many countries no organized fire protection exists. The concept of a fire fighter or of fire prevention simply does not exist. There are some countries that do have fire protection but those fire fighters do not have any interaction with the public. In still other cases, the fire department represents the

government—an institution that is viewed with suspicion and with which any interaction is avoided.

If any of these scenarios apply to the immigrant group with which you are working, it is critical that time is invested at the beginning of the initiative to gain the trust of the influential members of the group and from that gain credibility as a person and program concerned about their welfare and there to help them. In a real sense you may have to create their first positive experience with a government agency.

You must also understand the reality of the situation with some immigrant groups. Currently there is a clash between the need for low-cost labor that can be provided by immigrants and the illegal entry of those immigrants into the country. The very group you may be trying to reach is working hard to *not* be reached by a government agency. Initially you will probably be viewed as an agency with the authority to cause problems and even return them to their native country. Overcoming this stigma will require work by not only the fire safety educator but also by every member of the organization who interacts with the group. Word will quickly spread if the fire department and the fire safety educator are trying to ensure the fire safety of the members of the immigrant community. Likewise, word will spread just as quickly if the fire department ignores or worsens the living situation and safety of the group.

Independence or Interdependence of the Group. In terms of interaction and support from the rest of the community, is the group independent or interdependent? By the time you have answered the other questions you should understand how the group interacts with the community. If the immigrant group is well established in the community most likely there will be a large degree of interdependence, which means that members of the group are employed throughout the community, utilize the medical facilities on a regular basis, own businesses, participate in school activities, are active in civic groups, and so on. When interdependence exists it is much easier to reach the members of the immigrant or ethnic community. Keep in mind that in a well-established immigrant community there may be one or two generations of the ethnic group that were born and raised in this country.

OTHER EDUCATIONAL TECHNIQUES

Questioning Techniques[29]

During a presentation, questioning is an extremely effective educational technique. Questions encourage thinking, the exchange of ideas, and the molding of opinions, attitudes, and values. As a result, what the fire and life safety educator *asks* the audience may be as important as what the educator *tells* the audience.

Effective questions have the following traits:

- Are "open-ended" or require more than a "yes" or "no" answer
- Do not suggest the answer
- Seek information but do not make the audience feel uninformed

There are four kinds of questions:

1. *Direct questions* are aimed at one person in the audience. Because direct questions can intimidate the audience, they are not often used with adults.

2. *Overhead questions* are aimed at the whole group, and anyone is free to respond. Because these questions are particularly helpful in starting thinking or in bringing out ideas and opinions, they are frequently part of a case study or brainstorming discussion.

3. *Rhetorical questions* are directed at the entire group, but an answer is not expected. A rhetorical question can be an effective "attention getter." For example, a fire and life safety educator might open a presentation by saying, "What are the most important things that you and your family can do to protect yourselves from a home fire? By the end of this presentation, you will know how to answer that question."

4. *Relay questions* are those that the audience asks and the educator sends back to the audience. Relay questions are a good technique for opening up discussion. Relay questions should not be used to avoid a question that the educator cannot answer or to force the audience to guess about facts or techniques.

It is important to note that the use of questions may be limited with younger children. Preschool children may not understand the meaning of a "question" and may answer the question with a story. Also, the effective use of questions requires the learner to have some experiences from which to answer the question. This technique requires the educator to thoughtfully plan his or her questions based on the topic, the developmental stage of the audience, and the experiences of that audience.

Managing the Learning Environment

The term *learning environment* refers to the physical facilities where the learning will take place. The learning environment supports everything that the educator does in the classroom. For this reason, managing the physical learning environment is as important as selecting the best instructional method or educational material.

Individual factors that make up the learning environment include the *room size, temperature,* the level of *light, ventilation,* background *noise, acoustics,* the *comfort* of chairs and tables, and the *physical arrangement* of the room.

Experienced educators inspect the room before arriving for a presentation. It may be possible to move the program to another room or to correct what is wrong with the room. For example, removing extra chairs and rearranging chairs into a circle can make a huge room feel smaller. Videos or films *can* be shown in rooms with uncurtained windows—if the screen or monitor is placed so that the windows are behind the audience.

Rooms can be arranged in several ways, depending on the size of the group and whether or not tables are used. The choice of a room arrangement lies in satisfying three criteria:

1. Can everyone in the audience see and hear the educator and audiovisual materials?
2. Can everyone in the audience see and hear each other?
3. Does the arrangement place as many people as possible as close to the educator as possible?

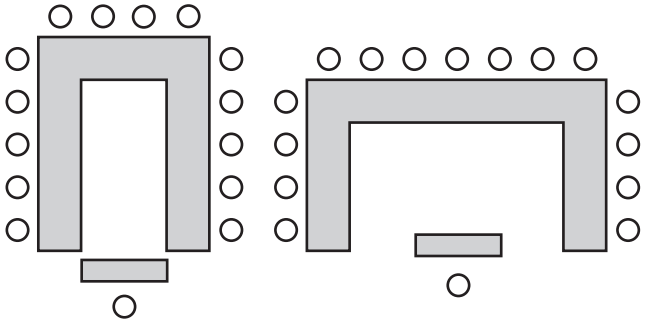

FIGURE 5.1.2 Examples of U-Shaped Arrangements

When tables are used for small groups, three common arrangements are (1) a U-shaped setup, (2) a hollow square, and (3) a conference table. The U-shaped arrangement offers eye contact between the educator and audience, as well as among members of the audience. The fire and life safety educator is able to move around the open U. All participants are able to see a screen or video monitor placed behind the educator's table. The U-shape can either be flat or long. The flat U-shape lets more members of the audience be closer to the educator and audiovisual material (Figure 5.1.2).

The hollow square is very similar to the U-shaped room setup. Participants may feel farther away from each other, even though the distance is the same as the U-shaped arrangement. A conference table setup is essentially a solid U-shaped arrangement. This arrangement is more commonly used for meetings but may be used for a class (Figure 5.1.3).

For larger groups that need tables, several classroom styles are available. The traditional classroom style setup is the most restrictive and provides little eye contact among participants. The chevron (sometimes called herringbone) and fan-style classroom setups place more members of the audience closer to the educator—and let participants see each other (Figure 5.1.4).

The most common way to arrange chairs without tables is the amphitheater or auditorium style. Rearranging the chairs into a slight semicircle provides for better eye contact between the educator and the audience (and among members of the audience). The semicircle also improves the audience's line of sight to a screen or video monitor (Figure 5.1.5).

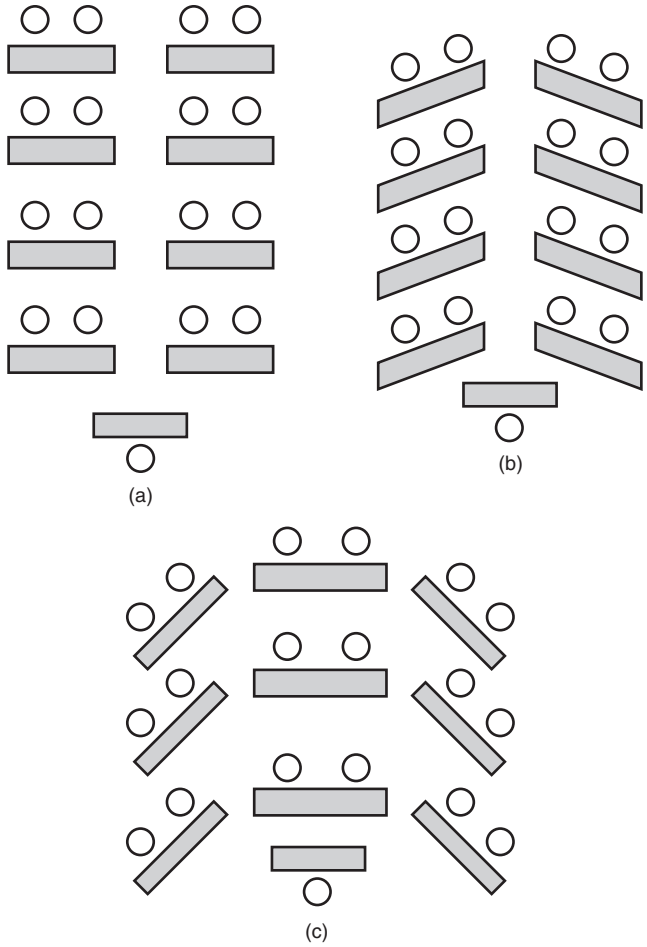

FIGURE 5.1.4 (a) Traditional Classroom Setup; (b) Chevron Arrangement; (c) Fan-Style Classroom. Note that these same seating arrangements can be used without tables.

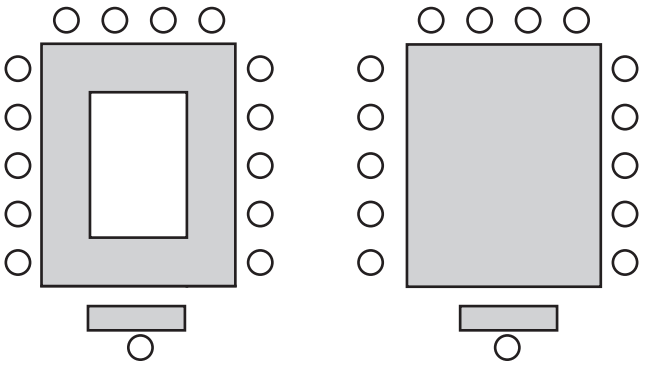

FIGURE 5.1.3 Examples of the Hollow Square (left) and Conference Table (right) Arrangements

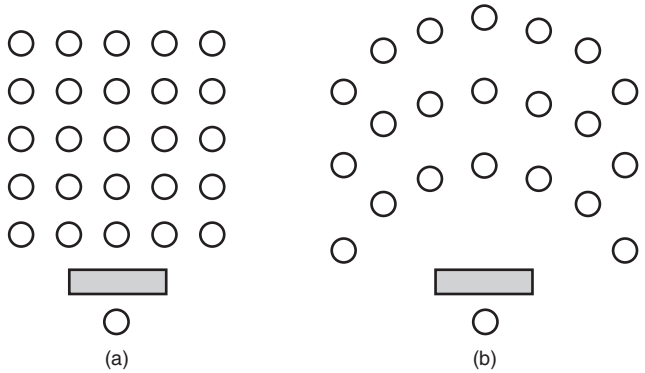

FIGURE 5.1.5 (a) Amphitheater or Auditorium Setup; (b) Semicircle Setup

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire and life safety education principles and techniques discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following document.)*

NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*

Chapter 2

Fire and Life Safety Education Messages

Ernest Grant ■ Rodney Eksteen

Chapter Contents

Education, Message, and Communication Defined
The Communication Process
Appropriate and Effective Messages
Five-Step Planning Process as a Tool for Message Development
Ongoing NFPA Activities

Key Terms

communication, communications cycle, communications medium, community assessment survey, education, education message, five-step planning process, injury prevention, message

One of the most important tools used by the fire and life safety educator is the educational message. These messages are intended to change the receivers' understanding of fire safety and/or inspire them to take some type of safety action. These effective messages use appropriate language, put the information in the correct social and cultural context, consider the physical abilities of the receiver, and are communicated in a manner so the message is easy to understand.

Many commercially developed messages are available for use by the fire safety educator. Unfortunately, not all of them are effective. In fact, some may even communicate information or behaviors that are contrary to accepted fire and life safety practice. It is the responsibility of the fire safety educator to be able to recognize messages that are not appropriate and then make the needed changes so that the information will be understood by the receiver.

The purpose of this chapter is to introduce the educator to the concept of an appropriate fire or life safety message and how the communication process fits into the effective use or application of a message. Sample fire safety messages developed through a NFPA demonstration project will also be introduced to illustrate one process of message development.

See also Section 3, Chapter 4, "Use of Fire Incident Data and Statistics"; Section 4, Chapter 1, "Human Behavior and Fire"; Section 5, Chapter 5, "Reaching High-Risk Groups"; Section 5, Chapter 7, "Using Data for Public Education Planning and Decision Making"; Section 5, Chapter 8, "Evaluation Techniques for Fire and Life Safety Education"; and Section 12, Chapter 19, "Community Risk Reduction."

EDUCATION, MESSAGE, AND COMMUNICATION DEFINED

In lay use, the terms education, message, and communications are sometimes used almost interchangeably. The terms are certainly closely related to each other. In fire and life safety education practice and in this chapter, however, the terms have distinct meanings as described below.

Education Defined

Webster's Collegiate Dictionary, 10th edition, has at least two potentially relevant definitions of "educate." The first is "to provide with information." The second definition is "to persuade or condition to feel, believe, or act in a desired way."[1] NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator,* defines public fire and life safety education as "comprehensive community fire and injury prevention programs designed to eliminate or mitigate situations that endanger lives, health, and property."[2]

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Education Message Defined

A fire or life safety education message is a spoken or written transmission of information that is satisfactorily received and understood, as demonstrated by a change in belief or behavior to produce greater fire and life safety.

Communication Defined

Although communication today involves many more methods than in years past, the goal and basic process of communication remains the same. The goal of communication is to "transmit information, thought or feeling so that it is satisfactorily received or understood."[3] In the case of fire and life safety messages, the goal of communication becomes the transmission of fire safety information and behaviors so that each is satisfactorily understood by the intended target audience or individual.

THE COMMUNICATION PROCESS

In the case of fire and life safety messages, the goal of communication becomes the transmission of fire safety information and behaviors so that each is satisfactorily understood by the intended target audience or individual. There are six elements in this communication process: the sender, the receiver, the fire or life safety message, the medium of communication, barriers to communication, and feedback between the receiver and the sender. The relationship of these six elements is sometimes described as the *communications cycle* or *communications loop*.

The Sender

The sender is the person who wishes to communicate some piece of information to another person or group. In the case of public fire and life safety education, the sender is typically the fire or life safety educator.

The Receiver

The receiver is the person or target audience for whom the message is meant. In some cases, the receiver will be a specific target audience. For example, the fire safety message "Tell an adult if you find matches or lighters" is intended for young children. In other cases, the receiver is the general public. For example, the fire safety message "Test your alarm" is meant for the general population, including older children.

For guidance on targeting messages for receivers at particularly high fire risk, see Section 5, Chapter 5, "Reaching High-Risk Groups."

The Message

The message is the information the sender wishes to convey to the receiver. Messages can be either informational or behavioral. Note that both informational and behavioral fire safety messages are intended to fulfill the objectives of education—that is, to provide with information, to persuade or condition to feel, believe, or act in a desired way.

Informational Messages. Some messages are informational in nature and designed to increase the awareness of the receiver about a certain fire or life safety issue. Informational messages are designed to persuade the receiver to feel or believe about fire safety in a specific manner. For example, the fire safety message "Smoke alarms save lives" is intended to educate the receiver about the importance of having smoke alarms.

Behavioral Messages. Behavioral messages are designed to persuade the receiver to act in a desired way, to inspire or convince the receiver to take some kind of action—to behave in a certain way. "Change your clock, change your battery" is intended to inspire the receiver to take a specific action: changing the battery in their smoke alarm.

It is not necessary for the sender and receiver to perceive the message in the same way, at least in all aspects. Any message unavoidably carries with it some information other than what was intended to be sent, including implied or inferred attitude of the sender toward the receiver. The purpose of the rest of this section is to provide a specific example of how a seemingly appropriate message can fail. In the example "Change your clock, change your battery," the intended message from the sender is that the receiver understands that this action is necessary to ensure that the smoke alarm will continue to work properly and provide an early warning in the event of a fire. In other words, the sender is inferring that the receiver understands this rationale, so there is no need to provide an explanation. The receiver, on the other hand, may not understand why there is a need to change the battery in the smoke alarm, other than the fact that he or she may be familiar with the campaign, or because someone the receiver views as having a position of authority has instructed him or her to do so. Because the receiver may not fully understand the rationale behind the need to change the smoke alarm battery, he or she may elect not to do so.

A message can fail to produce an intended change in belief and behavior in many ways. The receiver may not find the information contained in the message to be sufficiently compelling, intellectually or emotionally, to justify a change in belief. Most often, when a message fails to produce the desired result, the reason is at least in part a difference in understanding between the sender and the receiver. No message is entirely self-contained. Every message requires the receiver to provide some information, from the simple (what do these words mean?) to the complex (what am I supposed to do about this?). When the sender and receiver fill in different information—when they perceive the message in different ways—the result can be a failed communication.

Communication Medium

The medium or channel is the method used to deliver the message from the sender to the receiver. The medium may be direct delivery, such as during a fire safety presentation to young children. It may involve mass media such as television or radio delivery of fire and life safety education messages. The medium can also be a flyer, brochure, or other material such as a billboard along a major highway. A single medium or material can contain multiple messages. The medium is selected based on the

characteristics of the target audience. In other words, the mediums that are most likely to deliver the message to the receiver are those that should be used.

Barriers

There are barriers that can diminish the effectiveness of the communication process. The barriers may involve the receiver, the sender, the message itself, or the medium of communication. Some examples of barriers involved in the sender or receiver include language skills, beliefs and prejudices, cultural influences, or lack of experience with fire safety. Examples of barriers involving the message include improper use of language, the social or cultural context of the message, and the receiver's perceived relevance of the message. Examples of barriers involving the medium include selecting a medium that does not reach the receiver frequently enough for education to occur.

Feedback

Feedback is communication from the receiver back to the sender after the message has been received. Feedback allows the sender to evaluate the effectiveness of communication. In other words, has the receiver understood the message as intended by the sender? During presentations, feedback may be immediate through questions asked by the audience, the behavior being performed by children in class, and so on.

However, feedback from other mediums such as mass media or flyers is more difficult to observe or document. Surveys may be used to determine the effectiveness of the communication process and the changes that occurred as a result of the message. Reliable feedback may come in the form of fire and injury statistics. A change in occurrences of fire following a fire safety campaign may indicate that the messages were effective. It is important to note that other factors may be impacting the reduction in fires; it is the responsibility of the fire safety educator to evaluate all potential factors so the reasons for the reduction are accurately identified and understood.

Once feedback is received by the sender, the communication loop is closed. The sender may then choose to send additional messages to the receiver. This circular flow of information and feedback is illustrated in Figure 5.2.1.

APPROPRIATE AND EFFECTIVE MESSAGES

As mentioned earlier, appropriate and effective messages are those that reach the desired receiver and result in a change in understanding or behavior regarding fire or life safety. When developing a fire safety message, there are three factors to consider: the language used in the message, the social and cultural context of the message, and the relevance of the message to the receiver.

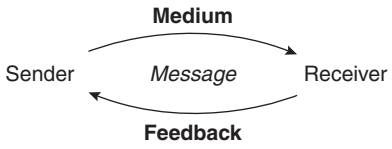

FIGURE 5.2.1 The Communications Loop

Language

A message must use language that can be easily understood by the receiver. Most of the time, this will involve the level of complexity of the text. Too much information, long words used in complex sentences, and technical language are confusing.[4] The message becomes even more confusing when dealing with someone who has limited literacy skills. The use of written materials becomes essential to assist with getting the message across. Such materials should be prepared at the lowest possible level of reading difficulty—generally fifth grade level or lower.[5]

For example, a message intended for adults should use words and grammar that are easily understood. Likewise, a message for second graders must use simple words and sentences. Keep in mind that the target audience may not be able to read the written word. In these instances, the message will have to be communicated verbally instead of in writing. Other forms of communication may include pictorial diagrams or demonstrations.

Another consideration of language is the native language spoken or read. If the target audience is immigrants who do not speak or read English, the group's native language must be used. Again, do not assume that everyone in the group will be able to read their native language.

Social and Cultural Context

The second factor of the message is its social and cultural context. Social context includes all aspects of the social environment that affect the audience day to day. A message may encourage the audience to take some type of action. The audience must, however, have the social resources available to take the action. For example, a message may stress the importance of always placing a child in a car seat. If affordable car seats are not available to the audience, the action—that is, using a car seat—is not possible. In this example the social condition of a lack of available car seats was not considered.

Similarly, cultural context comprises the values, beliefs, language, history, and habits of the culture to which the audience belongs. This may include specific behaviors, such as the use of candles to celebrate holidays. It may include general values, such as a strong sense of family. Failure to consider this context may create an immediate and significant barrier to communication.

The ability to make certain your message can be delivered across many cultures requires the sender to understand the attitudes and behaviors of a culture. Specific aspects of how the message may be used in the culture must be considered. In her book, *Cultural Issues in Business Communication,* Elaine Winters discusses the importance of communicating across cultures. She points out that one hidden aspect that differentiates cultures is the amount of context a culture's members expect in social interactions. People who study such things divide cultures into those that are high context and those that are low context. In general, high context cultures place great importance on ambience, decorum, the relative status of the participants in a communication,

and the manner of a message's delivery. People in low context cultures tend to ignore such things and emphasize the content of a communication, an attitude that might be expressed in the phrase "cut to the chase."[6] A primary consideration would be the possibility that the message changes going from one culture to another. Are there words in the culture to portray the same intended meaning as the sender had intended?

For example, consider the fire safety message that states "Candles kill—do not use candles at home." This message could be offensive to a culture that uses candles in the home to celebrate religious holidays and other important events. A better message, one which considers that culture, would be "Keep your home safe—use candles wisely." Please note that even the sample culturally appropriate message still fails to identify appropriate actions. NFPA's Educational Messages Advisory Committee (discussed later in the chapter) has developed the following official educational messages related to candles:

- Keep candles at least 12 inches from anything that can burn.
- Use sturdy, safe candleholders.
- Never leave a burning candle unattended. Blow out candles when you leave a room.
- Avoid the use of candles in bedrooms and sleeping areas.
- Use a flashlight, not a candle, for emergency lighting.
- Be careful not to splatter wax when extinguishing a candle.[7]

Another social/cultural context to consider is the specific or desired receiver of the message. Is it the father? The mother? The grandparent? In some cultures, the male head of the household may be the best receiver as he makes decisions about such things as installing smoke alarms. In other cases, the mother may be the best receiver because she is responsible for the care of the young children.

Finally, the last factor is the perceived relevance of the message to the receiver. This element is directly impacted by ensuring the social and cultural context of the message is appropriate. The receiver must perceive that the message applies to him or her. The greater the perceived relevance, the more likely the receiver is to act on the information—that is, the more likely education will occur. If the receiver's perception is that the message does not apply to them, for whatever reason, the message will be disregarded.

For example, a message on wildland fire safety will not have any relevance to a person living in the center of a large metropolitan city. There are no forests and there is no chance a wildland fire will destroy the receiver's home.

Characteristics of Appropriate and Effective Messages

Appropriate messages share certain characteristics. Those characteristics are self-containment, conciseness, comprehensibility to the receiver, logic, accuracy and technical soundness, and action orientation.

Self-Containment. When receivers of information say a message is not clear, they may mean that they have been provided too little or may require additional information to understand the message, some of which may not be known to them or may involve choices they are not sure how to make. (For example, I don't know what the action "feel" means in "feel the door" and I don't know how to choose which part of the door to feel.)

Conciseness. A message is more concise if it includes less (or no) information that is not essential to its intended content and the receiver's understanding. Concise does not mean that shorter is always better, because a brief message can sacrifice clarity by omitting essential information. For example, "feel the door" by itself is too concise; it leaves too many essential questions unanswered.

Comprehensibility to the Receiver. A message is more comprehensible if it fits well with the context of communication applicable to the receiver. For example, the message should use words and concepts as they are used in the receiver's culture, and it should use the receiver's language, including no language (i.e., pictures only) if the receiver has limited literacy.

Logic. A message is more logical if the sequence of concepts and ideas it communicates are arranged in a logical order, for example, in terms of the sequence in which they become relevant to the subject behavior. A message that is less logical will be difficult to follow. For example, "Stop, drop, and roll" is a perfect example of a message with parts arranged in a logical order.

Accuracy and Technical Soundness. A message is more accurate and technically sound if its stated or assumed facts can all be substantiated by reference to best evidence, scientific or otherwise. A message often has a long list of assumed facts that may not be recognized as such by the sender. These assumed facts can be identified by extensive review of the message by people with diverse relevant experience. (For example, what is the evidence to support feeling this part of the door versus that part of the door, using this part versus that part of your exposed flesh?

Action Orientation. A message is more action oriented if it makes clear what behavior the receiver should perform or what belief the receiver should change. Major campaigns have been built around phrases such as "Only you can prevent forest fires" or "Was somebody careless?" These phrases may serve to heighten attention to fire and life safety issues, giving them more urgency or higher priority, but they provide no information on recommended actions or behaviors.

FIVE-STEP PLANNING PROCESS AS A TOOL FOR MESSAGE DEVELOPMENT

A variation of the Five-Step Planning Process[8] can be used to develop appropriate fire and life safety messages or to revise existing fire and life safety messages to enhance the effectiveness of the message. The five steps are as follows:

1. Conduct a community assessment survey.
2. Define the injury problem.
3. Set goals and objectives.

4. Plan and test interventions.
5. Implement and evaluate interventions.

Table 5.2.1 summarizes the implications of each step in message development.

Community Assessment Survey

A comprehensive community assessment is done to identify potential injury-related problems. This assessment should provide demographic characteristics of the community, including individual neighborhoods and especially the population at highest risk. The survey should include information on culture, ethnicity, income, social services and resources available, and so on. It essential that this step be comprehensive as it provides invaluable background information about the target audience that is necessary for the development of effective messages.

The assessment should also determine if there are existing campaigns already being conducted by other groups or organizations. The duplication of such programs is rarely a good use of the educator's time or resources. Keep in mind that access to all data may not be possible; however, you should be able to gather enough to give a picture of the situation within the identified survey area.

Injury Problem Definition

Based on the community assessment data, the information received should allow the specific problem to be expressed in more quantitative terms. The answers to who, what, when, where, and how should be defined in more precise terms. This includes the specific behaviors involved, contributing factors, and so on. For example, it might be suspected that burns are a major concern within the state. After gathering the community assessment data, it was determined that burns were indeed a problem, but more precisely to young children (under a specific age) of a certain nationality, who reside in a certain geographical region, and so on. Having chosen the problem that may exist within the community, the next action is to decide how to actually accomplish reduction of the injury, usually through a change in behavior.

TABLE 5.2.1 Planning Implications for Message Development

Planning Step	*Implications*
Conduct a community assessment survey.	The survey provides valuable information on the demographics of the community.
Define the injury problem.	This will clearly identify *and* describe the fire or injury problem(s) involving the target audience.
Set goals and objectives.	The goals and objectives establish what is to be accomplished.
Plan and test interventions.	The messages are developed and incorporated into the interventions. The messages should be reviewed by members of the target audience.
Implement and evaluate the interventions.	The interventions are implemented and the messages are evaluated as to their effectiveness. Revisions are made as needed.

Goals and Objectives

The differences between goals and objectives are important considerations. A *goal* is a broad, general statement about the long-term outcome of the initiative. For example, a goal for a safety message may be that everyone feels the door in the correct manner.

An *objective* makes a time-limited and quantifiable statement about an initiative. The objectives will determine which issues will be addressed, what messages are needed, target audiences, and so on. There are two types of objectives. A *process objective* states how the program will be implemented, for example, a certain number of classes conducted within a certain amount of time. An *outcome objective* states what the program or message will change, including behaviors and attitudes. Keep in mind that baseline data are required to determine outcome.

Intervention Planning and Testing

Intervention may be defined as the actions taken to accomplish the identified goals and objectives. Examples of interventions include presentations, written materials, and public service announcements. There are generally five injury prevention categories: education/behavior change, environmental improvements, engineering modifications, enforcement of legislation/regulations, and economic incentives that are effective at reducing the incidence and severity of unintentional injury and death. These categories are sometimes referred to as the "5 Es of injury prevention." When considering any of the methods, it is imperative that the target population be evaluated to ensure that the interventions are culturally appropriate, understandable, and acceptable. It is also imperative that the educator clearly understands the social and cultural characteristics of the target audience so that all the interventions selected are culturally appropriate and understandable to the target audience.

Intervention Implementation and Evaluation

The final step of implementation and evaluation is actually a combination of smaller, recurring steps. For example, when you launch your initiatives, you will at the same time be evaluating the process and making improvements. Remember, implementation is not a one-time effort—prevention programs may take place over a number of months and require constant monitoring and improvement.

CASE STUDY: Creating Fire Safety Messages in South Africa. In 2000, the National Fire Protection Association provided assistance to the fire service of South Africa in the development of department-based fire safety education programs. The initiative was facilitated by NFPA's Center for High Risk Outreach. One of the primary goals of the initiative was the implementation of the *Learn Not to Burn Curriculum*® into South African schools, especially in high-risk areas.

While the *Curriculum* proved to be successful in South Africa in reducing fires and burn injuries, many of the messages were not appropriate due to differences in language, culture, and living environment. A decision was made to develop specific messages for South Africa that would be relevant to the target audiences and would be compatible with the nature of the fire problem and the social and cultural context of the country.

In 2005 a team from NFPA traveled to South Africa to work with leading fire safety and burn prevention educators, community leaders, and medical care providers to develop the unique South African fire safety messages. The target audience selected for the messages was 3- to-5-year-old children living in townships and informal settlements, as well as the care providers of these children. Figure 5.2.2 illustrates typical cooking facilities in the township environment.

Factors Leading to Burn Injury and Death

Using a group discussion process, the situations that most commonly led to burn injuries to the target group were identified and included the following:

- Child left unattended and fire begins (unsupervised)
- Shack fire starts; child does not or cannot escape
- Hot liquids spill from pot on stove
- Hot liquids spill from table
- Paraffin (kerosene) stove or candle tips, falls over, and starts fire
- Open flames of stoves cause clothing fire
- Stove not in proper working order
- Caregiver under the influence of alcohol
- Criminal action starts fire (intentional)

Although these identified events were not an exhaustive list, they painted an accurate picture of the common risks and main causes of burns in the shantytown environment.

The next step in the process was to prioritize the causes. The highest priority was given to those causes that occurred most frequently. Participants then developed a chain of events for each cause. From this chain of events, reasonable interventions were identified—that is, interventions that were possible for the children and caregivers. The following is a chain of events identified for a fire resulting in a burn to a child:

- A poor family builds a shack near urban areas for work opportunities.
- The family purchases a cheap paraffin stove to cook food.
- The interior of the shack is covered with cardboard and newspaper to insulate from cold.
- Combustibles contact the open flame of the stove.
- A fire spreads rapidly to other combustibles.
- Children have been left unsupervised and do not escape the burning shack.
- A child's clothes catch fire and the child is severely injured.
- An adult treats the burn wound with a traditional remedy (e.g., toothpaste, soap, metal cleaner).
- Transport of the child to the hospital is delayed.
- The child dies from burn injuries.
- The family rebuilds the shack as it was before.

FIGURE 5.2.2 Typical Cooking Facilities in a South African Township

Resulting Messages

The educational interventions were selected for development into messages. When developing the specific text of each message, the following elements were considered for a child 3 to 5 years of age:

- Linguistic readiness (will they understand the message)
- Emotional readiness (as stress levels increase, decision-making abilities decrease)
- Cognitive readiness (can they reason)
- Physical readiness (in terms of age/ability)
- Culturally appropriate (within value set they have been raised with)
- Language appropriate (remember idiomatic language/dialect)
- Child's locus of control (what they can/cannot influence)

As a result of this process, eight fire safety messages were developed for a new educational program, *Learn Not to Burn—Preschool, South Africa.* The eight messages are as follows:

1. Stay away from hot things; they can burn you.
2. Stay away from flames; they can burn you.
3. Stay away from paraffin; it can hurt you.
4. Matches and lighters are not toys; leave them alone.
5. If your home is on fire, go outside and stay outside.
6. If your clothes are on fire, stop, drop, and roll.
7. Cool a burn with water.
8. The fire fighter is a helper.

ONGOING NFPA ACTIVITIES

We as a society are in the midst of a major social transformation—a transition to a new way of living and acting. Our reliance on websites, podcasts, webonnaires, instant messaging, and texting

for news and information—as opposed to traditional sources of TV, radio, or print media—is an example of how our lives have changed over the past few years. Recognizing that, the National Fire Protection Association (NFPA) convened a meeting of fire and life safety experts from across the United States and Canada in 2003. The purpose of this meeting was the establishment of the Educational Messages Advisory Committee. The committee, meeting on an annual basis, is responsible for providing expert advice to NFPA public education staff on safety education messages.

The goals of the advisory committee are as follows:

1. Review current educational safety messages and determine if research is needed to validate the message
2. Create two versions of each educational message (one in an easy-use format for children and those who may not be able to comprehend more detailed information and a second version in an expanded format)
3. Develop a rationale for each educational message (using evidence-based outcome where possible)
4. Produce an educational message document to be made available on the NFPA website

The committee easily reached consensus on the elements of a good message: the message should be informative, short, concise, direct, and comprehensive. The next step was to consider the role the fire and life safety educator has in promoting and addressing change as it relates to safety messages in today's society. Educators must make a commitment to adapt to changing forces. In other words, rather than simply suggesting that everyone and everything must change, the educator must lead by example. The educator not only serves as a witness to change but must also show others how to adapt changes in their own lives.

For example, when advising the public about the use of security bars, the homeowner's main concern is safety from intruders. The educator's main concern may be a blocked means of egress in the event of a fire. In an attempt to compromise or adapt to change, the educator would advise the homeowner to install security bars with a quick release device (if a key is used, it should be kept nearby so everyone can find it). The homeowner is more likely to adapt to the suggested change (recognizing that his concern of security is met) and the educator will have succeeded in getting the homeowner to move fire safety higher up on the list of priorities.

Next, the committee addressed other forces of change such as updated life safety education for persons with disabilities or people who reside in multistoried buildings, new technology (i.e., ten-year lithium battery smoke alarms), and residential sprinklers. Educational messages on these topics have been around for quite some time; however, because technology has made some products simpler and less expensive, new messages must be designed to accommodate these changes.

The Educational Messages Advisory Committee has developed official educational messages on smoke alarms, escape, burns, smoking, candles, the "stop, drop, and roll" technique, and fire extinguishers. These messages can be viewed on the NFPA website: http://www.nfpa.org.

SUMMARY

Developing and revising fire and life safety messages is a critical skill for fire and life safety educators. Appropriate messages must consider the language used in the message, the social and cultural context of the message, and the perceived value by the receiver. Messages must also be comprehensible to the receiver, logical, accurate, technically sound, and action oriented. Messages that address these characteristics are more likely to successfully communicate the desired information to the target audience.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire and life safety education messages discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following document.)*

NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*

Chapter 3

Disaster Preparedness Education

Gerri Penney

Chapter Contents

Types of Disasters
Fire and Life Safety Educator
Pre-Disaster Organizations, Programs, and Activities
Roles/Activities Before, During, and After a Disaster
Natural Disaster Messages
Tornado-Specific Messages
Hurricane-Specific Messages
Winter Storm–Specific Messages
Landslide-Specific Messages
Retooling to Include Disaster Preparedness Education
Disaster Preparedness Resources

Key Terms

disaster, disaster preparedness, emergency operations center (EOC), hurricane, landslide, national incident management system (NIMS), public fire and life safety educator, public information officer, tornado, winter storm

Today's fire and life safety educator has an ever-expanding role in the community with regard to disaster preparedness education. The chapter starts with the definition of *disaster preparedness,* provides examples of different types of disasters (both natural and those caused by humans), and discusses organizations that are currently dealing with disasters, as well as the formation of collaborative interagency partnerships. Consideration is also given to the processes for identifying and analyzing community risks. A large part of this chapter deals with the educational programs currently addressing disaster preparedness, and the disaster-specific messages they provide for actions to take before, during, and after the disaster. Recommendations are made for "retooling" a fire and life safety education program to include disaster preparedness education. Finally, a list of resources and references for further information on this topic is made available. This resource list is by no means a complete and exhaustive one because disaster preparedness education is a fast-growing area with constant new information and many governmental agencies being designed or realigned. It does, however, provide a beginning pathway for the fire and life safety educator who is adding disaster preparedness education to his or her role in the community.

For related topics, see the following chapters in Section 5: Chapter 1, "Principles and Techniques of Fire and Life Safety Education"; Chapter 2, "Fire and Life Safety Education Messages"; Chapter 4, "Media's Role in Fire and Life Safety Education"; and Chapter 8, "Evaluation Techniques for Fire and Life Safety Education." See also Section 12, Chapter 12, "Disaster Planning and Response Services."

TYPES OF DISASTERS

According to *Merriam-Webster's Collegiate Dictionary,* a *disaster* is defined as "a sudden, calamitous event bringing great damage, loss, or destruction." Disasters can be natural or weather-related incidents, such as tornadoes, hurricanes, snow blizzards, landslides, earthquakes, flooding, and volcanic eruptions; or they can be caused by humans either unintentionally, such as a tanker rollover in icy conditions, or intentionally, such as acts of terrorism.

Natural or Weather-Related Disasters

Natural or weather-related disasters have increased in number and intensity over the past several years, due to changes in weather phenomena, including El Niño and global warming. Loss of life and destruction of property as a result of the Asian tsunami of December 2004 were astronomical. It left nearly 170,000 people dead or missing in the Indonesian province of Aceh alone. In addition, at least 5400 people died in Thailand and many remain missing.[1]

Similarly, the 2004 and 2005 Atlantic hurricane seasons were unprecedented. In 2004, Florida was hit by four major hurricanes in a six-week period. And the year 2005, which saw 28 named

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storms, was the first time in history that hurricanes had to be named based on the Greek alphabet because all of the names associated with the letters of the English alphabet had been used. As of the writing of this chapter, the largest natural disaster in the history of the United States was Hurricane Katrina, which occurred on August 29, 2005, along the Gulf Coast (Figure 5.3.1). Six months later, on February 23, 2006, the White House released its report, entitled *The Federal Response to Hurricane Katrina: Lessons Learned.* The following excerpt is taken from the report's Chapter 1, "Katrina in Perspective."

> The flooding destroyed New Orleans, the Nation's thirty-fifth largest city. Approximately 80 percent of the city was flooded. . . . Hurricane Katrina impacted nearly 93,000 square miles across 138 parishes and counties . . . an estimated 1,330 people died as a result of the storm. The vast majority of the fatalities—an estimated 80 percent—came from the New Orleans metropolitan area; Mississippi suffered greatly as well, with 231 fatalities. Many of the dead were elderly or infirm . . . As of February 17, 2006, there were still 2,096 people from the Gulf Coast area reported missing. Around 770,000 people were displaced. . . . The total cost to date is 96 billion dollars.[2]

CASE STUDY: Hurricane Katrina. Several national urban search and rescue (USAR) teams based in Florida, anticipating landfall of Hurricane Katrina in the Florida panhandle, had been deployed to the northern area of the state. When it was evident the hurricane would hit the Gulf Coast, these teams were sent on to that area. The fire marshal and a battalion chief from Palm Beach County Fire Rescue were sent in to assist in the establishment of the incident command post (ICP) in Biloxi, Mississippi, and were assigned the position of "liaison."

FIGURE 5.3.1 Hurricane Katrina Devastation (Source: National Oceanic and Atmospheric Administration)

The ICP was set up in the Gulf Coast Coliseum, which had taken on floodwaters up to the first balcony. When the water had receded and the ICP was established, the job of the USAR teams was to search three counties along the Gulf Coast and three counties to the North (Figure 5.3.2). The devastation that they saw was unbelievable. One of the lessons shared by the fire marshal upon his return was the necessity of staying focused on the job. The need was so great everywhere that, if the team members were not focused, they would be pulled in too many directions and would not complete the task at hand. James Lee Witt in his book, *Stronger in the Broken Places,* wrote: "The first mistake people often make in responding to a crisis is in trying to fix everything, respond to everything, all at once . . . they call it triage in medicine, the act of making split-second decisions about the priority of treating one medical case over another one."[3]

In an interview with the *Washington Times,* R. David Paulison, acting director of FEMA after the resignation of Michael Brown, said about Katrina, "It overwhelmed everyone; the system was not set up to deal with a catastrophe of that size. . . . Normally, we house [3,000 to 5,000] disaster victims a year. We went way beyond that, and we had to make up the rules as we went along." While preparing for the 2006 hurricane season, FEMA was still aiding 800,000 families affected by the previous year's storms, which had damaged 90,000 square miles.[4]

In addition to hurricanes, other types of natural disasters include earthquakes, floods, landslides, snow blizzards, tornadoes, volcanic eruptions, and wildfires. Fire and life safety educators, in whatever area of the country they may reside, will no doubt be affected by some type of natural disaster. In the past fire and life safety educators have left disaster response to line officers who have experience in special operations or to the emergency management divisions of their municipalities. Today, however, they consider it part of their jobs to help the people of their community know what to do by encouraging disaster preparedness before a catastrophe takes place.

Human-Caused Disasters

Although we commonly think of natural disasters as those caused by weather-related incidents, disasters can also be caused by humans, whether unintentional (such as a tractor-trailer hauling gasoline rolling over on the highway), or intentional (as in acts of terrorism). The hazards associated with human-caused disasters also need to be dealt with by fire and emergency services personnel. Many fire rescue departments have special operations teams that have been dealing with hazardous materials for many years. Hazards can be chemical, biological, radiological, nuclear, or explosive (CBRNE). The following case study highlights a bioterrorist event that happened within one month of the attack on the World Trade Center and the Pentagon.

CASE STUDY: Anthrax Mailing. An example of bioterrorism occurred when a 63-year-old male photo editor in Boca Raton, Florida, was diagnosed with inhalation anthrax on October 2,

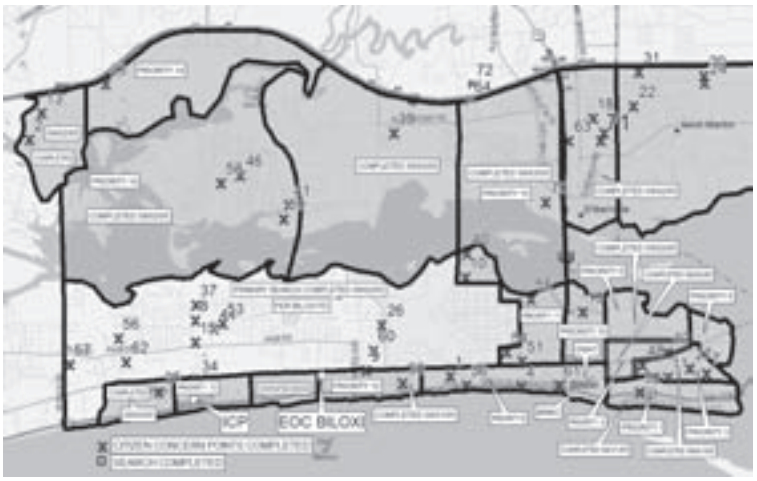

FIGURE 5.3.2 USAR Search Map After Hurricane Katrina (Courtesy of Fire Marshal, Deputy Chief Steve Jerauld)

2001. He died three days later. An environmental assessment of his workplace, American Media, a publisher of a national tabloid magazine, uncovered anthrax in the mailing and packaging facility. This story received a good deal of press coverage. The Centers for Disease Control assisted the local and state health departments in the investigation.[5] When the Palm Beach County Fire Rescue received many emergency calls from panicked residents because of the "white powder" scare, all personnel, including staff in the community education section, were involved in educating the public about safety precautions and steps to take if they suspected letters or packages of containing white powder.

Further press coverage continued when letters addressed to prominent news and political figures started to show up. The nation was on high alert as anthrax-laced letters surfaced in several places. NBC anchorman Tom Brokaw, two U.S. senators, and the offices of the *New York Post* were among the targets. The anthrax attacks killed five people and made 17 people ill.[6]

Many fanatical groups and terrorist cells have used explosive devices to make their statements. Bombs can be planted in vehicles or strapped to humans, who then become martyrs for their cause. However not all explosions in buildings have the same results. The National Science Foundation, in a report entitled *Preparing for the Worst—Making Buildings Stronger,*[7] discusses strengthening buildings as a good way to minimize fatalities.

CASE STUDY: El Nogal Social Club, Bogotá, Colombia. On February 7, 2003, a bomb demonstrated the critical benefits of solid construction when El Nogal social club in Bogotá, Colombia, withstood a devastating blast. Terrorists had used approximately 600 pounds of ammonium nitrate and chlorate mixed with fuel oil to create an enormous explosive device, which was placed in an automobile parked on the fourth floor of a 12 story building. At the time of the blast, 750 people were in the building; 38 were killed and 170 were injured. However, because the building remained standing, fatalities were minimized. El Nogal, composed of a 12 story structure and an adjacent four story structure, was designed to withstand seismic shaking (Figure 5.3.3).[7]

In comparison, the Oklahoma City bombing at the Alfred P. Murrah Federal Building (a structure not designed to withstand seismic shaking) resulted in a total of 168 people killed, including 19 children, and more than 500 injured. The building was later razed and a park was built on the site.[8]

Regardless of whether a disaster is caused by a natural event such as severe weather or is the result of a planned, intentional act of terrorism, the results are the same. People are killed or

FIGURE 5.3.3 Terrorist Attack on El Nogal Social Club, Bogotá, Colombia (Source: National Science Foundation)

injured, property is annihilated or damaged, and recovery takes time and money. People who survive a disaster need help to pick up the pieces and try to put their lives back together again.

FIRE AND LIFE SAFETY EDUCATOR

Fire and Life Safety Educator's Role

The role of today's fire and life safety educator has changed significantly over the past 20 years. Originally, someone in this position was involved in teaching only fire safety; however, as fire departments evolved and took on a more active role in rescue and emergency services, fire and life safety educators expanded their role to include teaching injury prevention.

After September 11, 2001, the world changed and, with it, the role of the fire and life safety educator. Terrorist incidents had actually taken place in the United States prior to that event; for instance, the Oklahoma City bombing on April 19, 1995, was "the first presidential declared disaster that was also a crime scene."[9] The difference, however, was that up until the time of the assault on the World Trade Center and the Pentagon, no large-scale, planned, direct attack on the nation had been executed by a hostile entity and had resulted in such a large loss of life. Since 9/11, the country has become more aware of hazards caused by humans, as well as the natural disasters that are happening more frequently and on a larger scale. The increasing strength and number of natural disasters—such as Hurricane Katrina; the Asian tsunami; and California, Texas, and Florida wildfires, which have caused such large life loss and massive property damage—have given rise to a focus on all hazards. As a result, the role of the fire and life safety educator has expanded to encompass disaster preparedness education.

Disaster Organizations and Programs

Organizations. Fire and life safety educators are great networkers. They often belong to and work with many coalitions, committees, and associations to expand the safety message in the community. They may undoubtedly have worked with organizations that deal with disasters on other projects. For instance, they may already be working with the American Red Cross on first aid, CPR, or the vial of life program. (In the latter, medical information is completed for the homeowner and placed on the refrigerator door. In an emergency, paramedics can take this information with them to the hospital.) They may have worked with the American Red Cross on the After the Fire program or on drowning prevention and water safety. The links are already there in the community even if the fire and life safety educator may not have been involved in disaster preparedness education.

Training Programs. One of the first places for fire and life safety educators to start is right inside their own department. Whether the department is career, volunteer, or a combination, it is still involved with training. The Department of Homeland Security has put a high priority on having every organization trained in the national incident management system (NIMS). Fire departments have been using the incident command system (ICS) for many years and it fits well within NIMS. If fire and life safety educators are not already trained in these programs, they would benefit from becoming familiar with such programs. A variety of courses are also available through the independent study program on the FEMA website.[10]

Emergency Operating Center. A municipality's emergency operating center is another great source of information on disaster preparedness education. Although the center may or may not have a person designated as an emergency management educator, the center's coordinator will have made contacts with all essential organizations in the community who would staff the EOC during a disaster. The state will also have an emergency management organization that can assist fire and life and safety educators. A list of national organizations that deal with disaster preparedness can be found at the end of this chapter. Many of these national organizations have an affiliation at the state or local level.

PRE-DISASTER ORGANIZATIONS, PROGRAMS, AND ACTIVITIES

Forming Collaborative Interagency Partnerships

Preparation *before* disasters strike is essential. Forming local coalitions that meet on a regular basis throughout the year will make all stages of dealing with a disaster run more smoothly.

Message Content. Statewide coalitions can be of great help to ensure consistent message content is provided for the public. When a collaborative interagency partnership is formed, all groups can reach a consensus on what messages to publish so that the same information is passed on regarding preparedness, disaster box contents, evacuation routes, and the like. These messages should be published on as many different websites and in as many different media outlets as possible. With consistent messages, the public will be more informed and less confused during all phases of the emergency. It is very important for agencies to form coalitions and share information to avoid giving mixed messages to the public. Remember to include media persons in this coalition group.

Resource Availability. Equally as important as a community analysis of risks and hazards is an analysis of the resources on hand and what resources could be obtained in the event of a disaster. Fire and life safety educators and public information officers have often built up networks and are familiar with what is available in their communities. This collaborative interagency partnership will allow everyone involved to know exactly what resources are available in the community.

Identifying and Analyzing Community Risks

Most fire departments have probably already done some type of community risk assessment to determine exactly what kind of hazards are present and where the hazardous occupancies in their jurisdiction are located. This risk assessment may have

been done with the aid of a software program or through a community risk assessment, prefire plans on the part of operations, and an examination and summary of inspections of properties, run reports, call volume, and the like. Such an assessment can be used to justify staffing, to apply for grant funds, to determine the location of future stations, to prepare for the accreditation process, and so on. With regard to emergency management and disaster preparedness, an assessment can help determine, for example, which areas may need to be evacuated, which populations may need special care during a disaster, which occupancies could be specific targets for terrorist activities, or which services could be affected during a major flood. Being familiar with the risks and hazards in the community will allow for preemergency planning. Having a plan in place to deal with a particular hazard beforehand makes disaster response easier.

Educational Programs Addressing Disaster Preparedness

Organizations put out many educational messages to address different types of disasters. These messages can be directed to adults and/or to children.

Programs for Children. Some websites tailor their messages and their graphics specifically to children—for instance, "FEMA for Kids" at http://www.fema.gov/kids/qzbwl01.htm and "Ready Kids" at http://www.ready.gov/kids/home.html.

From a comprehensive standpoint, an excellent program that addresses students from kindergarten through eighth grade is the NFPA curriculum, *Risk Watch: Natural Disasters.* Similar to the *Risk Watch: Unintentional Injuries* curriculum, *Risk Watch: Natural Disasters* was also put together by a technical advisory group of experts in the field of disaster preparedness. Funding in support of the program came from the Home Safety Council and FEMA. The curriculum is divided into five teaching modules (pre-K/kindergarten, grades 1–2, grades 3–4, grades 5–6, and grades 7–8), each of which addresses the following topics: general preparedness, earthquakes, floods, hurricanes, tornadoes, wildfires, and severe winter storms. Teachers and students can get additional support online from the website http://www.nfpa.org/riskwatch/RWND/faqs.html.

Another comprehensive educational program for children regarding disaster preparedness is the *Masters of Disaster* curriculum created by the American Red Cross. It consists of three teaching modules that cover grades K–2, 3–5, and 6–8. Disaster areas covered in each of the modules include general preparedness, hurricanes, floods, tornadoes, lightning, and earthquakes. Website support includes background for the teacher, general information on the disaster, and lesson plan adaptations. Teachers and students can get additional support on the program from the website http://www.redcross.org/disaster/masters/kit1.html.

Programs for Adults. Educational programs on disaster preparedness for adults are plentiful. Many training courses are available through the FEMA virtual campus. In addition, the http://www.ready.gov website has specific areas for businesses as well as for adults and children. (See the Disaster Preparedness Resources section at the end of this chapter.)

ROLES/ACTIVITIES BEFORE, DURING, AND AFTER A DISASTER

It is important that all local agencies meet and know what each agency's role will be. Establishing these roles well before disaster strikes will make everything run as smoothly as possible. Because several agencies may have positions for public information officers (PIO) and public educators, establishing well-defined roles will make better use of staffing and avoid duplication.

Pre-Disaster Roles/Activities

Before disasters, most public educators and PIOs are busy trying to help educate the public on how to be prepared. Agencies need to form coalitions and share information to avoid giving mixed messages to the public. Media people should be included in this coalition group. Each agency and media outlet needs to have the *same* messages regarding the following:

- Location of shelters
- Contents of disaster preparedness kit or box for the anticipated event
- When evacuation will be necessary
- Which areas should expect evacuation and suggestions on where to go
- How citizens need to prepare

Roles/Activities During Disasters

In past disasters, PIOs and public educators who were given specific jobs seemed to feel they were the most effective in such roles. Some were placed at emergency operation centers (EOC) where they were able to communicate with other agencies, making the best use of materials and staffing during disasters. They were also able to relay information back to their respective agencies. Also, at the EOC, they were available if other agencies needed anything from them. Some were placed in shelters and assigned the job of helping to keep the occupants as calm and informed as possible. Their calming presence was of great help to the volunteers working in the shelters.

Roles/Activities After Disasters

Public educators and PIOs assumed a wide variety of duties after local disasters. Some gathered information and wrote reports to FEMA and/or other governmental agencies. Some remained in their local emergency management facilities, keeping communication up and running efficiently between agencies. Others helped to ride streets and radio in as to where hazards prevented rescue equipment from safely passing, what equipment was needed to clear main streets, and what the priority was regarding needed emergency equipment. Because they are usually very familiar with the geographic area and which citizens might need assistance, public educators and PIOs are valuable personnel during disaster events.

Areas Needing Improvement

Almost everyone can agree that improvement could always be made in communication, especially from state or federal

agencies to local ones. Establishing good lines of communication by telling each entity what is expected of them and what they can expect from each other will avoid a lot of confusion.

NATURAL DISASTER MESSAGES

Pre-Storm Messages

Pre-storm messages include messages on the following topics:

Generators

- Provide information on proper exterior placement of generators.
- Provide information on carbon monoxide poisoning.
- Provide information on fire safety when using a generator.
- Provide information on amount of fuel that can be stored on the property.
- Refer citizens to the USFA website for general information on generators.

Pets

- Ensure that all pets have information tags.
- Ensure pets' vaccinations are up-to-date.
- Prepare a pet disaster kit.
- Investigate options for shelters that take animals.
- Consider making reservations for pets at pet shelters.

Power

- If you evacuate, be sure to shut off the main electric breaker in your home in case of a power outage.
- Turn gas main off, then have gas company turn it back on.

Tree Trimming

- Make sure that trees are trimmed before the storm season.
- Contact the local electric company if tree limbs interfere with wires.
- Do not put tree trimmings out for trash pickup before a storm.

Public Safety Response

- Warn citizens about the possible delayed response of emergency vehicles.

Messages During a Storm

Messages during a storm include the following:

- Provide information on candle safety.
- Suggest the use of flashlights, not candles, in a power outage.
- Provide information on using grills and generators outside the house or garage.
- Suggest not cooking or cooking safely on an outdoor grill.
- In a power outage, shut off the main electric breaker, so there will be no surge when electricity resumes. This also prevents fires if the stove was turned on before the power outage.

Post-Storm Messages

Post-storm messages include the following:

- Beware of foodborne illness; dispose of foods that have thawed or been without refrigeration.
- Stay off roads until told that they are safe for travel.
- Stay away from downed power lines.
- Stay away from flooded areas.
- Practice safety around generators.
- Practice safety when using candles.
- Repair downed/damaged pool enclosures and fences.
- Practice safety around loose pets and other animals.
- Practice safety around electricity.
- If it is safe, consider making welfare checks on elderly persons who did not evacuate.
- Provide adult supervision of children.
- Practice safety around water hazards such as drainage; sewage; storm drains; ponds, creeks, and canals.
- Pay attention to your municipality's information on drinking water.
- After the storm, remove shutters or plywood from windows and exits.
- Be aware that some family members may need help dealing with stress after the storm.
- After the storm, do a damage assessment and contact your insurance provider.

TORNADO-SPECIFIC MESSAGES

Tornado Defined

According to the *Glossary of Meteorology,* a tornado is "a violently rotating column of air, pendant from a cumuliform cloud or underneath a cumuliform cloud, and often (but not always) visible as a funnel cloud."[11] In order for a vortex to be classified as a tornado, it must be in contact with both the ground *and* the cloud base (Figure 5.3.4).

Weather scientists have not found it so simple to classify and define tornadoes. There is also disagreement as to whether

FIGURE 5.3.4 Sand Point, Alaska, Tornado (Source: National Oceanic and Atmospheric Administration)

separate touchdowns of the same funnel constitute separate tornadoes. The difference is unclear between a strong mesocyclone (parent thunderstorm circulation) on the ground and a large, weak tornado. It is well known that a tornado may not have a visible funnel. Tornadoes can last from several seconds to more than an hour; most last less than ten minutes.

A waterspout, which is a tornado over water, is common along the southeast U.S. coast, especially off southern Florida and the Keys. Waterspouts can happen over seas, bays, and lakes worldwide.

Tornado Safety

There is no such thing as guaranteed safety inside a tornado. Freak accidents happen; the most violent tornadoes can level and blow away almost any house and its occupants. Extremely violent tornadoes are very rare, though. Most are much weaker and can be survived using the safety suggestions provided in the following sections.

Pre-Tornado Planning. At home, have a family plan in place, based on the kind of dwelling you live in and the safety tips provided below. Know where you can take shelter in a matter of seconds, and practice a family tornado drill at least once a year. Have a predetermined place to meet after a disaster. Flying debris is the greatest danger in tornadoes, so store protective coverings (e.g., mattress, sleeping bags, thick blankets, etc.) in or next to your shelter space, ready to use on a few seconds' notice.

When a tornado watch is issued, think about the drill and check to make sure all your safety supplies are handy. Turn on local TV, radio, or NOAA Weather Radio and stay alert for warnings. Forget about the old notion of opening windows to equalize pressure; the tornado will blast open the windows for you. If you shop frequently at certain stores, learn where the bathrooms, storage rooms, or other interior shelter areas in these stores are that are away from windows and make note of the shortest ways to get to these areas. If you are planning to build a house, especially east of the Rockies, consider an underground tornado shelter or an interior "safe room."

Tornado Signs and Sounds. Besides an obviously visible tornado, the following are some signs to look and listen for:

- Strong, persistent rotation in the cloud base
- Whirling dust or debris on the ground under a cloud base; note that tornadoes sometimes have no funnel
- Hail or heavy rain followed by either dead calm or a fast, intense wind shift; many tornadoes are wrapped in heavy precipitation and cannot be seen
- Day or night: a loud, continuous roar or rumble that doesn't fade in a few seconds like thunder does
- Night: small, bright blue-green to white flashes at ground level near a thunderstorm (as opposed to silvery lightning up in the clouds); these flashes indicate power lines are being snapped by very strong wind
- Night: *persistent* lowering from the cloud base, illuminated or silhouetted by lightning, especially if it is on the ground or there is a blue-green-white power flash underneath

Tornado Safety Tips

The following are safety tips for actions to take depending on where you are when the tornado strikes.

House with a Basement

- Avoid windows.
- Get in the basement and under some kind of sturdy protection (heavy table or work bench), or cover yourself with a mattress or sleeping bag.
- Know where very heavy objects (pianos, refrigerators, waterbeds, etc.) rest on the floor above and do not go under them.

House with No Basement, Dorm, or Apartment

- Avoid windows.
- Go to the lowest floor, to a small center room (like a bathroom or closet), under a stairwell, or in an interior hallway with no windows.
- Crouch as low as possible to the floor, facedown, and cover your head with your hands. A bathtub may offer a shell of partial protection.
- Cover yourself with thick padding such as a mattress or blankets to protect against falling debris.

Office Building, Hospital, Nursing Home, or Skyscraper

- Go directly to an enclosed, windowless area in the center of the building, away from glass. Interior stairwells are usually good places to take shelter, and if not crowded, allow you to get to a lower level quickly.
- Crouch down and cover your head.
- Stay out of elevators.

Mobile Home

- Get out! Even if your home is tied down, you are probably safer outside, even if the only alternative is to seek shelter out in the open.
- If there is a sturdy permanent building within easy running distance, seek shelter there.
- Otherwise, lie flat, facedown on low ground away from your home, protecting the back of your head with your arms.
- Use open ground away from trees and cars.

School

- Follow the drill!
- Go to the interior hall or room in an orderly way as you are told.
- Crouch low, head down, and protect the back of your head with your arms.
- Stay away from windows and large open rooms like gyms and auditoriums.

Car or Truck

- Vehicles are extremely dangerous in a tornado. If the tornado is visible, far away, and traffic is light, you may be able to drive out of its path by moving at right angles to the tornado.
- Otherwise, park the car as quickly and safely as possible, out of traffic lanes.

- Get out and seek shelter in a sturdy building.
- If in open country, run to low ground away from any cars (which may roll over on you).
- Lie flat and facedown, protecting the back of your head with your arms.
- Avoid seeking shelter under bridges, which can create deadly traffic hazards while offering little protection against flying debris.

Open Outdoors

- Seek shelter in a sturdy building.
- If no building is available, lie flat, facedown on low ground, protecting the back of your head with your arms.
- Get as far away from trees and cars as you can.

Church or Theater

- Do not panic.
- Move quickly but in an orderly fashion to an interior bathroom or hallway, away from windows.
- Crouch facedown and protect your head with your arms.
- If there is no time to do that, get under the seats or pews, protecting your head with your arms or hands.

Post-Tornado Activities. After the tornado has left your vicinity, take the following actions:

- Keep your family together and wait for emergency personnel to arrive. Carefully render aid to those who are injured.
- Stay away from power lines and puddles with wires in them; they may be carrying electricity.
- Watch your step to avoid broken glass, nails, and other sharp objects.
- Stay out of any heavily damaged houses or buildings; they could collapse.
- Do not use matches or lighters, in case of leaks in natural gas pipes or fuel tanks nearby.
- Remain calm and alert, and listen for information and instructions from emergency crews or local officials.

HURRICANE-SPECIFIC MESSAGES

Hurricane Defined

The *Encarta* dictionary defines a *hurricane* as a severe tropical storm with torrential rain and extremely strong winds above 74 miles (119 km) an hour. Hurricanes originate in areas of low pressure in equatorial regions of the Atlantic or Caribbean, and then strengthen, traveling northwest, north, or northeast. Hurricanes can be dangerous killers. Learning the hurricane warning messages and planning ahead can reduce the chances of injury or major property damage (Figure 5.3.5).

Pre-Hurricane Activities

Planning an Evacuation Route. Plan an evacuation route. Contact the local Emergency Management office or American Red Cross chapter and ask for the community hurricane preparedness plan. This plan should include information on the safest evacuation routes and nearby shelters. Learn safe routes inland. Be ready to drive 20 to 50 miles inland to locate a safe place.

FIGURE 5.3.5 Airplane Destroyed by Hurricane Charley in Florida in 2004 (Photo by Andrea Booher, FEMA)

Assembling Hurricane Supplies. Assemble hurricane supplies before hurricane season. The following supplies will be essential if you plan to shelter in place and are not in an evacuation area:

- Cash
- Flashlight and extra batteries
- Portable battery-operated radio and extra batteries
- Lantern
- First aid kit and manual
- Emergency food and water (food should be nonperishable—e.g., canned meat and fish, canned fruits and vegetables, canned soups and puddings, canned fruit juices, dried fruits, baby formula and baby food, bread, cookies, crackers, peanut butter and jelly, coffee and tea—and 2 gallons [75 L] of water per person for 7 days is a good rule of thumb)
- Nonelectric can opener
- Essential medicines
- Pet food
- Disposable plates
- Infant care items such as diapers and wipes
- Sturdy shoes
- Emergency cooking facilities
- Matches
- Masking or duct tape
- Canned heat (Sterno®)
- Outdoor camping stove or grill with adequate fuel supply
- Plastic trash bags
- Plastic sheeting or drop cloth
- Bleach
- Fire extinguisher
- Telephone that plugs directly into the phone line and does not require electricity. Note: These are usually the old style and not the cordless variety.

Other useful hurricane supplies to assemble include the following:

- Hammer

- Screwdriver
- Pliers and wrenches
- Handsaw
- Razor knife
- Ax or chainsaw with adequate fuel
- Rope and wire
- Caulking
- Nails and screws
- Bucket, mop, broom, scrub brush, rags
- All-purpose cleaner
- Ladder
- Shovel, rake, wheelbarrow
- Tree pruner

Hurricane Evacuation Kit. Assemble a hurricane evacuation kit. In the event that you chose to (or are ordered to) evacuate, the following items are essential:

- Cash
- Foods that do not need cooking
- Drinking water (2 gallons per person per day)
- Special dietary food, if required
- Identification, valuable papers, insurance policies, and photos in a waterproof container
- Personal hygiene items (soap, deodorant, shampoo, toothbrush, toothpaste, aspirin, antacid, diapers, washcloth, towel)
- Utensils (manual can opener, disposable plates, cups, forks, knives, spoons, napkins)
- Personal aids (eyeglasses, hearing aids, prosthetic devices)
- Prescription medications
- Specific medical information
- Books, magazines, cards, toys, games
- Infant care items (baby formula, baby food, wipes, disposable diapers)
- Battery-operated radio
- Flashlight or lantern
- First aid kit, including betadine, gauze bandages, adhesive tape, sterile pads, bandages, triangular bandages, safety scissors, and nonprescription medication
- Extra batteries for radio and flashlights
- Sleeping bag or blanket, sheet, pillow
- Change of clothing
- Rainwear

Other Pre-Hurricane Activities. Other pre-hurricane activities range from what to do about pets to developing an emergency communication plan, as follows:

- Remember that alcoholic beverages and weapons are not allowed inside emergency public shelters.
- Make arrangements for pets because they may not be allowed into emergency shelters for health and space reasons. Contact your local humane society for information on local animal shelters.
- Make sure that all family members know how to respond after a hurricane. Teach family members how and when to turn off gas, electricity, and water. Teach children how and when to call 9-1-1, police, or fire department and which radio station to tune to for emergency information.
- Protect your windows. Permanent shutters are the best protection. A lower-cost approach is to put up plywood panels. Use ½ inch (1.25 cm) plywood cut to fit each window. Marine plywood is best. Remember to mark which board fits which window. Pre-drill holes every 18 inches (45.72 cm) for screws. Do this long before the storm.
- Trim back dead or weak branches from trees. Do this well before storm season. Leaving yard waste by the road the day before the storm arrives is dangerous.
- Check into flood insurance. You can find out about the National Flood Insurance Program through your local insurance agent or emergency management office. There is normally a 30 day waiting period before a new policy becomes effective. Note that homeowners polices do not cover damage from the flooding that accompanies a hurricane.
- Develop an emergency communication plan. In case family members are separated from one another during a disaster (a real possibility during the day when adults are at work and children are at school), have a plan for getting back together. Ask an out-of-state relative or friend to serve as the "family contact." After a disaster, it's often easier to call long distance. Make sure everyone in the family knows the name, address, and phone number of the contact person.

Hurricane Watch and Hurricane Warning Activities

Hurricane Watch. A hurricane watch is issued when there is a threat of hurricane conditions within 24 to 36 hours. The following are actions to take during a hurricane watch:

- Listen to a battery-operated radio or television for hurricane progress reports.
- Check emergency supplies.
- Fill the car's fuel tank.
- Bring in outdoor objects such as lawn furniture, toys, and garden tools; anchor objects that cannot be brought inside.
- Secure buildings by closing and boarding up windows. Remove outside antennas.
- Turn the refrigerator and freezer to their coldest settings. Open them only when absolutely necessary and close quickly.
- Store drinking water in clean bathtubs, jugs, bottles, and cooking utensils.
- Review the evacuation plan.
- Moor boats securely or move them to a designated safe place. Use ropes or chains to secure boats to trailers. Use tiedowns to anchor trailers to the ground or house.

Hurricane Warning. A hurricane warning is issued when hurricane conditions (winds of 74 miles per hour or greater or dangerously high water and rough seas) are expected in 24 hours or less. The following are actions to take during a hurricane warning:

- Listen constantly to a battery-operated radio or television for official instructions.

- If in a mobile home, check tiedowns and evacuate immediately.
- Store valuables and personal papers in a waterproof container on the highest level of your home.
- Avoid elevators.

Activities During a Hurricane

The following are actions to take during a hurricane:

- Stay inside, away from windows, skylights, and glass doors.
- Keep a supply of flashlights and extra batteries handy. Avoid open flames, such as candles and kerosene lamps, as a source of light.
- If power is lost, turn off major appliances to reduce power "surge" when electricity is restored.
- Use flashlights instead of candles or kerosene lamps.
- Continue to conserve refrigeration. Open the refrigerator as infrequently as possible.
- If the calm eye of the hurricane passes through your area, continue to stay indoors. Beware: The wind will pick up again from the opposite direction, possibly with greater force than before.
- Remain indoors until the official "all clear" is given.

If officials indicate evacuation is necessary, take the following actions:

- Leave as soon as possible. Avoid flooded roads and watch for washed-out bridges.
- Secure your home by unplugging appliances and turning off electricity and the main water valve.
- Tell someone outside of the storm area where you are going.
- If time permits, and you live in an identified surge zone, elevate furniture to protect it from flooding or better yet, move it to a higher floor.
- Bring preassembled emergency supplies and warm protective clothing.
- Take blankets and sleeping bags to shelter.
- Lock up home and leave.

Post-Hurricane Activities

The following are actions to take after a hurricane:

- Stay tuned to local radio for information.
- Return home only after authorities advise that it is safe to do so.
- Help injured or trapped persons.
- Give first aid where appropriate.
- Do not move seriously injured persons unless they are in immediate danger of further injury. Call for help.
- Avoid loose or dangling power lines and report them immediately to the power company, police, or fire department.
- Enter your home with caution.
- Beware of snakes, insects, and animals driven to higher ground by floodwater.
- Open windows and doors to ventilate and dry your home.
- Check refrigerated foods for spoilage.
- Take pictures of the damage, both to the house and its contents, for insurance claims.
- Drive only if absolutely necessary and avoid flooded roads and washed-out bridges.
- Use the telephone only for emergency calls.
- Inspect utilities in a damaged home:
  - Check for gas leaks. If you smell gas or hear a blowing or hissing noise, open a window and quickly leave the building. Turn off the gas at the outside main valve if you can and call the gas company from a neighbor's home. If you turn off the gas for any reason, a professional must turn it back on.
  - Look for electrical system damage. If you see sparks or broken or frayed wires, or if you smell hot insulation, turn off the electricity at the main fuse box or circuit breaker. If you have to step in water to get to the fuse box or circuit breaker, call an electrician first for advice.
  - Check for damage to sewer and water lines. If you suspect sewer lines are damaged, avoid using the toilets and call a plumber. If water pipes are damaged, contact the water company and avoid the water from the tap. You can obtain safe water by melting ice cubes.

WINTER STORM–SPECIFIC MESSAGES

Heavy snowfall and extreme cold can immobilize an entire region. Even areas that normally experience mild winters can be hit with a major snowstorm or extreme cold (Figure 5.3.6). Winter storms can result in flooding, storm surge, closed highways, blocked roads, downed power lines, and hypothermia. Figure 5.3.7 shows winter storm occurrences by state.

Winter Storm Terms

Familiarize yourself with the following terms to help identify a winter storm hazard:

FIGURE 5.3.6 Snow Drifts After a Major Snowstorm (Source: NASA)

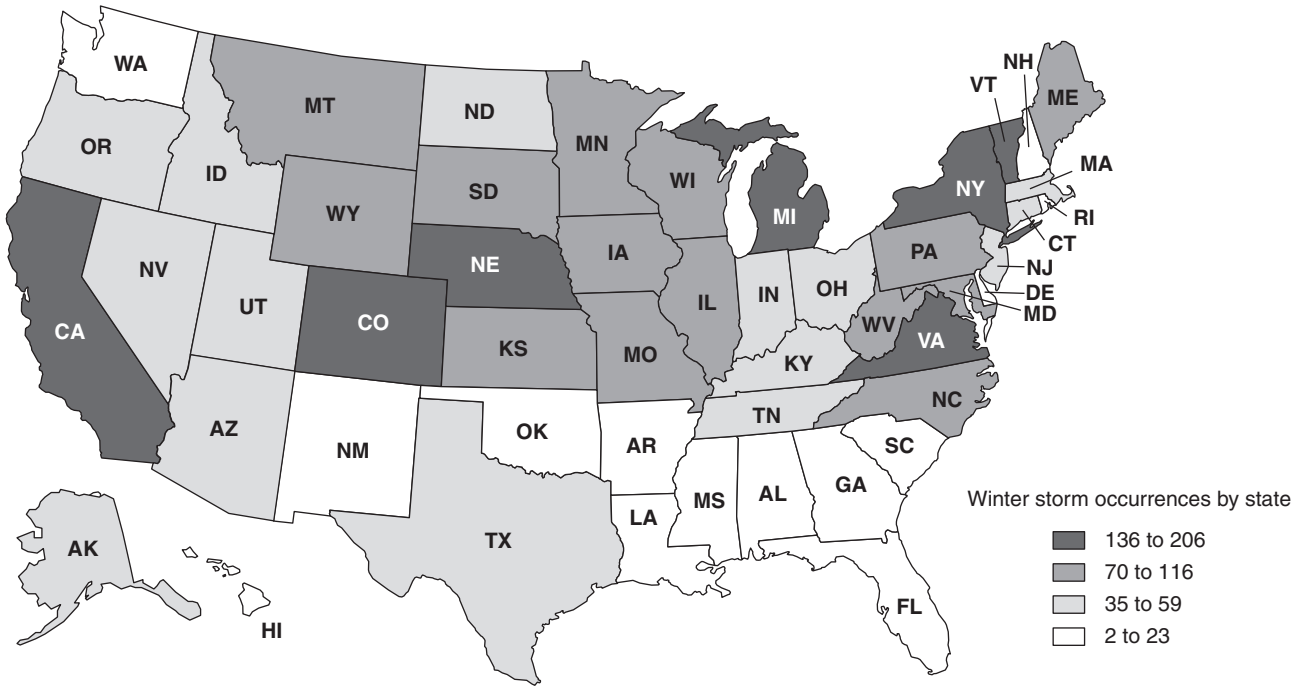

FIGURE 5.3.7 Winter Storm Occurrences by State (Source: ITS Mapping and Analysis Center, National Oceanic and Atmospheric Administration, Washington, DC, 2003)

Freezing Rain. Freezing rain is rain that freezes when it hits the ground, creating a coating of ice on roads, walkways, trees, and power lines.

Sleet. Sleet is rain that turns to ice pellets before reaching the ground. Sleet also causes moisture on roads to freeze and become slippery.

Winter Storm Watch. A winter storm watch is an advisory that a winter storm is possible in your area. Tune in to NOAA Weather Radio, commercial radio, or television for more information.

Winter Storm Warning. A winter storm warning is an advisory that a winter storm is occurring or will soon occur in your area.

Blizzard Warning. A blizzard warning indicates a condition of sustained winds or frequent gusts to 35 miles per hour or greater and considerable amounts of falling or blowing snow (reducing visibility to less than a quarter mile) are expected to prevail for a period of three hours or longer.

Frost/Freeze Warning. A frost/freeze warning is an advisory that below freezing temperatures are expected.

Pre–Winter Storm Activities

Disaster Supplies Kit. Before the arrival of winter storms and extreme cold, prepare a disaster supplies kit, including the following:

- Rock salt to melt ice on walkways
- Sand to improve traction
- Snow shovels and other snow removal equipment

Home Heating. Take the following actions to ensure keeping your home and yourself warm:

- Consider buying emergency heating equipment, such as a wood- or coal-burning stove or a kerosene heater as a backup.
- Prepare for possible isolation in your home by having sufficient heating fuel. (Regular fuel sources may be cut off.) For example, store a good supply of dry seasoned wood for your fireplace or wood-burning stove.
- Have fireplace and woodstove chimneys inspected annually to ensure the residue left by burning wood has not accumulated.
- Winterize your home to extend the life of your fuel supply by properly insulating walls and attics. Caulk and weatherstrip doors and windows. Install storm windows or cover windows with plastic from the inside. Protect pipes by wrapping them in insulation and let faucets drip to prevent freezing.

Road Safety. Take the following actions to prepare for safe winter driving:

- Ensure that the battery and ignition system are in top condition and battery terminals are clean.
- Ensure antifreeze levels are sufficient to avoid freezing.
- Ensure the heater and defroster work properly.

- Check and repair windshield wiper equipment; ensure proper washer fluid level.
- Ensure the thermostat works properly.
- Check lights and flashing hazard lights for serviceability.
- Check for leaks and crimped pipes in the exhaust system; repair or replace as necessary. Note that carbon monoxide is deadly and usually gives no warning.
- Check brakes for wear and fluid levels.
- Keep cars and other vehicles fueled and in good repair.
- Check oil for level and weight. (Heavier oils congeal more at low temperatures and do not lubricate as well.)
- Consider snow tires, snow tires with studs, or chains.
- Replace fuel and air filters. Keep water out of the system by using additives and maintaining a full tank of gas.

Activities During a Winter Storm

During winter storms and extreme cold, take the following actions:

- Listen to your radio, television, or NOAA Weather Radio for weather reports and emergency information.
- Eat regularly and drink plenty of fluids, but avoid caffeine and alcohol.
- Avoid overexertion when shoveling snow. (Overexertion can bring on a heart attack—a major cause of death in the winter.) If you must shovel snow, stretch before going outside.
- Wear several layers of loose-fitting, lightweight, warm clothing rather than one layer of heavy clothing. Other garments should be tightly woven and water-repellent.
- Wear mittens, which are warmer than gloves.
- Wear a hat.
- Cover your mouth with a scarf to protect your lungs.
- Watch for signs of frostbite, including loss of feeling and white or pale appearance in extremities such as fingers, toes, ear lobes, and the tip of the nose. If symptoms are detected, get medical help immediately.
- Watch for signs of hypothermia, including uncontrollable shivering, memory loss, disorientation, incoherence, slurred speech, drowsiness, and apparent exhaustion. If symptoms of hypothermia are detected, get the victim to a warm location, remove wet clothing, warm the center of the body first, and give warm, nonalcoholic beverages if the victim is conscious. Get medical help as soon as possible.
- Conserve fuel, if necessary, by keeping your residence cooler than normal. Temporarily close off heat to some rooms.
- Maintain ventilation when using kerosene heaters to avoid buildup of toxic fumes. Refuel kerosene heaters outside and keep them at least three feet from flammable objects.
- Drive only if it is absolutely necessary. If you must drive, take the following precautions:
  - Drive only at speeds dictated by conditions and increase distances between vehicles.
  - Share travel schedules and routes and stay on main roads. Carry a cell phone.
  - Travel in daylight and do not travel alone.
  - Many states have free road condition hotlines. Be familiar with your state's services.

LANDSLIDE-SPECIFIC MESSAGES

Landslide Hazards

Landslide hazards occur in many places around the world and include fast-moving debris flows, slow-moving landslides, and a variety of flows and slides initiating from volcanoes. Each year, these hazards cost billions of dollars and cause numerous fatalities and injuries.

Mudslides. Landslides are caused by disturbances in the natural stability of a slope. They can accompany heavy rains or follow droughts, earthquakes, or volcanic eruptions. Mudslides develop when water rapidly accumulates in the ground and results in a surge of water-saturated rock, earth, and debris (Figure 5.3.8). Mudslides usually start on steep slopes and can be activated by natural disasters. Areas where wildfires or human modification of the land have destroyed vegetation on slopes are particularly vulnerable to landslides during and after heavy rains.

Volcano Landslides. Volcano landslides range in size from small movements of loose debris on the surface to massive collapse of the entire summit or sides of a volcano. Steep volcanoes are susceptible to landslides because they are built partly of layers of loose volcanic rock fragments. Landslides on volcano slopes are triggered when eruptions, heavy rainfall, or large earthquakes cause these materials to break free and move downhill.

Health Threats. In the United States, landslides and debris flows result in 25 to 50 deaths each year. The health hazards associated with landslides and mudflows include the following:

- Rapidly moving water and debris that can lead to trauma
- Broken electrical, water, gas, and sewer lines that can result in injury or illness
- Disrupted roadways and railways that can endanger motorists and disrupt transport and access to health care

At-Risk Areas. Some areas are more likely to experience landslides or mudflows, including the following:

- Areas where wildfires or human modification of the land have destroyed vegetation
- Areas where landslides have occurred before
- Steep slopes and areas at the bottom of slopes or canyons
- Slopes that have been altered for construction of buildings and roads
- Channels along a stream or river
- Areas where surface runoff is directed

Pre–Intense Storm and Rainfall Activities

Before intense storms and rainfall, take the following actions:

FIGURE 5.3.8 Mudslide Caused by Heavy Rain (Source: National Oceanic and Atmospheric Administration)

- Assume that steep slopes and areas burned by wildfires are vulnerable to landslides and debris flows.
- Become familiar with the land around you. Learn whether debris flows have occurred in your area.
- Watch the patterns of storm-water drainage on slopes near your home, noting especially the places where run-off water converges, increasing flow over soil-covered slopes.
- Watch the hillsides around your home for any signs of land movement, such as small landslides or progressively tilting trees.
- Learn whether landslides or debris flows have occurred previously in your area by contacting local authorities, a county geologist or the county planning department, state geological surveys or departments of natural resources, or university departments of geology.
- Contact local authorities about emergency and evacuation plans in your area.
- Develop emergency and evacuation plans for your family and business.
- Develop an emergency communication plan in case family members are separated.
- If you live in an area vulnerable to landslides, consider evacuation.

Pre-Landslide Signs

The following signs and features may be noticed prior to major landslides:

- Springs, seeps, or saturated ground in areas that have not typically been wet
- New cracks or unusual bulges in the ground, street pavement, or sidewalk
- Soil moving away from foundations
- Ancillary structures such as decks and patios tilting and/or moving
- Tilting or cracking of concrete floors and foundations
- Broken water lines and other underground utilities
- Leaning telephone poles, trees, retaining walls, or fences
- Offset fence lines
- Sunken or down-dropped roadbeds
- Rapid increase in creek water levels, possibly accompanied by increased turbidity (soil content)
- Sudden decrease in creek water levels, although rain is still falling or just recently stopped
- Sticking doors and windows and visible open spaces indicating jambs and frames out of plumb

Pre-Landslide Activities

If you suspect imminent landslide danger, take the following actions:

- If possible, evacuate.
- Contact your local fire, police, or public works department.
- Inform your family and neighbors of your destination.

Activities During Intense Storms and Rainfall

During intense storms and rainfall, take the following actions:

- Listen to the radio or watch TV for warnings about intense rainfall or for information and instructions from local officials.
- Be aware of any sudden increase or decrease in water level in a stream or creek that might indicate debris flow upstream. A trickle of flowing mud may precede a larger flow.
- Look for tilted trees, telephone poles, fences, or walls, and for new holes or bare spots on hillsides.
- Listen for rumbling sounds that might indicate an approaching landslide or mudflow.
- Be particularly alert when driving. Roads may become blocked or closed due to collapsed pavement or debris.
- If landslide or debris flow danger is imminent, quickly move away from the path of the slide. Getting out of the

path of a debris flow is your best protection. Move to the nearest high ground in a direction away from the path.
- If rocks and debris are approaching, run for the nearest shelter and take cover (if possible, under a desk, table, or other piece of sturdy furniture).

Post-Landslide Activities

After a landslide or mudflow, take the following actions:

- Stay away from the site. (Flooding or additional slides may occur after a landslide or mudflow.)
- Check for injured or trapped people near the affected area, if it is possible to do so without entering the path of the landslide or mudflow.
- Listen to the radio or TV for emergency information.
- Report broken utility lines to the appropriate authorities.
- Consult a geotechnical expert (a registered professional engineer with soils engineering expertise) for advice on reducing additional landslide problems and risks. Local authorities should be able to tell you how to contact a geotechnical expert.

RETOOLING TO INCLUDE DISASTER PREPAREDNESS EDUCATION

Many fire and life safety educators believe that if a fire department responds to a call, then they should also be involved in creating an educational program that addresses that risk area. Although traditionally fire and life safety educators have not been heavily involved with disaster preparedness education, today's emphasis on *all hazards* has brought disaster education to the forefront as a very important and relevant topic. Because fire and life safety educators and public information officers already have networks and coalitions formed for other topics such as injury prevention, it would take minimal effort to include disaster preparedness education. Creating a liaison with emergency management and working with the organizations with which they already have partnerships would seem to be a natural fit. This seems to be the most direct way to retool the program in order to include disaster preparedness education.

DISASTER PREPAREDNESS RESOURCES

- Air Force Reserve Command Fire
  http://www.afres.af.mil/~fire/pages/firehome.htm
- Alaska Volcano Observatory
  http://www.avo.alaska.edu/
- American Meteorological Society
  http://atm.geo.nsf.gov/AMS
- American National Red Cross
  http://www.redcross.org
- American Red Cross/CNN/IBM
  http://www.disasterrelief.org
- Center for Earth Research and Information
  http://www.ceri.memphis.edu
- Center for Excellence in Emergency Management
  http:// website.tamc.amedd.army.mil
- Centers for Disease Control and Prevention: Emergency Preparedness and Response
  http://www.bt.cdc.gov
- Central U.S. Earthquake Consortium
  http://gandalf.ceri.memphis.edu/~cusec/index.html
- Corporation for National Service
  http://www.nationalservice.org
- Department of Agriculture
  http://www.usda.gov
- Department of Transportation
  http://www.dot.gov/affairs/index.htm
- Disaster Communications
  http://www.law.indiana.edu/law/disaster
- Disaster Connection
  http://www.itn.is/~gro/disaster
- Disaster Preparedness and Emergency Response Association, International
  http://www.disasters.org/deralink.html
- Doctors Without Borders
  http://www.dwb.org
- Earthquake Engineering Research Center, University of California at Berkeley
  http://www.eerc.berkeley.edu
- Earthquake Maps and Information—Association of Bay Area Governments (ABAG)
  http://www.abag.ca.gov/bayarea/eqmaps/eqmaps.html
- Earthquake Reporting Service
  http://quake.wr.usgs.gov
- Environmental Protection Agency
  http://www.epa.gov
- Eye on the World—Violent Planet Page
  http://www.iwaynet.net/~kwroejr/violent.html
- Federal Emergency Management Agency
  http://www.fema.gov
- Humane Society of the United States
  http://www.hsus.org
- Institute of Emergency Management and Planning
  http://www.ias.unt.edu:9510
- Insurance Information Institute
  http://www.iii.org
- Intellicast
  http://www.intellicast.com
- International Decade for Natural Disaster Reduction
  http://www.quipu.net
- Internet Disaster Information Network—USA
  http://www.disaster.org
- Massachusetts Institute of Technology—U.S. Weather Map
  http://www.mit.edu/usa.html
- NASA Images Catalog
  http://rsd.gsfc.nasa.gov/rsd/images
- National Drought Mitigation Center
  http://enso.unl.edu/ndmc
- National Emergency Management Association
  http://www.nemaweb.org
- National Interagency Fire Center
  http://www.nifc.doi.gov
- National Oceanic & Atmospheric Administration
  http://www.noaa.gov

- National Severe Storms Laboratory
  http://www.nssl.uoknor.edu
- National Voluntary Organization Active in Disasters
  http://www.vita.org/nvoad
- National Weather Service Homepage
  http://www.nws.noaa.gov
- Natural Hazards Center at the University of Colorado
  http://adder.colorado.edu/~hazctr/Home.html
- NOAA Weather Venues
  http://www.nnic.noaa.gov/weather.html
- Online Guide to Meteorology
  http://covis1.atmos.uiuc.edu/guide
- Operation Fresh Start
  http://www.sustainable.doe.gov/freshstart
- Public Seismic Network
  http://gandalf.ceri.memphis.edu/~rond/psn
- Saint Louis Earthquake Research and Information
  http://www.eas.slu.edu/Earthquake_Center/earthquakecenter.html
- The San Francisco Bay Area Governments' Earthquake Hazard Maps
  http://www.abag.ca.gov/bayarea/eqmaps/eqmaps.html
- Small Business Administration
  http://www.sba.gov
- Storm98
  http://www.storm98.com
- Storm Chaser Homepage
  http://taiga.geog.niu.edu/chaser/chaser.html
- Tropical Prediction Center
  http://www.nhc.noaa.gov
- United States Army Corps of Engineers
  http://www.usace.army.mil/inet/functions/cw
- United States Fire Administration
  http://www.usfa.fema.gov
- United States Geological Survey
  http://www.usgs.gov
- University of Washington Geophysics Program
  http://www.geophys.washington.edu/welcome.html
- *USA Today:* Weather Front Page
  http://www.usatoday.com/weather/wfront.htm
- USGS/David A. Johnston Cascades Volcano Observatory
  http://vulcan.wr.usgs.gov/home.html
- Volcano World
  http://volcano.und.nodak.edu
- The Weather Channel
  http://www.weather.com
- West Coast and Alaska Tsunami Warning Center
  http://www.alaska.net/~atwc

SUMMARY

After defining disaster preparedness and providing case studies and specific examples that focused on both natural disasters and those caused by humans, the chapter discussed the role of today's fire and life safety educator, specifically as it relates to disaster preparedness education. Because life and safety educators work with coalitions and organizations already formed in the community, expanding their role into disaster preparedness education seems like a natural fit. Educational programs and detailed messages specific to the different types of disasters, such as tornadoes, hurricanes, extreme winter storms, and landslide hazards, were expanded on. In addition, steps for "retooling" the fire and life safety education program to include disaster preparedness education were suggested. The chapter concludes with a list of disaster preparedness resource websites for further information on the topic.

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10. "Independent Study Program," http://training.fema.gov/emiweb/IS/crslist.asp, Federal Emergency Management Agency, Emergency Management Institute, Emmitsburg, MD.
11. *Glossary of Meteorology,* 2nd ed., American Meteorological Society, Boston, MA, 2000.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on disaster preparedness education discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA *101®, Life Safety Code®*
NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*

Chapter 4

Media's Role in Fire and Life Safety Education

Revised by
Robin J. Adair

Chapter Contents

Defining Terms
Communication Goals
Community Media Services
Matching the Medium with the Message
Publicity Campaigns
Emergency Scene Public Information
Exploring Legal Issues
Future Communication Technologies and Public Education
Evaluating Efforts

Key Terms

broadcast media, copyright, fire and life safety educator, Freedom of Information Act, Health Information Portability and Accountability Act (HIPPA), practical publicity, print media, public information officer, public service announcements

Since the goal of fire and life safety educators is to improve safety knowledge and skills in their communities, they must find effective ways to communicate with the public. This requires the educator to develop a working relationship with members of the media. Whether it is in a large city where the fire department employs full-time media relations staff, in a small town where all the fire fighters know the only local reporter, or anywhere in between—the media are a means to reach the community as a whole or in specific target audiences. The mass media can be an effective, cost-efficient, and appropriate way to reach some education goals.

The goals of fire and life safety educators, however, are not always the goals of the media. Reporters sometimes need facts before educators know what the facts are. The media may ask for details that educators may consider an infringement on privacy. Newspeople want to get accurate information disseminated as quickly as possible and to deliver it in a compelling manner that will interest the audience. Those priorities are not always in harmony with fire service concerns.

These differences do not need to be interpreted as conflicts, however. Fire service information officer Leo M. Brown writes, "The 'us against them' philosophy, which has dominated our relationship with the media for years, is inaccurate and counterproductive."[1] The media are necessary to the success of educators, and the fire department can meet the needs of the media and the public we both serve. Fire and life safety educators need to understand the media—and the educators' own options for dealing with the media—to best pursue the educators' goals. That is the focus of this chapter.

Entire books are written every year on communications, media, and education. This chapter outlines just the basics and aims to provide practical information to aid fire personnel who communicate with the media. Specifically, this chapter will discuss the following topics:

- *Fire department communication goals.* Internal and external audiences
- *Media community services.* Who is out there, and what do they do?
- *Matching the medium to the message.* Similarities and differences in media
- *Publicity campaigns.* Media as part of structured public appeal
- *Emergency scenes.* When the educator is the public information officer
- *Legal issues.* Privacy, free speech, and asking permission
- *Evaluation.* Measuring the effectiveness of communications efforts
- *Future communication technologies and public education.* What's next?

See also Section 5, Chapter 2, "Fire and Life Safety Education Messages"; and Section 5, Chapter 8, "Evaluation Techniques for Fire and Life Safety Education."

DEFINING TERMS

Public Relations, Public Education, and Public Information

The distinctions among public relations, public education, and public information are fine but critical. There are many similarities among these concepts. All require a carefully thought-out planning

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process, including a solid implementation strategy. All can and should be evaluated for their effectiveness. The goals of communication for each, however, are different.

The goal of a public relations strategy is to improve or sustain the positive working relationship between the fire service and the community that supports it.[2] The goal of a public education program is to enlighten people, giving them the knowledge and skill to improve their existence.[2] The goal of a public information officer is to service requests for information within the unique scope of the department so that listeners see and understand issues the way the department does.

Both public education and public information delivery can contribute to good public relations, although that is not their primary goal. Both rely on good public relations for their effectiveness.

A public relations professional might describe *public relations (PR)* as "communicating specific messages at targeted publics as a means of helping to achieve an organization's goals and objectives."[3] Tim Birr aptly describes PR as "the art of doing something well and getting caught at it."[3]

Some departments believe the public information officer (PIO), who is responsible for disseminating information to the media at disasters and emergency incidents, serves solely as the department's spokesperson. The International Fire Service Training Association's *Public Information Officer* manual,[4] however, broadens the definition to include one who may also provide education to the public, promote public safety, and talk about the services the department provides. As a PIO, the ultimate goal is to enhance the public perception of the department.

Communications

Communications is the process by which people interact and, thereby, influence each other.[5] To communicate is to impart information. However, information is not necessarily knowledge. Information converts most effectively into knowledge when it is needed, useful, and sought. The PIO should keep two points in mind:

- The audience is *always* in the driver's seat in any communications situation. Audience members ultimately decide whether to listen to, accept, reject, or act on any new information.
- No one—including our audience—has much interest in operating totally within the confines of someone else's agenda.[6]

Active listening and using focus groups and community surveys can help with this process of understanding.

Media

A *medium* is defined as the physical environment through which information can be transmitted by controlled variations in that environment. Variations may be ink patterns on paper, electronic patterns in wires or in air, or sound variations in air. Media include radio, television, newspapers, magazines, motion pictures, direct mail, cable television, books, records, tapes,[7] e-mail, and websites. Different media outlets within the community have different advantages and disadvantages in terms of the messages they send (e.g., short versus long, emotionally stripped versus emotionally laden) and the audiences they reach within the community.

Media Relations Terms

The PIO should be familiar with media relations terms. The following definitions clarify several terms commonly used in media relations.

Advance. A news story written before an event and held for later release. Also called an "advancer"[5] or "advisory."

Fact Sheet. An information handout of one or more pages about a person or event provided to assist the media.[4] The name and telephone number of a contact person should be provided at the top of the front page. Each page ends with a completed paragraph and "(more)" typed across the bottom of the page if necessary. The last page ends with "-30-" or number signs (###) typed at the bottom.

News Release. A short, factual description of an event prepared for the media. Although some use the terms *press release* and *news release* interchangeably, be aware that "press" indicates print media, and broadcast or electronic media members are often sensitive about this issue. The first sentence (the "lead") in a news release summarizes what needs to be conveyed, particularly these details: who, what, where, when, why, and how. The release should be written as if you expect it to be printed verbatim or read word for word to the public. The PIO should always provide the source of the information, the headline, the date or dates of the event, and whom to contact for additional information.

The PIO should use the "inverted pyramid" writing style, with the most important facts presented in the beginning paragraphs, followed by facts of lesser significance. An editor can then decide the article's value with only a glance. The news release should meet the following requirements:

- Be doubled-spaced, with 2-inch margins
- Be printed on only one side of the paper on agency letterhead
- Carry the date at the top
- Have "FOR IMMEDIATE RELEASE" inserted when prompt publishing is desired
- Have "FOR RELEASE ON (DATE)" on releases that need to be held until a certain date
- Be limited to one page whenever possible
- Have pages numbered, if more than one page, with "(more)" placed at the bottom of continued pages and "end" or "-30-" or "###" inserted at the bottom of the final page

News agencies usually have a preference for whether they receive news releases online, via fax, or by mail. The PIO should ask if the news organization wants the material sent electronically. For online releases, the PIO should try to limit the length to two screens and should include any related websites.[8]

Several reference books specified at the end of this chapter offer more in-depth advice on how to compose effective news releases for different types of media.

Press Conference. A meeting between members of the press and a newsworthy figure in which statements are made and/or questions are asked.[5]

Media Kit. A portfolio of news releases, pictures, background information, and so on distributed to the press for publicity purposes.[7] Historically, the media kit was called a "press kit" and focused on providing print-ready graphics, logos, and photos for the newspapers or magazines. Today, media kits might include video clips, audio recordings, or digital files as well (Figure 5.4.1).

Public Service Announcements (PSAs). Any announcement for which no charge is made and which promotes programs, activities, or services of federal, state, or local governments or programs, activities, or services of nonprofit organizations and other announcements regarded as serving community interests[9] (Figure 5.4.2). PSAs may be provided to the media as simple written scripts or as fully produced, ready-to-air broadcast pieces.

COMMUNICATION GOALS

Communications Within the Fire Department

Fire department administration should have goals for communication within the fire department, but the public educators, public relations officer, and PIO also have goals defined by external audiences. These goals usually require assistance and participation by people in the fire department beyond the staff dedicated to communications. The goals themselves may be shaped by concerns or information held by others in the department. Therefore, internal fire department communication must be effective in the following areas:

- Employee/employee communication
- Staff/suppression communication
- Fire fighter/fire chief communication

Fire and life safety educators and PIOs need the backing and support of the fire department before proceeding into the community and introducing themselves to the media. They must know which areas the department wishes to highlight, which departmental goals need an explanation, and how the department wishes to address potentially difficult situations. They must also know whether other members are willing to be available for interviews and whether media representatives are welcome to stop by the department.

After devising a plan to work with the media, department members must help prepare campaigns and programs. Fire department administrators need to review news releases prior to dissemination to prepare for reporters' calls.

A good relationship between the educator/PIO and operations personnel is essential. Members of the agency are a tremendous source of story ideas for the media and educational suggestions for the community. Every fire fighter, inspector, and EMS provider has daily opportunities to promote good media relations and further educational efforts to the public. By maintaining a positive working relationship and regular communications, the educator/PIO can include operations personnel in the cooperative effort to inform the community.

FIGURE 5.4.1 NFPA Fire Prevention Week Media Kit

Communications Outside the Fire Department

A second, more obvious, mission includes communicating information to the public, both before an emergency occurs and at the scene of the emergency. Fire service members possess extensive information. Media representatives are interested in the information educators can provide.

One key to successful media relations is identifying the audience. Identifying a very general audience may ease the communications planning but will complicate all other parts of the process. It results in diluted messages and weak delivery and compromises the timing of messages. It also wastes time and materials, forcing fire chiefs, fire and life safety educators, and PIOs to send messages to persons who have neither need for nor interest in them.[7] For example, a smoke alarm installation campaign would be well suited to older neighborhoods where alarms are scarce but not for areas of new growth where smoke alarms are required by code. Therefore, the target audience could be reached by street address or zip code, through homeowner's groups, or during neighborhood events more efficiently than through "mass" media such as regional television or daily newspaper.

The audience should be specifically identified; this greatly increases any program's potential effectiveness. Fire and life safety educators or public information officers who define their audience as "everyone" or "the general public" lack a sufficiently clear understanding of whom they are trying to reach and should not proceed any further until they clarify who their audience is.[6]

Organization Name on Letterhead

[Heading information can be single-spaced.]

For Information Release	Contact:	Name, title
Date of release		Phone number
Story by [optional]		Fax number
		E-mail address

NEWS RELEASE

[Leave about 2 inches before heading.]

Headline

[Double-space body copy.]

DATELINE—*[Insert location for the origin of the release (in capital letters) plus a dash, followed by the first line of the lead.]*

Lead: *[Start with a hard-news lead, particularly on releases for news events or announcements.]*

Body: *[Write tightly. Limit copy to one page if possible, no more than two. If you have two pages, write "more" at the end of the first page and number the pages.]*

Ending: *[As part of the ending, tell where more information is available such as graphics and websites.]*

—30—, —End—, or ###

FIGURE 5.4.2 Format for a Public Service Announcement (Source: *Writing and Reporting News*[8])

Each news station, newspaper, and news outlet claims a particular audience and a particular area as its own. Media outlets within the fire department's service delivery area can provide information on their particular target audiences.

A second key to media success is choosing the right PIO. NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator* (2005 edition), includes job performance requirements for the PIO (Figure 5.4.3).

8.1 General Requirements. The Public Information Officer shall meet the job performance requirements defined in Sections 8.1 and 8.2.

8.1.1 General Requisite Knowledge. Report writing, professional appearance based on situation, media characteristics, news process, organizational policies, methods for informal dissemination, and laws and procedures pertaining to release of information.

8.1.2 General Requisite Skills. Communicate orally and in writing, exhibit professional demeanor, manage interaction with the media, utilize various means of information technology.

8.2 Administration.

8.2.1 Conduct media interviews, given incident information, Public Information Officer (PIO) worksheets, and departmental policies, so that all information compiled on worksheets is disseminated to the media in a timely, accurate, and understandable manner.
- **(A) Requisite Knowledge.** Interview methodology.
- **(B) Requisite Skills.** Demonstrate interviewing skills, collect incident information, complete PIO worksheets.

8.2.2 Establish a media area at an emergency incident, given incident information, departmental policies, and types of media present at incident, so that the area provides for the safety of all media, enables communication with incident commander, and is accessible and clearly visible.
- **(A) Requisite Knowledge.** Incident management system, incident safety considerations, other responding agencies.
- **(B) Requisite Skills.** Manage media area participants, coordinate communication between command and media.

8.2.3 Coordinate dissemination of information to specific nonmedia groups, given departmental policies and methods available for contacting other groups and organizations available to assist, so that the information is communicated to the groups accurately and within the desired time frame.
- **(A) Requisite Knowledge.** Awareness of nonmedia groups.
- **(B) Requisite Skill.** Maintain liaison with community groups.

8.2.4* Write news releases, given incident information, departmental policies, and news release format, so that the news releases are accurate, pertinent, and concise.
- **(A) Requisite Knowledge.** Media requirements for news releases.
- **(B) Requisite Skill.** Compose information in accordance with media source specifications.

8.2.5* Write a media advisory, given information to be disseminated, media advisory format, and departmental policy, so that the media advisories are accurate, pertinent, and concise.
- **(A) Requisite Knowledge.** Media requirements for media advisories.
- **(B) Requisite Skill.** Compose information in accordance with media source specifications.

8.2.6 Disseminate information to the media, given news release or media advisory, characteristics of local media including deadlines, departmental policies, and methods available to reach media, so that, prior to the deadline, the information reaches the media in a form usable to each specific local medium.
- **(A) Requisite Knowledge.** Specific methods for disseminating information to the media.
- **(B) Requisite Skill.** Maintain liaison with media group.

8.2.7 Disseminate information to organizational personnel, given incident or event information, departmental policies, methods available to reach personnel, and time frame for releasing information, so that the information reaches all desired personnel within the time frame and is accurate and concise.
- **(A) Requisite Knowledge.** Specific methods for disseminating information within the organization.
- **(B) Requisite Skills.** Maintain liaison with organizational personnel, operate office information systems.

8.2.8 Coordinate a press conference for local media, given an event or issue, local media characteristics, methods available for reaching media, and departmental policies on press conferences, so that a site is obtained, desired media are notified, a press conference agenda is established, a media information package is produced, and participants in the press conference are notified.
- **(A) Requisite Knowledge.** Event planning requirements.
- **(B) Requisite Skills.** Establish liaison with media, disseminate information, coordinate site selection and use, review media materials.

FIGURE 5.4.3 Job Performance Requirements for Public Information Officer (Source: NFPA 1035, 2005 edition)

Certain traits and skills make some individuals more suited than others to the position of public information officer. First and foremost, an agency should choose a PIO who does *not* view the media as adversaries and is able to function as part of a team with a diverse membership. Furthermore, just as it would be difficult to manage a fire incident without knowledge of fire behavior, a PIO will benefit from knowledge about media behavior. A background in communications, journalism experience, or personal interest in media operations is a valuable characteristic. Knowledge of "new" media and computer skills is essential. Since PIOs are often agency spokespersons in both verbal and written forms, they should have the ability to speak effectively in front of cameras and the public. They should also be able to write in a clear, concise, conversational manner. The U.S. Department of Labor includes those traits in its PIO job description and suggests that a good public relations person should also be one who exhibits creativity, initiative, and good judgment on a regular basis. The best PIO will have strong skills for decision making, problem solving, and research. In terms of personality, the Department of Labor recommends a person who is outgoing, self-confident, understands human psychology, and is enthusiastic about motivating people.

COMMUNITY MEDIA SERVICES

Another key to successful media relations includes understanding the media's various roles. To do so, educators need to identify

local media, establish credibility, and identify key players at each outlet. In an age of global communications—immediate, on-the-spot news coverage and fast-paced marketing—fire service information must be provided faster than ever to be considered timely, but it must still be accurate and delivered calmly and courteously despite the heightened time pressure. To provide information effectively, fire service personnel must understand the workings, the goals, and the changing world of the media: how the media function, how reporters and editors view their jobs, and how the fire service may best utilize ever-changing communication resources.

Identifying Local Media

To create a positive relationship with the media, fire service personnel must take time to understand each media outlet's responsibilities and target audience. The essential issues are (1) What sort of relationship can full-time fire and life safety educators and PIOs develop with local media representatives? and (2) How can they work cooperatively with writers, editors, and broadcasters?[6]

Media relations means more than just contacting the media. It is establishing a rapport and mutual respect and understanding of each other's professions.[10]

It is critical that relationships be established *prior* to emergency incidents or the launch of a new public education campaign. Reporters often emphasize that PIOs need to be available when the media need them—not just when the fire department needs the media. Be sure every reporter or editor on your calling list has your number, too—to contact a spokesperson for the fire department, night or day. Reporters, who live under constant deadline pressure, greatly appreciate a PIO who gets back to them right away. Tim Padmore of the *Vancouver Sun* says, "Return phone calls from reporters immediately. It will make them love you. Do this even if you have nothing to report."[11] A Denver radio reporter explained, "The department is fulfilling the reporter's need to relay information and the public's need for news while building a relationship of trust with both the reporter and the public." When the media call on you, always deliver the "Five F's": be frank, factual, friendly, fast, and fair.[12]

Fire department representatives must meet reporters, editors, photographers, and station managers and get to know them and become familiar with their specific job responsibilities. That may be accomplished simply by scheduling appointments with the various media personnel in the area. Some regions have public information officer organizations that arrange opportunities to network with media members. Efforts may include educating future journalists by setting up a time for the local college journalism classes to visit the station, learn about the fire service, and interview the chief.

Some departments hold half-day media academies to allow journalists an opportunity to interact, learn, and build relationships with fire service personnel. Others such as the City of Phoenix Fire Department provide extensive weeklong training sessions (Figure 5.4.4).

Job turnover occurs regularly in the media business. Reporters and editors move frequently, so getting to know new personnel is a never-ending task. PIOs should keep a contact list and update it regularly. Media sources can be identified in several ways: (1) by checking media directories, (2) by scanning the Yellow Pages of the phone directory, (3) by talking with other public relations personnel in the community, and perhaps most effectively (4) by contacting media outlets directly to obtain contact information.

Certified Fire Journalists

The City of Phoenix Fire Department invited media to train as certified fire journalists. The fire department held an intensive training academy for members of the media, requiring them to commit to a full 40-hour, 5-day week. The class size was limited to a maximum of 12. The benefit to the media was the loan of protective gear and certification, allowing the graduates inside fire lines to photograph and report closer to the action on both fire and medical emergencies.

The training program included fireground operations; fire behavior; fire suppression; search and rescue; hazardous materials; helicopter, trench, and mountain rescue; emergency vehicle driving (a favorite); emergency medical services; flash over/back draft chamber; and stress management. All students took advantage of an optional hour of physical training. The academy ended with the traditional "Barrel Squirt" competition.

FIGURE 5.4.4 Certified Fire Journalists

PIOs should enhance published media lists by including neighborhood ethnic, specialty, trade, and suburban publications. Thorough PIOs or educators should not overlook printed and e-mailed newsletters for homeowner associations, community service groups, and special interest groups they may wish to target. They should collect and learn the names, titles, phone numbers, and fax numbers or e-mail addresses of those in charge.

Figure 5.4.5 shows an example of a media quick-call list that can be used during an emergency. Pertinent names and telephone numbers are readily accessible to the PIO, whose role is the one most likely to be prominent in an emergency. In the event of a crisis, the PIO will benefit greatly from having preprogrammed call lists, e-mail groups, and broadcast fax numbers into whatever devices are available to deliver messages. The PIO should keep copies of the lists at home, in the office, and in the vehicle generally used in emergencies.

Establishing Credibility and Identifying Key Players

Building the fire department's reputation with the media is critical. Reporters, editors, station managers, and producers can quickly form opinions about a person's operating style and credibility. To establish credibility, the PIO must (1) understand what makes news, (2) know what the media need to know, and (3) use imagination and creativity to find new ways to keep the media updated on the fire organization.[13] Reporters need to know the latest trends and opportunities, activities, and resources. The PIO should assure them that accurate and timely facts will be

Medium	Contact Person	Phone #	Fax #	E-mail
Print organizations				
1.				
2.				
3.				
Notes				
Radio				
1.				
2.				
3.				
Notes				
Television				
1.				
2.				
3.				
Notes				

FIGURE 5.4.5 Quick-Call List Form

provided, promises will be kept, and deadlines will be met. Then the PIO should *follow through.* Deadlines are critical in broadcasting and journalism; being late is inexcusable.

Creating an archive system is an efficient way to keep track of much departmental information and to be prepared for grant requests, media inquiries, and city manager details (Figure 5.4.6). Having information at one's fingertips may make the difference between being or not being in the nightly newscast. Educators must identify key players at local television and radio stations and newspapers and must understand what reporters, station managers, and editors do. In turn, local television and radio station personnel will most likely better understand the fire and life safety educator's role in the fire service.

MATCHING THE MEDIUM WITH THE MESSAGE

All communications channels have distinguishing features. Each situation is different, and each requires a fresh look.[5] The nature of the message should be considered when choosing an appropriate medium for delivery.

Broadcast Media

Radio. Radio has been called the medium of the mind;[13] the absence of pictures allows more room for the listeners' imagination to be engaged. Radio is also cost-effective, and most of it is local. Radio appeals to audiences for many reasons. An intimate medium, far less intrusive than television, it demands less concentration than do newspapers. Portable, it can be listened to while doing most anything.

Given the way people listen to radio, programs are built in short segments. The medium, therefore, works best when used to notify, remind, or tell easily remembered, uncomplicated stories. Radio messages must be simple and concise. Radio reporters rely on lively interviews to add color to their stories. Broadcasters suggest stories 20, 30, and 60 seconds in length.

The station manager (general manager) oversees all operations. The program director oversees news and sports. Fire

How to Create an Information Archive System

Here are some general suggestions for setting up an Information Archive System for publicity and proposal purposes. Although publicity and proposal needs may be similar, bear in mind that the information you send should "speak" to the audience in their language and fit the purpose. For instance, there are some items of information that may be required for a grant proposal that would not be appropriate if given to the media.

What to Include

- Articles and editorials that mention your program specifically
- Articles and editorials that relate to or support the work of your program
- Photographs that were taken for articles or brochures
- Video tapes of broadcasts of interviews or those that relate to your program
- Support letters and "nice notes" from various resources
- Copies of website printouts that relate to your program
- Printed listing of websites of importance to program
- Current organizational charts, staff and board lists, operational flow chart
- Documentation of significant fires and statistics for both your site and others of importance
- Resource needs list of items with value, current operating budget, mission statement
- Brochures, flyers, and other program-specific information

How to Store the Information

- You will use an assortment of binders, files, and computer storage for the information.
- Newspaper clippings, support, and photos are best saved in sheet protectors placed in binders. Put original clipping in its own protector and mark on it "original do not remove." Make copies for distribution. BE SURE to record publication name and date of clipping on the original and copies. BE SURE to have name of professional photographer on photo for photo credit.
- Clippings, photos, and other information can be scanned for even more convenient storage.
- Computer storage of files, charts, clippings, and photos should be maintained in a well-organized directory. BE SURE to back up this directory regularly.
- Videotapes and dupes should be well labeled. Master copies should be kept locked from dupes so that they are not given away accidentally.
- Keep copies of brochures in file folders or in a binder separate from regular inventory. This ensures that you always have enough for publicity and proposal needs.

Where to Store the Information

- Keep the information in a central location that is easily accessible to those who need to distribute the information.
- Keep files for grant proposals in a special drawer in a file cabinet for easy access.
- You may want to consider keeping your Information Archive locked if it is housed in an area where you share space.

Maintaining the Information

- Establish procedures and train staff so that everyone is on the same wavelength when it comes to saving and distributing the information.
- Keep information current! You could be disqualified for funding or ruin a media opportunity if information is obviously outdated.
- Have program kids assist you in clipping articles and maintaining photo and clipping files.
- Keep a master inventory of the types and quantity of information you have on hand so that you always have enough copies.
- Keep an inventory sheet in the file to record when an item is removed, who removed it, and what purpose the item was used for.
- Pick a regular time once a month or quarter (minimum) to review the files to ensure that they are in order, stocked, and up-to-date.

FIGURE 5.4.6 Creating an Information Archive System (Source: © Mary Beth Miller, The Right Steps Resource)

service personnel work frequently with the radio news director or, at larger stations, with individual reporters. Note, however, that at smaller stations the station manager could be the owner, program director, and chief engineer. Figure 5.4.7 shows the general organization of a radio station. Individual stations vary considerably, depending on their size and programming. The fire department should identify persons in the offices shown, however, and maintain contact with the news director and individual reporters, as well as the promotion director and public affairs director.

Television. "When nightly television news began in 1948, newscasts were 15 minutes long. In 1963, the first 30 minute newscast was broadcast. Today, CNN, MSNBC and other national and local cable networks broadcast news around the clock. Since then, television has become America's predominant source of news."[14] Just as with radio, understanding the television system helps the fire department receive coverage and may increase its credibility.

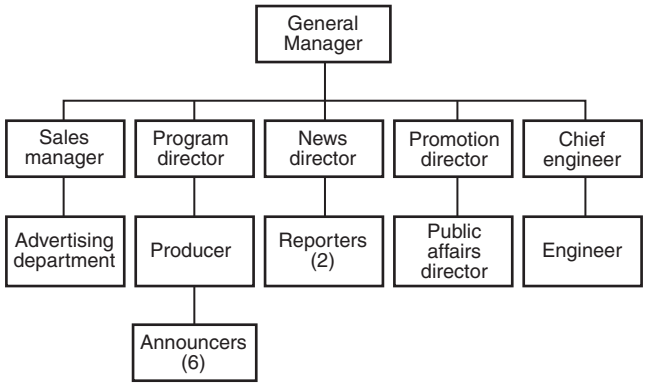

FIGURE 5.4.7 Generalized Organization of a Radio Station

Key contacts in the television news department include the news director, who oversees news and broadcast staff; the assignment editor, who assigns reporters to stories and ensures coverage of major stories and "beats"; the news producer, who determines which reports will air; and reporters who cover the stories. At an emergency scene, often the videographer is the primary contact for the PIO. For information on television public affairs, the PIO should approach the public affairs director or the public service director.

Figure 5.4.8 shows the general organization of a television station. Stations in larger population centers have large staffs, sometimes numbering into the hundreds. Key contacts include the vice president for news, the news director, the assignment editor, and individual reporters, as well as the vice president for public affairs and members of the public affairs staff, such as the public service director and the editorial writer. Before approaching a television news department with a story idea, the PIO should know the station's format and the individual to whom the idea should be pitched.

Television reporters believe the best stories have strong visual elements that grab and hold a viewer's interest. A television reporter is attracted to activities that make exciting or interesting footage and to interview subjects who talk in clear, concise language.[13]

Public Access Television. Public access television is another excellent and inexpensive way to provide community education programs. Approximately 2000 public educational or governmental access channels in the United States are either city supported, member based, or franchised from the cable company. The community cable company can explain how the system operates locally.

Local talk shows also provide an excellent forum for sharing information. Educators should take time to view a segment of a program before agreeing to appear.

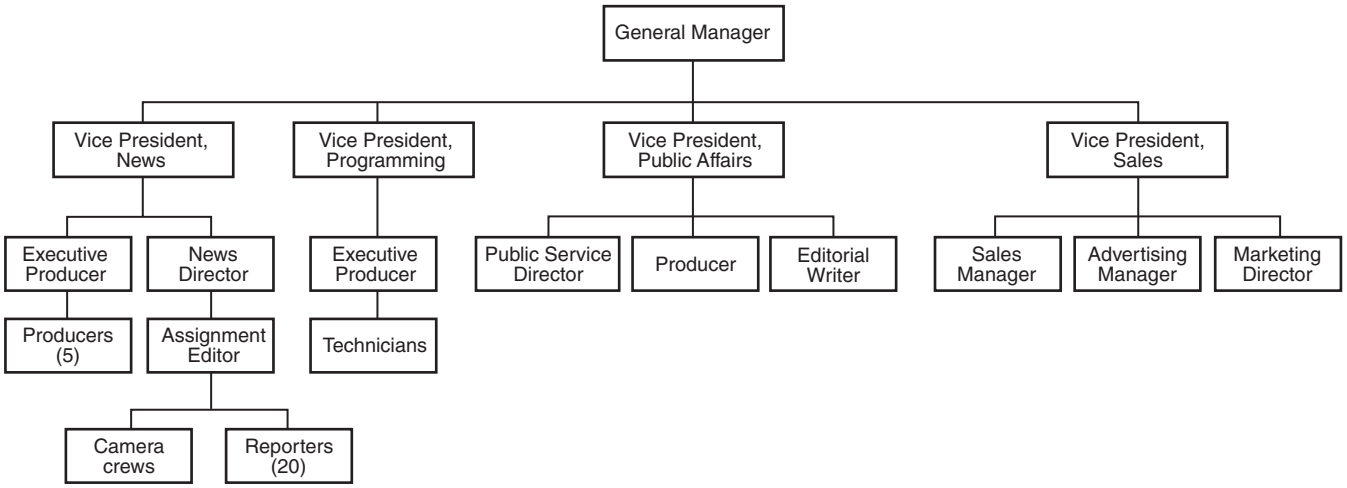

FIGURE 5.4.8 Generalized Organization of a Television Station

Television tends to be underutilized for educational purposes. In the emerging information age, when the trend is to move "from institutional help to self-help," television and videotapes can be the educator's forum to speak with millions of people in the places where they live, study, work, and play. The equipment is in place. The channels are open. The medium is available and waiting for the message.[13]

Print Media

Print journalism includes daily and weekly newspapers, magazines, and wire services. Print media have space for longer items—long enough to have an educational impact, not just awareness—and their readers are receptive to such longer pieces. Never underestimate the ability of publications with small circulation numbers. Although the number of newspapers has declined, the number of newspaper copies read and the average circulation of weekly publications have climbed—and smaller community newspapers are at a near all-time high for readership.[15]

As in broadcast media, understanding the print media hierarchy is helpful. Most newspapers are staffed similarly with the same general titles; however, the work done under those titles varies from paper to paper and city to city. To better understand this, look at the major divisions in a large daily newspaper. There are generally three: (1) the corporate board and executive committee, (2) the business division, and (3) the editorial division.[16]

The first two divisions have little to do with the fire department's publicity and media needs. The editorial and news staffs can provide more assistance. A large daily, for example, the *Washington Post,* contains many sections. For that reason, it is important for the PIO to identify the sections of the paper most likely to use safety information and the person on the staff best suited to help.

When dealing with a medium-sized newspaper, the PIO will likely have contact with the news editor, assistant news editor, features editor, and one or two reporters on the mailing list.

Figures 5.4.9 and 5.4.10 show the organization of weekly newspapers. The small weekly newspaper has an average circulation of 7600 readers. Editors and reporters of a paper this size can all be used as publicity contacts. Efforts should be made, however, to identify precisely the "beats" or areas for which each editor and reporter is responsible. A newspaper or magazine reporter will generally interview sources in person or on the telephone, looking for photographic possibilities or statistics for an eye-catching piece of graphic art.[13]

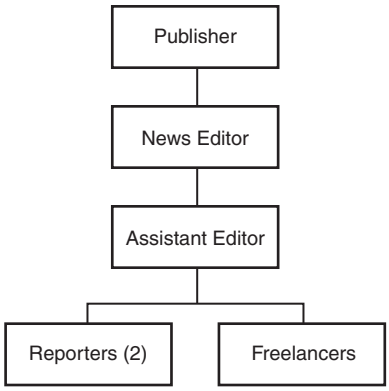

FIGURE 5.4.9 Generalized Editorial Structure of a Small Weekly

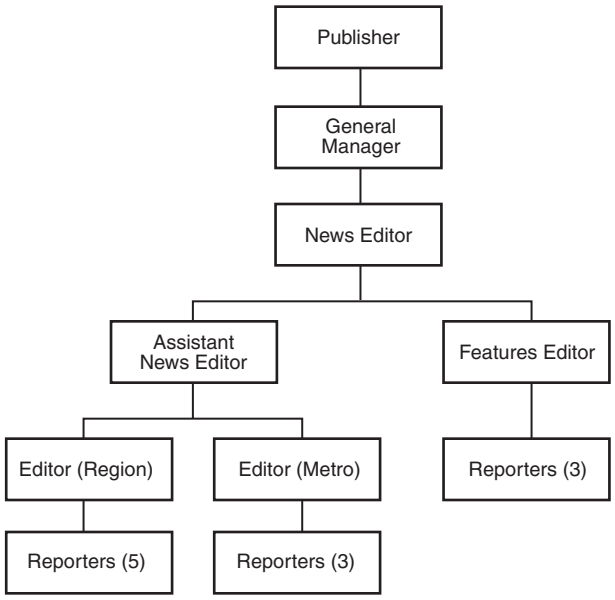

FIGURE 5.4.10 Generalized Editorial Structure of a Medium-Sized Weekly

News Trends, "New" Media

In disseminating information the Internet has taken shape as an established news medium alongside television, radio, and the press. The Internet is also now a full participant in the process of incorporating media into the event itself.[17] The team of Web editors and designers, working in the same building in Atlanta from which the television networks are also administered, clearly want their technology to be "television only better." In response, older electronic and print media are seeking to reaffirm their status within our culture as digital media challenge that status.[17] Immediacy is more important to the media than ever before.

Today's reporters often are multitaskers. The radio station may expect a reporter to place broadcast news stories and information on the station's website. The television station may post news clips from the 6 p.m. broadcast on its Internet site. This concept, called convergence, is the blending of print, audio, and video to create multimedia news products for television, newspapers, and the Internet.

The Internet and the explosion of cable and satellite TV channels are blurring the boundaries between news and information. This does not mean the end of newspapers or TV news programs. It surely means that they will lose influence and dispense less "traditional" news.[18]

Many large and even small communities have media bureaus to aid in the distribution of information and the design of brochures and ads. Others have no such resources. With the advent of personalized Web pages, however, any department may offer information by simply establishing a presence on the Internet. Fire and life safety educators need to understand how technology has transformed the mass communications landscape. PIOs should be prepared for and monitor changes that will affect how the fire department does business with the media.

Public Service Announcements (PSAs)

Public service announcements (PSAs) are prepared for radio and television stations. They are short announcements, generally running between 10 and 60 seconds. Broadcasters are no longer required by law to provide a minimum amount of public service airtime as they once were; however, many stations have a continuing commitment to the community and still use PSAs when possible.

In a small-to-midsized market, the educator may deliver PSAs and reasonably expect that they may be used. In major markets, placing PSAs becomes increasingly difficult. Because competition is strong, many stations stylize their newscasts to stand out on the crowded dial. They simply refuse to run anything their competition might have also received. In most large markets, it is best simply to become a news source. Provide information in a regular and timely fashion.[13]

Another place PSAs may be utilized is on local access cable television or other community access channels. They may also be delivered via the Internet through the fire agency's website.

Understanding What Makes News

News may be defined as any piece of information that will affect your head, heart, or pocketbook.[13] News reports something new—information that is a break from everyday events. Some news is information that people need in order to make sound decisions about their lives.[19] News editors decide if information they receive is indeed newsworthy by checking news values or news pegs. These news pegs are the basis for deciding what makes it to print and what does not.

Michigan State University conducted a survey of journalists, and from their viewpoint, five factors determine an event or an idea's newsworthiness:

- *Consequence.* Is it important? To how many?
- *Interest.* Is the event an unusual, rare, odd, or interesting situation?
- *Timeliness.* Are the events immediate or recent? Is there a new angle or a trend?
- *Prominence.* Does the event involve well-known personalities or institutions?
- *Proximity.* Does the event occur within the circulation or broadcast area?[18]

At least three-fourths of all news stories fall into the first two general categories of consequence and interest.[19]

News is relative. Each day, changing dynamics define "news." These dynamics include how much news occurred that day, the advertising load for the day, the type of audience, and the type of medium.

Hard News. Hard news is "perishable" and must be covered immediately or it becomes stale. Today's news is not necessarily tomorrow's news. Fire and emergency disasters are in the category of hard news. If the facts about an emergency emerge slowly, the story may develop longevity while remaining hard news.

The basic hard news story for the Web, for print, or for broadcast is written in what is called an inverted pyramid style. The most pertinent details appear at the top of the story; less important details are toward the bottom of the story, allowing the editor who is short on space or time to cut the bottom of the story while still preserving the most important information.

Soft News. Many news items do not fit the emergency (hard news) model yet are still newsworthy or educational. "Soft" news is less urgent, more complex, and often has more perspective than hard news. Soft news items that originate as such usually cannot be committed to a specific day; news editors decide how or when to place these items. By identifying an event, writing an appropriate headline, relating how it affects the community, and explaining how this information can help to avoid another incident, an educator can increase the chances of the media using the information.

Although local fire service stories lack the urgency of a hard news event, ample community interest exists to warrant sharing information. Many fire service activities are considered news, and announcements of them may be locally broadcast and printed. Local media and community members may want to know of meetings, rallies, seminars, and open houses. Workshops, National SAFE KIDS Campaign® activities, bicycle safety demonstrations, and checkpoints can raise citizens' safety consciousness.

Public statements on local affairs, awards given and received, fund drives, calls for membership, and the appointment and resignation of organization officials can generate considerable interest. Announcements of the availability of free speakers, films for loan, and the findings of reports and surveys conducted by the department have community news value. There is no limit to the activities that can generate publicity—especially for a well-organized, positively focused, energetic group. The PIO should let the media know—in their terms—how fire service information provides their audiences with useful, creative, positive information. Be cautioned, however: educators should never overstate or distort the significance of an event, inflate serious issues, or be theatrical in an attempt to solicit news coverage.

Interviews

Reporters are experts in reporting; otherwise they are usually generalists. Especially in radio and television, they report on a wide variety of topics from day to day. Most of them are bright and dedicated workers, but even the best of them may be relatively unknowledgeable about your particular subject or issue.[20] Be ready to provide some basic education about your topic and do not assume reporters will know what you are talking about.

Providing Firsthand Information. Be aware that although most reporters are happy to receive *information* from the PIO, they would greatly prefer to get the *interview* with someone on the front line. To bring their audience closer to the action and to provide the energy level needed to maintain viewer interest, stories should feature firsthand accounts as often as possible (Fig 5.4.11). This is one reason fire departments should consider training all fire fighters and prevention personnel in basic media relations—so they will be more confident and prepared when they are the ones being asked to step in front of the camera. This is also one reason all departments should have a media relations policy in place and familiarize personnel with proper procedures for on-duty media inquiries.

For the educator/PIO and for all whom the media may approach for comment, here are some guidelines.

Interview Tips. An interview is a formal exchange of information. The PIO should know as much as possible about the reporter(s), audience(s), and issue(s) before providing an interview. The PIO must be aware that the message goes to all readers, listeners, and viewers to whom the interviewing reporter provides information.

FIGURE 5.4.11 Fire Fighter Interview at Fire Scene

Communicating clearly and credibly and defining the "headlines" that the audience should see or hear are essential in an effective interview. When being interviewed keep the following points in mind:

- *Be prepared.* Review all pertinent information before the interview. Anticipate and prepare for questions the interviewer is likely to ask. Have reference notes. When possible, practice your answers out loud.
- *Be professional.* Dress appropriately. Avoid unnecessary movements and gesture calmly. Move more slowly than you normally would. Avoid chewing gum, smoking, or eating when providing reporters with information. Be confident. Look the reporter in the eye. During an interview, resist the temptation to look straight into the camera or at yourself on the TV monitor.
- *Be newsworthy, factual, and correct.* Double-check information before releasing it to the media.
- *Plan points to be made.* Present two or three main points as quotable single-sentence summaries. Begin the interview by stating the most important points or conclusions.
- *Be understood.* Use common language; avoid fire fighter jargon and technical terms. When technical terms must be used, explain them.
- *Assume that all is "on the record."* Anything said can and likely will be used. Assume that the camera is always on—including before and after the interview. And remember, modern lens microphones can collect audio and video from *very* far away.
- *Never say "no comment."* It invites speculation. Rather, say "I don't have enough information to properly answer that question."
- *Avoid "traps."* If the reporter's question contains objectionable words, don't repeat them in any answer, even to refute them. If a reporter poses a hostile or inaccurate remark, respond by saying, "First let me correct a misperception that was part of your question."
- *Maintain composure.* Some interviewers try to provoke angry responses to get additional information. Always remain calm and courteous.
- *Be prepared to restate your policy or position.* Do not attempt to answer hypothetical questions. Refocus the interview on the issue by saying, "Here's the situation we are focusing on."
- *Don't be afraid to say, "I don't know."* If the answer to a question is not known, say so. Follow with, "As soon as I get the information, I'll get right back to you." Make note of the question and get the answer.
- *Stay on track.* Don't digress from the subject. Lead a reporter who starts to wander back to the subject at hand.
- *Be accountable.* Never assign blame or criticize.
- *Be available.* Offer to answer any follow-up questions a reporter may have and help clarify problems that may arise as the story is being written or edited.
- *Be honest.* Never lie or "stretch the truth." Such tactics rarely work and, when discovered, can have severe consequences.
- *Be patient and willing to teach.* Reporters have different professional knowledge and backgrounds. They need education on some fire and life safety issues.

- *Stand up and be counted.* Keep records of media calls. See how and if department comments were used. If a serious misinterpretation becomes apparent, call the reporter or editor and ask for a correction. If reporters used comments in an appropriate and effective way, tell them so.

Another consideration for the PIO on an emergency scene is to keep the media out of harm's way and prevent them from interfering with operations, while still providing them their constitutional rights to public property access and freedom of speech. Therefore, the PIO should establish a plan with commanders in advance on how and where the media should be accommodated.

PUBLICITY CAMPAIGNS

Practical Publicity

Fire and life safety educators must carefully plan how to spend limited money and time. One approach is practical publicity. *Practical publicity* is used here to mean a program with a substantial public relations front end that is designed to set up a public education campaign with broad reach. First, educators get the public's attention. Second, they build interest and trust. Finally, they teach. Distributing Frisbees shaped like smoke alarms and imprinted with "Test Your Detector" helps provide departmental recognition. More complex examples might include an open house or a mass CPR training.

Three-Phase Publicity Framework

There is no single "best" way to run a publicity campaign. Communities have individual traits and characteristics. Groups within communities have specific needs and interests. However, a three-phase publicity framework from which to build exists; it can also be used as a benchmark for evaluation.[16]

Kick-Off Phase. This "name recognition" phase explains who the group is—that is, the education division of the fire department, its foundation and origin, and its plans for the future. Billboards, lawn signs, placards, news releases, flyers, and rallies support this phase.

Expansion/Issue-Oriented Phase. This phase comes after the public knows what the public education group in the fire department does and believes it to be credible. At this stage, the goal is to acquaint citizens with issues important to the fire department. The key is to emphasize issues, educate, and inform. Providing accurate information maintains credibility. Use seminars and workshops, radio and television editorials, newsletters, PSAs, and news releases. Meet the people face-to-face.[16] Note that this phase is still a public relations activity, but by moving from a broad department focus to an issues focus, it sets the stage for education.

Culmination Phase. After establishing an identity, informing citizens, and focusing on important issues, the fire department can educate.[16]

Use local as well as national statistics and data to add credence to a specific campaign, for example, statistics concerning increased use of sprinkler systems within new residential construction. Begin to work more closely with like-minded agencies such as the National SAFE KIDS campaign, local police department, park district, water conservation specialists, and cooperative extension agencies. The more groups there are sending a similar message, the more likely "airtime" will come for all involved.

Educators could investigate hiring (or soliciting a donation of effort from) a public relations firm if there is a specific issue that needs to be addressed. They could call on the already informed public if a popular issue, for example, passing fireworks reform legislation, arises. Phone "trees" (in which one group of people calls a second group, the second group calls a third group, etc.), newsletters, direct mailings, letters to the editor, letters to politicians, press releases, news releases, citizen editorials, and media coverage are effective after publicity efforts have made issues newsworthy. The effect is an amplification of the group's plea—a far greater noise than the group could ever make alone.[16]

Other options for the public relations phase include alternative outlets and campaign strategies, such as the following:

- Exhibits and displays
- Newsletters
- Poster contests
- Attention-grabbing methods (e.g., hot-air balloons)
- Instructional slide shows or videos
- Signs, billboards, and bumper stickers
- Safety trailers
- Flyers, brochures, grocery bags, and placemat announcements

EMERGENCY SCENE PUBLIC INFORMATION

Role of the PIO

Often the fire department media liaison or public information officer who conveys information to reporters in times of emergency is the fire and life safety educator. The PIO is responsible for gathering, preparing, and providing information to the media. The PIO helps convey the needed story safely, quickly, and efficiently and serves as the contact between the incident commander and the media. The PIO's goal is to help the media present an accurate, understandable, fact-filled account of the emergency and to ensure that reporters are safe and not interfering with those who are attempting to secure the scene.

The emergency scene is also a place where extremely effective public education can be accomplished. There is no more opportune moment to convince the community of a safety message than when that message is illustrated by an immediate, compelling example close to home. The PIO has the opportunity not only to provide accurate, timely information but also to impart knowledge in a learning environment like few classrooms—an environment where the audience is intensely interested.

Public information officers link the fire service and the community. The PIO, acting in a professional capacity, assembles as much timely and accurate information as possible and informs

reporters so they, in turn, can provide it to their viewers, listeners, and readers. The job of PIO is a "role rather than a rank."[21]

On an emergency scene or during any other activity that involves the Incident Command System, it is important to remember that the public information officer position is a component of the command staff, reporting directly to the incident commander. Every PIO should be trained in the National Incident Management System and follow the procedural and functional guidelines established for that position.

The professional PIO does not attempt to stand in the limelight or upstage a fire officer. After gathering information, the PIO streamlines the process of providing reporters with needed information as fire fighters continue their work. Some excellent resources that should be in the library of every PIO include the following:

- Birr, Tim, *Public and Media Relations for the Fire Service,* Fire Engineering Books and Videos, PennWell Publishing Company, Saddle Brook, NJ, 1999, 156 pp.
- Charlesworth, Michelle, *Public Information Officer,* International Fire Service Training Association, Fire Protection Publications, Oklahoma State University, 1999, 104 pp. and disc with forms.
- NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator.*
- Brown, Leo M., *Media Relations for Public Safety Professionals,* Jones & Bartlett Publishers, Sudbury, MA, Feb. 2004, 180 pp.
- Schaper, Frank, and Greg Gerber, *Public Information Officer, Winning with the Media,* 1st ed., Thomson Delmar Learning, Florence, KY, 2007.

As in every other aspect of the fire and life safety educator's job, the PIO will be more efficient and effective if planning and thought have been put into practice ahead of time, before the inevitable emergency arises.

Creating and Following Standard Operating Procedures (SOPs)

Creating standard operating procedures (SOPs) expedites work with news media at an emergency scene or at any other time or place reporters might be contacted. SOPs establish (1) who in the department may speak with the media on behalf of the agency and (2) how the fire chief wants media matters handled. Figure 5.4.12 is an example of specifics that may be included in a media policy.

The PIO provides the bridge between the fire department and the community served. Often the community does not understand the fire department's day-to-day operations and activities. The community may not know how the modern fire service operates or the various tasks fire personnel perform despite impressive efforts in evidence. In most jurisdictions, the percentage of citizens who call the fire department for emergency assistance is low. Although the fire service conducts many public education and community service activities, a high percentage of the community learns of these activities only through the media. Providing clear, concise, and timely information to the media benefits everyone.[22]

PIO Tools

When facing reporters at an emergency scene, the PIO needs essential tools:

- A radio. Having a radio enables the PIO to communicate with fire command and other suppression personnel.
- Two pencils, a notepad, and a small tape recorder. Addresses, names of persons injured, telephone numbers, and so on can easily be forgotten in the rush of a large emergency. The PIO should write them down. If the PIO's style is to include every detail, the conversation should be taped. Taping conversations allows self-critiquing later. If inaccurate reporting becomes a problem, the tape recorder may show reporters that the PIO expects them to provide correct information.
- A cellular telephone for updating the news media and communicating with others involved in the situation. Wireless Internet access and the ability to upload news releases and/or photos from the scene are valuable if available.
- A media quick-call list. The quick-call list provides up-to-date phone numbers and is a short version of the media address and phone list. In an escalating emergency, the PIO must be prepared to notify media sources or update them as the situation changes. The list includes essential local broadcast and print media news reporters and personnel (as seen earlier in Figure 5.4.5).
- Basic question list. The list should contain a media work sheet, including basic interview tips, fire information, EMS information, hazmat information, and rescue information (Figure 5.4.13).

EXPLORING LEGAL ISSUES

The fire department must be aware of various legal terms and issues. Copyright laws, privacy acts, broadcast regulations, and the federal Freedom of Information Act (FOIA) should be understood and addressed. PIOs should develop a working relationship with the department's legal counsel.

Copyrights

Copyright questions arise frequently. Downloading a photo or document from the Internet without permission is a violation of copyright laws. U.S. copyright laws protect everything written the minute the information is offered in "fixed form," which includes online or print information.

Enacted in 1997, the No Electronic Theft Act provides penalties of up to $500,000 and five years in jail for copying software or online materials even if no profit is made. The Digital Millennium Copyright Act of 1998 provides further penalties of up to $1 million for copying online materials for profit.[8] The fire department user must receive permission from the author or publisher. Copyright laws dictate that copyright owners have the exclusive right to reproduce, distribute, and use original works of expression fixed in a tangible medium.

NFPA's Sparky® is an example of a registered trademark. The National Fire Protection Association's legal office must grant permission before a fire department may use Sparky for any promotion, activity, or brochure.

Public Information Officer Guidelines

The following are examples of details that may be included in operating procedures for PIO. Some are based on actual policies of agencies across the country. Guidelines for each agency may vary depending on policies and organizational structure.

DEFINITION: The Public Information Officer (PIO) is a member of the Command Staff, providing timely information to the media regarding emergency incidents and department activities. Any employee may be assigned to this position under the direction of an Incident Commander. The PIO will follow the responsibilities and procedures outlined by the National Incident Management System.

SCOPE: The PIO position will be established for any incident involving multiple alarms, a death or serious injury, Special Operations (Dive Team, hazmat, etc.), events of community interest, and any other activity for which Command determines a PIO is appropriate.

PURPOSE: To specify the procedure for release of fire department information to the news media and the public.

POLICY: It is our policy to maintain a positive and cooperative relationship with the public and the news media, and to provide in a timely manner all information deemed open for public access by law. Media inquiries will receive a response from a designated PIO at the earliest possible time. Every employee is expected to respond to the media and members of the public in a helpful, concerned, and respectful manner.

PROCEDURE: Command is responsible for the release of information to the media. The Incident Commander or Battalion Chief may designate an individual or group to perform this function. Other employees who receive media inquiries on an emergency scene or during day-to-day operations should refer those questions directly to Command Staff or to the on-call PIO. Employees may freely provide the on-call PIO pager number to the media.

On an emergency scene, the PIO will report to the Incident Commander. As soon as possible, the PIO will begin gathering information regarding the incident. The agency PIO work sheet may be used as a guide. The PIO will communicate with all media representatives on scene to establish safety and operational boundaries and to designate a time and location for information updates or briefings if needed. The PIO is responsible for advising the media of the need for protective equipment when necessary.

NO information is to be released regarding medical patient names or personal medical information, the identities of deceased or seriously injured victims (prior to notification of family), or any issue under investigation. NEVER broadcast this protected information over fireground radio channels.

The PIO will obtain video and still photography records of the incident, or will designate an incident photographer, and is responsible for storage and release of those images.

FIGURE 5.4.12 Sample Media Policy

Copyright statutes, revised in 1976, take into account developments in photocopiers, videotapes, motion pictures, broadcasting, cable television, and other technologies developed after the act's adoption in 1909.

To claim a copyright, follow this procedure:

- Place a copyright notice on the work. This information, written in the upper-right-hand corner of the work, claims the copyright.
- Complete a copyright form and pay the designated fee (optional, see below).
- Register the work with the copyright office in Washington, DC.

Registration is not necessary for a valid copyright, but if a suit is brought, the work must be registered. Generally, copyrights last the author's lifetime plus 50 years. For copyright information, contact the copyright office at this address:

Copyright Office
Information and Publications Section, LM-455
Library of Congress
Washington, DC 20559
http://www.copyright.gov

Further, when using copyrighted material, include the following information:

FIGURE 5.4.13 Phoenix Fire Department Public Affairs Media Guide (Source: Phoenix Fire Department, courtesy of Fire Chief Bob Khan)

- The word "copyright," the abbreviation "Copr.," or the symbol "©"
- The name of the owner of the copyright
- The year of publication

Publications available include the following:

- Catalogue of materials published
- Highlights of new copyright law (#R99)
- Copyright basics (#R1)
- Trademarks (#R13)

Freedom of Information Act

What rules pertain when a citizen asks for access to a private meeting? When must meeting transcripts be released? *Freedom of information* is defined as the "access to government documents that do not compromise national security or violate privacy rights of individuals."[7] "Sunshine" laws address media access to public meeting records. Varying from state to state, these laws generally cover these topics:

- The amount of notice required to hold a public meeting
- Whether or not a meeting is open to the public
- Requirements on meeting minutes or transcripts
- Executive session rules

The federal Freedom of Information Act, a 1966 statute, requires all federal executive and administrative agencies to furnish information to the public when it is requested, unless that information is in one of nine protected categories. The scope of the act was expanded in 1974.[5] A model for many state laws, it is designed to make government information available to the public. The government has 10 days to respond to a request and 20 days to respond to an appeal if records are denied.[19]

Libel and slander laws protect the reputation of a person or institution. Libel is written defamation. It is essentially a false or defamatory attack on a person's reputation or character in written form. Broadcast defamation is libel because there usually is a written script. Oral or spoken defamation is slander.[19] The fire department must be constantly watchful for photographs and statements that might defame or invade another's privacy.

HIPAA

The federal Health Information Portability and Accountability Act (HIPAA) restricts the release of personal medical information, including information that would identify the patient in certain emergency medical situations. Because the PIO is responsible for information release at the scene of an incident where patients are involved, familiarity with the specifics of these restrictions is crucial. Fire agencies may need to seek legal counsel for specific answers to their questions regarding HIPAA policies. Generally, HIPAA restricts releasing the name, address, phone number, specific injuries, or known medical history (such as heart attack or diabetes)[1] of a patient. Some nonidentifying information is releasable. Fire agencies that provide medical treatment and/or transport should have HIPAA procedures in place. For more specific details, visit the HIPAA website at http://www.hhs.gov/ocr/hipaa.

FUTURE COMMUNICATION TECHNOLOGIES AND PUBLIC EDUCATION

Today's PIOs and fire and life safety educators have the world at their fingertips: databases, e-mail, educator groups, and millions of websites. With an Internet connection and account and a computer, they may pick the brains of the best and the brightest fire and life safety educators across the globe. The Internet is filled with pages containing hundreds of valuable links.

Indeed, advances in computer technology have strengthened the relationship between communications and education. What once seemed impossible is today commonplace. Fire service personnel need to be trained and updated frequently on not only the advances in suppression technologies but also developments in computer technologies.

Self-education via online classes and CD-ROM is common today. Personalized educational programs may be found on many departmental websites. Pull-down menus allow people to create personal home escape plans, hunts for hazards, or search for specific injury or prevention information.

The success of the Internet and online magazines such as http://www.firehouse.com have made information gathering decidedly more friendly than in the past. Up-to-the-minute updates may be found with a click of the mouse. More information and data than a mind can comprehend may be located with that same mouse.

Computing, publishing, entertainment, communications, and consumer electronic devices all use and produce digital data. In this uncharted information environment users may copy, move, and interchange all types of data. This leads to one caution: Everything on the Internet may appear to be official. It is easy to assume it is fact. Often, however, information posted on the Web is incorrect. PIOs should always double-check facts with another source and develop their own tough standards for which sources are reliably accurate and credible.

Educating with computer-based media offers numerous possibilities, for example, one-to-one teaching, continuing education, and professional development for fire and life safety educators. Many North American universities use computer-based communication technologies. Among the technological possibilities are audioconferencing, satellite videoconferencing, and computer-based interactive exchanges. Portions of these educational resources are available, at minimal cost, to fire and life safety educators through cooperative extension offices that operate through partnerships with federal and state authorities and through community colleges and other communications facilities.

The challenges and opportunities for the PIO and fire and life safety educator are limited only to their creativity, energy, and the technologies available to them. Amidst the explosive expansion of these opportunities, however, the basic and fundamental steps of researching, face-to-face communications, and understanding how the "other side" thinks will never go out of style.

EVALUATING EFFORTS

In any process, the final stage is evaluation. To assess success, PIOs should compare the results of a program with its original objectives. Although it is not this chapter's purpose to discuss evaluation in depth, PIOs should understand the importance of evaluation and feedback. For example, if the percentage of the public that is aware of bike safety as an issue increases by half after the fire and life safety educator provides three public service announcements and appears on local community calendar talk shows, the value of the effort is evident. If the number of bike-related injuries decreases by half after the educator conducts a school program to teach bike safety, the value is evident. If most of the public is aware of a recent large fire, can describe its points accurately, and can report that they trust the information provided by the fire department, then PIO efforts have been successful by those measures.

Evaluations may be conducted either throughout the program or after completion of the program. If the objectives are met, pertinent information for future planning becomes available. If the objectives are only partially met, reasons for failure can be explored.

See also Section 5, Chapter 8, "Evaluation Techniques for Fire and Life Safety Education."

SUMMARY

Honest, forthright communications, data collection, and evaluation are at the heart of any outstanding public relations/public information campaign. Wise administrators recognize the value of training fire personnel in communication skills and marketing techniques. The positive dividends reaped through targeting

identified audiences allow citizens to be trained appropriately and money to be well spent. Emphasis and training on public information services enhance the positive relationship fire departments worldwide value and enjoy with the citizens they serve.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the media's role in fire and life safety education discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following document.)*

NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*

Chapter 5

Reaching High-Risk Groups

Sharon Gamache

Chapter Contents

Preschool Children
Older Adults
Low-Income Audiences
First Nations Populations
Fire Safety for People with Disabilities
Home Security and Fire Safety
National Programs in the United States
International Programs

Key Terms

fire risk, *Learn Not to Burn® Curriculum,* occupant characteristics, public fire and life safety education, *Remembering When: A Fire and Fall Prevention Program for Older Adults™, Risk Watch®*

Certain groups are disproportionately affected by fires. Even though civilian fire deaths in the United States have dropped substantially over the past century and fairly steadily over the past several decades (e.g., from 7395 in 1977 to 3900 in 2004), and even though progress in fire safety has been made across the board, the same groups continue to incur disproportionate rates of fire deaths and deaths from other unintentional injuries.[1]

In particular, preschool children, older adults, and people who are disadvantaged (by income or education) are at highest risk of fire deaths in the United States. Children under age 5 are 74 percent more likely to die in a home fire than the average person. Adults 65 and older are roughly twice as likely to die in a fire and adults 75 and older have nearly three times the risk. The two high-risk groups—ages 5 and under and ages 65 and over—have been increasing their domination of home fire deaths. Together they accounted for 38.9 percent of home fire deaths in 1980 and for 53 percent in 2002.[2]

Statistics show that high fire death rates are often associated with key measures of socioeconomic disadvantage, starting with poverty and the lack of a high school education among adults.[3] For fire departments to be effective in continuing to reduce deaths, injuries, and fires in their communities, they will need to be sure that their programs at least include and at best focus on those at greatest risk.

See also Section 4, Chapter 5, "Strategies for Occupant Evacuation During Emergencies"; Section 5, Chapter 1, "Principles and Techniques of Fire and Life Safety Education"; and Section 5, Chapter 2, "Fire and Life Safety Education Messages."

PRESCHOOL CHILDREN

Children age 5 and younger have a fire death rate nearly twice the national average based on 1999–2002 yearly averages. Each year in the United States until 1995, 700 children age 5 and under had died in fires in the home each year. Beginning in 1995, that death toll has dropped sharply and was just under 270 in 2002. Representing 12 percent of the home fire deaths from 1999 to 2002, this age group still had a fire risk nearly twice the national average.[2] Preschool-age children are less able than older children to control their environments, are more dependent on adults, and are less likely to receive or understand information about fire safety.

Characteristics of This Group

The leading cause of fire deaths of preschool children is children playing with fire, usually matches or lighters. From 1994 to 1998, child-playing fires accounted for 36 percent of home fire deaths of children age 4 or younger, whereas by 1999 to 2002, child-playing fires, though still the leading cause, accounted for only 26 percent of home fire deaths in this age group. Part of this decline reflected a real decline linked to the child-resistant lighter standards that became effective in 1994. Part of the decline reflected changes in incident coding and may not reflect real changes in risk. NFPA's best estimate for 2002 was that 13,900 structure fires were started by children playing with fire. These fires resulted in 210 civilian deaths, 1250 civilian injuries, and $339 million

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in direct property damage. Preschool children accounted for the majority (55%) of child-playing home fire deaths in 1999 to 2002, and the fatally injured children were often younger siblings or playmates of the firesetters rather than the firesetters themselves.[4]

How Preschool Children Learn. An instructive video, *From Theories to Play: Providing a "Creative" Developmentally Supportive Environment for Young Children,*[5] reviews characteristics of play in an environment for young children. This video can help fire safety instructors with developing or using appropriate safety activities with young children.

The following are some general principles discussed in the video:

1. Children need a variety of play environments. They need outdoor and indoor play and a variety of play materials that support sensory/motor, dramatic, and constructive play. Construction materials can range from fluid, such as sand and paints, to more complex materials, such as puzzles or interlocking building blocks. The *Learn Not to Burn® Preschool Program,*[6] created by NFPA's Learn Not to Burn Foundation (now the NFPA Center for High-Risk Outreach), adopted this general developmental insight into one of its basic approaches when teaching young children: "Don't scare children. Teach them what to do." Young children learn in several ways. Lessons to preschoolers should use a variety of activities to get behaviors across. Children learn best when they can use all the senses—through what they see, hear, smell, taste, and touch, as well as how they move.

2. Activities should provide opportunities for children to interact with adults and other children in a language-rich environment. Children should be provided experiences with music, puppets, stories, and dramatic play to enhance language development.

3. Children like to create or recreate dramatic activities in the miniature, using items, such as little characters, building blocks, puppets, and so on, or with activities, such as acting out family scenes with costumes and props.

4. Children at this age have difficulty waiting for turns. Games with rules are inappropriate at this time, as children of this age do not understand the concepts of winning and losing.

In a Federal Emergency Management Agency (FEMA) investigation on how children respond to disasters, Children's Television Workshop (CTW) found that young children ages 3 and 4 look to adults to help interpret their world, whereas children ages 5 through 7 begin to recognize cause and effect in relation to the disaster. This natural dependence on adults is also an opportunity to introduce new adults, such as fire fighters, into the child's environment, allowing those new adults to assist in interpretation of fire safety, their special area of expertise.[7]

As noted in Section 5, Chapter 1, "Principles and Techniques of Fire and Life Safety Education," frightening images do not motivate effective learning of fire safety behaviors in any age group. Such images typically inspire efforts to flee the images, either physically or otherwise, for example, by looking away. The *Learn Not to Burn Preschool Program* teaches fire safety awareness and skills in a nonthreatening way. Caregivers do not scare children by showing them burned toys or pictures of burned people.

Lessons need to be repeated for reinforcement. Participatory activities do not seem so repetitive even when they are. Embedding lessons in songs can also make repetition more acceptable and even enjoyable. The *Learn Not to Burn Preschool Program*'s English-language version makes extensive use of songs as aids to learning behaviors.

Legislation and Engineering

Since children playing with fire represents the single greatest source of their above-average fire risk, it is appropriate that legislative and engineering strategies focus on this hazard.

In 1994 the U.S. Consumer Product Safety Commission (CPSC) enacted legislation making it a requirement that all disposable and some novelty cigarette lighters be child resistant. This legislation specified that 85 percent of children age 2½ years to 4½ years tested must not be able to activate these lighters. Canada enacted its own legislation in 1995, making child-resistant lighters mandatory.

The U.S. standard has resulted in a reduction of fires and property loss and, more importantly, of deaths and injuries of children age 5 and younger playing with matches and lighters. CPSC estimated that 70 deaths occurred in residential structure fires caused by children younger than age 5 playing with cigarette lighters in 1998. In the absence of the standard, there would have been an estimated 200 deaths. CPSC reports that the difference of 130 deaths represents deaths prevented during 1998 because of the standard.[8]

An estimated 480 injuries occurred in residential structure fires caused by children younger than age 5 playing with cigarette lighters in 1998. In the absence of the standard, CPSC estimates that 1430 injuries would have occurred. Again, the difference of 950 represents injuries prevented during 1998 that CPSC attributes to the standard.[8]

However, a significant number of fires that kill young children are begun by matches.[4] It is, therefore, extremely important to get the message to adults and caretakers to keep all lighters and matches away from children.

Reaching Young Children Through Others

Because preschool children need and rely on adults to learn, a strategy of reaching these high-risk children through adults is essential. Adults are the ones who control the environment and are responsible for safety measures to be taken in the house, such as safely storing matches and lighters, safely using candles, and ensuring that there are adequate smoke alarms.

An adult component must be included in a comprehensive safety education program for preschoolers. The NFPA *Learn Not to Burn Preschool Program* has the following three letters for educators to send home to parents or caregivers at different times during the course that teach eight key behaviors to young children:

1. The introductory letter tells parents what behaviors the children are learning in school but reminds parents that, although

children are learning these fire safety behaviors, fire safety is still the parents' responsibility. It emphasizes four points for parents; for example, keep matches and lighters out of the reach of children, preferably in a locked cabinet.

2. A second letter is sent home when the match and lighter lesson is taught. This letter emphasizes that children must be taught to stay away from matches and lighters and to tell a grown-up when they see matches and lighters. It then repeats the information to parents to keep matches and lighters away from children.

3. The third letter describes how to design and practice a fire escape plan and emphasizes the importance of having smoke alarms in the home.

Drawings or art activities from preschool programs can also be sent home to parents or caregivers to reinforce understanding of what the children are learning in school. Some parents may not always read information sent home, but some of these are more likely to respond to a video shown at parent meetings or at home.

The NFPA Center for High-Risk Outreach produced *A Lighter Is Not a Toy*™ video[9] for the parents of young children. The 8 minute video depicts several scenes of preschool children interacting with their parents or grandparents. It suggests actions that can prevent serious burns and deaths from fires started by children who have access to matches and lighters.

Programs to reach preschool children through their parents or other caregivers can be targeted through child care centers; public housing developments; foster care training; Women, Infants, and Children's (WIC) programs; parenting skill programs; and babysitting classes. Reaching young children in child care settings directly is probably the easiest way to deliver a program. There are child care centers, preschools, and prekindergarten programs in public school systems.

Since day care providers are not necessarily linked under one organization, it is often necessary to contact several groups before identifying all day care providers in a community. Many states have programs. These organizations often provide training and are a good resource when working at the state level. In Canada, the Ministry of Social Services and various provincial child care associations help coordinate activities.

Teaching Young Children

Fire safety materials must be appropriate for preschoolers. This means that they cannot be simply adapted from materials used to teach children in elementary schools.

The developmental limitations of young children mean that fire safety must be taught in an environment providing interaction with adults. This is necessary because, in the absence of a strong adult role, lessons transmitted by television, for example, are likely to be misunderstood, perhaps dangerously so, or simply not understood at all. This conclusion has been reached repeatedly in the history of design of fire safety education for children.

In 1979 the U.S. Fire Administration (USFA) asked Children's Television Workshop (CTW) to explore ways of including burn prevention and fire safety messages in its *Sesame Street*® programming. Initial research recommended against this course of action.[10]

> Because of the one-way nature of viewing, television presents a difficult challenge especially with regard to such serious and important topics. For example, we need to be concerned that if a child viewed (the program) alone, questions could not be answered or clarified by an adult and a dangerous misunderstanding could occur.[10]

Resulting from this initial research was the USFA-funded *Sesame Street* fire safety curriculum, one of the first available fire safety programs for preschool children.

In 1990 the Learn Not to Burn Foundation concluded that public service advertising to young children with messages on matches and lighters would most likely be ineffective.[11] The foundation tested 50 children in day care settings with a video prototype and found that the youngest children (3 and 4 years old) did not understand the safety message well enough to risk putting the public service announcement on television; that is, mere exposure to the message and pictures of matches and lighters without comprehension could have the opposite effect on children, possibly causing them to have more of an interest in playing with or exploring matches and lighters.

Because they do not understand "if-then" situations, young children need to act out different scenarios. For example, if preschoolers only learn the behavior "stop, drop, and roll," they are likely to do that behavior for every fire situation (e.g., when there is fire and smoke in the room, if they burn themselves, etc.).

For many years fire safety programs for preschoolers have taught basically the same behaviors. In order to examine whether these behaviors are still appropriate and which behaviors are most effectively taught at ages 3, 4, or 5, Oklahoma State University worked on a project funded by a Fire Act grant.[12] The project was based on two assumptions: "(a) children can only be expected to understand and use fire safety messages when they have achieved the necessary physical, cognitive, and socioemotional milestones; and (b) the better educators understand the capabilities of children, the greater the likelihood a fire safety program has at succeeding."[12]

The project report provided an introduction to developmentally appropriate practice (DAP) and a checklist of developmentally appropriate expectations (CDAE) applied to the eight fire safety messages used by popular fire safety programs for preschoolers. The study used ages 3, 4, and 5 as milestones of development and described those milestones in three realms: physical (gross and fine motor) skills, cognitive skills, and socioemotional skills. The following are some points made in the analysis of "cool a burn" behavior. Under fine motor developmental education strategies, 3-year-olds can complete the "cool a burn" message physically by turning on the water but they cannot cognitively understand it. This is a difficult message for 3- and 4-year-olds because it is a three-part directive: go to a sink, turn on cold water, and put burn under cold water. Five-year-olds have the fine motor skills to turn on cold water. They have a basic grasp of right and left but they mix them up at times.

The authors hope that their analysis of this behavior and others will help early childhood and fire safety educators adapt and implement existing programs or develop new programs to reduce fire and burn injury in young children.[12]

Evaluation and Innovation

Preschool programs should be field-tested, pretested, and posttested in their development and implementation. However, one cannot use written tests to evaluate young children's knowledge gain. Using and documenting one-on-one interviews in which children demonstrate specific behaviors prior to and after the program is one way to assess children's knowledge gain.

In 2002, the Community Education and Child Advocacy Department of Riley Hospital for Children conducted pretest and posttest evaluations of the *Learn Not to Burn (LNTB) Preschool Program.* Riley Hospital had already worked with the Healthy Child Care America campaign managed through the American Academy of Pediatrics training 600 child care providers on the *LNTB Preschool Program* and 150 "supertrainers" to teach the program throughout the state between 1996 and 1999.

The goal of the study was to evaluate what gains in knowledge occurred in children ages 3 to 5 who had been taught the eight basic fire safety behaviors presented over 1 month's time compared to over a 3-month period. Children in a control group received fire and burn information on health and safety topics. A 2-hour training session was conducted at each of the 12 child care settings from the corp of "supertrainers." Pretests and posttests were administered on a one-on-one basis with each child participating in the study by the supertrainers working with the site. The pretest and posttest were the same instrument and consisted of 15 questions asking the children to demonstrate fire safety knowledge and behaviors. Results were compared with pretests and posttests of children receiving instruction over 1 month and over 3 months. Also pretests and posttests from children receiving the *LNTB Preschool Program* were compared with pretests and posttests of children at control sites. The percentages of improvement in test scores by intervention groups were the following: control group, 12.2%; 1 month group, 23.3%; and 3 month group, 33.5%. Children at ages 2 and 3 realized the greatest gains in knowledge.[13]

Although it is important to measure the knowledge gain accomplished by a fire safety education program, it is even more important to measure the effectiveness of the program in reducing fire deaths and injuries in the target population. The use of evaluation is well illustrated by the experience of the Portland (Oregon) Fire and Rescue Department, which implemented the use of the *Learn Not to Burn (LNTB) Preschool Program* and *Play Safe! Be Safe!*®.[14] (The Play Safe! Be Safe! program is a safety education program for children ages 3 to 5 created by the Bic Corporation. It uses video lessons, storyboards, and other games and activities to teach fire safety behaviors.[15]) In fiscal year 1992–1993, the *LNTB Preschool Program* was delivered to 29 Head Start classrooms in Portland. The primary means of evaluation was a focus on behavioral changes, which would be measured against the history of the juvenile fire problem in Portland. In 1994 and 1995, the Fire Bureau decided to expand the outreach to preschool-age children in group child care facilities, serving 12 or more children in nonresidential settings. The *Play Safe! Be Safe!* program was used for the children in these settings. In all, more than 200 copies of both programs were distributed into formal learning settings in the Portland area.

Some of the positive findings of the evaluation were the following:

- In the target age group of 3- to 5-year-olds, the success measure was the reduction in the percentage of children having to be referred to the juvenile firesetting intervention program for reasons of low knowledge and skills. The preprogram referral rate of 6.2 percent was reduced to a low of 1.8 percent by fiscal year 1996–1997.
- Prior to the implementation of this program, the city of Portland experienced an average of two deaths a year attributed to child-set fires. Since the implementation, the death rate due to child-caused fires has dropped to one death every 6 years, on average.
- The rate of child-set fires per thousand children in the targeted population, expressed as a fraction of the rate of child-set fires per thousand children in the entire community, has declined by roughly half.

Portland Fire and Rescue is convinced that this level of reduction in the different success measures points to education as the key to success.[14]

More evaluation such as the pretesting and posttesting and impact studies such as those done in Portland should be conducted. Too many programs are still in use based only on the reasonableness of their design assumptions and favorable, but unquantified, impressions of them by their lead adopters. The need for more evaluation will only grow as various preschool programs are adapted for international use.

Programs should continue to be developed and existing ones improved. It is also important to develop more lab research on how young children learn fire safety behaviors to get a better sense of whether young children understand the message and whether we are giving the right messages and teaching the right behaviors.

New programs for caregivers should also be developed and tested. Messages and programs for a variety of cultural groups should be studied and evaluated. New implementation methods should be used to reach children who are not in formal child care settings. Funding to conduct longitudinal, full program, sustained behavior change and impact evaluations should be obtained from groups such as the Centers for Disease Control and Prevention.

Even when a strategy emphasizes an engineering change, it needs an educational counterpart for maximum advantage. As an example, consider the standard on child-resistant lighters. Some children will be able to operate child-resistant lighters. Among the children younger than age 5 who ignited cigarette lighters in the CPSC study, about one-third were older than 4 years and 3 months, the oldest age of the children required to be tested by the CPSC standard-testing protocol.[8]

OLDER ADULTS

Older adults are the only one of the high-risk groups that is growing rapidly. In 2002, there were 36.6 million people age

65 or older representing 12.3 percent (or roughly one-eighth) of the population of the United States. The number of older adults has increased 10.2 percent since 1992. This compares to an increase of 13.5 percent in the population under age 65. Another significant increase, however, is that of Americans aged 45 to 65, who will all reach age 65 over the next 20 years. Their numbers increased by 38 percent in the same period. By 2030, adults age 65 or older will represent a projected 20 percent of the population.[16]

Internationally the population is also aging rapidly. One can see the increases in certain developed countries, such as Japan and Western Europe. However, even developing countries are seeing an increase. As pointed out by Dr. Alexandre Kalache, chief of aging and health for the World Health Organization, the developed world became rich before it got old, whereas the developing world is going to get old before it gets rich. This has important implications since poorer countries do not have the resources to deal with injuries that are available in the developed world.[17]

Although only 17.2 percent of persons age 65 and older in the United States are minorities, the rate of growth in numbers of minorities is increasing rapidly. By 2030 it is projected that minorities will represent 26.4 percent of the elderly population. Between 1999 and 2030, the white population age 65 and older is projected to increase by 77 percent compared with 223 percent for older minorities, including Hispanics (342%), African Americans (164%), American Indians, Eskimos, and Aleuts (207%), and Asians and Pacific Islanders (302%).[16]

In targeting programs to reach older adults, it should be noted that older adults vary in their physical and mental abilities and probably in their risk of death from fires and burns. As health care has improved and more is known about exercise and nutrition, people are more active and in good health and involved longer in the community. Also many older people are financially secure and living in good housing.

People age 85 and older or the "vulnerable elderly" have the greatest risk. Not only do they have the highest risk for both fire deaths and fire injuries but also their injury rate is 57 percent higher than the national average. From this statistic, one may infer that this is a different population from those people age 65 to 74 whose risk of home fire injury is actually lower than the all-ages average.[2]

Putting all this together, fire death risk continues to increase as people age, beginning at about age 50. People age 65 and older have about twice the risk of dying in a home fire as the general population. For people age 75 and older, the risk is almost three times as high, and it is almost four times as high for people age 85 and older.

Characteristics of This Group

For older adults, the principal causes of fatal fires are primarily the same ones as for other adults. They suffer less from child-playing fires.

Most fire safety messages for older adults are similar to those for other adults, but there are some variances in patterns that may affect relative emphasis on messages by an educator. Smoking-related fires are the leading cause of fire deaths. Heating equipment fires rank second, but they are a close second only for the oldest adults, accounting for nearly 21 percent of deaths among the 85 and older age group as compared to smoking materials (25%).[2]

Older adults are more likely than others to be intimately involved with the ignition source. For adults 65 and older, more than 14 percent are intimate with the ignition in structure fires. Males are a high-risk group compared to females for nearly all age groups. The death rate for males from 1999 to 2002 was 12.1 fire deaths per million population, which was 38 percent higher than the death rate for females at 8.8 fire deaths per million population. The largest difference was for age 85 and over, where the male death rate of 58.5 deaths per million was nearly twice the rate of 27.8 for females.[2] Men age 85 and over also had the highest risk of injury from fires of all ages.[2] Programs developed for older adults should be appealing to both men and women because men are at higher risk, but women make up a larger portion of the older population.

With so many important and distinct causes of injury, programs developed for older adults need to be multifaceted. For example, *Remembering When: A Fire and Fall Prevention Program for Older Adults*™[18] developed by the NFPA Center for High-Risk Outreach and the Centers for Disease Control and Prevention uses three strategies for reaching older adults: group presentations, home visits and smoke alarm installation, and fall intervention. (*Remembering When* is described in more detail later in this chapter.) Figure 5.5.1 is a sample fire message card from *Remembering When.*

How Older Adults Learn

In 2005, the U.S. Consumer Product Safety Commission staff examined consumer product safety issues associated with adults age 65 and older by conducting a literature review to identify changes or differences associated with aging that could affect an individual's ability to interact successfully with a product. The resulting study provided product- or environment-related interventions that could compensate for the age-related differences. The information learned could also be applied to those trying to teach fire and life safety education lessons to older adults. Sensory differences identified included such factors as glare sensitivity, reduction in peripheral vision, reduction in ability to hear higher frequencies, and difficulty understanding speech in noisy environments. In the study, the CPSC staff recommends interventions such as the following to compensate for differences:

- Increase levels of illumination, especially in situations where consumers must read information.
- Use nonreflective, matte, or semimatte finish to reduce the potential for glare on surfaces that include warnings or other information that consumers must read or focus on.
- Provide high contrast between text or graphics and the background.
- Use at least 12- or 14-point and preferably 18-point type for consumers 80 years of age and older.
- Increase the intensity of speech relative to background noise.[19]

The study also looked at cognitive differences that may affect product design. The processing resources most commonly cited that limit cognition in older adults were memory capacity

FIGURE 5.5.1 Sample Message Card on Kitchen Fire Safety from *Remembering When*

and, to a somewhat lesser extent, attention capacity. The authors suggest environmental supports that could be useful as external cues, such as pictures and lists or restructuring a task to allow individuals to rely on relevant prior knowledge.

Memory for previously acquired skills generally does not decline with increasing age. There is evidence, however, that it takes longer for older adults to acquire news skills than it takes for younger adults, especially for complex tasks or those where an individual must unlearn a previously acquired skill.

The authors concluded that opportunities for practice and training were very important for older adults. Training that focuses on procedural information is more important for older adult understanding than conceptual information. Training that gives "hands-on" practice tends to be better than training that simply presents facts and descriptions.[19]

In addition, older adults in focus groups conducted by the NFPA Center for High-Risk Outreach and the Centers for Disease Control and Prevention said that a program should focus on the key safety messages dealing with the major causes of fires and falls and how they can be prevented. To encourage program attendance, respondents said that program leaders should provide transportation for older adults who do not have transportation, provide food, and advertise that they will have food. The majority of those surveyed felt that the ideal time to hold an educational program is about 10 o'clock in the morning.[20]

Results indicated that older adults wanted both group presentations and home visits. Older adults thought visits to people in the home should be one-to-one and conducted by someone with whom older adults felt comfortable, such as a fire fighter or someone who already visits the home.[19]

Legislation and Engineering

Properties designed to provide special care to older adults are covered by the NFPA *101®*, *Life Safety Code®*, other model codes, and related governmental requirements. Many other engineering provisions—for example, to reduce the risk of fall injuries—are contained in guidelines such as those contained in NFPA's *Remembering When.*

Most older adults, however, live in their own homes, where there is less control and regulation for their safety. However, there are many engineering solutions that can be helpful for older adults. Advancements such as 10-year lithium battery smoke alarms, alarms that can be tested by a remote, or interconnected smoke alarms can provide more convenience and better protection for older adults.

Although the use of smoke alarms is associated with a reduction in fire fatalities in the general population, recent studies suggest that older adults may not fully benefit from conventional smoke alarm systems, particularly during sleeping hours. The tendency for older adults to experience high-frequency hearing loss has been attributed as a potential fire safety problem, since typical residential smoke alarms have a high-frequency signal between 3000–4000 hertz. The findings of a study by the NFPA Research Foundation[21] together with previous literature indicate that a mixed frequency T-3 signal has performed better than the current high-frequency (T-3) signal in its ability to awaken sleepers in every sample group tested so far. This includes children, young adults (sober and alcohol intoxicated), and older adults. Voice signals appear to be as effective as the mixed T-3 for the children and young adult groups but are less effective than the mixed T-3 for older adults.

In the meantime, the following are some recommendations that can increase the chance of sleeping individuals waking to a fire:

1. Encourage interconnected alarms. Interconnected alarms that include an alarm in the bedroom will mean that the volume at the pillow is likely to be above 85 dBA.

2. Consider the special hearing needs of older adults with "normal hearing." Given the hearing thresholds for high frequencies of older adults, it is inadequate to require their current high-frequency smoke alarm to be a minimum level of 70 dBA at the pillow. The current study shows that those older than 75 years of age were particularly poor at waking to the current high T-3 (median of 65 dBA for high T-3 compared with 40 dBA for the mixed T-3). One possibility would be to recommend that older adults should have interconnected alarms or at the very least stand-alone alarms (with the current signal) in their bedroom. An additional more satisfactory possibility is for smoke alarm manufacturers to market special alarms for this age group that emit a mixed T-3 signal and suggest placement, as a minimum, in the bedroom.[21]

Also, advocating for engineered product changes such as home fire sprinklers, flame-resistant sleepwear, and fire-safe cigarette legislation is another priority for those working to reduce deaths and injuries among older adults. Mandating fire-safe cigarettes can be beneficial to people of all ages but particularly older adults. The highest death rate from cigarette fires is suffered by people aged 65 or older, even though they are only half as likely to smoke as are younger adults.[22] By the end of 2006 firesafe cigarette legislation had been passed in six U.S. states, as seen in Table 5.5.1. The National Fire Protection Association also formed the Coalition for Fire-Safe Cigarettes made up of more than 50 national organizations to work toward state-by-state legislation.

Reaching Older Adults Through Others

Many older adults have people who provide them with care or support, but the typical independent older adult does not cede authority to any of these volunteer caregivers. The options available to caregivers of young children do not exist in the same form for caregivers of older adults.

TABLE 5.5.1 States with Legislation for Fire-Safe Cigarettes

State	*Percentage of U.S. Population*	*Law in Effect*
New York	6.5%	June 28, 2004
Vermont	0.2%	May 1, 2006
California	12.2%	January 1, 2007
Illinois	4.3%	January 1, 2008
New Hampshire	0.4%	October 1, 2007
Massachusetts	2.2%	January 1, 2008
Total	25.9%	

Source: http://firesafecigarettes.org, February 5, 2007.

Teaching Older Adults

The earlier lessons on how older adults learn can be translated into the following concise set of generic guidelines for constructing an effective safety education program for older adults:

- Find venues where older adults congregate and are receptive to an educational program. Older adults can be reached through a variety of organizations including senior housing, parks and recreation departments, places of worship, nutrition centers, or AARP chapters.
- Construct interactive presentations focused on specific safety behaviors, so that the interactive participation by the older adults can help to lock in the safety knowledge and serve as a start on practicing the safety behavior.
- Tailor the presentation to address potential physical limitations of the audience but unobtrusively and without overcompensation based on stereotypes.
- Use the presentations to set up home visits for follow-up. Extend the reach of the programs by arranging home visits with additional older adults who may not desire or be able to be involved with organizations that sponsor presentations.
- Involve older adults on every facet—from program design to program delivery—to assure that the high level of respect and credibility needed for success is achieved consistently.

Sample Programs for Older Adults

Older and Wiser. In response to the disproportionate number of fire deaths that occurred among older adults in the Canadian province of Ontario, the Ontario Fire Marshal's Public Fire Safety Council organized an older adults task force to reduce fires, injuries, and fire deaths among adults age 65 and older.

Research into the fires showed several different fire scenarios in which older adults were dying or being injured. To effectively address each scenario, a program had to be developed using a multipronged approach because those dying in fires were either very active in the community or lived on their own and were often isolated in urban and rural areas.

The Ontario Fire Marshal's Public Education Office developed a fire safety resource kit entitled *Older and Wiser*[21] based on the research and testing by the older adults task force. The kit includes a checklist for friends and families of older adults, a large-print pamphlet with fire safety tips, a high-rise pamphlet, a fire safety quiz, a booklet on working with the media, and an instructional booklet entitled "Getting the Community Involved." Program aids such as a booklet entitled "Planning for Success" and a presentation script help program leaders deliver a presentation to groups of older adults. The Ontario Fire Marshal's Office also provides a presentation to older adults in PowerPoint, overhead, or slide show formats to fire safety educators.[23]

Older and Wiser was distributed free of charge to every fire department in Ontario with funding by the City of North York. (North York experienced several fire deaths of older adults in 1997.) Surveys are sent out periodically to determine who is

using the program, how it is being used, and to see if there is need of additional resources or tools to educate this group.

Some of the most important community partners for *Older and Wiser* are the home support workers who visit the homes of older or physically and mentally challenged people to assist them with their daily chores. Many support workers test alarms in the homes of their clients. An *Older and Wiser* checklist was developed and field-tested by home care agencies in Ontario. In some communities fire service personnel train home support workers to conduct basic fire safety checks in the homes they visit. Smoke alarms are installed or replaced, and older adults are taught how to prevent fire and protect themselves if there is a fire.

Part of the success of the *Older and Wiser* program is attributed to the fact that in Ontario public fire safety education is mandatory. Under the Fire Protection Act, municipalities must deliver public education programs based on local needs and circumstances. Because many communities have many older people, a program that provides materials and resources to help reduce fires among this group is often welcomed.

Remembering When: A Fire and Fall Prevention Program for Older Adults.[18] In 1997 the NFPA Center for High-Risk Outreach had many programs to reach high-risk fire groups but had few materials to use to reach older adults. The center met with representatives from the Centers for Disease Control and Prevention Division of Unintentional Injury (CDC), which also had an interest in reducing fires among older adults. Both organizations agreed that a program designed for older adults regarding preventing fires could also include how to prevent unintentional injury from falls. (Fires and falls are the leading cause of unintentional injury in the home among older adults.) Many fire service personnel respond to emergency calls for older people falling as well as fires. Also, since many more older adults had experienced a fall than had been in a fire, the two organizations thought there would be more interest in a program that included both injury areas. Research was conducted at all stages of program development.

Because no single agency is responsible for reaching all older adults in a given community or jurisdiction, *Remembering When* is designed to be implemented by coalitions of local fire departments, public health departments, service clubs, social and religious organizations, area agencies on aging, and other organizations. As a team, coalition members can decide how to best approach the local older population.

Once the program was developed, 5000 free copies were made available to fire fighters, public health workers, other professionals serving older adults, hospital workers, and other organizations throughout North America. Some state organizations and corporations funded distribution of *Remembering When* for each fire department and other organizations in their states. Most people who received the program materials implemented the program without extra outside technical assistance. The NFPA Center for High-Risk Outreach has a corps of diverse trainers who provide training on the *Remembering When* program for state and local conferences of fire safety educators, organizations serving older adults, and public health officials.

The Centers for Disease Control and Prevention Division of Unintentional Injuries provided 3-year grants for the implementation of *Remembering When* in Arkansas, Maryland, Minnesota, North Carolina, and Virginia. Between 2000 and 2003 in the CDC project, 511 group presentations were made, 3566 home presentations, 4308 smoke alarms installed, 3221 bath mats given out, and 6251 night lights handed out; nearly 500,000 older adults were reached through the *Remembering When* program. The evaluation also included a written pretest and posttest for the implementation.[24] For other local groups that want to evaluate the program, the Center for High-Risk Outreach provides a local evaluation packet including questionnaires and a template for a final report to local officials.

The *Remembering When* program focuses on 16 fire and fall prevention messages. The program uses the following approaches to reach older adults:

- *Group presentations.* This section gives steps on reaching older adults through senior centers, high-rise housing, and other places people gather in groups. Three optional lesson plans feature interactive activities such as a trivia game to support the presentations.
- *Home visits.* This section focuses on reaching older people in their own homes through service providers who already visit the home. It includes several visitation formats, support checklists, and handouts.
- *Installation and intervention.* This section outlines how to organize a smoke alarm installation and fall intervention program, including the installation of smoke alarms and the distribution of night lights, nonskid bath mats, and other items.

Evaluation and Innovation

When the *Remembering When* program was in development, a formative evaluation was conducted. Hundreds of older adults in the five test sites participated in the group presentations and home visits.

In addition to the 3-year implementation and evaluation of five states by the Centers for Disease Control and Prevention mentioned in the preceding section, the CDC's Division of Unintentional Injury conducted an additional evaluation through Georgia State University. The state of Virginia was picked as the evaluation site because it had a particularly robust implementation program. Knowledge pretests and posttests of those attending presentations showed a significant pretest to follow-up change on 8 of the 19 knowledge items whereas the control site showed a significant pretest to follow-up change on 3 of the 19 knowledge items. The average increase for the fire items from pretest to follow-up was more than double in the treatment site versus the control (i.e., 11.3 percent versus 4.4 percent). The average increase for fall items from pretest to follow-up was 7.5 percent for the treatment site and 5.1 percent for the control site. In addition there was a home assessment evaluation of 23 items between the initial and follow-up home visits. In particular, the treatment site had significant home safety changes on three of the smoke alarm messages, including increased number of smoke alarms, working smoke alarms outside the bedroom, and at least one smoke alarm on every level of the home. Home

assessments showed no significant smoke alarm changes in the control site.[25]

Fire departments worldwide need to conduct a sustained effort on reaching older adults. This population will continue to grow rapidly. Training of fire service personnel should include not only the content of the program such as *Remembering When* but also model sensitivity to older adults and cultural relevancy to the period history of events that older persons have experienced. Also humor and fun activities should be part of all training and programs to overcome possible preconceived ideas many have regarding the target group. Fire and life safety educators who have worked over the years with older adults report enjoying their work with this group.

Programs should also be targeted to the adult children or nieces and nephews of older adults. This group could benefit by learning more about how they can assist their parents, aunts, and uncles in making their homes safer as well as learning how to design their own homes to be safer as they age and to increase their safety behavior.

LOW-INCOME AUDIENCES

Today's urban and rural environments offer challenges to anyone working to improve schools or provide health services, city services, crime prevention, or fire and life safety measures. Traditionally programs for fire safety tended to reach those who needed it least. And without concentrated effort to understand the urban or rural poor situations, it is unlikely that programs developed for more affluent communities will be effective.

A number of statistical studies, stretching back at least a quarter of a century, have demonstrated that the risk of fire or fire death is higher among low-income populations.[26] Many measures of what it means to be disadvantaged have shown this relationship to high risk, but the various conditions all tend to be correlated with each other, so it is probably impossible—and unnecessary—to determine which condition is most critical in creating higher fire risk. Lack of income (poverty) and lack of education are the two conditions that most consistently show a substantial relationship to high risk. Only 65 percent of poor household heads are high school graduates, compared with 81 percent of all household heads.[27]

The correlation with poverty and low education appears to explain why race and age of housing, by themselves, appear to be factors in high risk. When the effects of poverty and low education are removed, neither race nor age of housing appears to be a good predictor of high risk. Although blacks are overrepresented among the poor, whites make up 67 percent of America's poor compared with 83 percent of the overall population. Blacks, who represent 13 percent of the population, make up 29 percent of the poor. The black ratio has barely budged since the mid-1960s.[27]

Similarly, fire risk is high both in large cities and in small, rural communities, the two sizes of communities with the highest shares of this population living in poverty. And among regions of the United States, the higher incidence of rural poverty, in particular, provides an explanation for the consistently higher fire death rates in the South.

A more recent study of deaths and injuries from house fires in the city of Dallas, conducted from 1991 through 1997 and reported in the *New England Journal of Medicine,* confirmed the previous findings. It found that the rate of injuries was highest among older adults, low-income populations, minorities, and in houses without functioning smoke alarms.[28] Homes with low incomes are less likely to have smoke alarms.[29] The study also showed that census tracts with the lowest median incomes had rates of injury 20 times as high as the rates in tracts with high median incomes[28] (Table 5.5.2).

As noted earlier, older adults account for one-fourth and young children account for one-sixth of the population. People with low incomes are the smallest part of these high-risk populations, depending on how the condition is measured.

More than one in seven Americans live in poverty, including more than one of every five children. This means that people do not earn enough to feed, clothe, and house their families at a level that the federal government considers adequate. The minimum incomes needed to do this are $7363 for singles to $14,763 for a family of four to $29,529 for a family of nine or more.[27]

Older adults are less likely to be poor than other age groups, thanks in large part to Social Security, Medicare, and Medicaid. In 2002 about 3.6 million persons age 65 and older (10.4%) were below the poverty level. The historic level of 9.7 percent was reached in 1999. Another 6.4 percent of the elderly were classified as "near poor" (income between the poverty level and 125% of this level). Older women had a higher poverty rate (12.4%) than older men (7.7%) in 2002. Older persons living alone or with nonrelatives were much more likely to be poor (19.2%) than were older persons living with families (6.0%). The highest poverty rate (47.1%) was experienced by older Hispanic women who lived alone.[16]

Of the elderly white population, 8.3 percent were poor in 2002, compared to 23.8 percent of elderly African Americans and 21.4 percent of elderly Hispanics. Higher than average poverty rates for older persons correlated with living in central cities (12.2%), in rural areas (11.9%), and in the South (12.7%).[16]

Poor families are not unusually large families. The average poor family receiving Aid to Families with Dependent Children (AFDC) consists of 2.9 people. The typical American family is 3.2 people.

Although everyone grows out of the high-risk group of young children and often into the high-risk group of older adults, being disadvantaged is often regarded as a lifelong affliction. This stereotype misses a sizable share of the disadvantaged who do leave the group. Studies show that although about a third of the poor are elderly or disabled and, thus, unlikely to climb out of poverty, one of every five poor people in a given year isn't poor in the following year. Isabel V. Sawhill, a senior fellow at the Urban Institute think tank, estimates that roughly a third of the nation's poor remains impoverished only temporarily because of job loss, illness, or divorce.[27]

Characteristics of This Group

Only 9 percent of poor working-age adults work full-time year around compared with 42 percent of all working-age adults; 40 percent of the poor do work part-time or part of the year, compared with 69 percent of all adults.[27]

TABLE 5.5.2 Rates of House Fires and Injuries Related to House Fires, According to the Median Income of the Census Tract, in Dallas from 1991–1997[a]

Median Income per Year	*No. of House Fires*	*No. of Houses*	*No. of Injuries*	*Population*[b]	*Injuries per 100,000 Population per Year*	*Relative Risk (95% CI)*[c]	*House Fires per 1000 Houses per Year*	*Relative Risk (95% CI)*[c]	*Injuries per 100 House Fires*	*Relative Risk (95% CI)*[c]
<$20,000	1681	33,411	75	107,944	9.93	8.1 (2.5–32.0)	7.19	2.4 (2.1–2.8)	4.46	4.1 (1.2–16.2)
$20,000–$39,999	4085	97,205	121	286,892	6.03	4.9 (1.5–15.4)	6.00	2.0 (1.8–2.3)	2.96	2.7 (0.8–10.7)
$40,000–$59,999	800	40,454	17	103,242	2.35	1.9 (0.5–8.2)	2.83	1.0 (0.8–1.1)	2.13	1.9 (0.5–8.4)
$60,000–$79,999	340	24,104	7	74,810	1.34	1.1 (0.3–4.2)	2.02	0.7 (0.6–0.8)	2.06	1.9 (0.4–9.2)
≥$80,000	273	13,154	3	34,833	1.23	1.0	2.96	1.0	1.10	1.0

[a]Data on the median income of the census tract were missing for 5034 persons and 11 house fires.
[b]Population indicates the number of people living in houses, which were defined as nonmobile residential structures with one or two units.
[c]$P < 0.001$ by the chi-square test for trend for each income category. CI denotes confidence interval.
Source: *New England Journal of Medicine,* Vol. 344, No. 25 (June 21, 2001). Copyright © Massachusetts Medical Society. All rights reserved.

It is not true that most of the poor live in inner-city ghettos. Only about one in eight poor Americans lives in census tracts with poverty rates of 40 percent.[27] Part of the reason for this fact is that poor people can be found in most communities that are not poor. A more important reason for this is the large share of poor people located in rural communities where census designations are not defined at the tract level. If relative fire rates and fire death rates are any indication, then rural poverty is a greater risk factor than urban poverty.

Special Fire Risk Characteristics. One reason that rural poverty is a greater risk factor than urban poverty is the larger number of rural poor who are located in the South. Here winters tend to be milder, and it is possible to at least attempt to heat whole housing units with portable or fixed-space heaters designed for safe use only in smaller spaces. Fire deaths due to heating equipment fires account for a larger share of all fire deaths in the rural South than elsewhere.[30]

The other fire causes for which the poor have distinctly higher risk than others, at least in large cities, are child-playing fires and incendiary or suspicious fires, which are known to be dominated by juvenile firesetting. A possible explanation for this pattern follows this chain: Most of the poor live in single-parent households headed by women. Just over half of the poor families (52%) in America are headed by single females compared with only 18 percent of all U.S. families.[23] Single-parent families have less total person-time available for close supervision of children, which creates more opportunities for children to start fires, as well as reduces the ability of the family to respond quickly and effectively to help children escape any type of fire that may occur.

Other factors related to poverty that also contribute to high fire deaths are unattended or unsupervised children; a lack of utilities; the use of safety devices, such as window bars, to prevent crime; a lack of smoke alarms; and older electrical wiring.[30]

A study investigating the social and demographic relationship of nonfatal structural fire injury rates for the civilian population of Philadelphia census tracts during the 1993–2001 period was conducted by the Department of Sociology of Villanova University. Findings showed that those tracts with older housing, low income, the prevalence of vacant houses, and the lack of ability to speak English have significant independent effects on fire injury rates in Philadelphia. The problem of the housing is not its age alone but the combination of housing and low income. The proportion of vacant houses was highly significant not just that injuries occurred in vacant housing but also that the presence of vacant housing was a significant indicator of decline in the areas and had an even more important indirect effect on fire injures in a census tract.[31]

How the Group Becomes Safer. Any effective fire and life safety program targeting the disadvantaged must reflect the limitations that low income and less education impose. Even one single-station smoke alarm with a battery may be beyond the poor family's budget, let alone annual battery replacement. Reading levels need to be kept low if educational materials are to be readily grasped by a target disadvantaged population.

For a number of low-income communities, there may also be language barriers. In most urban and some suburban and rural communities, the fire safety educator must be prepared to provide instruction and information in languages other than English. According to the U.S. Census Bureau, there were 28.4

million foreign-born residents (10.4% of the total U.S. population) in 2000. Among the foreign born, 51 percent were born in Latin America, 25.5 percent were born in Asia, 15.3 percent were born in Europe, and the remaining 8.1 percent were born in other regions of the world.[32]

Almost half of the foreign born lived in the central city of a metropolitan area (43.1%), compared with slightly more than one-quarter of the native population (people born in the United States, 27.5%). The percentage living outside these large central cities but within a metropolitan area was slightly less for the foreign born than for the native population (48.8% and 51.0%, respectively). The percentage of the foreign born living in nonmetropolitan areas (5.1%) was much smaller than the percentage of natives (20.7%).[32]

Although a large proportion of immigrants moves to the large metropolitan areas, many smaller communities also experience changes in their ethnic makeup. For example, Sioux Falls, a city of about 140,000 in the mostly rural state of South Dakota, estimates that 17 percent of its population was not born in the United States. The Sioux Falls school district has documented 47 different languages spoken by students in grades K–12. In addition the Sioux Falls Multicultural Center states that there are over 80 languages and dialects spoken in the community.

Challenges to the fire department there include not only reaching families, especially adults who speak a different language, but also reaching people with cultural and socialization issues related to fire, such as teaching people to use stoves with several burners and ovens when they may have cooked on an open fire in their native country and teaching people not to use hibachis or barbecue grills inside their homes. In the last 10 years there have been 12 fire deaths in the community. Seven of these deaths were to immigrants. In order to address this community risk Sioux Falls Fire Rescue along with the Sioux Empire Safety Village (a local nonprofit organization) translated a locally written, 11-page home fire safety guide into 15 languages and produced a video series covering the same information in 13 of the same languages.[33]

The multilingual nature of Canada is growing as a result of increased immigration. In 2001, there were 5.3 million people who reported a mother tongue other than English or French, which was a 12.5 percent increase from 1991. This increase was three times greater than the overall growth rate of the Canadian population (4.0%). The number of people reporting English as their mother tongue increased by only 2.6 percent from 1996 and those reporting French increased by only 1.1 percent. Chinese is the third most common mother tongue. People reporting Chinese as their mother tongue accounted for 2.9 percent of the total Canadian population.[34]

The trend of multilingualism is likely to increase in Canada and the United States. Europe, Australia, and other nations are also experiencing growth in immigrants who speak other native languages. This presents a challenge to public educators as they try to reach people in their communities with safety messages and culturally appropriate programs.

Legislation, Engineering, and Government

The principal concern with safety programs for low income populations is that normal program funding dynamics will tend to target *away* from the disadvantaged rather than *toward* them. Resources that can be tapped for safety programs anywhere else are likely to be missing in a poor neighborhood or community.

One Chicago neighborhood, North Lawndale, according to the *Chicago Tribune,* has one bank, one supermarket, 48 state lottery agents, and 99 licensed bars and liquor stores. "With only one bank, there are few loans available for home repair; private housing has therefore deteriorated rapidly."[35]

In his book *Other People's Children: Savage Inequalities, Children in America's Schools,* Jonathan Kozol reports further that in the school system the city often relies on low-paid substitute teachers who represent one-fourth of Chicago's teaching force. Even substitute teachers are in short supply. On an average morning in Chicago, 5700 children in 190 classrooms come to school to find no teacher.[35] In his 2005 book, *The Shame of the Nation: The Restoration of Apartheid Schooling in America*, Kozol goes on to demonstrate the isolation of poor and minority children in major cities in the United States. In Chicago by year 2000–2001, 87 percent of Chicago public school enrollment was black or Hispanic and less than 10 percent of children in schools were white. School funding for schools in the city of Chicago is considerably less than more affluent suburbs as well. For example, in the 2002–2003 school year the spending per student (grades K–8) for Glencoe with 1 percent low-income families was $10,935 and for Chicago with 85 percent low-income families was $8,482 per student (grades K–8).[36]

Lack of adequate smoke alarms in homes in poor communities can especially put people at risk. Any education program targeting low-income communities should provide a mechanism in which residents can get alarms installed in their homes. Homes with smoke alarms have a death rate that is about 40 to 50 percent less than the rate for homes without alarms. Based on a telephone survey as of 2004, 96 percent of U.S. homes had at least one smoke alarm. However, four of every ten home fires reported to U.S. fire departments still occurred in the small share of homes without alarms.[29] Although telephone surveys conducted for NFPA showed 96 percent of homes had alarms, results from surveys filled out by installers in a 2005 NFPA smoke alarm program reaching more than 8000 residences in high-risk communities in Mississippi, Alabama, and the Navajo Nation showed a much lower presence of alarms in homes before the new alarms were installed. In targeted communities in these three locations presence of alarms were 33 percent in the Navajo Nation, 43 percent in Mississippi, and 63 percent in Alabama. In the years 2003–2004 NFPA/USFA conducted an installation program reaching nearly 4000 residences in Holmes County, Mississippi, one of the poorest counties in the United States. Surveys of installers working in Holmes County reported that 53 percent of the homes had at least one smoke alarm before the installers put in new alarms.[37]

Reaching the Group Directly and Through Others

Community-Based Fire Safety Education Model. A community-based fire safety education model[32] has been designed to address the challenges of the poor urban areas, for example, working with tight budgets, large numbers of unsupervised children, non-English-speaking residents, and other issues

related to social and economic changes. An important concept of the community-based approach is that no two communities are exactly alike. Fire departments must adjust approaches to fire safety education to fit the audience they are trying to reach.

The fundamental principles of the community-based approach are geographic targeting, market research, and grassroots community involvement, which are explained as follows:

- *Geographic targeting.* Identify specific neighborhoods or areas where the fire problem is most severe and concentrate efforts on reaching residents of these high-risk areas.
- *Market research.* Use methods developed by the advertising industry to learn more about the target audience to understand how they get information and what will motivate them to listen and respond to fire safety messages.
- *Grassroots community involvement.* Invite the active participation of as many of the targeted audience members as possible in each aspect of the program.[38]

Community involvement is not just a means for disseminating information but also should be a goal in itself. When people actively participate in a program, they develop a personal stake in fire safety that they bring back to family, friends, and neighbors.[39]

The following basic steps are the foundation of a successful community-based fire safety education program:

- Educators analyze fire data to identify the geographic target areas with the most fires and deaths and to determine the main causes.
- A market researcher or other qualified individual conducts focus groups among people in the target area to identify the leaders in the community and determine the best strategies for communicating fire safety messages to residents.
- Meetings are held with the leaders of community groups identified during the market research.
- Educators implement the program with the cooperation of the community groups. Some programs give free smoke alarms and educational materials as part of each pilot program. Most of the programs include a door-to-door canvass of households in the target area. Fire fighters or trained volunteers install the detectors.
- The success of each program is evaluated by documenting citizens' response and analyzing fire data by comparing the number of fires or fire deaths and injuries before and after the program's implementation.[39]

The qualities necessary to be an effective fire and life safety educator in low-income and other communities are very similar to those necessary to be a community organizer trying to improve overall conditions in neighborhoods. The following list identifies qualities needed by fire and life safety educators:

- Being able to find leaders in the community
- Being able to find the networks and organizations in the community that really work for people
- Understanding the enlightened self-interest of the person or persons to be motivated
- Recognizing differences without stereotyping people
- Having imagination or empathy
- Being ready to give volunteers and leaders in the community recognition and empowering others to act and lead on their own
- Having a sense of humor

School-Based Programs. School-based programs have been very popular in reaching children and their parents. Example programs are (1) ones in which the fire department does all the teaching directly to students in their classrooms or in auditoriums, (2) fire safety houses and trainers, and (3) ones that concentrate on training the teacher to teach fire and life safety as part of the ongoing curriculum.

The public educator needs to take into account what teachers and administrators are dealing with in schools in urban or rural communities. There are many groups eager to provide their messages to children in these schools; therefore, in order to get fire and life safety on the priority list, the fire and life safety educator must be able to communicate the urgency of the safety issue and provide new resources to the school system.

An example of a fire department reaching children in urban schools is the Philadelphia Fire Department. The department implements NFPA's *Risk Watch*®[40] curriculum in 40 schools in high-risk communities. (*Risk Watch* teaches eight safety subjects of motor vehicle safety; fire and burn prevention; choking, suffocation, and strangulation prevention; poison prevention; falls prevention; firearms injury prevention; bicycle and pedestrian safety; and water safety for preschool to grade 8.) The communities were targeted by observing census tract information showing low incomes combined with information on areas where there was a greater rate of fire deaths and injuries.

Joseph Flores, former captain in the Philadelphia Fire Department and community outreach liaison for the University of Pennsylvania to the Philadelphia Fire Department, supplemented the *Risk Watch* materials in order to address the needs of urban children. Some of the subjects for which he wrote supplemental materials were children playing on playgrounds with glass, needles, or crack vials; children playing in abandoned cars or houses; and children opening fire hydrants during the summer to cool off. The department also added information on lead paint and dog bites—other problems in the city.

In addition to the *Risk Watch* curriculum implementation, a Philadelphia-wide smoke alarm program provides for the installation of free smoke alarms in the homes of any child who does not have a home smoke alarm. The department also installs 10-year battery smoke alarms in homes in high-risk areas.[41]

Another innovative use of *Risk Watch* was organized by the Rochester, New York, Fire Department for mothers and children living in homeless shelters. "Shelters and Safety" was funded by the Rolf H. Jensen Memorial Public Education Grant awarded by the NFPA. The seventh- and eighth-grade module of *Risk Watch* is the primary resource for the program. The women in the program create a personal journal, called *My Safety Book,* that they are encouraged to read to their children. Each adult attendee must participate in the exercises of the program and demonstrate proficiency in the prevention of each of the eight *Risk Watch* risk prevention areas. Pretests and posttests are administered to measure the success of the program. Each woman who successfully completes the program receives a graduation

certificate. When the graduate moves into her own apartment, she receives a housewarming gift of safety-related materials, including smoke and carbon monoxide alarms, pot holders, bath mats, bicycle helmets, car seats, and cupboard locks and latches.[42]

Spanish-Language Materials from NFPA. In response to the dramatic growth of Latinos in the United States (Latinos now make up 12% of the U.S. population)[43] and the demand for bilingual materials in schools, the NFPA Center for High-Risk Outreach developed its *Learn Not to Burn Preschool Program* in Spanish. It is entitled *Mis primeros pasos en prevención contra incendios*®[44] or *My First Steps to Prevent Fires.* Project staff not only translated the teacher's guide into Spanish but also produced eight original Latin songs on a cassette tape to accompany the guide. Each song was written in a different Latin style characteristic of the music in a variety of Latin American countries (e.g., the Cuban cha-cha-cha, the Puerto Rican plena, the Mexican polka norteña, and the Dominican Republic merengue). The words for the new songs were reviewed by a team of Latino fire safety educators to determine that all words were appropriate for Latinos having varied countries of origin (Figure 5.5.2).

Individual songs were given to child care providers for Spanish-speaking children. The teachers would try them out over several weeks to determine if the children understood the messages of the songs, whether there were words that children did not recognize, and if the children could sing the songs easily. Changes in the song were made after feedback was given to the project team.

Artists were hired from Mexico to provide new illustrations in a style attractive to the Latino audience. To implement *Mis primeros pasos* in the United States, the center trained a network of Latino fire fighters from various communities in the United States with a large number of Latinos.

A partnership between NFPA and the National Association of Hispanic Firefighters (NAHF) introduced the program to the National Association of Bilingual Educators. "One of the goals of NAHF was to make sure that the Latino community had a culturally relevant education program in their school and community. For many of the children who are immigrants, this is the first time that they have ever received any fire safety education because in the past, public fire safety education was not provided in their mother countries. We want to improve the well-being of the Hispanic community in the communities where Hispanic fire fighters serve," according to Sal Morales, past president of the National Association of Hispanic Firefighters.[45]

Fire fighters from other countries began hearing about *Mis primeros pasos* after its introduction outside the United States at the Mexican Association of Fire Chiefs Conference in Leon, Mexico, in 1997. The center's four bilingual trainer/consultants have trained users in Argentina, Mexico, Costa Rica, and Puerto Rico, and comprehensive programs are being conducted in Argentina, Costa Rica, and Puerto Rico. Figure 5.5.3 illustrates one such session.

NFPA's *Remembering When* program has been translated into Spanish. It is entitled *Los buenos recuerdos* (*The Good Memories*), and it too will be implemented in the United States and Latin America. Using the program in other countries requires working through the appropriate networks in those countries to keep the program going. Some of the challenges include difficulties in getting materials, lack of money for materials in poor communities, and lack of availability of safety devices such as smoke alarms or child-resistant lighters.

In 2002 in order to provide local fire fighters and teachers with public education skills and leadership abilities to implement *Mis primeros pasos* and *Los buenos recuerdos* in Mexico, the Center for High-Risk Outreach created the Mexican Champion (*Campeone*) program. Candidates send in their application with support letters from their fire chief and local schools. The Center for High-Risk Outreach provides training and free materials for the *campeones* to use in the schools in various Mexican states. Results from teacher surveys and parent questionnaires show an increase in the understanding of fire safety behaviors

FIGURE 5.5.2 Elementary School Children in East Los Angeles Demonstrating Things That Can Get Hot and Singing "Cuidado, Puede Estar Caliente" ("Careful, It May Be Hot") from NFPA's Spanish-Language *LNTB Preschool Program*

FIGURE 5.5.3 A Teacher Training Session Conducted in the State of Aguacaliente in Mexico

and positive reaction from Mexican families. They also bring to the program leaders' attention related problems, such as not being able to locate residential smoke alarms in stores and families often not practicing the escape plan when there are no alarms in the home.

Other Resources to Support Foreign-Language Materials. It is essential to use professional translators to create foreign-language versions of fire safety materials. Professional associations such as the American Translator Association[46] can help locate translators. Educators should use an advisory group of people who are native speakers of the language to review the copy.

Educators should be sensitive to the audience. Foreign-language populations may include some who are not literate in their own spoken language; therefore, the educator may have to rely on illustrations to describe the message.

Furthermore, translated materials may be best given to the consumer with one side in English and one side in the foreign language because household members may be at different levels in their reading skills in English, with some primarily reading English and others primarily reading their mother tongue.

FIRST NATIONS POPULATIONS

In the United States native populations may be called the First Nations, American Indians, Native Americans, or by the name of a specific nation. In Canada, they may be called the First Nations, aboriginals, First Peoples, or by the name of a specific nation. Regardless of nomenclature, many of them qualify as disadvantaged populations.

During the 1997–1998 period, fire death rates were 2.1 times greater for Native Americans/Alaska Natives than for whites, with the highest death rates occurring among children 0–4 years old.[47]

The 2003 fire death rate in First Nations communities, expressed as the number of deaths per 100,000 population, was 3.0. The rate has generally been declining, except for sharp increases in 1988 and 1993. The 2003 rate shows a slight decline but is still higher than the 1998 figure of 1.7. The rate is 2.4 times higher than the 1999 Canadian national average of 1.27 (the latest available figure), which is considered high among first world countries.[48]

First Peoples in Canada

To help reduce fire deaths and injuries among First Peoples in Canada, the Assembly of First Nations of Canada, in cooperation with NFPA and the Aboriginal Fire Fighters Association of Canada, obtained funding from the Canada Mortgage and Housing Corporation to develop *The Wisdom of the Fire—Learn Not to Burn®*,[42] an adaptation of NFPA's *Learn Not to Burn Programs* for children of First Peoples in grades K–2. The program's purpose was to blend technical knowledge of fire safety behaviors with First Peoples' cultural teachings and traditions emphasizing the respectful and constructive use of fire. The program teaches 22 key fire safety behaviors. It employs the use and development of thinking skills and action/doing skills. Each activity is marked with a single eagle for activities for students to do alone and a group of eagles for activities for children to do together. They are designated as follows: think it out alone; think it out together; try it out alone; or try it out together.[49]

The program addresses the differences that exist among First Peoples by including blank and completed templates to provide examples of First Peoples' community profiles, positive fire safety behavior, fire safety words for translation into original languages of First Peoples, and First Peoples' legends and teachings about fire. The eagle was selected as a generic symbol to represent the culture of First Peoples.

"Flying high above the earth, the eagle has been given the gifts of farsightedness, strength, and speed; it watches the movement of all creatures and guards the well-being of others."[49] Children using the curriculum are named Junior Fire Eagles to fit within this theme. About 80 new illustrations by a Navajo artist are used to demonstrate the behaviors for the total curriculum and the pre- and postknowledge tests for kindergarten and first grades. In the illustration in Figure 5.5.4, children are instructed to circle the part of the illustration that shows what to do if there is smoke in a room.

Navajo Nation

The Navajo Nation is the largest American Indian nation in the United States and is about the size of the state of West Virginia. It is located in parts of the states of Arizona, New Mexico, and Utah and is divided into 110 governing chapters.

When a manufactured-home fire took the lives of two children and their mother in 1996 in the Navajo Nation, the Navajo Nation Bureau of Indian Affairs Safety Office contacted the NFPA Center for High-Risk Outreach for assistance in establishing a coalition to help reduce fires among the people in the Navajo Nation. The fire was caused by an improperly installed wood stove, a leading cause of home fires on reservations in the winter. About 30 people representing various organizations of the Navajo Nation such as the Navajo Fire Department, the Red Cross, the Indian Health Service, and a Navajo tribe from

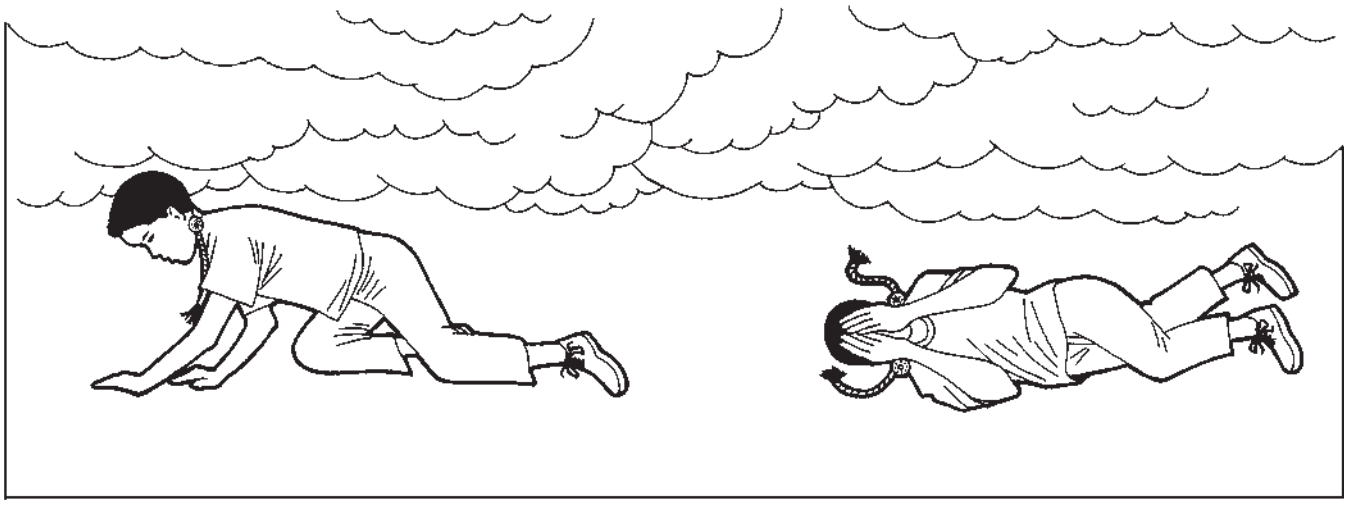

FIGURE 5.5.4 Artwork by Navajo Artist Irving Toddy, Used in the Knowledge Test for the *Wisdom of the Fire—Learn Not to Burn Program*

northern New Mexico and eastern Arizona attended a meeting. At the meeting the group learned that in 1995 there were 93 major home fires that left 400 people homeless in the Navajo Nation. Due to the lack of infrastructure of fire protection services in the Navajo Nation, 82 of the homes involved in these fires were completely destroyed. The group formed the Navajo Nation Fire Safety Coalition and began working on strategies to provide more fire safety programs for the 220,000 residents of the nation.

The coalition supported efforts in cooperation with the NPFA Center for High-Risk Outreach to implement the the *Learn Not to Burn Program.* Ten train-the-trainer sessions were conducted, reaching more than 350 teachers serving 6000 students. In addition the coalition implemented *Risk Watch* and *Remembering When* in selected chapters. In 1997 the Center for High-Risk Outreach conducted focus groups among Navajo people from the five major sections of the Navajo Nation: Eastern Navajo, Fort Defiance, Chinle, Western Navajo, and Shiprock. The purpose was to identify the needs, concerns, and cultural beliefs of the Navajo people and to educate attendees about various fire safety issues relevant to the Navajo Nation. Some recommendations resulting from the focus group included the following:

1. Make personal testimonies an important part of the program. House presentations should encourage people to talk about fire experiences and allow sufficient time for discussions.
2. Use public service announcements on KTNN, the reservation-wide Navajo radio station. Because many people do not have electricity, transistor radios are an important means to receive information.
3. Pair brochures, other written materials, and videos showing nonnative people with other materials depicting Navajos and using the Navajo language in addition to English.[50]

In 2005 with funding from a U.S. federal Fire Act grant, part of the Assistance to Fire Fighter Grant Program of the Department of Homeland Security, the Center for High-Risk Outreach worked in cooperation with the Navajo Nation Fire and Rescue. They trained dozens of trained installers who then installed nearly 10,000 smoke alarms in more than 3000 homes in the Navajo Nation. With the support of another Fire Act grant, the Center for High-Risk Outreach and the Navajo Nation Fire and Rescue planned to install another 8000 alarms in 2006 to 2007.

***First Nations Remembering When*™.** According to the Centers for Disease Control and Prevention (CDC), Native Americans age 65 and older are almost twice as likely to die in a fire than the general population of the same age. In order to address this need in 2005, the Center for High-Risk Outreach obtained funding from the Prevention and Safety Program Grant, part of the Assistance to Firefighter Grant Program of the Department of Homeland Security and the Office of Domestic Preparedness, to develop the *First Nations Remembering When* program to reach Native Americans age 65 and older. The program is an adaptation of *Remembering When: A Fire and Fall Prevention Program for Older Adults.*[51]

NFPA worked with a creative group that included fire department members, senior center directors, and older adults from the Navajo and Hopi tribes of New Mexico and Arizona, as well as the Fond du Lac Band of Lake Superior Chippewa to complete the *First Nations Remembering When* program for elderly people in tribes in the United States and Canada. The adaptation features Native American older adults from the various tribes demonstrating safety behaviors. Navajo artist Irving Toddy designed a logo and humor cards. The First Nations logo that Toddy created shows faces of elderly people woven together. The colors in the logo represent life, water/air, earth, and plants and when shown together signify the environment or the balance of man and mother earth.

The program includes several hands-on activities, checklists, and reproducible handouts. It also includes new reminder

sheets on wood stove and propane safety. An "Our History, Our People" trivia game highlights the history and accomplishments of First Nations people. The questions are coupled with safety questions aimed at reviewing the 16 key fire and fall prevention messages that form the basis of the program (Figure 5.5.5).

The program is implemented through the Indian Health Service, tribal senior centers, places of worship, community health representatives, fire service personnel, and educators.[51]

FIRE SAFETY FOR PEOPLE WITH DISABILITIES

According to a report released by the U.S. Census Bureau entitled "Americans with Disabilities: 2002," about 18 percent of Americans in 2002 said that they had a disability and 12 percent had a severe disability. That is approximately 51.2 million people who said they had a disability and 32.5 million who had a severe disability.[52] Persons have disabilities if they have difficulty performing a specific activity such as seeing, hearing, bathing, or doing light housework or had a specified condition such as Alzheimer's disease or autism. People are considered to have a severe disability if they are completely unable to perform one or more of these tasks or activities, need personal assistance, or have one of the severe conditions described in the report.[52]

People with disabilities also are much more likely to live in poverty than the general population. Median earnings for people with no disability are $25,000. The median income for people with a nonsevere disability is $22,000 and $12,800 for those with a severe disability.[52]

There are about 230 civilian deaths per year related to physical disability. Two-thirds of these deaths are to people age 65 and older.[53]

A person with a disability can be at greater risk to dying in a fire because it may be harder for the person to escape a fire. Or when a person is injured in a fire the particular disability the person may have may make him or her more likely to die from the injuries than the general population.

Since 1999 there has been a growing interest by the fire service for the issues of people with disabilities. In one of the NFPA Center for High-Risk Outreach free give-a-way programs fire departments and other organizations were required to fill out an application for a free version of the *Remembering When* older adults program. The form asked, "What new programs should NFPA develop?" One of the most frequent answers to this question was "develop fire safety education programs that fire departments could use to serve people with disabilities in their communities."

In the same time frame, the need to address the fire safety needs of people with disabilities came up in two symposiums entitled Solutions 2000 and Beyond Solutions 2000 that were organized in collaboration with the North American Coalition for Fire and Life Safety. These symposiums, held in 1999[54] and in 2001,[55] addressed the education, engineering, and enforcement needs of those who may not be able to take lifesaving action in a timely manner in the event of a fire, specifically young children, older adults, and people with disabilities. Leaders attending the symposiums who expressed the most dismay at there not being enough relevant programs were the group representatives of people with disabilities.

FIGURE 5.5.5 "Wear Safe Shoes" Fall Prevention Message from *First Nations Remembering When*™

To develop an action plan from the two symposiums, the Center for High-Risk Outreach and Oklahoma State University Fire Protection publications created the Fire Safety for People with Disabilities Task Force. In meetings held by the task force during 2002 to 2005 an action plan was developed, existing educational brochures and curriculum were reviewed with recommendations for inclusion and appropriateness for people with disabilities, education speaker sessions were conducted at NFPA World Safety Conferences, and new materials were developed to meet the needs of people with disabilities.

Among the criteria for public fire safety educators were the following:

1. Make materials accessible to all audiences both in format and design. Provide materials in alternate formats, such as Braille, audiocassette, interactive tactile (charts, games, props), music, close captioning, and so forth.
2. Make programs diverse and make art, content, and format sensitive to all areas of diversity, including socioeconomic status, ability, culture, and living situation. Include messages and pictures of people with disabilities integrated into general fire safety brochures addressing all people.
3. Make materials understandable. Illustrate what to do in photos or illustrations and use simple language. Provide explanations of pictures for people who are blind.
4. Make sure that information is not only technically accurate but also reflective of a variety of living situations.
5. Make materials compelling. Design and action should be practical and be convincing enough to motivate action.
6. Include experts in a variety of disabilities in all stages of the design and review of all materials.[56]

New materials that were developed on the recommendation of the task force included the "Fire Safety for People with Disabilities"[57] brochure (Figure 5.5.6) that gives tips on home fire safety and the "Workplace Safety for People with Disabilities"[58] information handout that gives both employers and employees with disabilities advice on escape planning in the workplace.

FIGURE 5.5.6 Representative Illustration from "Workplace Safety for People with Disabilities" (Illustrations by L. S. Pierce. © National Fire Protection Association)

Other successful fire and life safety education programs and materials that have been created for people with disabilities are described next.

Fire Prevention Program for Adults with Developmental Disabilities

Stacy F. Everson, executive director, Seeds Educational Services, worked with the University of Oklahoma Fire Protection Publications to develop a fire safety education program, *How to Be Fire Safe,*[59] for adults with developmental disabilities who live on their own. "There was a great need to create a fire safety curriculum that treats adults with developmental disabilities with dignity, respect, and provides correct information," explained Ms. Everson. "Understanding how people with developmental disabilities learn but not treating adults like children was crucial for communicating fire safety information to this audience."[60] Seeds hired a consultant with development disabilities to assist in a focus group to create the curriculum. The curriculum was then pilot-tested in California, Minnesota, and North Dakota. The program consists of a curriculum, a teacher's manual, a fire safety poster, and a fire assessment.

Content of the program includes smoke alarm maintenance and home escape planning. The poster that can be posted on the home refrigerator reinforces the material that has been taught through classrooms and individual home presentations. The curriculum has multiple pictures that enhance the presentations.

Presentations are given primarily through instructors of people with disabilities who understand people with disabilities. The curriculum requires four weeks to deliver. Three weeks of classroom instruction and one lesson right in the home are recommended. "My students don't generalize information; they need concrete in-the-home training," said Everson.[59]

There is a pretest and posttest assessment to gauge learning. A party is provided for participants at completion and graduation from the program.

Smoke Alarm Installation and Public Education Programs

People with disabilities may need smoke alarms with special features to ensure that they have early warning to escape a fire. People who are deaf or hard of hearing will often need to have smoke alarms with flashing lights to warn them. Generally, smoke alarms with flashing lights cost 5 to 10 times more than other smoke alarms. Communities that are conducting general smoke alarm programs will need to provide for those who will not be able to hear the regular alarms. Indeed, some smoke alarm programs have prioritized and focused their alarm installation programs on people who are deaf.

In 2004–2005 the Massachusetts Office of the State Fire Marshal in partnership with the Massachusetts Commission for the Deaf and Hard of Hearing (MCDHH) and the Massachusetts Department of Public Health (MDPH) secured a Fire Act grant to provide smoke alarms and fire safety education to people who are deaf or hard of hearing living in western Massachusetts. The Office of the Fire Marshal hosted a series of eight community meetings presenting general fire safety and instructions on how to install the detectors with strobe lights. The local partners provided applications for the detectors, liability waivers, gave out the smoke alarms, and arranged for a follow-up visit to check that the alarms were installed correctly and to instruct residents on how to test them.

A variety of communication methods were used in presentations to the audience. Presentations were delivered with assistance from both American Sign Language interpreters, certified deaf interpreters, and CART (Communication Access Real Time) readers.[61] CART interpreters type what is being said just like court stenographers and the text is projected onto a screen as for television except the interpreters also try to convey emotion, such as laughter. A PowerPoint presentation was designed with input from the Massachusetts Commission for the Deaf and Hard of Hearing for low English literacy that used many pictures. The project organizers also invited local fire department public education officers to the presentations in order to introduce them to people who are deaf and living in the towns they served.

There were 2300 alarms distributed to agencies and groups for installation. Data were received for 869 alarms installed in 428 homes.

Another smoke alarm installation program was sponsored by Fire Protection Publications and Oklahoma ABLE Tech, both at Oklahoma State University, entitled *Fire Safety Solutions for Oklahomans with Disabilities.*[62] This program provided installation of free smoke alarms not only for Oklahomans who are deaf or hard of hearing but also people who are blind or have low vision and people with mobility disabilities. Two types of alarms were used for this program: one using a strobe light and bed shaker for people who are deaf or hard of hearing and the other using a smoke alarm with a 10-year lithium battery that can be tested by using a television remote control for people with vision or mobility disabilities.

Installers also gave out several sets of educational handouts in large print on escape planning and prevention, tailored for people who have mobility impairments, persons who are hard of hearing, persons who are deaf, and persons who are blind or have low vision. The installers spent 1–2 hours in the home installing the alarm, helping draw up the escape plan, and reviewing the fire safety messages. The smoke alarm installation program reached people in 66 of Oklahoma's 77 counties.[63]

Other resources developed in this program included *Fire Safety for You at Home,*[64] an educational DVD in American Sign Language, and *Social Etiquette: For Fire Fighters Who Work with People with Disabilities,*[65] to help fire fighters better interact with people with disabilities. All these resources are available from Oklahoma State University, http://www.ifsta.org.

Fire Safety Programs for Children with Disabilities

Riley Hospital for Children has developed several programs to assist children with disabilities. With initial funding from the Department of Homeland Security, Assistance to Fire Fighters, Fire Prevention and Safety Grant, a hospital-based safety store and safe escape product distribution program was developed to ensure that children with disabilities or special health

care needs will escape safely in the event of a fire. During 2005, 700 families were provided adaptive fire safety products and education. Some of the fire safety items included smoke alarms with strobe lights and bed shakers, portable stretchers with hand grips to drag a child with mobility disabilities out in a fire, and fire-smothering blankets. Families with children with disabilities who visited the safety store got the free adapted fire safety products and fire safety education. Riley Hospital also provides free brochures and posters for parents of children with disabilities. In the poster and materials the message of "Stop, Lock, and Roll" is used for children in wheelchairs instead of "Stop, Drop, and Roll" for reaction to clothing fires.[66]

All communities have people of all ages with disabilities. If fire safety educators don't see them at presentations that they give it may very well be that the presentations have not been made accessible. The more that the fire service makes presentation forums accessible and that materials are provided in accessible formats the more likely that persons of all abilities will become involved and will become recipients of important fire and life safety messages.

HOME SECURITY AND FIRE SAFETY

People can become at high risk for fire as an inadvertent side effect of actions taken in good faith in response to other problems considered in isolation. An emerging example has been the elevated fire risk arising from certain steps taken for home security. One example is entrapment caused by bars on windows and doors installed to keep out intruders.

It is hard to measure the exact numbers of deaths and injuries that occur as a result of exits blocked by bars on windows and doors. Those observing the home security industry believe that more and more people are blocking themselves in their homes with bars or other measures, such as nailing windows shut or even blocking doors and windows with plywood or furniture. For example, four children perished in a fire in 1997 in Tampa, Florida; a family of five died in a fire in Bessemer, Alabama; and in East Palo Alto, California, nine people were killed in a fire. In 2002, an Alabama fire killed two adults and a 5-year-old. The same year, a Georgia fire killed three adults.[67] The Home Security and Fire Safety Task Force of the NFPA Center for High-Risk Outreach has worked on this issue since 1993, focusing on engineering, education, and enforcement approaches. The following are some of the key messages:

- Make sure windows open easily and fully enough to allow escape.
- Make sure all security-barred windows needed for escape have emergency-release devices and that everyone can open them (Figure 5.5.7).
- Make sure locked or barred doors operate quickly and easily and that everyone knows how to open them.
- Practice exit drills in the home and use them to identify and correct obstructions of doors and windows needed for escape.
- Have working smoke alarms on each level of the house and outside of every sleeping area.[68]

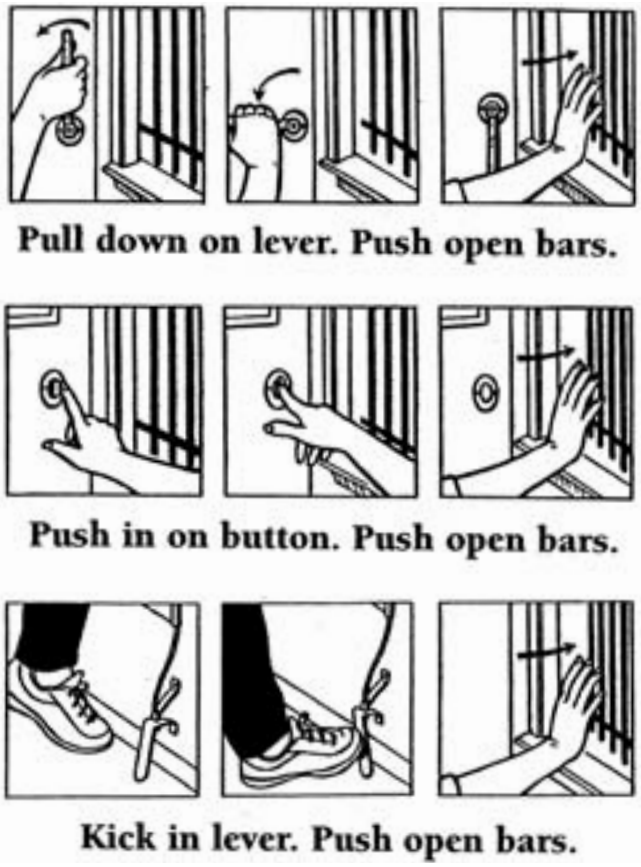

FIGURE 5.5.7 Types of Emergency Release Devices (Source: Exhibit S6.2, *Life Safety Code® Handbook,* 2006 ed.; illustrations by L. S. Pierce. © National Fire Protection Association)

Several cities have formed coalitions to provide retrofitting of security bars with emergency-release devices and community educational programs on fire safety and home security. One of the most comprehensive local programs was organized by Steve Kastner, fire marshal for the city of Ft. Lauderdale, Florida. This program was initiated by the combined Fire-Rescue and the Building Departments. The program was composed of public education, financial assistance, and enforcement. The department received $108,000 from a federal Community Development Block Grant to pay for the cost of retrofitting one window per bedroom of homes with security bars on the windows. Those grants were available to owner-occupied, single-family homes or duplexes for owners with low and moderate incomes. The Fire and Building Department identified a quality contractor to work for the city to retrofit the windows with bars.[69]

Community inspectors did sidewalk surveys to identify properties that had bars on windows. Building inspectors later visited properties and issued notices of violation. Property owners were given 30 days to initiate action. Since the program's inception in 1997, over 800 properties were cited. Of these, 80 percent went before the Code Enforcement Board and 50 percent had complied by May 2001.[69]

The education component of this program included the development of an informational brochure on security-bar hazards and code requirements and how to access financial assistance. This brochure was distributed to homeowner groups and civic associations. Presentations were also given to civic associations, targeted neighborhoods, and the city commission. In order for this program to succeed, the following internal and community partnerships were needed: the mayor, city commissioner, city manager, fire chief, fire marshal, building official, Council of Civic Associations, individual civic associations, homeowner associations, community service and action organizations, and other city agencies.[44]

In June 2005 the Home Security and Fire Safety Task Force decided to address the problem of other barriers to safe escape in the home. Some of those barriers included doors and windows painted or nailed shut, clutter, furniture, or appliances blocking doors or windows, plywood over windows, and hurricane shutters left in place after a hurricane is over. A new free literature piece titled "Clear Your Escape Routes!" was made available on NFPA's website.[70]

NATIONAL PROGRAMS IN THE UNITED STATES

National Center for Injury Prevention and Control (NCIPC) Smoke Alarm Programs

One of the best ways that communities can reduce fire deaths and injuries in high-risk communities is by implementing smoke alarm programs. Homes with smoke alarms typically have death rates about 40 to 50 percent less than the rate for homes without alarms.[29]

To reduce deaths in high-risk communities, the National Center for Injury Prevention and Control (NCIPC) of the Centers for Disease Control and Prevention (CDC) funds 18 states through three 5-year cooperative agreements with the state health departments to provide fire injury prevention programs. These programs provide installation of smoke alarms and education on fire safety and escape plans. Each state focuses on communities within their state that have fire incidence rates above the state average and mean household income below the poverty line. The state health department staff provides oversight and technical assistance to the local program officials and fosters partnerships between local communities and fire safety personnel. From October 1998 to December 2005, more than 382,000 homes have been canvassed through the program; 275,000 smoke alarms have been installed in 157,000 high-risk homes.[71]

Successful techniques learned in the CDC projects include the following:

- Partnering with local fire departments in the community (both paid and volunteer)
- Partnering with community-based organizations to assist in canvassing homes
- Getting support from community leaders
- Being flexible in the hours and days of the week that canvassing activities are conducted
- Advertising the program through all available media

National Fire Academy Class

Several organizations have recognized the need to reach those most vulnerable to fire and burns. In 2000, the United States Fire Administration in cooperation with the NFPA Center for High-Risk Outreach developed a new 2-week National Fire Academy Class, *Discovering the Road to High-Risk Audiences.*[47] The course takes an in-depth focus on topics that include the impact of social and economic diversity on the fire problem, fire and life safety for people challenged with disabilities, the aging process and fire risk, and the effect of fire on very young children.[72]

The class is designed for personnel who have responsibility for public fire and life safety education in their fire departments and who have more than 1 year in this functional area. The class discusses what factors make the audience vulnerable, ways to reach each group, and how to plan programs for them. Both the urban and rural audiences are woven into the course material. It uses evaluation methods such as small group learning exercises and case studies.

In 2006 the National Fire Academy added a new class titled *The Changing American Family at Risk.* It emphasizes the importance of and methods for reaching America's families to protect them from fire. The content includes the changing family structure in America, the means and methods of reaching families on the hazards of fire, and the relationship between the American family and fire risk.[73]

INTERNATIONAL PROGRAMS

Many innovative fire safety education programs are occurring outside North America in both developed and developing countries. Leaders of these programs have also found the importance of targeting their high-risk populations. A description of two of the initiatives follows.

South Africa

Factors that exist in South Africa that make people at greater risk include the use of paraffin (kerosene) for cooking and lighting, large number of security bars on windows and doors because of a high crime rate, poor housing construction, lack of fire-safe construction, and poverty. In the past the City of Johannesburg Emergency Management Services fire safety education program for children consisted of demonstrating fire safety skills to children by showing them how the fire department extinguished a fire.[74]

To provide a more successful delivery of fire and injury prevention education in the city, a public education division was developed for the Emergency Management Services. Several programs are conducted by the public education division, including the *Learn Not to Burn Preschool Program* and *Risk Watch*. Community Emergency Response Teams (C.E.R.T.) were developed to provide fire safety skills as well as to provide instruction on how to extinguish a fire in its earliest stage to people who live in informal settlements with a high incidence of fires.

In 2005 various injury prevention and health organizations formed the National Burn Prevention Reference Group to work

with NFPA to produce a South African version of the *LNTB Preschool Program.* The group adapted the eight fire safety behaviors for South African children and is working to make the program culturally appropriate for South Africa.[75]

For more information on the programs of South Africa, see Section 5, Chapter 2, "Fire and Life Safety Education Messages."

Australia

The 1991 census indicated that there were more than 2.7 million people (17.4%) age 5 and older in Australia whose first language spoken at home was other than English. In the state of Victoria, 22.6 percent of the population fell into this category; in the city of Melbourne in Victoria, 28.8 percent were in this category.[50] Fire departments have used a variety of strategies to reach this segment of the population, including translations of printed materials, advertisements, involvement in wider programs sponsored by other organizations, lectures, and use of radio stations targeted to ethnic audiences.[76]

One unique program implemented jointly by the Melbourne Fire Brigade and the Adult Migration Education Services in Victoria is *Flames—Better English Through Fire Safety Program. Flames* is a collection of activities that a teacher can integrate as a subtheme into a broader course in English as a second language. The materials are divided into levels of proficiency and focus on the themes of smoke alarms, escape from fire, fire hazards and prevention, and calling the fire brigade. Some of the materials used in the program are an audiotape with scripts, student work sheets, a reader, a quiz, and a board game.[51]

A fire fighter visit highlights the program. Fire fighters have been given preparation on how to talk to adults who are learning English as well as information about students' levels of English.[77]

SUMMARY

Many mainstream fire and life safety education programs fail to reach those who are at greatest risk. Programs implemented among the general population do not automatically trickle down to those at most risk—preschool children, older adults, the disadvantaged, and those who speak languages foreign to the country in which they are living.

This chapter presented characteristics of the various high-risk groups that put them at high risk to fire and provided samples of programs and strategies to reach those groups. It pointed out societal trends and demographic changes that help to anticipate new needs as communities grow or change. The chapter emphasized not only educational solutions but also samples of engineering and legislative changes that will make the total outreach program more successful.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire and life safety education reaching high-risk groups discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA *101®*, *Life Safety Code®*
NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*

Chapter 6

Juvenile Firesetting

Paul Schwartzman

Chapter Contents

Terminology
Magnitude of the Problem
Characteristics of Children Involved in Firesetting Behavior
Motivation for Firesetting Behavior
Response to Juvenile Firesetting
Pitfalls
Training
Information Resources

Key Terms

arson, Dynamic-Behavioral Theory, fireplay, firesetting, Juvenile Firesetter Intervention Specialist (JFIS), public fire and life safety education

The fire service has known that children are accountable for many fires. In a small city in northern Pennsylvania, a presentation was being made on children and fire. The fire chief wanted to highlight their local fire museum and escorted a group to take a tour. On entering the museum, a fire department run-log from the late 1800s was displayed on a pedestal under a glass cover. The log was open to a handwritten entry describing a house fire with extensive damage. The cause was listed as "children playing with matches."

Prior to the mid-1970s, there were few, if any, programs or even concepts on how to change the behavior of children playing with matches. Some in the fire community took the view that "kids will be kids," treating firesetting by children as a normal and harmless stage of development. On the other end of the spectrum were those who believed that children who misused fire were psychologically disturbed. This view saw juvenile firesetting as neither normal nor harmless but still as unpreventable. Both views left the fire community with no effective intervention other than effective fire fighting.

The mid-1970s brought about major change. The fire service began working with mental health professionals to better understand firesetting behavior and evolve more effective intervention and prevention strategies. The past 25 to 30 years have brought about a much greater understanding of young people's misuse of fire and what can be done to prevent and minimize further incidents. This chapter highlights many of these findings and procedures that the fire service can implement to reduce fire incidents involving young people.

See also Section 5, Chapter 1, "Principles and Techniques of Fire and Life Safety Education."

TERMINOLOGY

An important aspect of understanding children and fire is being familiar with the language frequently used to describe this behavior. Different words and phrases are employed depending on perspective and position. Discussions on the standardization of terminology are currently ongoing among fire professionals and others involved in addressing this concern. Common use of terms would facilitate more precise statistics describing the magnitude of the problem as well as directing appropriate prevention and intervention strategies.

The primary distinction in labeling behavior is intent. Children who do not understand the consequences of their use and have no specific intent of starting a fire traditionally have had this behavior referred to as "fireplay." The terms *accidental* or *unintentional* have also been used to describe this behavior.

These terms have become quite controversial. Associating the concept of play with children's use of fire has raised concerns. Play is a positive aspect of child development and many have questioned whether using the term *fireplay* minimizes the risk and normalizes the behavior.

The term *accidental* formally implies a behavior or incident that could not be avoided or prevented. This notion when applied to children's use of fire also raises concerns because these incidents are not truly accidental. In fact, it is argued that almost no fire cause is "accidental." Enhanced supervision or storage of ignition materials can usually prevent these incidents. Advocates

Paul Schwartzman is a nationally certified psychotherapist with over 25 years' experience working with children and families. In 1981, while on staff at the University of Rochester, he and his colleagues in cooperation with the City of Rochester Fire Department began doing research on children and fire. This research led to the development of a model Juvenile Firesetter Program. He has a private counseling practice and consulting service in Rochester, New York.

of these perspectives prefer the terms *fire experimentation* or *fire starting,* believing that this phrase is more accurate and better describes the intent. Critics of these alternative terms, however, argue that *experimentation* and *starting* imply more conscious intent, deliberation, and knowledge than are typically present. So far, the search for a phrase free of misleading connotations has been unsuccessful.

The label of *firesetting* implies a deliberate effort to start a fire. The term *firesetting* is often associated with arson. *Arson* is a legal term that implies a deliberate intent to cause damage or injury. Similar to the concern involving the term *fireplay,* arson or firesetting carries an ominous tone and raises objections. Some feel that the use of these terms causes avoidance of the issue because of the stigma attached to these terms. Fire fighters are resistant to labeling a young child a firesetter or arsonist. In many jurisdictions, the legal age of accountability precludes young people from being charged and the terms are not applied.

Common terminology can go a long way to clarify and facilitate better responses to the problem of children and fire. It is not the intent of this chapter to establish a standard terminology. Doing so will require more dialogue among the various organizations to come to consensus. The terminology used in this chapter will echo common terms currently used in report forms and among fire service officers and line fire fighters.

MAGNITUDE OF THE PROBLEM

Based on fires reported to U.S. fire departments in 2002, there were 13,900 structure fires attributed to children playing with fire the latest year for which data were available. Children's fireplay resulted in 210 civilian deaths, 1250 civilian injuries, and $339 million dollars in direct property loss.[1]

Although this will be further explored later in this chapter, it is clear that a significant portion of fires involving young people goes beyond "child-playing" and is more intentional. Incendiary fires that are intentional can be considered arson. The Federal Bureau of Investigation (FBI) Uniform Crime Report for 2002 indicated that 51 percent of arson arrests were children under the age of 18, the ninth straight year that the juvenile share has been 50 percent or more. One-third of juveniles arrested for arson were under 15, and 3 percent were younger than 10[2] (Figure 5.6.1).

In 2002, 68,245 incendiary fires reported to U.S. fire departments resulted in an estimated 630 civilian deaths, 2030 fire injuries, and $1.9 billion in direct property loss. If half of these incidents and losses are assigned to juveniles, it means that 34,000 fires can be attributed to juvenile incendiarism, as can a death toll comparable to that for child-playing fires.

This does not include the many fires that never come to the attention of the fire service. Past studies have estimated unreported fires at 10 to 20 times the number of reported fires, although most are small cooking fires. Changes in the way that fires are reported and coded in the National Fire Incident Reporting System may also contribute to variations in the number of incidents. Putting the juvenile share (51%) of 2002 arson arrests together with the estimated total number of reported U.S. fires due to incendiary or suspicious causes, and then adding

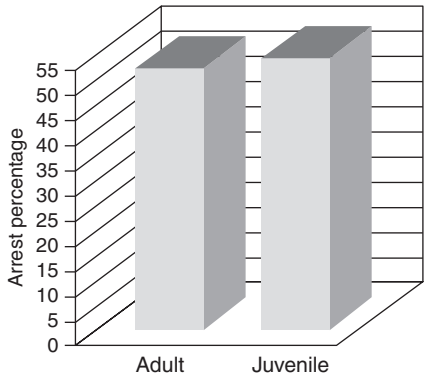

FIGURE 5.6.1 Juveniles Arrested for Arson as a Percentage of All Arrests, According to FBI Statistics

in the 2002 child-playing fires, the estimated total of reported fires started by children in 2002 is at least 50,000 fires, 545 civilian deaths, 2212 civilian injuries, and $1 billion in direct property loss. Precise numbers will remain elusive, but it is clear that juvenile firesetting remains a significant and dangerous problem.

The good news is that the total number of such fires and associated losses have consistently plunged since 1994. Mental health professionals assessing the problem of children and fire believe that a significant proportion of this reduction is due to the efforts of the fire service systematically addressing juvenile firesetting along with the introduction of a child-resistant requirement for lighters by the U.S. Consumer Product Safety Commission.

CHARACTERISTICS OF CHILDREN INVOLVED IN FIRESETTING BEHAVIOR

Age

In Rochester, New York, the city fire department tracked fire incidents over a nine-year period to determine youth involvement. The study identified children from 18 months to 18 years of age who had been involved in an incident that required a fire department response. The majority of fire incidents involved youth between the ages of 4 and 9 years.[3,4] Additional studies in other cities that systematically respond to fires with youth involvement have paralleled these numbers.

Preschool children under age 6 are disproportionately likely to be killed in child-set fires, accounting for more than 66 percent of deaths in child-playing home fires and about 15 percent of deaths in incendiary or suspicious fires, while accounting for only 9 percent of the population. Fireplay remained the leading cause of fire deaths among preschoolers. It is often not the children who were playing with fire who die. Very often it was a sibling or playmate. Most of the people killed by child-playing fires are under age 6.

The above-mentioned Rochester studies further determined that a third of youth involved in fire incidents were between 10

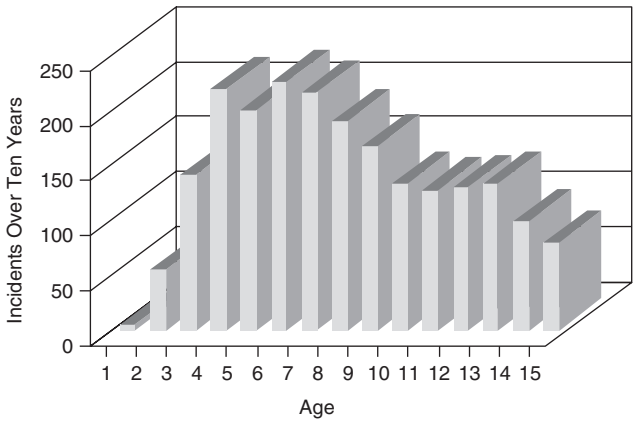

FIGURE 5.6.2 Age of Children Involved in Actual Fires, According to the Rochester Study

and 17 years of age, with 98 percent of these being under age 15 (Figure 5.6.2).

Gender

Firesetting is predominantly a male behavior. Studies tracking youth involved in fire incidents consistently report that young people who come to the attention of the fire service average 85 percent male and 15 percent female. This closely matches the gender breakdown for arson arrestees of all ages. Males tend to be more highly represented in risk-taking and acting-out behaviors of all kinds.

Interestingly, a developmental study[5] of school-age children looking at behavior with fire found a higher percentage of females. Children in grades 1 through 8 were asked if they ever experimented with fire. In this group, the male to female ratio was 2:1. Therefore, on comparing young people who come to the attention of the fire service because of a fire concern with a general population of school children who have not come to the attention of the fire service, the percentage of female involvement more than doubled (from 15 percent to 33 percent). When asked how they used fire, females stated that they lit matches and lighters, whereas males tended to use such implements to ignite other things, making their experimentation riskier and perhaps more detectable.

Family Type

Firesetting occurs in all family types but is somewhat overrepresented among single-parent households, as is the fire incidence in general. This is believed to be more a factor of increased stress and decreased time for supervision rather than family structure.

Socioeconomic Status

Poverty is highly correlated with firesetting. In a longitudinal study examining children who came to the attention of the fire department,[3] over 90 percent were found to be on a free or reduced lunch plan in school compared to 35 percent in the district as a whole. This indicates that the family falls below the poverty line. Families living in poverty typically have more difficulty providing structure, appropriate supervision, and effective parenting due to household chaos and chronic stress, evidenced by relationship discord and unemployment. Families in poverty typically have less education and are, therefore, less likely to possess the awareness and judgment to provide a safe environment. The same lack of effective supervision that makes ignition more likely also makes it more likely that fires will grow large enough to require fire department intervention and become reported fires. The inability of a poor household to readily absorb fire damage as a result of poor construction and high housing density may also make it more likely that their fires will come to the attention of the fire department.

Race and Ethnicity

Race and ethnicity are not associated with firesetting behavior, although they appear to be in studies that do not adjust for correlated socioeconomic conditions, such as poverty. Children are represented proportionately to the presence of their race or ethnicity in the general population.

MOTIVATION FOR FIRESETTING BEHAVIOR

Fire fascinates us all. Its power, beauty, and functionality parallel few entities existing on our planet. It is, therefore, natural that people of all ages express curiosity about fire. However, for young people with limited skills and understanding, turning curiosity into fire play can be deadly. Young people are motivated to use fire for various reasons. This section will present the underlying philosophy of how firesetting behavior develops and describe profiles describing different motivations or goals.

Dynamic-Behavioral Theory

At the outset of this chapter, it was mentioned that collaboration between the fire service and mental health community during the mid-1970s brought about new understanding. One of the major outgrowths of this collaboration resulted in a conceptual framework designed to explain firesetting behavior. This framework, known as the Dynamic-Behavioral Theory, was developed primarily by Dr. Kenneth Fineman, a clinical psychologist working closely with the Los Angeles County Fire Service and the United States Fire Administration.

The Dynamic-Behavioral Theory views firesetting as an interaction among the individual, the family, social circumstances, and immediate environmental conditions. The major contribution of this theory is that characteristics of firesetting youngsters can be organized and classified by using this conceptual framework and observed and measured. The Dynamic-Behavioral Model is an additive factor model. Models similar to this model have been used in all kinds of injury control studies and have wide acceptance.

Individual characteristics consist of demographic, physical, emotional, motivational, and psychiatric descriptors. Social

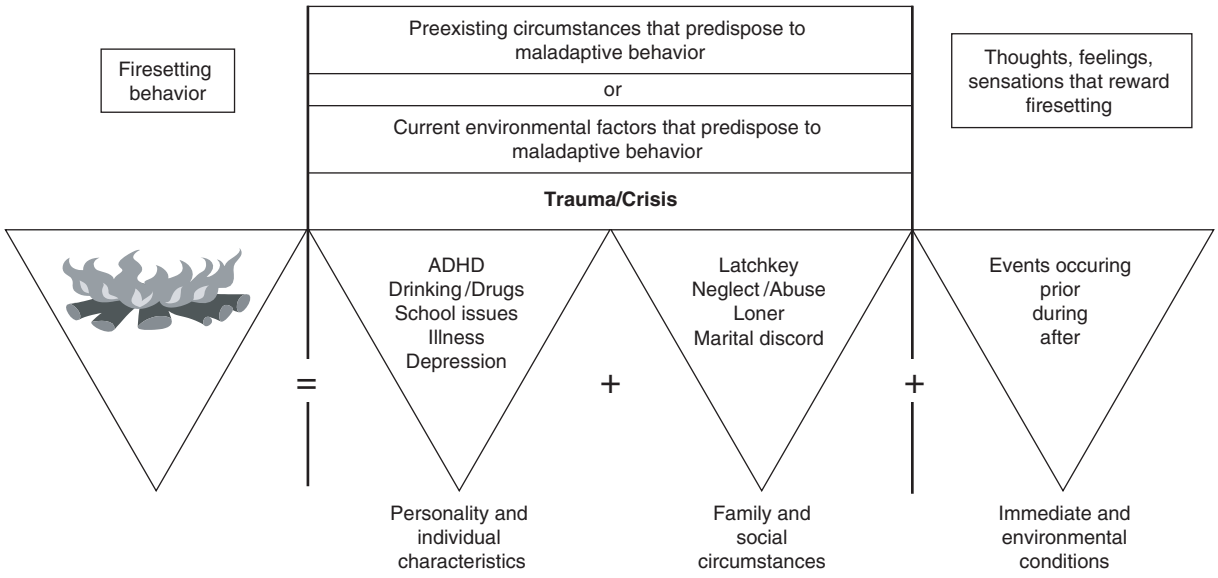

FIGURE 5.6.3 The Dynamic-Behavioral Model (Source: Paul Schwartzman and Ken Fineman)

circumstances are composed of family, peer, and social descriptors. Environmental conditions refer to events occurring immediately prior, during, and after firesetting. These variables interact to produce firesetting or increase the risk of firesetting. Figure 5.6.3 illustrates the sequence of how these dimensions may evolve to produce firesetting behavior.

Types of Firesetters

Many "types" of firesetters are listed in the literature concerning firesetting behavior. Researchers have categorized firesetters by focusing on a variety of personality and other factors, which specify a quality of the personality of firesetters and of their previously set fires. Any attempt to categorize the firesetter should serve the pragmatic purpose of helping describe the firesetter's risk level for future fire-related dangerous behavior and help guide prevention and intervention efforts. Dangerous in terms of firesetting are behaviors that destroy property or do physical and/or emotional harm. Another concern is the probability that the juvenile will set more fires.

It is important to understand that these categories are not exclusive. In fact, a firesetter may have multiple motives for his or her behavior. The following firesetter types focus on the firesetter's psychological state or diagnostic category, what is set on fire, or whether the fire is set as a function of the firesetter's need to bring attention to himself or herself or the need to use fire to direct attention elsewhere.

Curiosity Type. The most common profile describes children who act primarily out of curiosity and do not developmentally understand the consequences of their behavior. The few studies[3,4,6–8] that have examined representative samples of children converge on this point. The majority of children who start fires do so out of experimentation and may not have other psychological problems. Children motivated exclusively by curiosity tend to be young, primarily between 5 and 10 years of age, and to be involved in only one reported fire incident.

Although this curiosity-driven fire play is apparently not pathological, it is nevertheless potentially dangerous and a concern. Individual, family, and environmental factors predict whether children engage in fire play and serve as guides to preventive intervention. Access to ignition materials, momentary lapses in supervision, the perception that they would not be disciplined if they were caught playing with fire, and premature exposure to and responsibility for activities involving fire are all associated with curiosity fire play.[5] Children also often have an unrealistic sense of their ability to control a small fire. Teenagers trying to conduct science experiments could fall into this group.

Case Example. Jonathan, age 9, lives with his mother and father in a single-family house. One evening at about 7 p.m., Jonathan was in his bedroom while his parents were downstairs watching television. Jonathan's mother smokes and had left her cigarette lighter on the dresser in her bedroom. Jonathan saw the lighter on the dresser and took it into his room. He lit the cigarette lighter and touched the flame to some school papers he had piled in his room. The papers quickly ignited and Jonathan became frightened and dropped the papers on the floor near his bed. The flame spread to the bedding. Jonathan slapped at the flames with a nearby blanket and yelled for his father. Fortunately, Jonathan was able to put the fire out but not before singeing the bedding. His father arrived dismayed but glad that Jonathan was not injured and that there was no further damage. Jonathan was very remorseful and frightened. He was crying and apologetic and insisted that he did not mean to start a fire.

Cry-for-Help Type. The cry-for-help type includes children of all ages. These juveniles consciously or subconsciously wish to bring attention to an intolerable life stress, for example, a

personal problem such as feelings of depression or anger. It could also be associated with an interpersonal concern such as family stress and dysfunction, stressful life events, separation and divorce, and remarriage. This type of firesetting is more likely to continue without intervention. Physical and sexual abuse and chronic neglect are frequently associated with recidivism.[3,4,6–8]

Case Example. Mark, age 12, lived with his mother and stepfather. Mark had a younger brother, age 10, who was the birth child of his mother and stepfather. Mark frequently felt left out and believed that his stepfather treated him more harshly than his brother. Mark and his brother would argue frequently. During an argument, Mark's father became extremely angry and grabbed Mark and pushed him across the room, telling him that he would have to go live elsewhere if he did not stop fighting with his brother. Mark strongly felt that his brother was as responsible as he for these arguments, but his stepfather would not acknowledge this possibility and kept blaming Mark, claiming that he was older and knew better. Mark was sent to his room for the rest of the day. Shortly thereafter, a neighbor reported seeing smoke coming from the eaves outside of Mark's bedroom window and called the fire department.

Delinquent Type. The delinquent type usually involves adolescents between the ages of 11 and 15. Typically their firesetting is part of a larger constellation of conduct and aggression problems. This behavior most often occurs with other juveniles. An interest in vandalism and hate crimes is noteworthy. As juveniles manifesting this type, though frequently showing little empathy for others and little conscience, they usually avoid harming others with fire. Significant property damage is common. In this group, firesetting behavior is more easily extinguished than other personality and behavioral problems that usually accompany the firesetting.[3,4,6–8]

Case Example. Seven youths under the age of 18 began setting fires in dumpsters, then graduated to setting them in automobiles and vacant buildings. In March 1996, members of this group set a fire in an illegal tire dump beneath an interstate highway, resulting in damages estimated at $8 million to the overpasses. Commuter and interstate traffic was disrupted during the incident and for months during the repair. Various members of this group are linked to intentionally set fires in 18 vacant buildings in the same area.

Severely Disturbed Type. The severely disturbed type—the rarest type—includes young people who are suffering from serious mental health problems that may include paranoid and psychotic symptoms. Often, the firesetting may be reinforced because it creates a profound sense of elation or sensory reinforcement. Sensory reinforcement describes those for whom the sensory aspects of the fire are sufficiently reinforcing to cause fires to be frequently set. The reinforcement histories of many suggest an early fixation on fire. A subgroup of this type is the "self-harm" type, whose members use fire to harm or kill themselves. Prognosis is guarded with this severely disturbed group.[3,4,6–8]

Case Example. Lenny, age 7, was subdued by his parent after he attempted to set fire to his little brother. The police and fire department were immediately dispatched to the scene. The juvenile firesetter intervention specialist began talking to the young boy about his behavior. Lenny explained that he was directed to burn his little brother by the devil. When the fire investigator asked how he communicated with the devil, the boy stated that the devil was present in the room and that they had a regular conversation. Lenny was admitted to the child psychiatric hospital for further observation and treatment. Lenny had several firesetting incidents and was described by others to behave bizarrely.

Cognitively Impaired Type. The cognitively impaired type includes the developmentally disabled and the organically impaired types. This group, although tending to avoid intentional harm, lacks good judgment. Significant property damage is common.[7] The organic group includes those persons whose cognition ability or ability to control impulses is significantly affected by their neurological or medical state. Also included in this group are persons with severe learning disabilities and those who were affected by fetal alcohol syndrome or by drugs taken by their mothers during pregnancy.

Case Example. Ken, age 14, was referred to the fire department by his parents. The parents were afraid because Ken had started several fires in and around their home. Ken was severely learning disabled and impulsive. He attended a self-contained special education program to assist him with his learning disabilities and impulsive behaviors. Ken was also on several medications to control impulsivity and other behavior concerns. Ken had suffered from these behaviors since birth, and his parents stated that he needed constant supervision. Although they worked hard to control the environment and keep ignition materials from him, he was persistent. Ken is a very concrete thinker and when he does understand and accept an idea or concept, he internalizes it. Ken's parents hoped that the fire department might be able to provide information and education that Ken would find meaningful and affect his behavior.

Sociocultural Type (including the uncontrolled mass hysteria type, the attention-to-cause type, the religious type, and the satanic type). This category includes those who set fires in the midst of civil unrest and are either enraged and enticed by the activity of others and follow suit or set fires with deliberation in order to call attention to the righteousness of their cause. Those involved in uncontrolled mass violence frequently lose control and harm others, though initially the intent to do so may not be present.[7]

Case Example. The Earth Liberation Front is a group of older adolescents and young adults who are currently attempting to bring attention to a cause. This group targeted a ski resort in Vail, Colorado, by burning five buildings and four ski lifts because they believed that the development threatened the lynx. This group has also targeted housing projects in wildland regions because they feel these properties are infringing on nature. They justify their behavior with rhetoric, explaining the injustice imposed on others.

RESPONSE TO JUVENILE FIRESETTING

Juvenile firesetting is a community problem. The fire service is in a unique position to address it. Although specific responsibilities can be distributed among different agencies, depending on resources and demographics, the fire service is usually in the best position to manage the community response.

Successful program models have been examined for several years. An Office of Juvenile Justice and Delinquency Prevention (OJJDP) and United States Fire Administration (USFA) initiative to assess effective programs addressing juvenile firesetting identified seven critical components.[9] A recent review conducted by a group of researchers on behalf of the National Association of State Fire Marshals (NASFM) funded by OJJDP confirmed that these program components remain state of the art.[10] The components are as follows:

1. A *program management* component to make key decisions, coordinate interagency efforts, and foster interagency support.
2. A *screening and evaluation* component to identify and evaluate children who have been involved in firesetting.
3. An *intervention* services component to provide primary prevention, early intervention, and/or treatment for juveniles, especially for those who have already set fires or shown unusual interest in fire.
4. A *referral* component to link the program with the full range of community support agencies that might help identify juvenile firesetters and provide services to them and their families.
5. A *publicity and outreach* component to raise public awareness of the intervention program and encourage early identification of juvenile firesetters.
6. A *monitoring* component to track the program's identification referrals and treatment of juvenile firesetters.
7. A *juvenile justice* system component to establish relationships with the juvenile justice agencies that often handle juvenile firesetters.

Program Management

Effective programs need structure and standard operating procedures. In most instances, juvenile firesetter intervention programs (JFIP) are incorporated into ongoing department operations such as fire prevention, investigation, or inspection. It is recommended that JFIP efforts be incorporated into the day-to-day responsibilities of these programs, with specific responsibilities assigned to trained individuals.

Whether programs are located in a specific department is a matter of philosophy and personnel resources. Some juvenile firesetter specialists recommend locating programs in specific areas. Some propose that programs are better positioned within the investigation units so that fire circumstances can be more carefully reviewed and that the law enforcement aspects are preserved for incidents involving intentionally set fires. Figure 5.6.4 illustrates one way to locate juvenile firesetter programs within a fire department.

Other juvenile firesetter specialists propose that the educational aspects of children and fire need to be emphasized due to the primary motivation of curiosity and experimentation and that programs should be situated in fire education units. Both concerns are valid and essential. Most important is that programs include the components just listed and that the response to all concerns regarding children and fire be handled systematically and thoroughly, whether the response is to a big fire or to no fire at all.

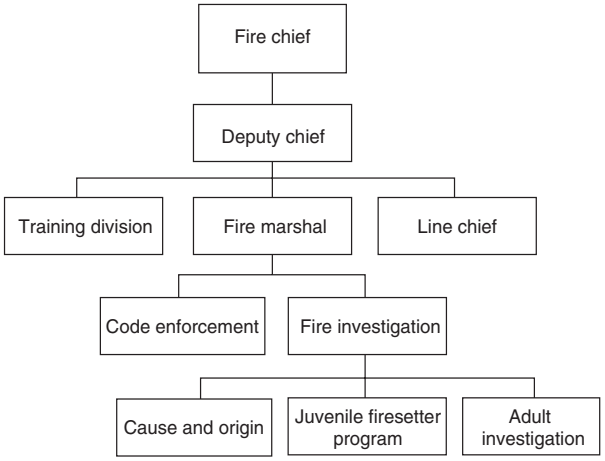

FIGURE 5.6.4 Sample Organizational Chart of a Juvenile Firesetter Intervention Program Within a Fire Department

Figure 5.6.5 illustrates the flow of a well-organized program. Referrals can be initiated from anyone with awareness or concerns regarding firesetting behavior. The process remains the same whether there is an actual fire or no fire at all. Therefore, a careful information-gathering procedure to assess motivation and direct interventions is needed. This is succeeded by a follow-up contact to assess the effectiveness of the intervention and the need for any additional services.

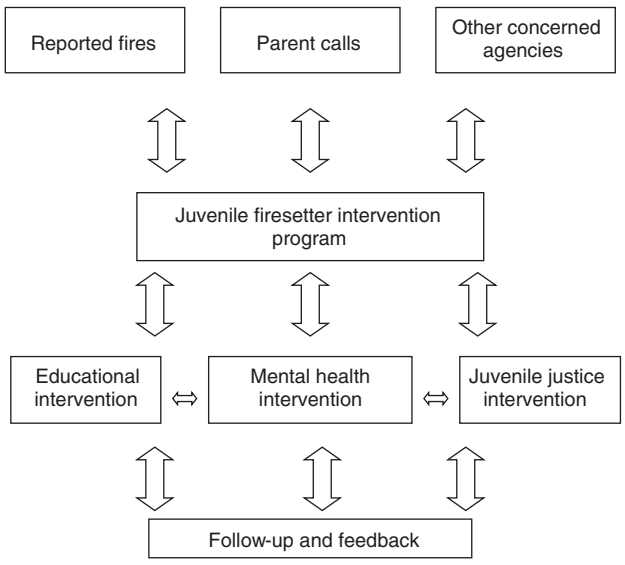

FIGURE 5.6.5 Referral Flow Chart

For the first time, the 2000 edition of NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*, includes two chapters outlining job performance requirements for Juvenile Firesetter Intervention Specialist I and Juvenile Firesetter Intervention Specialist II.[11] The standard is a resource to facilitate development of job responsibilities and procedures.

A Juvenile Firesetter Intervention Specialist I is an individual assigned with the day-to-day tasks of conducting a juvenile firesetter intervention program. This individual is responsible for keeping records of contacts, conducting assessment interviews, delivering educational interventions, and making referrals given the direction and feedback of a supervisor, but he or she does not have program management or oversight responsibilities.

A Juvenile Firesetter Intervention Specialist II is the program coordinator or manager. His or her responsibilities address key management concerns such as record management, compliance with government regulations, referral procedures, supervision of assessment and intervention personnel, establishment and maintenance of interagency networks, public relations, and program development and evaluation.

In a smaller program or department, it is likely that a single individual performs the role of Juvenile Firesetter Specialists I and II. In 2005, the Juvenile Firesetter Specialists I and II requirements in NFPA 1035 were revised to reflect the most current trends in the field (Table 5.6.1).

Screening and Evaluation

An essential component of an effective JFSI program is the screening and evaluation procedure to determine primary motivation and potential risk for future firesetting. This component typically includes structured interviews with the children and parents conducted by a trained juvenile firesetter intervention specialist. Most JFSI programs conduct the initial screening interviews themselves; if additional concern is generated, children are referred to identified specialists to conduct more comprehensive assessments. Some programs prefer to have all assessments initially conducted by an outside agency or professionals who are certified to work with youth and families.

The goal of the interview is to obtain background information about the child(ren), family, and fire behavior. Usually, the interviewer explains the purpose of the meeting, interviews the children and parents separately, and then reconvenes the family to explain the outcome and recommendations. Different programs based on philosophy and resources conduct this interview either at home or at an approved facility outside the home such as fire department administrative offices.

Both procedures have been demonstrated to be effective. There are advantages and disadvantages to each location. In the family home, the interviewer has the opportunity to assess the physical environment and observe the family interaction in their natural setting. However, the interviewer sacrifices an element of control in the home and sometimes children and families are more accountable in an "official" location.

The Federal Emergency Management Agency/United States Fire Administration (FEMA/USFA) has supported the development and distribution of manuals and community training materials.[12–17] FEMA manuals include copies of structured interview forms[18–20] and guidelines for their use. These interview forms were initially developed in the late 1970s by Dr. Fineman and are based on the Dynamic-Behavioral Theory mentioned earlier in this chapter. The manuals and the interview forms were revised in 2000 and are currently available from FEMA/USFA.

The revised FEMA manual includes a "short form," which is a subset of the complete interview designed to be a preliminary assessment. Figure 5.6.6 displays a page from the full assessment. Many practitioners have advocated a shortened procedure. This abbreviated interview is a relatively new procedure and will require a longitudinal study to determine its ultimate reliability. The initial caution is that any reduced inventory will possibly miss important information, but it might provide useful information to make a preliminary decision in the field by less experienced personnel.

The FEMA forms are not the only forms available. Well-established programs throughout the United States have taken the initial concepts and revised them to meet their own needs and procedures. Many of these programs have worked with local universities and researchers to establish reliability. A few examples of these are the Phoenix Fire Department in Arizona, the Portland Fire Department in Maine, the Monroe County Fire Bureau in Rochester, New York, and the State Fire Marshal's Office in Oregon. Most programs are proud of their efforts and welcome inquiries regarding their screening and assessment procedures.

The following is an example of the assessment procedure. The FEMA (child, parent, and family) forms are designed to assist in determining risk for additional firesetting behavior. The questions are scored and totaled to indicate the degree of risk. The scale ranges from little risk to extreme risk. The FEMA *Juvenile Firesetter Intervention Handbook*[21] defines the categories of risk as little risk, definite risk, and extreme risk.

Little Risk. Curiosity or experimentation accounts for the majority (60 to 65%) of children's involvement in fire in the little risk category. Most of these children are of little risk of repeating their behavior if they receive the proper supervision and educational intervention.

Definite Risk. Approximately 30 to 40 percent of children and adolescents fall into the definite risk category and are very likely to be involved in future fire behaviors. They are in need of interventions in addition to educational interventions. The cry for help and delinquent types described earlier typically fall into this category.

Extreme Risk. Less than 1 percent of children and adolescents fall into the extreme risk category. The severely disturbed types suffering from severe mental illness are most likely to be of extreme risk.

Interventions

Juvenile firesetting is a community problem requiring a community response. A comprehensive program is balanced between

TABLE 5.6.1 Professional Requirements for Juvenile Firesetter Intervention Specialists I and II

Job Performance Requirement (JPR) Group	*Juvenile Firesetter Intervention Specialist I*	*Juvenile Firesetter Intervention Specialist II*
Administration	**9.2.1** Assemble forms and materials, given approved forms, program policies, and procedures, so that the intake process is conducted according to those program policies and procedures. **9.2.2** Assemble interview tools and material resources, given tools and materials as determined by program policies and procedures, so that an interview with a juvenile and his or her family can be conducted. **9.2.3** Utilize personal work schedule, given contact name and requested time, so that all interviews are conducted on time and in a location agreeable to all parties. **9.2.4** Report case information to supervisor, given a case file that includes approved forms, the intake/interview information, and selected intervention(s), so that the supervisor can ensure that the intervention process meets all required program policies and procedures. **9.2.5** Record and secure data, given case information, approved forms and/or database, and program policies and procedures, so that statistical analysis can be completed.	**10.2.1** Formulate program policies and procedures, given a community needs assessment; program goals; community and agency resources, services, and organizations; so that the program policies and procedures match and support the goals of the program and the needs of the community. **10.2.2** Develop a program budget, given program policies and procedures, program needs, and revenue sources so that capital, operating, and personnel costs are determined and justified. **10.2.3** Identify and assign a JFIS I or other qualified personnel trained to conduct the intake/interview, given the program needs, resources available, and program policies and procedures, so that intakes/interviews are conducted according to the program policies and procedures. **10.2.4** Supervise the JFIS I assigned to the case, given program policies and procedures, so that a consistent body of information is collected, performance is evaluated, and continuous direction and feedback are given. **10.2.5** Maintain records and case files of each juvenile firesetter, given all data collection forms, program policies and procedures, and legal requirements, so that consistent and accurate documentation on process and content is available for each case, legal issues are addressed, progress is tracked, the program is evaluated, and federal and state/provincial reporting requirements are met.
Planning and Development		**10.3.1*** Develop an interagency network, given a current list of agencies, an interagency agreement, and protocol, so that roles and responsibilities are clarified; the mission, interagency agreements, and intervention are established; and duplication of services is avoided. **10.3.2*** Develop or select approved forms and materials, given existing forms or the option to create your own, so that the forms meet the needs of the program and follow the program policies and procedures. **10.3.3** Design a training program for program personnel, given a training curriculum, approved forms and materials, so that program personnel are able to perform intakes/interviews and interventions, including education, referral, follow-up, and evaluation. **10.3.4** Develop a community awareness program, given a mission statement, state/provincial program policies and procedures, and incident data, so that the community recognizes juvenile firesetter issues and available intervention resources. **10.3.5** Create a data collection system, given all approved forms and materials, legal requirements, and program policies and procedures, so that consistent and accurate documentation is maintained.

TABLE 5.6.1 Continued

Job Performance Requirement (JPR) Group	*Juvenile Firesetter Intervention Specialist I*	*Juvenile Firesetter Intervention Specialist II*
Education and Implementation	**9.4.1** Review a case file, given intake information, so that before speaking with the child and his or her family, the juvenile firesetter intervention specialist becomes familiar with the circumstances of the firesetting incident(s). **9.4.2** Initiate contact with the family, given the case file, so that the juvenile firesetter intervention specialist contacts the family; explains the program and its benefits; schedules a time, date, and place for the intake/interview; and advises the family of possible intervention options. **9.4.3** Conduct an intake/interview, given approved forms and guidelines, so that the juvenile firesetter intervention specialist can establish the purpose and limits of the intake/interview, establish rapport, gather relevant information, identify and intervene in any immediately life-threatening situations, report any suspected abuse or neglect, record and report observations, and summarize findings. **9.4.4** Determine intervention(s) and referral options with regard to educational, mental health, and/or possible legal consequences, given the case file, completed intake/interview forms, and knowledge of fire safety, so that specific educational material can be selected, mental health options explored, and legal consequences explained. **9.4.5** Implement educational, mental health, and legal interventions, given the case file, educational materials, and referral resources, so that the firesetter and his or her family complete the intervention(s). **9.4.6** Implement referral process, given current interagency network list and program policies and procedures, so that the juvenile firesetter and his or her family can expediently gain access to needed services and priority needs are met in a timely fashion.	**10.4.1** Deliver a training program for program personnel, given a training curriculum and approved forms and materials, so that program personnel are able to perform intakes/interviews, interventions, referrals, follow-ups, and evaluations. **10.4.2** Maintain a current interagency network, given established interagency agreements, so that responsibilities and program goals are met. **10.4.3** Deliver community awareness training to current interagency network members, given the training program, so that continued support is maintained for the juvenile firesetter program and juvenile firesetters are identified and referred to the program.
Evaluation	**9.5.1** Collect and record feedback from the juvenile firesetter and his or her family at designated intervals, given completed intervention(s) and referrals and approved forms and materials, so that the firesetter and the family have the opportunity to provide feedback. **9.5.2** Measure changes in juvenile firesetter and family behavior, given completed feedback forms, so that program results are documented.	**10.5.1** Evaluate the program, given program goals, feedback, records, and case files, so that program outcomes are determined and met. **10.5.2** Analyze the effectiveness of the program, given the evaluations, including information on recidivism, so that any necessary changes to the program can be made. **10.5.3** Prepare a program report, given evaluation results and program goals, so that the community and current interagency network are informed and support is generated for the program.

Source: Chapters 9 and 10, NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator,* 2005 edition.

	C-1	C-2	C-3	P-1	P-2	P-3
BEHAVIOR ISSUES						
10. Do you get in trouble frequently at school? Yes (C-2) No (C-1)						
11. Do you usually not do things you are asked to do? Yes (C-2) No (C-1)						
12. Have you ever stolen or shoplifted? Yes (C-2) No (C-1)						
13. Do you frequently lie? Yes (C-2) No (C-1)						
14. Have you ever used drugs, alcohol, or inhalants? Yes (C-2) No (C-1)						
15. Have you ever beat up or hurt others? Yes (C-2) No (C-1)						
Behavior Issues Subtotals						
COMMENTS:						

FAMILY ISSUES						
16. Do you like going home? Yes No Why? _____						
17. How well do you get along with your mother (female caregiver)? always get along (P-1) usually get along (P-1) sometimes get along (P-2) don't get along very often (P-2) never get along (P-3)						
18. Do you fight or argue with your mother? always (P-3) usually (P-2) sometimes (P-1) rarely (P-1) never (P-1)						
19. Are you afraid of your mother? always (P-3) usually (P-2) sometimes (P-1) rarely (P-1) never (P-1)						
20. How well do you get along with your father (male caregiver)? always get along (P-1) usually get along (P-1) sometimes get along (P-2) don't get along very often (P-2) never get along (P-3)						
21. Do you fight or argue with your father? always (P-3) usually (P-2) sometimes (P-1) rarely (P-1) never (P-1)						
22. Are you afraid of your father? always (P-3) usually (P-2) sometimes (P-1) rarely (P-1) never (P-1)						
23. Do your mother and father fight? [If the parents fight, have the child elaborate on the fights] always (P-3) usually (P-2) sometimes (P-1) rarely (P-1) never (P-1)						
24. Tell me about your brothers and/or sisters. How well do you get along with them? *(If there is a variability in the relationship among siblings, rate the most serious.)* always get along (P-1) usually get along (P-1) sometimes get along (P-2) don't get along very often (P-2) never get along (P-3)						
25. Do you see your mom as much as you'd like? Yes (P-1) No (P-2)						
26. Do you see your dad as much as you'd like? Yes (P-1) No (P-2)						
27. What do you do that gets you into trouble at home? _____						
28. What happens at home when you get in trouble? grounded him/her (P-1) physical punishment (P-1) or (P-2) nothing (P-2) talked/lectured (P-1) or (P-2) sought outside help (P-1) yelled (P-1) or (P-2) abused (P-2) or (P-3) other (P-1) or (P-2) Explain _____						
29. Do you get spanked/punished too much? Yes (P-2) No (P-1) If so, by whom ____						
Family Issues Subtotals						
COMMENTS:						

FIGURE 5.6.6 Sample FEMA Assessment Form (Source: K. Fineman, "Comprehensive Fire Risk Assessment," in Poage et al. (Eds.), *Colorado Juvenile Firesetter Prevention Program: Training Seminar Vol. 1,* Colorado Division of Firesafety, Denver, CO, 1997)

prevention and intervention services. This section will sample some fundamental intervention strategies and methods.

Primary Prevention. The goal of primary prevention is to reduce the likelihood of children and adolescents engaging in unsupervised activity with fire. As illustrated in Figure 5.6.7, primary prevention is a multifaceted approach based on the prevention triangle and the three E's: Educate, Engineer (sometimes called Environmental Change), and Enforce.

Education is the responsibility of the fire service, parents, teachers, media, community, neighborhood groups, and many others to provide relevant messages. Education messages that are aimed at children and fire should put emphasis on providing consistent supervision to children and adolescents, restricting access to ignition materials, teaching fire and life safety, and assigning age appropriate responsibility.

The developmental study[5] mentioned earlier explored the relationship between premature assignment of responsibility for tasks involving fire and subsequent unsanctioned use of fire. Premature assignment of responsibility may be defined as children cooking or building a fire in the fireplace before fully understanding the consequences or responsibilities of this action. Children who perceive their parents approve of this behavior feel a greater sense of control and permission and are more apt to be involved in unsupervised, nonsanctioned use of fire.

Effective prevention programs encourage the utilization and creation of products and environments that are engineered to prevent fire use or minimize the consequences from misuse. An excellent example of this is the manufacture of the child-resistant lighter designed to restrict the ability of preschool age children from igniting the flame on a disposable lighter. Additional examples range from the use of sleepwear and bedding with flame-retardant fabrics to the installation of residential sprinkler systems.

Intervention programs are designed to respond to actual concerns or incidents and can vary depending on the risk level determined in the assessment and the circumstances of the fire. Effective intervention programs have a range of interventions and include educational interventions, mental health counseling, juvenile justice consequences, and child welfare actions. Depending on the motivation and outcome of the risk assessment, one or all of these interventions might be implemented.

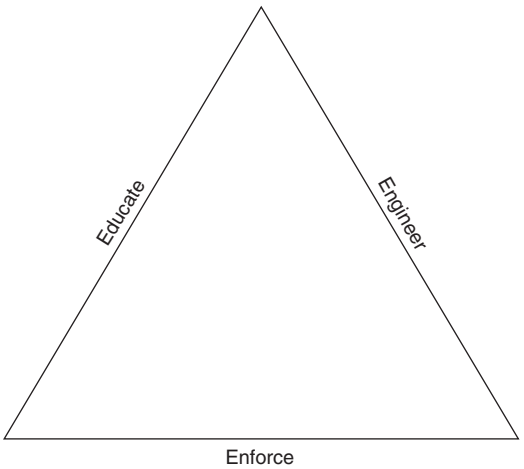

FIGURE 5.6.7 Fire Prevention Triangle

Educational Intervention. Educational interventions are recommended for most young people who demonstrate an inappropriate interest in or use of fire. The majority of presentations are going to be primarily motivated by curiosity. Well-constructed education programs are effective for changing this behavior.

Educational interventions need to be aimed at the youth involved in the incident as well as primary caretakers. Programs traditionally include reactive fire safety behaviors that teach what to do in the event of a fire such as "stop, drop, and roll" and "know two ways out." This information is clearly essential and saves lives, but it does not address the curiosity and misinformation that empowers young people to experiment with fire. Educational interventions need to be age appropriate. Information should be presented in a concrete manner and without scare tactics.

Table 5.6.2 illustrates objectives particularly appropriate for the listed age categories. Providers should feel flexible to amend objectives based on individual needs.

The priority for preschool children is to teach them that matches and lighters are for adult use only and that children should tell a grown-up if they discover matches or lighters in their environment. Preschool children are capable of learning basic life safety messages such as "crawl under smoke" and should be taught these skills. Caregivers should be included and encouraged to have children practice these behaviors so that the skills are rehearsed.

Many of the objectives are appropriate for adolescents as long as they are adjusted to be age appropriate. Many intervention programs include projects that require young people to create escape plans and home safety drills. Community impact statements have also proved successful in creating empathy and understanding. In a community impact statement, youth are required to complete a project that highlights the impact their actions have had on others.

The only exception to providing an educational intervention concerns the timing of the intervention rather than the omission of this procedure. In certain cases, children or

TABLE 5.6.2 Educational Intervention Objectives

Parents or Caregivers	*Ages 5–8*	*Ages 9–11*
Fire safety	Power of a single match	False sense of control
Limit access to ignition materials	How quickly fire spreads	Responsibility and fire
Supervision	False sense of control	Consequences of misuse
Age-appropriate responsibility	What burns	Personal vulnerability
Clear rules and consequences		Peer pressure

adolescents may be of imminent harm to themselves or others or may be in crises and, therefore, not able to process the information. When the situation stabilizes, it is suggested that an appropriately leveled educational intervention be implemented. Research at the University of Pittsburgh conducted by Dr. David Kolko specifically demonstrated the effectiveness of a structured intervention program that incorporates fire safety education for reducing the likelihood of future misuse of fire.[22] This was compared to a more casual intervention in which fire fighters make a brief visit to the home to discuss with parents ways to prevent children from using fire and to hand out educational materials.

Mental Health Intervention. As indicated in the Dynamic-Behavioral Theory and the crisis profile type, firesetting behavior is often motivated by the interaction of the individual with his or her family or social circumstances. Frequently, the individual lacks sufficient coping or problem-solving skills. Referral for individual and family counseling is imperative.

Counseling juvenile firesetters is not substantially different from interventions with others, but some critical aspects need to be understood and addressed. The specific mental health interventions are beyond the scope of this chapter but are generally built around a case management model, which allows for careful coordination of services and includes focus on the firesetting behavior. Mental health treatment for juvenile firesetters needs to be personalized to the firesetting type, motivation, and circumstances. Treatment tools include individual treatment, family counseling, cognitive techniques, behavior management, empathy and social-skill building, parenting skills, problem-solving methods, and relaxation techniques.

Referrals should always be made to mental health professionals who have specific understanding of juvenile firesetters. When knowledgeable mental health providers are not available, the fire service should facilitate access to training and information to develop these resources. A comprehensive overview of treatment strategies is available in the National Association of State Fire Marshal's Juvenile Firesetter Intervention Project Research Report.[10] This information is downloadable free of charge at the website www.firemarshals.org. The section is entitled "Juvenile Firesetter Mental Health Intervention: A Comprehensive Discussion of Treatment, Service Delivery, and Training of Providers," and comprises areas 1 and 2 of the overall report. The bibliography of the NASFM report references several resources that further address treatment concerns. The references at the end of this chapter also contain additional treatment resources by this author and others.

Social Service Intervention. It is well established that a critical predictor of repeat firesetting is documented incidents of neglect and abuse. In the Rochester study,[3,4] recidivism, or repeat firesetting, increased fivefold in families in which children were victims of chronic neglect and physical or sexual abuse. Juveniles who experience this in their lives feel powerless and helpless and sometimes use firesetting because of its power to bring attention to a serious concern in a dramatic way.

Dr. Alan Feldberg, director of Cornell Abraxis, a residential treatment facility in Pennsylvania, has conducted some initial case studies of the participants in his program who have all been adjudicated as juvenile firesetters with an average of 27 fires. Thirty-eight percent have a documented history of being sexually abused, 76 percent experienced chronic verbal abuse and humiliation, 78 percent were physically abused, and 100 percent suffered chronic neglect.

It is essential that a juvenile firesetter intervention program have an established relationship with the child welfare agency charged with responding to abuse and neglect. Parents and primary caretakers must be held accountable in these cases and children protected from further abuse. Social services agencies can assist with evaluation and help determine the need for placement and mandate services.

Referral Component

Juvenile firesetting is not just a fire service problem; it is a community problem. If there is any single aspect that can enhance the likelihood of success, it is the relationship among key stakeholders in a community. Effective intervention demands a comprehensive network of services, clear interagency communication, ongoing support, and follow-through.

Many juvenile firesetter intervention programs have established community advisory panels to facilitate the development and maintenance of their program. Perhaps one of the best established advisory panels based on its longevity and influence is the Phoenix Fire Department Community Advisory Panel.[23] Figure 5.6.8 displays the organizations represented on the Phoenix Fire Department Community Advisory Panel.

All State Insurance Agency
Arizona Burn Center at Maricopa County Medical Center
Behavioral Health
Childhelp USA
Child Protective Services
Foundation for Burns & Trauma
Judicial Officer for Juveniles
Juvenile Probation
Maricopa County Attorney's Office
Maricopa County Public Defender's Office
Phoenix Parks, Recreation & Library
Phoenix Police Department
Raising Arizona Kids Magazine Publisher
School Principal
School Psychologist
United Phoenix Firefighters Local 493
Valley Wide Fire Departments

FIGURE 5.6.8 Phoenix Fire Department Community Advisory Panel (Source: Phoenix Fire Department)

The panel meets on a bimonthly basis to help determine actions and services necessary to address juvenile firesetters. The goals of the advisory panel are as follows:

- To utilize the members collective resources and expertise to reduce youth firesetting in the community
- To identify potential funding sources
- To increase the awareness of the program to its member agencies and to provide training
- To encourage ongoing collaboration in the community

The panel of community stakeholders is in the best position to help define what entails an appropriate referral to any given agency or service and the procedures to make the referral. Particular attention should be paid to necessary forms, funding, hours, feedback to referring party, availability, and waiting lists. All participants need to be trained in these procedures and kept abreast of any changes.

Confidentiality is frequently perceived to be a roadblock to interagency cooperation. This is often interpreted too narrowly. *Confidentiality is not intended to deter services.* It is critical that agencies serving children and their families share information that enables them to coordinate and provide more effective services. A failure to provide information generally results in fragmentation and duplication of services.[24]

In all circumstances, information can be shared with the consent of a juvenile's parent or guardian. A release of information signed by a parent or guardian allows information to be freely shared. Disclosures on a need-to-know basis can also be made when there is immediate need for information to prevent imminent harm to self and others. Children who are at high risk to start fires could be argued to fall under this umbrella.

Other arrangements can be made to facilitate communication between agencies. A memorandum of agreement can be established between two agencies that bind the providers in each agency to confidentiality under the regulations of each agency. Information can be provided when a school initiates legal action against a student or when a lawfully issued subpoena is presented.

Florida passed legislation designed to facilitate the sharing of information between entities. The state passed legislation to require the State Department of Juvenile Justice to establish an early delinquency intervention program with cooperation of local law enforcement agencies and community service agencies that work with children. Comparable laws exist in other states.[25]

It is beyond the scope of this chapter to detail all the circumstances in which information can be shared. Communication is facilitated in an environment where there is awareness, trust, and ongoing relationships to clarify how information is to be used. Confidentiality is not intended to hinder effective interventions when trying to help young people.

Publicity and Outreach

Generally, a program is only as successful as its reputation. Awareness of the program goals and how the public and relevant agencies can access the program should be regularly disseminated. The advisory panel is an excellent body to help distribute information among its members and outside. Public service announcements can be a useful method to reach a broad audience. The United States Fire Administration has developed brochures and videotape-based programs that can be used for presentations to service organizations, schools, and other community groups to increase awareness.

Publicity and outreach programs should be designed to fit the profile of the community so that the messages clearly define the problem in terms of types of fires, who is at risk, demographics, and cultural influences. Messages should be designed to inform and not frighten the community. More diverse communities should design outreach that is multilingual and fully utilizes the media to maximize exposure.

There is plenty of room for creativity to extend reach at low cost. One community in upstate New York arranged to print messages regarding match and lighter safety with program contact information on the grocery bags of a major grocery chain, thus enabling the message to reach thousands without any direct cost to the program.

Monitoring

Careful record keeping to measure program utilization and results can help programs survive in environments where resources are highly sought after or scarce. Feedback of this nature also helps managers structure programs to best meet the needs of the community. Program personnel should monitor at least the kinds of referrals that come into the program, the basic demographics of clientele, types of firesetting behavior, source of referrals, and referral dispositions.

It is also recommended that program personnel document their activities. Keeping track of presentations, interventions, program development activities, and interagency networking will help to ensure that adequate resources both in personnel and monies are allocated to the maintenance of the program over time.

Methods of tracking these data should be carefully considered. It is generally recommended to collect information as individual data points and not in a summary or aggregate form. Data can always be grouped to generate a summary but cannot be unbundled once aggregated.

Program managers should decide whether program activities and data will be tracked specifically to the program or whether there will be a central system for collecting and storing information within the department. Regardless, data should be easily retrievable.

Program personnel will want to determine whether an individual has had prior contact with the program as well as generate reports for reporting and monitoring systems. Computerized data management systems are available. Dr. Fineman and the Orange County Fire F.R.I.E.N.D.S. (Firesetter Regional Intervention Education Network and Delivery System) have recently developed a Web-based data system based on the FEMA forms. The database covers all aspects of the incident as well as individual and family data. The database has specific data fields with many drop-down menus that encourage systematic data collection and accuracy. This system is available to programs that are registered with this group and that are willing to

share aggregate data toward the development of a national data collection system. Many fire departments around the United States have developed custom systems using desktop computers. Some departments have adapted the National Fire Incident Reporting System to store information and some still utilize the old-fashioned method of file folders and index cards.

Programs with several years of history and documentation in states such as New York, Oregon,[26] Arizona,[23] Massachusetts, Indiana, and Illinois[27] consistently demonstrate reductions in rates of repeat firesetting among young people who have come to the attention of their programs. Communities that have established primary prevention programs document reductions in the numbers of fires and resulting loss of young lives and property, especially among preschool age children.

Juvenile Justice

Children and adolescents need to be accountable for their actions. In the earlier referenced developmental study,[5] it was demonstrated that children are less likely to misuse fire if they perceive that their behavior will have a consequence. The juvenile justice system has a critical role. The juvenile justice system has the power to mandate services and to hold juveniles and their families accountable.

The juvenile justice system usually comprises the juvenile unit of the probation department and family court. Family court is designed to address behaviors that would be considered crimes if committed by an adult. The ages of culpability (age at which a child can be held accountable) vary from state to state and typically range from 7 to 16 years of age. Children older than 16 may be treated as adults in many areas of the United States. Given the chaos in the lives of many cry-for-help and delinquent-type firesetters and the risk to the community, this power is a pivotal factor in addressing juvenile firesetting.

Effective juvenile justice programs maintain graduated sanctions. These sanctions consist of mandated counseling interventions, restitution, accountability, and community service on an initial level; and secure confinement in community settings, training, and aftercare on more severe levels. The juvenile justice system in each community needs to work with the juvenile firesetter intervention program to aggressively support programs that address juvenile problems through a continuum of services and sanctions that consider youth needs, family needs, community safety, and victim restoration.[28,29]

PITFALLS

Clearly, juvenile firesetting is a serious concern requiring a systematic response that is institutionalized and supported. The following comments are intended to highlight common pitfalls that can undermine programs or prevent them from being maximally effective.

Too often juvenile firesetter programs are initiated by an individual who appreciates the problem and has a passion to do something to help. Although it is true that an individual's efforts can start something that can make a difference, attempting to maintain a program single-handedly threatens the life of the program over time.

When a program is generated and maintained by an individual, it is unusual to find replacements that have the same level of energy and ownership to carry on these efforts. Individuals retire, get promoted, reassigned, or simply burned-out and with these changes go the program. Individuals who have a passion to work with juveniles involved with fire will best serve the mission by making a concerted effort to institutionalize the program so that the program's longevity can be their legacy.

Programs need to be recognized and supported from top to bottom within a fire department. It was stated earlier that juvenile firesetting is not just a fire service problem but a community problem. However, when attempting to establish and maintain a program within the fire department, it needs to be acknowledged that this is not just the responsibility of the prevention or investigation unit conducting the program.

TRAINING

Training opportunities are widely available. The National Fire Academy in Emmitsburg, Maryland, has established a series of courses focusing on Juvenile Firesetter Intervention Specialists I and II as defined by NFPA 1035. These courses are offered at the academy and regionally around the United States. A leadership curriculum has been developed to correspond with these courses. The United States Fire Administration has revised and reissued its manual and forms. Statewide coalitions in states such as Oregon and Massachusetts conduct annual conferences with comprehensive seminars on a wide variety of related topics.

The National Fire Protection Association provides training and awareness via the annual World Fire Safety Conference and Exposition in June. In addition, several training entities are establishing certification programs based on NFPA 1035 in cooperation with state certifying bodies. Many of the consultants and providers who helped establish these programs are available to work with individual communities to assist in developing personalized training, program development, and evaluation services. Distance-learning opportunities have also spawned Web-based courses on juvenile firesetting and related areas. A number of professional publications have also been published in the past few years and a comprehensive book on treatment of juvenile firesetters by this author and colleagues is being readied for publication.

Awareness of the juvenile firesetter issue needs to be incorporated on an ongoing basis at all levels of training and professional development within the fire service. The Rochester, New York, Fire Department has its juvenile firesetter intervention specialists present an overview of the issue and the intervention process to every graduating class at its fire fighter training academy. In this way, all new recruits begin their careers with a basic understanding of children and fire. Officer training programs should adopt this model as well.

Effective juvenile firesetter intervention depends on suppression, prevention, investigation, and inspection divisions all working together. It is the responsibility of every line fire fighter and officer to be sensitive and alert to the possibility of juvenile involvement and to initiate intervention.

Programs that are highly successful have support not only from the hierarchy within the department but also from the entire fire service ranks. Oregon established an infrastructure that supports juvenile firesetter intervention statewide. The Oregon State Fire Marshal established a full-time coordinator responsible for supporting juvenile firesetter intervention programs, which includes facilitating all the program elements illustrated earlier.

Although the importance of establishing formal programs within the fire service is advocated, it is also important to acknowledge that programs should be designed to meet the demand however large or small. Programs can be undermined when they are underutilized. Program managers need to be sensitive to the size of the community and to the potential number of referrals. Rural communities may not want to put extensive resources into maintaining an individual program but may want to combine personnel and resources between a few departments to establish a regional or county-based program.

At the opposite end of the continuum, programs that are understaffed will also be undermined. Program credibility will be lost in the community if referrals cannot be responded to in a timely or comprehensive manner. Staff turnover will increase if personnel perceive that they are not able to protect children and their families due to inadequate support or feel they cannot perform their duties competently.

INFORMATION RESOURCES

Fire departments can build on the experience of many established programs throughout North America. Technology allows the transfer of information and materials unlike that in any period in our history. Several websites have been established solely for supporting efforts to address juvenile firesetting. Many of these sites offer links to other sites and provide references for materials, training, and speakers (Table 5.6.3).

In addition, several state coalitions and providers have established newsletters and publications that are published regularly. Perhaps the best known is *Hot Issues,* published by the Oregon State Fire Marshal's Office for Juvenile Firesetting. The newsletter is published quarterly and features program issues, treatment recommendations, current research, and resources.

TABLE 5.6.3 Juvenile Firesetter Websites

Organization	*URL*
National Association of State Fire Marshals	http://www.firemarshals.org
National Fire Protection Association	http://www.nfpa.org
Oregon State Fire Marshal—Hot Issues	http://www.osp.state.or.us/sfm/html/hot-issues.htm
Phoenix Fire Department JFIP	http://www.ci.phoenix.az.us/FIRE/firesetr.html
SOS Fires Youth Intervention Programs	http://www.sos.fires
United States Fire Administration	http://www.usfa.fema.gov

SUMMARY

The fire service has never been in a better position to be the leader in addressing the problem of juvenile firesetting. Juvenile firesetter intervention programs work. Years of collective experience and research have proven that the fire service is in a unique position to make a critical difference and to do what it has always been recognized for doing—saving lives and protecting property.

Our communities are struggling with many complex and frustrating problems and challenges endangering our youth. Clearly there is always room to grow and perfect our understanding, but the problem of children and fire is one that we have considerable knowledge about and the immediate ability to impact.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on juvenile firesetting discussed on this chapter. (See the latest version of The NFPA Catalog *for availability of the current edition of the following document.)*

NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*

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Chapter 7

Using Data for Public Education Planning and Decision Making

John R. Hall, Jr.

Chapter Contents

The Role of Data in Community Fire Education Planning
Problem Definition
Intervention Strategies
Target Audience Considerations
Mapping Program Delivery
Was the Target Audience Reached?
Did the Strategy Work?

Key Terms

high-risk audience, program, public fire and life safety education, risk, strategy

Successful fire and life safety education begins with good decisions by the managers of fire and life safety education—decisions that identify the major fire problems and target audiences, design a program best able to address those problems with that audience, and deliver the right program to the right people. At every stage of this process, good decisions depend on the proper use of good data.

See also Section 3, Chapter 1, "An Overview of the Fire Problem and Fire Protection"; Section 3, Chapter 4, "Use of Fire Incident Data and Statistics"; and Section 5, Chapter 8, "Evaluation Techniques for Fire and Life Safety Education."

THE ROLE OF DATA IN COMMUNITY FIRE EDUCATION PLANNING

Community Fire Education Planning

Community fire education planning is a way of making necessary decisions within a structure and specifically using a five-step process developed by the U.S. Fire Administration:

Step 1: Conduct a community analysis.
Step 2: Develop community partnerships.
Step 3: Create an intervention strategy.
Step 4: Implement the strategy.
Step 5: Evaluate the results.

Steps 1 and 5 are primarily data-driven exercises, and the other three steps may also benefit from data analysis in some respects. The uses of data may be grouped into the following six sections, which will be used to organize this chapter:

- What is the problem to be addressed? (This is the question for which Step 1, the community analysis, is conducted.)
- What is the strategy to address the problem? (This is the question for which Step 3 is conducted, and there may be additional analysis to refine the strategy during implementation as part of Step 4.)
- Who is the target audience? (Step 2, development of community partnerships, will reflect both the choice of strategy and the identified target audiences, because these two choices will suggest appropriate groups and agencies for partnership.)

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- Was the target audience reached by the strategy? (Step 5 includes answering this question.)
- Did the strategy change the target audience as intended? (Step 5 also includes answering this question.)
- Did the fire problem decline? (Step 5 also includes answering this question.)

The first three question groups give the design for the program. The second three question groups indicate what was accomplished. Because most programs are not one-time affairs, the lessons learned regarding accomplishments will then feed into the next cycle of program redesign decisions.

This chapter addresses matching the right data with the questions posed, interpreting that data correctly, and eventually using data and all other available resources to save lives and property. Many of the issues and themes of this chapter have counterpoints elsewhere in this handbook.

The reader is particularly encouraged to read Section 3, Chapter 4, "Use of Fire Incident Data and Statistics," which provides additional guidance on techniques of data interpretation for fire safety not limited to public education; Section 5, Chapter 8, "Evaluation Techniques for Fire and Life Safety Education," which provides more detailed guidance on question groups four through six than will be provided here; and Section 5, Chapter 5, "Reaching High-Risk Groups," which provides more information for those (common) occasions when the target audience includes a number of high-risk groups.

Data and Public Fire Education

This chapter does not propose that analysis of readily available data is necessary or sufficient to answer all questions in the design and evaluation of public fire and life safety education programs (or any other kind of program). It is claimed that answers are sounder when they reflect the best data available and are ill-advised if they contradict, without engaging, the best data analysis.

Use data to challenge assumptions, even the ones that seem most obvious. If the data are not strong enough or detailed enough to dictate the specific answer needed, then use the data to reduce the range of possibilities before applying judgment to make the final choices. Do not be afraid to use data to support choices and persuade third parties; however, do not confuse that exercise with the use of data to shape and assess choices. Decision making and advocacy of decisions are both essential, and both can be done better with data analysis.

For advocacy purposes, representative statistics may be less effective than more specific examples that allow people to put a human face on the fire losses and the program activities. Match appropriate data to the target audience. Supervisors, managers, local legislative officials, and budget officials tend to want hard numbers, although even they will have an easier time grasping the need and the plan with examples. The general public, the press, and organizations outside the fire safety arena may relate primarily to the examples. Additional resources at the end of this chapter, particularly the National Fire Protection Association (NFPA) "One-Stop Data Shop," can help locate accurate statistics and relevant case histories.

PROBLEM DEFINITION

This first stage requires the fire safety education team to define the objectives explicitly. What aspects of the fire problem should be addressed? What scales measuring fire loss is the team willing to use to measure success and hold the team accountable for results? The answer may appear obvious—save lives and prevent injuries, for example—but here, and at every other stage in the data use process, the team will learn a great deal about real objectives as it wrestles with the problem of setting performance criteria that are measurable, meaningful, and realistically achievable.

Start with the basics. Is the team comfortable being judged by changes in the size of the fire problem? If so, team members will be taking responsibility for outcomes that are not totally under their control. Fire safety or risk is affected by both the behaviors people learn and the products and other physical aspects of their environment. Education directly affects only the behaviors. On the other hand, if success is measured only by the number of children taught or the fraction of all children reached, then the team can guarantee success, given sufficient resources. But reaching children does not necessarily mean teaching children, and learning does not necessarily mean safety.

The following three examples are different ways to fail, relative to the only criterion that ultimately matters—are people safer? And yet each of these examples of unequivocal failure would be judged a success by some, even many, methods of evaluation:

1. To take an extreme example, an educator can stand in front of a class full of sight- or hearing-impaired or non-English-speaking children and deliver a standard fire safety education program. Although this may add 20 to 25 children to the tally of people reached, one can say with confidence, based on the mismatch between the standard medium of delivery and the special needs of these audiences, that the behaviors of this target audience will not change at all.
2. Or, an educator can deliver a program to a classroom of children who pass the test at the end of the day with "flying colors" but who forget everything they learned by the start of the next day's classes.
3. Or, an educator can teach a program that stays with the children for the rest of their lives, changing their behaviors as intended, but that somehow misses the behaviors that will prove to be most important in coping with the fire hazards they will face as adults.

Why address evaluation/success at this early stage? Because the design of a program—and the data appropriate to help design the program—should anticipate the way it will be evaluated. That is, at the very end, when evaluating whether the "problem" was reduced, it should be the same problem identified at the outset that inspired the design of the program.

Type of Loss

There are four principal measures of home fire loss:

- Fire incidents (count each fire once)
- Deaths
- Injuries
- Monetary loss

In settings other than homes, other measures may be of particular value, such as environmental impact, continuity of operations, and protection of cultural resources. The latter two measures are increasingly important in commercial settings. If a particular education effort leads to, for example, presenting a training session at the local chemical plant that employs a large number of the community's people and provides a large part of the community's tax base, then the educator may be less concerned about preventing a "typical" $10,000 fire at the plant than about preventing a catastrophic fire that might put thousands out of work and release a vapor cloud that could force evacuation of thousands more.

Choosing the Type of Loss to Measure. Which is the right measure to use? Most fire and life safety educators have a principal concern with saving lives, so deaths should be a measure of fire loss of concern to them. But should it be the only measure used?

Injuries are another measure of loss often targeted by fire safety educators. Injuries are several times more common than deaths, and some injuries are extraordinarily expensive, painful, and tragic. Most people value reducing the risk of death much more highly than reducing the risk of injury. However, injuries are more common, which means that injury statistics can provide significant, hard evidence of a program's positive effects much sooner. For that reason, measuring success by fire incidents, regardless of severity, also has advantages.

In the end, decisions must be made on which measure(s) of loss will be used. For each measure of loss, there needs to be an explicit rationale for the measure, which will provide guidance on how to interpret it and how much importance to attach to it. Different measures of loss will yield different priorities and multiple measures of loss can pull in different directions. For example, child-playing and smoking fires are major contributors to deaths and injuries, but only minor contributors to fire incidents (Table 5.7.1). Cooking fires are major contributors to fire incidents and injuries, but much less so to deaths. Smoke alarms have major impact on the risk of death but very minor impact on the risk of injury. And so on. Design the education program to

TABLE 5.7.1 Leading Causes of Structural Fires in Homes, 1999–2002 Annual Averages

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Cooking equipment fire	105,400	(28%)	270	(9%)	4,230	(28%)	519	(10%)
Identified cooking equipment	*75,600*	*(20%)*	*270*	*(9%)*	*3,750*	*(25%)*	*509*	*(9%)*
Confined cooking fire	*29,800*	*(20%)*	*0*	*(0%)*	*470*	*(3%)*	*10*	*(0%)*
Heating equipment	53,700	(14%)	320	(11%)	1,270	(8%)	637	(12%)
Identified heating equipment	*40,300*	*(11%)*	*320*	*(11%)*	*1,240*	*(8%)*	*628*	*(12%)*
Confined chimney or flue fire	*10,600*	*(3%)*	*0*	*(0%)*	*10*	*(0%)*	*7*	*(0%)*
Confined fuel burner or boiler malfunction or fire	*2,900*	*(1%)*	*0*	*(0%)*	*10*	*(0%)*	*2*	*(0%)*
Intentional	34,400	(9%)	550	(19%)	1,500	(10%)	738	(10%)
Electrical distribution or lighting equipment	32,400	(9%)	220	(8%)	960	(6%)	679	(10%)
Smoking materials	24,800	(7%)	850	(29%)	1,900	(12%)	455	(8%)
Candle	18,200	(5%)	160	(5%)	1,640	(11%)	392	(2%)
Exposure to other fire	15,800	(4%)	30	(1%)	90	(1%)	319	(6%)
Playing with heat source	14,000	(4%)	220	(8%)	1,360	(9%)	249	(5%)
Clothes dryer or washer	13,300	(4%)	10	(0%)	280	(2%)	97	(2%)

Note: These are the leading causes, obtained from the following list: intentional (from the NFIRS field "cause"); playing with fire (from factor contributing to ignition); confined heating (including confined chimney and confined fuel burner or boiler fires), confined cooking, and contained trash or rubbish (from incident type); identified heating, identified cooking, clothes dryer or washer, torch (including burner and soldering iron), electrical distribution and lighting equipment, medical equipment, and electronic, office, or entertainment equipment (from equipment involved in ignition); smoking materials, candles, lightning, and spontaneous combustion or chemical reaction (from heat source); and mobile property involved (from mobile property involved in ignition). The statistics on smoking materials and candles include a proportional share of fires in which the heat source was heat from an unclassified open flame or smoking material. Exposure fires include fires with an exposure number greater than zero, as well as fires identified by heat source or factor contributing to ignition when no equipment was involved in ignition and the fires were not intentionally set. Because contained trash or rubbish fires are a scenario without causal information, they are shown at the bottom of the table if they account for at least 2% of the fires. Causal information is not routinely collected for these incidents. The same fire can be listed under multiple causes, based on multiple data elements.

These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest ten, and direct property damage is rounded to the nearest million. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey.

produce results on the measures that matter most, not the measures that will show results the soonest. For example, suppose the team chooses to measure fire incidents as early evidence of program success and fire deaths are the measure of the real objective. Then the team should design the program not for its leverage on the rate of fire incidents but only for its leverage on fire deaths.

Refining the Measure. Even after a measurement scale is chosen, more decisions are needed to select a specific measure. For example, suppose fire deaths are chosen as a measure of fire loss. This can be translated into four very different specific measures: (1) deaths in fires, (2) fatal fires, (3) multiple-death fires, or (4) deaths in multiple-death fires.

Counting fatal fires rather than total deaths reduces the emphasis on deaths occurring in multiple-death fires. Under what circumstances might this make sense? Imagine a fire and life safety education manager in Las Vegas in the early 1980s. The MGM Grand Hotel fire caused more deaths in one fire than the city had experienced in all other fires combined in many years. In that kind of situation, counting deaths individually—and targeting programs accordingly—will mean devoting all educational resources to ensuring that the city never has another fire like the MGM Grand Hotel fire. This is a worthy goal, but it is not the only worthy goal. How many lives would be worth losing in ordinary home fires in order to ensure, say, that the odds against another MGM Grand–sized fire were a billion to one instead of only a hundred million to one? A similar argument would apply to office or high-rise fires in New York City because of the World Trade Center tower collapses, or to wildfires in Los Alamos, New Mexico, or to nightclub fires in West Warwick, Rhode Island, or in the entire state of Rhode Island. In each case, a single event of historic severity can justify expanded attention, but not exclusive attention.

Alternatively, the team could decide up front to concentrate exclusively on multiple-death fires. The public often seems to be far more upset by one fire that kills five people than by five fires that kill one person each. If the intention is not so much to increase safety as to increase feelings of safety or to reduce public distress over gaps in safety, then the team might devote more attention to boosting the safety factors of programs that prevent large fires rather than programs more likely to save people in the circumstances in which deaths are actually occurring.

Sometimes, there are multiple measures of loss that each seems to point in a different direction in terms of defining the problem. Table 5.7.2 shows the five primary types of space heating equipment, ranked in descending order by fire death rates relative to population, rates relative to population of deaths due to either fire or unvented carbon monoxide, and total fire deaths not adjusted for usage population.

The inclusion of carbon monoxide makes electrically powered equipment look better than any fueled equipment, and sorting by death toll produces a ranking almost exactly opposite the ranking by fire death rates. Portable liquid-fueled devices have the highest rates on the two rankings by deaths per million population, but they would have ranked second to fixed gas-fueled devices if 1985–1990 fire data had been used instead of 1995–1999 data. Only fixed, electrically powered devices consistently rank lowest, and this is one of the least used types of equipment of the five.

TABLE 5.7.2 Measures Related to Risk of Death for Five Leading Types of Space Heaters

Fixed vs. Portable	*Fuel or Power*	*Civilian Deaths*
1995–1999 Fires; 1997 High and Low Usage—Deaths per Million Households		
Portable	Liquid (e.g., kerosene)	9.93–12.41
Portable	Electricity	5.95–7.11
Fixed	Gas (e.g., LP-gas)	4.49–5.35
Fixed	Solid (e.g., wood)	3.32–3.91
Fixed	Electricity	0.65–1.42
1995–1999 Fires and Deaths Due to Unvented Carbon Monoxide; 1997 High and Low Usage—Deaths per Million Households		
Portable	Liquid (e.g., kerosene)	12.02–15.02
Fixed	Gas (e.g., LP-gas)	9.70–11.56
Portable	Electricity	5.95–7.11
Fixed	Solid (e.g., wood)	3.69–4.34
Fixed	Electricity	0.65–1.42
1995–1999 Fires Deaths Not Adjusted for Usage		
Portable	Electricity	90
Fixed	Solid (e.g., wood)	60
Fixed	Gas (e.g., LP-gas)	60
Portable	Liquid (e.g., kerosene)	40
Fixed	Electricity	10

Note: Deaths shown to nearest ten.

Source: NFPA analysis of data from NFIRS, NFPA survey, and U.S. Department of Energy.

Sometimes the message of the data is that all parts of the problem are worthy of attention by some relevant criterion, and so it makes sense not to narrow or target the problem.

Differences in Fire Risks Around the World

In Japan young children are not a distinctively high-risk group for fatal fires. Their rate of fire deaths per million population is nearly the same as the rates for their parents and for older children. By contrast, in the United States, preschool children face a risk of dying in fire that is considerably more than double the risk for everyone else.

At the other end of the age spectrum, however, Japan faces a much more severe problem than does the United States. The gap between fire risks for older adults and those for everyone else is much wider in Japan than in the United States. There may be lessons here for both countries. Child-rearing and child-supervision approaches in Japan may deserve some credit for their better experience in protecting the youngest of their people, whereas the better experience in protecting older people in the United States may reflect some of the distinctive U.S. practices. Only in-depth research can establish a credible link between differ-

ences in practices and differences in outcomes, because usually there are more than enough of the former to explain the latter.

In Russia and much of Eastern Europe, fire death rates overall are higher than they are in North America (the United States and Canada, in particular), Western Europe, and the Pacific Rim (particularly Japan). An obvious explanation is that the use and abuse of alcoholic beverages appears to be higher in Russia and Eastern Europe as well, to the extent that available statistics can be trusted to quantify such behavior. Two-fifths to one-half of U.S. adults who die in fire each year are legally intoxicated at the time; therefore, there is no doubt that abuse of alcohol is associated with elevated risk of fire death.

The use of smoking materials is also a point of distinction. In Europe, the percent of the adult population who smoke—and the range of places where smoking routinely occurs—is much larger than it now is in North America and is in fact reminiscent of the 1950s in North America. Coupled with better European success in preventing or mitigating many other types of fires, this distinctive behavior with regard to smoking is, not surprisingly, associated with a much higher percentage of fire deaths being attributed to smoking materials.

As around the globe, so within the United States, local differences in the problem to be solved should be identified early and incorporated into the design of an appropriate fire safety program.

Prioritizing by Risk

Choices and Concerns of Prioritizing by Risk. A similar set of choices arises in choosing the properties of interest. Suppose the concern is with fire deaths, and the community, like most, suffers 80 percent of its fire deaths in home fires. This situation clearly argues for special attention to homes. But should the team target all homes and should homes be the only target? If not all homes, which homes should be targeted? If not exclusively homes, what other properties should be targeted?

Data on the fire problem will indicate where to target programs if targeting is done, but the same data will indicate the high price paid for targeting of any kind. Targeting based on fire problem data will mean targeting high-risk places and people. However, targeting the highest-risk places and people may mean giving up in advance any chance of reducing the large share of the fire problem cumulatively accounted for by places and people having less than the highest risk. It may be that 1 percent of the community accounts for 20 percent of fire deaths, for example, but if that group is targeted exclusively, then 80 percent of fire deaths will be left untouched, even if the program works perfectly on its targeted group.

In addition, there are other legitimate concerns, many of which also have data that can be used in choosing the types of properties to target. For example, there are costs involved in delivering the program. If there is need to travel to selected sites (e.g., schools, homes) to deliver the program (e.g., school-based fire safety education, home inspections), then those costs are likely to be sensitive to the scatter of locations of targeted properties. It will cost much less, for example, to go to the highest-risk block in the city than to go to the 25 highest-risk households in the city. Also, the program itself needs to have multiple parts if it is to address several very different property types. After homes, the property class that accounts for, by far, the largest share of fire deaths is road vehicles. But the fire problems of cars and trucks are far different from those of homes. An educational program designed for homes would be much easier to adapt to other residential properties—or to any group of buildings—than to vehicles, where the educator might as well start over from scratch.

In fact, it is difficult to find any fire safety educational program designed for vehicles, and this challenge brings up another problem. Data analysis may do more than help choose among alternative educational programs. It may indicate a need to go beyond education in designing an effective prevention or mitigation program, for example, through codes and standards or other means for changing the physical characteristics of an engineered environment.

Public Priorities. Public priorities do not always follow patterns of risk, either. The public wants most of all to be protected from fire risks associated with strangers, even though they are much more at risk from themselves and their families and friends. Risks are less acceptable when they are unfamiliar or involuntary, hence, the tendency to focus on strangers.[1] Homes and private vehicles account for more than 90 percent of all fire deaths, but they account for much less than 90 percent of people's exposure, as measured by, say, time.[2] The public worries about fire risks to children, even though school-age children are the lowest-risk age group in the population.

Much of the public worries about fire risks to people like themselves more than they worry about fire risks to people in other social groups.[3] Hence, programs targeted on the comparatively small high-risk groups may draw less public support than programs that make people with average-to-low risk even safer. This question may seem purely philosophical or ethical, but most fire safety educators are able to operate only because other people decide to give them funding and other resources. A program designed with an eye to the special concerns of the people who control the resources is more likely to obtain the resources it needs to succeed.

Questions to Consider When Prioritizing by Risk. All of this needs to be considered, and all of it can be reduced to data. Should the educator target properties with a history of fire deaths? Or places with unusually vulnerable populations (e.g., schools, nursing homes, hospitals), even if their actual fire history has been extremely low? Or places with high occupancy (e.g., arenas, high-rise buildings), just because of the number of people potentially exposed to fire? Or places with unusual hazards, because the complex knowledge and behaviors required for their fire safety are the furthest from simple common sense? Should only buildings be targeted? Are other agencies or organizations being implicitly expected to address the fire safety needs of places not targeted?

Trend Versus Current Size

Another point to examine in data analysis to define the fire problem is the question of trends. From a national perspective, for

example, total fire deaths have been declining, and the risk of death from fire relative to the size of the population has been declining even faster. Trends for fire deaths involving particular fire causes, however, have shown different trends.

In 1980 the top two major fire causes, in terms of home fire deaths, were (1) smoking and (2) heating. Since then, these two causes have been among the fastest declining.

Confirmed and suspected arson declined in terms of fire deaths, but not so steadily and not so steeply, and it moved past heating as the second leading cause of home fire deaths in the late 1980s. Child-playing fire deaths rose in terms of share of fire deaths, ranking fourth in 1993 behind smoking, arson and suspected arson, and heating. With the help of the new child-resistant lighter standard, introduced in 1994, however, child-playing fire deaths plunged. In recent years, child playing has consistently fallen below 10 percent of fire deaths. Which cause should a new educational program target first? Should it be smoking, which is still, as far as the most current statistics indicate, the leading cause of fire deaths? Should it be arson and suspected arson, which could be the leading cause in a few years? Should it be heating, which of all the leading causes involves behaviors that are easiest to change through education and so might still produce the most lifesaving value for a given level of effort? Or should it be cooking, which has had the least favorable trend of the four leading causes?

There is no one best answer to these questions. Any declining problem that is given priority in a new program may turn out to be a case of overkill. Any increasing problem that is given priority may turn out to have been varying around a constant or even declining trend line; that is, the "increase" may turn out to have been an artifact of when and how the baseline statistics were analyzed. Then again, any problem *not* given priority may suddenly "take off" and, once increasing, may lead to considerable loss and suffering before it can be controlled. For example, heating fire losses increased from the late 1970s to the early 1980s before intensified educational efforts, combined with other factors, brought that fire problem back under some degree of control.

Figure 5.7.1 shows that in the early 1980s, fires started by children playing with matches far exceeded fires started by children playing with lighters. The death toll with matches, not shown on the graph, also was usually higher than for lighters.

In the mid- to late 1980s, some fire safety advocates noticed that the match component was declining rapidly, while the lighter component was not clearly declining at all. This situation led to support for changes to lighters to make them more child resistant. A counterargument at that point was that matches still seemed to be the larger problem, at least in terms of fires and deaths and possibly as rates relative to numbers of uses of the two products. For these opponents, the danger was that, by chasing the problem with a less favorable trend, we might shift people to a product (match) that might be riskier, leading to an increase in fires and deaths.

In a case in which the good data do not all point in the same direction, the ideal response is more research and more data. Research found that children playing with lighters tended to be younger than children playing with matches—too young to be reached with confidence by educational programs. Further data from the early 1990s showed the lighter component passing the match component, first in fire deaths and eventually in fires.

As noted earlier, the introduction of the child-resistant lighter requirement in 1994 produced an immediately and substantial trend reversal, which has been sustained and extended through a number of years. Unexpectedly, this change in lighter design coincided with a resumption of the dramatic decline in fires due to children playing with matches. This decline sug-

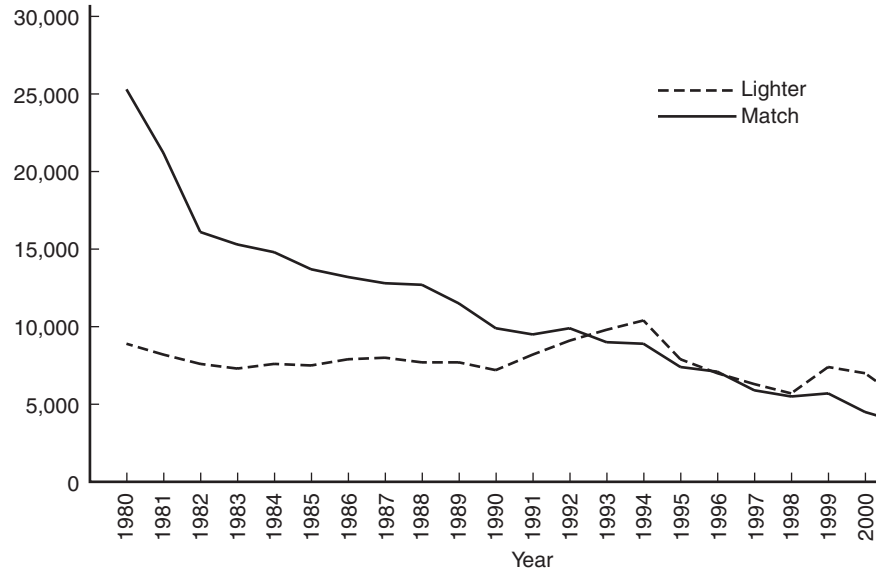

FIGURE 5.7.1 Child-Playing Home Structure Fires Involving Matches or Lighters. For 1999 and later, all fires attributed to "playing" are included, and so statistics may not be limited to fire play by children. (Source: NFIRS and NFPA survey)

gested some positive changes not fully explained as intended effects of the product change. In fact, the most obvious explanation seems to be that educators put more emphasis on educating parents and other caregivers about the dangers of these fires, and that awareness and education in turn both reinforced the positive effects of the product change and produced positive results of their own on matches.

Putting It All Together

The previous paragraphs were heavier on questions and issues than on answers. For those who prefer answers and guidance, the following tips may provide a reasonable way forward.

Design the program to reduce the risk of fire death among the people whose safety is the responsibility of the educator's team, which may be a community, an age group, a company's employees, an organization's members, and so on. Treat every death as equally important and potentially preventable. Although fire deaths should not be the only measure, because they take too long to show statistically significant effects, deaths should be regarded as the primary measure of success.

As an example of how long it takes to show success, measured by fire deaths, however, consider the Louisville, Kentucky, home smoke alarm campaign of the 1980s (Figure 5.7.2). Louisville fire officials properly used a 5-year baseline that stretched back before the program began. The average fire death toll in that period was 15, including a declining trend in the last 3 years of the baseline. The first year of the program showed a death toll of 10, well below any year in the baseline and even below the improved level one might have computed from the baseline trend. However, a prudent program manager would want to see multiple years of data in order to determine whether the excitement surrounding the program had produced a first-year improvement that could not be sustained or whether some other fluke or normal variation asserted itself. With 4 years of post-program data, it seemed clear that a substantial (more than one-quarter) decline in fire deaths had occurred.

But suppose the 1987 death toll of 16 had occurred in 1985. That statistic would have presented a real blow to the program and might have prematurely aborted it, even though time would show that it was a fluke. Or, suppose someone put forward a theory based on changes already in the works in 1982–1984 and claimed that the 1985–1988 success was only a continuation of that earlier trend and not a result of the program. It might have taken much more analysis or more years of data to sort out these conflicting claims.

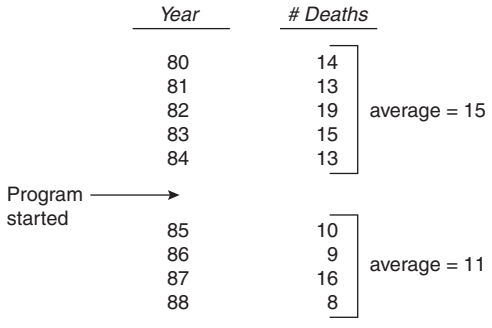

FIGURE 5.7.2 Louisville, Kentucky, Fire Deaths and a Home Smoke Alarm Program (Source: Philip Schaenman, et al., *Proving Public Fire Education Works,* TriData Corporation, Arlington, VA, 1990, pp. 92–93)

As it is, the substantial difference between 15 deaths a year in 1980–1984 and 11 deaths a year in 1985–1988 is not yet statistically significant. The difference between the two averages (15 and 11) is about 1.2 standard deviations, if the entire nine years is treated as one set of years with death tolls randomly chosen from what is assumed to be a constant risk of fire death, subject to variation. Statisticians usually look for at least 1⅔ standard deviations for significance in a one-sided test. A trend line analysis might look better, given that three of the four lowest years came after the program was begun, but it would still probably take quite a few additional years of progress to satisfy a classical test of statistical significance.

This illustrates the special challenge involved in focusing on fire deaths as an outcome measure.

When extending the scope to include injuries, property damage, or some other objective, treat all such objectives as secondary to the risk of fire death. That is, design the program to achieve a reduction in the fire death toll, and only then, if some latitude in the design of the program exists (i.e., room for a few more behaviors to be taught), look for program design features that will address the other objectives. The reason for this is that, even though other kinds of losses are more frequent, deaths are preemptively more important.

Use at least a 5-year baseline of the community's or organization's fire experience for analysis as was done in Louisville. More years will be needed if the community or organization has fewer than 100,000 people. If the target population is closer to 10,000, or even less, the community or organization's own data will comprise too small a base to analyze or track success by the fire death toll in any reasonable period of time. In that event, use historical national fire death data—or, if obtainable, state data or data on a group of similar communities—for analysis to design the program.

Many fire safety education programs are aimed primarily at fire prevention, as opposed to mitigation after fire starts, as is true for programs based on home smoke alarms or sprinklers. If so, it is appropriate to use fire incidents, rather than fire deaths, as the primary outcome measure. Because fires are 50 to 100 times as common as fire deaths, a shift from deaths to fires greatly improves the analyst's ability to quickly confirm statistically significant program impacts. Figure 5.7.3 is an example of such a tracking, in which a Waterford, Connecticut, school-based education program covering several fire safe behaviors was used to reduce the number of reported fires (excluding vehicle fires, which were considered outside the range of impact of the behaviors included in the program).

Note, too, that there is still room for interpretation and debate. The program in Waterford was introduced at the end of a two-year period of increases in the number of reported fires, which followed a two-year period of decreases. The program appears to have been successful. An immediate and substantial drop in the number of fires occurred, followed by

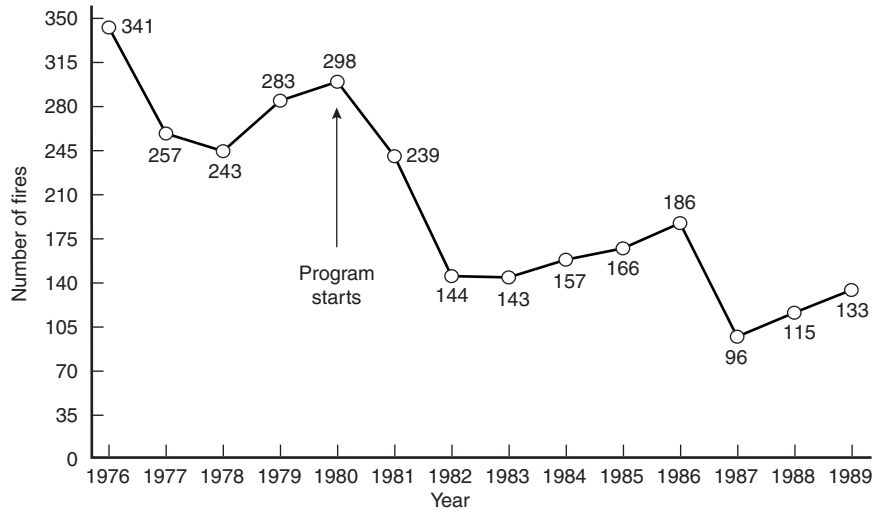

FIGURE 5.7.3 Waterford, Connecticut, Fires (Excluding Vehicles) and a School-Based Education Program (Source: Philip Schaenman, et al., *Proving Public Fire Education Works,* TriData Corporation, Arlington, VA, 1990, pp. 39–41)

an even larger decline the next year. These gains have been largely sustained through the seven years that followed. But as with the other examples, one could make the case that the 1976–1978 decline was the real long-term trend, that the 1978–1980 increase was a temporary fluke, and that the 1980–1989 declines were therefore more attributable to a resumption of the already established declining trend and not so much to the new program.

In a situation like this, in which the data are not conclusive, the obvious, simple interpretation is also the one that favors the program, and a positive impact from the program is what everyone would have expected. Nevertheless, if there were already some well-defined programs underway in the mid-1970s and a good case could be made that their full effect had not yet been achieved, one would want to make sure that the older programs were kept in force alongside the new program, thereby assuring that the favorable impact on fire rates continues, no matter what the principal factors in the trend might really be.

Analyze the historical database for major patterns that will be useful in selecting or refining programs or in targeting or reaching selected audiences. (See the following two sections.)

Do a "snapshot" analysis of the baseline, that is, one that ignores trends. Then, only after the initial conclusions have been set, look at major trends and consider making a few adjustments based on the trends. Minimizing use of any apparent trend information other than major trends will (1) avoid the dangers of overreacting to statistical fluctuations that are not real trends and (2) avoid the temptation to change the program before it has finished "doing its job" (which is analogous to stopping the antibiotics as soon as symptoms improve).

Figure 5.7.4 shows a trend line of civilian fire deaths involving children playing with lighters, showing eight years before and after 1994, the year when the child-resistant lighter requirement was introduced by the U.S. Consumer Product Safety Commission. This is as close as we will ever come to a program showing immediate and sustained, substantial improvement. Given that disposable lighters turn over frequently, it is not surprising that the improvement was immediate, as would not be expected with a long-lived product such as a mattress. Even for a program with immediate, sustained, substantial improvement, however, the effects show signs of leveling off with what is still a high death toll.

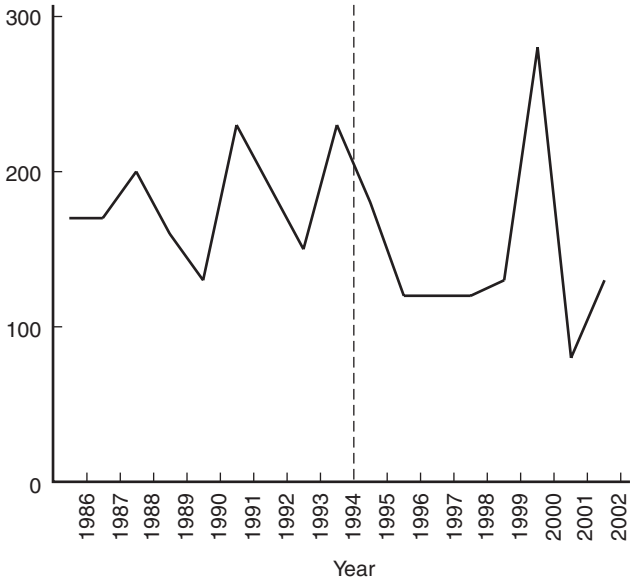

FIGURE 5.7.4 Deaths in Child-Playing Home Structure Fires Involving Lighters, 1986–2002. For 1999 and later, all fires attributed to "playing" are included, and so statistics may not be limited to fire play by children. (Source: NFIRS and NFPA survey)

INTERVENTION STRATEGIES

The purpose of data analysis is to set the stage for design or selection of a program that will reduce the fire problem as defined. However, many programs already exist; so do not "reinvent the wheel"—or any other parts of the car. This fact means the analysis will be most useful if it identifies patterns in the fire problem that favor some strategies and programs or help to set specifications for the selected strategies and programs.

For example, if the education team has data on fire deaths by home smoke alarm status (e.g., how many fires were in homes with no smoke alarms, how many in homes where smoke alarms were not working, how many in homes with an insufficient number of smoke alarms, how many in homes with smoke alarms in the wrong place) or related variables (how many in homes where there was no escape plan), then the team will have a much better idea whether to build the program around home smoke alarms, and if so, what specific points the education should address. Some of the data cited in this example will be retrievable from a typical state or local fire department database on fire incidents. Other data might require a survey. The analysis done will depend on the data available. If data specific to the target audience are not available, analysis based on national data may be available and used.

Fire cause data is similarly of interest because each cause corresponds to specific fire prevention behaviors that may be emphasized if the cause is a major concern.

A key danger at this stage lies in committing oneself too early to a particular approach. For example, if fires are analyzed by cause—and only by cause—this may lead to an education emphasis on prevention, to the exclusion of the kind of education that can save lives even when fire occurs. It is far better to develop at the outset a comprehensive view of all the programs one could pursue, and then let the specifics of those programs guide the selection of analyses that will help decide the best programs and refine them to best fit the team's particular circumstances.

Keys to Program Success—Reach and Effectiveness

The central point to remember when setting priorities is that success requires substantial leverage, which comes from two equally important sources:

1. The educational program has to be effective enough to make a major difference in the fire risks faced by everyone the program reaches.
2. The program has to reach most of the people, representing most of the existing fire risk, or else even a highly effective program will have little effect on the size of the total fire problem.

People cannot be saved if they are not reached or if they are reached by a program that makes little or no difference. Frequently, the need to reach a large audience and the need to be effective with those reached will compete with one another. One can affordably reach many people with billboards and radio public service announcements, but it is not clear that such media, by themselves, make much difference. The educator can dramatically reduce the fire risk to people by using a comprehensive fire safety curriculum, but it takes significant resources to do so, and even then, such a program directly reaches only school-age children. A full unintentional-injury curriculum provides high effectiveness over a wider range of injuries, but it poses the same challenges in achieving reach to the full target population.

Effectiveness, in turn, can be assessed only against a clearly stated objective, and a single program may be used to achieve many distinct objectives. What are the objectives with a school-based program, for example? (1) Is the program objective to teach the schoolchildren how to be more fire safe during their school-age years? (2) Is the program objective to teach them fire safety for the rest of their lives? (3) Is the program objective to have them deliver fire safety to their families?

The first program objective involves a narrow reach (only the students and only for a limited time), but a high degree of effectiveness that can be readily measured. The second objective involves a wider reach (only the students but for their entire lives), but a lesser degree of effectiveness (many will forget what they have learned without practice) or a need to expand the program (how can fire safety refresher training be given to adults who learned fire safety in schools as children?). The third objective involves the widest reach (potentially everyone who knows a school-age child), but the least effectiveness (a lot will be lost in translation before the students can pass on their knowledge to their families).

To evaluate the impact of a program, a baseline is needed that addresses all the objectives. If the educator intends to teach the schoolchildren only while they are present, only a pretest and a posttest are needed to check gains in knowledge, what fraction of the class learned all behaviors, and so on. However, if the goal is to teach children for life, methods must be found to test adults five, ten, and so on years out of school, to determine their retention levels. And if the goal is to teach families through their children, then pretests and posttests are needed for family members as well as for schoolchildren.

Selection and refinement of the program using data analysis require application of the data collection protocols that support the kinds of evaluation implied by the objectives set.

Programs Implement Broad Strategies

At this stage, consider the difference between the strategy and the program. For an educational program, the strategy is to impart specific knowledge and change specific behaviors for a designated target audience. The program includes the materials used to accomplish that end, the people taught, and the people they teach, together with the materials they have to use. For example, the city of Portland, Oregon, won a national fire safety award for a program that involved targeting high-risk neighborhoods by working through respected, trusted neighborhood groups.[4] The fire department taught the church leaders, who took the lead in teaching the neighborhood.

Fire code inspection programs are also education programs. NFPA research conducted in the 1970s indicated that the successful fire code inspection programs are the ones that have nearly universal reach and that educate and motivate building

occupants to make changes, even when the inspector is not there.[5] Most fires and losses involve behaviors and transitory hazards that may not show up in an annual inspection. Unless the occupant has been convinced to act as a year-round inspector, which means education, the value of the inspection wears off very fast, even if the inspector is very thorough and enforcement is very effective.

Six General Approaches to Prevent Fire Loss

During development of the initial list of candidate educational programs, for which objectives will be assigned and reach and effectiveness assessed, it may be useful to use the following set of categories, introduced in Section 3, Chapter 1, "An Overview of the Fire Problem and Fire Protection." They are (1) prevention, (2) slowing the rate of growth of initial fire, (3) early detection, (4) early suppression, (5) preventing unusually rapid spread of fire or its effects, and (6) evacuation. Each of these categories has engineering and educational approaches, which ideally should work together. And each can be pinpointed as a possible priority through data analysis.

Analysis of fire deaths by major causes, defined in terms of behaviors and heat sources, can identify a number of possible priorities for prevention education. Most educational programs include a number of prevention-oriented behaviors and so can benefit from an analysis by major causes. Bear in mind, however, that conventional educational techniques are of limited or unproven effectiveness in dealing with some leading causes of fatal fires; for example, smoking, arson, and children playing with fire. Before assigning a high effectiveness to the program, make sure it will be effective on a large fraction of targeted fires and consider product changes as a strategy. For example, a serious program to address smoking fires includes consideration of efforts to pass a state law mandating reduced-ignition-strength cigarettes (commonly called "fire-safe cigarettes"). The state level approach is suggested, because it is not practical to try to make such cigarettes mandatory, or even available, in a single community.

Analysis of fire deaths by the first burnable item ignited may shed some light on the problem of rapid early fire growth. Flammable and combustible liquids and gases can promote such rapid growth, as can large pieces that are ordinary combustibles, such as upholstered furniture. Most educational programs contain some guidance on storage of such materials, on limiting quantities, or on the use of potential heat sources near them, but the educator might also consider guidance on selecting items to reduce risk (e.g., choosing upholstered furniture made to the industry's voluntary standard on resistance to cigarette ignition) and on positioning items (e.g., how close are furniture pieces to walls and to each other?).

National analyses of fire deaths by detector performance typically show the value of home smoke alarms and of keeping them operational. So will analysis by sprinkler performance, which should be included as an option in any fire safety program.[6] Analysis of fire deaths by extent of flame damage—and, in particular, whether or not fire is confined to the room of fire origin—will always show the importance of blocking fire spread. For an educational program, the analysis will be enough to justify including guidance on the need to avoid creating avenues of rapid flame spread (e.g., untreated wood paneling on walls, especially on stairway or corridor walls).

Analysis of fire deaths by the victim's condition before fire began and activity at time of fatal injury will give some insight into the importance of evacuation issues. Typically, most victims never get as far as trying to escape. They were asleep, impaired by drugs or alcohol or disability, or too young or too old to act effectively. Every such finding translates into a point for education, but be realistic about what can be achieved. The educator probably cannot convince people not to get drunk—and certainly cannot change disabilities or the limitations associated with various ages—but he or she may be able to convince people to develop and practice escape plans that are tailored to their circumstances.

Putting It All Together

Assemble and brainstorm a list of promising educational programs. Include any available evidence on these programs' track record of effectiveness. Lacking such evidence, try to develop some estimates, for example, by asking for quantitative estimates from a variety of national experts and others familiar with the programs.

Set up a flowchart showing how specific actions will lead to changes in and actions by other parties, and from them to changes in the target audience, and from those changes to reductions in fire deaths and other forms of fire loss and risk. Fill in anticipated effects of changes at each stage and how effective the changes will be, based on the predicted effects.

Based on a review of available resources (and other considerations in the following section), rough out how large a version of each program can be launched. Translate that into an estimate of reach, that is, the fraction of the target audience that can probably be reached.

Despite the emphasis on data analysis throughout this exercise, it is important to think qualitatively more than quantitatively. Look for big differences in likely impact, and do not be too wrapped up in small percentages. It should be obvious by now that much of the information will involve best guesses. Pay particular attention to any points in the flowchart at which there is a real risk that the whole program will go "off track" if some key group does not do its part.

For programs that still look attractive after this analysis, use data analysis of fire experience to specify program details (e.g., which prevention behaviors will be emphasized?). Based on these details, estimate what fraction of the total fire problem the program will target.

Even program details such as timing can be informed by data. If your program includes a component for heating equipment fires, develop a graph like Figure 5.7.5, showing such fires as they vary over time. By refining the graph (or table), you can find the week(s) when heating equipment fires traditionally begin climbing. Or, if you are very ambitious, you can plot daily temperatures (peak, low) and estimate the trigger temperature for widespread activation of heating equipment and onset of related fires. With this information, you can time a public awareness campaign that will hit just when most members of

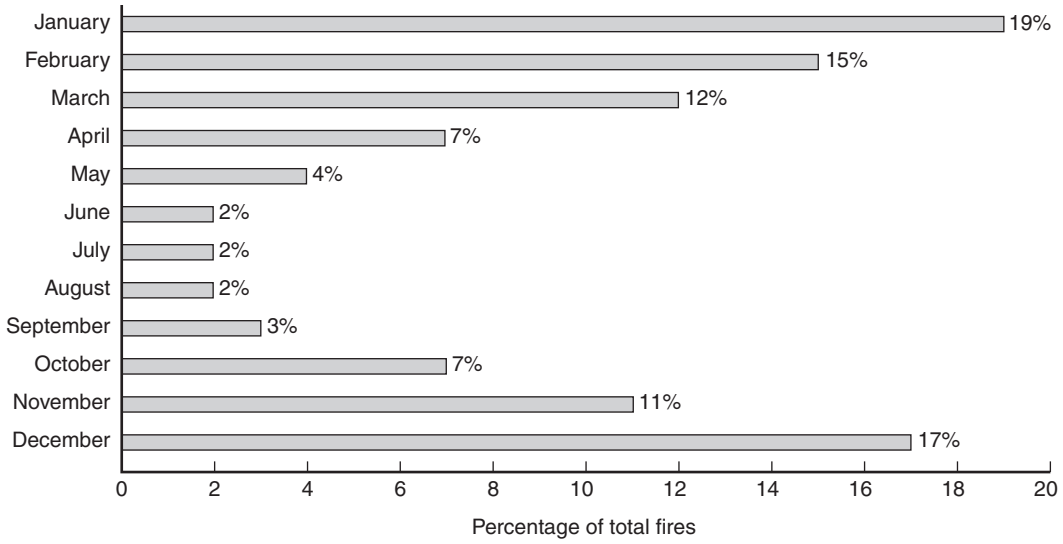

FIGURE 5.7.5 Home Heating Equipment Fires by Month, 2000–2004 Annual Averages

the community are already beginning to focus on their heating equipment and the need to bring it back in service.

TARGET AUDIENCE CONSIDERATIONS

Types of Audiences

Most public education programs target one of the following four groups: (1) the general population, (2) high-risk populations, (3) schoolchildren, or (4) people where they work. The first two are targeted because they represent all or a large share of the total fire problem, which gives the program a large reach. The second two are targeted because they find people under circumstances in which they can and will spend significant time in an ideal learning environment, able to listen to lessons, practice behaviors, and be tested for what they learn. Conversely, the first group is hard to reach in ways that are highly effective, and the second group is just hard to reach. The last two groups have below-average fire risk to begin with, which may mean that high impact requires extending the reach of the program.

For programs aimed at the general population, serious questions have to be asked at the outset as to how effective the program will be. It is almost impossible to devise a program for the general population in which the participants practice fire safe behaviors. Can the program even ensure that everyone will read or hear the lessons? Mailed materials and materials dropped off by people on rounds will often be discarded without being read. Billboards and public service announcements are within viewing range of only a fraction of the population and will be ignored by many of those.

Cost alone is usually enough to force a program to target only a fraction of the general population, in which case the program should be targeted at high-risk populations. If forced instead to target a partial program based on greatest ease or lowest cost, the education will almost inevitably, albeit inadvertently, end up targeting low-risk populations, the people who need the program least. The safest neighborhoods for home inspections, the most receptive neighborhoods for community meetings, the participants in fraternal organizations and other social groups, and the best and most receptive schools, all tend to favor the more affluent, better educated, and lower fire risk people.

It takes a great deal of work to hit the target of high-risk populations, so much so that Section 5, Chapter 5, "Reaching High-Risk Groups," is devoted to that topic alone.

High-Risk Audiences

Once the decision to target high-risk populations is made, they must be identified and creative ways must be determined to reach them. If high-risk populations are defined by where people live, use actual fire history to find parts of the community where fire rates and fire death rates, relative to population, are unusually high. This will lead naturally to programs that deliver fire safety within those neighborhoods. (High-risk areas can easily have rates several times the community-wide average. Again, do not focus too much on small differences, such as slightly above-average fire rates.)

At this stage, effectiveness considerations, already discussed, will become as important as extent of coverage, or reach. Door-to-door programs offer more potential for substantial learning but are very resource intensive. How many can the program afford to reach in this fashion? Assembling people through the guidance of some community group is more cost-effective but permits less individualized teaching and therefore may not result in as much practice of behaviors by the entire target audience. Such programs also tend to draw disproportionately from the lower-risk occupants of even a high-risk neighborhood. Mailing or dropping off materials is even more affordable and even less likely to change behavior. Use available data on effectiveness with estimates of projected numbers of people reached to compare different programs.

Older Adults. High-risk populations need not be defined by neighborhood or community, however. Older adults are a high-risk population, for example. Use data analysis to check every assumption for these programs.

For example, in 2000 (the latest year for which published data were available from the U.S. Census Bureau, at press time), there were 2.0 million resident patients in nursing homes, compared to a total of 35.0 million U.S. residents who were age 65 or older.[6] That is, there were about 16.5 older adults living at home for every one living in a nursing home; therefore, any program intending to target older adults as a high-risk population would only "scratch the surface" by targeting the nursing home population.

Further, older adults living in nursing homes already may have much lower fire risk than older adults living at home, because of the much greater built-in fire protection and supervision afforded in nursing homes. The population ratio may have been 16.5:1, but the ratio of fire deaths in the same period was more like 100:1. Therefore, within the high-risk older adult population, the people living in nursing homes need additional fire safety least.

With creativity, an educator might try to target a program for older adults in homes but without ignoring nursing homes altogether. For example, nursing homes or like facilities could be used as magnets to draw in older adults from homes throughout the community.

The need for data analysis lies in the need to check assumptions, because assumptions are an inevitable part of crafting a fire and life safety education program to fit within limited resources. The example just discussed started with a (presumed) fact: it is not affordable to target everyone in the population, and so limited program resources should be applied where they will do the most good. That means large reach and/or high effectiveness. Targeting high-risk populations gives the most reach (in terms of share of the fire problem) per population reached. First assumption: older adults are a high-risk population. Data confirm this; they have more than twice the fire death rate of the general population. Second assumption: nursing homes are a compact, efficient way to reach older adults. Data disprove this, as shown. Third assumption: a program can be devised with enough effectiveness to produce high impact when targeted to older adults. Data can best address this only after the program is specified (targeting nursing homes did not work) and alternative programs are specified, against which to compare the older-adult program.

If targeting nursing homes had proved to be a good idea, it would still be necessary to be creative, challenge assumptions, and analyze data to specify details of a program. For example, should the educational program target the patients or the staff? Both are possibilities, and both types of programs may have data on effectiveness. Or would a mixed program, targeting both groups, be best (where "best" takes account of affordability, too)?

Fire-Related Characteristics and Target Audiences. In fact, every fire-related characteristic can be examined as a basis for identifying high- versus low-risk populations, and, hence, for targeting fire and life safety education programs. Smoking material fires lead the list of causes of fatal fires. How about an educational program that works through points of sale of cigarettes? Heating equipment fires still rank fairly high. How about educational materials distributed where portable or fixed space heaters are sold, serviced, or maintained? These are examples of what can be an iterative process, wherein data help in design and selection of existing educational programs but also suggest unmet needs that may spark ideas for entirely new kinds of educational programs. Data analysis can be a stimulus to that kind of creativity as well as a reality check on assumptions about what will work and who most needs attention.

Targeting schools or workplaces presents its own set of questions, similar in form but different in specifics. Does the program provide that participants will practice fire safe behaviors, or (less effective) take a written or oral test after being taught about fire safe behaviors, or (even less effective) be lectured on fire safety with no testing or interaction, or (least effective) be notified of the availability of materials on fire safety?

Note the variations implied by this question. After a target audience and a set of information to be used in an educational program are specified, success (effectiveness) in getting the audience to learn, know, and be able (and likely) to act on the information may depend on the manner and intensity of the interaction. The easier it is for the audience to "drop out" of the exchange, by ignoring the materials or even by not examining them at all, the more likely it will be that many people will not be educated.

And reach takes many forms. Do all classrooms in the school, all schools in the system, all areas in the workplace, and all facilities in the industry participate? Or do only the most motivated, self-selected ones, who probably have the lowest fire risk already, participate?

MAPPING PROGRAM DELIVERY

Divide your community into areas on a map. The areas could be large, like a census tract, or not so large, like a census block, or small, like an individual building, or very small, like an individual occupancy (e.g., one apartment in an apartment building, one store in a mall, one tenant in an office building). When choosing how small to make the areas—how fine to make the grid—think in terms of how much ground you can cover with program delivery in a day or a week. Or, think in terms of the smallest unit in which it could make sense to deliver the program to that area and not immediately move on to the neighboring area. Visiting one apartment unit and then leaving the building makes no sense, even if there is a huge difference in risk between one household and all the others. On the other hand, breaking off at the major highway that borders a census tract could seem quite natural.

Loss Value

Next, for each area, enter the area's loss value—such as average fires or fire deaths over the past five years. Do not include losses in properties your program will not visit; for example, a home inspection program will not include a grocery store in the neighborhood. Next, if you deem it appropriate, discount the loss value by your predicted success rate in reaching the area's population and effecting change. For example, you might

predict more cases of finding no one home in one type of neighborhood (e.g., where nearly everyone works or attends schools) than another (e.g., with more retired people or stay-at-home parents). Or, you might predict more success in changing behavior in one neighborhood than in another (e.g., where few people speak English or more people are too poor to make changes called for in your program).

The resulting estimate is the fire safety benefit of delivering a program to that area. You now need a cost value to go with the safety benefit. Estimate the total cost of delivering the program to the area, and you may want to use more than one dimension (e.g., person time, out-of-pocket costs) for resources that have separate limits and cannot be traded off with each other.

Cost-Benefit Ratio

Finally, divide the area cost into the area benefit. Use these cost-benefit ratios to make a preference ordering of the area in the community. Draw a line below the last area you can fit into your overall budget. If you have separate budgets for different resources (e.g., time, money), then you may need to develop multiple lists (or use mathematical techniques for what are called "packing problems" in the field of operations research).

If this effort seems like a lot of work for limited program benefit, it well may be. Many communities have a single, compact high-risk area, which is so distinct from the rest of the community that everyone knows about it even before analysis is conducted. Nevertheless, many communities have more complex layouts, including different areas with elevated risk for different reasons. For these communities, a more sophisticated analytic approach may be worth the trouble.

WAS THE TARGET AUDIENCE REACHED?

At this stage, data are used not to design or select the program but to evaluate its impact. That evaluation may lead to some redesign, in which case it is necessary to move back to an earlier point, as appropriate. This first step in evaluation corresponds to the first effects the educator can hope to measure. It relies on *activity* measures—measures of the work already done.

The earlier discussion of intervention strategy selection called for estimating the likely reach of programs and strategies as a basis for choosing those to be implemented. After program implementation, it is necessary to measure the reach that was actually achieved.

To do this, begin with data on people and groups to whom the program was delivered. For example, which schools were sent materials? Usually, the materials will not have been sent directly to the target audience, and so it will be necessary to survey the addressees to determine how many of them passed on the materials, and to what fraction of the target audience members within their organization. Then it may be necessary to survey those individuals to determine how many of them used the materials.

Take the school materials example again. The program data will indicate which schools were sent the materials, but the educator will need to survey the principals to determine which classrooms took the materials, then survey the teachers from those classrooms to determine which ones used the materials and to what extent, and finally survey the teachers or the students to determine how many students in the classrooms participated in the exercise (e.g., omitting students who were sick or excused for other reasons).

Whatever method is used to build up the database, the goal is to estimate the fraction of the original target audience that was actually reached. Therefore, count people, not some more convenient distribution unit, such as classrooms, schools, workplaces, and so on.

This evaluation needs to be this thorough so that a realistic view of what was achieved can be obtained. There are many steps in a program in which targeted people may be missed, and so any such step not evaluated is a place where one might inadvertently overestimate the effective reach of the program.

DID THE STRATEGY WORK?

Measuring Change

This evaluation step corresponds to the design step that specified the strategy. It usually involves pretests and posttests of knowledge or learned behaviors for the target audience. This step calls for *change* measures—the most direct measures possible of the difference the program has made. Table 5.7.3 summarizes types of evaluation measures.

This comes later in the time sequence because, for most programs, the program objectives will imply a goal of long-term learning. The educator needs to ensure that the program has effects that last past the end of the program. This means, ideally, a sequence of posttests, for example, immediately after the program, one year out, five years out, and so on.

In time, enough may be known about patterns of retention of fire safety knowledge that it will no longer be necessary to conduct elaborate posttesting regimens for specific programs; but, at present, such information is quite useful.

Even at this stage, look primarily for changes that are substantive and closely linked to how lives are saved. Measure changes in knowledge (pretests and posttests) and behavior (by surveys, interviews, and other sample observation techniques). It may be interesting to note, for example, that school officials and fire officials are working together more now than before or that they enjoyed participating in the program or that they believe it made a difference; but these kinds of changes are too far removed from the hard evidence of program impact to deserve much emphasis in the evaluation.

Were Lives Saved or Losses Reduced?

This is the ultimate measure of benefit and impact—and the only one that truly matters. It is the evaluation counterpart to the design step that asked what the problem was. It involves comparing fire death rates and other fire loss rates after the program to those before the program. This step calls for *outcome* measures.

These are change measures, too, but they are measures of the intrinsically valuable changes to which all the work was meant to lead. If people learn more or know more, that

TABLE 5.7.3 Types of Evaluation Measures for Public Fire and Life Safety Education Programs

Type of Measure	*Purpose*	*Timing*	*Examples*
Activity measure	Determine whether the target population was reached with something.	Measure can be calculated based on plans and scheduled activity, before or during program delivery.	1. Number of schoolchildren contacted. Weak measure because it does not indicate fraction of total reached, any bias in selection of children reached, or possibly even whether contact stopped short of program delivery. 2. Percentage of schoolchildren taught, overall and by school, by grade, by part of community (distinguished by high vs. low fire risk). Strong measure because it indicates relative achievement of goal and checks for bias. 3. Breakdown of above measures by different risk populations (e.g., by income, gender, ethnic, or cultural grouping). Measures are to look for differential input and reasons for it.
Change measure	Of the people reached, determine whether learning occurred or whether behavior changed as a result.	Measure of learning can be calculated at end of program but should also be calculated 6–12 months later to check for decay in learning. Measure of behavior change takes time to measure but can also be calculated just after the end of the program and 6–12 months later.	1. Percent correct answers on posttest. Weak measure because it shows knowledge other than learning. 2. Percent correct on posttest minus percent correct on pretest. Better measure but still needs to be calibrated or interpreted by how much learning was needed. 3. One minus [(percent correct on posttest) / (percent correct on pretest)]. Measure addresses learning achieved, calibrated by learning needed. May still be misleading if very little learning was required, and form of the measure is sufficiently unfamiliar and complex that it will take educators a while to get comfortable with it. 4. Analogous measures can be applied to behavior, if a system can be established to observe representative samples of behavior. For example, bicycle-helmet-wearing behavior in school can be checked unobtrusively before and after program. 5. Breakdown of above measures by different risk populations (e.g., by income, gender, ethnic, or cultural grouping). Measures are to look for differential input and reasons for it.
Outcome measure	Determines whether enough people at risk were reached by a program with enough effectiveness or the knowledge, skills, and behaviors most important to that risk, resulting in reduced human losses (i.e., deaths and injuries)	Statistically significant data will require years to accumulate. Even more time will be required if analysis focuses on deaths and injuries involving the specific skills, knowledge, and behaviors targeted by the program.	1. Number of deaths and injuries among the target population, baseline vs. after program. Good measure of what the program is intended to affect, but not calibrated for program reach or effectiveness. 2. Number of deaths and injuries among the population taught vs. target population not reached, baseline vs. after program. Better measure calibrates for reach but not for effectiveness. Also useful to use population not reached as a control group. 3. Breakdown of measure No. 2 for deaths and injuries involving knowledge, skills, and behaviors targeted by program vs. deaths and injuries not involving those. Measures are not to gauge impact but to sort out reasons for impact or lack of impact. Does the program have limited impact or limited reach (among target population, among critical behaviors and risk factors) or both? 4. Breakdown of above measures by different risk populations (e.g., by income, gender, ethnic, or cultural grouping). Measures are to look for differential input and reasons for it.

is valuable only if they have fewer fires and fewer of them die (or are injured or whatever the chosen loss measure[s] for the objectives may have been). At the same time, these change measures may be affected by more than just the program. Time has passed since the baseline period. People may have gotten poorer or richer, smarter or less knowledgeable, more mature or more impaired by advanced age. And other groups will have been conducting programs: some directly and deliberately focusing on fire safety; others not intending to address fire safety but having some impact on it nevertheless. Therefore, although these measures are more directly indicative of the program objectives, their changes or lack of changes may reflect more than the program under scrutiny.

Therefore, it is useful to apply experimental techniques that can isolate the fire safety program from other influences. Some common phenomena should be checked, as described below.

Fire loss rates, including death rates, will vary randomly over time, often significantly. If the educator introduces a program at a time when those variations have pushed loss rates up to historically high levels, then significant reduction relative to that baseline can be expected, even if the program itself has no effect. Loss rates will return to "normal" levels or trends, and that return will look like an improvement. Because a random variation pushing up loss rates looks the same as a problem "spinning out of control," in need of immediate special attention, it is not unusual for programs to be launched at the top of one of these artificial peaks. Consider that possibility when interpreting data.

Consider, too, the Hawthorne effect. First noted in studies of industrial productivity, the Hawthorne effect refers to the tendency of populations to do better just because someone is paying more attention to them. Just being in a fire and life safety program may inspire participants to be more fire conscious, and so more fire safe, even if they really have not learned anything more. These motivational effects rarely outlast the program, or even the experimental phase of the program when publicity is most intense, so this possibility is another reason to check for effects over the long term. (It also can be checked by running a "placebo" program that has no educational content but delivers to a control group all the attention of being part of a program.)

Analyze data not only for how much impact a program produces but also for how the program achieves its impact. It is not unusual for a successful program to produce effects differently than expected. This analysis is important for design choices when moving from pilot programs to full-scale programs or from experimental programs to institutionalized programs, because it is crucial to emphasize those features that actually produced success.

One classic example was a fire department home inspection program whose introduction coincided with a large decline in home fire rates.[5] Detailed analysis, however, showed the decline often preceded the arrival of inspectors in a particular neighborhood, suggesting that the fire safety effects were produced more by the motivational effects of the program's introduction and the desire to "look good" for the inspectors when they arrived. This effect had implications for the program, because it suggested a need to emphasize mass-media publicity in support of the program on a continuing basis and to look for ways to encourage people to "clean up for the inspectors" rather than relying on the inspectors to find hazards on the spot and have them corrected.

See Section 5, Chapter 8, "Evaluation Techniques for Fire and Life Safety Education," for more detailed guidance on measurement techniques and guidelines for interpretation of these last three sections.

SUMMARY

Much of the design and evaluation work needs to be based on local data; these data include data specific to the team's program, community or organization, and target audiences. But a fair amount of the design work can be done on the basis of existing national data analysis, and even the evaluation can take advantage of existing data analysis already done on similar programs.

Guidance on analysis methods is given in Section 3, Chapter 4, "Use of Fire Incident Data and Statistics." For more details on sophisticated statistical analysis and modeling techniques, consult the *SFPE Handbook of Fire Protection Engineering,* published by NFPA.[7]

The most important caution to keep in mind regarding methods is this: the key weakness in most databases is not the quality of the reporting but the representativeness of the coverage. Databases do not have to be complete to be comprehensive; if they are properly representative, statistical methods will allow valid projection of totals from samples. Databases do not have to be totally accurate within each record to be very accurate for statistical analysis; errors usually balance each other out, as one person's miscoding is offset by an opposite miscoding by someone else.

The best national data for public education program design consist of what are called national estimates based on two national fire-department-based databases—the U.S. Fire Administration's National Fire Incident Reporting System (NFIRS) and NFPA's annual fire experience survey. Through the "One-Stop Data Shop," NFPA maintains a listing of dozens of reports covering all aspects of the home fire problem, including patterns, trends, comparative risk factors, major causes, victim patterns, and detection and suppression equipment roles in fire safety. NFPA encourages educators to seek this support.

The U.S. Fire Administration's National Fire Data Center (NFDC) is another valuable data analysis resource. In addition to its role in maintaining and distributing NFIRS to all fire data users, the NFDC has done more than any other organization to develop analyses at the state and local levels. NFIRS is not a complete database, having data on about half of all reported U.S. fires each year, so analyses below the national level are not possible for all areas; however, the NFDC is an excellent resource.

Another major source of fire data analysis at the national level is the U.S. Consumer Product Safety Commission (CPSC). In addition to a wide range of national estimate analyses focused on home fires—and a key role working with NFPA analysts in standardizing the methods used for making national estimates—CPSC is the nation's leading organization for special data collection and analysis projects applicable to home fires.

Watershed analyses of home electrical fires and smoke alarm usage and problems are only two of the best-known examples. CPSC's Hazard Analysis Group conducts these analyses and can describe what is available.

The best compilation of data-based evaluations of fire safety education programs is still a report by TriData Corporation. Anyone interested in evaluation of fire safety education programs should read *Proving Public Fire Education Works,* TriData Corporation, 1990.[8] This valuable report is no longer in print, but photocopies can be obtained from TriData, and many fire libraries have copies available for consultation or interlibrary loan.

Finally, the roughly 30,000 communities in the United States are resources for each other. Remember that, when creating programs or analyzing data for programs, it is likely that some other community has done so already and learned some useful lessons. NFPA's Champions program is building a network of leading-edge communities that have not only successfully demonstrated fire safety education programs but also committed themselves to sharing their knowledge and methods with others. Contact NFPA Public Education for more on the Champions network.

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3. This is an example of people's tendency to show concern with situations in which benefits go to others and costs or risks go to "us." See M. W. Merkhofer, *A Complete Evaluation of Quantitative Decision-Making Approaches,* Final Report, SRI Project 2102, National Science Foundation, Washington, DC, Apr. 1983.
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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on public fire and life safety education tasks and requirements that use data, as discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following document.)*

NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*

References

NFPA Champions Network, NFPA Public Education, National Fire Protection Association, Quincy, MA. Phone: (617) 984-7285.

NFPA, "One-Stop Data Shop," National Fire Protection Association, Quincy, MA. Phone: (617) 984-7450.

U.S. Consumer Product Safety Commission (CPSC), Hazard Analysis Group. Phone: (301) 504-0470.

U.S. Fire Administration's National Fire Data Center (NFDC), 16825 S. Seton Ave., Emmitsburg, MD 21727. Phone: (301) 447-1272.

Chapter 8

Evaluation Techniques for Fire and Life Safety Education

Revised by
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Chapter Contents

The Evaluation Process
Formative Evaluation
Process Evaluation
Impact Evaluation
Outcome Evaluation
Handling Uncontrollable Factors
Uses for Evaluation

Key Terms

formative evaluation, impact evaluation, juvenile firesetting, process evaluation, public fire and life safety education, *Risk Watch*®

Injuries from fire and other causes account for a significant number of deaths in all age groups in the United States, and unintentional injury is the leading cause of death in children aged 1–14.[1] In recent years scientists have come to better understand the risk factors involved in injuries and the potential of a wide range of engineering and education measures to successfully reduce injury occurrence or severity.[2] Proven interventions, such as smoke alarms, child safety seats, and bicycle helmets, can substantially reduce the number of fatal and nonfatal injuries and decrease the enormous dollar loss associated with these injuries, premature death, or long-term disability.[3]

However, these measures must be successfully implemented to be effective. Selecting the most effective strategies—or the best strategies one can afford—requires evaluation. Designing a chosen strategy for greatest impact requires evaluation. So does successful implementation.

Every reader or user of the *Fire Protection Handbook* section on fire and life safety education has to make decisions about educational programs. They may be decisions about whether to adopt an educational program in a community or school that has none. They may be decisions about how to modify or reinforce elements of an educational program to reflect the special needs or capabilities of a particular group of students. They may be strategic, tactical, or operational decisions. But in the end, every decision comes down to good information about better versus worse, about more versus less effective. *Evaluation* refers to any systematic process for gathering information about better versus worse.

The term *evaluation* means different things to different people. That leads to various concepts of how to evaluate a public fire and life safety education program. Some people evaluate programs based on how well the public education program is accepted and used by teachers, or how well it is liked by the target audience. Others evaluate a public education program from the point of view of features that are thought to constitute a good program, such as whether it has good graphics, is well targeted, and has input from various community groups.

Another type of evaluation asks whether a program causes "institutional changes," such as getting additional funding for public education materials, obtaining additional slots for public fire and life safety educators in the prevention bureau, having public education incorporated in the school curriculum, or stimulating local businesses and service organizations to participate in public safety education.

All of these concepts of evaluation are useful. All help indicate the path to program success. But they are several steps removed from being able to prove that public fire and life safety education works in achieving its main purpose: reduction of deaths, injuries, and dollar loss from fire.

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Many programs have side effects, secondary missions, or even hidden agendas. Public education, for example, can enhance the image of the fire department, demonstrate a caring city administration, and raise or lower public fears.

A sophisticated, comprehensive set of measures of effectiveness of a public program would consider such issues, which often are important in the minds of managers under their day-to-day political pressures. But the main purpose of public fire and life safety education is to improve safety, and unless one can demonstrate that a program is achieving this goal, it will be hard to convince decision makers in the long run that the program should be supported. Sooner or later questions will arise about the bottom line.

The purpose of this chapter is to present an overview of the evaluation process and a hierarchy of evaluation measures. In addition, the chapter will illustrate the evaluation process and hierarchy through examples based on the NFPA *Risk Watch*® curriculum.

Although these evaluation techniques are designed for use on public fire and life safety education programs, they can be applied just as well to more broadly based fire and life risk reduction strategies, in which educational programs are combined with engineering and enforcement strategies to provide the best possible leverage on the problem. Increasingly, fire departments are being asked to place their many fire safety programs, including public fire education, code enforcement, and special legislative initiatives, into a broader risk reduction context.

See also Section 3, Chapter 4, "Use of Fire Incident Data and Statistics"; and Section 5, Chapter 7, "Using Data for Public Education Planning and Decision Making."

THE EVALUATION PROCESS

Evaluation is the process of determining whether a curriculum, educational program, or community initiative is effective and appropriate, and it may indicate whether a program has unexpected benefits or creates unexpected problems.[4,5] Because evaluation is a process, it begins early, in the initial stages of program design, and continues throughout the development and implementation of the program.

Many injury prevention programs have been developed, but few have been rigorously evaluated and shown to be effective in reducing injuries. Reasons for this may include a lack of funding to support evaluation efforts, a focus on implementation and service delivery rather than evaluation, or a lack of understanding of the importance of evaluation. Target populations may be too small, or the injury event and safety behavior too rare to demonstrate significant effects, and in some cases program developers are simply unaware of evaluation techniques to use.[4]

When developing a safety program, one must remember that evaluation is an ongoing process: it begins with identification of goals and objectives, and continues throughout the program development cycle. As the program is implemented, final assessment is completed to determine the effectiveness of the program in meeting the stated goals and objectives.

Stages of Evaluation

Successful evaluation involves a series of steps, each of which must succeed in order for the goal of fire and life safety education—a changed human being whose behavior produces less risk and more safety—to be achieved. Professional program evaluators have developed a staged approach to evaluation, summarized in Table 5.8.1, which addresses these steps in a logical order. Table 5.8.2 provides several types of candidate evaluation measures and the evaluation steps they could support.

Formative Evaluation. Formative evaluation is qualitative, whereas process, impact, and outcome evaluation are quantitative; that is, they measure. The educational program has to be designed to target the behaviors associated with the most common or severe forms of harm. Teaching everyone how to safely operate a tractor, for example, would be mostly ineffective because most people will never have use for that information. However, teaching everyone how to select safe floor coverings to avoid unusual risks of falling will benefit nearly everyone.

TABLE 5.8.1 Stages of Program Evaluation

Stage	*Description*	*When Used*
Formative evaluation	The process of testing program plans, messages, materials, strategies, and activities for feasibility, appropriateness, acceptability, and applicability	During development of new program or modification of existing program
Process evaluation	The mechanism of testing whether a program is reaching the target population, such as by counting the number of people or households reached	From the start of program implementation throughout the life of the program; results used to fine-tune a program during implementation
Impact evaluation	The mechanism of measuring changes in the target population's knowledge, attitudes, beliefs, or behaviors associated with the program	Before program implementation and during and/or following the program
Outcome evaluation	The mechanism of determining how well a program achieves its goal of reducing morbidity and mortality; requires a large study population and analysis of the same data for a similar population that did not receive the program (control group)[6,7]	Before program implementation and after program completion

TABLE 5.8.2 A Hierarchy of Evaluation Measures for Public Fire and Life Safety Education

	Aspect Measured	*Examples of Evaluation Measures*
Outcome evaluation	End results (strongest proof)	• Number of deaths, injuries, dollar loss, or fires per capita • Anecdotes of saves linked to programs
Impact evaluation	Behavior or the environment	• Percent of households with a working smoke detector • Percent of households sprinklered • Percent of chimneys cleaned at least annually
	Awareness, knowledge	• Percent of public who know how to extinguish a grease fire • Percent of public who know how to use extinguishers • Percent of public aware of need to crawl low in smoke
Process evaluation	Extent of program outreach	• Percent of population (or a subgroup) receiving public education materials • Percent of elderly receiving safety lecture • Percent of schoolchildren with *x* hours of safety instruction each year
	Likeableness and usage of programs	• Percent of teachers who think program materials are good and use them
	Institutional change	• Introduction of safety curriculum in schools • Addition of service organization to aid dissemination

The educational program has to be designed to be effective for its intended audience. The key behaviors for the intended audience may not be the same as the key behaviors for the general public. If the audience were a high school in a farm community, for example, teaching members of the audience how to safely operate a tractor would be appropriate. If the community includes a large population of immigrants from non-English-speaking communities, then an effective program will need to deal with language issues.

Process Evaluation. Once the content of the program is selected and evaluated for its potential to make a difference, the next step is to evaluate the program's effectiveness in reaching its target audience. This step is dependent on program resources and the skill with which they are deployed. *Process evaluation* measures the adequacy of the program resources, delivery approach, and implementation plan generally to achieve its goal—the process for educating the target audience. There are all kinds of ways of targeting a program to achieve the maximum bang for the buck. But even with these targeting methods, too few bucks will mean too little bang. This situation is where evaluation of some secondary program goals cited earlier—obtaining additional funding or additional personnel slots, for example—may also be appropriate as part of program evaluation against the primary goal of reducing harm to people. But there are all kinds of reasons other than insufficient resources why a program may fail to reach its audience.

Impact Evaluation. If the program has targeted the key behaviors in a manner appropriate to the target audience and has been delivered effectively to that audience, it is now time to ask about direct educational effects. *Impact evaluation* measures changes in knowledge, attitudes, and beliefs. If those are confirmed, it goes on to measure changes in behavior.

As with the earlier stages of evaluation, there are many reasons why a program that has shown nothing but success in the prior stages of evaluation might nevertheless demonstrate serious problems in this stage. The specific educational content might prove ineffective with the audience. The audience might already have a high degree of relevant knowledge but might have deeply ingrained attitudes or beliefs that prove resistant to change.

At this point, if not before, it is useful (some would say necessary) to have a model of how people learn and how and why they change behavior. Table 5.8.3 describes three widely used and highly general examples.

Impact evaluation may also be the stage where the design and implementation of good measures is the most difficult. It is relatively straightforward to segment parts of the fire problem and characteristics of target audiences for formative evaluation, and data on these are often plentiful. It is entirely straightforward to count people reached for process evaluation, even though the information necessary for proper context and in-depth examinations can be more challenging.

But measuring overall changes in knowledge—based on a brief test with a few questions—can be done in many ways, none of them obviously the best. Measuring changes in attitudes and beliefs is notoriously difficult, because many people are not articulate or even fully aware of all their critical safety-related attitudes and beliefs, and some attitudes and beliefs are known to be widely disapproved and are likely to be concealed. In addition, measuring change in behavior is very difficult outside structured situations, when what is important is behavior in the places and at the times when the choice between safe and unsafe behavior will be done automatically, based on learning, and not with a heightened and artificial sensitivity to the needs of a test.

Outcome Evaluation. If impact evaluation is successful—if it is established that the target audience has received the education, learned new knowledge and new attitudes and beliefs, and modified its behavior—then it is time for the final, decisive stage of evaluation, which is *outcome evaluation.* Although the basic

TABLE 5.8.3 Selected Health Behavior Frameworks Used in Community-Based Interventions

Model Type	*Description*	*Comments*
Health Belief Model[8]	An individual's readiness to alter behavior depends on four conditions: • Perceived threat or susceptibility to the condition • Perceived severity of the condition • Perceived benefits of the health action • Perceived barriers or personal costs of the health action	Community-based interventions should be designed to convince the target population of the threat of injury and their risk while simultaneously instilling confidence that a particular action is effective in reducing their risk.
Social Learning Theory[9]	Behavior change occurs within a social context and is influenced by both active involvement in the learning process and identified consequences of the behavior change.	Strategies such as modeling behavior (i.e., having someone physically demonstrate the desired behavior) and promoting external reinforcement (e.g., offering money) or internal reinforcement (e.g., instilling a feeling of pleasure or pride) are key to successful behavior change. The ways in which social groups alter behavior support social learning theory; members change their behavior as a result of modeling or reinforcement by others, or by their own active involvement in the group.
PRECEDE Model (an acronym for Predisposing, Reinforcing, and Enabling Constructs in Educational Diagnosis and Evaluation)[10]	Predisposing, Reinforcing, and Enabling constructs work together toward behavioral change.	*Predisposing factors* include attitudes, beliefs, and values of the target population. *Reinforcing factors* include support for behavioral change, such as support from family, peers, teachers, or health care providers. *Enabling factors* consist of the individual skills necessary to adopt the proposed change, as well as the availability and accessibility of external resources to facilitate change. The *educational diagnosis* is the examination of predisposing, enabling, and reinforcing factors in the specific context of the proposed behavioral change. *Evaluation* is the quantification of the program's impact.

measures for outcome evaluation are in many ways simpler than those for impact evaluation, proper interpretation of the data can be enormously complex. The measure of a program's success is not simply the outcomes and events in the lives of its target audience; it is the change in those outcomes and events attributable to the program. Determining success means comparing outcomes to baseline experience prior to the program. It means considering preexisting trends and what they say about how bad or how much better experience would likely have been in the absence of the program, if other changes already underway had simply continued without additional intervention. Or, if simple extrapolation is considered unreliable, it may mean comparison of the educated group and its progress to a control group not exposed to the program.

FORMATIVE EVALUATION

Overview of Formative Evaluation

Formative evaluation is like a very thorough technical review; formative evaluation is qualitative rather than quantitative. It involves checking embedded assumptions against available relevant data. Are the hazards targeted the leading ones in this community, or are they the equivalent of tractor safety in Manhattan? Is there experience elsewhere with these materials and activities, and does the proposed approach fully incorporate lessons learned in those prior implementations? What are the key characteristics of the target audience, and are those fully reflected in the program's specific design? Has a diverse group collectively representing all relevant perspectives and types of expertise reviewed the program, and have their comments all been addressed? Are there issues of acceptability for the students, the teachers, or the community?

Formative Evaluation of *Risk Watch*®: An Example

Risk Watch®, designed for students grades pre-K through 8, is the first injury prevention program for children that is comprehensive in scope, addressing eight high-risk areas, including motor vehicle safety, bicycle and pedestrian safety, fire and burns, poisoning, choking, falls, water safety, and firearms safety. Developed in collaboration with injury prevention experts and educators, *Risk Watch* is a school-based curriculum designed to be

implemented as a community-based injury prevention initiative, emphasizing community participation and involvement.

One very important component of *Risk Watch*—the use of community volunteers (firefighters, EMS personnel, law enforcement officials, and health care providers) to visit classrooms to present and demonstrate safety messages to children—was the direct result of formative evaluation, in which teachers indicated their strong preference for the direct involvement of community helpers. The benefits of using community volunteers are twofold. First, children are presented important safety messages by front-line community role models.[11] Second, volunteers themselves become more involved in promoting the health of the community.

Before the *Risk Watch* curriculum could be evaluated in terms of impact—that is, effectiveness in improving children's safety knowledge and behavior—it first had to undergo a formative evaluation to assess core activities and safety messages. If the curriculum could not be easily taught by schoolteachers, or if the safety messages were inappropriate for the target age group of students, then one would not expect to see positive results in terms of knowledge gain or behavior change. The *Risk Watch* curriculum had been developed by injury experts, who suggested appropriate safety messages to relay to children, and by developmental specialists, who "translated" these messages into lessons that children of different ages and developmental levels could comprehend. For example, many songs and chants were used for young children grades pre-K through kindergarten, whereas story writing was used for older children in grades 6–8. Focus groups of teachers and educators were formed to discuss the appropriateness of the lessons and messages, and scripted interviews were administered to a large sample of teachers to obtain additional feedback. The information obtained from these studies constituted the formative evaluation and was used by curriculum writers to revise the lessons, clarify safety messages, and assure a user-friendly manual.

The next step in the *Risk Watch* development cycle was to complete a comprehensive field test of the curriculum. The purposes of the field test were to gather additional formative data (that would allow further "fine-tuning" of the program) and to begin to assess its effectiveness in terms of student knowledge gain. Five geographic test sites were chosen, with several schools participating at each site. A sample of teachers representing all grade levels from each site was trained, as were community volunteers who came into classrooms to augment the teachers' safety lessons. After teaching *Risk Watch* lessons, teachers completed surveys with questions relating to acceptability and usability of materials, as well as perceived learning by students. Results of end-of-lesson surveys and end-of-program surveys completed the formative evaluation. Many teacher suggestions and recommendations were incorporated into a new, revised *Risk Watch* curriculum.

Formative Evaluation of Hagerstown Programs: An Example

Hagerstown, Maryland, provides a case study of the uses of evaluation in a fire safety program based in a local fire department. Nearly 250 years old, Hagerstown is a small city whose 2000 population was just under 37,000. Located in western Maryland, it has recently experienced a high rate of residential development as well as rapid growth in adjoining suburban areas of Washington County.

In the mid-1980s the fire department assigned an officer full-time responsibility for designing, implementing, leading, and evaluating a comprehensive risk reduction strategy. After subject-matter training through the nearby National Fire Academy, author Weller designed and implemented a program that has now run for more than a decade.

Formative evaluation is a qualitative stage of testing a program to see whether its design features and target audience give it a good expectation of success. Most local fire and life safety educators will design a program by adopting and adapting model programs that have already been tested elsewhere. This situation means there is no need for a formal step of formative evaluation, but there is still a need to select program elements and decide how to adapt them.

Typically, a risk reduction officer will find that his or her community, like the nation as a whole, suffers most of its fire deaths and injuries in homes. It is advisable to review fire experience data to determine whether there are any nonhome areas worthy of attention, but the decision to target homes will usually be supported by such a data review.

Also, the officer may discover that the most readily implemented programs are educational programs, specifically those designed to improve prevention behaviors and use of smoke alarms. Changes to engineered products or to common fire protection and mitigation practices (e.g., use of fire sprinklers) tend to be implemented through building and fire codes or the actions of the U.S. Consumer Product Safety Commission. Therefore, even though some such programs can be quite effective, they are likely to be considered outside the scope of the risk reduction officer's authority and influence.

Using this framework, Hagerstown examined a decade of fire response data for leading causes of fire and the typical sequence of events leading to these risks. Hagerstown confirmed a significant share for all the national leading causes: cooking, intentional fires, electrical distribution equipment and electrically powered appliances, candles, heating, and smoking. Further analysis led Hagerstown to focus on cooking.

Cooking Fires in Hagerstown. The decision to focus on cooking was based on three approaches to interpreting Hagerstown data. First, cooking fires in general and unattended cooking fires in particular contributed a large or leading share of local fires. Therefore, it was the natural first choice if one cause were to be emphasized. Similarly large shares were seen in available national data, which supported the idea that Hagerstown was seeing something real and not some one-time fluke.

Second, the large shares for Hagerstown were larger than the local people had expected prior to the analysis. Therefore, their sense of the degree to which this problem was under control changed.

Finally, an informal check with neighboring towns suggested that Hagerstown's cooking fire shares might be higher. Ideally, one would go beyond impressions to a comparative analysis, and as local databases suitable for analysis have

become ever more widespread, this formal step has become easier to do than it was perceived to be at that time. It could be that the impressions of neighbors regarding their cooking shares would have been found to be low, just as the impressions in Hagerstown were found to be when the analysis was performed. However, this informal check was at least consistent with the direction provided by the other analysis, namely, a focus on cooking made sense for Hagerstown, at least because it had a large cooking fire problem, at most because it may have had an unusually large cooking fire problem.

Having decided to focus on cooking fires, Hagerstown next asked for more specifics on target behaviors and target audiences. Local and national data indicate most cooking equipment fires involve stovetop cooking, and both the Hagerstown data and national data showed no reason to focus more on gas or electric stoves.

The occurrence of the problem was distributed city-wide, with an expected higher rate of incidence in the greater downtown area where poverty was of significant concern.

Hagerstown Goals and Approaches. Hagerstown was now in a position to specify its goals and its programmatic approach. The goals were reducing cooking fires by 30 percent and improving smoke alarm usage to 90 percent, both within 10 years. The programs were to involve increases and improvements in the K–12 school education efforts and a door-to-door awareness and smoke alarm installation program, the latter at a targeted pace of 4000 homes per year, conducted during the spring season. (Spring meant more daylight hours than winter, and experience had shown that resistance was more likely after dark or on weekends, including Friday evenings. Daylight hours during summer can be quite hot, and this factored into the decision to avoid summer. In the same spirit, fall would have meant competition with the staff time required for the school-based part of the program.)

Local data not available on a national basis provided detailed insights into why unattended cooking was unattended. The primary behavior identified was leaving a pan of grease unattended on a stove after being distracted by things such as children, TV, phone, Internet, neighbors—or just thinking one had time to go do other things while the grease heated or the food fried. Additional local-only data indicated what kind of inappropriate fire-fighting techniques were being used and helped to explain injuries suffered while fire-fighting. All of this extra detail was available to inform choices about educational messages and model programs to be used.

Neighborhood tours of burned homes, conducted by fire fighters, were incorporated as part of the door-to-door effort. And an all-media awareness campaign, focused on cooking fires and smoke alarm usage, completed the program design.

Finally, Hagerstown used testing by local focus groups to select among the specific candidate educational materials to be used within its general approach. This testing was the part of formal formative evaluation that made sense for a local program using already-tested national model program components. The fire department enlisted help from professional educators, marketing specialists, and citizens. By having members of target populations review proposed materials and initiatives, Hagerstown obtained a good idea of what might lead to successful impact and outcome over time.

This strategy worked well as several concepts that proved ineffective during pilot testing were deleted in favor of those exhibiting stronger potential for success. One example was a door card that showed fire fighters extinguishing a grease fire. It was deleted in favor of an image of responding fire apparatus with the slogan "Don't Invite Us to Dinner—Stay in the Kitchen When Cooking."

PROCESS EVALUATION

Process evaluation involves more than just counting students taught or households reached. It involves more than comparing such numbers to the size of the target audiences and determining the degree of coverage, penetration, or reach. It involves evaluating the reasons for shortfall and also information on reactions that may bear on the program's likely acceptance if its target audience is broadened. In other words, the *process* of delivery of the material needs to be evaluated.

Process Evaluation of *Risk Watch*

Figure 5.8.1 is part of a process evaluation questionnaire for *Risk Watch.* The first question, on time allotted per lesson, is one of many that may provide insight into hidden problems with the quality of delivery. The second and third questions, on enthusiasm from the students and teachers respectively, may give insight into sources of resistance down the road or help explain why teaching might occur and learning still not occur.

Process Evaluation of Hagerstown Programs

Hagerstown got the baseline information it needed through a household survey of most of the city and through school-based knowledge tests at various grade levels, to see what school age students knew about fire safety.

The face-to-face survey of 7000 citizens asked what they knew about Hagerstown's fire problem and how to prevent it:

- Citizen knowledge of the leading causes of fires in the community
- Citizen knowledge of how to best prevent stovetop fires
- Citizen knowledge of how to best extinguish a grease fire
- Presence, location, operability, and overall condition of smoke alarms in homes

Unattended cooking was identified by 24 percent of respondents as the leading cause of fire and related injury. Although this indicated a need for greater awareness, it is not a bad starting point. (The size of the group surveyed far exceeded the number needed for statistically significant results, but Hagerstown chose to use the survey not only for its informational content but also as a first step in outreach to the community.)

More disturbing in the survey was the discovery that only 60 percent of households contacted had smoke alarms, a level far behind the reported usage levels nationally at that time. People without smoke alarms were asked why, and as with similar national surveys, the dominant answer was a lack of perceived

Representative Teacher Survey Questions

1. On average, how much classroom time do you spend teaching a *Risk Watch*® lesson? (Select only *one* response)

   ☐ Less than 30 minutes
   ☐ Thirty minutes
   ☐ Forty-five minutes
   ☐ One hour
   ☐ More than one hour

2. How enthusiastic about each lesson were your students? (Please answer on a scale of 1 to 10 with 1 being NOT enthusiastic and 10 being VERY enthusiastic.)

	Not enthusiastic									Very enthusiastic	
Lesson 1: Motor Vehicle Safety	1	2	3	4	5	6	7	8	9	10	n/a
Lesson 2: Fire & Burn Prevention	1	2	3	4	5	6	7	8	9	10	n/a
Lesson 3: Choking, Suffocation, & Strangulation Prevention	1	2	3	4	5	6	7	8	9	10	n/a
Lesson 4: Poisoning Prevention	1	2	3	4	5	6	7	8	9	10	n/a
Lesson 5: Falls Prevention	1	2	3	4	5	6	7	8	9	10	n/a
Lesson 6: Firearms Injury Prevention	1	2	3	4	5	6	7	8	9	10	n/a
Lesson 7: Bike & Pedestrian Safety	1	2	3	4	5	6	7	8	9	10	n/a
Lesson 8: Water Safety	1	2	3	4	5	6	7	8	9	10	n/a

3. Overall, how much do you like teaching *Risk Watch*?

1 2 3 4 5 6 7 8 9 10

Do not like teaching *Risk Watch* — Like teaching *Risk Watch*

FIGURE 5.8.1 Representative Teacher Survey Questions

need. A smoke alarm distribution program needs funding beyond the normal budget of the fire department to succeed. Hagerstown was able to fund its program with support from the U.S. Department of Housing and Urban Development.

The downtown area, with its higher fire rate, was split in two, with half to be covered every 2 years. The rest of the city was to be covered every 6 years, based on 2 out of 12 census tracts per year. "Covered" meant that every home in the target zone was approached. About 40 percent were successfully contacted. This could mean the cycle time for contacting everyone would move up from 2 and 6 years to 5 and 15 years—or worse, if some of the missed households constitute hard-core, chronic refusals. This is why contact rates are critically important statistics in process evaluation.

Quality control for the large team of fire fighters acting as educators was provided by random surveys of contacts. It was important to ensure that variations were minimized from one fire fighter to another in what information was being disseminated (e.g., educational messages) and what information was being collected (e.g., knowledge tests, smoke alarm usage).

IMPACT EVALUATION

Impact evaluation usually proceeds in two successive steps. First is evaluation of changes in knowledge, attitudes, and beliefs. Second is evaluation of changes in behavior.

Measuring Change in Knowledge

One of the most common types of evaluations of fire safety education is the classic multiple-choice test. Often such tests are given before a program starts, or at the beginning of the first class, and then repeated at the end of the training using the same test instrument. Sometimes the "after" test uses a slightly

different set of questions. The results of the "before" test not only establish a baseline but also give insight into exactly where the group is weak. The "after" test shows the increase in knowledge.

Pre- and posttests do not have to be elaborate. Sometimes a few well-chosen questions can suffice.

Figure 5.8.2 shows profiles of test scores before and after a class that was conducted over a four-day period. The graphs show the profile of scores for different questions. It is very clear that the class dramatically improved. Although this example was drawn from a class of fire fighters taught about fire safety education, the data could have been for a classroom of children or a group of elderly.

In addition to the graphic presentation in Figure 5.8.2, the average score and the range of scores for the pretest versus the posttest describe the change quantitatively. This type of evaluation can be done separately for each class or group of people, or all classes can be lumped together. The separation by class is especially useful when there are differences in the composition of the classes or when the classes are taught by different instructors.

Retention Tests. Giving a posttest immediately at the end of training may reflect only short-term retention, though the test itself may promote retention. It is desirable, therefore, to administer another test several weeks to a year after the last training session. That test would measure retention and present an opportunity for a "booster shot" or reminder of the safety lesson to the students.

Practical Tests. Another testing problem is that a paper test may not reflect what a person will remember or do in a crisis. Physical, hands-on training and demonstrations of competence may be better indicators of actual performance. Few people would certify someone as competent in cardiopulmonary resuscitation (CPR) or first aid based solely on a multiple-choice test, yet this can occur in fire safety program evaluation.

Different Pre- and Posttests. When the same test is used for pre- and posttesting of the same group, there might be some improvement in the score even if nothing were taught, due to increased familiarity with the questions and discussion of answers among the students. This situation is not necessarily detrimental—the test itself can be part of the learning experience. But there are ways to circumvent the problem:

1. Slightly different wording of questions can be used in pre- and posttests, though some of the changes measured might result from differences in the test wording rather than changes in knowledge.
2. Test one group before it is taught the prevention material, and test another group after it is taught the material. If the groups are reasonably similar in composition, the differ-

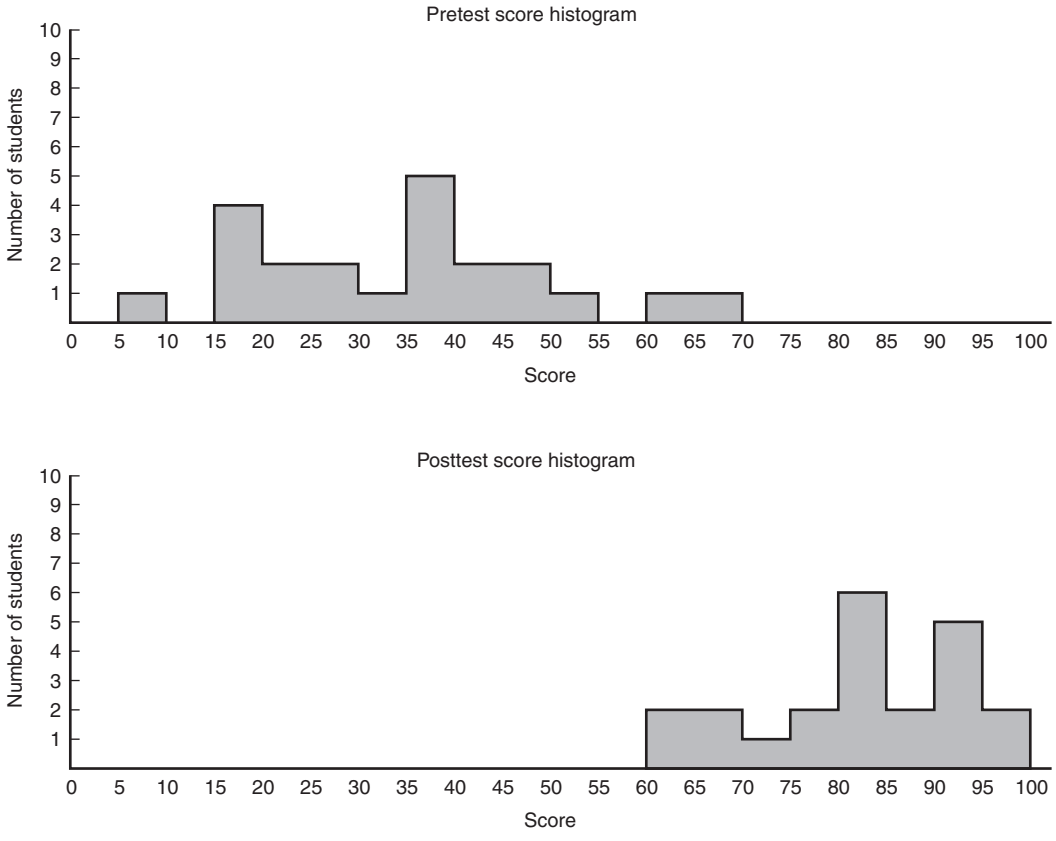

FIGURE 5.8.2 Profile of Test Scores Based on Bolitin/Histogram

ence in test results will show the effectiveness of the program in improving knowledge, while requiring only one test per class and allowing all students to receive the prevention material.

This approach works particularly well when a large number of reasonably similar classes are to be taught the same fire and life safety material, for example, all grade 5 classes. The test might be given to every other class before the material is taught, with the remainder given the posttest. The large number of classes is likely to make the difference between the two groups unimportant. To take the other extreme, one would not want to use this approach on only two classes, especially if one were a "slow" class and the other an honors class.[12]

Impact Evaluation of *Risk Watch*

NFPA worked with an external evaluation firm to conduct a three-year analysis of the impact of *Risk Watch* on children's knowledge of safety behaviors. The field test was designed to gather impact data, and instruments were developed to measure knowledge change in children exposed to *Risk Watch.* A pretest/posttest methodology was used, comparing knowledge gain of students exposed to the curriculum (study group) with knowledge gain of students who did not experience *Risk Watch* in their classrooms (control group).

Pretest/Posttest Methodology. Pretest/posttest exams had to be created with developmental characteristics of the audience in mind, such as children in the youngest classrooms (pre-K–1) who were nonreaders. Teachers in the latter classrooms administered exams verbally and by using pictures, whereas exams for older children consisted of short answer questions and multiple-choice type questions, each of which had three answer choices.

After teachers in the pilot site classrooms conducted a pretest of knowledge with students, *Risk Watch* was implemented by using the NFPA collaborative model. A team approach was used to deliver course content to students, with representatives from fire and police departments, EMS, and numerous other community resources augmenting the work of teachers in presenting *Risk Watch* lessons. After all lessons were completed, a posttest was conducted. A comparison of the pretest and posttest scores was used to indicate knowledge gain within each risk area. This incremental change was then compared to a control group who received the same pretest and posttest as the experimental group did without receiving *Risk Watch* lessons.

Analyzing Initial Pretest/Posttest Data. NFPA's evaluation researchers analyzed data from pilot sites, using t-tests from the Statistical Package for the Social Sciences (SPSS) to determine the equivalence of the *Risk Watch* (study site) students and comparison (control site) students in terms of their pretest knowledge.[13] This important concept should be considered when using a pretest/posttest design to measure impact on knowledge, because if pretest scores are very high, students will not be able to show much growth in knowledge from pretest to posttest. This situation occurred with the initial *Risk Watch* knowledge tests. Students, even with no exposure to *Risk Watch,* got the great majority of test items correct. This occurrence makes it almost impossible to demonstrate change, or growth in knowledge, as a result of participating in *Risk Watch.* Either the initial tests leaned too much on widely shared safety knowledge, in which case more difficult tests would show the value of *Risk Watch* as these initial tests did not, or *Risk Watch* was teaching children only what they already knew and was not an effective program.

Redesigning Tests. NFPA's evaluation researchers developed new, more difficult knowledge tests that were administered to children in a pretest/posttest style, as had been done in the field test. Results demonstrated statistically significant gain in knowledge between pretest and posttest scores of children exposed to *Risk Watch.* Although comparison (control) group scores also improved, the increases in score were greater for the *Risk Watch* students in all grade levels.[14] Table 5.8.4 displays the differences between target and control groups, using the redesigned test.

There were statistically significant improvements in both the test group and the comparison group. For *Risk Watch,* the important result is not the significance of the differences. Rather, it was important that the *Risk Watch* student gains were larger, by enough of a margin that it was considered statistically demonstrated that the superiority of the *Risk Watch* students over their comparison group was real and not due to chance. However, this gain also demonstrated that students learning safety outside a structured program, and a less sophisticated evaluation, might well have overestimated the particular contribution of *Risk Watch.*

Previous studies have suggested a link between knowledge gain and behavior change, and several educational interventions have been shown to increase a safety behavior (use of motor vehicle restraints) of preschool children.[14,15] For some safety behaviors, there is also evidence that adoption of the behavior

TABLE 5.8.4 Comparison of *Risk Watch* Target and Control Groups

Target Group	*Pre-K–K*	*1–2*	*3–4*	*5–6*
Gain (in items)	3.10	1.26	2.0	1.97
Gain (in percent)	9	6	8	8
Significance	<.0001	<.0001	<.0001	<.001
Sample size	74	114	83	78
Control Group				
Gain (in items)	1.32	1.05	.82	.75
Gain (in percent)	4	5	3	3
Significance	<.0001	<.0001	<.05	<.05
Sample size	65	135	67	71

(such as wearing a bicycle helmet) is strongly associated with a decrease in injury rates (such as head injury).[16] Several observational studies have reported beneficial effects of increased use of safety practices on childhood injuries.[17,18]

Nontest data collection strategies have been designed to determine whether student behavior changes as a result of participation in *Risk Watch.* This determination is a difficult undertaking, for although direct observation is a natural technique for identifying behavioral changes, fully half of the topics covered in *Risk Watch* are almost impossible to observe. Many of the safety behaviors associated with *Risk Watch* do not occur in the school environment, where researchers could easily complete observations of all children. If researchers move off site from the school, they would need to be sure that every child they were observing were exposed to *Risk Watch* in the study area, and every child they observed in a control area had not been in a *Risk Watch* classroom. With so much crossover in school populations (i.e., children attending "magnet" schools out of district or attending private schools some distance from their homes), this control would be difficult. Further, many of the behaviors taught in *Risk Watch* occur relatively rarely, making observation of such behaviors difficult.

As a simple example, the chance of one student participating in a *Risk Watch* evaluation study being involved in a fire during the time period of the study is, fortunately, small. The chance that enough students would be involved in fires to allow valid conclusions to be drawn about their response to such an emergency situation is, just as fortunately, nearly infinitesimal. Although no observational studies have yet been completed to evaluate the effect of *Risk Watch* on behavior change, several have been designed and can serve as examples of additional evaluation techniques. One such study was designed to include children and households in a rural, high-risk geographic area. The evaluation uses a pretest/posttest design in an intervention community and a control community. Data collection was accomplished by direct observation of the behavior of children in the areas of motor vehicle safety, bicycle safety, and pedestrian safety. In addition, home visits are planned to complete a safety survey. These observations were recorded prior to the implementation of *Risk Watch* in all classrooms of the intervention community's schools. Repeat observations will be completed in both the study county and a control county after the school year has ended to gather postintervention data.

Measuring Impact on Behavior Through Inference: An Example

Direct observation of natural behavior with safety implications is extraordinarily difficult. In even the best evaluated programs, evaluation is likely to be limited to some behaviors in artificial environments and some other behaviors that lend themselves to unobtrusive observation in a natural setting, but may not be collectively representative of the range of behaviors covered by the educational program.

One method of compensating for the lack of direct observational data is inference from established research demonstrating the conditions linking knowledge to behavior change for similar educational programs on other matters of safety or health. The developers of *Risk Watch* have used this technique on at least a temporary basis, to strengthen their impact evaluation.

Impact Evaluation of Hagerstown Programs

Pretest and posttest scores on school-based programs were monitored. During every annual neighborhood canvass, citizen knowledge of fire causes was evaluated and the number of homes equipped with smoke alarms carefully tracked.

These tests all showed slow but steady and cumulatively significant progress. Baseline and postprogram fire safety knowledge grew among schoolchildren. Citizen knowledge of the cooking fire problem grew in some neighborhoods by as much as 50 percent (e.g., a baseline of 16 percent knowing that cooking was the leading fire cause might grow to 24 percent, which is 50 percent higher than 16 percent, $(24 - 16)/16 = ½ = 50\%$).

OUTCOME EVALUATION

For outcome evaluation, it may be assumed that the general measures of interest are deaths and injuries due to the targeted hazard, that is, fires and falls. The more detailed guidance in this section has to do with techniques and issues in using anecdotes as evaluation evidence, selecting focused outcome measures to better fit the programs, and using basic approaches to making comparisons.

Using Anecdotes

One of the favorite means of evaluating public education programs is through anecdotes of survivors who testify that they learned a safety behavior from a public education program, and it saved their own life or that of another. Anecdotes are wonderful human interest stories and can attract the attention of the media. To most people, including decision makers, they are more interesting and more understandable than statistics. But anecdotes alone can be dismissed as weak evidence, especially if there are only one or two. Despite the frequently made statement that "this program is worth it if only one life is saved," politicians and budget managers do not always see it that way.

Nevertheless, anecdotes are a legitimate form of evaluation, especially when used in conjunction with statistics. An anecdote provides insight into a program and proves that at least in one case the program worked. Multiple anecdotes are much stronger evidence than single anecdotes, because one event might be considered a fluke.

Anecdotes are most credible when documented in writing by survivors or firsthand witnesses and when they describe not only an appropriate behavior but also where that behavior was learned. Preferably the anecdote should be verified by at least a telephone call or second witness. The more anecdotes on a program, the better. NFPA's *Learn Not to Burn*® curriculum[19] has accumulated more than 202 documented cases where its messages saved lives or reduced injury to 554 people. Similarly, there are 15 *Risk Watch* documented incidents in which 31 lives were saved. Anecdotes are also more impressive when at least some of them are fresh (because programs and program delivery change) and when there is a series of anecdotes, indicating consistent, long-term results.

Because it is virtually impossible to collect anecdotes for all saves associated with a program, one needs the relevant overview statistics as well. A budget manager is much more likely to continue to fund a public education program where fire deaths decreased by ten over the previous year and anecdotes were used to show that the program was a factor in the decline, than where only the statistics or only the anecdotes are used. Together the picture portrayed is much more convincing.

Some people belittle the use of anecdotes because they do not add up to statistical "proof." But at the local level or even nationally it does not take that many anecdotes to drastically change the fire loss picture. If public education programs reached half the people in each community and saved more persons per 100,000 people reached by public education per year than at present, the nation's fire death rate would be cut in half. (To see this, consider that one out of 100,000 is equivalent to 2500 saves out of 250,000 people and the annual fire death toll per year has been about 5000.)

Selecting Focused Measures

When a fire safety education program is targeted at a particular type of fire, such as grease fires on the stove, Christmas tree fires, or kerosene heater fires, the evaluation, too, should focus on how that type of fire changes over time and how it compares to other types of fires for which there was no current program. Sometimes focusing on one type of fire may raise awareness and have a beneficial effect on many types of fires, and so the overall change in the fire problem needs to be monitored, too. But the primary focus should be on the type of fire that was the target of the program. The same philosophy of targeting the evaluation properly applies to programs aimed at changing people's response to fire, such as escaping quickly or closing doors or using extinguishment methods properly.

Unfortunately, those attempting to undertake evaluations often look for changes only in the larger universe of fires rather than in the target group they were after. They measure the change in all fires when a program was targeted just to residences, or they measure the change in all residential fires when the program was aimed solely at cooking fires, or they look at all cooking fires when the prevention message was targeted solely at grease fires.

The chance of detecting results increases if one keeps the focus as narrow as the category the program message addresses. Otherwise, the results are diluted amid a larger pool of fires, and one may not be able to detect them.

Table 5.8.5 gives examples of some targeted messages and associated measures of their effects. In each case one also should compare the change in the targeted type of fire to the change in other types of fires, or fires in general, as a control. If cooking fires are targeted and they dropped in number, check whether heating and children-playing fires dropped, too. And check whether cooking fires dropped in nearby communities where there was no program. If there were reductions in other types of fires or in other communities, forces other than the education program may be at work. Or the program may have broader impact than what it targeted.

It may be difficult to obtain the data for exactly what one wants to measure. Therefore, it may be necessary either to (1) retreat and find a surrogate measure or (2) measure the impact on the next larger category that includes the type of fire or behavior targeted. For example, one runs a public service announcement (PSA) about sliding a lid on grease fires, but cannot easily measure the number of grease fires; therefore, the number of cooking fires might be used instead. Further, if a school program is focused on the need for children to escape quickly from home fires, but one cannot measure the number of injuries from not escaping quickly, it might still be useful to track the number of injuries to children in home fires.

TABLE 5.8.5 Sample Measures for Specific Education Focuses

Education Theme	*Examples of Measures to Use*
Use of smoke detectors	Number of households with detectors Number of reported fires (early detection leads to occupant extinguishment and fewer reports) Number of fire deaths
Getting out quickly from residential fires	Number of injuries while attempting fire control in residential fires Number of fire deaths Number of severe injuries
Need to clean chimneys	Number of chimney fires
Careless smoking	Number of fires or deaths involving careless smoking
Safe storage of flammable liquids at home	Number of nonarson fires where flammable liquid was material first ignited
Children playing with lighters or matches	Number of residential fires where heat of ignition was a match (or lighter) and ignition factor was "children playing" Number of children injured in above type of fire

Using Basic Approaches to Making Comparisons

This section presents a short, condensed summary of the complex subject of data measure evaluation. A more in-depth treatment on evaluation in general is available from the Urban Institute's book, *Public Program Evaluation.*[20] Another excellent reference specifically on evaluating public fire education is the National Fire Academy's fire education evaluation guide.[21]

Perhaps the most basic concept of an evaluation is to demonstrate that some benefit can come from having a prevention program compared to not having it. There are several approaches to making the desired comparisons:

1. Compare the targeted community's experiences over time to see if there is a difference after a program started compared to the "baseline" before it started. (Changes in the community that occurred during the period used in the

comparison and that could affect the results must be taken into consideration.)

2. Compare one part of the community to another, to see whether there is a difference between areas that have public education programs versus other areas that do not yet have the program, or had it for a shorter time or with less intensity.
3. Compare the community to other communities, especially to similar communities that have not had a comparable public education program recently. A variation is to compare like parts of different communities, such as inner-city neighborhoods or high-rise dwellers.
4. Compare changes in a targeted type of fire or hazard (or safety behavior) to the trend in other types of fires or hazards (or other safety behaviors). For example, consider the change in cooking fires versus the change in heating fires after a campaign that targeted cooking fires.

Measuring Change over Time. The most straightforward way to show that a public fire education program has had an impact is to demonstrate improvement after the program started (Figure 5.8.3).[22]

In some cases, the effects are not immediate, and time must be allowed to observe results. In other cases, the effect is expected to be immediate and wear off with time, in which case speed of measurement is necessary. In yet other cases, the changes result from uncontrollable factors outside the program. All of these issues must be addressed.

Although ideally a public education program produces a drop in hazardous events, injuries, or deaths, the impact sometimes may be to reduce the magnitude of an increase, or change the rate of an increase. Data from statewide fire and life safety education programs in South Carolina provide further information (Figure 5.8.4).[22]

Often, there are random fluctuations in fire experience; these are especially noticeable when the community is small and the number of fires few. It may be necessary to observe data that zigzags for weeks or years before being able to discern the trend (Figure 5.8.5). There are sophisticated statistical analysis tests that can help.

Also, patterns may be more apparent visually if one uses rolling multiyear averages (e.g., 1995–1997, 1996–1998, 1997–1999, 2004–2006). The speed with which a prevention program has impact varies with the fire safety behavior being targeted, the frequency and timing of the message, and the receptiveness of the audience. It also may vary with the size of the audience reached. For example, if one-third of the population of a city is reached by a PSA associated with a popular television show—a very large audience for television—one might expect an immediate drop in the type of fires targeted. If instructions in the PSA were on how to prevent and extinguish a cooking fire, and the city averaged nine reported cooking fires per week, it might be reasonable to expect an average of six or fewer after the broadcast, if the program was designed to reach a broad cross section of households. The behavior change can be immediate for those who saw the PSA. It does not require any accumulation of knowledge over time, because the message is simple.

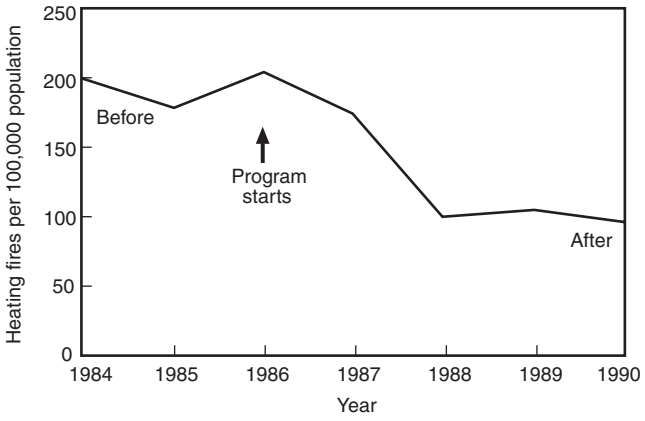

FIGURE 5.8.3 Hypothetical Example of a Change over Time Showing a Successful Program's Impact

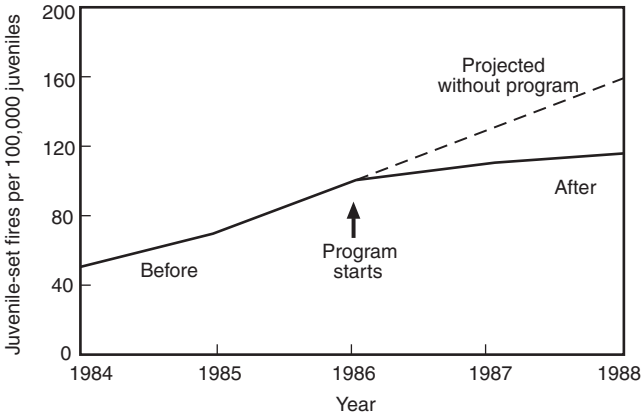

FIGURE 5.8.4 Hypothetical Example of a Change in the Rate of Increase Showing a Successful Program's Impact

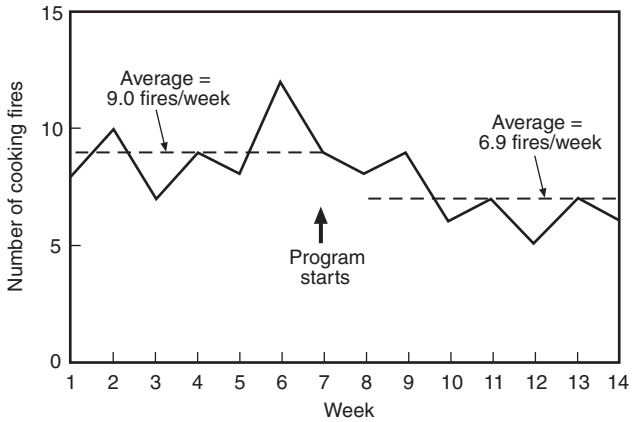

FIGURE 5.8.5 Hypothetical Example of a Change in Trend Visible Even with Fluctuating Data

Effects of a program may be delayed when the safety behavior being sought takes time and money to implement. For example, when people are instructed to test their detectors and replace the batteries, it may take some time before they get around to doing the test, then buying the batteries or alarms, and then installing them. In contrast, there is no delay in being able to implement "crawl low under smoke" or "slide a lid on a grease fire."

The speed with which a prevention program has an impact also depends on the nature of the audience. If the audience comprises mostly "safe households" with a low incident injury rate, it may take a while to see any further impact.

In contrast, a PSA targeted to areas with disproportionately high fire rates may impact faster, because there is more opportunity to create a larger change. However, if these households tend to ignore safety information, there could be no change. One needs to consider the status of the audience in assessing program impact, especially when comparing different programs or the same program in different areas.

The effects of a program also may be delayed when the target audience is young. For example, teaching students in junior high school to slide a lid on a grease fire may not have its full effect until they begin cooking more for themselves (though they may pass the information to other members of their households or intervene in a fire themselves).

Measuring a drop in reported hazardous events as a result of a public education program can be thwarted due to the unpredictable effects publicity can have on people's likelihood to report a fire. It is known that many fires go unreported. Almost all of the unreported ones are small, though they include fires that injure and that cause hundreds or even thousands of dollars in damages.

When a fire and life safety education program brings attention to a fire problem, more of these small fires might get reported than is usual, making it appear to the fire department that the problem is worsening when it actually is not. For example, encouraging people to evacuate their home quickly may cause some who previously would have extinguished their own fire and not reported it to leave and report the fire. The education program thus could cause an upsurge in reporting of fires. As another example, asking people to refer children who set fires to a juvenile firesetter program could encourage reporting of fires that might otherwise have gone unreported because of the perceived futility of reporting them.

The only way to know for sure whether a surge in reported fires is due to reporting of previously unreported fires is to periodically survey the population to determine the degree of their underreporting and the reasons for it. Then one can determine whether fires are being shifted from being unreported to being reported or are truly increasing in number.

Increasing Chances for Identifying Changes. Although there are a number of reasons why it may not be easy to see a change in trend as a result of public education, there are several ways to increase the likelihood of detecting a success.

One way is to use more sophisticated statistical techniques to see whether there is some signal of a change amid the noisy, erratic data coming from the outside world. Some fire departments have people on their staff or from nearby universities or other organizations who have training in statistical analysis. Modern, easy-to-use statistical computer software packages may help too. By all means use them if available. But if it takes extremely sophisticated statistical techniques to identify a change caused by a program, the program is not likely to be having a large effect. That is, if one cannot see the effect of the program looking at the data with the "naked eye," chances are that the effect is probably not very large. There are exceptions, and even if a change is small, it may be cost effective if only a correspondingly small effort were required to produce it.

An easier approach than employing sophisticated techniques is to collect more data over time. Average the data before the program started and compare that to the average after the program starts, as in Figure 5.8.5. The averaging will take out some of the random fluctuations, and some of the problems inherent in having only small numbers of deaths, injuries, or fires for smaller areas. Compute the trend lines (Figure 5.8.6). Look at fires, not just deaths, because there are usually about 100 times more fires than deaths. The impact of a program aimed at ignition prevention will show up sooner and more clearly for fires than deaths. If the program is directed toward education about escape or preventing bodily harm after a fire starts, rather than preventing or mitigating the fire itself, look at the number and severity of civilian injuries, and not just deaths. There tends to be about four times more injuries than deaths, and again the effects of a program may be more readily detected.

If the targeted community's population has not remained constant over the period of analysis, look at the data per 10,000 or per 100,000 population. (One also should look at the data on a per capita basis when comparing the community to others.) If the targeted community's population is increasing but the number of fires or deaths remains approximately the same, the rate per 10,000 people will be going down. That is, when more people are at risk but the community is not experiencing more fires or deaths, that can be an indication of a successful program.

Comparing Different Parts of the Community. As an evaluation tool, comparing parts of the community against each other

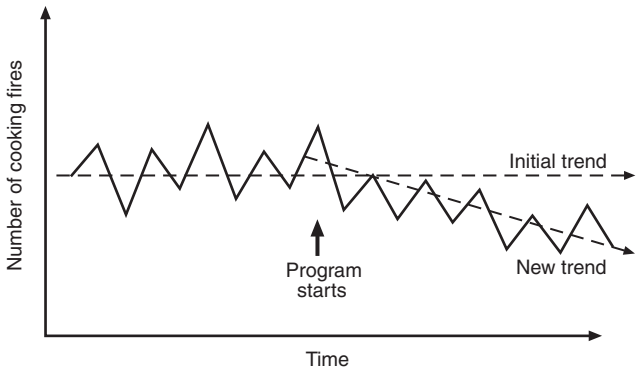

FIGURE 5.8.6 Hypothetical Example of Plotting Trends in Noisy Data

is most useful when a program is introduced to one area of the community and not to the others. Then one can compare the "treated" population to the "untreated" population, as is done in medical research (Figure 5.8.7).

For example, an educator might introduce to the schools in one neighborhood a program directed at getting smoke alarms tested and properly installed. The students might be asked to count the number of smoke alarms they have at home and to test them. This can be a homework exercise. Then the students can be taught the importance of maintaining alarms and periodically testing them. Results can be monitored for the next three months by looking at fires in that school area, and determining the percent of fires in which alarms were found working versus how that area did prior to the program, and how it compares to the areas of the community without the program. If the program appeared successful immediately, it could be tried in other areas. If not successful immediately, the material might be repeated and monitoring of results continued. An attempt might also be made to determine whether any outside factors were causing a counter, that is, negative, impact.

As another example, for one year one might equip the schools in a selected neighborhood or district with a fire safety curriculum. Results would then be monitored for the trial neighborhood versus the rest of the community. If the program shows some success, perhaps in a few types of fires such as "children playing," then it might be implemented in the rest of the community. Chances of getting expanded implementation are much greater if one can show quantitatively that the program really made a difference in the area of the trial.

Sometimes a program applied in one area of a community inadvertently may have effects on the whole community. A notable example came from Edmonds, Washington, where a door-to-door home inspection program in the mid-1970s using paid elderly women to make the inspections was found to have had about as much impact in the census tracts that had *not* been visited by the program as in the census tracts that had been visited. The suspicion was that the publicity attendant to the program caused people to "clean up their act" in anticipation of having a stranger inspecting their house. The program raised awareness of fire safety even in areas that did not receive the door-to-door inspections. If one compared the areas visited by the program to the areas not visited by the program, it could be concluded that the program was not very effective, when in fact the overall impact of the program was a drop in fire incidence by a remarkable two-thirds. The before-and-after comparison for the city as a whole made clear what had most likely happened.

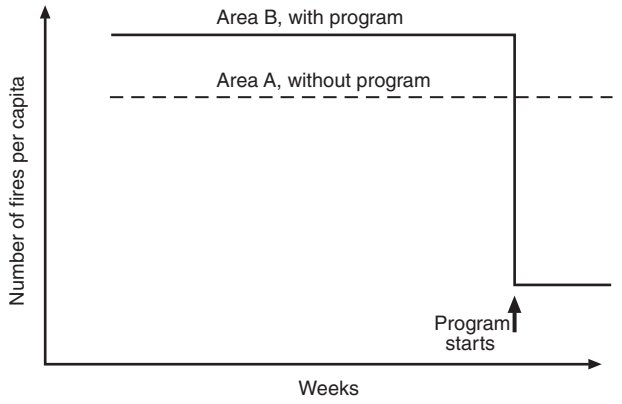

FIGURE 5.8.7 Hypothetical Example of Comparing Area with Prevention Program to Area Without Program

It is sometimes politically difficult to run an education program in one area of the community and not in others unless (1) it is clearly labeled a pilot program and (2) a plan exists for subsequently introducing the program everywhere. Nevertheless, whenever possible, introduce a program in one area first, and test the results in that area versus the rest of the city. Even for proven programs this initial test can help the educator make adjustments in the program before introducing it everywhere.

When comparing different parts of the community, one should compare *like areas,* if possible. For example, compare a program in a low-income area against how other low-income areas are doing without the program, or compare a moderate-income area to other moderate-income areas. This is especially important if all similar areas have been trending in the same direction, and the impact of the program is to reduce the rate of rise or accelerate the drop in fires or casualties.

Comparisons among areas are best made over a period of time. Data are needed for each area from before and after the time when a program was first started, to know whether differences between areas result from differences in their characteristics or differences in the program.

Comparing the Community to Other Communities. Similar in principle to comparing different areas within a community is to compare the community to other communities—especially to other communities that are generally similar to the target community. A variation on this is to compare the community's experience to that of its state. Comparisons among communities (or areas) should be made on a per capita basis or in terms of percentage changes or trends in the magnitude of the problem. Otherwise, differences observed in the numbers of fires or casualties may be due to differences in the numbers of people protected rather than from the results of the program.

Outcome Evaluation of Hagerstown Programs

The number of homes having smoke alarms rose to nearly 99 percent overall and at least 97 percent in every census tract, from far worse than the national usage rates to much better than those rates. Cooking fires declined by one-third over a decade, which is a larger reduction than the national data show over more than two decades (Table 5.8.6).

As with any program or survey, not all homes were reached. The successful contact rate was about 40 percent, and it would not be surprising if the noncontacted homes had a lower smoke alarm usage rate, perhaps closer to the 1997 baseline. Even if this possibility were true, the success of the program against a 90 percent target usage rate would not be in question. And there have been programs that have documented large progress in both the contacted and noncontacted target properties, perhaps because of other trends, perhaps because of the motivational

TABLE 5.8.6 Hagerstown Outcomes (Smoke Alarms) by Census Tract

Census Tract	*1997 Percentage of Homes with Smoke Alarms*	*Latest Year Checked After Program*	*Percentage of Homes with Smoke Alarms*	*Percentage of Homes with Working Smoke Alarms on All Levels and Less Than 10 Years Old*
1	92	2002	99	86
2	93	2001	99	87
3.01	87	1999	99	85
3.02	88	2005	97	76
4	84	1998	97	73
5	84	1998	99	85
6.01	88	1999	98	89
6.02	93	2003	99	91
7	83	1999	98	84
8	89	2000	98	84
9	87	2000	97	77
10.01	88	2003	98	86
111	99	2004	99	86

impact of publicity surrounding the program and the desire of many households to be part of something. In any event, program evaluations need to consider contact rates and other sources of uncertainty in the program statistics when drawing conclusions about the program's relative success.

With these successes, the program could now shift focus to secondary outcome measures, such as the percentage of households with fully compliant, working smoke alarms. Hagerstown has documented deficiencies in up to a quarter of the households visited. Deficiencies are noted if a home does not have working smoke alarms less than 10 years of age on all levels; see the last column of Table 5.8.6. The most common deficiencies have been aging alarms and alarms with dead batteries. To help address these issues, the program has begun using long-life lithium-battery alarms that feature a tamper-resistant design.

In addition to reducing loss, Hagerstown's *measurable* prevention strategies began generating side benefits. School administrators, government decision makers, and citizens began to view the department as a true subject-matter expert in the field of risk reduction. This credibility led to additional staffing, an increased prevention budget, and the receipt of numerous federal grants. These benefits were realized because the department invested the time to plan and evaluate its overall prevention strategy carefully.

HANDLING UNCONTROLLABLE FACTORS

It often is not enough to show that there was a change in knowledge or behavior or in bottom-line measures, such as injuries or dollar loss. One also needs to demonstrate that the observed changes were caused by the education program and not by other factors, such as an unusually warm winter that caused fewer heater fires or a dramatic national fire in the news that raised awareness. Likewise, one needs to check whether positive effects of a program may have been masked by uncontrollable factors, such as a weakening economy that leads to an increase in vandalism and arson fires during the implementation of an arson control program.

The sociology of fire is complex. There are many causes of fire and many uncontrollable factors that may affect the environment or behaviors leading to fires. A social scientist or statistician might never be totally satisfied with the degree of rigor of most evaluations that are practical, because it is difficult to account for all of the uncontrollable variables without much effort, and perhaps not even then. Nevertheless, evaluations can be useful if undertaken with a little care, because they generally lead one in the right direction.

Table 5.8.7 lists some of the factors that might affect evaluation results. The first column in Table 5.8.7 contains variables that are largely out of the hands of the fire and life safety educator to affect. The most classic examples perhaps are the weather and the economy. The second column has factors that may not be controllable in the short run, though they may be affected by codes and other prevention efforts in the longer run. The third column has the initial conditions that need to be considered, even though they can be affected by public education.

Evaluations can be made more meaningful by comparing results for situations in which these external variables are reasonably similar, or at least by acknowledging the possible influence of these variables.

The need to consider uncontrollable variables can cut more ways than one. A modest reduction in the number of wood-burning stove fires that would have followed the introduction of an intense education program on the need to clean chimneys might be masked or negated by an unusually severe winter. The colder temperatures might cause a sharp increase in the use of stoves and a corresponding increase in fires that overwhelms the decrease from more people cleaning their chimneys. But the increase might be less than in earlier years when no prevention effort took place, which could be a demonstrable positive impact of the program. If there were a decrease in chimney fires in spite of a particularly cold winter, that would suggest that the

TABLE 5.8.7 Examples of Factors Affecting Evaluation Results

Uncontrollable Factors	*Semicontrollable Factors*	*Starting Conditions*
• Age profile of population • Income distribution of population • Education level of population • Geographical scatter of population • Ethnic groups in population • Weather or climate change • Economic changes • Migration of people in or out of community • Nature of local business and industry • Changes in fire reporting procedures	• Condition of housing • Architecture of the homes • Hazards of new technology	• Severity of fire problem (fire and death rates) • Previous exposures of population to fire safety information • Current level of detector usage and condition

program was being extremely effective, not only in reducing the normal toll, but doing so in the face of increased stove use.

The reverse situation is also possible: an ineffective public education program might appear to be effective if chimney fires drop because the winter is relatively mild and the use of stoves decreases. That type of external factor has to be considered before one starts claiming success. It should be noted, however, that the chimney fire situation is a somewhat difficult example because relatively mild winter weather can cause people to reduce airflows to the firebox to reduce the intensity of the fire, which in turn can increase creosote buildup and lead to more house fires, instead of fewer.

To understand whether changes in fire incidence or casualties are due to the public fire and life safety education program or to climate change, one needs to look at the data on the weather in the period in question, and perhaps some nearby communities that did not change their public safety education programs but had the same weather. Looking at the data averaged across several winters may also reveal whether a program is having an impact independent of fluctuations in climate (unless the climate takes a several-year shift in one direction).

Another approach is to compare the data from years when the uncontrollable factor—in this case the climate—was the same. Nebraska's Forest Service provided a brilliant example of this approach. Fire rates in years of relatively similar dryness were compared with respect to the intensity of the prevention programs in those years. Comparing results from years with similar weather allowed the impact of the program to stand out. Otherwise the fluctuations in dryness masked the effects of the fluctuation in the intensity of the program.

Besides considering factors that are uncontrollable by the fire department, evaluation of public education programs needs to consider the relevant preexisting fire situation in the community. This is especially important to do when effectiveness is compared to resources expended; that is, when productivity is to be measured. Table 5.8.7 includes a list of several starting conditions to consider. The existing level of smoke alarm usage, for example, will affect the apparent effectiveness of a new effort on smoke alarms. It is easier to get the middle 20 percent of households to install smoke alarms than the last "hard-core" 20 percent. It usually is easier to reduce a high fire death rate than it is to further reduce a very low death rate. It is easier to maintain new alarms than old alarms, because the new ones use less expensive batteries, begin with fresh batteries, and are less worn out. Although one may use the change in the percent of households with working smoke alarms as a measure of effectiveness, it must be realized that it gets harder and harder to reach the last 10 households.

Measuring Change in Juvenile Firesetter Programs: An Example. Juvenile firesetter programs are different in nature from other prevention programs, and their evaluation requires some special considerations. First, juvenile firesetter programs often are aimed both at the curious child and the disturbed or malicious child. The "bottom-line" effect of the program is manifested by whether there is a reduction in (1) children-playing fires and/or (2) arson. Both of these categories need to be monitored, because sometimes fires are simply relabeled and shifted from one category to the other rather than truly reduced. A "get-tough" policy with children can result in labeling fires as arson that previously would have been called "children playing." Conversely, a more sympathetic attitude toward juvenile firesetters could cause a shift from labeling fires as "arson" to "children playing." Differences in legal definitions between jurisdictions also can muddy intercommunity comparisons if both categories of fires are not considered.

Second, a common practice in evaluating juvenile firesetter programs is to consider "recidivism rates," that it, the rates of repeat fires from children who have been treated by the program. Recidivism rates usually are quite different for the curious firesetter than for the disturbed or malicious firesetter. It is easier to "cure" the curious child than the disturbed child. Rates therefore should be measured separately for these two categories. If not, one program can appear to be more successful than another, simply because one has a greater proportion of the easier-to-cure, curious-child cases.

Also, curious firesetters may have a low recidivism even without any program. A truly fair evaluation would consider their recidivism rates, with and without the program. A recidivism rate of 5 percent might appear good at first, but would not be so good if the rate without the program were 4 percent.

Statistical Change—Determining Whether Change Is a Fact or a Fluke. The evaluator often must address factors that

confound simple statistical approaches. The majority of fire departments do not have a trained statistician, though many departments have someone with some knowledge of formal statistical techniques. Unfortunately, real-world statistical situations often require considerable expertise to be able to say that "with such and such a confidence level" the impact of a program is real.

Standard statistical formulas actually may be invalid for many situations, such as when the samples collected are not truly random samples and the assumptions behind the formulas are not met. It is recommended that fire departments seek statistical expertise either from among their own personnel or from outside sources, such as local universities or statistical consultants, to assist in their evaluations.

Despite these caveats, some basic idea of statistics can give at least a rough, "ballpark" feel for whether observed changes are likely to be significant.

What many statisticians do not like to reveal is that, in many cases, common sense and good judgment are needed to say whether a change is likely to be real or not, and not just complex statistical formulas.

It is also useful practice to periodically review previous evaluations to see whether initial findings about effectiveness or lack of effectiveness held up over time. Sometimes what seemed like a true program impact may appear to be a fluke after a few years of data are collated. Sometimes it goes the other way; a program with little impact initially starts to have a large cumulative impact after a year or two.

Another kind of statistical evaluation problem comes when trying to separate the impacts of two or more programs that overlap in time. For example, it is difficult to separate the impact of fire department programs on smoke detector purchases versus the impact of television ads. Comparing communities with and without fire department programs but exposed to the same television ads may give some insight into whether the programs in question add anything. Sophisticated statistical techniques can be applied but are virtually unusable without expert statisticians. Suffice it to be flagged as a complex problem here.

Unintentional Impacts

The evaluation of a program should include a check for unintentional impacts along with expected desirable results. Some common unexpected side effects are the following:

1. *Greater reporting of minor fires that previously went unreported.* Encouraging the public to flee a fire and call 9-1-1 instead of trying to put it out can lead to an increase in reported fires. Other positive aspects of a public education program sometimes are partly or entirely masked by this surge. Looking at the number of small fires apart from large fires can be a check on this.
2. *Increase in fires set by children.* Sometimes raising the subject of fire to children boomerangs and greater curiosity is generated instead of being lessened.
3. *Scares, nightmares, and other psychological problems.* Young children can have a new fear added unwittingly by a program that is too scary for their age group. Children may become fearful instead of careful.
4. *Intrusion into parents' lives.* Getting a child to harass parents to improve home safety or to purchase safety devices the parents feel they cannot afford can lead to complaints by the parents. Usually this is outweighed by positive feedback from parents whose safety consciousness is improved. But complaints should be taken seriously, and the curriculum and instructors reviewed to see whether the safety message can be delivered effectively without unwanted side effects.

Proving Effectiveness After a Program Is Terminated

Sometimes the value of a program is not evident until after it is gone. Proving that there was a real loss of benefit after a budget cut or reallocation of resources causes the demise of a program is one way to fight for its restoration. It also is a valuable type of hindsight from which the profession can learn.

Just as a drop in fires, fire casualties, or dollar loss after a program is initiated can prove it worked, so can a rise in these measures after the program is dropped. Likewise, drops in smoke detector maintenance, drops in fire safety knowledge, and increases in numbers of hazards found per home after a program terminates can all indicate the effectiveness it had.

Of special importance after a program ends (or after an initial test of a program in one area) is to see how long the good results last. One might be able to show, for instance, that half of the people exposed to a public service announcement continue to test their detectors for three months after seeing it and then begin to forget and stop testing. Information on how fast the initial effect wears off is highly valuable for identifying the minimum repetition frequency a message needs to have to produce a continuing impact on the majority of those who receive it. This information can be used to optimize the use of scarce prevention resources.

The problem of unintentional injury is one of the most significant public health issues facing society today, and effective injury prevention programs need to be developed and implemented to address this problem. Evaluation is a key component of any program and should include assessment of the program's feasibility, cost-effectiveness, and efficacy. Data gathered early in the development cycle can be used to help create better programs, modify implementation strategies, revise interventions, and monitor progress toward goals and objectives. Outcome data can be used by policy makers, funders, and practitioners to expand successful programs to larger populations.

Education is an important component of safety and prevention programs, but acquiring knowledge is just one step in reducing injuries. Successful programs use multiple strategies, such as teaching children in schools, involving families and communities, and promoting changes in the home or community environment. *Risk Watch* is an example of such a program. Recent reviews have shown that many communities have the commitment, desire, and ability to share the responsibility for reducing unintentional injuries. In consultation with community leaders, future studies should continue to evaluate the effectiveness of well-designed community-based approaches aimed at improving safety behaviors and reducing injuries.

Hagerstown Case Study—Next Steps

Part of the ongoing monitoring was the identification of new fire problems that were now of greater relative importance, because of the success in reducing cooking fires or because of unrelated adverse trends in those fire problems. The next round of programs for Hagerstown would need to address emerging fire problems involving children playing with fire, candles, and smoking. Some of these problems showed up particularly in a recent adverse trend in fires causing at least $100 in damage, a threshold used locally to identify more serious fires.

Another part of the ongoing evaluation has tracked any contrary trends that threaten to undercut the program's successes. This tracking would include evidence of the disabling of smoke alarms installed by fire fighters.

The disabling problem led to a refinement of the program, focused on renters. The 2000 Census showed that 58 percent of Hagerstown housing units are renter occupied, and these homes account for roughly 90 percent of Hagerstown's home structure fires. Hagerstown also recognized that some of the lowest percentage gains in knowledge were registered in the low-risk neighborhoods where transient professionals occupy predominantly rental housing. Although some of these low gains could reflect the fact that higher initial scores left these households with less room for improvement, part of the reason was that the high turnover of busy people made for a lower contact rate (i.e., fewer people at home when contact was attempted) and far less potential for long-term impact, because new occupants would mean a need to start all over again.

All these findings encouraged Hagerstown to look for ways to work through landlords rather than just occupants. Hagerstown realized that certain options for dealing with landlords are even stronger than those for dealing with owners of owner-occupied housing.

As a financial incentive in this new approach, property owners are provided with free smoke alarms. In return, property owners are required to install the alarms and instruct tenants how to test and care for smoke alarms. They also educate tenants about the leading causes of fire in Hagerstown and solutions to current challenges. Tenants also are given printed and visual materials that reinforce the information provided by property owners. Property owners are also encouraged to incorporate a 12-point fire safety contract into their leases with tenants. Violation of the terms by a lack of fire safe behavior results in the possibility of financial sanctions levied by owners on tenants in the event of a fire.

The last problem still awaiting a fully developed programmatic response is dynamic. As noted earlier, development has been rapid in areas adjacent to Hagerstown. Like many cities of all sizes, Hagerstown has seen a disproportionate outflow of affluent, lower-risk households to its new suburbs, leaving behind a higher concentration of more challenging households. These dynamics change the landscape to which programs are tailored. Sometimes, they provide more reasons to work through landlords more than through occupants. Sometimes, they create a need to identify new established local networks and local opinion leaders. But regardless, they show the value of evaluation as a source of information to continually reshape the program to best build on past successes.

USES FOR EVALUATION

As demonstrated above, the evaluation of public fire and life safety education programs requires effort—effort that might seem out of reach to the busy educator. Because evaluation is central to improved fire and life safety education, as reflected by its inclusion in NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator,* it is useful to review the many uses of information gained during the evaluation process. Uses included those directly related to the fire problem, those related to target audience, and those related to process, impact, and outcome evaluation.

Uses for Evaluation Related to the Fire Problem

National data can be obtained by contacting organizations such as the Centers for Disease Control and Prevention, the Consumer Product Safety Commission, the NFPA, and the U.S. Fire Administration's National Fire Data Center. Local data can be collected from emergency services reporting systems, local hospitals, and health departments. These data can be used to do the following:

- Identify and prioritize local risks
- Identify where, when, and how often problems are occurring
- Identify who is causing the problem
- Identify who is being affected by the problem
- Identify what the problem is costing the community
- Identify the sequence of events leading to the occurrence of leading risks
- Develop a community risk profile
- Prioritize local risks based on objective data
- Develop comprehensive intervention strategies to address priority local risks

Uses for Evaluation Related to the Target Audience

National, state, and local data can be used to accomplish the following:

- Identify the demographics of a community
- Understand how human behavior is contributing to a risk issue
- Identify high-risk populations such as toddlers, elders, people with disabilities, and people affected by poverty
- Identify primary and secondary target populations
- Identify characteristics of target populations and knowledge/attitudes they have about the risk issue
- Identify a relationship between target populations and risk issues
- Develop intervention strategies to address risks

Uses for Process, Impact, and Outcome Evaluation

Process, impact, and outcome data from one fire and life safety education program can capture gains from a given program as well as document information and gains for use in other subse-

quent programs. For example, process evaluation data can do the following:

- Help document the steps needed to create a specific risk reduction program
- Document the creation and monitor implementation of risk reduction programs
- Evaluate the performance of staff members as they implement and deliver programs
- Track and document outreach into the community
- Evaluate the overall public opinion of a program or initiative
- Document the allocation of additional funding or positions to address risk reduction

Similarly, impact evaluation data can help with the following:

- Evaluate knowledge gain
- Track behavioral and environmental changes
- Document adoption of codes, standards, and pertinent legislative actions
- Document behaviors leading to institutionalized risk reduction as a core value at both the organizational and community level

Finally, outcome evaluation data can be used to help with the following:

- Monitor and document changes in statistical data that identify leading risks and associated causation behaviors
- Gather and document anecdotal evidence supporting risk reduction initiatives

SUMMARY

Evaluation is a key component of fire and life safety education programs for two reasons. First, evaluation is a technique for making the most effective use of limited fire and life safety education resources. Second, evaluation provides the educator with the feedback needed to know whether fire and life safety education is indeed reducing incidents and preventing incidents. Either reason is a strong argument for the merits of evaluation. Together, the two reasons make a compelling case for undertaking evaluation activities.

ACKNOWLEDGMENT

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on evaluation techniques discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following document.)*

NFPA 1035, *Standard for Professional Qualifications for Fire and Life Safety Educator*

SECTION 6

Characteristics of Materials and Products

Robert P. Benedetti

6.1 Fire Hazards of Materials
6.2 Combustion Products and Their Effects on Life Safety
6.3 Concepts and Protocols of Fire Testing
6.4 Wood and Wood-Based Products
6.5 Fibers and Textiles
6.6 Upholstered Furniture and Mattresses
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6.17 Tables and Charts

Section 6 of the *Fire Protection Handbook*® presents detailed information about the fuel portion of the fire tetrahedron. The section includes one new chapter: Chapter 3, "Concepts and Protocols of Fire Testing." For the convenience of the reader, tables and charts formerly included in an appendix are now located at the end of this section.

Chapter 1, "Fire Hazards of Materials," is the most fundamental of the section's 17 chapters. This overview chapter discusses burning of materials, extremes of burning behavior, measuring and controlling hazards, flame resistance treatments and fire performance testing, and hazards of smoke.

Chapter 2, "Combustion Products and Their Effects on Life Safety," describes the toxicity of smoke and fire gases. The chapter provides appropriate background information on the several toxic components of combustion products. It discusses the measurement of the hazards of combustion gases and describes test protocols used to assess the effects of combustion products on life safety.

For the first time, the *Fire Protection Handbook* includes a chapter focusing on concepts and protocols of fire testing. Chapter 3, "Concepts and Protocols of Fire Testing," addresses the use of fire tests that measure the fire performance of materials and products and also the manner in which to select those that are more likely to be usable for fire safety engineering calculations and can assess fire hazard risk. Topics include classification of fire tests, fire resistance tests, and reaction-to-fire tests.

The next several chapters concentrate on individual materials. Chapter 4, "Wood and Wood-Based Products," is an overview of those characteristics of solid wood and of products made from wood and wood-based cellulosic material that influence their ease of ignition and burning behavior. The chemistry of cellulose is described, as is the behavior of wood and wood-based products as structural components under conditions of fire exposure. Chapter 5, "Fibers and Textiles," parallels Chapter 4, covering similar topics for commonly used fibers and textiles. It presents an overview of their manufacture, combustibility, and end use. Also discussed are fire-retardant treatments for textiles and fabrics and the test methods employed in evaluating and creating standards for the use of fibers and textiles. Chapter 6, "Upholstered Furniture and Mattresses," addresses the performance of upholstered furniture and mattresses when exposed to cigarettes and other flaming sources of ignition. Chapter 7, "Fire-Retardant and Flame-Resistant Treatment of Cellulosic Materials," presents a more detailed discussion of the basic principles of treatments that impart various degrees of fire and flame retardancy, as well as their limitations.

Chapter 8, "Dusts," looks at the factors that influence the explosibility of dusts and the various ways in which dust clouds are ignited. The chapter also describes the deflagration characteristics of selected combustible dusts, discusses factors that influence how destructive a dust explosion can be, and describes some test protocols used to quantify dust explosions.

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Chapter 9, "Metals," covers the fire hazard properties of combustible metals and the means to prevent their ignition or explosion.

The goal of Chapter 10, "Gases," is to provide information on the properties of gases, their classification, and the equipment needed to store gases safely, including key safety devices. The chapter also provides information on the properties, storage, and hazards of gases. Chapter 11, "Medical Gases," covers types and hazards of medical gases, including those used for respiratory therapy and anesthesia, and in health care facility laboratories, hyperbaric chambers, and ambulatory care facilities. The safe practices and hazards discussed in Chapter 11 apply to all health care facilities and the home health care environment.

Chapter 12, "Flammable and Combustible Liquids," addresses hazards and classification of flammable and combustible liquids and their physical characteristics. Emphasis is placed on their burning behavior. Fire prevention methods for the use, handling, and storage of liquids complete the chapter.

Among other topics, Chapter 13, "Polymeric Materials," covers major groups of plastics, their uses, additives and blends, fire behavior, fire tests, and appropriate fire- and flame-retardant treatments.

Chapter 14, "Pesticides in the Workplace," provides an overview of the requirements and practices in location, construction, and administration of facilities that handle pesticide products, from manufacturing facilities to local businesses and farms. Emergency plans and security concerns are covered.

Chapter 15, "Explosives and Blasting Agents," describes the nature and types of explosive materials, as well as their manufacture, transportation, and storage. Chapter 16, "Manufacture and Storage of Aerosol Products," discusses the hazards of flammable aerosol products, their classification, and their safe storage.

Chapter 17, "Tables and Charts," was formerly Appendix A.

Chapter 1

Fire Hazards of Materials

Revised by
Robert P. Benedetti

Chapter Contents

Burning of Materials
Extremes of Burning Behavior
Measuring and Controlling Hazards
Flame Resistance Treatments and Fire Performance Testing
Hazards of Smoke

Key Terms

auto-oxidation, cellulosic material, combustion, flame resistance, flame spread, heat of combustion, heat release rate, hydrocarbon-based material, organic materials

This chapter provides an overview of the fire hazards of materials. Specifically, it concentrates on how those fire hazards can be quantified and how they are related to the physical and chemical characteristics of the materials with which they are associated. Subsequent chapters in this section deal in detail with the fire problems of particular classes of materials.

This chapter focuses on materials, by which is meant substances of relatively uniform composition, as distinguished from products, which are assemblies of materials intended for a specific use. For example, upholstered furniture is a product; the wood, cushioning and fabric of which it is made are each materials. The distinction between materials and products is not always a sharp one because many materials are themselves products, but it is an important distinction because the fire performance of a product is often quite different from that of the materials of which it is made. Hence, a laminated composite may show considerably lower flame spread than most or all of its layers would exhibit when tested individually. In other cases, assembling the materials may degrade their fire performance.

Another distinction which is useful (but also sometimes imprecise) is between materials whose contribution to fire hazard is active—that is, they affect the initiation, the growth of the fire, or its effects—and passive—that is, by how they respond to heat. The structural steel elements of a high-rise building, for example, are unlikely to ignite even in the most severe fires, but how well they retain their strength at high temperature can have a profound effect on fire safety. This, of course, was demonstrated by the collapse of the World Trade Center buildings. Most of the discussion that follows, however, addresses materials that burn.

For additional information on this and related topics see the following chapters: Section 3, Chapter 4, "Use of Fire Incident Data and Statistics"; Section 3, Chapter 7, "Fire Hazard Analysis Techniques"; Section 6, Chapter 2, "Combustion Products and Their Effects on Life Safety"; and Section 6, Chapter 17, "Tables and Charts."

BURNING OF MATERIALS

Ordinary burning is combustion, the chemical reaction of a material with atmospheric oxygen accompanied by the release of sensible energy as heat and usually light. The products resulting from combustion are oxides, that is, they contain oxygen as part of their chemical makeup. Once a material is in its fully oxidized form, it is no longer susceptible to combustion. For this reason, many materials suitable for use at high temperatures, such as asbestos and most ceramics, are basically oxides.

One descriptor of hazard is the maximum amount of energy produced as heat per unit weight of material burned. This quantity, commonly called the heat of combustion, is also a measure of the material's value as a fuel. The heat of combustion is determined almost entirely by the chemical

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composition of the material. The speed with which the heat is produced, on the other hand, is determined by the material's physical form. For example, excelsior burns more quickly than a solid block of wood, although equal weights of the two will produce essentially the same amount of heat. In some cases, the physical form of the material is the principal determinant of hazard. Aluminum in its familiar forms, for example, rarely burns even in major fires but aluminum powder or shavings can, under certain conditions, be explosive.

Organic Materials and Energy Production

Any discussion of the fire hazards of materials centers on those materials that are organically derived, that is, based on carbon, because organic materials as a class are ubiquitous. The simplest organic compounds, such as methane and propane, are common gaseous fuels. Organic liquids are fuels, solvents, and chemical intermediates, but the richest variety of materials are organic solids. They include everything from specific compounds, such as aspirin, to common but complex everyday materials, such as wood, paper, textiles, and plastics. These materials have carbon as their principal constituent; almost all contain some hydrogen; and many contain oxygen, nitrogen, and other elements in varying amounts.

The molecules of most common organic structural materials are large, that is, they are "macro" molecules or polymers. They consist of many simple molecules linked together in a regular pattern to form the chains and networks necessary for useful mechanical properties. Some polymers are of natural origin, such as the cellulose in wood or cotton, or the protein-based fibers of wool. Plastics are manufactured polymers. Polyethylene, for example, is made (as the name suggests) by chemically linking, or polymerizing, many molecules of ethylene, a gas, to form a nonvolatile solid with many everyday uses.

Most organic materials burn readily. The common products of combustion of organic materials are water, which is the oxide of hydrogen, and carbon dioxide. A tabulation of the heats of combustion of organic materials is contained in Section 6, Chapter 17, "Tables and Charts." Those figures are based on complete burning. In practice, there may be insufficient oxygen available to convert all of the carbon to carbon dioxide; some carbon monoxide and soot may be formed, so the heats are upper limits of the actual amount expected from combustion under normal conditions.

Examination of the heats of combustion tables in Section 6, Chapter 17 will show that although the heat of combustion is quite different for different organic materials, the heat produced per unit weight of oxygen consumed is the same within about 10 percent. This fact, sometimes called Thornton's Rule,[1] allows one to use oxygen consumption as a reasonable measure of the heat produced by a burning organic material.

Organic materials fall into two broad classes: (1) hydrocarbon based and (2) cellulose based. The former are derivatives of the unoxidized hydrocarbon building blocks: —CH_2—, or —CH—. The latter are based on a partly oxidized carbon unit: —CH(OH)—. In a sense, cellulose-based material is already partly oxidized in its natural state, so that when the two classes are combusted to carbon dioxide and water, cellulose consumes less oxygen and produces less heat. On a weight basis, the difference is greater: hydrocarbons produce over twice the heat per unit of weight as do cellulosics. Hence, from an energy viewpoint, oil and natural gas, both hydrocarbons, are better fuels than wood, which is composed largely of cellulose.

Rate of Burning

The rate at which the fire products are produced is controlled by the rate at which a material burns. Later sections of this chapter address the measurement of this quantity, but it is instructive to examine some of the general physical factors that contribute to the burning rate.

The material that constitutes the fuel may be gaseous, liquid, or solid, but the oxygen in the air is gaseous. For the necessary chemical reactions to occur, the fuel and oxygen must be brought into contact at a molecular level, and this, in turn, means that burning is generally a vapor-phase phenomenon.

The rate of burning is a function of how fast the chemical reaction of oxidation occurs. In premixed flames, that is, those in which mixing has occurred before the combustion is initiated, the burning rate is the inherent rate at which the substances combine. This is generally quite fast; flames propagate under premixed conditions at more than a meter per second. It is for this reason that the contact of air and combustible vapors is so dangerous; the process, once started, is virtually impossible to interrupt, except in closed spaces specifically equipped for that purpose.

Liquids and solids commonly burn in diffusion flames, shown schematically in Figure 6.1.1. Diffusion flames differ from premixed flames in that the fuel vapor and the air mix by diffusion as burning occurs, and so the burning rate is generally controlled by the rate at which the scarcer component, fuel vapor or oxygen, enters the combustion zone.

Energy is required to convert the fuel in the fuel bed from its original liquid or solid form to the vapor state and this has an important influence on the intensity of the fire. Specifically, the rate of heat release of a material is proportional to the ratio of its heat of combustion to its heat of vaporization, a parameter sometimes called the combustibility ratio.[2] A liquid hydrocarbon

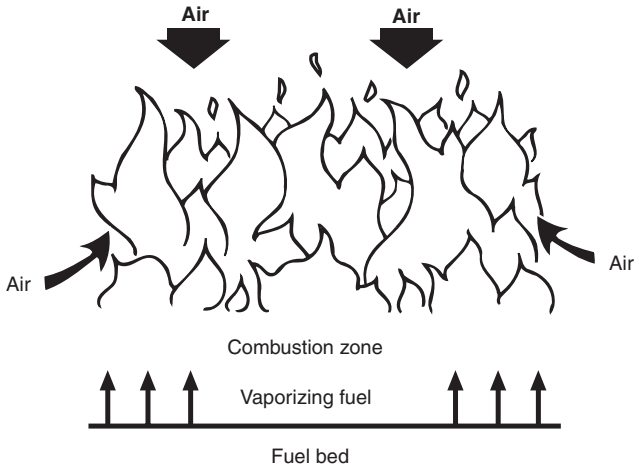

FIGURE 6.1.1 Schematic View of a Burning Surface

such as heptane has a combustibility ratio of about 93, whereas polyethylene, which has roughly the same chemical composition, has a combustibility index near 25.[3] One therefore expects that, to a first approximation, a burning pan of heptane would produce heat almost four times as fast as a pan of the same size containing polyethlylene granules. From a microscopic viewpoint, the difference is that the heptane molecules are readily vaporized and can be transported into the combustion zone without decomposition. For fuel vapor to reach the combustion zone from the polyethylene, however, volatile fragments must actually be broken off the polymer chain; that is, chemical bonds must be ruptured. This process requires considerably more energy than does simple vaporization.

Liquids and solids are more concentrated fuels than are gases. Propane, for example, burns completely according to the following expression:

$$C_3H_8 + 5\ O_2 \rightarrow 3\ CO_2 + 4\ H_2O$$

One volume of propane gas consumes five volumes of oxygen, or about 25 volumes of air. By contrast, liquefied propane is some 300 times denser than propane gas under normal conditions. This means that one volume of the liquid will produce 300 times as much heat, but it will also require 300 times as much air. Thus, the burning of highly volatile liquids and solids is sometimes limited by the rate of delivery of oxygen to the combustion zone, especially under poorly ventilated conditions.

Except for hypergolic combinations of materials (i.e., those that ambient temperatures are sufficient to ignite), the initiation of the combustion reaction requires added heat. This heat must be sufficient to vaporize enough of the fuel to initiate reaction and to accelerate the chemical combustion reaction to a rate where it can sustain itself. The heat required for ignition is greatly dependent upon the physical state of the materials and the heat transfer properties of its environment. Thus, a combustible material present as a dust, that is, with a large surface-to-volume ratio, may burn very readily or explode, whereas the same material in a solid block may be very difficult to ignite at all.

EXTREMES OF BURNING BEHAVIOR

The extremes of burning behavior differ from normal burning principally in the time scale over which burning occurs. At the fast end of the spectrum are explosions and at the slow end are the phenomena of auto-oxidation and smoldering. Explosions are a source of substantial hazard and are discussed in detail in several chapters in this handbook. The slow processes, however, are less well known. Auto-oxidation is the combination of a material with oxygen at a rate too slow to produce the observable heat and light normally associated with fire. Metals are particularly prone to auto-oxidation, demonstrated by the rusting of iron and the tarnishing of silver, as are many organic materials. The deterioration of rubber and plastics over time is often the result of slow oxidative processes. Antioxidants can be added to such materials in order to increase their durability and working life. Such additives operate either by being themselves oxidized in preference to the organic material or by chemically inhibiting the oxidation reaction.

Self-heating and eventual spontaneous ignition can occur if the heat produced by auto-oxidation is not removed. This is especially true in porous solids, such as coal, where air can diffuse into the interior of the material, but the heat produced is effectively contained by the insulating properties of the material.

Smoldering is a distinct burning process, quite different from flaming. Only a small fraction of combustible materials, those that produce a porous char during the course of combustion, will smolder. This char allows air to reach the smoldering region, which is on or below the surface of the fuel. Compared to flaming, smoldering is a slow process. Temperatures in the smolder zone are typically 900 to 1600°F (480 to 870°C), whereas temperatures in a flame typically reach 2700°F (1480°C). When materials smolder, the degree of combustion is usually less complete than when the same materials burn under flame. Most smolderers are organic and all are solids.

MEASURING AND CONTROLLING HAZARDS

The vastly different burning characteristics of gases, liquids, and solids pose different types of hazards. The methods for measuring and controlling them are also different. Table 6.1.1 shows the different kinds of measurement techniques available for different components of hazard. It is most convenient to think of hazard control in terms of first controlling the likelihood of ignition, then controlling or containing the fire spread, and finally managing fire impact if ignition and spread cannot be prevented.

Fire Hazards of Gases and Dusts

Combustible gases and dusts burn rapidly once ignited, so avoidance of ignition is very important. The two steps for doing this are (1) the determination of flammability limits, that is, the concentration range of a particular gas or dust (usually in air) within which ignition will occur, and (2) operating in a manner such that the concentration is maintained outside those limits. It is also possible to reduce the likelihood of ignition of a gas or dust by adding chemical inhibitors to raise the lower flammability limit. In practice, however, this is rarely done, either because of expense or because it alters otherwise desirable properties.

Ignition control is generally effected by stringent storage and handling safeguards; the bulk of the discussion in the chapters of this handbook on flammable gases are concerned with these procedures. It is also possible in closed environments to reduce the amount of oxygen available and thereby to raise the effective flammability limit. Conversely, atmospheres that are enriched with oxygen beyond normal atmospheric concentrations offer special explosion hazards for vapors and dusts. The intensity of a fire resulting from gases, vapors, or dust is a function of the density of gas or the concentration and particle size of the dust. Gases (hydrogen, for example) and very finely divided dust are rapidly dispersed and can lead to the onset of explosive conditions in short periods of time. Fire and explosion control efforts concentrate on containing the products and, under specialized conditions, providing for automatic suppression of an incipient explosion. This is done by rapidly introducing a

TABLE 6.1.1 Means of Measuring and Controlling Fire Hazards of Materials

	Ignition		Spread and Growth		Fire Impact	
Hazard Component Material	*Measurement*	*Ignition Control*	*Measurement*	*Control of Spread and Growth*	*Measurement*	*Control of Fire Impact*
Gases	Flammability limits	1. Storage and handling safeguards 2. Inerting of atmospheres	Flammability limits, density, diffusion coefficient	Tank venting procedures	Placarding, NFPA hazardous materials identifiers	1. Emergency response and evacuation 2. Placarding, NFPA hazardous materials identifiers
Liquids	Flashpoint	1. Handling safeguards 2. Hazard classification systems	Volatility	1. Ventilation and flame arrest 2. Storage and tank separation	Placarding, NFPA hazardous materials identifiers	1. Emergency response and evacuation 2. Placarding, NFPA hazardous materials identifiers
Solids 1. Textiles, cushioning materials	1. Ease of ignition tests and small-scale flame spread tests	1. Flame-resistive materials and treatments 2. Protective layers	1. Supported flame spread 2. Rate-of-heat release	1. Material selection and assembly 2. Detection and suppression	1. Smoke hazard assessment	1. Breathing apparatus for fire fighters 2. Smoke control systems
2. Structural materials, building components and finishes	Same	Same	Flame spread, rate-of-heat release	1. Fire resistivity 2. Low combustibility 3. Fire-resistive coatings 4. Detection and suppression	1. Fire endurance (stability, integrity, insulation) 2. Smoke hazard assessment	Same, plus construction design: compartmentation; separation

suppressant, such as water vapor or a chemical inhibitor, into the exploding cloud. To be effective, automatic suppression must occur in a time scale of a few hundredths of a second.

There has been concern over the possibility of large flammable gas fires in populated areas. With vast quantities of gaseous fuels now being transported either in bulk or by pipeline and the renewed interest in importation of liquefied natural gas by oceangoing tank vessels, the likelihood of such occurrences commands attention. The principal means by which the impact of such accidents is minimized is the use of hazardous material identification systems, for example, placarding and NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response.* In the absence of a major breakthrough in the prevention or suppression of such fires, the most appropriate means of minimizing fire impact is the advanced planning, preparedness, and response of trained emergency personnel.

Fire Hazards of Liquids

Since burning actually occurs in the vapor phase, the most hazardous combustible liquids are those with a high vapor pressure, or volatility. An empirical measure that combines volatility with the heat-producing capabilities of the vapor is the flashpoint determination. The flashpoint is simply the temperature at which a liquid gives off vapors that can be ignited under specified laboratory conditions. Flashpoint determinations give rise to hazard classification systems, the most severe hazard being afforded by those liquids with the lowest flashpoints. As in the case of gases, however, the principal means of controlling the ignition of combustible liquids is in handling safeguards. Elaborate procedures exist to minimize the escape of flammable vapors in the handling of volatile liquids and to avoid sources of ignition.

If a fire involving such materials is initiated, means are also available to prevent the supply of additional combustible

fuel to the fire. These means include designs for the safe venting from storage tanks of vapors produced by heating due to fire exposure as well as flame arrestors to guard against the travel of the flame into the storage area itself. Storage and separation criteria for bulk storage of flammable liquids are also used to minimize the likelihood that additional supplies of flammable liquids will come in contact with the fire. As described in a previous section, the intensity of the fire once begun is controlled by (1) the fuel's volatility and (2) the amount of heat released when the fuel burns. Thus, heavy oils or tars may be difficult to ignite, but can burn readily once underway.

Some fire-fighting techniques interfere with the passage of fuel from the liquid to the vapor phase. These include cooling the liquid to slow vaporization and the use of foam to cover the liquid surface.

Fire Hazards of Solids

The part of Table 6.1.1 relating to solids concentrates on common materials; it ignores the large group of chemicals that are primarily found in specialized industrial environments. Unless these materials are present as dusts, foams, or in other forms that present high surface areas, their fire hazards are similar to those of liquids.

In Table 6.1.1, solid materials are divided into two major classes: (1) flexible materials, such as textiles and cushioning; and (2) structural materials, which can include everything from steel and concrete to wood and synthetic structural plastic foams. For both of these classes of materials there is a variety of tests to determine their susceptibility to ignition. However, since ignition requires the volatilization of some of the solid fuel, ignition behavior is strongly dependent on the amount of heat applied to the surface. Therefore, different ignition tests often give different results, depending on the size of the ignition source. The same principle applies to tests that attempt to measure flame spread over small samples. In many such tests, a sample receives no radiant heat load except that available from its own burning. The larger the amount of sample burning, the greater the heat transferred to the unburned area ahead of the flame and a large sample will appear to have a higher flame spread rate than a small one.

The fire hazards posed by inorganic structural materials are most likely to be passive. For example, steel can lose its strength, concrete can crack and spall, and glass can break and melt on exposure to high temperature. Such materials are therefore rated on their ability to withstand such high-temperature effects.

FLAME RESISTANCE TREATMENTS AND FIRE PERFORMANCE TESTING

Improvements in ignition control of materials have come about as a result of flame-resistant treatments developed for both natural and synthetic materials. One is the incorporation of flame-inhibition agents, which commonly contain large amounts of chlorine, bromine, or phosphorus, into the material. With natural materials, such as wood or cotton, this is accomplished by topical or pressure treatment. With synthetic materials, such agents are usually added during the polymerization process. Another approach, useful for plastics, is dilution of the material with an inert or energy-absorbing filler, such as calcium carbonate or alumina trihydrate. A third route is the fabrication of materials with very high effective heats of vaporization. An elevated heat of vaporization often accompanies charring, because the formation of char structures can compete with, or inhibit, the release of volatile fuel vapor.

Flame spread tests are probably the best-known fire performance tests. The most widely used of these are the Steiner Tunnel Test, contained in NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials* (ASTM E84), and the radiant panel test, included in ASTM E162, *Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source.* These tests attempt to simulate spread of fire across a plane surface and, because flame spread under actual conditions often occurs over preheated surfaces, the latter test includes radiant heating of the sample from an imposed external heat flux.

The role of heat release rate in determining fire hazards is characterized by two standard test methods: (1) ASTM E906, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using a Thermopile Method,* and (2) ASTM E1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter.* These tests measure the rate at which heat is produced, generally as a function of the imposed radiant energy. Because of the importance of an imposed flux in real fire hazard, these measurements have utility in predicting fire hazards. Ideally, the effects of fire-resistant treatments should be detectable as diminished heat release rate measurements.

It is important to recognize that claims for flame resistance are tied closely to the test method that is used to evaluate fire performance. Materials that resist ignition or behave acceptably in small-scale tests may be wholly inappropriate for use when more severe or substantially different fire conditions are encountered. Figure 6.1.2, for example, shows that the burning rate depends heavily on imposed heat load (external flux). The steepness of this dependence can be estimated from the combustibility ratio. The higher the ratio, the more burning rate will increase with increasing external flux.

The relative performance of materials under a radiant heat load of 1 or 2 W/cm^2 may be different from their performance at 5 W/cm^2, an external flux representative of what might be experienced by an exposed surface in a well-developed room fire. This makes it important that materials be tested under conditions that duplicate those expected in real fires whenever possible.

HAZARDS OF SMOKE

Because smoke* is usually the primary threat to life safety, it receives a great deal of attention. Traditionally, smoke has

*Smoke is defined in most NFPA standards as the total airborne effluent from heating or burning a material. Expressions such as "smoke and toxic gases" are, by this definition, redundant.

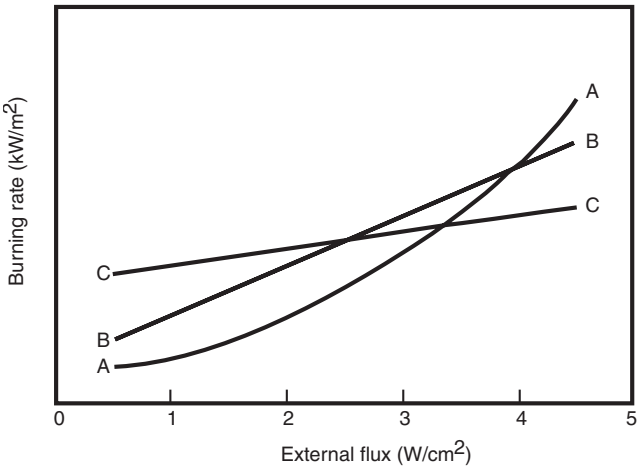

FIGURE 6.1.2 Burning Behavior of Various Materials as a Function of External Flux (W/cm^2)

been characterized simply by its ability to obscure light. As synthetic materials have become common components of building construction and furnishings, however, there has been increasing interest in the identity and effects of combustion products themselves.

Three major effects have been identified: light obscuration, toxicity, and postfire impact. The first two effects are closely related: smoke can reduce visibility, thereby slowing escape and making one more vulnerable to its toxic properties. The third can include any toxic effects encountered by fire fighters during overhaul, but it is more usually interpreted as a property issue in situations where smoke deposition can affect the behavior of sensitive equipment and circuitry.

There are measurement techniques (not necessarily NFPA standards) for all three effects (see in particular NFPA 269, *Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling*) but, in each case, the hazard depends as well on the burning rate of the material. The latter in turn is the result of a host of material-related and situational variables. Thus, characterizing the hazards of smoke involves analyzing or assessing the hazards of the fire itself. Indeed, smoke hazard assessment is an important component (often the dominant one) of fire hazard analysis. This important discipline is described in more detail in Section 3, Chapter 4, "Use of Fire Incident Data and Statistics," and Section 3, Chapter 7, "Fire Hazard Analysis Techniques."

SUMMARY

The fire hazards of a given material stem from the material itself (whether hydrocarbon or cellulosic, for example) and on the form of the material: gas, dust, liquid, or solid. Regardless of form, a material can be evaluated in terms of ignition potential, fire spread and growth, and fire impact. Fire performance testing can be used to assess a material's ignition potential and fire spread and growth.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the fire hazards of materials discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 259, *Standard Test Method for Potential Heat of Building Materials*
NFPA 269, *Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling*
NFPA 270, *Standard Test Method for Measurement of Smoke Obscuration Using a Conical Radiant Source in a Single Closed Chamber*
NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*
NFPA 285, *Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components*
NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*
NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*

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ASTM E1740, *Standard Test Method for Determining the Heat Release Rate and Other Fire Test Response Characteristics of Wallcovering Composites Using a Cone Calorimeter,* ASTM International, W. Conshohocken, PA, 2002.
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Chapter 2

Combustion Products and Their Effects on Life Safety

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Along with heat, the burning of every combustible material or product* produces smoke—gases and aerosols that, in sufficiently high concentration, present hazards to people in the vicinity. Products near those already burning may also contribute to the smoke as they decompose from exposure to the heat from the fire. Predominant among the hazards, which generally occur simultaneously, are the following:

- Sensory irritation of the upper and/or lower respiratory tract, which can affect speed of movement and the ability to negotiate escape and, at higher exposures, can lead to incapacitation or death
- Central nervous system depression resulting from inhalation of asphyxiant fire gases, which can, in ascending exposures, lead to impaired judgment, disorientation, loss of motor coordination, unconsciousness, and, ultimately, death
- Thermal effects, including hyperthermia and thermal burns of the skin and respiratory tract

Exposure to these hazards is often prolonged by eye irritation and diminished visibility due to smoke obscuration, which can affect the ability of occupants to see and negotiate escape routes efficiently. Survivors from a fire may also experience postexposure complications that can lead to delayed health effects or even death.

The *nature and concentration* of the generated smoke depends on a variety of factors. These include the quantity of the product that is burning, whether the product is flaming or pyrolyzing, the ventilation in the area, and distance from the fire. Thus, smoke toxicity is not a singular property of a product.

The *threat to people* from the heat and smoke depends on additional factors, including the entire ensemble of burning products, the location of people relative to the fire, the locations of exits from the burning enclosure and the paths to those exits, the time (in the fire growth history) at which people are in the vicinity of the fire-generated atmosphere, and individual susceptibility of each person to the components of the smoke. Thus, the hazard and risk to people from exposure to the fire effluent (heat and smoke) from a burning product is also not a singular property of the product.

See also Section 2, Chapter 3, "Flammability Hazard of Materials"; Section 4, Chapter 2, "Calculation Methods for Egress Prediction"; and Section 6, Chapter 3, "Concepts and Protocols of Fire Testing."

*In this chapter, *product* refers to a finished commercial item, and *material* refers to a single substance. Thus, for example, a chair (the product) is composed of several materials (e.g., a wooden frame, polyurethane padding, cotton batting, an aramid fire barrier, and a polyester/cotton cover fabric).

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Key Terms

asphyxiant, available safe egress time (ASET), carbon dioxide, carbon monoxide, combustion product, cup furnace test, fractional effective dose, hydrogen cyanide, irritant, LC_{50}, mass loss model, N-gas model product of combustion, pyrolysis, radiant panel test, required safe exit time (RSET), smoke, Station Nightclub fire, stoichiometric, supertoxicant, test, toxic gas model, toxicity, University of Pittsburgh (UPITT) device

FIRE AND COMBUSTIBLE MATERIALS

Pyrolysis and Combustion

Almost all polymeric materials, both natural (e.g., wood) and synthetic (e.g., polyurethane or nylon), can undergo pyrolysis and/or combustion. *Pyrolysis* is defined as a "process of simultaneous phase and chemical species change caused by heat," with combustion being defined as "a chemical process of oxidation that occurs at a rate fast enough to produce temperature rise and usually light, either as a glow or flame."[1] The processes of pyrolysis and combustion have both physical and chemical aspects.[2]

Polymeric materials, on exposure to sufficient thermal energy, typically first undergo phase change, such as melting in the case of thermoplastics, followed by chemical decomposition. These are endothermic processes, resulting in the production of volatile low-molecular-weight products, which may or may not then undergo actual combustion.

If pyrolysis produces gases that are themselves combustible, flaming may occur if the following exist in the same volume:

- Sufficient oxidizing agent (air)
- An ignition source of sufficient intensity
- Sufficient gaseous fuel vapors or volatiles

The nature of the gases generated by the pyrolysis can have a significant effect on when and whether ignition takes place. For example, a material that contains a readily volatile fire retardant may not ignite until the fire retardant has been sufficiently depleted. Should the fire retardant and the host polymer continuously volatilize until the polymer is depleted, ignition may be prevented altogether.

For the process of combustion to be self-sustaining, it is necessary for the burning gases to impart sufficient heat energy to the material to continue the production of ignitable volatiles. The process is a continuous feedback loop: heat transferred to the material causes the generation of flammable volatiles, these volatiles react with oxygen in the air to generate heat, and a part of this heat is transferred back to the material to continue the process. The chemical oxidation processes for flaming combustion of organic materials are generally quite exothermic, with more than enough energy being produced to continue the pyrolysis and bond-breaking processes if the heat transfer is efficient and heat losses to the environment are not too great.

Smoldering is a different form of combustion occurring only in certain porous materials. Here, air diffuses into the pores of the material and reacts directly with the interior surfaces of the pores. The combustion products from this slower process are typically quite different from those from flaming combustion. They are, however, a significant cause of fire deaths when a person is close to the smoldering product, as can occur following cigarette ignition of a bed or piece of upholstered furniture.[3]

Flammability Properties of Materials and Products

It is difficult to generalize the flammability properties of materials, since fire performance is influenced by a number of factors, including the chemical composition and structure of the material, the use of additives in formulated systems, and even the conditions of the fire. Highly crosslinked thermoset polymers normally burn less readily than thermoplastics. Cellular plastics (foams) generally burn quite readily due to their large surface area and good thermal insulating properties, which prevent dissipation of heat. Polymer systems containing halogen atoms (e.g., polyvinyl chloride [PVC]) burn with difficulty; however, the addition of plasticizers increases the propensity of these polymer systems to burn. Fire-retardant additives, which include organic halogen and phosphorus-containing compounds and several metal oxides and hydrates, are employed to increase resistance to ignition and/or lower burning rates of polymer systems.[4] However, inherently fire-resistant polymers and polymer systems containing fire-retardant additives will still burn under sufficiently severe thermal conditions.

GENERATION OF FIRE GASES

Smoke is commonly defined as "the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion."[1] The particulates and aerosols produced affect occupants' visibility as they attempt to escape from a fire; this will be addressed in a later portion of this chapter. Consideration will be given first to the formation and toxicity of the gases commonly produced in fires.

Carbon Dioxide

In well-ventilated flaming fires, nearly all the carbon lost from the combustibles is converted to carbon dioxide (CO_2). Even in postflashover fires, the fraction of carbon conversion to CO_2 is fairly high. Thus, the yield* of CO_2 has been used to estimate the burning rate of products when a direct measurement of mass loss is not possible. Carbon dioxide is also generated in smoldering fires, but the generated carbon monoxide is far more hazardous.

Carbon Monoxide

Carbon monoxide (CO) is produced from both smoldering and flaming combustion. The production of CO from smoldering fires is quite slow, but these fires are not accompanied by vigorous mixing and diluting of the combustion products with room air. Thus, lethal concentrations of CO can be generated in the immediate vicinity of the ignition within 10 minutes. Lethal concentrations of CO elsewhere in the room may take 1 to 3 hours. By then, smoldering may have ceased or may have undergone transition to flaming combustion.[5]

The production of CO from flaming combustion is a gas phase process. The fuel vapor or carbon-containing decomposition products react in a complex sequence with the oxygen in the air to form carbon monoxide. Subsequent reaction further oxidizes the CO to CO_2. The completeness of this process is largely dependent on the local supply of oxygen. Oxygen available to

*The yield of a fire-generated gas is defined as the mass of the gas produced divided by the mass of the combustibles consumed in the burning. A parallel definition applies to the overall yield of smoke.

a fire can be limited either by lowering the oxygen concentration in the incoming air supply or by reducing the volume flow of air to a fire. The formation of CO is related to the fuel-to-air equivalence ratio,[6] which is defined as

$$\phi = \frac{(\text{kg fuel/kg air})}{(\text{kg fuel/kg air})_{\text{stoich}}} \quad (1)$$

where "stoich" denotes conditions at which the ratio between fuel and oxygen is that required for complete combustion, with no excess oxygen. Thus, when $\phi = 1$, exact stoichiometric conditions exist between fuel and air. For values of $\phi < 1$, the fire is fuel-lean and well ventilated; for values of $\phi > 1$, the fire is fuel-rich and ventilation controlled. These latter conditions ($\phi > 1$) are ones that favor the formation of CO.

Studies have shown that under well-ventilated conditions ($\phi < 0.5$), yields of CO are very low, typically less than 0.01.[6] Above equivalence ratios of about 0.5, the yield of CO increases rapidly as the value of ϕ increases. For compartments of moderate size and ventilation, this rise in the yield of CO occurs near the point of flashover. Flashover occurs when the thermal environment is sufficiently intense that many or all the combustibles in the compartment burst into flame. The result is a high density of combustible vapors, a decrease in the oxygen within the compartment, and thus a sharp increase in ϕ. This is the same condition that favors generation of CO. According to NFPA 269, *Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling,* once ϕ reaches a value greater than about 1.5, the CO yield becomes rather constant at about 0.2 kg CO/kg fuel consumed, with the production rate being dependent principally on the mass burning rate. For a sufficiently large fire whose flame radiative heat flux and mass generation rate of material vapor have approached their asymptotic values, the mass burning rate remains rather constant, and, thus, the CO production rate is also fairly constant (until the fuel supply becomes depleted).[7] These phenomena have been observed with large-scale fire tests involving fully furnished rooms.[8]

The ratio of the concentrations of carbon dioxide to carbon monoxide, often used as a descriptive characteristic of a fire, depends more on the ventilation conditions of the fire than on the nature of the materials being burned.[9] Studies of the dependence of CO_2/CO ratios on the equivalence ratio show that for well-ventilated fires (i.e., $\phi \ll 1$), essentially all the fuel carbon is oxidized to CO_2 and the ratio exceeds 20.[10] Once the equivalence ratio has exceeded that associated with flashover, indicating a fuel-rich or ventilation controlled fire, the CO_2/CO ratio reaches a plateau at about 2 to 10.[6,10] The bases for this range have not been established.

Hydrogen Cyanide

The generation of hydrogen cyanide (HCN) is both material-dependent and temperature-dependent. In smoldering fires and pyrolysis from flaming fires, HCN can be produced by decomposition of some nitrogen-containing polymers. HCN can be generated from nitrogen-containing polymers during flaming combustion as well. In neither case is there evidence of toxicologically significant HCN formation by fixation of the nitrogen in the air. In contrast to CO, there have been insufficient studies on HCN to enable quantitative prediction of its formation in fires. If sufficient oxygen is present, oxides of nitrogen (NO_x) may also be formed from nitrogen-containing materials. Although one study reported NO_x production from nitrogen-containing fuels to be far less than that for HCN, there are conflicting data in the literature.[11] HCN has also been seen to be oxidized to NO_x when flames extended from a flashed-over room and continued to burn outside the doorway.[12]

Halogen Acids

Polymer systems containing halogen atoms (fluorine, chlorine, or bromine) result in the formation of the halogen acids—hydrogen fluoride (HF), hydrogen chloride (HCl), and hydrogen bromide (HBr), the production of which is largely material-dependent as long as thermal decomposition temperatures are reached. The halogen acids are formed in the pyrolysis component of the combustion process and are not oxidized further. Thus, the halogen acids are produced even if flaming combustion does not occur. Since the production efficiencies for the formation of HF, HCl, and HBr are close to being unity, maximum yields might be expected in fires. For example, HCl is readily evolved from polyvinyl chloride (PVC) at temperatures of about 437 to 527°F (225 to 275°C).[2] Since HCl can be released before significant carbon from the material is combusted, the mass yield of HCl can exceed the stoichiometric value early in the material's decomposition. Nonetheless, the maximum possible concentrations of halogen acids are generally not encountered. Far lower yields have been found from PVC that contains a high fraction of calcium carbonate filler.[13] Presumably, this reflects reaction with the chlorine atoms to form (solid) calcium chloride, which is thermally stable under ordinary fire conditions. Furthermore, halogen acid concentrations decay rather quickly in the presence of adsorptive surfaces[14] and water droplets present in most fire effluents at temperatures below 212°F (100°C).

Organic Irritants

Pyrolysis and/or incomplete combustion of organic materials can lead to a wide variety of organic irritant species. Those considered to be the most important toxicologically are formaldehyde, unsaturated aldehydes (especially acrolein), and isocyanates (from nitrogen-containing polymers[15]). The first two result from partial oxidation of the carbon in the material. (Further oxidation leads to the formation of CO and then CO_2.) Acrolein, in particular, has been demonstrated to be present in many fire atmospheres.[16] It is also formed from the smoldering of all cellulosic materials and from the oxidative pyrolysis of polyethylenes.[17]

Other Gases and Aerosols

Depending on the composition of the combusting products, additional toxic components of smoke can be produced in a fire. For example, phosphorus-containing fire retardants can result in phosphoric acid aerosol, and sulfur-containing polymers can generate sulfur oxides. There is yet no predictive capability for the yields of such species.

TOXICITY OF FIRE GASES

Fire gas toxicants are usually considered as belonging to one of three basic classes:

1. Asphyxiants, or narcosis-producing toxicants
2. Sensory/upper respiratory irritants or pulmonary irritants
3. Toxicants exhibiting other or unusual effects; although always a possibility, this class has few documented examples

The toxicological effects of smoke produced from fires usually involve relatively high concentrations of toxicants inhaled over quite short periods of time. Thus, many criteria commonly used in conventional toxicology to describe hazardous conditions, such as threshold limit values (TLVs[18]) and occupational long-term exposure values, are normally of little use in combustion toxicology.

This section addresses the toxicity of the major fire gases in a largely descriptive manner. It also provides guidance on limiting criteria for exposure of humans in fires.

Asphyxiants

In combustion toxicology, the term *narcosis* refers to the effects of asphyxiant toxicants that are capable of resulting in central nervous system depression, with loss of consciousness and ultimately death. Effects of these toxicants depend on the accumulated dose, that is, both concentration and duration of the exposure. The severity of the effects increases with increasing dose.

Carbon Monoxide. The toxic effects of carbon monoxide are those of anemic hypoxia.[19] Hypoxia refers to the condition in which there is an inadequate supply of oxygen (O_2) to body tissue, with anemic hypoxia being characterized by a lowered oxygen-carrying capacity of the blood, even when the arterial partial pressure of O_2 and the rate of blood flow are normal. This is due to competition between O_2 and CO for the heme-binding sites of hemoglobin, with the affinity of hemoglobin for CO being about 250 times greater than that for O_2.[19] Even partial conversion of hemoglobin to carboxyhemoglobin (COHb) significantly reduces the oxygen-transport capability of the blood such that serious toxic signs and symptoms are produced. Additionally, partial conversion of hemoglobin to COHb causes oxygen that is bonded as oxyhemoglobin (HbO_2) to be more tightly held and less available to body tissues. The extent to which blood hemoglobin is converted to COHb can readily be measured in a clinical laboratory and is expressed as percentage of COHb saturation. An ISO standard for these measurements is being processed in ISO TC 92/SC 3.[20]

The signs and symptoms produced by exposure to CO are directly related to the percentage of blood hemoglobin that is converted to COHb.[21] Deaths of humans exposed to CO produced in fires have been associated with COHb saturations ranging from 1 to 99 percent.[22] Although most deaths have been reported to be in the 50 to 70 percent COHb range, both lower and higher values are not unusual.[23,24] Low COHb values in fire victims may be due to preexisting physiological conditions, such as pulmonary insufficiency or cardiovascular disease, which may have already compromised the individual. The high oxygen demand resulting from physical exertion may also cause a person to succumb to low COHb saturation. High COHb values at death may be attributed to the low oxygen demand of a person either at rest or at quite low physical activity. There is no specific COHb saturation below which one would be expected to live and above which death would occur. As with essentially all biological responses, there is a distribution of COHb saturations associated with death.[24] Sometimes, in the case of even a single exposure, permanent harm may result from hypoxic damage to neural structures.[19] The peak incidence of such delayed neurological impairment is with the elderly.[25]

Binding of O_2 and CO with hemoglobin occurs as an equilibrium, with both association and dissociation taking place.[19] Thus, CO and hemoglobin are in equilibrium with COHb, with the concentration of COHb being dependent on the partial pressure (or concentration) of CO in the atmosphere. Each concentration of CO is associated with an equilibrium COHb saturation, or, stated another way, for any given value of COHb saturation there is a minimum concentration of CO that will attain it. At any given O_2 concentration, higher equilibrium COHb saturations can be obtained only by increasing the concentration of CO.

The competition between O_2 and CO for bonding sites on hemoglobin is defined by the Haldane equation:[19]

$$\frac{(\text{COHb})}{(\text{HbO}_2)} = M\frac{(P_{\text{CO}})}{(P_{\text{O}_2})} \tag{2}$$

where

$(\text{COHb})/(\text{HbO}_2)$ = Ratio of carboxyhemoglobin to oxyhemoglobin

$(P_{\text{CO}})/(P_{\text{O}_2})$ = Ratio of the respective partial pressures (or concentrations)

M = A constant that is, to some extent, species dependent

The Haldane equation is commonly used to calculate the CO concentration that would be in equilibrium with any given COHb saturation.

The time required for a human subject to attain a given COHb saturation can be approximated from the Stewart-Peterson equation:[26]

$$\%\ \text{COHb} = (3.32 \times 10^{-5})(\text{CO})^{1.036}(\text{RMV})(t) \tag{3}$$

where

(CO) = CO concentration (μL/L)*

RMV = Respiratory minute volume (L/min)

t = Exposure time (min)

At rest, the RMV for humans averages approximately 8.5 L/min,[23] but may increase during strenuous activity to as much as

*The concentration in μL/L is numerically equal to the frequently used unit of "ppm." The use of the latter unit is discouraged.

100 L/min. Curves showing the relationship between CO concentration and time of exposure for various COHb saturation values for humans have been constructed using the Stewart-Peterson equation.[27]

Studies using rats have shown that elevated temperatures have an exacerbating effect on CO intoxication,[28] possibly through increased rate of respiration. This is likely to occur with humans as well. The obvious treatment for persons exposed to CO is to provide for inhalation of fresh air or even pure oxygen. For example, the half-recovery time in terms of blood COHb levels for resting adults breathing air at 1 atmosphere is 320 minutes.[19] When oxygen is given at 1 atmosphere, the time is reduced to 80 minutes.

Hydrogen Cyanide. Hydrogen cyanide (HCN), whose lethal dose is approximately 25 times smaller than that of carbon monoxide, is a very rapidly acting toxicant.[29] The action of HCN is due to the cyanide ion, which is formed by hydrolysis in the blood. Unlike CO, which remains primarily in the blood, cyanide ions are distributed throughout the body water and make contact with the cells of tissues and organs. Cyanide ions readily react with the enzyme cytochrome oxidase to form a cytochrome oxidase–CN complex and also with methemoglobin to form cyanomethemoglobin. If the concentration of cyanide ions is not sufficiently great to cause death, the ions are slowly released from the complexes with cytochrome oxidase and methemoglobin and converted to thiocyanate ions by the enzyme rhodanese. This detoxification process, along with the fact that cyanide is distributed throughout the body, makes correlation of blood cyanide content with actual exposure to HCN difficult.

Cytochrome oxidase occupies a central role in the utilization of oxygen in practically all cells. Its inhibition rapidly leads to loss of cellular functions (cytotoxic hypoxia) and then to cell death. In contrast to CO, cyanide ions do not decrease the availability of oxygen but rather prevent the utilization of oxygen by cells. The heart and brain are particularly susceptible to this inhibition of cellular respiration, with bradycardia, cardiac arrhythmia, and EEG brain wave activity, indicative of central nervous system depression, having been reported in studies using monkeys.[30] Although cardiac irregularities are often noted in HCN intoxication, the heart tends to outlast respiration, and death is usually due to respiratory arrest of central nervous system origin.

A complication resulting from the inhalation of HCN is one of respiratory stimulation or hyperventilation,[23] presumably due to the body's regulating chemoreceptor cells responding to a need for oxygen. This causes a more rapid uptake of not only HCN but also other toxicants that may be present. The hyperventilatory effect of HCN may also account for its rather steep dose-response relationship.

Data relating symptoms in humans to various concentrations of HCN are very limited. One widely referenced descriptive account of HCN intoxication of humans reports that 50 µL/L may be tolerated for 30 to 60 minutes without difficulty, 100 µL/L for that same period is likely to be fatal, 130 µL/L may be fatal after 30 minutes, and 181 µL/L may be fatal after 10 minutes.[31]

The role of HCN as a causative agent in human fire fatalities is considerably less clear than that of CO. Documented cases are rare in which HCN alone can be shown to be the primary toxicant. Blood can be analyzed for cyanide, but the procedure is more complex than that for CO, and the reliability of the results is dependent on proper blood storage conditions prior to analysis. Analyses should be interpreted with caution, with consideration given to the analytical method used, the blood storage history, and the past performance of the responsible laboratory. It is generally held that blood cyanide concentrations greater than 1.0 µg/ml are indicative of possibly significant toxicological effects due to inhalation of HCN.[22,32] Blood cyanide levels greater than 3.0 µg/ml are generally considered to be lethal. Significant concentrations of blood cyanide are normally found associated with carboxyhemoglobin saturation due to inhalation of CO.[32,33] The contribution of each to death often cannot be determined with confidence. There is no evidence for synergism between HCN and CO, and it is generally agreed that these two toxicants are additive in their effects.[34,35]

Carbon Dioxide. Carbon dioxide (CO_2) is quite low in its own toxicological potency and is not, by itself, normally considered to be significant as a toxicant in fire atmospheres. However, it does stimulate both the rate and depth of breathing, thereby increasing the RMV. The RMV, increasing about 50 percent with only 2 percent CO_2, may be as much as 8 to 10 times normal in the presence of 10 percent CO_2. Such respiratory stimulation causes accelerated inhalation of other toxicants leading, for example, to an increased rate of formation of blood COHb from inhalation of CO. However, the same equilibrium COHb saturation of blood is reached as in the absence of CO_2.[36]

Increased incidence of lethality of rats has also been reported with combinations of CO and CO_2, particularly occurring after the exposure period.[37] This effect may be associated with the combined insult of respiratory acidosis (caused by CO_2) and metabolic acidosis (caused by CO), a condition from which the rodent has difficulty recovering postexposure. Whether or not this latter effect of CO_2 also occurs with people has not been determined.

Oxygen Depletion. Since oxygen is consumed in the combustion process, oxygen depletion or vitiation must also be considered a toxic component of smoke. When oxygen drops from its usual level of nearly 21 percent in air to approximately 17 percent, a person's motor coordination may be impaired. When oxygen drops to the range of 14 to 10 percent, a person can be still conscious but may exercise faulty judgment and will be quickly fatigued. In the range of 10 to 6 percent, a person loses consciousness and must be revived with fresh air or oxygen within a few minutes to prevent death.[38] During periods of exertion, increased oxygen demands may result in oxygen deficiency symptoms at higher oxygen levels.

Irritants

Both inorganic irritants (e.g., halogen acids and those formed from nitrogen oxides) and organic irritants (e.g., aldehydes) can be formed in fires. Irritant effects, produced from exposure

to essentially all fire atmospheres, are normally considered by combustion toxicologists as being of two types:

1. Sensory irritation, including irritation of the eyes and the upper respiratory tract
2. Pulmonary irritation affecting the lungs

Most fire irritants produce signs and symptoms characteristic of both sensory and pulmonary irritation.

Eye irritation, an immediate effect that depends primarily on the concentration of an irritant,[39] may significantly impair a person's escape from a fire. Nerve endings in the cornea are stimulated, causing pain, reflex blinking, and tearing. Severe irritation may also lead to subsequent eye damage. Victims may shut their eyes, partially alleviating these effects; however, this action may also impair their escape from a fire.

Airborne irritants also enter the upper respiratory tract, causing burning sensations in the nose, mouth, and throat, along with the secretion of mucus. These sensory effects are also primarily related to the concentration of the irritant and do not normally increase in severity as the exposure time is increased.[39]

Following signs of initial sensory irritation, significant amounts of inhaled irritants may also be quickly taken into the lungs, with the symptoms of pulmonary or lung irritation being exhibited. Lung irritation is often characterized by coughing, bronchoconstriction, and increased pulmonary flow resistance. Tissue inflammation and damage, pulmonary edema, and subsequent death may follow exposure to high concentrations, usually within 6 to 48 hours. Inhalation of pulmonary irritants also appears to increase susceptibility to postexposure bacterial infection. Unlike sensory irritation, the effects of pulmonary irritation are dependent both on the concentration of the irritant and on the duration of the exposure.

Halogen Acids. The halogen acids have received particular attention, with the most prevalent case being hydrogen chloride (HCl) resulting from the decomposition of polyvinyl chloride (PVC). HCl is both a potent sensory irritant and a strong pulmonary irritant. Volume fractions as low as 75 to 100 µL/L are extremely irritating to the eyes and the upper respiratory tract, suggesting possible impairment of physical activity such as is needed for escape.[40] Although HCl was found not to be physically incapacitating to baboons subjected to volume fractions up to 17,000 µL/L for 5 minutes, postexposure deaths were reported from doses that did not appear to incapacitate.[41] Comparable studies have not been conducted using actual PVC smoke.

Another study, using baboons exposed for 15 minutes to (flaming) PVC smoke containing 5000 µL/L HCl, did not show any smoke-related impairment of pulmonary function when tested at 3, 90, 180, and 360 days postexposure.[42] Lesions to mucosal surfaces of the mouth were observed, however, along with evidence of bronchoconstriction and lowered PaO_2 (arterial oxygen) levels during the exposure.

Considerable controversy has existed as to what concentration of HCl may be hazardous to humans. It is questionable whether data from numerous studies with rodents can be directly extrapolated to humans because of significant anatomical differences between the respiratory tracts of the rodent and the primate which, in turn, result in very different responses to HCl. Rodents exhibit a decrease in respiratory rate and minute volume on exposure to HCl, whereas these values have been shown to increase for primates.[43] Interestingly, exposure doses (concentrations × time) of HCl causing postexposure lethality in rats are in the same range as those that have resulted in postexposure deaths of baboons.[44] However, the data for baboons are very limited, and the comparison made is rather subjective. From studies using exposure of baboons, HCl would not appear to be physically incapacitating, nor would it seem to produce significant chronic respiratory complications after short exposures to volume fractions of 5000 µL/L and below. Although acute symptoms, ranging from severe discomfort to noticeable upper respiratory tissue damage, may be experienced, significant pulmonary function changes would not be expected except at higher concentrations.

It would still be prudent, however, to recognize that HCl is likely to be dangerous to humans at concentrations far below those indicated from studies using baboons. Evidence of bronchoconstriction and markedly lowered PaO_2 levels from inhalation of HCl were observed with baboons,[45] suggesting a potential for adverse effects with humans. Furthermore, persons having preexisting compromised pulmonary function may be more susceptible than healthy individuals.

Fire-retardant additives based on chlorine or bromine are also sources of halogen acids in fires. Fluoropolymers are a major source of HF. Although studies using the halogen acids HF and HBr have been very limited, it would appear that these acid gases exhibit irritant effects similar to those of HCl at comparable concentrations.[23]

The determination of incapacitation threshold criteria for the initial effect of the halogen acids (and for irritant gases in general) has involved considerable controversy, since very few controlled studies have been made that relate to the effects of human exposure. Most information has been only anecdotal. Taking expert cognizance of relevant published information, ISO 13571 suggests the following incapacitating volume fractions:[46] F_{HCl} = 1000 µL/L, F_{HBr} = 1000 µL/L, and F_{HF} = 500 µL/L. These are for use in Equation (7) on p. 6-20.

Nitrogen Oxides. Nitrogen dioxide (NO_2) and nitric oxide (NO) are the major components of a mixture of nitrogen oxides usually referred to as NO_x. Nitric oxide is only about one-fifth as potent as NO_2.[11] Studies on rats exposed to NO_2 under the conditions of smoke toxicity test methods indicate NO_2 to have a lethal toxic potency comparable to HCN.[47] In contrast to HCN, the toxicity of NO_x is primarily due to its properties as a pulmonary irritant, with lethality of rats being postexposure, usually within one day. A consensus (ISO 13571) incapacitating volume fraction is F_{NO_2} = 250 µL/L.

Other Inorganic Irritants. As indicated above, the presence of other atoms in the burning materials can lead to the generation of inorganic oxides and acids, which behave as irritants as well. The toxic effects of these gases are likely to be additive with the irritants discussed above. A consensus value for the incapacitating volume fraction of SO_2 is 150 µL/L. Consensus values for other inorganic irritants have not yet been determined.

Organic Irritants. Although numerous organic irritants may be produced in fires, only acrolein has received significant attention in combustion toxicology. It is deemed to be the most potent of the organic irritants. Volume fractions of acrolein as low as a few μL/L are extremely irritating to the eyes and upper respiratory tract. Interestingly, studies with baboons showed that volume fractions up to 2780 μL/L (5700 g/m^3) for 5 minutes were not physically incapacitating during exposure.[41] Pulmonary complications caused by that and even lower concentrations resulted in death within hours after the exposure, however. Values of incapacitating volume fractions for acrolein and formaldehyde are 30 μL/L and 250 μL/L, respectively.[46] However, given the results of the baboon studies, this figure for acrolein seems conservative.

Supertoxicants

Concern regarding potential "supertoxicants" (materials generating smoke of extremely high potency) in fire atmospheres was prevalent in the 1970s and 1980s. With more experience in the testing of materials, this concern has diminished, since there have been few documented examples. One involved the formation of a neurotoxin from the thermal decomposition of a noncommercial rigid polyurethane foam,[48] whereas another concerned the extreme toxic potency exhibited by polytetrafluoroethylene in some laboratory tests. The latter eventually came to be regarded as largely an artifact of the test methods.[49] For most materials and products it is now widely accepted that smoke toxicity can, to a large extent, be explained both qualitatively and quantitatively on the basis of a small number of common toxic gases.[50,51] A protocol for identifying a supertoxicant is presented below in the section Test Methods for Toxicity of Smoke.

QUANTIFICATION OF TOXIC POTENCY

The LC_{50}

The standard in combustion toxicology for quantifying the toxic potency of individual fire gases or of smoke has mostly been the LC_{50} for 30 minute exposure of rats.[52,53] The LC_{50} is defined as the volume fraction of toxic gas in μL/L or smoke in g/m^3 statistically calculated from concentration-response data to produce lethality in 50 percent of test animals within a specified exposure and postexposure time.* The IC_{50} is similarly defined for incapacitation. It is significant that consensus among experts has been to recognize that the rat is a reasonably acceptable animal model for human exposure to smoke when the principal effects are due to inhalation of asphyxiant toxicants.[27,54] Over the years, LC_{50} values have been experimentally determined for rodent (and less frequently, other laboratory animals) exposure to individual fire gases,[54] as well as for many materials and products.[55]

*"Within a specified exposure" refers to the time interval during which the animals can inhale the gas or smoke. A "specified postexposure time" refers to a length of time after that, when the animals are breathing fresh air.

Lethal Toxic Potency from Chemical Analysis

Although individual fire gas toxicants may exert quite different physiological effects through different mechanisms, when present in a mixture each may result in a certain degree of compromise experienced by an exposed subject. It should not be unexpected that varying degrees of a partially compromised condition may be roughly additive in contributing to death. The extensive bank of rodent lethality data became useful in the development of a strategy for calculating smoke LC_{50} values from combustion analytical data without the need for exposure of animals. As early as 1972, Tsuchiya and Sumi proposed that a toxicity index could be constructed from the sum of terms for all the gases generated by a fire. Each term was the ratio of the actual concentration of the gas divided by the concentration fatal to a person in a 30 minute exposure.[56] Three further developments made this concept tractable for estimating lethal toxic potency.

Additivity Studies

The additive effects of combustion gases were demonstrated in a number of studies using rodents.[34,35] As a result, it is now fairly well agreed that the asphyxiants CO and HCN are additive. Furthermore, analysis of data from experiments exposing rats to mixtures of HCN and CO, and also mixtures of HCl and HCN, suggests that their effects leading to lethality may also be approximately additive.[57,58]

Fractional Effective Dose (FED)

The additive effects of fire gases was advanced to include consideration of variable exposure time. This strategy is commonly referred to as the fractional effective dose (FED) methodology.[34,59,60] The FED is "the ratio of the *Ct* product (concentration × time) for a gaseous toxicant produced in a given test to that *Ct* product of the toxicant that has been statistically determined from independent experimental data to produce lethality in 50 percent of test animals within a specified exposure and postexposure time."[53]

The additivity of FEDs has become a useful tool in combustion toxicology for the calculation of lethal toxic potencies from combustion product analysis data, as well as for the assessment of potential toxic hazards to humans.[51] Mathematically, the principle is expressed as

$$\text{FED} = \sum_{i=1}^{n} \sum_{t_1}^{t_2} \frac{C_i}{(Ct)_i} \Delta t \qquad (4)$$

where

C_i = Concentration of toxic component i

$(Ct)_i$ = Specific dose (concentration × time) required to produce lethality

t = Time increment (min)

When the accumulated FED = 1, it is expected that the mixture of gaseous toxicants would be lethal to 50 percent of exposed animals, that is, the LC_{50}.

N-Gas Model

The combustion of the complex formulations used in commercial products generates hundreds of different gases. The evaluation of the FED values and the nature of the combination of those FED values would have been a daunting, if not insurmountable, task. Researchers at the National Institute of Standards and Technology (NIST) proposed the N-gas model. This concept suggests that the toxic potency of most commercial products could be estimated from the contributions of a small number, N, of the combustion gases.[35,51] The results of rat exposure experiments to single and mixed gases were compared with experiments in which rats were exposed to the gases generated by the combustion of a number of materials. The mean FED value corresponding to the LC_{50} was 1.07, using the "N-gas" calculation, with 95 percent confidence limits of 0.20.[61] This provided substantial support for this concept.

Two equations have been developed to fit rodent data.[52] The first, Equation 5, was developed empirically by Levin and coworkers[9] from exposure of laboratory rats to individual and mixed gases:

$$\text{FED} = \frac{m \cdot f_{CO}}{f_{CO_2} - b} + \frac{21 - f_{O_2}}{(21 - 5.4)} + \frac{f_{HCN}}{150} + \frac{f_{HCl}}{3700} + \frac{f_{HBr}}{3000} \quad (5)$$

where m and b are, respectively, the slope and intercept of the interactive curve of CO and CO_2, which depicts the increasing toxicity of CO as CO_2 concentration increases. The values of m and b depend on the volume fraction of CO_2. If $f_{CO_2} \leq 0.05$, $m = -18$ and $b = 122{,}000$. If $f_{CO_2} > 0.05$, $m = 23$ and $b = -38{,}600$. Confirmatory work using this model has been published by Pauluhn.[61]

The terms f_x are the volume fractions of those species in µL/L, except for O_2 and CO_2, where the volume fractions are in volume percent.

The second, Equation 6, was developed by Purser,[62] fitting the rat LC_{50} data obtained mainly by Levin et al.[61,63] and Kaplan and Hartzell.[27]

$$\text{FED} = \left(\frac{f_{CO}}{LC_{50,CO}} + \frac{f_{CN}}{LC_{50,HCN}} + \frac{f_X}{LC_{50,X}} + \frac{f_Y}{LC_{50,Y}}\right) V_{CO_2} + A + \frac{21 - f_{O_2}}{(21 - 5.4)} \quad (6)$$

where, in addition to the definitions for Equation 5,

f_{CN} = The volume fraction of HCN in µL/L, corrected for the presence of other nitriles and the protective effect of NO_2, and is equal to $f_{HCN} + f_{\text{total organic nitriles}} - f_{NO_2}$

$LC_{50,X}$ = The LC_{50} of each acid gas irritant in µL/L

$LC_{50,Y}$ = The LC_{50} of each organic irritant in µL/L

V_{CO_2} = A multiplication factor for CO_2-driven hyperventilation equal to $1 + e[(0.14 \cdot CO_2\%) - 1]/2$

A = An acidosis factor equal to $f_{CO_2} \times 0.05$

The 30 minute LC_{50} values used in Equation 6 are given in Table 6.2.1.[54]

Between the two equations, there are small numerical differences in the LC_{50} values for HCN, HCl, and HBr. These differences are within the uncertainties of the experiments from which the values were derived.

There are also functional form variations in the way CO, CO_2, and depleted O_2 are included in the two equations. These variations will lead to modest differences in the calculated values of the FED. A reasonable estimate of agreement between the two equation calculations is ±30 percent for FED values ≈ 1.

Sublethal Effects of Fire Smoke

Smoke inhalation can lead to a succession of sublethal effects that each can affect how readily a person can find safety from a fire. For nearly all of these, there are few quantitative data from controlled experiments or actual fire experience for the degree to which these effects alter the ability of laboratory animals or people to escape from a fire. Although tests have been developed for assessment of incapacitation due to sensory irritation,[64] they have not received significant use. This is due, at least in part, to a lack of validation between the tests and actual effects on humans. This has led the experts assigned to ISO TC92 SC3 to affirm that the focus should be on incapacitation.[10] Incapacitation is defined as the inability to take action to accomplish an escape from a fire.

Some measurements have been made of incapacitation on rodents.[27] A literature review of the animal exposure data for CO and HCN showed that the concentrations that caused incapacitation were one-third to one-half those that resulted in death.[27] A subsequent review was performed of the literature of the animal exposure data for exposure of animals to combustion smoke from a wide variety of materials and products.[55] The mean value of the ratios of the IC_{50} to the LC_{50} and the standard deviation were 0.50 and 0.21, respectively.

Although considerable attention was once directed toward incapacitation studies, testing for smoke toxicity ultimately made no such assessment. Incapacitation is simply inferred from lethality data, with combustion toxicologists generally regarding incapacitating exposure doses to be about one-third to one-half of those required for lethality.[27]

TABLE 6.2.1 30 Minute LC_{50} Values for Rats

Combustion Product	*30 min LC_{50} (µL/L)*
CO	5700
HCN	165
HCl	3800
HBr	3800
HF	2900
SO_2	1400
NO_2	170
Acrolein	150
Formaldehyde	750

Source: Data from International Organization for Standardization.

TEST METHODS FOR TOXICITY OF SMOKE

Evolution of Testing

In the 1970s and 1980s, the dominant philosophy was that smoke toxicity was a property of a material and that control of this property was the proper approach to improving life safety in fires. Accordingly, a number of bench-scale apparatus were developed to measure the toxicity of smoke produced from the burning of materials and, sometimes, products.[65] These tests exposed a sample of a material or a finished product to a thermal exposure that was deemed appropriate to simulate a fire. Multiple rats or, less commonly, mice were exposed to the combustion products. Sufficient experiments were performed to estimate the LC_{50} for a 30 minute exposure and frequently within a postexposure period of up to 14 days. The LC_{50} values were expressed in units of g/m^3, that is, grams of the test specimen that were consumed (and presumed to be present as smoke) per unit exposure chamber volume (for closed box apparatus) or total air flow (for flow-through apparatus). One test method, The University of Pittsburgh (UPITT) device, expresses the LC_{50} only as grams of material subjected to the test protocol, which is not a true expression of concentration. In general, care should be taken in comparing LC_{50} values obtained from different test methods to ensure that the basis for reporting data is the same.

Although this type of testing may have led some manufacturers to not market certain products, regulation on this basis was limited. For a number of years, the state of New York required the testing and filing of test data for certain construction and finish materials using the "LC_{50}" value from the UPITT method. However, when it became widely recognized that the results of such testing were often irrelevant to the toxic hazards of real fires, the regulation was repealed and most of the laboratory testing ceased. At present, there are no laboratories conducting nonproprietary animal tests for smoke toxicity on a routine basis.

In recent decades, there has been growing resistance to the routine use of laboratory animals for testing products, whether this be for skin care or fire safety. This has resulted in a move toward the N-gas concept. Unfortunately, there were, and continue to be, some regulations based on limiting the concentration of one or more gases generated using a particular test apparatus. As noted in the introduction to this chapter, this is not likely to help achieve a desired level of fire safety, since the gas yields are not singular properties of a product.

More recently, there has been enhanced awareness that the proper use of smoke toxic potency data is as input to a fire hazard or risk assessment, rather than stand-alone pass/fail testing of materials or products.[10] The values to be used are the yields of the toxic gases. This is the mass of the gas generated divided by the combusted mass of the test specimen. Less commonly, the calculations use the specimen mass subjected to the test conditions. (These values will be identical if the specimen is completely combusted with no residue.)

Per NFPA 269 and ASTM E1678-02,[53] there is now a protocol that balances the need for accuracy in toxic potency measurement while minimizing the use of laboratory animals. In this method, the measured concentrations of the principal toxicants that are generated when a test specimen is combusted are used to estimate the LC_{50} using the N-gas equation. Rats are then exposed to smoke at concentrations 30 percent below and 30 percent above this value. If the animal mortality agrees with the predicted LC_{50}, then it is presumed that the smoke is "normal" and the estimated value is used. This will generally be the case for a product whose chemistry is similar to other products for which the animal confirmation test was successful. If the smoke is unusually toxic to rats, then additional research or testing is warranted.

The question then arises as to which of the many tests available gives toxic potency values that are "right." ISO 16312-1 describes the characteristics of the ideal fire effluent toxicity test method:[66]

- The combustor (or physical fire model) replicates one or more fire stages (radiative pyrolysis, well-ventilated flaming, etc.).
- The test specimens are representative of as-used products.*
- The apparatus itself does not affect the results.
- The apparatus is straightforward to use.
- The method generates gas/smoke yields and specimen mass loss data.
- The method has demonstrated accuracy relative to real-scale fires.
- The results are repeatable and reproducible.

The standard then provides criteria to evaluate a real method. ISO/TR 16312-2 (not a Standard, but a Technical Report that presents the ISO TC 92/SC 3 assigned experts' appraisal) applies these criteria to twelve test methods in use today.[67]

The following sections present the essential features of some of the tests whose data are most likely to appear in the published literature or which are more commonly used for the regulation of materials and products. For a broader coverage of the many apparatus that have been developed over the years, the reader is referred to more complete compilations.[66,67]

Cup Furnace Test

The cup furnace test,[68] described in Figure 6.2.1, combusts a test specimen in a quartz beaker (the "cup"); the effluent rises and expands to fill an 0.2 m^3 closed box. Data for both nonflaming and flaming combustion are obtained by conducting tests just below and just above the autoignition temperature of the specimen, respectively. In each test, six rats are held in tubular restrainers, with their heads inside the box. They inhale the smoke for 30 minutes and then are observed for the following 14 days. Multiple experiments are conducted, with varying masses of the test specimen placed in the cup furnace, leading

*This may be the most difficult of the characteristics with which to comply. Some test methods can accommodate a specimen prepared to resemble, as much as possible, a product in its form of use as it would be exposed in a fire. Other test methods require, or can only accommodate, a ground or crumpled specimen. The latter is less representative of a product having complex construction (e.g., layers of different materials). These two approaches may yield different results for the toxicity of smoke produced by a product.

to different concentrations of smoke in the box. The number of animal deaths per test is plotted against the smoke concentration (specimen mass in the furnace divided by the box volume). Statistical analysis of the data then generates an estimate of the LC_{50} (30 minute exposure plus 14 day postexposure period). Chemical analysis of the principal toxicants enables a second estimation of the LC_{50} using Equation 5 for FED = 1. The use of rats can be minimized by using the animal check test protocol as noted above under "Evolution of Testing."

Extensive data on individual fire gases, combinations of those gases, materials, and products have been produced using this method. The data can be found in the references to Levin and coworkers in the bibliography of this chapter. This method is no longer in use since the radiant furnace apparatus (discussed next) manifests a more fire-like exposure of the test specimen. However, the data from the cup furnace method are still widely referenced.

Radiant Furnace Test

The radiant furnace test[53] uses the same 0.2 m^3 box as the cup burner test. However, the cup furnace is replaced by an assembly that applies a fixed radiant flux to the test specimen, as shown in Figure 6.2.2.[69] A spark source is used to ignite the fuel vapors. The test is particularly applicable to layered products, such as furniture or wall coverings. In the operation of the method,[9] a test specimen up to 10 cm by 15 cm by 5 cm thick is exposed to a radiative flux of 50 kW/m^2 for 15 minutes. The smoke enters the box through the center hole of a three-slot chimney. Air from the box is recirculated to the combustion zone through the two outer slots. The rat exposures and gas analyses are the same as with the cup furnace test. Successive tests are performed, with the top surface area of the specimen being varied to vary the concentration of smoke in the box.

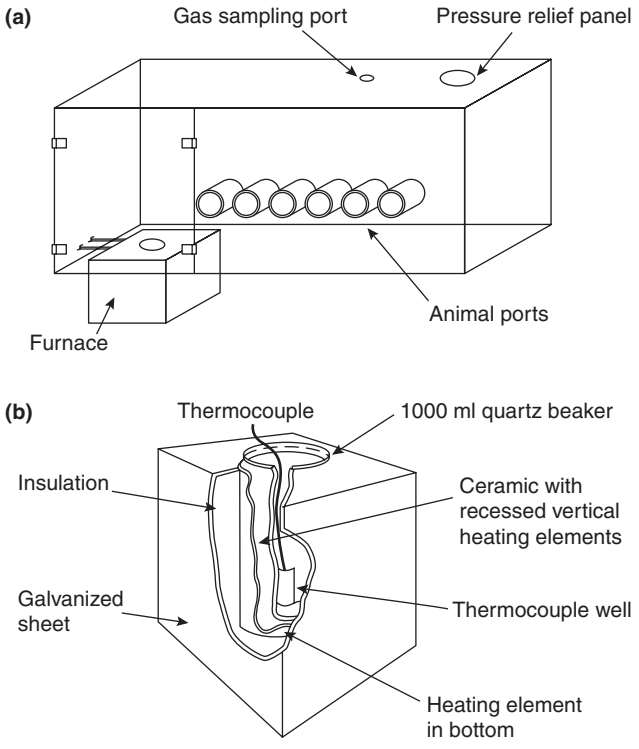

FIGURE 6.2.1 Schematic of the Cup Furnace Apparatus. (a) Orientation of furnace to exposure box. (b) Details of cup furnace. (Source: National Institute of Standards and Technology)

The lethal toxic potency, LC_{50}, of the smoke from the test specimen is predicted from the combustion atmosphere analytical data by first calculating the FED for the test. The 30 minute LC_{50} is then calculated as that specimen mass loss that would yield FED = 1 within a chamber volume of 1 m^3 from the equation:

$$LC_{50} = \frac{\text{Specimen mass loss}}{\text{FED} \times \text{Chamber volume}} \quad (7)$$

where the specimen mass loss is in grams and the chamber volume is 0.2 m^3. The resulting LC_{50} has the units of g/m^3. The predicted LC_{50} is then confirmed in limited tests using rats to ensure that the monitored toxicants account for the observed toxic effects.

The apparatus and procedures have been standardized (identically) as ASTM E1678, *Standard Test Method for Measuring Smoke Toxicity for Use in Fire Hazard Analysis*[53] and NFPA 269, *Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling.* Both standards also provide for a mathematical adjustment of experimental LC_{50} values in order to make them appropriate for the toxic hazard assessment of oxygen-vitiated, postflashover fires.

The test results have been compared to results from room-scale postflashover fires.[70] Prior to performing the comparison, an adjustment was made to the CO yield. Following flashover, the oxygen concentration in a room drops precipitously. Were this condition replicated in the current test, the animals would succumb to the reduced oxygen, regardless of the effects of the other gases in the smoke. A literature search indicated that postflashover fires typically generate yields of CO of about 0.2 kg CO per kg fuel consumed. This yield is substituted for the CO yield determined in the tests. For five different criteria, the bench-scale apparatus produced results consistent with the room-scale data. Accuracy to within a factor of three was established as both attainable and practical.

University of Pittsburgh (UPITT) Test

The UPITT test,[71] shown in Figure 6.2.3, exposes four mice per test to fire effluent produced in a flow-through system from the 68°F (20°C) per minute ramped heating of a specimen in a box or muffle furnace. Exposures are for 30 minutes, starting when 1 percent of the sample weight has been lost. The animals are also observed for 10 minutes following the exposure to the combustion gases. Animal measurements include concentration-response for lethality and time-to-death. Although the results are reported as LC_{50} values, the values are actually the weight of test specimen charged to the furnace, rather than actual concentrations of smoke, which varies considerably during a test. Thus, "LC_{50}" values obtained from this test are not directly comparable to those from other methods. Between 1987 and 1998, this

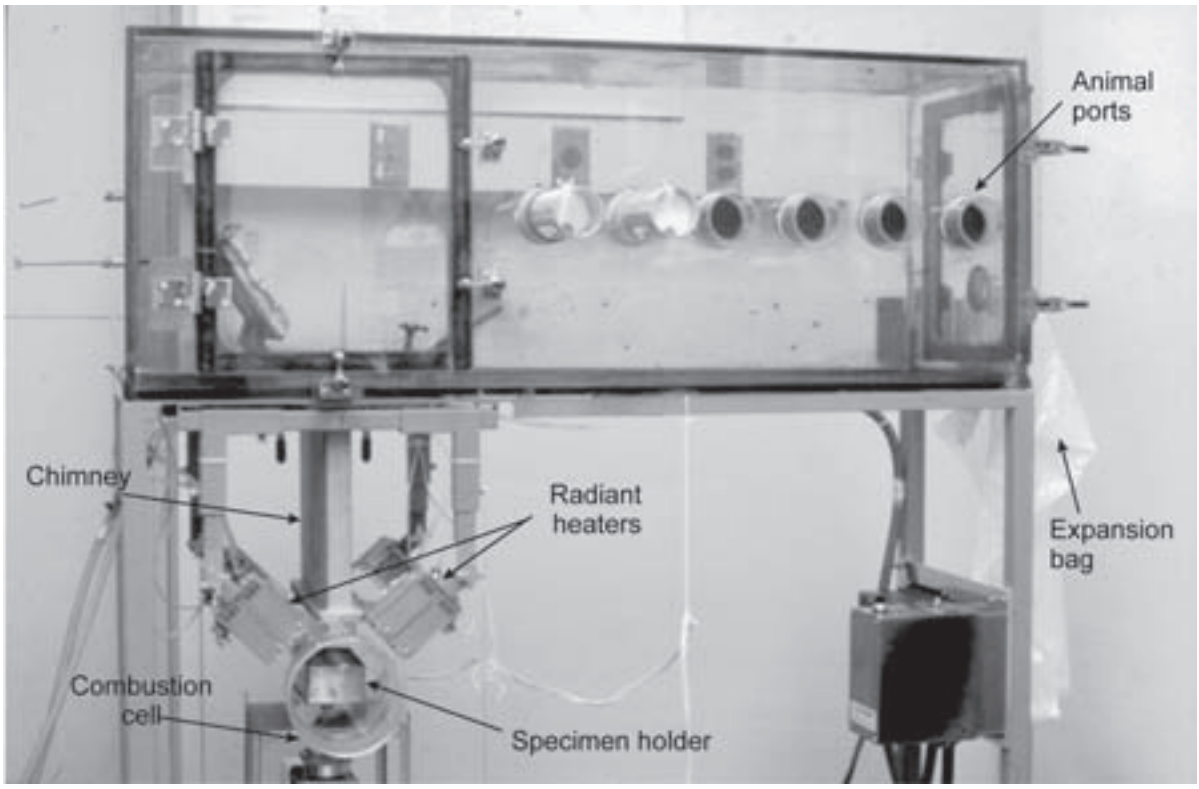

FIGURE 6.2.2 ASTM E1678/NFPA 269 Test Apparatus (Source: National Institute of Standards and Technology)

test was required by the state of New York for certain construction and finish materials. No acceptance levels or criteria for classification of materials were ever set. During the years over which testing was conducted, LC_{50} values were reported and filed with the state of New York for over 15,000 products.[72]

There are a number of differences between real-scale fires and the conditions in this apparatus. There is no ignition source, so the samples autoignite or don't, depending on the mix of gases generated, the point in the temperature ramp, and the sufficiency of the oxygen at that point. Furthermore, it is not clear

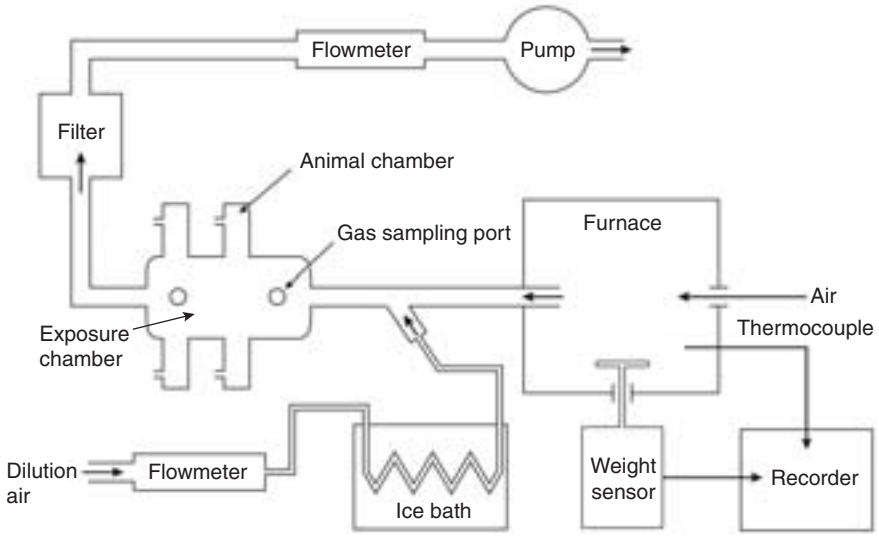

FIGURE 6.2.3 Schematic of the University of Pittsburgh Apparatus (Source: National Institute of Standards and Technology)

when the combustion conditions in the furnace resemble preflashover burning, postflashover burning, or neither. Because the combustion gases flow past the mice, the mice can be exposed to some gases in series, rather than concurrently.

Closed Cabinet Toxicity Test

The closed cabinet toxicity test is illustrated in Figure 6.2.4. This apparatus, standardized in NFPA 270, *Standard Test Method for Measurement of Smoke Obscuration Using a Conical Radiant Source in a Single Closed Chamber,* and ISO 5659-2,[73] was designed for measurement of smoke optical density. However, with the addition of gas concentration measurements, it is used by the International Maritime Organization and the European Union, among others, as an acceptance test based on gas concentrations.

In a test, a planar test specimen, 7.5 cm by 7.5 cm by up to 2.5 cm thick, is exposed to a radiant flux of either 25 kW/m^2 or 50 kW/m^2 for 10 minutes. A pilot flame is standard, but provision is made for testing without the pilot flame. The combustion products accumulate in the 0.5 m^3 chamber. Combustion products are sampled through a probe whose tip is located at the geometric center of the chamber. Should the concentration of any of the specified fires gases exceed a prescribed limit, the material or product fails the test.

During the course of a test, the air in the chamber becomes vitiated, and the generation rates of the combustion products evolve.[74] Thus, it is not clear what stage of a fire is being replicated. It follows that the use of the gas concentration data are of questionable value as an indicator of fire safety. There have been no reported comparisons of data from this apparatus with data from real-scale fire tests of the same materials or products.

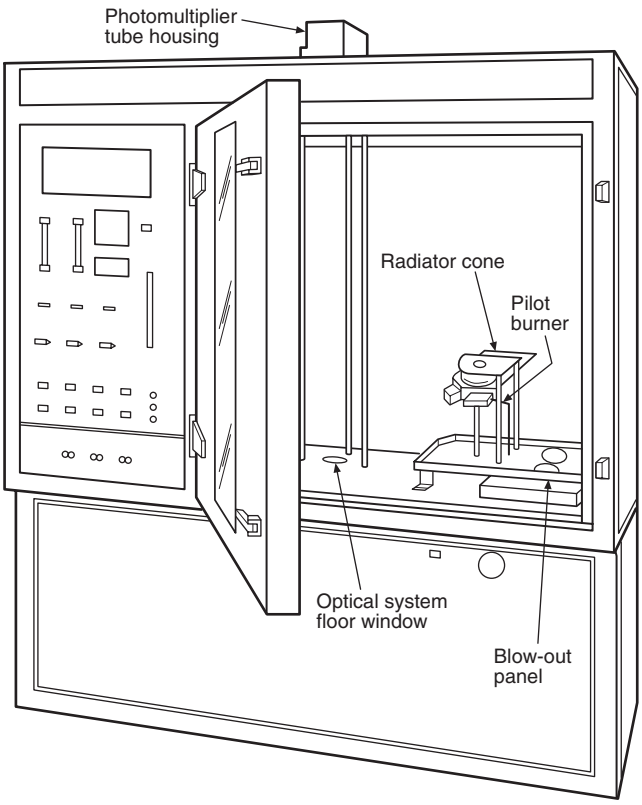

FIGURE 6.2.4 Typical Arrangement of the Closed Cabinet Test Chamber (Source: NFPA 270, *Standard Test Method for Measurement of Smoke Obscuration Using a Conical Radiant Source in a Single Closed Chamber,* 2002 ed., Figure 4.1)

Tube Furnaces

There are a number of designs of these apparatus in use around the world. Two are described here, the first because of the data that have been generated, the second because of its potential as an ISO standard.

The DIN 53436 Test, developed by the German Standards Institution and shown in Figure 6.2.5, is characterized by the use of a moving cylindrical tube furnace operating at a constant temperature in the range of 392 to 1832°F (200 to 1000°C).[75] The furnace is programmed to travel the length of a quartz tube containing the sample, which has a volume of about 40 mL. Decomposition, taking place in an air stream countercurrent to the direction of furnace travel, is intended to result in the continuous flow of fire effluents of constant composition. The standard procedure includes exposure of 10 rats to the effluent and measurement of the gases generated.

This test device, used in six European countries, offers a rather wide range of well-controlled combustion conditions. Ratios of CO_2/CO can be made to vary widely, depending on the air flow used. Thus, both well-ventilated and ventilation-limited fires may be simulated. Specimens may undergo either flaming or nonflaming combustion, depending on the imposed heat flux.

Combustion product analytical data obtained from the DIN 53436 test have been used for the calculation of LC_{50} values using the FED principle, as well as the N-gas method described in connection with the ASTM E1678 test. [76] Comparisons between calculated and experimental LC_{50} values for over 30 materials tested revealed fairly good correlation and predictability, giving additional credibility to the concept that lethal toxic potency can largely be attributed to a small number of major toxic gases.

The tube furnace used in ISO/TS 19700[77] is larger in diameter (4.3 cm) than the DIN furnace. It is described in Figure 6.2.6. The test specimen fills a boat that is at least 0.8 m long. The boat is driven through a tube furnace at a set temperature, 660°F (350°C) for oxidative pyrolysis, 1200°F (650°C) for well-ventilated flaming combustion, and 1520°F (825°C) for postflashover combustion. The fixed sample speed and the variable air flow though the tube allows predetermination of the equivalence ratio. There is a small open box at the exit end of the tube from which the effluent gases are sampled. The box can be adapted for exposing laboratory animals. The apparatus is identical to the tube furnace in BS 7990;[78] there is a less well-defined version that has been adopted by the International Electrotechnical Commission.

Because of the wide variation in tube furnaces, ISO/TS 19700 was developed to encourage broad construction of uni-

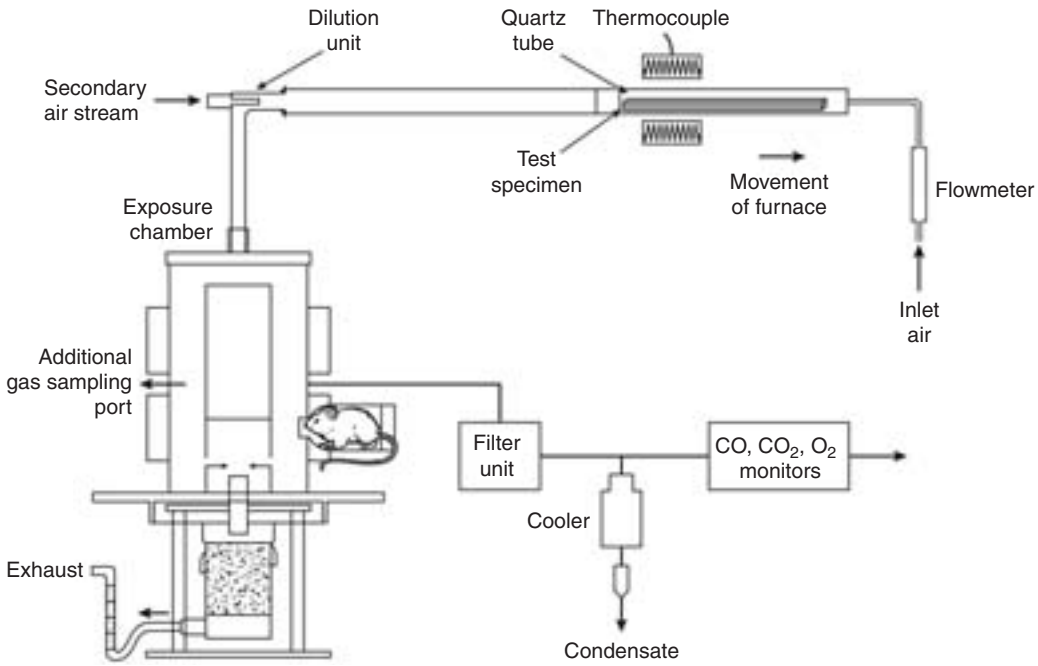

FIGURE 6.2.5 Schematic of the DIN 53436 Tube Furnace (Source: National Institute of Standards and Technology)

form devices. A correlation has been found between CO yields in real-scale fire tests and those from the tube furnace.[79]

ESTIMATION OF TOXIC HAZARD IN FIRES

The fundamental principle in designing for the safety of people in fires is to provide sufficient time for them to escape or find a place of refuge before being overcome by the flames, heat, or smoke. In quantitative terms, the objective is for ASET to be greater than RSET. ASET, the *available safe egress time,* is the interval between the time of ignition of the fire and the time at which an individual is incapacitated. RSET, the *required safe egress time,* is the time it takes that individual to find a safe location. Each person may have a different value for each of these terms, depending on such factors as his/her starting location, physical condition, and susceptibility to smoke. The magnitude of the difference between ASET and RSET is an indicator of the degree of safety being provided.

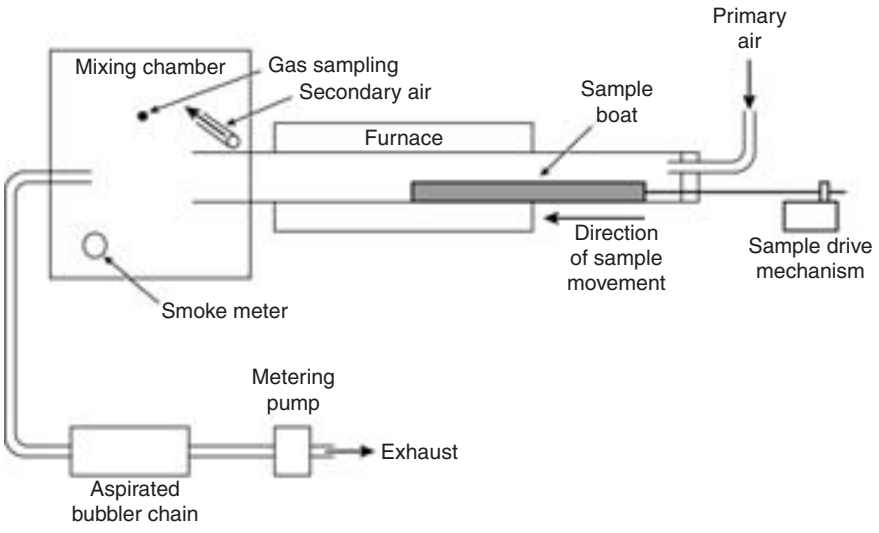

FIGURE 6.2.6 Schematic of the ISO/TS 19700 Tube Furnace (Source: National Institute of Standards and Technology)

A fire simultaneously generates gases, heat, and aerosols. Each of these three can lead to a state in which a person cannot effect his or her own escape, which is the definition of incapacitation. Typically, one estimates an independent ASET value for flames, heat, or smoke.* The limiting hazard is the effluent component that leads to the shortest value of ASET.

The following sections summarize the consensus of the assigned experts to ISO TC 92/SC 3 regarding the best representation of incapacitating levels of these three threats. Additional information may be found in ISO 13571.[46]

Response of People to Fire Gases

The modeling of this component of toxic hazard assessment can take either of two forms, depending on the nature of available input data. [80] In each case, a person moves from a location at the time of ignition to a final location (which may be a site of safety or a site of incapacitation), passing through a time-varying field of combustion products. In some simplified calculations, the person remains in a fixed location. The tenability of various locations is then examined as a function of time following ignition of the fire. There are very few data on exposures of an hour or more. Thus, using the following information for estimation of incapacitation or lethality due to long exposures to very low levels of heat and smoke is not advised.

Toxic Gas Model

The toxic gas model is most useful in considering fires where the time varying concentrations of the individual fire gases can be simulated using a fire growth and effluent spread model, such as the Fire Dynamics Simulator (FDS).[81†] The effects of asphyxiant toxicants and sensory/upper respiratory irritants are considered separately. This is because effects due to asphyxiants are related to their accumulated exposure dose (concentration × time), whereas the initial effects due to sensory/upper respiratory irritants are related largely to their concentration. Thus, the model also requires as input the exposure dose for each asphyxiant and concentration for each irritant that would be expected to cause incapacitation. These latter values are obtained from exposure of laboratory animals, with the results then being extrapolated to people. ISO 13571 contains consensus estimates of the incapacitating values and two equations, one for the effects of asphyxiant gases and one for the effects of irritant gases.

The modeling of the asphyxiant gases involves the same FED concept used to calculate LC_{50} values from analytical data. As before, incremental exposure doses of each gas are accumulated over time, with the incremental time interval being at the discretion of the modeler. However, rather than determining the accumulated FED by integration over 30 minutes, here the exposure doses of the gases are accumulated until the time at which a chosen FED criterion is reached.[46] For example, the time required to reach FED = 1 can be defined as the most frequently expected time for incapacitation to occur. ISO 13571 indicates lower FED criteria could provide safety for a larger fraction of the population at large, as well as for the subpopulations that are more sensitive to fire smoke.[46]

The FED equation for incapacitation due to asphyxiants is

$$\text{FED} = \sum_{t_1}^{t_2} \frac{[\text{CO}]}{35{,}000\ \mu\text{L/L} \cdot \text{min}} \Delta t + \sum_{t_1}^{t_2} \frac{\exp\left([\text{HCN}]/43\right)}{220\ \text{min}} \Delta t \qquad (8)$$

where CO and HCN volume fractions are in µL/L. Equation 8 is derived from actual incapacitation experiments using nonhuman primates.[23,41] It is most applicable when oxygen volume fractions are not lower than 0.13, and CO_2 volume fractions do not exceed 0.02.

The sensory/upper respiratory irritant component of toxic hazard is addressed in a somewhat analogous manner, with the exception that instantaneous concentrations, rather than accumulated doses, are used. For irritants, the time at which the total fractional effective concentration (FEC) becomes equal to 1 is the time at which the average person will become incapacitated.

A generic equation for incapacitation due to sensory/upper respiratory irritants is

$$\text{FEC} = \frac{f_{\text{HCl}}}{F_{\text{HCl}}} + \frac{f_{\text{HBr}}}{F_{\text{HBr}}} + \frac{f_{\text{HF}}}{F_{\text{HF}}} + \frac{f_{\text{SO}_2}}{F_{\text{SO}_2}} + \frac{f_{\text{NO}_2}}{F_{\text{NO}_2}} + \frac{f_{\text{acrolein}}}{F_{\text{acrolein}}} + \frac{f_{\text{formaldehyde}}}{F_{\text{formaldehyde}}} + 3\frac{f_{\text{irritant}}}{F_{\text{irritant}}} \qquad (9)$$

where irritant volume fractions are in µL/L. Consensus values of the denominator constants, *F,* were given in the prior section of this chapter.

Mass Loss Model

For many combustibles, there are no data and no predictive capability for the yields of the toxic gases as a function of time. However, if an LC_{50} or an IC_{50} value has been measured, a simulation of toxic hazard is still possible. Rather than generating individual gases and then distributing them throughout the building, this model distributes a single "gas," the combusted mass from the burning fuels. The basic FED concept is then employed, giving Equation 10.[46]

$$\text{FED} = \sum_{i=1}^{n} \sum_{t_1}^{t_2} \frac{\Delta m}{V(Ct_i)} \Delta t \qquad (10)$$

where

Δm = Average accumulated mass loss (g) over the time increment, Δt

V = Volume (m^3) into which fire effluents are dispersed

Δt = Time increment (min)

(Ct_i) = ½$(LCt)_i$ in $g \cdot m^{-3} \cdot min$ as determined from test methods (e.g., NFPA 269)

*Although it is likely that the three components of the fire effluent act in combination to retard the escape process, there are very few data on which to base the quantification of the interactions. Thus, for example, it is not known whether or how elevated temperature affects a person's ability to find his or her way through dense smoke.

†FDS, as well as all current "fire" models, does not contain the chemistry to predict the generation rates of fire gases or aerosols. The yields of these species are input parameters, and the computational model distributes the species around the building.

As with the toxic gas model, the time required to reach FED = 1 can be defined as the most frequently expected time for incapacitation to occur for the person of median susceptibility to fire smoke. The mass loss model represents a considerable simplification for assessment of the life-threatening effects of combustion atmospheres:

- It combines the effects of irritant and asphyxiant gases. Although there are data to indicate the additive effect of HCl and CO on the lethality for rats, there are no published data to verify this (or any other mode of combination) for people.
- It also presumes that the two types of gases stay in the same proportion to each other as they spread away from the fire. In this sense, the mass loss model is conservative, because the acid gases, for instance, are likely to stick to surfaces. Their concentrations thus diminish relative to those of the narcotic gases as one gets farther from the fire.

Further Simplification

An even further simplification employs a "generic" LCt_{50} value for lethal toxic potency when combustible fuel in a fire consists of a mixture of materials and products that are unidentified as to their nature and relative quantity. Suggested "generic" LCt_{50} values are 900 g/m^3·min for well-ventilated, preflashover fires and 450 g/m^3·min for vitiated, postflashover fires.[46] For incapacitation, values of (Ct_i) in Equation 8 then become 450 g/m^3·min for well-ventilated, preflashover fires and 220 g/m^3·min for vitiated, postflashover fires. It is cautioned that these "generic" LCt_{50} values represent only an approximation and their use should be subject to expert toxicological and engineering judgment.

Whereas compiled data of laboratory determination of LC_{50} values have a mean value of about 30 g/m^3 for well-ventilated combustion, the measured values range from about 5 to 60 g/m^3.[55] Thus, there are some materials whose smoke is over five times as potent as the average material. Fortunately, flaming fires of toxicological importance generally involve a mixture of materials, and it is infrequent that such large fires would be dominated by a single product whose smoke is of very high toxicity. Nonetheless, the person performing the hazard or risk analysis should be aware of the presence of such materials.

Variability of Human Responses to Fire Gases

The variability of the responses of people to the toxicological insults of fires is best represented by a statistical distribution that takes into account their varying susceptibilities. The overall human population contains a number of subpopulations that exhibit a greater than average sensitivity to fire gas toxicants. The largest of such subpopulations are the very young, the elderly, and those who suffer from compromised respiratory systems (e.g., asthmatics). Infants and young children are particularly susceptible to asphyxiant toxicants due to a greater volume of air inhaled per minute relative to their body weight. The elderly, particularly those with compromised cardiovascular systems, are also especially susceptible to asphyxiant toxicants. Asthmatics, along with sufferers of other lung conditions such as chronic bronchitis and reactive airways dysfunction syndrome, are particularly susceptible to bronchoconstriction from even brief exposure to low concentrations of irritants, with collapse and sometimes even death resulting. To provide a degree of protection to these more vulnerable subpopulations, safe levels for exposure of the human population to fire gas toxicants must always be significantly lower than those that might cause incapacitation or other adverse effects with healthy young adults.

According to the methodology described, FED and/or FEC values of 1.0 are associated with sublethal effects that would incapacitate persons of average susceptibility. In the absence of information to the contrary, a log-normal distribution of human responses is a reasonable choice, with FED and/or FEC values of 1.0 corresponding to the median value of the distribution. (Half the population would be more susceptible to an insult and half would be less susceptible.) Statistics then show that at FED and/or FEC criteria of 0.3, 11.4 percent of the population would be susceptible to less severe exposures (lower than 0.3) and, therefore, be statistically subject to incapacitation.[82]

Lower criteria would reduce that portion of the population. These would be appropriate for occupancies in which the people are expected to be more susceptible to heat and smoke or for whom escape is more difficult and thus might take longer. Examples of such occupancies are hospitals and schools for very young children. Note, however, that there is no criterion so low as to be statistically safe for all people. For proper balance between the effects of narcotic and irritant gases, the FEC and FED threshold criteria should be equal.

A consequence of the statistical distribution of human responses resulting from exposure of people to smoke atmospheres is that the distributions for two such responses, such as incapacitation and death, may overlap. This gives rise to a probability that some may die without others even being incapacitated. It is known that this occurs in real fires.

Extrapolation of Rodent Data to Humans

The propensity for smoke to have the same effects on humans in fires can only be inferred to the extent that the rat or mouse can be correlated with humans as a biological system. As a result of comparisons of rodent data with limited human and nonhuman primate data, the use of the rat as an acceptable model for human exposure, at least for the asphyxiant gases, has received general endorsement among smoke toxicologists.[54] The 30 minute exposure time for animals in laboratory smoke toxicity tests is considered by some to be rather long compared to most human exposures to smoke in fires. Traditional extrapolation of toxic potency test data for shorter exposures has presumed that the product of lethal concentration and exposure time is a constant.

A recent publication[83] provides an estimation method for relating the normal rat lethality data to incapacitation values for smoke-sensitive people:

- For materials and products that do not generate strong acid gases, assume that CO (as a surrogate for asphyxiants) is the primary toxicant and use one-fourth the 30 minute rat LC_{50} as the 5 minute human IC_{sens}.
- For materials and products that do generate strong acid gases, narcotic gases still generally account for the majority

of the combined incapacitating effect of narcotic and irritant gases. Based on the relative generation rates of CO and HCl cited above, one could use one-fifth of the 30 minute rat LC_{50} as the 5 minute human IC_{sens}.

- Because the narcotic component dominates the IC_{sens} values, the use of C^2t as a time scaling formula is preferred.

Gann[83] estimates that, for an unknown mixture of combustibles, a generic value for the concentration of smoke that would incapacitate a rat of average sensitivity in 30 minutes would be 30 g/m^3 ± 20 g/m^3 for a well-ventilated flaming fire and 15 g/m^3 ± 3 g/m^3 for a postflashover fire. Incorporating the above guidance leads to corresponding values for the concentration of smoke that would incapacitate smoke-sensitive people in 5 minutes: 6 g/m^3 for a well-ventilated fire and 3 g/m^3 for an underventilated postflashover fire. The user of these values needs to be mindful of three key factors:

1. There is a wide range of smoke toxicity values reported for various materials. Some of these have significantly higher or lower values than these generic values.
2. These generic values are estimated with significant assumptions in their derivations. An estimated uncertainty is about a factor of two.
3. People involved in fires are often excited and physically active. Both of these can increase the intake of the smoke-laden air and increase its toxic potency. At present, there is no quantitative literature on these effects or any way to apply them to the population as a whole.

Response of People to Heat

The burning of most materials is an exothermic chemical oxidation process. Enthalpy from the process is evolved as heat, which possesses both convective (hot gases) and radiative components, each measured as a heat flux (kW/m^2).

Heat produced from a fire presents significant physical danger to humans in three basic ways: burns to the skin, hyperthermia or heat stroke, and respiratory tract burns. Before skin can absorb sufficient heat to raise its surface temperature, the body's heat-dissipating capabilities must be defeated. The body dissipates heat by evaporative cooling (perspiration) and by circulation of blood. If the total heat energy reacting with the body surpasses the capability of the physiological defense processes to compensate, a series of events can occur, ranging from minor injury to death. Up to a critical exposure, one can reasonably tolerate excess heat, but above that exposure, tolerance decreases exponentially.

For radiant heat, there is a threshold radiant flux below which significant heating of the skin is prevented, but above which quite rapid heating occurs. The tenability limit for exposure of skin to radiant heat is approximately 2.5 kW/m^2, below which exposure can be tolerated for 30 minutes or longer without significant consequences.[23,46] Above this threshold, the time to burning of skin decreases very rapidly to about 20 seconds and less. Clothing offers a degree of protection and increases tolerance times.

Skin tissue burns commonly are classified as first-, second-, or third-degree. First-degree burns involve only the outer layer of the skin and are characterized by abnormal redness, pain, and sometimes a small accumulation of fluid underneath the outer layer. Second-degree burns penetrate more deeply into the skin. The burned area is moist and pink, the skin blisters, and there is usually a considerable amount of subcutaneous fluid accumulation. Third-degree burns usually are dry, charred, or pearly white. If a large percentage of the body skin tissue has suffered third-degree burns, postexposure consequences may be extremely critical, often leading to death. A relationship for time (min) to the second-degree burning of skin due to radiant flux, q (kW/m^2), is shown in Equation 11.[84]

$$t_{I,rad} = 6.9q^{-1.56} \tag{11}$$

The effects of exposure to convective heat are also a strong inverse exponential function of temperature. An empirical relationship between temperature and the time to incapacitation is shown in Equation 12.[85]

$$t_{I,conv} = 4.1 \times 10^8\, T^{-3.61} \tag{12}$$

where $t_{I,conv}$ is the time (min) to thermal collapse and T (°C) is the temperature at the skin surface.

Thermal tolerance data for unprotected skin of humans suggest a limit of about 248°F (120°C) for convected heat, above which considerable pain is quickly incurred along with the production of burns within a few minutes or less.[23] Depending on the length of exposure, convective heat below this temperature may still result in hyperthermia. Hyperthermia occurs if the body absorbs heat faster than it can be dissipated by evaporation of surface moisture and outward radiation. The entire body temperature is thereby elevated sufficiently above normal to cause damage to the central nervous system and, possibly, death.

Thermal burns to the respiratory tract from inhalation of air containing less than 10 percent by volume of water vapor do not occur in the absence of burns to the skin or face. Thus, tenability limits with regard to skin burns are normally lower than for burns to the respiratory tract.

Moisture can be present in a fire environment as the result of natural humidity, from the combustion itself, and from the application of water for extinguishment. The effects of exposure to heated air are greatly exacerbated by the presence of moisture. With higher moisture content, transfer of heat energy is more efficient and the body is less able to rid itself of the heat burden. If excessive heat is conducted rapidly to the lungs, a serious decline in blood pressure may result, along with capillary blood vessel collapse leading to circulatory failure. Severe heat may also cause fluid buildup in the lungs.

In fire tests conducted by the National Research Council of Canada, 300°F (149°C) was taken as the maximum survivable breathing air temperature.[86] A temperature this high can be endured for only a short period and not at all in the presence of moisture. The city of Los Angeles selected 150°F (66°C) at 1.5 m above the floor as the design temperature beyond which teachers and children could not be expected to enter a corridor from a relatively cool room.[87] This selection assumed exposure to dry air and only for the brief period of time necessary to reach exits.

Response of People to Visible Smoke

In addition to fire gases, smoke also consists of particulate matter, formed from the burning of most materials under the conditions of incomplete combustion, and suspended liquid droplets known as aerosols. Since the average size of the particulates and aerosols is about the same as the wavelength of visible light, light is scattered and vision through smoke can be obscured. Petroleum-derived materials, especially those from aromatic hydrocarbons, are particularly prone to the formation of dark, sooty smoke. There is, however, no established relationship between the color of the smoke and the toxicity of fire gases that may be present.

Since smoke obscures the passage of light, visibility to exits may be hampered, impairing escape from a fire. The development of quantities of smoke sufficient to impair egress can be very rapid and usually is the first hazard to occur in a fire. As evidenced in nearly every one of the Los Angeles school fire tests, smoke in the corridors arising from fires in the basement reached untenable levels before temperatures attained hazardous condition.[87] Smoke was therefore the principal hazard. Although smoke frequently provides an early warning of fire, it also limits visibility because of its blinding and irritating effects, slowing escape.

Obscuration of vision due to smoke is related to its concentration and is usually expressed as optical density per meter, OD (m^{-1}). Visibility is, then, the reciprocal of the OD. People's response to obscuration of vision and its detrimental effects on the speed of movement and way-finding efficiency is highly variable. Visibility requirements for escape depend to a large extent on the size of an enclosure and occupants' familiarity with escape routes. Suggested OD limits for impairment of egress have ranged from 0.5 m^{-1} (2 m visibility),[88] for occupants of small rooms who are familiar with escape routes, down to about 0.065 m^{-1} (15 m visibility),[89] for large enclosures in which occupants are unfamiliar with their surroundings.

For visible smoke, the equivalent of toxicological incapacitation for fire gases is an inability to orient oneself with one's surroundings. This is the equivalent to not being able to see one's hand in front of one's face. ISO 13571 estimates that this occurs when a person is confronted with a fuel mass loss concentration of 20 g/m^3 for well-ventilated fires and 10 g/m^3 for underventilated fires.[46] This is based on a minimum detectible contrast of 0.02[90] for a distance of 0.5 m, published smoke yields,[91,92] and a generic value of the mass specific extinction coefficient of the smoke[91] of 10 m^2/g. At these high smoke densities, the presence of light-reflecting or light-emitting exit signs does not change the incapacitation criterion significantly. The equivalent smoke optical density is 1.7 m^{-1}.

The analog to people who are sensitive to the inhalation of fire gases is people who require a higher degree of contrast to discern an object against a background. If one intended to provide the same additional degree of protection as with, for example, the FED value of 0.3, the incapacitating concentrations of smoke would be 15 g/m^3 for well-ventilated fires and 7 g/m^3 for underventilated fires. This reflects the logarithmic dependence on the capacity for visual perception.

Smoke particulates and aerosols also can be harmful when inhaled, and long exposure may cause damage to the respiratory system. Also, smoke particulates often are of a sufficiently small size that enable them to be inhaled deeply into the lungs, where adsorbed toxicants may produce damage to the respiratory system. These effects have not been sufficiently studied to enable a full understanding of their consequences.

DEVELOPMENT OF TOXIC HAZARDS IN FULL-SCALE FIRES

Importance of Full-Scale Experiments

While lab-scale tests and fire models can provide valuable insight into ignition and fire growth, full-scale experiments are still necessary to understand and validate critical fire phenomena. Full-scale fire reconstructions can document many important interactions within a fire environment not captured by small-scale tests or fire models. These interactions can include how fuel density can impact fire growth, how the thermal feedback from a hot smoke layer may increase the pyrolysis of the fuel, how specific fuels may generate toxic gases in vitiated smoke layers, or how the lack of ventilation can limit fire development. Full-scale experiments or reconstructions are often used to better understand the development of toxic hazards in specific fire incidents, especially scenarios with unusual conditions. An example of an incident that exhibited some unusual conditions, including rapid fire growth, quick smoke layer development, and multiple toxic gas species, was a fire that occurred on February 20, 2003, in the Station Nightclub in West Warwick, Rhode Island.

Reconstruction of Station Nightclub Fire

Full-scale experiments were conducted at NIST to reconstruct the fire and better understand how the toxic hazard may have developed that night in the Station Nightclub.[93] During a band performance at the nightclub, pyrotechnics ignited polyurethane foam insulation that lined the walls and ceiling of the band platform. The fire spread quickly along the walls and ceiling area over the dance floor. Smoke was visible in the exit doorways in a little more than 1 minute, and flames were observed breaking through a portion of the roof in less than 5 minutes. Egress from the nightclub, which was not equipped with sprinklers, was hampered by crowding at the main entrance to the building. One hundred people lost their lives in the fire.

In order to characterize the fire growth and spread in the early stage of the fire, two real-scale mockup experiments reconstructed approximately 20 percent of the nightclub with polyurethane foam covered walls, a drummer's alcove, a raised platform, carpeting, and wood paneling. Figure 6.2.7 shows the dimensions of the mock-up floor plan and Figure 6.2.8 compares the test compartment to a floor plan of the nightclub. Full-scale data, including gas temperatures, heat fluxes, and gas concentrations, provided insight as to how quickly the toxic hazards, in particular, the generation of CO and HCN, can develop during the early stages of a fire.

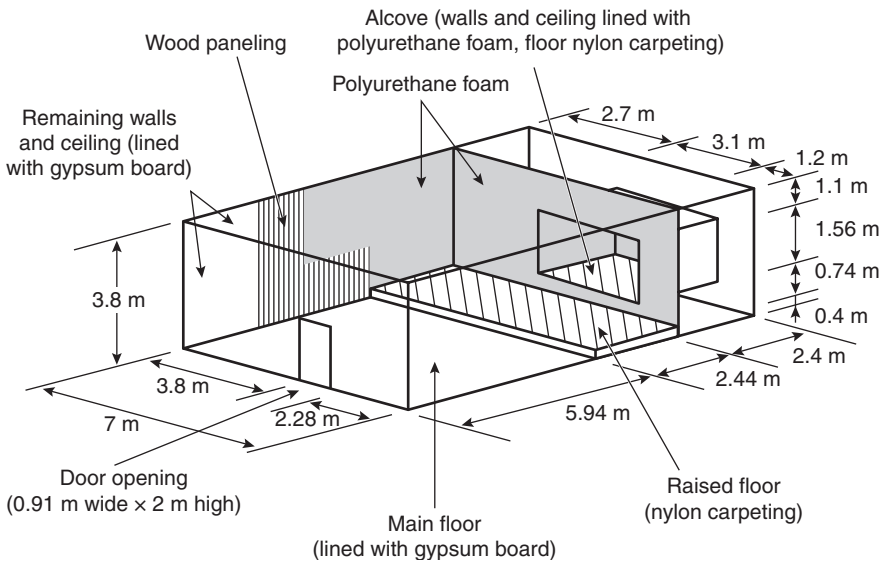

FIGURE 6.2.7 Isometric View of Test Compartment and Fuels (Source: National Institute of Standards and Technology)

A physical mock-up was created at the NIST Large Fire Laboratory with overall floor dimensions of the test room of 10.8 m by 7.0 m, and a ceiling height of 3.8 m. A single opening, 0.91 m wide and 2.0 m high was located in the wall opposite the alcove. The test area was constructed with a structural steel frame, lined with two layers of 12 mm thick calcium silicate board, covered with 12 mm thick gypsum board. The walls of the alcove and the raised floor area had 5.2 mm thick plywood paneling installed over the gypsum board. The paneling had a flame spread index of 200 or less, as tested by ASTM E84, *Stan-*

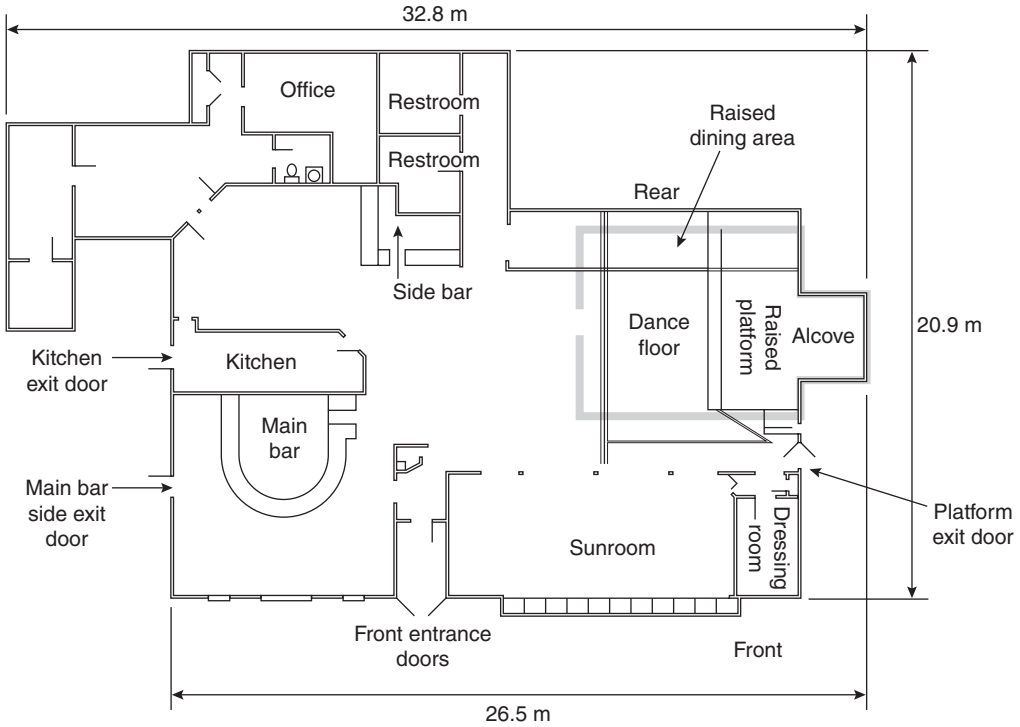

FIGURE 6.2.8 Full-Scale Mock-Up Floor Plan Versus Station Nightclub Floor Plan (Source: National Institute of Standards and Technology)

dard Test Method for Surface Burning Characteristics of Building Materials,[94] according to the manufacturer. The plywood paneling extended 3.6 m from the raised floor along the rear wall of the test area. The rear wall was adjacent to the platform on the right as one stands on the platform facing the audience (stage-right). A non-fire-retardant, ether-based polyurethane foam was glued over the paneling in the alcove and along the walls on both sides of the alcove opening and to the rear wall. The flat side of the foam was mounted next to the plywood and the convoluted side was left exposed. The foam was installed from the top of the wall down to 1.35 m above the floor. It was also applied to the ceiling of the alcove and extended for 2.4 m from the raised floor along the rear wall.

The test room (Figure 6.2.9) was equipped with thermocouples, video cameras, heat flux gauges, bidirectional probes, and gas extraction probes to measure CO, CO_2, O_2, and HCN. In addition, fixed temperature and rate-of-rise heat detectors were installed, as were sprinklers. Data for 194 channels were recorded at 1 second intervals. Ignition of the foam was initiated simultaneously using electric matches at two locations on the outer corners of the alcove, 1.66 m above the raised floor area. The fire gases that emerged from the open door on the end of the test room were captured in the hood of the oxygen depletion calorimeter. The succession of video frames in Figure 6.2.10 show how rapidly the fire spreads during the first 90 seconds.

Data were collected at several locations as indicated in Figure 6.2.9. Selected data (collected at Location D, on the centerline of the doorway and 6 m from the front of the drummer's alcove) including gas concentrations (O_2, CO, CO_2, and HCN), gas temperatures, and heat fluxes, are presented in Figures 6.2.11 and 6.2.12. As can be seen in Figure 6.2.10, the fire was ignited at two locations on either side of the drummer's alcove. The fire spread up the polyurethane foam wall lining on both sides of the alcove and within 60 seconds the alcove was fully involved. The smoke layer continued to descend quickly and, within 90 seconds, the layer was near the floor of the mock-up compartment.

In less than 90 seconds, conditions at Location D and 1.4 m above the floor included gas temperatures exceeding 750°F (400°C), total heat flux in excess of 30 kW/m^2, O_2 volume fractions below 0.05, and HCN and CO volume fractions greater than 0.0015 and 0.03, respectively. The tenability of the compartment deteriorated quickly due to high temperature, high heat flux, O_2 depletion, and toxic concentrations of HCN and CO. Exceeding the tenability limit does not imply that any or all occupants who are present in that environment will succumb due to a particular limit exceeded. The length of time exposed, the rate of change of the environmental conditions, the individual's starting location, his/her breathing rate, and the susceptibility of the individual all play a role. Occupants in this compartment would have likely have had less than 1½ minutes to escape safely from this rapidly growing fire.

A second mock-up experiment was also conducted and was a duplicate of the first except that automatic water sprinklers were installed and charged. Sprinkler heads began to activate in less than 30 seconds and quickly controlled the fire growth. Throughout the second experiment, conditions in the compartment at

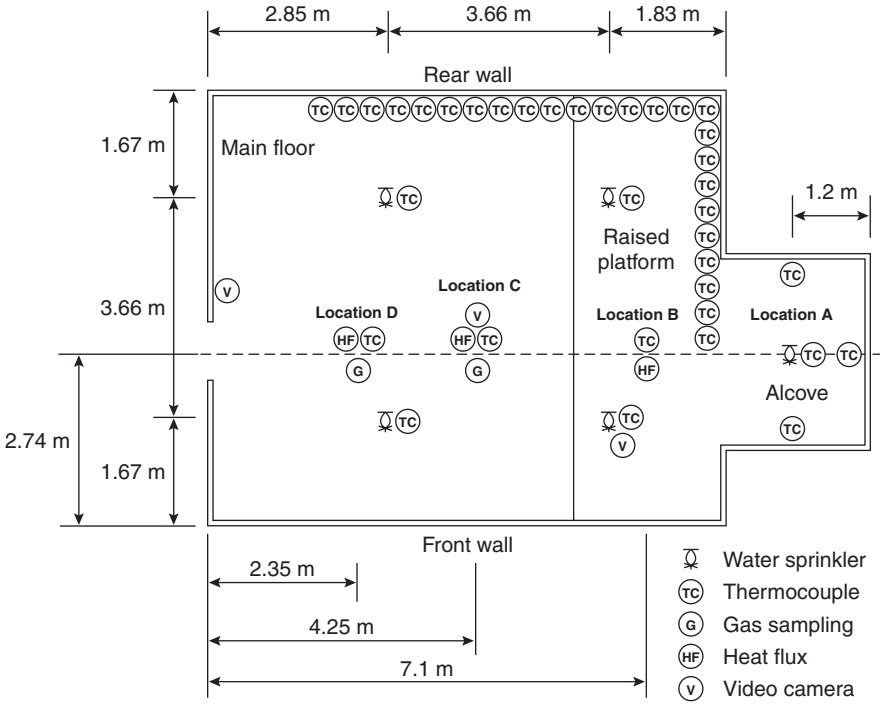

FIGURE 6.2.9 Schematic Floor Plan with Instrumentation Positions (Source: National Institute of Standards and Technology)

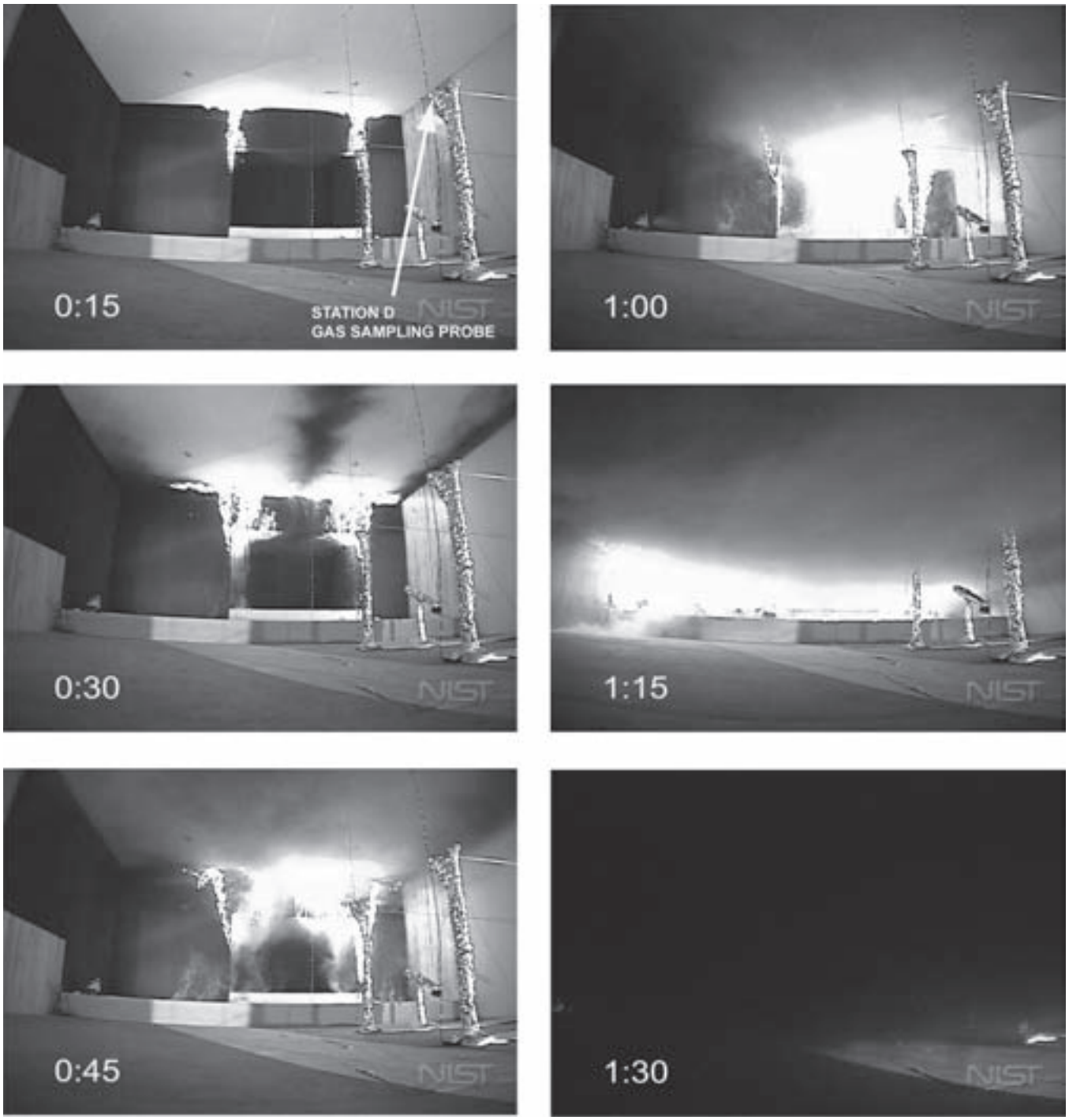

FIGURE 6.2.10 Still Frames Taken from Video of Full-Scale Mock-Up Experiments. Time after ignition is indicated in lower left of each frame. (Source: National Institute of Standards and Technology)

Location D remained tenable in terms of temperature, heat flux, O_2 depletion, and concentrations of HCN and CO.

SUMMARY

All combustibles produce heat and smoke that, in sufficiently high concentration, may be hazardous to life safety. Incapacitation can result from exposure to the asphyxiant gases, irritant gases, and heat. Irritant gases and visible smoke can reduce a person's ability to find and negotiate escape routes efficiently. Survivors of the acute effects of exposure during a fire may also experience serious postexposure health effects. Responses of people to the effects of exposure to the combustion products of fire vary considerably. This is due both to the degree of physi-

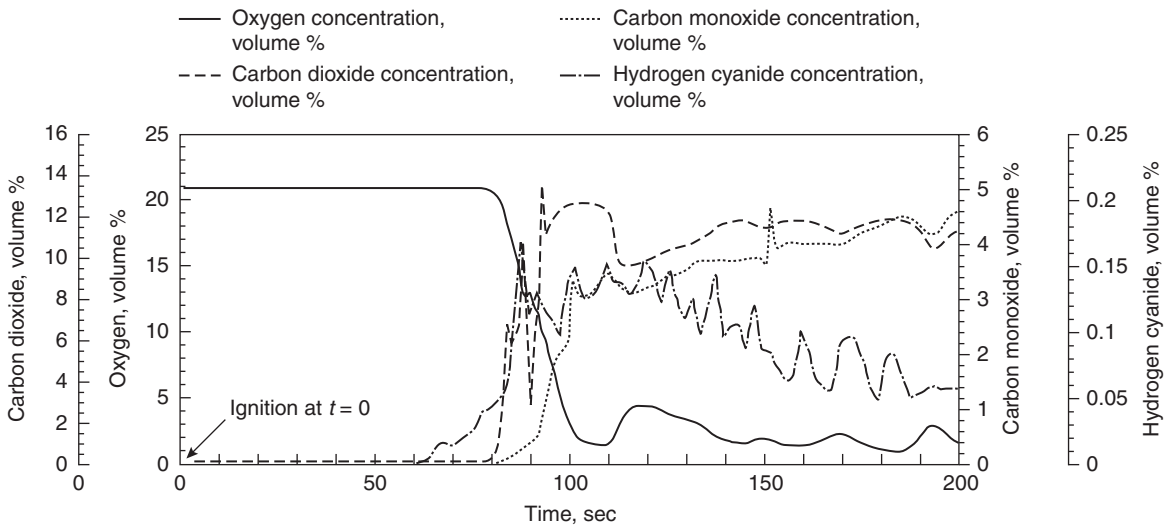

FIGURE 6.2.11 Gas Concentrations Measured at Location D During First 200 Seconds of Unsprinklered Mock-Up Experiment. Gas sampling probe was located 1.4 m above the floor. Ignition occurred at $t = 0$. (Source: National Institute of Standards and Technology)

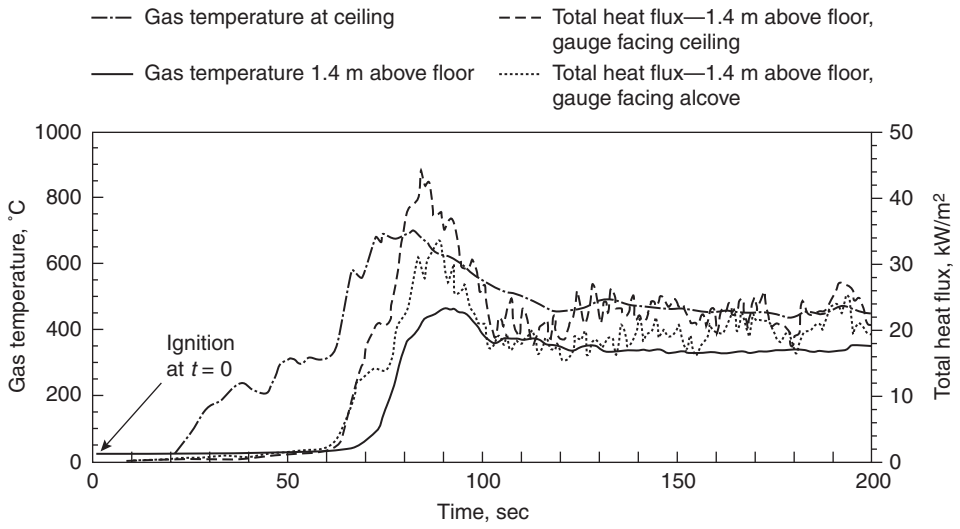

FIGURE 6.2.12 Gas Temperatures and Total Heat Fluxes Measured at Location D During First 200 Seconds of Unsprinklered Mock-Up Experiment. Ignition occurred at $t = 0$. (Source: National Institute of Standards and Technology)

cal activity during exposure and to the vulnerability of certain subpopulations. Techniques are available for estimating the fire environments that can led to incapacitation of building occupants. The understanding for estimating other sublethal effects and postexposure harm is not yet developed.

The testing of materials and products in the laboratory does not, in itself, address their toxic hazards when involved in fires. Numerous other factors, including their heat release and mass burning rates, contribution of other combustibles present, size and configuration of the enclosure, ventilation, smoke transport, the nature of the occupants, and occupant movement also affect toxic fire hazard. These factors must all be considered in concert.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on combustion products and their effects on life safety discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 269, *Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling*

NFPA 270, *Standard Test Method for Measurement of Smoke Obscuration Using a Conical Radiant Source in a Single Closed Chamber*

Reference

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Chapter 3

Concepts and Protocols of Fire Testing

Marcelo M. Hirschler

Chapter Contents

Background
Classification of Fire Tests
Fire Resistance Tests
Reaction-to-Fire Tests

Key Terms

cone calorimeter, design fire, fire load, fire resistance, fire test, flame spread, fuel load, heat release, ignitability, ignition temperature, lateral ignition and flame spread test (LIFT), oxygen index, room-corner test, smoke release, Steiner tunnel test, time-temperature curve

The traditional approach to fire safety has been the use of prescriptive measures based on fire tests that give pass/fail or categorized results. If someone designs a structure, that person is told to follow certain rules, such as the test criteria a material or product must meet to be considered acceptable and the limitations on physical dimensions and often on chemical composition with which the material or product must comply. Whereas the use of such materials coupled with proper installation is deemed to create a building safe from the effects of fire, there is no explicit requirement to create a design that is safe in case of fire. The type of requirements represented by such prescriptive rules, present either in codes or in specifications, limit material choices to certain applications and work to ensure proper fire safety in most circumstances. There may be extraordinary circumstances, however, in which safety cannot be guaranteed. Such traditional prescriptive requirements involve the implicit assumption that the prescribed design is fire safe, which is often the case. The prescriptive measures, in turn, imply a level of fire safety deemed acceptable by the authority having jurisdiction (AHJ), based on the conclusions of the code writers, which is sometimes, but not always, quantified in numerical terms. There are two alternative ways this can be applied: (1) by using fire tests that produce results that can be used as input for fire modeling and fire hazard assessment and (2) by requiring the use of fire hazard assessment for any fire safety approach, while ensuring that this is done without ignoring other solutions involving active or passive fire protection.

Codes tend to address those construction and material products that (1) have the largest size or (2) have traditionally been shown to represent a specific problem. Thus, a building code will regulate type of construction, exterior walls and roofs, exterior veneer, interior finish, insulation, and glazing. Other codes will regulate hazardous materials and some furnishings and contents, such as upholstered furniture, mattresses, curtains and drapes, and "decorations of an explosive, or highly flammable character" (as stated in NFPA *101®, Life Safety Code®*). This means that there is no guarantee that all products that could have a large impact on fire safety are controlled. One reason for this is that individual code changes rarely involve an effort to consider the overall picture, as this tends to happen only when codes are first designed. Committees reviewing such changes will, however, normally consider how such changes can affect the "bigger picture." Of course, the larger items tend to have the greatest potential contribution to fire safety. However, smaller items may present a severe problem if they represent a large source of effective heat of combustion and thus have the potential to release heat very rapidly. This is the second, and principal, reason that some potentially dangerous products might be ignored: traditional tests cannot assess heat release and cannot produce test results in units that can be used for fire safety engineering assessments. This is a key problem, because heat release is a key property for fire safety when considering individual component and material properties:[1] the peak heat release rate is the intensity of a fire.

Regulations can call for improved fire safety via passive fire protection, through requirements for materials, products, and assemblies that exhibit better results in fire tests; via active fire protection, through requirements for sprinklers and smoke detection systems; or via a combination of the two, through construction modifications wherein differing fire test requirements are allowed when enhanced active fire protection systems are present.

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This chapter addresses the use of fire tests for assessing the fire performance of materials and products and also how to choose those that are more likely to be usable for fire safety engineering calculations and assessments of fire hazard and fire risk.

For related topics, see Section 2, Chapter 3, "Flammability Hazard of Materials"; Section 2, Chapter 4, "Dynamics of Compartment Fire Growth"; Section 2, Chapter 5, "Basics of Fire Containment"; Section 6, Chapter 1, "Fire Hazards of Materials"; Section 6, Chapter 2, "Combustion Products and Their Effects on Life Safety"; and Section 18, Chapter 2, "Interior Finish."

BACKGROUND

Changes in fire safety requirements often follow large fires. The Great Fire of London in 1666, the 1871 Chicago fire, and the 1906 San Francisco earthquake and fire destroyed large parts of great cities where wood construction was prevalent and societal fire protection was nonexistent. By the time of the Chicago fire, insurance companies started to see the potential for minimizing huge losses by means of prevention. Thus, organizations like the National Fire Protection Association (NFPA), the American Society for Testing and Materials (ASTM), and Underwriters Laboratories (UL) started, around the transition of the nineteenth century to the twentieth century, to develop recommendations for obtaining public fire safety, including standard fire tests. The most frequent way to change fire safety requirements has always been, and continues to be, public demand following fire incidents that result in numerous fire deaths or injuries and severe property damage. Thus, multiple fire fatalities occurring in a single large fire—for example, a hospital, hotel, school, or nursing home—can be expected to trigger some major changes in code requirements that will address the specific cause of that particular tragedy. However, such solutions often do not fully take into account the probability of such a fire occurring. Some of the changes to the codes, however, may address the specific event, but may also be equally effective in other fire events that may occur.

Not surprisingly, many advances in fire safety tend to be reactive rather than proactive and, in some cases, address a narrow rather than a comprehensive issue. Also, they tend to be prescriptive rather than flexible. All of this is important in setting the context for fire testing, a context that shapes the concepts and protocols, which in turn shape the specifics of test design and of the interpretation and usage of test results.

These tragedies usually represent a small fraction of overall structure fire fatalities but do, however, represent a significant portion of the fatalities for a specific occupancy. Even when the relatively inclusive NFPA definition of catastrophic fire (one that kills three or more people, or five or more people in a residential property) is used, such incidents almost invariably represent less than 10 percent of the overall structure fire fatalities (Table 6.3.1). This means over 90 percent of all fire deaths occur in fires that rarely merit headlines and may not even receive press coverage outside the area where they occur. For example, fires where at least 25 people die—fires serious enough to merit headlines across the country—are extremely rare. There were only five such incidents from 1991 to 2005, and they represented only 5 percent of overall structure fire fatali-

TABLE 6.3.1 Structure Fire Fatalities in the United States, Overall and in Catastrophic Fires

Year	*Total Civilian Fire Deaths in Structure Fires*	*Civilian Fire Deaths in Catastrophic Fires**	*Deaths in the Deadliest Fire*	*Percentage Civilian Structure Fire Deaths in Catastrophic Fires (%)*
1991	3765	252	25	6.7
1992	3940	145	11	3.7
1993	3980	269	47	6.8
1994	3590	235	9	6.5
1995	3985	320	168	8.0
1996	4220	159	9	3.8
1997	3510	181	10	5.2
1998	3420	171	11	5.0
1999	3040	172	7	5.7
2000	3535	118	8	3.3
2001	5671	2943	2451	51.9
2002	2775	111	8	4.0
2003	3385	254	100	7.5
2004	3305	115	10	3.5
2005	3105	98	15	3.2

*Catastrophic fires are residential structure fires in which five or more people die and other fires in which three or more people die. The following are the 1991–2005 structure fires in which at least 25 civilians died:
World Trade Center (2326), New York, NY, attack; Pentagon (125), Arlington, VA, attack, 2001
Murrah Federal Building (168), Oklahoma City, OK, 1995
Station Nightclub (100), West Warwick, RI, 2003
Branch Davidian dormitory (47), Waco, TX, 1993
Poultry processing plant (25), Hamlet, NC, 1991

Source: NFPA Fire Experience Survey and Fire Incident Data Organization.

ties, with most of those occurring in the September 11, 2001, terrorist attacks.

This way of defining fire safety priorities primarily by reacting to major incidents is not unique to the United States but can be seen in many (if not most) countries. In fact, the vast majority of fire fatalities in the United States and other countries occur in private homes and private vehicles, where the public tends to feel safest, the clamor for more fire safety is weakest, and fire safety requirements are minimal.

CLASSIFICATION OF FIRE TESTS

Fire tests have been developed to address almost every fire property, and those developed by NFPA, UL, ASTM International, and the International Organization for Standardization (ISO) are shown in the references at the back of the chapter. Fire tests typically relate to two types of fire properties: fire resistance and reaction to fire.

Fire resistance is associated with construction assemblies, such as structural members and fire barriers (walls, floors, columns, doors, windows) and with the protection of openings. Thus, fire resistance tests on these assemblies are concerned with preventing fire from penetrating from the compartment of fire origin through the assembly and into adjacent compartments.

Reaction-to-fire tests are concerned with the measurement of the fire properties of the material or product being tested that might cause damage. Materials in this type of test are developed to minimize or eliminate the release of heat, smoke, and combustion products, or minimize or prevent the spread of flame. Reaction-to-fire tests are thus usually associated with interior finish furnishings, contents, and consumer products. Fire safety engineering calculations concerned with the intensity of fires and the ease of escape from fires often use results of reaction-to-fire tests. Table 6.3.2 shows the test designations from NFPA and other fire test development organizations.

FIRE RESISTANCE TESTS

Fire resistance tests are based on the concept that structures are required to meet the protection and separation requirements of a code that describes the fire resistance ratings applicable to each construction element for each type of building. The fire resistance performance of construction members under fire exposure conditions is an issue of major importance in ensuring construction that is safe. The analysis of the code requirements is done on the basis of an assessment of the potential fire exposure as a function of the use of the structure, its contents, ease of escape, and other such factors.

Standard Time-Temperature Curve

The fire test most often used to assess fire resistance ratings in the United States is NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials,* or its corresponding equivalent procedures, ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials,* or UL 263, *Standard for Fire Tests of Building Construction and Materials.* Performance in these tests is the time, designated as the "fire resistance rating," during which the assembly "resists" the standard exposure before the first critical end point is observed. If a safety factor greater than that inherent in the test conditions is desired, a relevant increase needs to be made in the specified fire resistance rating. In the test, the construction element is exposed to a fire that becomes more severe with time, following a standard time-temperature curve (Figure 6.3.1).

It is important to note that a fire resistance rating applies to the entire assembly as tested and not to its individual components. For walls and partitions, the failure criterion is a temperature rise of 250°F (140°C) above the test specimen's initial temperature on the unexposed side, with a specified maximum temperature rise allowed for each individual thermocouple on the unexposed side. The time until the first occurrence of the critical temperature rise is measured on the unexposed side is the fire resistance rating. Figure 6.3.2 shows a wall assembly undergoing a fire resistance test. The assembly has just failed the test.

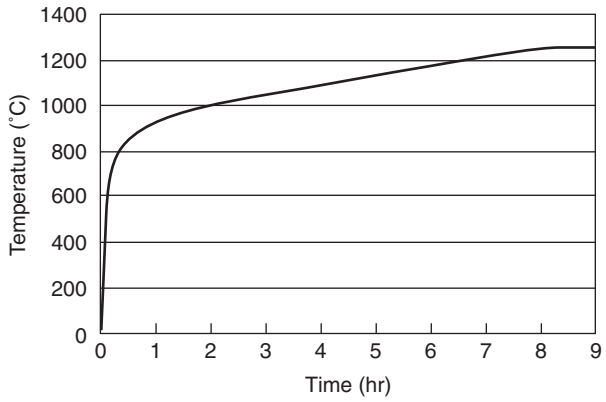

FIGURE 6.3.1 Standard Time-Temperature Curve

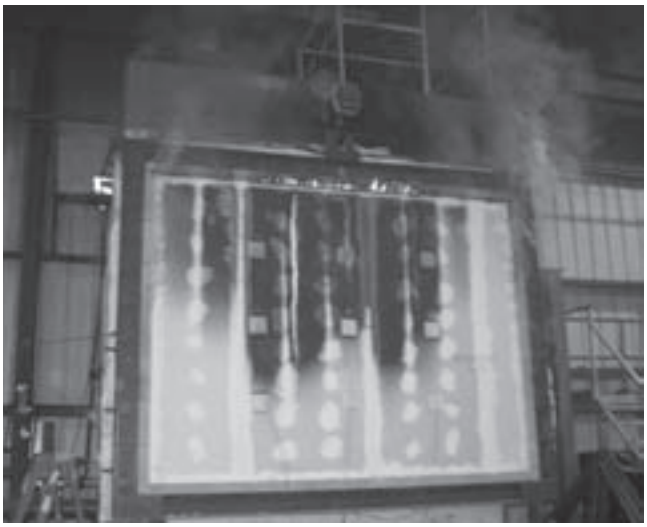

FIGURE 6.3.2 Wall Assembly Undergoing a Fire Resistance Test

TABLE 6.3.2 Equivalent or Similar Fire Test Standards from Different Organizations

Fire Test Standards	*NFPA*	*ASTM*	*UL*	*ISO*
Fire Resistance	251	E119	263	834[a]
	252	E2074 (replaced E152)	10B	3008[a]
	288	—	—	—
	257	E2010 (replaced E163)	9	3009[a]
	—	E814	1479[a]	—
	—	E1966	2079[a]	—
Exterior Fire Tests	256	E108	790	12468[a]
	268	—	—	—
	285	—	—	—
	—	—	—	13785
Ignitability	—	D1929	—	871
	—	—	—	5657
Steiner Tunnel Surface Flame Spread	255	E84	723	—
	262	—	910 (withdrawn)	—
Lateral Flame Spread	—	E162	—	—
	—	E1317, E1321	—	5658
Smoke Obscuration (Static)	258 (withdrawn)	E662	—	—
	270	E1995	—	5659-2
	—	—	—	5924
Floor Coverings	253	E648	—	9269
	—	D2859	—	—
Room-Corner Heat Release Tests	265	—	1715[a]	—
	286	—	—	—
	—	E2257	—	9705
Large-Scale Product Heat Release Tests	266 (withdrawn)	E1537	1056 (withdrawn)	—
	267 (withdrawn)	E1590	1895 (withdrawn)	—
	274	—	—	—
	289 (draft[b])	—	—	—
	—	—	1975	—
	—	E1822	—	—
Heat and Smoke Release (Bench Scale and Intermediate Scale)	271	E1354	2360	5660
	263 (withdrawn)	E906	—	—
	272	E1474	—	—
	—	E1740	—	—
	—	D6113	—	—
	—	F1550	—	—
	—	E2102	—	13927, 17554
	287	E2058	—	—
	—	E1623	—	TR 14696
Potential Heat, Heat of Combustion, and Noncombustibility	259	—	—	—
	—	E136	—	1182[a]
	—	D5865	—	1716
Cigarette Ignition Tests	260	E1353	—	—
	261	E1352	—	—
	—	E2187	—	—
Smoke Toxicity	269	E1678	—	—
Smoke Corrosivity	—	D5485	—	11907-4
	—	—	—	11907-2
	—	—	—	11907-3
Fabric Flammability	701	D568 (withdrawn)	214 (withdrawn)	—
	705	—	—	—
Plastics Flammability	—	D2863	—	4589
	—	D635, D3801, D4804, D4986, D5048	94	9772, 9773, 12992

Note: This table contains NFPA and ASTM fire test standards that are technically equivalent and those fire test standards from UL and ISO that are similar, even if not technically equivalent.
[a]Tests are not technically equivalent to the NFPA or ASTM tests in columns 2 or 3.
[b]NFPA 289 is still under development.

For load-bearing structural elements, fire resistance tests also monitor the load-carrying capability of the test specimen during the test exposure. When required, the fire exposure is followed by application of a specified standard fire hose water stream. It is also critical to point out that these fire resistance ratings are somewhat arbitrary and the fact that an assembly has been tested to give a certain fire resistance rating does not mean that it will fail in a fire after that amount of time; rather, the fire resistance rating represents a relative representation of expected fire resistance performance of the rated assembly. In other words, fire exposure intensity that is less than the prescribed test will provide a longer fire resistance duration. Conversely, a fire intensity greater than that called for in the test may result in lower fire resistance duration.

If penetrations in a building element assembly, such as those through which pipes, wires, or cables pass from one compartment to another, are unprotected, they will generally negate the barrier qualities of the assembly and will lead to rapid spread of fire to the other compartment. This can be solved, however, if the penetrations are protected by filling the voids with fire-rated materials, typically known as firestop materials. In order to ensure that the firestop material is adequate, it will have to be tested to the same time-temperature curve as the building element it is protecting and that is done by testing to ASTM E814, *Test Method for Fire Tests of Through-Penetration Fire Stops*. Fire resistance tests using the same time-temperature curve are used for testing doors (NFPA 252, *Standard Methods of Fire Tests of Door Assemblies*), windows (NFPA 257, *Standard on Fire Test for Window and Glass Block Assemblies*), floor doors (NFPA 288, *Standard Methods of Fire Tests of Floor Fire Door Assemblies Installed Horizontally in Fire Resistance–Rated Floor Systems*), and joints (ASTM E1966, *Test Method for Fire-Resistive Joint Systems*).

The standard time-temperature curve used in NFPA 251 and ASTM E119 is considered to represent a severe building fire.[2] The curve was adopted in 1918 as a result of several conferences by eleven technical organizations, including testing laboratories, insurance underwriters, fire protection associations, and technical societies.[3,4]

Other Time-Temperature Curves

Internationally, a different time-temperature curve was initially developed in the United Kingdom and was eventually adopted by the ISO Technical Committee on Building Products, ISO TC92, as the fire resistance standard ISO 834, *Fire Resistance Tests*. The ISO 834 time-temperature curve is very similar to that in NFPA 251/ASTM E119, albeit not identical. Two other standard time-temperature curves exist that are significantly more severe than the one in NFPA 251/ASTM E119—namely, the curves in ASTM E1529, *Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies,* and UL 1709, *Standard for Rapid Rise Fire Tests of Protection Materials for Structural Steel,* which are similar to one another and intended for structures that must withstand the assault of a hydrocarbon fuel fire (e.g., overhead piping supports in petrochemical facilities).

A key consideration is that very few, if any, studies have been conducted on the precision of fire resistance testing, principally due to the complex and costly nature of conducting the tests. There is, thus, an inconsistency between what the codes require (where, for example, a 1-hour fire resistance rating may be called for and a material or assembly that fails the test after 59 minutes is not permitted to be used) and actual test results (where differences of a few minutes are to be expected).

Differences in test results can be due to variability in the fire test (precision), variability in the execution of the test instructions by the laboratory (part of the uncertainty), and variability in the test specimen (typical manufacturing variability). This actually means that materials that were tested many years ago using the test methods of that time, and for which compliance with certain test requirements has become accepted, do not need to perform as well as new materials, which must pass the current requirements of updated (and usually improved) editions of the same tests. This also means that "shopping" for the best test results can occur, as manufacturers can conduct the test several times (perhaps even in different laboratories) until the desired outcome is obtained and no further testing is needed. Efforts to address reproducibility and consistency in test outcomes within and between testing laboratories is an ongoing theme and topic of debate.

Concepts for Predicting Fire Resistance Rating of Construction Elements

Of course, the time temperature relationship represented by any standard curve cannot represent more than a single fire scenario. Data have been developed to evaluate the fire resistance performance of assemblies under other fire exposure conditions, ones that may be more representative of particular fire situations, that is, using different time-temperature curves to simulate a different fire scenarios.[3,5–13] Also, Harmathy[14] developed a series of 10 rules that can be used as concepts for predicting the fire resistance rating of construction elements, thereby extending the usefulness of test results. The rules can be paraphrased as follows (replacing the term "fire endurance" used by Harmathy by the current terminology, namely, "fire resistance"):

1. The "thermal" fire resistance of a construction consisting of a number of parallel layers is greater than the sum of the "thermal" fire resistance characteristics of the individual layers when exposed separately to fire.
2. The fire resistance of a construction does not decrease with the addition of further layers.
3. The fire resistance of constructions containing continuous air gaps or cavities is greater than the fire resistance of similar constructions of the same weight, but containing no air gaps or cavities.
4. The further an air gap or cavity is located from the exposed surface, the more beneficial is its effect on the fire resistance.
5. The fire resistance of a construction cannot be increased by increasing the thickness of a completely enclosed air layer.
6. Layers of materials of low thermal conductivity are better utilized on that side of the construction on which fire is more likely to happen.

7. The fire resistance of asymmetrical construction depends on which side is exposed to the test fire.
8. The presence of moisture, if it does not result in explosive spalling, is beneficial to fire resistance.
9. Load-supporting elements, such as beams, girders, and joists, yield higher fire resistance when subjected to fire resistance tests as parts of floor, roof, or ceiling assemblies than they would when tested separately.
10. The load-supporting elements (beams, girders, joists, etc.) of a floor, roof, or ceiling assembly can be replaced by such other load-supporting elements which, when tested separately, yield fire resistance not less than that of the assembly.

More important, however, is the concept that time-temperature curves should be based on design fires applicable to the fire scenario being investigated. Therefore, there is a tendency to move away from "one size fits all" fire resistance testing and toward specific fire resistance testing that takes into account the fire load (or the potential for release of heat due to the building products, furnishings, and contents present) and other issues representative of the fire scenario in question.

Developing Standardized Methodology

Two complementary activities are under way to develop standardized means of generating appropriate design fires. The Society of Fire Protection Engineers (SFPE) Task Group on Fire Exposures to Structural Elements has produced a guide, the *SFPE Engineering Guide to Fire Exposures to Structural Elements,*[15] intended to develop guidance on estimating fully developed fire heat transfer exposures for the purpose of performance-based analysis and design. This guide is intended to be developed into a standard by an SFPE committee so as to provide a standard methodology to predict thermal boundary conditions for fully-developed fires to a structure over time. The NFPA Technical Committee on Hazard and Risk of Contents and Furnishings is working on NFPA 557, *Standard Fire Loads for Structural Fire Protection Design,* which is intended to standardize the fire load portion of this issue.

Fuel Load and Fire Load Concepts

The original fuel load concept (at that time called "fire load") incorporated the premise that the duration of a fire is proportional to the mass of combustible material per unit floor area. It has long been believed that there is a relationship between the mass of combustible material and the duration of a fire; this was done on the basis of fire tests in structures incorporating a variety of materials. In its simplest terms, the fuel load theory states that 50 kg of combustible material per m^2 of floor area (roughly 10 lb per ft^2) will produce a fire of 1 hour duration.[16] That concept has now been superseded with increased understanding of material fire performance and overall fire testing and it is now clear that a greater number of factors are important, including the type of combustible materials, the distribution of the fuel load, fire scenario characteristics, such as geometry and ventilation in the fire compartment, and characteristics of the compartment walls, floors, and ceilings.

With that in mind, more modern concepts address fire load instead of fuel load. Although these terms are sometimes used interchangeably, the concepts used here are that fire load will refer to the energy density per unit area and fuel load will refer simply to the total mass of combustibles. With that in mind, it is possible to define *fire load* as "The heat energy of all combustibles available from the constituent materials of a certain fuel package, expressed in energy units (e.g., MJ)." For comparison, *fuel load* would then be defined as "the quantity of combustible contents of a building, space, or fire area, including interior finish and trim, expressed in mass units (e.g., kg)." The key difference between the two is that fire load takes into account the twin concepts that different combustible materials will have different heats of combustion (MJ/kg) and that the heat released in fires is usually not the total heat content of the materials burning. In other words, there is a difference between the theoretical (or gross) heat of combustion and the effective heat of combustion. It is the latter that should be considered in fire hazard analyses.

The analysis conducted by the National Institute of Standards and Technology (NIST) on the World Trade Center disaster of September 11, 2001, indicated that it is critical to use proper design fires for the assessment of appropriate structural fire protection, rather than rely exclusively on standardized fire tests.[17] NIST considered future research in areas of high priority, such as prevention of progressive collapse, fire resistance design and retrofit of structures, and fire-resistive coatings for structural steel. The recommendations stemming from the investigation may result in changes in the area of fire resistance testing and in code requirements for structural fire protection.

REACTION-TO-FIRE TESTS

The bulk of the fire testing currently being conducted addresses reaction-to-fire properties. The typical fire properties being assessed are ignitability, ease of extinction, flame spread, smoke release, heat release, and toxic gas release. Plastic materials are often assessed by a specific flammability test, which assesses a combination of ignitability, ease of extinction, and flame spread, and is addressed separately.

Ignitability

Unless a material ignites, there is no fire. Therefore, low ignitability is the first line of defense in a fire. All combustible materials do ignite, but the higher the temperature a material has to reach before it ignites, the safer it is. Therefore, measures of ignition are of three types, as follows:

1. Minimum temperature for ignition (in the absence or presence of a pilot source of ignition)
2. Time to ignition under a certain applied thermal insult (typically an incident heat flux or a flame of a particular size)
3. Minimum (or critical) heat flux required to reach ignition (because temperature and heat flux can be correlated with the Stefan-Boltzman constant and black-body radiation)

Traditional Method of Assessing Ignition Temperatures. The traditional method of assessing ignition temperatures is done

with a test such as the Setchkin chamber, ASTM D1929, *Test Method for Determining Ignition Temperature of Plastics,* which has been used for many years to determine self-ignition temperatures and flash ignition temperatures (i.e., with an applied pilot flame). ASTM D1929 specimens are small pieces (typically pellets) exposed inside a vertical furnace tube. Specimens are electrically heated under a slow air flow. ASTM D1929 test results are no longer considered truly indicative of fire hazard because the exposure is not fully representative of real fires. However, results from this test are frequently required in specifications and quoted in data sheets. The test is referenced in building codes to determine the suitability of some plastics for use in construction because test results are reported as an easily understandable single number.

On the other hand, the time to ignition at a certain incident heat flux is an excellent way of comparing material properties. Unfortunately, such a measurement will yield a numerical result only if the heat flux is high enough to cause ignition. The advantage of the critical heat flux for ignition is that it can always be assessed. It results from extrapolation after measurements made at a variety of incident heat fluxes. As such, it is a measure that has value for fire safety engineering calculations or fire modeling.

This parameter is typically obtained from tests that also measure heat and smoke release, such as the cone calorimeter (NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*/ASTM E1354, *Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*/ISO 5660, *Reaction to Fire Tests—Heat Release, Smoke Production, and Mass Loss Rate*), the Ohio State University calorimeter (ASTM E906, *Test Method for Heat and Visible Smoke Release Rates for Materials and Products*), and the FM Fire Propagation Apparatus (NFPA 287, *Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using a Fire Propagation Apparatus (FPA)*/ASTM E2058, *Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus (FPA)*), or by the Lateral Ignition and Flame Spread Test (LIFT, ASTM E1321, *Test Method for Determining Material Ignition and Flame Spread Properties*), the primary purpose of which is to assess flame spread.

Whereas a longer time to ignition represents better performance in terms of ignitability, the higher a critical ignition flux is, the better fire performance it represents. A caveat is needed here: extrapolated critical fluxes for ignition are not reliable if such heat fluxes are lower than 15 kW/m^2 and it is recommended that all such data be shown as "≤ 15 kW/m^2."[18]

Other Traditional Ignition Test Methods. There are other traditional ignition test methods: a radiant cone heater with an intermittent gas flame igniter (ISO 5657, *Reaction-to-Fire Tests—Ignitability of Building Products Using a Radiant Heat Source*) and tests for materials coated onto wires, such as those issued by the International Electrotechnical Commission (IEC) and by ASTM, including IEC 60695-2-2, IEC 60695-2-10, ASTM D3874, *Test Method for Ignition of Materials by Hot Wire Sources,* and ASTM D6194, *Test Method for Glow-Wire Ignition of Materials.* The glow wire test (IEC 60695-2-10 and ASTM D6194) involves bringing an electrically heated wire in contact with the material; it simulates the thermal stresses resulting from faults or overload conditions during cable use. Just like ASTM D1929, these tests are also of minor use in performing an engineering assessment of hazard in fire scenarios.

Flammability of Plastic Materials

Plastic materials, as stated above, are often assessed by a test that does not fit as a test for ignitability, ease of extinction, or flame spread, but addresses some of these characteristics. That test, one of the most widely used tests for evaluating the flammability of plastic materials, is UL 94, *Standard for Tests for Flammability of Plastic Materials for Parts in Devices and Appliances.* The test has several component parts:

- 50 W (20 mm gas burner flame) Horizontal Burning Test (ASTM D635, *Test Method for Rate of Burning and/or Extent and Time of Burning of Self-Supporting Plastics in a Horizontal Position;* IEC 60695-11-10, *Fire Hazard Testing Part 11-10: Test Flames 50W Horizontal and Vertical Flame Test Methods*); classification: UL 94 HB.
- 50 W (20 mm gas burner flame) Vertical Burning Test (ASTM D3801, *Test Method for Measuring the Comparative Burning Characteristics of Solid Plastics in a Vertical Position;* IEC 60695-11-10); classifications: UL 94 V-0, V-1, or V-2.
- 500 W (125 mm gas burner flame) Vertical Burning Test (ASTM D5048, *Test Method for Measuring the Comparative Burning Characteristics and Resistance to Burn-Through of Solid Plastics Using a 125-mm Flame;* IEC 60695-11-20, *Fire Hazard Testing Part 11-20: Test Flames 500W Flame Test Methods;* ISO 9772, *Cellular Plastics—Determination of Horizontal Burning Characteristics*); classifications: UL 94 5VA or 5VB.
- 50 W (20 mm gas burner flame) Thin Material Vertical Burning Test (ASTM D4804, *Test Method for Determining the Flammability Characteristics of Nonrigid Solid Plastics;* ISO 9773, *Plastics—Determination of Burning Behaviour of Thin Flexible Vertical Specimens in Contact with a Small-Flame Ignition Source*); classifications: UL 94 VTM-0, VTM-1 or VTM-2.
- 50 W (20 mm gas burner flame) Horizontal Burning Foamed Material Test (ASTM D4986, *Test Method for Horizontal Burning Characteristics of Cellular Polymeric Materials;* ISO 9772); classifications: UL 94 HF-1, HF-2, or HBF

The 50 W/20 mm flame versions of the test, as applied to solid plastics to yield UL 94 classifications of V-0, V-1, V-2, or HB (in decreasing order of fire performance), are the most frequently specified and can be applied to test specimens 125 mm long and 13 mm wide, with thicknesses up to 3 mm. This test is most often used when materials are being characterized in terms of their probability of being ignited by the heat generated from electrical sources contained within an electrical appliance. The test provides an adequate representation of the way materials used for plastics parts perform in such scenarios. By extension, the test is being adequately used as a simple way to compare

the fire performance of plastic materials when subjected to a low-intensity heat source, as a comparative indication of material fire safety in specifications and plastic material information sheets, and as a quality control and material development tool. However, the test is also used with less justification for code compliance as an approval tool for light-transmitting plastics in building construction. It is unsuitable for fire safety engineering calculations.

Ease of Extinction

Ease of extinction is a fire property of interest once a material has ignited. Under those conditions, the easier it is to extinguish the material, the lower is the fire hazard of a product made from the material. ASTM D2863, *Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index),* is used to determine the oxygen index (or limiting oxygen index, LOI), which is the minimum oxygen concentration in a flowing mixture of oxygen and nitrogen required to support candlelike downward flaming combustion. Thus, in principle, as a normal atmosphere is composed of about 20.9 percent oxygen, a material with limiting oxygen index values above 25 percent should only burn under extreme conditions. In reality the test serves merely as a measure of how easy it is to extinguish the material if it is already burning.

The small specimen is placed vertically inside a glass column and ignited at the top with a small gas flame (Figure 6.3.3). This test method has excellent repeatability and reproducibility and can generate numerical data covering a very broad range of fire performance. However, the test method is inappropriate as a predictor of real-scale fire performance, mainly because of the low heat input and the artificiality of the high oxygen environments used. It is also unsuitable for fire safety engineering calculations. Nevertheless, the test is widely required in specifications for plastic materials. It is, therefore, often quoted in data sheets. The oxygen index test method is also suitable as a quantitative quality control tool during manufacturing. Another use is as a semiqualitative indicator of the effectiveness of additives, during research and development, but in this case its results are primarily applicable to low incident energy situations (e.g., heat fluxes not exceeding 20–25 kW/m^2).

FIGURE 6.3.3 Oxygen Index Apparatus

Flame Spread

A critical aspect of fire performance is the assessment of the tendency of a material to spread and propagate a flame away from the fire source. It has always been understood that this knowledge is a key component in understanding the potential fire hazard. Flame spread tests may refer to materials, to components in diverse applications, or to products and structures.

Classification of Flame Spread Tests. Flame spread tests can be classified in terms of the angle between the exposed surface of the specimen and the horizontal. This angle may vary between 0° (a horizontal material burning on its upper surface), through 180° (a horizontal material burning on its lower surface), 240° (a material burning on its lower surface but rotated a further 60° from the horizontal), up to 270° (for a material burning vertically downwards).[19] This surface angle is closely related both to the extent to which the gaseous products of combustion heat the surface before the flame front reaches it and to the extent to which the hot gases penetrate into the tested material. Sample sizes range widely, from the size of a candle to quite large—24 ft × 22 in. (7.3 m × 0.56 m) in NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*/ASTM E84, *Test Method for Surface Burning Characteristics of Building Materials,* otherwise known as the Steiner tunnel test.

Steiner Tunnel Test. The Steiner tunnel test is widely used for specifications and building code requirements. The test is unsuitable for fire safety engineering calculations, primarily because it produces a nondimensional numerical flame spread index (FSI) and does not produce results in proper engineering units. The Steiner tunnel test was developed for building materials,[20] such as "fireproof paint" coatings, wood, or gypsum board. It is perhaps the most widely accepted test for surface flammability (but only in North America) and there are a large number of applica-

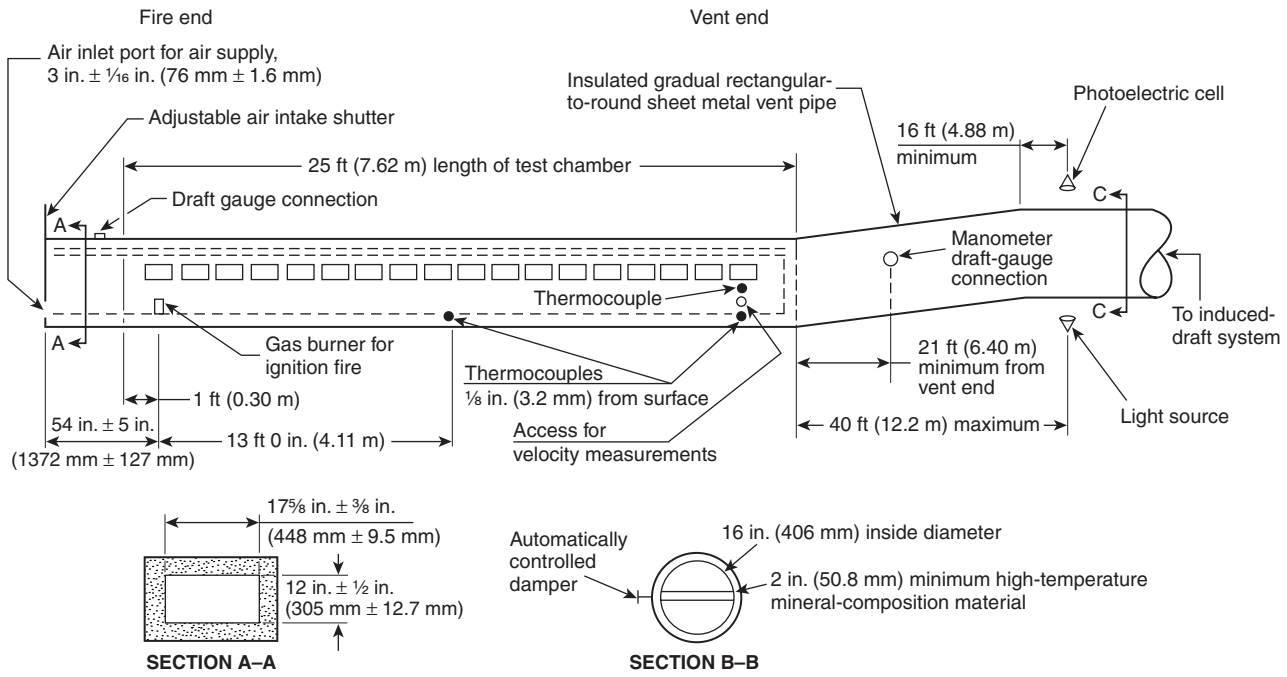

FIGURE 6.3.4 Schematic of the Steiner Tunnel Used in NFPA 255 (Source: NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials,* 2006 ed., Figure 4.1.1(a).)

tions tests developed from it. One such test is used for electrical cables intended for installation in plenums, NFPA 262, *Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces.* Other application tests exist for pneumatic tubing (UL 1887, *Standard for Fire Test of Plastic Sprinkler Pipe for Visible Flame and Smoke Characteristics*), fire sprinkler piping (UL 1820, *Standard for Fire Test of Pneumatic Tubing for Flame and Smoke Characteristics*), optical fiber raceways (UL 2024, *Standard for Optical Fiber and Communication Cable Raceway*), and other products.

The specimen is a building material (normally up to 0.15 m thick), either in one unbroken length or in separate sections joined end to end, mounted face downwards so as to form the roof of a horizontal tunnel 305 mm high. Figure 6.3.4 shows a schematic of the test method. The fire source, two gas burners, ignites the sample from below with an 88 kW fire source. Figure 6.3.5 shows the gas burners as seen from the air inlet end of the tunnel.

FIGURE 6.3.5 Gas Burners at Inlet End of the Steiner Tunnel

Flame Spread Index (FSI). The normal output of the NFPA 255/ASTM E84 test is a flame spread index (FSI). This is a relative number based on the area under the flame spread distance versus time curve of the test, with an FSI of 0 assigned to cement board and an FSI of 100 (approximately) assigned to red oak flooring. Building codes use the test results as "classes," each class representing a range of flame spread indices, as shown in Table 6.3.3. The test method also assesses smoke obscuration and assigns a smoke developed index (SDI) based on a similar concept to the FSI, except that in this case the area assigned to red oak flooring is exactly 100 by definition. To be classified as Class A, B, or C, a material must have an SDI not exceeding 450, as shown in Table 6.3.3.

When plastics were initially used in construction, they were tested in the Steiner tunnel, in spite of the fact that the tunnel was not always appropriate. For example, samples that cannot be retained in place above the tunnel floor or which melt and continue burning on the tunnel floor (typical behavior for thermoplastic materials) are still being tested with this equipment, even though results are often misleading. The Steiner tunnel test can also produce wrong results for thin materials,[21] particularly when they are tested using "poultry

TABLE 6.3.3 Flame Spread Index and Smoke Developed Classes for Use in Building, Fire, and Life Safety Codes

Class	*Flame Spread Index*	*Smoke Developed Index*
Class A	FSI ≤ 25	SDI ≤ 450
Class B	26 ≤ FSI ≤ 75	SDI ≤ 450
Class C	76 ≤ FSI ≤ 200	SDI ≤ 450
Plenum materials	FSI ≤ 25	SDI ≤ 50

netting" support, which absorbs much of the heat generated by the test specimen (see examples in Table 6.3.4). Single-layer membranes or thin laminates consisting of a limited number of similar or dissimilar layers not intended for adherence to another surface are often supported on poultry netting placed on steel rods in the Steiner tunnel. The metal dissipates much of the heat generated by the burning material, thus decreasing the flame spread artificially.

The ASTM technical committee on fire standards, ASTM E05, has developed standard practices for specimen preparation and mounting methods associated with the Steiner tunnel. Three practices have been issued: one for pipe and duct insulation materials (ASTM E2231, *Standard Practice for Specimen Preparation and Mounting of Pipe and Duct Insulation Materials to Assess Surface Burning Characteristics*), one for paper and vinyl wall and ceiling coverings (ASTM E2404, *Standard Practice for Specimen Preparation and Mounting of Paper or Vinyl Wall or Ceiling Coverings to Assess Surface Burning Characteristics*), and one for site-fabricated stretch systems (using fabric or vinyl) (ASTM E2573, *Standard Practice for Specimen Preparation and Mounting of Site-Fabricated Stretch Systems to Assess Surface Burning Characteristics*).

Radiant Panel Index (I_s). ASTM E162, *Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source,* is another test method used to assess flame spread (Figure 6.3.6). The results obtained from this radiant panel test are expressed in terms of an index; however, this index, now known as the radiant panel index (I_s), is different from the more familiar one produced by the Steiner tunnel, known as the flame spread index (FSI). The radiant panel index is calculated as the product of a "flame spread factor" and a "heat evolution factor," using techniques described in the standard.

TABLE 6.3.4 Effect of Poultry Netting on Steiner Tunnel Test Flame Spread Index

Material	*Flame Spread Index with Poultry Netting*	*Flame Spread Index Without Poultry Netting*
Sample 1	20	340
Sample 2	25	310
Sample 3	55	105
Sample 4	15	45

FIGURE 6.3.6 Radiant Panel Test Apparatus

The test equipment consists of a gas-fed radiant panel that exposes test specimens to a radiant flux equivalent to a blackbody temperature of 670°C (943 K) (approximately 45 kW/m^2) in the presence of a small gas pilot flame. The test specimen (150 × 460 mm, with a normal maximum thickness of 25 mm) is inclined at a 30° angle. Alternate specimen holders can accommodate thicker specimens. The ignition is forced near the upper edge of the specimen and the flame front progresses downward.

The flame spread factor results from the measurements of flame front position and time. The heat evolution factor is proportional to the maximum temperature measured in the exhaust stack. This test has also been shown not to be an adequate predictor of real-scale fire performance and not to be suitable for fire safety engineering calculations. Once more, if the specimen melts or causes flaming drips, such behavior is likely to affect the flame spread in a way that is uneven. The standard simply requires that such events be reported. Moreover, if flame spread

is very rapid, flame spread information is potentially lost unless recording is continuous, which is also not a requirement.

This apparatus is often referred to as the radiant panel test; a variant has been developed for testing foamed materials, ASTM D3675, *Test Method for Surface Flammability of Flexible Cellular Materials Using a Radiant Heat Energy Source.* Results from the relevant test are frequently required in regulations, particularly for transportation environments (both foamed and rigid materials) and in specifications for detention environments (foamed materials).

LIFT Test. Another test apparatus suitable for assessing flame spread of materials is the Lateral Ignition and Flame Spread Test, or LIFT (ASTM E1321). The LIFT apparatus was developed as an improvement on the radiant panel apparatus used by ASTM E162,[22] because it can produce data in engineering units and its results can be used successfully for predictions of full-scale flame spread performance.[23] The specimen size for flame spread studies is 155 mm × 800 mm by a maximum thickness of 50 mm (a smaller specimen is used for ignition studies).

The test method determines the critical flux for flame spread, the surface temperature needed for flame spread, and the thermal inertia or thermal heating property (product of the thermal conductivity, the density, and the specific heat) of the material under test. These properties are mainly used for assessment of fire hazard and for input into fire models. A flame spread parameter, Φ, is also determined and this can be used as a direct way of comparing the responses of the specimens. This test method appears well-suited for materials or composites of materials that are nonmelting and can be ignited without raising the incident flux to potentially dangerous limits. A slight variation on the LIFT test is one used by the marine industry to assess flammability of surface finishes: ASTM E1317, *Test Method for Flammability of Marine Surface Finishes,* also known by its International Maritime Organization (IMO) designation as "Part 5 of the IMO Fire Test Procedures Code." This test is required extensively for marine deck finishes and overlays.

In the area of electric cables, low flame spread is a frequent requirement. NFPA 70, *National Electrical Code®,* contains requirements in terms of flame spread for both electrical and optical fiber cables and subdivides them into 4 categories:

1. Cables that are listed as "being suitable for use in dwellings and for use in raceway" and as "being resistant to flame spread." This category represents minimal improved fire performance. A cable is tested individually in a vertical configuration using the VW-1 (vertical wire) flame test in UL 1581, *Reference Standard for Electrical Wires, Cables and Flexible Cords.*

2. Cables that are listed as "suitable for general-purpose use, with the exception of risers, ducts, plenums, and other space used for environmental air," and as "being resistant to the spread of fire." This represents somewhat better fire performance. Cables are tested in a grouped configuration using the vertical cable tray flame test (20 kW) of UL 1581. Cables are not allowed to spread fire to the top of the 2.4 m tray. An alternate, more severe, test for the same application is the Canadian Standards Association (CSA) vertical flame test for cables in cable trays, CSA C22.2 No. 0.3, *Test Methods for Electrical Wires and Cables.* In this procedure, the cables are also tested in a grouped configuration using a 20 kW flame, but with a more severe application. Cables are not permitted to exhibit char length (basically equivalent to flame spread in concept) larger than 1.5 m up the tray.

3. Cables that are listed as "suitable for use in a vertical run in a shaft or from floor to floor" (risers) and "having fire-resistant characteristics capable of preventing the carrying of fire from floor to floor." This category is the next level up in fire performance. Such cables must pass the requirements of UL 1666, *Standard Test for Flame Propagation Height of Electrical and Optical-Fiber Cable Installed Vertically in Shafts,* whereby cables in a grouped configuration are exposed vertically, in a two-story facility, to a 145 kW flame.

4. Cables that are listed as "suitable for use in ducts, plenums, and other space for environmental air" and as "having adequate fire-resistant and low smoke-producing characteristics." This is the highest level of flame spread fire performance required for cables. Such cables must pass the requirements of NFPA 262 (an application of the Steiner tunnel test, as discussed previously) by exhibiting a maximum flame travel distance of 1.52 m, a maximum peak optical density of 0.5, and a maximum average optical density of 0.15, when tested, in a grouped configuration, horizontally to an 88 kW flame.

In Europe, the fire performance of cables is being assessed by an alternate vertical cable tray flame spread test, IEC 60332-3, which is similar to the North American vertical cable tray tests (same ignition source but a longer cable tray, 3 m high) but slightly less severe. There exists also a European version of the UL 1581 VW-1 test, namely IEC 60332-1. In the late 1990s, a European project developed a first attempt at a classification method for fire performance of cables, the FIPEC project.[24] This is an important development, as the test method, a variation of the IEC 60332-1 vertical cable tray test, also incorporates heat and smoke release and will probably be used for the European classification of cables in terms of reaction to fire, as EN 50399. This will be discussed in greater detail later.

Smoke Release

In a fire, smoke causes impairment of visibility, which results in greater difficulty for exposed people to escape or be rescued. Therefore, many regulations and specifications require that materials or products exhibit reduced smoke emission. The most traditional test used for assessing smoke released by materials is the static smoke chamber developed by the National Bureau of Standards (now National Institute of Standards and Technology, NIST), and standardized as ASTM E662, *Test Method for Specific Optical Density of Smoke Generated by Solid Materials.*

In this fire test, a vertical specimen, 7.5 mm × 7.5 mm by up to 50 mm thick, is exposed to a 25 kW/m^2 radiant heat source, with or without a pilot igniter, inside a 0.5 m^3 closed chamber (i.e., this is a static test, as opposed to tests such as the Steiner tunnel or the cone calorimeter, which have air and smoke circulation and are dynamic tests). In the test, the reduction in visibility within the chamber is assessed by measuring the light transmitted.

This test has been severely criticized for its various deficiencies,[25–29] but is very widely used throughout the world. Results from this test are included as parts of many specifications and requirements, typically for transportation vehicles and for carpets and other floor coverings. The test is also a common tool in material development.

Some of the deficiencies, especially the problem of test specimen dripping, have been addressed by the development of ASTM E1995, *Test Method for Measurement of Smoke Obscuration Using a Conical Radiant Source in a Single Closed Chamber, with the Test Specimen Oriented Horizontally,* NFPA 270, *Standard Test Method for Measurement of Smoke Obscuration Using a Conical Radiant Source in a Single Closed Chamber,* and ISO 5659-2, *Plastics—Smoke Generation, Part 2—Determination of Optical Density by a Single-Chamber Test,* which employ a horizontal test specimen and a conical radiant heater in the same chamber. This chamber is used extensively in the marine environment. An earlier type of smoke chamber was developed for testing light-transmitting plastics, ASTM D2843, *Test Method for Density of Smoke from the Burning or Decomposition of Plastics,* and it is still included in codes as one of the qualifying tests for such materials. One serious problem with all of these small-scale smoke tests is that they normally cause complete destruction of the test specimen, even for materials with excellent fire performance in real fires. Consequently, a material that would not burn up completely in an actual fire (and would thus yield less total overall smoke obscuration than would appear from total material consumption) can appear to have poor smoke performance in these tests due to the characteristics of the test itself.

For electric cables, European requirements call for the 3 m cube test (IEC 61034), which is a large static smoke chamber. Its fire model is a very intense liquid hydrocarbon pool which is sufficient, often, to consume completely the combustible portion of the cables, due to the geometrical arrangement. Thus, the test suffers from most of the same defects that plague small-scale static smoke chamber tests.

The ultimate measure of fire performance of a material or product is, of course, the way the actual product reacts in a real fire, as opposed to testing the component materials individually. Fires typically involve finished products and not individual materials. Thus, the best approximation to fire performance and to the associated smoke release will be found with room-size fire tests, where products can be tested in end-use configurations or as close to them as possible. As the single most important fire property is the heat release rate, since its peak value will determine the peak intensity of the fire, tests that assess smoke release together with heat release will tend to give more realistic smoke results. The fire science community has understood this concept only relatively recently, but the result has been the development of several such tests, which measure smoke obscuration together with heat release. They are discussed as part of heat release test methodology.

Heat Release

As stated earlier, heat release is the most important property in a fire, as the peak heat release rate is the answer to the key fire question: How big is the fire? When a product burns, it will spread the fire to nearby products only if it gives off enough heat to ignite them. Moreover, it has to give off that heat fast enough that it is not "lost" while traveling through the colder air that surrounds a product that is not burning. Therefore, fire hazard is dominated by the rate of heat release.[30–32] In fact, heat release rate has been shown to be much more important than either ease of ignition, smoke toxicity, or flame spread in controlling the time available for potential victims of a fire to escape.[1]

OSU Heat Release Rate (HRR) Calorimeter. In the late 1960s, Professor Edwin Smith at Ohio State University (OSU) developed the first bench-scale (or small-scale) heat release test instrument, the OSU heat release rate (HRR) calorimeter, ASTM E906, to measure heat release rates from small-scale specimens.[33] The OSU calorimeter exposes a 150 mm × 150 mm test specimen vertically and assesses heat release by measuring temperature increases with a thermopile. The test was the first heat release test method to be widely used for regulatory purposes, once the Federal Aviation Administration (FAA) completed a series of full-scale tests that demonstrated that good performance (i.e., low heat release) in the calorimeter test correlated to more time available for escape in an aircraft.[34]

Since the late 1980s, the FAA has based requirements on this equipment (actually, the version of the test apparatus contained in the *FAA Aircraft Material Fire Test Handbook,* Chapter 5). The requirements, which apply to most large surfaces inside an aircraft cabin (such as wall panels and baggage stowage bins), are that the average maximum heat release rate during a 5 minute test not exceed 65 kW/m^2 and that the average total heat released during the first 2 minutes of test not exceed 65 kW min/m^2, with an incident heat flux of 35 kW/ m^2, for all commercial passenger airplanes manufactured after August 20, 1990, and that use United States airports.

The pass/fail criteria were calculated based on requiring a 5 minute escape time from an airplane that has suffered a survivable collision followed by a fuel tank rupture and fire. The success of this regulatory strategy can be seen in the excellent fire safety record of airplanes. For example, most recently on August 2, 2005, a commercial airliner was consumed by fire at the Toronto, Canada, airport with a full complement of passengers and crew, and yet neither fire fatalities nor severe fire injuries occurred. In contrast, hundreds of fire fatalities occur each year in passenger road vehicles, mainly private cars and vans, in the United States alone; there are no heat release requirements for the materials used in passenger road vehicles.[35–37]

FM Fire Propagation Apparatus. In parallel with the OSU calorimeter development, Archibald Tewarson (from FM Global) created the Factory Mutual fire propagation apparatus (FM FPA) (ASTM E2058, *Standard Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus (FPA)*).[38] One specific application of this apparatus is the testing of materials for use in cleanrooms (NFPA 287, *Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using a Fire Propagation Apparatus (FPA)*). This instrument is used for assessing heat release and fire propagation.

Heat release is assessed by measuring carbon dioxide generation instead of temperature increases with a thermopile. The protocol utilizes three small-scale tests (designated as ignition, combustion, and fire propagation). Ignition and combustion tests are conducted with horizontal test specimens (normally about 100 mm^2) and fire propagation tests are conducted with vertical test specimens (300 mm high by 100 mm wide by no more than 13 mm thick). Ignition tests assess time to ignition and critical ignition flux. Combustion tests are the ones that assess chemical and convective heat release and they are conducted at an incident heat flux of 50 kW/m^2. Fire propagation tests are also conducted at an incident heat flux of 50 kW/m^2, but at an oxygen level of 40 percent, in order to differentiate among the flame heat transfer characteristics of burning materials, in the absence of any imposed, high-intensity radiant flux.[39]

The use of this high oxygen concentration is somewhat controversial, with some researchers questioning its direct relevance to normal oxygen content (20.9%) and vitiated atmosphere fires. However, based on the results of these tests, a fire propagation index (FPI) can be determined for each material tested. The FPI is intended to represent the ease or difficulty of fire propagation on the surface of the material beyond the ignition zone, under simulated flame heating conditions expected in large-scale fires. Experience indicates that nonpropagating materials have FPI values at or below 6.0. Materials that meet the flammability protocol criteria require high heat fluxes to be ignited; once ignited, these materials can burn locally in the ignition area, but they are likely not to propagate a fire beyond the ignition zone.

Research at FM Global has shown that materials with a low fire propagation index determined by ASTM E2058/NFPA 287 are likely to perform well in a larger-scale FM flammability test known as the parallel panel test. FM Global developed three approvals standards that use this apparatus: FM 3972, *Cable Fire Propagation Specification Test Standard,* for electric cables; FM 4910, *American National Standard for Cleanroom Materials Flammability Test Protocol,* for cleanroom materials; and FM 4998, *Class 1 Conveyor Belting,* for coal mine conveyor belts.

Cone Calorimeter. In the early 1980s, Vytenis Babrauskas, at the National Institute of Standards and Technology, developed a new fire test method to measure heat release rate, the cone calorimeter (ASTM E1354/NFPA 271/ISO 5660)[40–41] (Figure 6.3.7), based on the principle of oxygen consumption.[42] This fire test instrument can also be used to assess a number of other fire properties, the most important of which are ignitability (as discussed above), mass loss, and smoke release. Fire test results from this instrument correlate with those from full-scale fires for a variety of products, including interior finish, upholstered furniture, mattresses, and electric cables.[43–45] In order to obtain the best overall understanding of the fire performance of materials, it is important to test the materials under a variety of conditions. Therefore, tests are often conducted at a variety of incident heat fluxes.[18]

Heat release test results from the cone calorimeter are now used for various purposes, beyond just research and development. Such test results are mainly used as primary inputs into models for assessing the fire hazard (and perhaps fire risk) of a fire scenario before a material, product, or system is incorporated into a design. In order to aid in this analysis, several cone calorimeter applications standards have been issued by ASTM: ASTM E1474, *Standard Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter* (equivalent to NFPA 272, *Standard Method of Test for Heat and Visible Smoke Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter*); ASTM F1550, *Standard Test Method for Determination of Fire-Test-Response Characteristics of Components or Composites of Mattresses or Furniture for Use in Correctional Facilities after Exposure to Vandalism, by Employing a Bench Scale Oxygen Consumption Calorimeter* (same as ASTM E1474 but intended to apply especially to vandalized mattress specimens, particularly for detention occupancy applications); ASTM E1740, *Standard Test Method for Determining the Heat Release Rate and Other Fire-Test-Response Characteristics of Wallcovering Composites Using a Cone Calorimeter* (for textile and other wall coverings); ASTM D6113, *Standard Test Method for Using a Cone Calorimeter to Determine Fire-Test-Response Characteristics of Insulating Materials Contained in Electrical or Optical Fiber Cables* (for both electric cables and cable insulating materials); ASTM D5485, *Standard Test Method for Determining the Corrosive Effect of Combustion Products Using the Cone Corrosimeter;* and ASTM E2102,

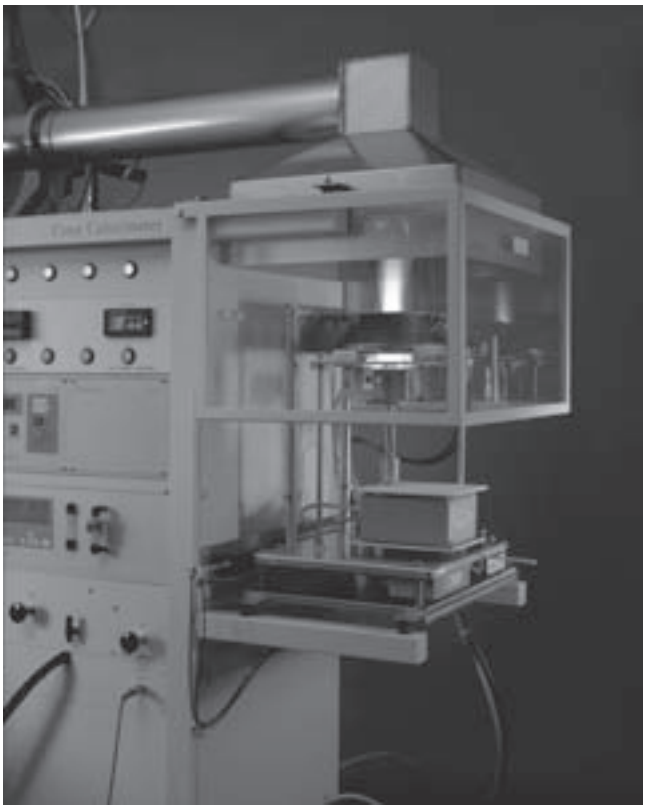

FIGURE 6.3.7 Cone Calorimeter Test Apparatus

Standard Test Method for Measurement of Mass Loss and Ignitability for Screening Purposes Using a Conical Radiant Heater (known as the mass loss cone, which is a screening test for mass loss and ignitability).

The cone calorimeter is also used as part of specifications and regulations, including its use for materials of construction of large garbage cans in health care occupancies (in NFPA 1, *Uniform Fire Code*™), for alternative design of materials in passenger rail applications, and for qualification of materials in the cleanrooms used in semiconductor fabrication facilities ("fabs"). The latter are approved based on testing in accordance with either UL 2360, *Standard for Test Methods for Determining the Combustibility Characteristics of Plastics Used in Semi-Conductor Tool Construction* (an application of the cone calorimeter) or NFPA 287 with the criteria contained in FM 4910, *Clean Room Materials Flammability Test Protocol.*

In all of the above tests, smoke release can be assessed on the same test specimen as heat release, resulting in more realistic smoke results. They are the tests that comply with the following four basic criteria that have been suggested[29] for small-scale smoke obscuration tests, as follows:

1. Tests must measure fire properties so that they can be used for purposes other than simple rankings or pass/fail criteria.
2. Tests should measure fire properties of considerable fire hazard interest, principally the rate of heat release.
3. Tests must have been proven to give results that are representative of the corresponding property in a full-scale scenario.
4. Tests must allow calculations to compensate for complete sample consumption, characteristic of small-scale tests.

In order to compensate for the complete consumption of the sample in small-scale smoke and heat release tests, it is possible to calculate derived combined heat/smoke magnitudes of smoke obscuration, such as the smoke factor, a product of total smoke released and peak heat release rate.[29] An attempt has been made to compare smoke chamber test results with those of full-scale tests and small-scale heat release test smoke obscuration results (cone calorimeter and OSU calorimeter).[46] The results indicate a lack of correlation between the smoke chamber test results and those of any of the other three tests. Moreover, the results also show a fair predictability of the combined heat/smoke parameters from the cone calorimeter and the OSU apparatus and the full-scale results for a variety of plastics.

Moreover, work also showed reasonable correlation between such cone calorimeter parameters and smoke measured in full-scale fire tests of cables in vertical trays.[45] In the same work,[47] the materials used to make the cables were burnt in the cone and in the OSU apparatus; heat release results from both instruments correlated well with one another, as did combined smoke factors in each instrument at different incident fluxes. All this suggests that, probably, the best way of measuring smoke obscuration in a meaningful way for full-scale fires, without conducting full-scale tests, is by using a small-scale heat release test, such as the cone calorimeter and compensating for incomplete burning of fire retardant materials by using the combined heat/smoke magnitude concept.

Intermediate Scale Calorimeter (ICAL) Test. However desirable and predictive small-scale tests are, they are often unable to deal with physical phenomena such as joints, multiple layers, and product irregularities. Intermediate-scale calorimeter tests have been developed to generate data similar to those from small-scale heat release tests, but in a scale that is more likely to allow the use of test specimens that are representative of real-scale products. The intermediate scale calorimeter ASTM E1623, *Test Method for Determination of Fire and Thermal Parameters of Materials, Products, and Systems Using an Intermediate Scale Calorimeter (ICAL),* and the single burning item fire test (SBI, EN 13823) are versions, developed in North America and Europe, respectively, of this concept. In the ICAL test a flat specimen (1 m × 1 m vertically) is exposed to a radiant heat source (a vertical gas-fired panel; Figure 6.3.8) at an incident heat flux ranging up to 50 kW/m^2. The results obtained include heat and smoke release, ignitability, and flame spread across the specimen surface. In North America, the ICAL test is extensively used as a predictor of full-scale fire performance, but not for regulatory purposes (or at least not yet).

Single Burning Item (SBI) Test. In the European Union, the SBI test, shown in Figure 6.3.9, was developed with the objective of using it to regulate building products. In the test, two test specimens, both 1.5 m high, with one 0.5 m wide and the other one 1 m wide, are placed in a corner and exposed to a 30 kW propane gas burner. Determinations are made of ignitability, flame spread, heat release, smoke release, and flaming droplets.

FIGURE 6.3.8 Radiant Panel of ICAL Apparatus

FIGURE 6.3.9 SBI Apparatus

Key new parameters that are calculated from SBI measurements are parameters that are intended to address fire growth rate (FIGRA) and smoke growth rate (SMOGRA); they are required to be reported by the European Commission for product regulation. FIGRA is "the maximum of the function of heat release rate versus time," starting at the time to ignition and it describes the fire growth rate. SMOGRA is "the maximum of the function of smoke production rate versus time," also starting at the time to ignition, and would describe the growth rate of smoke production. These parameters include the concepts of heat or smoke release and time to effect, so that a material or product that takes a long time to generate very high heat or smoke release will be assessed to have better fire performance than one that gets to the same heat or smoke value rapidly.

The SBI test is one of a battery of regulatory tests the European commission uses for building product regulation (mainly interior wall and ceiling finish and insulation). Excluded from this regulation are "linear products," such as electric cables, pipes and pipe insulation, and floor coverings. The other tests for construction products, excluding floorings, are not based on heat release. They are ISO 1182, *Reaction to Fire Tests for Building Products—Noncombustibility Test,* and ISO 1716, *Reaction to Fire Tests for Building Products—Determination of the Heat of Combustion,* both of which require better fire performance than that provided by typical SBI test results, and the small flame test, ISO 11925-2, *Reaction to Fire Tests—Ignitability of Building Products Subjected to Direct Impingement of Flame—Part 2: Single-Flame Source Test,* used for materials with minimal improved fire performance. Everything is then incorporated into EN 13501-1, *Fire Classification of Construction Products and Building Elements.* The SBI test is also used for the European classification/regulation of pipe insulation, but not for electric cables or floorings.

The ultimate way of assessing fire performance is by conducting full-scale tests; fire hazard or fire risk can only be assessed as a result of determining heat release. A number of modern full-scale fire test methods have been developed for products, relying on rate of heat release measurements, such as those involving testing of upholstered furniture (ASTM E1537, *Standard Test Method for Fire Testing of Upholstered Furniture*), mattresses (ASTM E1590, *Standard Test Method for Fire Testing of Mattresses*), stacking chairs (ASTM E1822, *Standard Test Method for Fire Testing of Stacked Chairs*), electric cables (ASTM D5424, *Standard Test Method for Smoke Obscuration of Insulating Materials Contained in Electrical or Optical Fiber Cables When Burning in a Vertical Cable Tray Configuration;* ASTM D5537, *Standard Test Method for Heat Release, Flame Spread, Smoke Obscuration, and Mass Loss Testing of Insulating Materials Contained in Electrical or Optical Fiber Cables When Burning in a Vertical Cable Tray Configuration;* and EN 50399), plastic display stands (UL 1975, *Standard for Fire Tests for Foamed Plastics Used for Decorative Purposes*), or wall lining products (NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Coverings on Full Height Panels and Walls;* NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth;* ASTM E2257, *Standard Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies;* and ISO 9705, *Fire Tests—Full-Scale Room Test for Surface Products*).

Room-Corner Tests. In fact, room-corner tests are being used in the newest editions of all codes, as alternatives to replace the NFPA 255/ASTM E84 (Steiner tunnel test), thus generating more useful results. Figure 6.3.10 shows a room-corner test layout. The standard room used for all these tests, except for the cable tray tests, is the same size: 2.4 m × 3.7 m × 2.4 m high, with a door in the center of one of the shorter walls and a hood/vent and outlet outside the door. Wall lining material tests, also known as room-corner tests, such as NFPA 265, NFPA 286, ASTM E2257, and ISO 9705, require that the tested material be lined on three walls (all except the wall with the door) or on three walls and the ceiling or on the ceiling only. A variety of burners and ignition source intensities are used and the details are indicated in each standard.

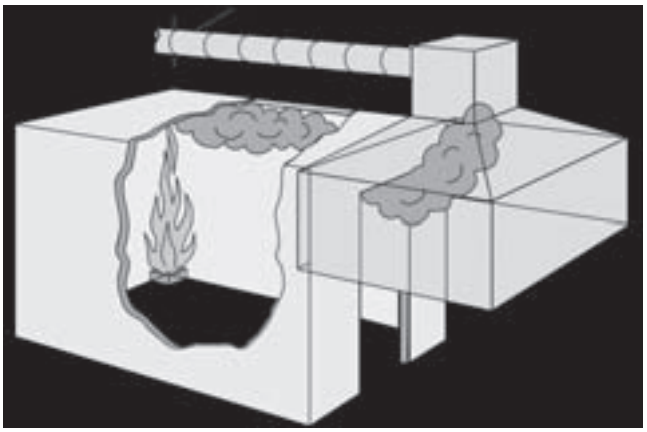

FIGURE 6.3.10 Room-Corner Fire Test Layout

In the case of ASTM cable tray tests, the standard room is 2.4 m × 2.4 m × 3.4 m high, with a door in the center of one wall and a hood/vent and outlet in the middle of the room; the IEC 60332 and FIPEC cable tray tests have a different size room. In all of these cases, other size rooms are permitted, within certain limits. Cable tray tests require that a vertical cable tray be placed in the middle of the test room, as shown in Figure 6.3.11.

Furniture standard tests (ASTM E1537, ASTM E1590, and ASTM E1822) require the item for test to be placed on a load cell near one of the corners and away from the door; again each standard test has different burners and ignition source intensities.

Furniture calorimeter tests are an added way of assessing heat release of full-scale items, where the product to be tested is placed on a load cell under a hood/vent and outlet. UL 1975 is a standard version of a furniture calorimeter and it is applicable to foam plastic displays and uses a 340 g wood crib as the ignition source. The NFPA Technical Committee on Fire Tests is developing another standard furniture calorimeter test, designated NFPA 289, which is intended to apply to all sorts of individual fuel packages and to use a variety of gas ignition sources, depending on the application. When testing does not have to follow standard protocols, ASTM E603, *Standard Guide for Room Fire Experiments,* and ASTM E2061, *Standard Practice for Full-Scale Oxygen Consumption Calorimetry Fire Tests,* offer adequate guidance.

FIGURE 6.3.11 Cable Tray Test Burn

Toxic Gas Release

All of the comments made for smoke release (i.e., smoke obscuration) are equally valid for the release of all combustion products, especially since it has now been demonstrated that smoke toxicity does not represent the most significant aspect of the fire hazard.[1] In fact, fire statistics and studies of fire fatalities have shown that (1) most fire victims die when fires have become large and have grown beyond the room of fire origin and (2) fire fatalities can be correlated to the amount of carbon monoxide generated in fires.[48–50] This is very important as carbon monoxide is generated by all combustibles and, in fires that extend beyond the room of fire origin, its yield is 20 percent of the burnt mass, irrespective of what is burning.[51–54] Thus, fires resulting from materials with better fire performance tend to generate less fire hazard, even if they generate more toxic gases or more smoke per unit mass burnt.[55] In other words, addressing purely the toxic potency of the smoke of a particular material can be very misleading. For example, materials associated with low heat release usually represent a much lower level of fire hazard, almost irrespective of the toxic potency of their smoke. It has been shown that, although redesigning an upholstered furniture item so that its heat release rate is doubled will lead to a 70 percent decrease in time to lethality in a small room, redesigning it so that the toxic potency is twice as high will have a negligible effect on the time to lethality.[1]

Reaction-to-Fire Tests and Fire Hazard

The key issue in terms of fire hazard is to ensure that a fire does not become self-propagating and remains small. At the very least, it is critical to ensure that flashover does not occur. Flashover is a stage in the development of a contained fire in which all exposed surfaces reach ignition temperatures more or less simultaneously and fire spreads rapidly throughout the space. Thus, an initial strategy for minimizing fire hazard is to prevent flashover; that requires a good measure of heat release or of the potential for materials and products releasing heat in a compartment.

NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover,* gives adequate guidance on how to assess or predict heat release in actual fires. Since estimates of heat release rate are critical in predicting whether or not flashover is likely to occur in a compartment, NFPA 555 provides techniques for measuring or estimating the heat release rate for various individual items or products in a compartment. NFPA 555 gives the following hierarchical order for preferred techniques for measuring/assessing heat release:

1. A full compartment fire test, including all items expected to be contained within the compartment
2. Full-scale fire tests on individual items
3. Tests on large-scale mock-ups of individual items
4. Small-scale tests, using composite samples representative of the end-use composite assemblies

5. Small-scale tests using individual materials rather than composites as samples
6. Use of estimation techniques for calculating heat release rate in the compartment as determined from the results of tests. This might be done by one of the following:
   - Quantitative estimation techniques
   - Relative estimation techniques

ASTM has also developed two guides that can assist those considering methods for evaluating potential for flashover: ASTM E2061, *Guide for Fire Hazard Assessment of Rail Transportation Vehicles,* and ASTM E2280, *Standard Guide for the Fire Hazard Assessment of the Effect of Upholstered Seating Furniture Within Patient Rooms of Health Care Facilities.*

It has been shown that heat release techniques can be used to adequately predict the fire performance of at least several types of products in actual full-scale fires: aircraft panels, upholstered furniture, mattresses, wall linings (interior finish), and electric cables.[24,34,56–63] Although the use of full-scale fire tests is the best "insurance" that the test results will be fully indicative of fire performance, it is clear that predictive tests will be used with increasing frequency, as they are much more cost effective and practicable to conduct.

The most common models to predict full-scale fire test results are correlative ones, which are based on comparing test results in both sets of tests and interpolating the expected test results from the material or product being investigated (and which has not been tested in full scale). Such predictions are often excellent when they are based on using variations of a set of materials or products (such as the same material with different sets of additives). They are less successful when they compare materials with different types of chemical composition or try to extrapolate results based on data that are not bracketed by full scale tests already conducted. Other models can be used that consider physical/theoretical aspects of the fire issue and yield results that are not (at least in concept) material dependent. This approach is much more complex but has been very successful for simple geometries, such as wall linings/interior finish.

One common problem encountered in regulatory and research studies of fire test results is that most manufacturers are responsible for developing a certain material, which will then become a component of a more complex or composite product or assembly. Such manufacturers often have limited control over the ultimate use of their material. However, it has by now been shown extensively that "the sum of the parts" does not give, in this case, an adequate picture of the "whole." Occasionally, an assembly or a composite system will have better fire performance than expected from individual test results on the component materials. However, very often, when testing individual materials, each may produce adequate test results, which meet the specifications or regulatory requirements, but the combination of materials may generate results indicating that the product would "fail" the required criteria. In such case, the testing of specimens simulating the final product, as intended to be used in the field, is essential.

Very often, it is not immediately apparent how to generate the most suitable test results in a fashion fully representative of the end use. Committees developing test methods have, in recent years, developed mounting practices and application standards that address these issues. As discussed above, such standards have been developed for the NFPA 255/ASTM E84 Steiner tunnel test, for the cone calorimeter, and for the

TABLE 6.3.5 European Community Concept for Fire Classes

Fire Class	*Test Simulations*		*Time to Flashover*	*Contribution to Fire Growth*
A1	Fully developed fire in a room	Single burning item in a room	No flashover	None
A2	Fully developed fire in a room	Single burning item in a room	No flashover	None
B	Small fire attack on limited area	Single burning item in a room	No flashover	Extra small
C	Small fire attack on limited area	Single burning item in a room	After 10 minutes	Small
D	Small fire attack on limited area	Single burning item in a room	2–10 minutes	Medium
E	Small fire attack on limited area		Before 2 minutes	Large
F	No A1 through E			

Essential definitions for European Community regulations:

Material: a single basic substance or uniformly dispersed mixture of substances, for example, metal, stone, timber, concrete, mineral wool with uniformly dispersed binder, polymers.

Homogeneous product: a product consisting of a single material, having uniform density and composition throughout the product.

Nonhomogeneous product: a product that does not satisfy the requirements of a homogeneous product. It is a product composed of one or more components, substantial and/or nonsubstantial.

Substantial component: a material that constitutes a significant part of a nonhomogeneous product. A layer with a mass per unit area ≥ 1.0 kg/m^2 or a thickness ≥ 1.0 mm is considered to be a substantial component.

Nonsubstantial component: a material that does not constitute a significant part of a nonhomogeneous product. A layer with a mass per unit area < 1.0 kg/m^2 and a thickness < 1.0 mm is considered to be a nonsubstantial component. Two or more nonsubstantial layers that are adjacent to each other (i.e., with no substantial component(s) in between the layers) are regarded as one nonsubstantial component and, therefore, must altogether comply with the requirements for a layer being a nonsubstantial component.

For nonsubstantial components, distinction is made between internal nonsubstantial components and external nonsubstantial components, as follows:

Internal nonsubstantial component: a nonsubstantial component that is covered on both sides by at least one substantial component.

External nonsubstantial component: a nonsubstantial component that is not covered on one side by a substantial component.

TABLE 6.3.6 European Community Classes of Reaction-to-Fire Performance for Construction Products Excluding Floorings, Linear Pipe Thermal Insulation Products, and Electrical Cables

Class	*Test Method(s)*	*Classification Criteria*	*Additional Classification*
A1	EN ISO 1182[a] and	$\Delta T \le 30°C$ and $\Delta m \le 50\%$ and $t_f = 0$ (i.e., no sustained flaming)	—
	EN ISO 1716	PCS ≤ 2.0 MJ/kg[a] and PCS ≤ 2.0 MJ/kg[b,c] and PCS ≤ 1.4 MJ/m^2[d] and PCS ≤ 2.0 MJ/kg[e]	—
A2	EN ISO 1182[a] or	$\Delta T \le 50°C$ and $\Delta m \le 50\%$ and $t_f \le 20$ sec	—
	EN ISO 1716 and	PCS ≤ 3.0 MJ/kg[a] and PCS ≤ 4.0 MJ/kg[b] and PCS ≤ 4.0 MJ/m^2[d] and PCS ≤ 3.0 MJ/kg[e]	—
	EN 13823 (SBI)	FIGRA ≤ 120 W/sec and LFS < edge of specimen and $THR_{600sec} \le 7.5$ MJ	Smoke production[f] and flaming droplets/particles[g]
B	EN 13823 (SBI) and	FIGRA ≤ 120 W/sec and LFS < edge of specimen and $THR_{600sec} \le 7.5$ MJ	Smoke production[f] and flaming droplets/particles[g]
	EN ISO 11925-2[i] Exposure = 30 sec	$F_s \le 150$ mm within 60 sec	
C	EN 13823 (SBI) and	FIGRA ≤ 250 W/sec and LFS < edge of specimen and $THR_{600sec} \le 15$ MJ	Smoke production[f] and flaming droplets/particles[g]
	EN ISO 11925-2[i] Exposure = 30 sec	$F_s \le 150$ mm within 60 sec	
D	EN 13823 (SBI) and EN ISO 11925-2[i] Exposure = 30 sec	FIGRA ≤ 750 W/sec and $F_s \le 150$ mm within 60 sec	Smoke production[f] and flaming droplets/particles[g]
E	EN ISO 11925-2[i] Exposure = 15 sec	$F_s \le 150$ mm within 20 sec	Flaming droplets/particles[h]
F		No performance determined	

[a]For homogeneous products and substantial components of nonhomogeneous products.
[b]For any external nonsubstantial component of nonhomogeneous products.
[c]Alternatively, any external nonsubstantial component having a PCS ≤ 2.0 MJ/m^2, provided that the product satisfies the following criteria of EN 13823 (SBI): FIGRA ≤ 20 W/sec; and LFS < edge of specimen, and $THR_{600sec} \le 4.0$ MJ and s1 and d0.
[d]For any internal nonsubstantial component of nonhomogeneous products.
[e]For the product as a whole.
[f]In the last phase of the development of the test procedure, modifications of the smoke measurement system have been introduced, the effect of which needs further investigation. This may result in a modification of the limit values and/or parameters for the evaluation of smoke production.
s1 = SMOGRA ≤ 30m^2/sec^2 and $TSP_{600sec} \le 50$ m^2; s2 = SMOGRA ≤ 180 m^2/sec^2 and $TSP_{600sec} \le 200$ m^2; s3 = not s1 or s2.
[g]d0 = No flaming droplets/particles in EN 13283 (SBI) within 600 sec; d1 = No flaming droplets/particles persisting longer than 10 sec in EN 13823 (SBI) within 600 sec; d2 = not d0 or d1. Ignition of the paper in EN ISO 11925-2 results in a d2 classification.
[h]Pass = no ignition of the paper (no classification). Fail = ignition of the paper (d2 classification).
[i]Under conditions of surface flame attack and, if appropriate to the end-use application of the product, edge flame attack.

ΔT = temperature rise
Δm = mass loss
t_f = duration of flaming
PCS = gross calorific potential
FIGRA = fire growth rate
THR_{600sec} = total heat release
LFS = lateral flame spread
SMOGRA = smoke growth rate
TSP_{600sec} = total smoke production
F_s = flame spread

TABLE 6.3.7 European Community Classes of Reaction-to-Fire Performance for Construction Products for Floorings

Class	*Test Method(s)*	*Classification Criteria*	*Additional Classification*
$A1_{fl}$	EN ISO 1182[a] and	$\Delta T \leq 30°C$ and $\Delta m \leq 50\%$ and $t_f = 0$ (i.e., no sustained flaming)	—
	EN ISO 1716	PCS ≤ 2.0 MJ/kg[a] and PCS ≤ 2.0 MJ/kg[b] and PCS ≤ 1.4 MJ/m^2[c] and PCS ≤ 2.0 MJ/kg[d]	—
$A2_{fl}$	EN ISO 1182[a] or	$\Delta T \leq 50°C$ and $\Delta m \leq 50\%$ and $t_f \leq 20$ sec	—
	EN ISO 1716 and	PCS ≤ 3.0 MJ/kg[a] and PCS ≤ 4.0 MJ/m^2[b] and PCS ≤ 4.0 MJ/m^2[c] and PCS ≤ 3.0 MJ/kg[d]	—
	EN ISO 9239-1[e]	Critical flux[f] ≥ 8.0 kW/m^2	Smoke production[g]
B_{fl}	EN ISO 9239-1[e] and	Critical flux[f] ≥ 8.0 kW/m^2	Smoke production[g]
	EN ISO 11925-2[h] Exposure = 15 sec	$F_s \leq 150$ mm within 20 sec	—
C_{fl}	EN ISO 9239-1[e] and	Critical flux[f] ≥ 4.5 kW/m^2	Smoke production[g]
	EN ISO 11925-2[h] Exposure = 15 sec	$F_s \leq 150$ mm within 20 sec	—
D_{fl}	EN ISO 9239-1[e] and	Critical flux[f] ≥ 3.0 kW/m^2	Smoke production[g]
	EN ISO 11925-2[h] Exposure = 15 sec	$F_s \leq 150$ mm within 20 sec	—
E_{fl}	EN ISO 11925-2[h] Exposure = 15 sec	$F_s \leq 150$ mm within 20 sec	—
F_{fl}		No performance determined	

[a]For homogeneous products and substantial components of nonhomogeneous products.
[b]For any external nonsubstantial component of nonhomogeneous products.
[c]For any internal nonsubstantial component of nonhomogeneous products.
[d]For the product as a whole.
[e]Test duration = 30 minutes.
[f]Critical flux is defined as the radiant flux at which the flame extinguishes or the radiant flux after a test period of 30 minutes, whichever is the lower (i.e., the flux corresponding with the furthest extent of spread of flame).
[g]s1 = Smoke ≤ 750%·min; s2 = not s1.
[h]Under conditions of surface flame attack and, if appropriate to the end-use application of the product, edge flame attack.

ΔT = temperature rise
Δm = mass loss
t_f = duration of flaming
PCS = gross calorific potential
F_s = flame spread

radiant panel test. In North America such application tests or mounting practices have been incorporated into a variety of codes. One example is the use of ASTM E2231 as the standard mounting method for using ASTM E84 when testing pipe and duct insulation materials, which is now in widespread use. It is important to note that simple statements such as "testing in the composite form is required," without further detailed explanations, are of little use and are likely to lead to misinterpretations.

In North America, testing using small- or medium-scale fire tests is infrequently used, although a key exception is OSU testing by the Federal Aviation Administration. In contrast, the European Community has developed a "reference scenario" fire test, namely the ISO 9705 room-corner test, and uses other tests as surrogates. Table 6.3.5 shows the concept of what each class is intended to represent in the European Community standard testing approach. The specific classification schemes for construction products, for floorings, for linear pipe thermal insulation products, and for electric cables are shown in Tables 6.3.6 through 6.3.9, respectively. The information on these requirements can be found as part of the European Union directives.

TABLE 6.3.8 European Community Classes of Reaction-to-Fire Performance for Linear Pipe Thermal Insulation Products

Class	*Test Method(s)*	*Classification Criteria*	*Additional Classification*
$A1_L$	EN ISO 1182[a] and	$\Delta T \le 30°C$ and $\Delta m \le 50\%$ and $t_f = 0$ (i.e., no sustained flaming)	—
	EN ISO 1716	PCS ≤ 2.0 MJ/kg[a] and PCS ≤ 2.0 MJ/kg[b] and PCS ≤ 1.4 MJ/m^2[c] and PCS ≤ 2.0 MJ/kg[d]	—
$A2_L$	EN ISO 1182[a] or	$\Delta T \le 50°C$ and $\Delta m \le 50\%$ and $t_f \le 20$ sec	—
	EN ISO 1716 and	PCS ≤ 3.0 MJ/kg[a] and PCS ≤ 4.0 MJ/kg[b] and PCS ≤ 4.0 MJ/m^2[c] and PCS ≤ 3.0 MJ/kg[d]	—
	EN 13823 (SBI)	FIGRA ≤ 270 W/sec and LFS < edge of specimen and $THR_{600sec} \le 7.5$ MJ	Smoke production[e] and flaming droplets/particles[f]
B_L	EN 13823 (SBI) and	FIGRA ≤ 270 W/sec and LFS < edge of specimen and $THR_{600sec} \le 7.5$ MJ	Smoke production[e] and flaming droplets/particles[f]
	EN ISO 11925-2[h] Exposure = 30 sec	$F_s \le 150$ mm within 60 sec	
C_L	EN 13823 (SBI) and	FIGRA ≤ 460 W/sec and LFS < edge of specimen and $THR_{600sec} \le 15$ MJ	Smoke production[e] and flaming droplets/particles[f]
	EN ISO 11925-2[h] Exposure = 30 sec	$F_s \le 150$ mm within 60 sec	
D_L	EN 13823 (SBI)	FIGRA ≤ 2100 W/sec and $THR_{600sec} \le 100$ MJ	Smoke production[e] and flaming droplets/particles[f]
	EN ISO 11925-2[h] Exposure = 30 sec	$F_s \le 150$ mm within 60 sec	
E_L	EN ISO 11925-2[h] Exposure = 15 sec	$F_s \le 150$ mm within 20 sec	Flaming droplets/particles[f]
F_L		No performance determined	

[a]For homogeneous products and substantial components of nonhomogeneous products.
[b]For any external nonsubstantial component of nonhomogeneous products.
[c]For any internal nonsubstantial component of nonhomogeneous products.
[d]For the product as a whole.
[e]s1 = SMOGRA ≤ 105 m^2/sec^2 and $TSP_{600sec} \le 250$ m^2; s2 = SMOGRA ≤ 580 m^2/sec^2 and $TSP_{600sec} \le 1600$ m^2; s3 = not s1 or s2.
[f]d0 = No flaming droplets/particles in EN 13823 (SBI) within 600 sec; d1 = No flaming droplets/particles persisting longer than 10 sec in EN 13283 (SBI) within 600 sec; d2 = not d0 or d1. Ignition of the paper in EN ISO 11925-2 results in a d2 classification.
[g]Pass = no ignition of the paper (no classification). Fail = ignition of the paper (d2 classification).
[h]Under conditions of surface flame attack and, if appropriate to end-use application of product, edge flame attack.

ΔT = temperature rise
Δm = mass loss
t_f = duration of flaming
PCS = gross calorific potential
FIGRA = fire growth rate
THR_{600sec} = total heat release
LFS = lateral flame spread
SMOGRA = smoke growth rate
TSP_{600sec} = total smoke production
F_s = flame spread

TABLE 6.3.9 European Community Classes of Reaction-to-Fire Performance for Electrical Cables

Class	*Test Method(s)*	*Classification Criteria (9)*	*Additional Classification*
A_{ca}	EN ISO 1716	PCS ≤ 2.0 MJ/kg[a]	
$B1_{ca}$	$FIPEC_{20}$ scenario 2[e] and	F_S ≤ 1.75 m and $THR_{1200sec}$ ≤ 10 MJ and Peak HRR ≤ 20 kW and FIGRA ≤ 120 W/sec	Smoke production[b,f] and flaming droplets/particles[c] and acidity[d,h]
	EN 60332-1-2	H ≤ 425 mm	
$B2_{ca}$	$FIPEC_{20}$ scenario 1[e] and	F_S ≤ 1.5 m and $THR_{1200sec}$ ≤ 15 MJ and Peak HRR ≤ 30 kW and FIGRA ≤ 150 W/sec	Smoke production[b,f] and flaming droplets/particles[c] and acidity[d,h]
	EN 60332-1-2	H ≤ 425 mm	
C_{ca}	$FIPEC_{20}$ scenario 1[e] and	F_S ≤ 2.0 m and $THR_{1200sec}$ ≤ 30 MJ and Peak HRR ≤ 60 kW and FIGRA ≤ 300 W/sec	Smoke production[b,f] and flaming droplets/particles[c] and acidity[d,h]
	EN 60332-1-2	H ≤ 425 mm	
D_{ca}	$FIPEC_{20}$ scenario 1[e] and	$THR_{1200sec}$ ≤ 70 MJ and Peak HRR ≤ 400 kW and FIGRA ≤ 1300 W/sec	Smoke production[b,f] and flaming droplets/particles[c] and acidity[d,h]
	EN 60332-1-2	H ≤ 425 mm	
E_{ca}	EN 60332-1-2	H ≤ 425 mm	
F_{ca}	No performance determined		

[a]For the product as a whole, excluding metallic materials, and for any external component (i.e., sheath) of the product.
[b]s1 = TSP_{1200} ≤ 50 m^2 and Peak SPR ≤ 0.25 m^2/sec. s1a = s1 and transmittance in accordance with EN 61034-2 ≥ 80%. s1b = s1 and transmittance in accordance with EN 61034-2 ≥ 60% < 80%. s2 = TSP_{1200} ≤ 400 m^2 and Peak SPR ≤ 1.5 m^2/sec. s3 = not s1 or s2.
[c]For $FIPEC_{20}$ Scenarios 1 and 2: d0 = No flaming droplets/particles within 1200 sec; d1 = No flaming droplets/ particles persisting longer than 10 sec within 1200 sec; d2 = not d0 or d1.
[d]EN 50267-2-3: a1 = conductivity < 2.5 µS/mm and pH > 4.3 ; a2 = conductivity < 10 µS/mm and pH > 4.3; a3 = not a1 or a2. No declaration = No Performance Determined.
[e]Air flow into chamber shall be set to 8000 ± 800 L/min. $FIPEC_{20}$ Scenario 1 = prEN 50399-2-1:2003 with mounting and fixing as below. $FIPEC_{20}$ Scenario 2 = prEN 50399-2-2:2003 with mounting and fixing as below.
[f]The smoke class declared for class $B1_{ca}$ cables must originate from the $FIPEC_{20}$ Scenario 2 test.
[g]The smoke class declared for class $B2_{ca}$, C_{ca}, D_{ca} cables must originate from the $FIPEC_{20}$ Scenario 1 test.
[h]Measuring the hazardous properties of gases developed in the event of fire, which compromise the ability of the persons exposed to them to take effective action to accomplish escape, and not describing the toxicity of these gases.

ΔT = temperature rise
Δm = mass loss
t_f = duration of flaming
PCS = gross calorific potential
FIGRA = fire growth rate
THR_{600sec} = total heat release
LFS = lateral flame spread
SMOGRA = smoke growth rate
TSP_{600sec} = total smoke production
F_s = flame spread
FIPEC = "Fire Performance of Electrical Cables"[24]

SUMMARY

Fire testing has undergone a significant change between the 1980s and the start of the twenty-first century. Before the 1980s, it was normal to use old-fashioned tests that generate a simple test result, often with little correlation to the fire scenario being investigated. In modern fire testing, products are tested in ways that are as representative as possible of the end use in the field. That has led to the development of modern tests, often assessing heat release parameters and usually employing test specimens that are indicative of the assemblies the public uses.

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NFPA Fire Test Methods

Reference to the following NFPA codes, standards, and recommended practices will provide further information on concepts and protocols of fire testing discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents and for information on other NFPA codes, guides, standards, or recommended practices.)*

NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 252, *Standard Methods of Fire Tests of Door Assemblies*
NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 256, *Standard Methods of Fire Tests of Roof Coverings*
NFPA 257, *Standard on Fire Test for Window and Glass Block Assemblies*
NFPA 259, *Standard Test Method for Potential Heat of Building Materials*
NFPA 260, *Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture*
NFPA 261, *Standard Method of Test for Determining Resistance of Mock-Up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes*
NFPA 262, *Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces*
NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Coverings on Full Height Panels and Walls*
NFPA 268, *Standard Test Method for Determining Ignitability of Exterior Wall Assemblies Using a Radiant Heat Energy Source*
NFPA 269, *Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling*
NFPA 270, *Standard Test Method for Measurement of Smoke Obscuration Using a Conical Radiant Source in a Single Closed Chamber*
NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*
NFPA 272, *Standard Method of Test for Heat and Visible Smoke Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter*
NFPA 274, *Standard Test Method to Evaluate Fire Performance Characteristics of Pipe Insulation*
NFPA 285, *Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components*

NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*
NFPA 287, *Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using a Fire Propagation Apparatus (FPA)*
NFPA 288, *Standard Methods of Fire Tests of Floor Fire Door Assemblies Installed Horizontally in Fire Resistance-Rated Floor Systems*
NFPA 290, *Standard for Fire Testing of Passive Protection Materials for Use on LP-Gas Containers*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*
NFPA 703, *Standard for Fire Retardant-Treated Wood and Fire-Retardant Coatings for Building Materials*
NFPA 705, *Recommended Practice for a Field Flame Test for Textiles and Films*

References

ASTM Fire Test Standards for Building Products and Other Products

ASTM D2859, *Standard Test Method for Flammability of Finished Textile Floor Covering Materials*
ASTM D5865, *Standard Test Method for Gross Calorific Value of Coal and Coke*
ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials*
ASTM E108, *Standard Test Methods for Fire Tests of Roof Coverings*
ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials*
ASTM E136, *Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C*
ASTM E162, *Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source*
ASTM E648, *Standard Test Method for Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source*
ASTM E662, *Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials*
ASTM E814, *Standard Test Method for Fire Tests of Through-Penetration Fire Stops*
ASTM E906, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products*
ASTM E970, *Standard Test Method for Critical Radiant Flux of Exposed Attic Floor Insulation Using a Radiant Heat Energy Source*
ASTM E1317, *Standard Test Method for Flammability of Marine Surface Finishes*
ASTM E1321, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*
ASTM E1352, *Standard Test Method for Cigarette Ignition Resistance of Mock-Upholstered Furniture Assemblies*
ASTM E1353, *Standard Test Methods for Cigarette Ignition Resistance of Components of Upholstered Furniture*
ASTM E1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*
ASTM E1474, *Standard Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter*
ASTM E1529, *Standard Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies*
ASTM E1537, *Standard Test Method for Fire Testing of Upholstered Furniture*
ASTM E1590, *Standard Test Method for Fire Testing of Mattresses*
ASTM E1623, *Standard Test Method for Determination of Fire and Thermal Parameters of Materials, Products, and Systems Using an Intermediate Scale Calorimeter (ICAL)*
ASTM E1678, *Standard Test Method for Measuring Smoke Toxicity for Use in Fire Hazard Analysis*
ASTM E1725, *Standard Test Methods for Fire Tests of Fire-Resistive Barrier Systems for Electrical System Components*
ASTM E1740, *Standard Test Method for Determining the Heat Release Rate and Other Fire-Test-Response Characteristics of Wallcovering Composites Using a Cone Calorimeter*
ASTM E1822, *Standard Test Method for Fire Testing of Stacked Chairs*
ASTM E1966, *Standard Test Method for Fire-Resistive Joint Systems*
ASTM E1995, *Standard Test Method for Measurement of Smoke Obscuration Using a Conical Radiant Source in a Single Closed Chamber, with the Test Specimen Oriented Horizontally*
ASTM E2010, *Standard Test Method for Positive Pressure Fire Tests of Window Assemblies*
ASTM E2058, *Standard Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus (FPA)*
ASTM E2074, *Standard Test Method for Positive Pressure Fire Tests of Window Assemblies*
ASTM E2102, *Standard Test Method for Measurement of Mass Loss and Ignitability for Screening Purposes Using a Conical Radiant Heater*
ASTM E2187, *Standard Test Method for Measuring the Ignition Strength of Cigarettes*
ASTM E2257, *Standard Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies*
ASTM E2307, *Standard Test Method for Determining Fire Resistance of Perimeter Fire Barrier Systems Using Intermediate-Scale, Multi-Story Test Apparatus*
ASTM E2336, *Standard Test Methods for Fire Resistive Grease Duct Enclosure Systems*
ASTM E2405, *Standard Test Method for Determination of Fire and Thermal Parameters of Materials Using an Intermediate Scale Test with Vertically Oriented Specimen*
ASTM F1085, *Standard Specification for Mattress and Box Springs for Use in Berths in Marine Vessels*
ASTM F1550, *Standard Test Method for Determination of Fire-Test-Response Characteristics of Components or Composites of Mattresses or Furniture for Use in Correctional Facilities After Exposure to Vandalism, by Employing a Bench Scale Oxygen Consumption Calorimeter*

ASTM Fire Test Standards for Plastics, Cables, and Fabrics

ASTM D635, *Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Self-Supporting Plastics in a Horizontal Position*
ASTM D1230, *Standard Test Method for Flammability of Apparel Textiles*
ASTM D1929, *Standard Test Method for Determining Ignition Temperature of Plastics*
ASTM D2843, *Standard Test Method for Density of Smoke from the Burning or Decomposition of Plastics*
ASTM D2863, *Standard Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index)*
ASTM D3014, *Standard Test Method for Flame Height, Time of Burning, and Loss of Mass of Rigid Thermoset Cellular Plastics in a Vertical Position*
ASTM D3675, *Standard Test Method for Surface Flammability of Flexible Cellular Materials Using a Radiant Heat Energy Source*
ASTM D3801, *Standard Test Method for Measuring the Comparative Burning Characteristics of Solid Plastics in a Vertical Position*
ASTM D3874, *Standard Test Method for Ignition of Materials by Hot Wire Sources*
ASTM D4151, *Standard Test Method for Flammability of Blankets*
ASTM D4804, *Standard Test Method for Determining the Flammability Characteristics of Nonrigid Solid Plastics*

ASTM D4986, *Standard Test Method for Horizontal Burning Characteristics of Cellular Polymeric Materials*
ASTM D5048, *Standard Test Method for Measuring the Comparative Burning Characteristics and Resistance to Burn-Through of Solid Plastics Using a 125-mm Flame*
ASTM D5132, *Standard Test Method for Horizontal Burning Rate of Flexible Cellular and Rubber Materials Used in Occupant Compartments of Motor Vehicles*
ASTM D5238, *Standard Test Method for Smoldering Combustion Potential of Cotton-Based Batting*
ASTM D5424, *Standard Test Method for Smoke Obscuration of Insulating Materials Contained in Electrical or Optical Fiber Cables When Burning in a Vertical Cable Tray Configuration*
ASTM D5485, *Standard Test Method for Determining the Corrosive Effect of Combustion Products Using the Cone Corrosimeter*
ASTM D5537, *Standard Test Method for Heat Release, Flame Spread, Smoke Obscuration, and Mass Loss Testing of Insulating Materials Contained in Electrical or Optical Fiber Cables When Burning in a Vertical Cable Tray Configuration*
ASTM D6113, *Standard Test Method for Using a Cone Calorimeter to Determine Fire-Test-Response Characteristics of Insulating Materials Contained in Electrical or Optical Fiber Cables*
ASTM D6194, *Standard Test Method for Glow-Wire Ignition of Materials*
ASTM D6413, *Standard Test Method for Flame Resistance of Textiles (Vertical Test)*
ASTM D6545, *Standard Test Method for Flammability of Textiles Used in Children's Sleepwear*
ASTM D7016, *Standard Test Method for Evaluate Edge Binding Components Used in Mattresses After Exposure to an Open Flame*
ASTM D7140, *Standard Test Method to Measure Heat Transfer Through Textile Thermal Barrier Materials*

ISO Fire Test Standards for Building Products

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ISO 834-5, *Standard Fire-Resistance Tests—Elements of Building Construction—Part 5: Specific Requirements for Loadbearing Horizontal Separating Elements*
ISO 834-6, *Standard Fire-Resistance Tests—Elements of Building Construction—Part 6: Specific Requirements for Beams*
ISO 834-7, *Standard Fire-Resistance Tests—Elements of Building Construction—Part 7: Specific Requirements for Columns*
ISO 834-8, *Standard Fire-Resistance Tests—Elements of Building Construction—Part 8: Specific Requirements for Non-Loadbearing Vertical Separating Elements*
ISO 834-9, *Standard Fire-Resistance Tests—Elements of Building Construction—Part 9: Specific Requirements for Non-Loadbearing Ceiling Elements*
ISO 1182, *Standard Reaction to Fire Tests for Building Products—Non-Combustibility Test*
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ISO 3008, *Standard Fire-Resistance Tests—Door and Shutter Assemblies*
ISO 3009, *Standard Fire-Resistance Tests—Elements of Building Construction—Glazed Elements*
ISO 4736, *Standard Fire Tests—Small Chimneys—Testing at Elevated Temperatures*
ISO 5657, *Standard Reaction to Fire Tests—Ignitability of Building Products Using a Radiant Heat Source*
ISO 5658-2, *Standard Reaction to Fire Tests—Spread of Flame—Part 2: Lateral Spread on Building Products in Vertical Configuration*
ISO 5658-4, *Standard Reaction to Fire Tests—Spread of Flame—Part 4: Intermediate-Scale Test of Vertical Spread of Flame with Vertically Oriented Specimen*
ISO 5660-1, *Standard Reaction-to-Fire Tests—Heat Release, Smoke Production and Mass Loss Rate—Part 1: Heat Release Rate (Cone Calorimeter Method)*
ISO 5660-2, *Standard Reaction-to-Fire Tests—Heat Release, Smoke Production and Mass Loss Rate—Part 2: Smoke Production Rate (Dynamic Measurement)*
ISO 5660-3, *Standard Reaction-to-Fire Tests—Heat Release, Smoke Production and Mass Loss Rate—Part 3: Guidance on Measurement*
ISO 5924, *Standard Fire Tests—Reaction to Fire—Smoke Generated by Building Products (Dual-Chamber Test)*
ISO 5925-1, *Standard Fire Tests—Evaluation of Performance of Smoke Control Door Assemblies—Part 1: Ambient Temperature Test*
ISO/TR 5925-2, *Standard Fire Tests—Smoke Control Door and Shutter Assemblies—Part 2: Commentary on Test Method and Test Data Application*
ISO/TR 6167, *Standard Fire-Resistance Tests—Contribution Made by Suspended Ceilings to the Protection of Steel Beams in Floor and Roof Assemblies*
ISO 6944, *Standard Fire Resistance Tests—Ventilation Ducts*
ISO 9239-1, *Standard Reaction to Fire Tests for Floorings—Part 1: Determination of the Burning Behaviour Using a Radiant Heat Source*
ISO 9239-2, *Standard Reaction to Fire Tests for Floorings—Part 2: Determination of Flame Spread at a Heat Flux Level of 25 Kw/M2*
ISO 9705, *Standard Fire Tests—Full-Scale Room Test for Surface Products*
ISO 10294-1, *Standard Fire Resistance Tests—Fire Dampers for Air Distribution Systems—Part 1: Test Method*
ISO 10294-2, *Standard Fire Resistance Tests—Fire Dampers for Air Distribution Systems—Part 2: Classification, Criteria and Field of Application of Test Results*
ISO 10294-4, *Standard Fire Resistance Tests—Fire Dampers for Air Distribution Systems—Part 4: Test of Thermal Release Mechanism*
ISO 10294-5, *Standard Fire Resistance Tests—Fire Dampers for Air Distribution Systems—Part 5: Intumescent Fire Dampers*
ISO 11925-2, *Standard Reaction to Fire Tests—Ignitability of Building Products Subjected to Direct Impingement of Flame—Part 2: Single-Flame Source Test*
ISO 11925-3, *Standard Reaction to Fire Tests—Ignitability of Building Products Subjected to Direct Impingement of Flame—Part 3: Multi-Source Test*
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ISO 12468-2, *Standard External Fire Exposure to Roofs—Part 2: Classification of Roofs*
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ISO 13784-1, *Standard Reaction-to-Fire Tests for Sandwich Panel Building Systems—Part 1: Test Method for Small Rooms*
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ISO 13785-1, *Standard Reaction-to-Fire Tests for Façades—Part 1: Intermediate-Scale Test*
ISO 13785-2, *Standard Reaction-to-Fire Tests for Façades—Part 2: Large-Scale Test*
ISO/TR 14696, *Standard Reaction to Fire Tests—Determination of Fire Parameters of Materials, Products and Assemblies Using an Intermediate-Scale Heat Release Calorimeter (ICAL)*
ISO/TR 15655, *Standard Fire Resistance—Tests for Thermo-Physical and Mechanical Properties of Structural Materials at Elevated Temperatures for Fire Engineering Design*
ISO 17554, *Standard Reaction to Fire Tests—Mass Loss Measurement*
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ISO 871, *Standard for Plastics—Determination of Ignition Temperature Using a Hot-Air Furnace*
ISO 4589-2, *Standard for Plastics—Determination of Burning Behaviour by Oxygen Index—Part 2: Ambient-Temperature Test*
ISO 4589-3, *Standard for Plastics—Determination of Burning Behaviour by Oxygen Index—Part 3: Elevated-Temperature Test*
ISO 5659-2, *Standard for Plastics—Smoke Generation—Part 2: Determination of Optical Density by a Single-Chamber Test*
ISO/TR 5659-3, *Standard for Plastics—Smoke Generation—Part 3: Determination of Optical Density by a Dynamic-Flow Method*
ISO 9772, *Standard for Cellular Plastics—Determination of Horizontal Burning Characteristics of Small Specimens Subjected to a Small Flame*
ISO 9773, *Standard for Plastics—Determination of Burning Behaviour of Thin Flexible Vertical Specimens in Contact with a Small-Flame Ignition Source*
ISO 11907-2, *Standard for Plastics—Smoke Generation—Determination of the Corrosivity of Fire Effluents—Part 2: Static Method*
ISO 11907-3, *Standard for Plastics—Smoke Generation—Determination of the Corrosivity of Fire Effluents—Part 3: Dynamic Decomposition Method Using a Travelling Furnace*
ISO 11907-4, *Standard for Plastics—Smoke Generation—Determination of the Corrosivity of Fire Effluents—Part 4: Dynamic Decomposition Method Using a Conical Radiant Heater*
ISO 12992, *Standard for Plastics—Vertical Flame Spread Determination for Film and Sheet*
ISO 13927, *Standard for Plastics—Simple Heat Release Test Using a Conical Radiant Heater and A thermopile Detector*
IEC 60695-11-10, *Standard for Fire Hazard Testing—Part 11-10: Test Flames—50 W Horizontal and Vertical Flame Test Methods*
IEC 60695-11-20, *Standard for Fire Hazard Testing—Part 11-20: Test Flames—500 W Flame Test Methods*

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UL 9, *Standard for Fire Tests of Window Assemblies*
UL 10B, *Standard for Fire Tests of Door Assemblies*
UL 10C, *Standard for Positive Pressure Fire Tests of Door Assemblies*
UL 94, *Standard for Tests for Flammability of Plastic Materials for Parts in Devices and Appliances*
UL 214, *Standard Tests for Flame-Propagation of Fabrics and Films (withdrawn)*
UL 263, *Standard for Fire Tests of Building Construction and Materials*
UL 723, *Standard for Test for Surface Burning Characteristics of Building Materials*
UL 790, *Standard Test Methods for Fire Tests of Roof Coverings*
UL 910, *Standard for Fire and Smoke Characteristics of Electrical and Optical Fiber Cables in Air Handling Spaces (withdrawn)*
UL 1056, *Standard for Fire Test of Upholstered Furniture (withdrawn)*
UL 1479, *Standard for Fire Tests of Through-Penetration Firestops*
UL 1666, *Standard Test for Flame Propagation Height of Electrical and Optical-Fiber Cable Installed Vertically in Shafts*
UL 1709, *Standard for Rapid Rise Fire Tests of Production Materials for Structural Steel*
UL 1715, *Standard for Fire Test of Interior Finish Material*
UL 1820, *Standard for Fire Test of Pneumatic Tubing for Flame and Smoke Characteristics*
UL 1887, *Standard for Fire Test of Plastic Sprinkler Pipe for Flame and Smoke Characteristics*
UL 1895, *Standard for Fire Test of Mattresses (withdrawn)*
UL 1975, *Standard for Fire Tests for Foamed Plastics Used for Decorative Purposes*
UL 2024, *Standard for Optical Fiber and Communication Cable Raceway*
UL 2043, *Standard for Fire Test for Heat and Visible Smoke Release for Discrete Products and Their Accessories Installed in Air-Handling Spaces*
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UL 2360, *Standard for Test Methods for Determining the Combustibility Characteristics of Plastics Used in Semi-Conductor Tool Construction*

Chapter 4

Wood and Wood-Based Products

John M. Cholin

Chapter Contents

Nature of Wood and Wood-Based Products
Physical Nature of Wood
Variables Influencing Combustibility
Ignition of Wood and Wood Products
Combustion of Wood and Wood-Based Materials

Key Terms

bound water, cellulose, fire resistance, flame propagation, flame spread, forest product, free water, heat release rate (HRR), spontaneous heating, thermal conductivity, water of constitution, wood, wood-based products, wood by-products, wood composite products

Wood, arguably the first structural material to be used by prehistoric man, is still arguably the single most versatile structural material in use today. It is light in weight, strong, durable, flexible, and resilient, yet it possesses an intrinsic beauty. These characteristics have made it a persistent first choice construction material. Furthermore, once dwelling spaces are constructed, those spaces are filled with furnishings that are often constructed of wood and wood products. The fact that this material is truly ubiquitous in modern society necessitates a thorough understanding of both its nature as a fuel and its behavior as a structural material under conditions of fire exposure.

One reason wood and wood products have been so universally adopted as a structural material is the fact that they can be processed into so many different forms that take specific advantage of the unique chemical and physical characteristics of wood as a raw material. The wood from a wide variety of trees can be transformed into structural timbers, dimension lumber, shingles, and veneers. These are called *primary forest products,* as only cutting and drying are required to derive these products from the log.

Raw wood can be used to make a variety of wood-based building products, including multiple-ply glue-laminations, fiberboard, insulation board, ceiling tile, plywood, flakeboard, strandboard, and particleboard. Each of these forms of wood has specific structural characteristics that makes it the material of choice for specific applications. These products are often referred to as *secondary forest products,* since secondary processes are necessary over and above cutting and drying to result in the product.

Primary and secondary forest products are usually not consumed directly. They are the material from which directly consumed products are constructed. The primary examples of these are housing and furnishings. Lumber, a primary forest product, is cut and shaped and assembled with other components to ultimately become a finished piece of furniture. Occasionally these are referred to as *tertiary forest products.*

The unique chemical composition of wood makes it possible to process it into materials that have no resemblance to the log from which they came. Wood is the major raw material source for paper and paper-based products, such as cardboard, box board, and corrugated board used in containers. Paper, used alone or combined with metal foils and plastics, is employed in the manufacture of many hundreds of products, including writing and wrapping papers, magazines, books, bags, wall coverings, and labels. Furthermore, when exposed to the appropriate chemical treatment, wood yields a material called cellulose, which is the fundamental raw material for a wide variety of products, including transparent films (e.g., Saran Wrap®), motion picture film, textile fibers, explosives and propellants, coatings, plastics, and foodstuffs.

Because wood and its cellulose derivatives are found in such a wide range of forms, it should come as no surprise that they are frequently involved in fires. The discussion of wood in this chapter is limited to solid wood and wood-based materials, including paper and paper derivatives. This chapter will address the chemistry of cellulose, the process of ignition of wood and cellulosic materials, and the behavior as a structural component under conditions of fire exposure. Those

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interested in a more detailed treatment on the subject should consult the list of references at the end of this chapter.

See the following chapters for related topics: In Section 6 see Chapter 2, "Combustion Products and Their Effects on Life Safety"; Chapter 5, "Fibers and Textiles"; Chapter 7, "Fire-Retardant and Flame-Resistant Treatment of Cellulosic Materials"; Chapter 8, "Dusts"; Chapter 13, "Polymeric Materials"; Chapter 15, "Explosives and Blasting Agents." See also Section 7, Chapter 1, "Storage and Handling of Solid Fuels"; Section 9, Chapter 1, "Woodworking Facilities and Processes"; Section 9, Chapter 2, "Spray Finishing and Powder Coating"; and Section 13, Chapter 5, "Wildland Fire Management."

NATURE OF WOOD AND WOOD-BASED PRODUCTS

To understand the behavior of forest products, both as fuel and as structural material under exposure to fire, one must start with an understanding of the material called "wood." This understanding starts with the chemistry of its principal component, cellulose.

Chemical Composition of Wood

Cellulose is a naturally occurring polymer constructed from the simple sugar, glucose. Its chemical structure is shown in Figure 6.4.1.[1]

The individual molecules of glucose are chemically linked together during the growth process of the living cell to produce a long-chain polymer, cellulose. In most cases, the average cellulose molecule is between 300 and 3000 glucose units long.[2] The long-chain polymer cellulose molecules are organized in bundles of parallel chains called fibrils. The fibrils are linked together via hydrogen bonding through a water molecule (Figure 6.4.2).

Adjacent fibrils are cemented together by the living cell with special linking polymeric molecules consisting of hemicelluloses and pectins, also called lignin. These polymeric chemicals bind adjacent fibrils together into a mat or sheet that forms the cell wall of the plant cell. The cells of the living plant are organized into long strands, like a string of pearls, and this gives rise to the cellulose fiber.

A collection of complex polymeric aromatic alcohols, called lignin, binds adjacent cellulose fibers together, forming a matrix around and between adjacent cellulose fibers. This matrix can be imagined as being similar to a microscopic plate of spaghetti, where the noodles are the cellulose fibers and the sauce is the lignin polymers, binding the fibers together. It is a structure that is not unlike glass fiber–reinforced plastic (fiberglass), and results in the wood fiber.

The cellulose molecule also has numerous hydrogen bonding sites along its length.[2] Wherever an –OH group exists along the length of the cellulose molecule, there exists a site where hydrogen bonding via an adsorbed water molecule can serve to bind adjacent cellulose fibers together. The combined effect of the hydrogen bonding via adsorbed water molecules and the chemical linkage formed by the lignin polymers binds adjacent wood fibers together into the material known as wood.

Obviously, wood is a complex structure with tremendous strength for its weight. It consists of bundles of hollow fibers, cemented together along their length, forming a rigid, yet flexible, structure (Figure 6.4.3).

Although wood is a complex of many substances, cellulose [chemical formula $(C_6H_{10}O_5)_x$] represents its major component. Hemicellulose is a five-carbon sugar consisting of carbon, oxygen, and hydrogen. Lignins are aromatic alcohols, also consisting of carbon, oxygen, and hydrogen. Consequently, the majority of the mass of any sample of dry wood consists primarily of carbon, hydrogen, and oxygen, with a small percentage of nitrogen from cellular proteins. There are small quantities of other elements that remain as an ash when wood is burned. It is interesting to note that untreated wood contains virtually no sulfur, distinguishing it from most other solid fuels (Table 6.4.1).

A sample of wood minus all water contains, on average, 50 percent cellulose by weight. Soft woods contain between 23 and

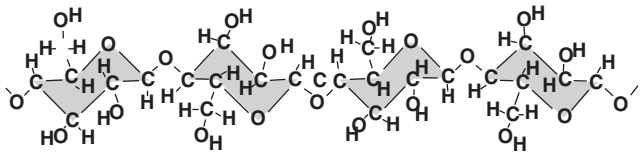

FIGURE 6.4.1 Cellulose, a Polymer of Glucose Units Produced by Plants

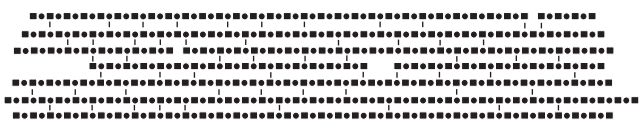

FIGURE 6.4.2 Cellulose Fibril

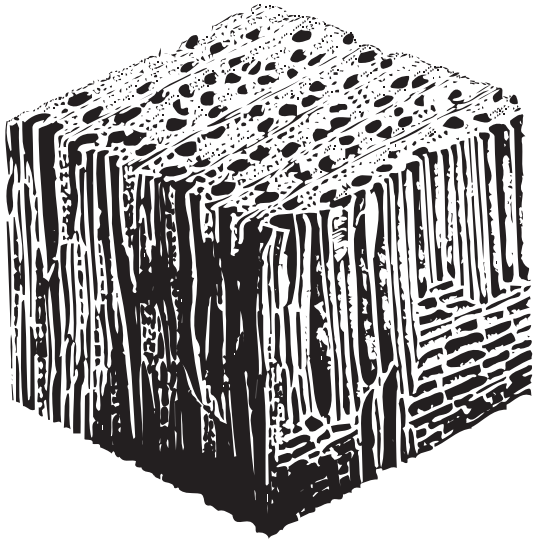

FIGURE 6.4.3 Photomicrograph of Red Oak

TABLE 6.4.1 Chemical Composition of Woods, Exclusive of Water

	Constituents (Percent by Weight)				
Species	*Carbon*	*Hydrogen*	*Oxygen*	*Nitrogen*	*Ash*
Oak	50.16	6.02	43.26	0.09	0.37
Ash	49.18	6.27	43.19	0.07	0.57
Elm	48.99	6.20	44.25	0.06	0.50
Beech	49.06	6.11	44.17	0.09	0.57
Birch	48.88	6.06	44.67	0.10	0.29
Pine	50.31	6.20	43.08	0.04	0.37
Poplar	49.37	6.21	41.60	0.96	1.86
Calif. redwood	53.50	5.90	40.30	0.10	0.20
Western hemlock	50.40	5.80	41.40	0.10	2.20
Douglas fir	52.30	6.30	40.50	0.10	0.80

33 percent lignin, by weight, whereas hardwoods contain between 16 and 25 percent.[3] Lignin is a three-dimensional phenylpropane that is critical in binding cellulose polymers together. Another 10 to 25 percent, depending on species, is hemicellulose. Different tree species yield slightly different percentages, but these values can be thought of as the average. In addition to the components noted, there are the *extractives.* These constituents include a wide range of organic compounds that vary widely with tree species and give the wood its characteristic color, aroma, rot resistance, and other characteristics. Finally, there is the inorganic constituent that generally comprises between 0.2 and 1.0 percent by weight. This takes the form of calcium, potassium, and magnesium salts, as well as trace quantities of phosphorous, sodium, iron, silicon, manganese, copper, zinc, and perhaps a few other elements derived from the soil.[3] The ash left over from burning wood is the mineral component and is primarily potash, potassium carbonate, with the remainder being the trace elements already mentioned.

Some woods, especially the soft woods (pines, spruces, and true firs), are quite resinous, with commensurately higher levels of the extractives and lower levels of hemicellulose and lignin. In these woods, the resins can become quite volatile, especially at elevated temperatures. In contrast, most hardwoods contain such small quantities of extractives that they are of little, if any, consequence to the fire protection specialist.

The major difference between various woods depends largely on the density (specific gravity) of the wood produced by a particular species of tree. This variation in density is related to cell wall thickness and translates into the dimensional stability and strength of that particular species of wood. The other species-dependent differences are the quantity and chemical composition of the extractives. In some species, these extractives are resinous materials, which produce combustible vapors. These vapors can produce hazardous atmospheres under the right conditions of temperature and confinement. Furthermore, some resins undergo an exothermic condensation reaction, which has been suspected to be the cause of spontaneous ignition in certain wood products, for example, piled chips of southern pine used in making paper.

Moisture Content

Wood exhibits a natural affinity for water and always contains significant quantities of moisture. Water plays an important part in the physical properties of wood through its contribution to the bonding between adjacent cellulose molecules. When the tree is alive, much of the space within the cells is occupied by water. However, when the log is cut, this moisture begins leaving the wood. The water in the cell interiors is slowly replaced by air. The moisture content varies with species and the degree that the sample has been dried. Regardless of prior processing, wood will always come to equilibrium with its environment. The energy liberated during the combustion of a wood sample is a net heat release, being the remainder after the energy expenditure of driving off the water component of the sample.

The water in a wood sample is generally categorized as *free water, bound water,* and *water of constitution.*[4] *Free water* is liquid water in the living tree (green wood) that is absorbed within the cellular structure of the wood and is free to flow through the cellular spaces and within the tubular veins that convey nutrients along the length of the sample, from the roots to the leaves. This water is readily able to flow from the wood sample and is in excess of the fiber saturation water that is chemically bound to the cellulose that comprises the wood. Free water readily leaves the log through air-drying. As the log dries, air replaces the free water within the veins and cells of the sample.

Bound water is water that exists in the form of adsorbed vapor, found in the veins and cell cavities, as well as adsorbed by the cell walls. The maximum amount of bound water in a sample is called the fiber saturation point (FSP) and represents that moisture content at which water begins to accumulate as liquid in the cellular spaces of the wood sample. The fiber saturation point is a characteristic of the species of tree from which the wood was obtained. At FSP a sample may still contain between 25 and 30 percent water, by weight. This moisture is called bound water since it is hygroscopically bound to the cellulose molecules by relatively weak hydrogen bonds. Bound water will slowly leave the log or board at a rate determined by the temperature, relative humidity and sample thickness. In temperate climates, air drying, given enough time, can achieve moisture contents as low as 10 percent, by weight, for most species. A kiln is usually used to accelerate the drying process.

As the moisture content approaches approximately 7 percent, by weight, very little additional moisture is lost with increases in temperature or duration of heating. The moisture content below the range of 5 to 7 percent is called the *water of constitution.* This water forms bonds between adjacent cellulose molecules and contributes to the structural strength of the wood fiber. This water cannot be removed without the physical destruction of the wood. Consequently, even "dry" wood always contains some moisture.

Construction lumber is considered to be dry at 19 percent moisture content (MC), but wood used for furniture is dried to 7 percent moisture content or less. Moisture content in wood is usually calculated as a percentage of the oven dry weight by the formula:

$$\text{MC} = \left(\frac{\text{Original weight} - \text{Dry weight}}{\text{Dry weight}}\right)100\%$$

Thus the moisture content is expressed as a percentage "dry basis," signifying that the basis for the percentage is the dry weight at which all of the bound water has been driven off.

Wood reaches an equilibrium moisture content (EMC) with its surroundings at a given temperature and relative humidity. In a heated building, the EMC of structural wood members is usually slightly less than 10 percent moisture content in the winter months and about 12 percent moisture content in the summer. The lumber in a newly constructed building is generally wetter than that in a building that has existed for some time. The moisture in wood is not uniformly distributed, and wood is often drier or wetter at the surface than in its interior. Surface layers, which control ignition and flame spread, respond much faster to changes in atmospheric conditions than the interior; thus, bulk moisture content measurement must be considered with this fact in mind. Figure 6.4.4 illustrates conditions under which equilibrium will be established at three different temperatures.

Air-dried wood usually attains a moisture content of approximately 10 percent water by weight. If wood is dried to a moisture content below this nominal 10 percent, in a kiln, for example, it will immediately begin absorbing moisture from the air when it is removed from the kiln. The overwhelming majority of the wood found in structures, either as part of the structure or contents, will be dried, usually kiln dried, and can be assumed to be at a nominal 8 to 10 percent (by weight) moisture content. A small variation about the nominal 10 percent moisture content has very little influence on the ignitability and heat release of wood. It does, however, affect the dimensions and strength of a given piece of wood substantially. This creates the incentive to dry wood to a minimum moisture content and maintain that level, especially with woods used for interior furnishings.

The level of moisture in a wood sample can have an impact on the ignition and combustion of that sample. "Green" wood, that which has not been dried, often contains as much as 50 percent water by weight. This free water boils off as the sample burns, absorbing a significant portion of the heat generated by the combustion of the cellulosic content. Dry wood is devoid of the free water and much of the bound water. Furthermore, the bound water effectively exists as vapor, not liquid, and does not have the ability to absorb heat through vaporization. This results in a combustible material with a significantly greater heat output during a fire.

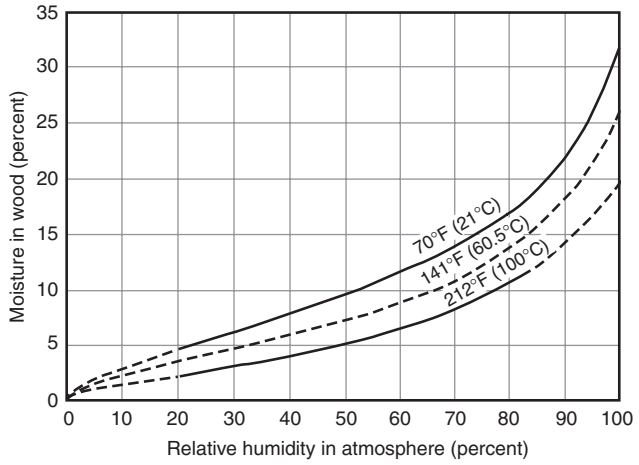

FIGURE 6.4.4 Equilibrium Moisture Content of Wood

Moisture content has an important bearing on the electrical properties of wood. Dry wood is a good insulator, but wet wood is a conductor. The electrical resistance of wood increases in approximate proportion to decreasing moisture content, from 25 percent down to about 6 percent moisture content, where it becomes too high to measure with a resistance moisture meter.

The rate of moisture loss or gain depends a great deal on the size and shape of the wood product. Some finely divided cellulosic materials absorb or lose moisture very rapidly, and their combustibility can vary from low to high within just a few hours. Examples are shredded newspaper, tissues, and loose forest litter (duff). Dense and compact combustibles, such as books or large timbers, change moisture content much more slowly. Rate of moisture loss depends on the relative humidity, the temperature, and the air velocity. Moisture loss is quite slow in air drying where there is no control over air velocity, temperature, or relative humidity; lumber may require 30 days or more to dry in such an environment. But in a kiln, where humidity, temperature, and air velocity can be adjusted, lumber can be dried in less than 24 hours. As a general rule of thumb, the amount of time required to dry lumber varies with the square of the thickness. Thus, a 1-in. (25.4-mm) thick board can be air dried in a few weeks, but a railroad crosstie or large timber requires 24 to 30 months. If wood is dried below the EMC it will reach in service, it will regain moisture slowly until it reaches that EMC.

Wood Derivatives

The chemical nature of wood and its cellulose is the basis for the diverse range of materials that are directly derived from wood. Most papers are made by a chemical process that removes the lignin and hemicellulose from the wood, yet leaves the cellulose fibers intact. This delignined cellulose is called "alpha-cellulose." These fibers are suspended in water and spread out in a thin layer. The layer is passed through sets of rollers that squeeze out the free water, and then through a dryer that drives off much of the remaining interstitial water, resulting in a sheet of paper. The cellulose fibers are held together, forming the sheet of paper, by the hydrogen bonds and the water bound to the cellulose. Newsprint is made by a process in which the fibers are separated by a mechanical or grinding process, that is, no chemicals are used. Some papers are made without any performance-modifying additives, for example, absorbent papers. However, most paper products contain performance-modifying additives, such as binders (wet-strength resins), fillers (clay), pigments (titanium dioxide), colorants (dyes), sizes (rosin, starch), and coatings (paraffins or plastics).

Wood is used as the primary feedstock for the production of purified cellulose. Purified wood cellulose fiber is used in dis-

posable sanitary applications, such as baby diapers and feminine protection products. Purified cellulose is a common ingredient of many food products where it is used to thicken liquids and to improve the texture of foods. It is commonly found in diet aids where it serves as a bulking agent and a source of dietary fiber. Many cellulose-based products are not discernible as being made from wood or paper. Chemically modified cellulose gives rise to such materials as nitrocellulose lacquers; cellulose acetate films; textiles and plastics; rayon textiles; cellophane; and smokeless powder used in small-arms cartridges.

Wood cellulose can be broken down to glucose, using appropriate chemical techniques, to make molasses suitable for cattle feed supplements, or fermented to make ethyl alcohol (grain alcohol). The hemicellulose portion of wood (composed of five-carbon sugars, such as xylose) can be fermented to make methylethylketone (MEK) or butyl alcohol (butanol), which are used as solvents.

Destructive distillation of wood releases the extractives and other products of the pyrolytic decomposition of wood. This process produces charcoal, methanol (wood alcohol), acetic acid, formic acid, and wood creosote, as well as a low-heat-output fuel that could be used to power internal combustion engines. Other processes are used to produce turpentine and rosin, known as naval stores, from standing pine trees, old stumps, or from the by-products of the manufacture of kraft paper by the sulfate process.

Wood-based products, paper, and paper-based products generally contain much less moisture than the wood from which they are derived, making them easier to ignite and more combustible than solid wood.

Wood By-Products

Bark is often encountered in the context of wood-waste utilization and specialty construction materials. Bark is an important by-product of forest products processing. It is often used for fuel in forest products facilities. Bark differs both structurally and chemically from wood. It consists of a cellulosic material called suberin, which finds use in the form of cork. Commercial cork, obtained from the bark of the cork oak, is resistant to high temperatures and ignition and burns with difficulty. Cork contains a natural adhesive that allows small particles to be bonded under heat and pressure to make composition cork. Bark and cork generally have lower moisture contents than wood. Bark is of commercial significance in that it contains tannin, which is extracted and used in the curing of leather.

Many other fibrous cellulosic materials behave in a manner similar to that of wood, and consequently can be included in this chapter. These materials include bagasse (spent sugar cane stalks), jute, hemp, and sisal. These materials have burning characteristics similar to wood-based materials. These and other similar products are often used as a source of fiber for construction materials, papers, and insulating materials. As with more traditional wood-derived materials, these fibers may be impregnated, pressure treated, or coated with a variety of chemicals, potentially altering the ignition and burning characteristics of such materials.

PHYSICAL NATURE OF WOOD

The cellular structure of wood provides a material that is light and strong. It appears to be an ideal structural material. However, it is not without its shortcomings, and it is these shortcomings that have precipitated the development of engineered wood-based materials.

Mechanical Properties

Although wood is strong, its strength is very dependent on the orientation of the stress relative to the grain of the piece under consideration.[5] The modulus of compressibility is good along the grain, but poor across the grain. The structural strength characteristics of wood are dependent on the moisture content. If the moisture content of a sample is allowed to stay above the fiber saturation point, removal of moisture has little effect on wood, other than to reduce its weight. However, once the moisture content is brought below the fiber saturation point, the strength properties improve considerably.

Solid wood is preferred where the nature of wood is consistent with the use. These are applications where strength versus weight, ease of fastening, and environmental endurance make it the most economical approach. Wood products made from solid wood include lumber, timbers, mine timbers, railroad ties, poles, and pilings. Other applications are driven by aesthetic concerns, such as upscale furnishings. Other solid-wood products are barrels, boxes, crates, and similar containers. Each of these uses takes advantage of specific and often unique characteristics of wood or a species of wood and the economies gained from those characteristics. Hardwoods are used primarily for selected interior finish applications, furniture, and as feedstock for cellulose fiber for engineered wood products and specialty papers. Softwoods are more commonly used for structural building components, such as timbers, beams, joists, and studs. They are also the wood of choice for mine timbers, railroad ties, pilings, and other uses where large dimensions are required.

Secondary wood products are designed to address one or more of the shortcomings of primary stock. Lumber dimensions vary with moisture content and the dimensional variation is dependent upon the orientation of the grain. This dimensional instability can be addressed by using wood products made from thin sheets of wood (veneer) bonded together with adhesives. These materials are termed *plywood* and *laminated veneer lumber* (LVL). Present-day large structural wood beams are often made from laminations of smaller dimension lumber.

The percentage utilization of a log is increased when it is converted to smaller particles that are bonded together with an adhesive resin. This yields an engineered wood composite material. Consequently, both the cost and dimensional properties of primary wood can be improved by conversion to a wood composite material. These materials are produced from wood that has been mechanically reduced in size to form flakes, strands, splinters, fibers, or particles. They are then mixed with thermoset plastic resins and processed to form a wood composite material with specific mechanical properties. This category includes a wide range of materials, such as flakeboard, oriented strand

board (OSB), medium-density fiberboard (MDF), particleboard, fiberboard, and hardboard.

Thermal (Heat) Conductivity

Thermal conductivity (*K* factor—the inverse of insulating value, *R* factor) of a particular material greatly influences how a material will burn. Thermal conductivity is a measure of the rate at which absorbed heat flows through the mass of material. Wood is a poor conductor of heat and thus has a high insulating value. The thermal conductivity of wood differs depending on whether the heat flow is across the grain or along the grain. It is also affected by density and moisture content. For most species the across-grain thermal conductivity can be computed from:

$$\lambda = \frac{(0.195\rho + 25.5)}{1000}$$

where

λ = Thermal conductivity, measured in W/m°K

ρ = Density, measured in kg/m^3

This relation provides a reasonably good fit to published experimental data.[6] The thermal conductivity along the grain is usually taken to be approximately 1.8 times that across the grain. Once the wood has charred, its thermal conductivity changes and can be quantified with the following relation:[6]

$$\lambda = 0.67S - 0.71$$

where

λ = Thermal conductivity, measured in W/m°K

S = Specific gravity of the char, roughly $\rho/1000$, when ρ is measured in kg/m^3

Thermal conductivity of wood in any direction is about one-third greater for moisture content above 30 percent than for drier wood.

The poor thermal conductivity of wood is a significant factor in the notably good performance heavy timber construction provides during a fire. When the exterior surface of a timber is exposed to the heat of a fire, the insulating nature of the wood slows the temperature rise of the core of the timber. Furthermore, the surface of the timber forms a char layer, which improves the *R*-factor of the timber and prevents atmospheric oxygen from penetrating into the timber, where it can support combustion.

The heat capacity of wood is predicted from the following relation:[6]

$$C = \frac{0.1031 + 0.003867T + 4.19M}{1 + M} + (0.02355T - 1.32M - 6.191)M$$

where

C = Heat capacity, measured in kJ/kg°K

M = Moisture content expressed as a fraction of dry weight

T = Temperature measured in °K

Once the wood becomes charred, the heat capacity, *C,* is usually taken to be 1.0, although there is a more precise relationship that expresses the heat capacity as a function of sample temperature:[6]

$$C = 1.39 + 0.00036T$$

where

C = Heat capacity, expressed in units of kJ/kg°K

T = Temperature in °K

Effect of Fire Retardants

Fire-retardant chemicals can be, and frequently are, added or applied to wood and wood-based products. (See Section 6, Chapter 7, "Fire-Retardant and Flame-Resistant Treatment of Cellulosic Materials.") When properly formulated and used, fire-retardant chemicals reduce the combustibility of these products. Depending on the formulations used, flame and surface combustion can be reduced once the outside source of heat is removed. Some fire-retardant treatments (FRTs) may adversely affect the strength of plywood sheathing and structural lumber, causing them to become brittle and to fail prematurely or under loads that one would normally expect them to bear without difficulty. There are a number of theories regarding the mechanism of this loss of strength, including chemical attack on the cellulose fibers in the wood by the fire-retardant chemicals and the high temperatures used to redry FRT plywood and lumber after treatment. Regardless, the impact of the use of fire retardants on the strength of wood members must be addressed when using these materials. Current building codes rightfully recognize the contribution these materials make in improving the fire safety of the structures where they are used and provide for derating to accommodate the possible loss of strength.

Effect of Preservatives

To resist rot and insect damage, many wood products are treated chemically with biocidal materials. These include railroad crossties, utility poles, pilings, landscaping timbers, and exterior dimension stock for decks and other wood structures. These wood products are usually pressure treated with various wood preservatives containing creosote (a mixture of single and conjugated ring aromatic compounds made from coal tar) or pentachlorophenol in solutions of oil similar to diesel or fuel oil, or with water-soluble salt solutions containing arsenic, chromium, copper, or phenol. All of these materials are toxic to humans in varying degrees if ingested or applied directly to the skin. Waterborne salts are usually used to treat dimension decking lumber and plywood, whereas the oil-based preservatives are more commonly used for treating utility poles, railroad ties, and pilings.

These treatments introduce two concerns for the fire protection specialist. First, they can affect the ignitability and burning rates of the treated wood products. Wood products freshly treated with creosote or pentachlorophenol in oil solutions can be more easily ignited because of the presence of the oil vehicle and can be expected to burn with a greater heat output. Second, these treatments introduce toxic chemicals into the wood that

will be released if involved in a fire. These materials can add to the toxicity of the smoke produced from such a fire.

Building Fashions

The prevailing trends in housing design have a significant impact on the types of wood products used in a particular structure. This affects the fire safety considerations for that structure, because the selection of construction materials affects the behavior of the structure in the event of a fire. During the 1970s, due primarily to a desire for a more "natural" appearance in homes and enactment of new legislation designed to encourage conservation and save energy, more external wood materials (wood shingles or siding) were used. In many parts of the country, a return to wood as a primary fuel (burned in fireplaces and stoves) and to log homes with wood shingle roofs created new and often unfamiliar fire risks. The 1980s saw increased use of vinyl-clad fiberboards used for building sidings, and substitution of oriented strandboards (OSBs) or flakeboards for plywood in construction. Use of wood shingles declined with a return to fiberglass and asphalt-derived materials. There has also been a marked increase in the manufacture and use of treated lumber and plywood in construction. More insulation products made from various organic and inorganic materials are now being used, whereas asbestos has been virtually eliminated in sidings and flooring materials. All of these factors have important bearing on the ignitability, fire growth rate, heat output, and structural performance of the building during a fire. However, for each period, there remain today millions of existing buildings reflecting the popular choices of that time.

VARIABLES INFLUENCING COMBUSTIBILITY

Whether one is primarily concerned with mere ignition or with the energies obtained from sustained combustion, there are several factors that consistently enter into the analysis.These include the physical form of the fuel wood, the thermal conductivity of the fuel wood (as discussed earlier), and the moisture content of the wood.

Physical Form

The influence of physical form on the ignition and burning characteristics of wood and wood-based products is illustrated by the fact that wood kindling will flame and burn from relatively small heat sources while heavier wood logs will resist ignition to a considerable degree. Paper is easier to ignite than small pieces of wood. The reason for this is that, as the size of the particle diminishes, the ratio of surface area to volume (mass) increases. Thus there is both greater exposure of fuel to air and less mass to conduct heat away from the particle; consequently, heat does not readily dissipate within the material.

It follows that small, thin forms of wood (such as excelsior), or other combustible solids (such as paper), will burn more readily than larger objects of the same material. This fact is most important when dealing with wood-derived combustible particulate solids. Wood dusts, chips, and shavings represent a serious fire risk, especially when pneumatically conveyed. Very finely divided wood particles, such as sander dust or wood flour (often made from nut shells), are prone to deflagration similar to other carbonaceous dusts. These materials create a serious threat of explosion in the pneumatic conveying and dust collection systems commonly used to handle them. Sawdust, router chips, shavings, and other wood waste are often thought of as less hazardous due to the much larger particle sizes. However, the pneumatic conveying of these particulates causes attrition of the particles, which results in fine dusts capable of undergoing a deflagration. Fires in pneumatic conveying and dust-control systems are a hazard in most wood manufacturing operations due to ignitability and pervasive presence of finely divided wood particulates.

Although paper is considered to be easy to ignite, large compact masses of paper, such as books or cut and packaged stacks of paper, do not burn readily due to charring and limited availability of combustion air in the interior of the mass. Additives such as binders, colorants, and sizes in the paper also serve to inhibit combustion. However, large rolls of paper or paper-based products stacked on end may unwind (exfoliate) during a fire, exposing long, single sheets of paper which are easily ignited and burn readily.

Moisture Content

Ignition and burning tests in the laboratory show that the behavior of combustible solids of the same size, shape, and chemical composition varies markedly depending on the moisture content. In research conducted by the British Department of Scientific and Industrial Research (now the Ministry of Technology), the influence of the moisture content of oak and western red cedar on the time necessary for these woods to ignite was studied; the results are shown in Figure 6.4.5.[7] Radiation intensity in this figure is expressed in terms of the number of calories falling on one square centimeter of the exposed wood in one second, using a test apparatus developed by the ministry.

Once a fire is well under way, the significance of the moisture factor decreases, because the heat radiation and therefore

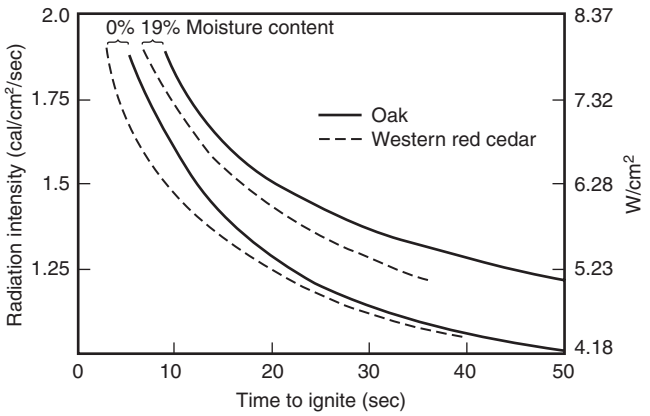

FIGURE 6.4.5 Effect of Moisture Content on the Ignition of Wood

the rate of pyrolysis increases. Under such conditions, even wood with a moisture content of 50 percent or more will burn.[8]

There is a time lag between changes in the fuel moisture content of cellulosic materials and changes in atmospheric humidity. Most solid cellulosic combustibles are not immediately absorptive of airborne water vapor; conversely, the moisture content of most solids will be retained for a longer period of time than air retains its moisture in suspension. Thus, the humidity in the ambient air is not always a reliable index of the moisture content of ordinary combustibles.

IGNITION OF WOOD AND WOOD PRODUCTS

Ignition of Wood

The ignition of a piece of wood is not a simple process; it is quite complex and subject to a number of variables. Furthermore, the process of ignition varies with the heat flux and rate of temperature increase to which the wood is exposed. In the past, different researchers have tried to establish a definitive ignition temperature of wood, each arriving at a different ignition temperature due to the different experimental methods employed. Consequently, no single model or scenario addresses the behavior of wood fuel components in all possible situations.

Babrauskas has performed the most recent review of the literature on ignition temperature and has concluded that, under short-term heating conditions, one should use the figure of 482ºF (250ºC) for the ignition temperature.[9] As the time over which the heat is applied increases, the temperature sufficient to attain eventual ignition decreases. There is one documented case where a steam pipe operating intermittently but repetitively at a temperature of 170ºF (77ºC) over many years eventually led to the ignition of the wooden structural members in contact with the pipe.[10] Indeed, this value is explicitly stipulated in the Building Code of the City of New York.[11] Consequently, one must exercise considerable care when wooden objects are placed in close proximity to heat sources.

The wide range of ignition conditions for wood can be understood when one considers its chemistry. Wood is not a homogeneous material, but a mixture of cellulose, hemicellulose, lignin, various extractives (alcohols, esters, and resins), bound water, and air in a complex cellular structure. As heat is applied to this complex mixture, these constituents undergo reactions that change the chemical makeup of the sample. This process is usually called *pyrolysis.* When one considers the effect of the pyrolysis on the chemical composition of the wood sample, the variability of ignition temperature as a function of heat flux and time is understandable.

Ignition begins with the application of heat of sufficient intensity and power to raise the fuel to a temperature at which pyrolysis begins. It is doubtful that a single temperature for the onset of pyrolysis, irrespective of a time variable, will ever be definitively determined. In all likelihood it will also vary with wood species, just as density varies with species. Numerous studies have been conducted in an effort to determine the conditions required for the onset of combustion reactions and Babrauskas suggests that an activation energy of approximately 125 kJ/mole is appropriate for whole wood such as dimension lumber stock.

The onset and rate of pyrolysis depends on both the temperature and the time frame over which heat is applied. Most studies have been conducted over relatively short time frames. In these short-term tests, as the temperature is raised, the bound water is driven off as water vapor. Evolution of carbon dioxide can also be observed at these temperatures. These products are noncombustible. There are some combustible materials evolved, including the low-molecular-weight extractives, if present, formic acid and acetic acid, that also vaporize and leave the sample as gases at this temperature. However, the heat necessary to drive them off from the sample is greater than the heat that can be derived from their combustion. Consequently, this phase is an energy-consuming (endothermic) phase. The loss of water from the sample is largely reversible if the sample is allowed to cool. But the loss of the low-molecular-weight alcohols, esters, and resins is not. The sample is permanently altered and subsequent heating will advance the reactions further. The outward manifestation of these changes is a gradual change in color from light to brown to black. These changes can occur from exposures to temperature ranging upward from 199°F (93°C).[12] One study showed that higher humidity during heating increased the extent of the charring.[12]

The studies of the behavior of wood between 212°F (100°C) and 424°F (200°C) show the development of a char with lower temperatures being sufficient if applied for longer periods of time and higher temperatures producing char layers in shorter exposure times. If a wood sample is raised to a temperature of 572°F (300°C) it will be charred regardless of the time frame.[12] By the time the sample has reached this temperature, the majority of the water has been driven off. The principal pyrolytic product is carbon monoxide. Whether the wood sample ignites in flaming mode combustion or burns as a glowing ember is determined largely by the rate at which the flammable carbon monoxide, alcohols, esters, and resins are driven off from the sample. If the sample is heated slowly, the concentration of flammable gases might never achieve sufficient concentration in the air surrounding the sample to support a flame. The sample will burn as a char as the pyrolysis reactions are exothermic once this temperature region has been attained. If the sample is brought to this temperature more quickly, the volatile component will be of sufficient concentration to produce a flame. As the temperature exceeds 572°F (300°C), the chemical reactions yield sufficient volatilized combustible chemical species to support flaming combustion.

When the heating is provided by an existing flame, it is called *piloted ignition.* Piloted ignition brings the wood sample up to the combustion temperature of the flame source very rapidly and yields fairly consistent ignition temperatures. For most tests, the range from 572°F (300°C) to 662°F (350°C) encompasses the piloted ignition temperature.[12] One research source concludes the piloted ignition temperature ranges from 572 to 592°F (300 to 311°C) for hardwoods and 660 to 687°F (349 to 364°C) for softwoods.[12]

Ease of ignition is related to the ignition temperature and the radiant power necessary to raise the temperature of a sample

to that temperature. It would take far more energy to reach the ignition temperature if wood were a better conductor of heat. The insulating qualities of wood are critical, allowing attainment of ignition temperatures with relatively small quantities of ignition energy. This is especially important in cases where spontaneous ignition is suspected.

Ignition from radiant flux has been studied. The flux sufficient to cause ignition varies not only with the species, moisture content, and time of exposure, but also grain orientation. A value of 12.5 kW/m^2 has been used for the minimum radiant flux sufficient to cause ignition.[13] But after surveying the published research, Babrauskas suggests using 20 kW/m^2 for short-term exposures and 4.3 kW/m^2 for long-term exposures.[12]

Spontaneous Heating and Ignition

Although coal and other organic materials have a reputation for "self-heating" and "self-igniting," there is little evidence to support the claims of self-ignition of wood products where those products have been stored at normal room temperatures. In general, wood, wood-based products, and cellulosic materials that are clean and dry will not self-heat and spontaneously ignite unless the temperature of the pile or mass of wood particulate has been raised by some external heat source. Normally a spark, open flame, contact with hot surfaces, or exposure to some other thermal radiator is necessary in order to raise the temperature of the wood to the point where pyrolysis begins. Once pyrolysis has begun, the chemical reactivity of the pyrolized wood can lead to self-heating. If this heat cannot escape it is possible to attain the ignition temperatures of wood-based fuels. In those episodes where it has appeared that wood products did ignite spontaneously, there were polymerizing resins involved that provided the exothermic reaction necessary to heat the wood to the temperature at which pyrolysis begins. Babrauskas has studied the phenomenon of self-heating and spontaneous ignition extensively and those cases where the process did occur the temperature of the material was always above 122°F (50°C).[12]

It has been shown that cellulosic materials contaminated with certain drying oils (e.g., linseed oil, tung oil, and turpentine) can self-heat when stored in unventilated spaces. The actual source of the heat is the exothermic chemical reactions involving the oils. In such cases if self-heating is allowed to continue, exothermic pyrolysis can be achieved and ignition can result.

Similarly, external heating can raise certain wood-based materials to a temperature where the exothermic pyrolytic reactions begin. Once this temperature is achieved, the material can then self-heat as long as the conditions are conducive to the retention of the heat generated by the pyrolysis. For example, if wood fiberboards are not subjected to a direct, artificial heat source either during manufacture or when installed in structures, they will not heat spontaneously. On the other hand, heating such fiberboards at relatively moderate temperatures can initiate an exothermic reaction leading to their ignition.

Wood and wood-based products are generally not susceptible to the same type of self-heating from microbiological action that is prevalent in certain agricultural products.

COMBUSTION OF WOOD AND WOOD-BASED MATERIALS

The factors that affect the ignitability of wood are also important factors governing the combustion of wood. The moisture content is an important factor in determining the heat output of a given sample and, hence, the heat available to perpetuate the fire. Likewise, the chemical composition is an important determinant of the combustion of a sample. Some chemical additives will reduce the heat output and yield a less violent flame, whereas other additives may actually increase the heat content of the fuel. Finally, the resin content of the fuel is important.

Wood smoke has a characteristic odor. It is bluish or dark when the wood is green or wet and low temperature or insufficient air is present, but with high temperature and excess air, the smoke is often almost invisible. This can be used to infer the range of size for the particulates that make up the smoke. Since particulates diffract light that is of a wavelength shorter than the particle diameter, the bluish smoke implies smoke particulates with an average diameter of approximately 0.4 microns, the wavelength of blue light. As the efficiency of combustion is improved, the particle diameters become even smaller resulting in "invisible" smoke. Burning wood produces smoke containing glowing particles and large amounts of gray ash. Wood burned under conditions of incomplete combustion in which little or no air is present produces charcoal, carbon monoxide, and a number of condensible yet combustible vapors which are called, in the aggregate, *creosote.*

Availability of Air

An adequate amount of air (oxygen) is essential for the complete combustion of celluslosic materials, regardless of physical form. It is generally accepted that 13,100 kJ of heat is released for each kilogram of oxygen consumed (5.6 Btu per pound of oxygen).[13] Since air is approximately 23 percent oxygen by weight, a heat release of approximately 3030 kJ is produced for each kilogram of air consumed by the fire (i.e., 1.3 Btu per pound of air). These values form the basis for oxygen consumption calorimetry that is used to measure the heat release of a wide variety of fuels.[14] The nominal heat of combustion for wood is about 18,600 kJ per kg (8000 Btu per lb).[13] Using a value of 1.19 kg/m^3 (0.07 lb/ft^3) for the density of air at 20°C (68°F), it can be shown that about 5.2 m^3 (83.5 ft^3) of air is required for the complete combustion of each kilogram (pound) of cellulosic fuel.[15]

When the fire is underventilated, destructive distillates are formed as the cellulose molecule decomposes due to the heat of the fire. These include carbon monoxide, formic acid, formaldehyde and other aldehydes, ketones, and carboxylic acids. All of these compounds are combustible and can deflagrate when exposed to a source of fresh air. This is a serious concern for firefighters that should not be overlooked.

The residue remaining after a fire can provide some insight into the combustion processes of that fire. The products of combustion and the residues remaining after combustion vary according to the degree of ventilation. When excess is available to a wood fire, the solid residue remaining after combustion is a light gray ash. When the residue is a black charcoal, it suggests

that the fire was underventilated or that it was extinguished before combustion was completed.

Rate of Combustion

Because the combustion of wood and wood products is a surface phenomenon, the rate of combustion can be influenced by the physical state and orientation of the fuel and any factor affecting the availability of combustion air. Increasing the volume of air available to the fire, regardless of the means used, accelerates the rate of combustion until the air velocity reaches a point where it begins diluting the pyrolysis gas concentration in air to levels below that necessary for optimum combustion efficiency. Then airflow becomes excessive and the air begins acting as a heat transfer fluid, robbing the fire of the heat needed to continue the pyrolysis necessary to maintain the supply of gaseous distillates that fuel the flame. If the air supply velocity is further increased, the volume of air may exceed the ability of the fuel mass to supply sufficient gaseous distillates, and the flame ceases. The combustion will continue but in a solid phase, evidenced by the glowing surface of the fuel, rather than the gaseous phase evidenced by the flame.

In most freely ventilated fires involving combustible solids, once ignition is achieved, the fire follows the t^2 growth curve until the entire surface of the fuel is involved. Once there is total surface involvement, the rate of combustion remains essentially constant until a limitation in fuel or combustion air is encountered. The rate of combustion is significantly influenced by the physical form of the combustible, the air supply present, the moisture content, and allied factors; but there is the fundamental need for progressive vaporization of the solid by heat exposure for combustion to proceed.

Speed of Flame Propagation

Speed of flame propagation over the surface of a combustible critically affects the severity of a fire in many cases. The 1959 Los Angeles School Fire Tests[16] showed that, under controlled test conditions, flames spread over combustible surfaces with such speed that observers had to flee the sudden release of heat and flame. In 1949, the British Department of Scientific and Industrial Research conducted full-scale dwelling fire tests on the influence of combustible wallboard versus the use of plaster finish.[17] The record of the British tests graphically illustrates the observed time-temperature curves in the living rooms of the two houses tested. Originating in an easy chair in the living room, the fires in their initial stages were identical in both dwellings. The loading of combustible materials was roughly proportional to the loadings observed in occupied dwellings in England. It should be noted that, in the United States and Canada, earlier ignition and faster flame spread on the combustible surfaces could be expected, since winter heating in these countries results in lower relative humidities and, thus, lower moisture content of the combustibles.

Currently, the comparative assessment of flame spread characteristics of building materials is performed per ASTM E84 (NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Burning Materials*) using the Steiner Test Tunnel.[18] Red oak was originally used as a reference standard to establish the performance rating equal to 100. Today the test method is referenced to specific performance parameters on a noncombustible surface. Nevertheless, red oak still achieves a rating of approximately 100, and most other wood species fall into the range between 90 and 160. Flame spread indexes for selected wood species are listed in Table 6.4.2.

Fire Resistance

The fire resistance behavior of wood panels has been reviewed using the ASTM E119 (NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*) test apparatus and procedure.[19] When wood panels are exposed to this test, surface ignition occurs in approximately 2 minutes.[20] Charring proceeds at a rate dependent upon the species and moisture content. However, the average char rate is approximately 1/30 in. (0.85 mm) per minute for the next 8 minutes. The insulating effect of the char layer slows the subsequent char rate to approximately 1/40 in. (0.63 mm) per minute. ASTM E119[19] test data has yielded a set of empirical relationships for predicting the rate of char in the direction transverse to the grain of the wood.[20]

TABLE 6.4.2 Flame Spread Indexes for Selected Wood Species, 1 in. (25.4 mm) Nominal Solid Dimension Lumber[20]

Species	*Flame Spread Index*	*Source*
Bald cypress	145–150	UL
Eastern red cedar	110	HUD/FHA
Alaska yellow cedar	78	CWC
Western red cedar	70	HPMA
Douglas fir	70–100	UL
Western hemlock	60–75	UL
Western white pine	75, 72	UL, HPMA
Eastern white pine	120–215, 85	UL, CWC
Lodgepole pine	65–110	CWC
Ponderosa pine	105–230	UL
Red pine	142	CWC
Southern yellow pine	130–195	UL
Redwood	70	UL
Eastern white spruce	65	CWC, UL
Sitka spruce	100	UL
Yellow birch	105–110	UL
Cottonwood	115	UL
White (sugar) maple	104	CWC
Red oak	100	UL
White oak	100	UL
Sweetgum	140–155	UL
Walnut	130–140	UL
Yellow poplar	170–185	UL

Note: Flame spread ratings developed for virtually all wood-based panel products are based upon ASTM E84, UL 723, or NFPA 255 flame spread rating tests, using the Steiner Test Tunnel.
CWC = Canadian Wood Council.
HPMA = Hardwood Plywood Manufacturers Association.
HUD/FHA = U.S. Dept. of Housing and Urban Development.
UL = Underwriters Laboratories Inc.

For Douglas fir, $R = 1/(57.4 + 1.16M)\rho + 8.4]$

For southern yellow pine, $R = 1/[(11.7 + 0.24M)\rho + 25.7]$

For white oak, $R = 1/[(40.1 + 0.81M)\rho + 15.0]$

where

R = Rate of char (in./min)

M = Moisture content in percent

ρ = Dry specific gravity

(For SI units: 1 in. = 25.4 mm)

Table 6.4.3 lists the burn-through rates for vertically fire-exposed wood panels of 1.0-in. (25.4-mm) thickness, under the ASTM E119[19] (NFPA 251) fire exposure test method. The specific gravity and rate are for samples at moisture content of 6.0 percent.

The temperature at the base of the char layer is usually in the neighborhood of 550°F (287°C), whereas ¼ in (6.3 mm) beneath the char the temperature is approximately 360°F (182°C).[20] This steep temperature gradient is typical of most wood species and demonstrates the insulating effect of the char layer. This allows wood structural members to retain their load-bearing capacity during a fire until the charring has reduced the residual cross-section of the member below the minimum necessary for the design load.

Heat Release and Heat Release Rate

The heat release rate of wood and wood-based fuels becomes an important consideration when analyzing the behavior of a space under fire conditions. The heat release per unit of mass and the quantity of material present predict the total heat release rate attainable and, hence, the potential for flashover.[21]

The heat of combustion of most species of wood falls within the range of 8000 to 12,000 Btu per lb (18,600 to 27,900 kJ/kg).[20] Under fire conditions, the heat release rate of the wood component of the fuel load depends on the incident radiant flux, moisture content, thickness, orientation, boundary conditions at the rear face, and the oxygen concentration of the ambient air. It is also a function of time, characterized by an early peak followed by a slow decay until flaming ceases. A second peak will also occur if the rear face of the specimen is insulated.

Heat release rates are determined with the ASTM E906 test method, which defines the conditions precisely.[22] For an oven-dry vertical pine board of nominal 1 in. (25.4 mm) thickness exposed to a thermal radiation level of 60 kW/m^2 in normal air with the rear face exposed to a water-cooled plate, a peak heat release rate of 250 kW/m^2 in 19 minutes was reached when the flame went out.[23] A series of wood products with moisture contents of about 8 percent exhibited peak heat release rates between 90 and 170 kW/m^2 under the same conditions. The heat release rate of wood products increases linearly with the density.[24] The total heat release rate of the materials of construction and furnishings is an important factor in determining whether a room will reach flashover conditions.[25]

Table 6.4.4 shows some figures for the heats released by various wood products and also gives comparative figures for some other materials. It should be noted that the heat of combustion of most dry wood products is less per pound (kg) than that of the other fuels listed. The trend of replacing wood furnishings with furnishings made of plastics actually increases the fire load per unit weight. This is an important factor when estimating the quantity of combustible materials exposed to a fire scenario. Such estimates must be adjusted for the nature of the combustibles when determining the needed fire resistance of structural elements or the optimum quantity of water required per unit of floor area for sprinkler discharge.

TABLE 6.4.3 ASTM E119 Fire Resistance Data for Selected Woods

Species	*Specific Gravity*	Rate *(in./hr)*	Rate *mm/hr*
Bald cypress	0.44	1.7	43.2
Basswood	0.42	2.4	61.0
Yellow birch	0.63	2.0	50.8
Chestnut	0.45	1.7	43.2
Douglas fir	0.45	1.6	40.6
Eastern hemlock	0.40	1.6	40.6
White (sugar) maple	0.64	2.1	53.3
Northern red oak	0.61	1.8	45.7
White oak	0.67	1.5	38.1
Eastern white pine	0.39	1.6	40.6
Ponderosa pine	0.42	2.1	53.3
Southern yellow pine	0.55	2.2	55.9
Sugar pine	0.32	2.0	50.8
Redwood	0.38	1.6	40.6
Sitka spruce	0.43	1.7	43.2
Sweetgum-sapwood	0.55	2.4	61.0
Sweetgum-heartwood	0.52	1.6	40.6
Yellow poplar	0.44	2.1	53.3

TABLE 6.4.4 Heat of Combustion of Various Wood and Wood-Based Products and Comparative Substances

Substance	Heating Value *Btu per lb*	Heating Value *kJ/kg*
Wood sawdust (oak)	8,493*	19,755
Wood sawdust (pine)	9,676*	22,506
Wood shavings	8,248*	19,185
Wood bark (fir)	9,496*	51,376
Corrugated fiber carton	5,970*	13,866
Newspaper	7,883*	18,336
Wrapping paper	7,106*	16,529
Petroleum coke	15,800	36,751
Asphalt	17,158	39,910
Oil (cottonseed)	17,100	39,775
Oil (paraffin)	17,640	41,031

*Dry.

The amount of fuel contributed by one combustible versus another, or different forms of the same combustible, can also be used to evaluate the desirability of utilizing the material in a given situation. This is particularly true for measuring the fuel contributed by certain forms of building materials.

Engineered Wood-Composite Products

Engineered wood-composite products include laminated veneer lumber, glu-lam beams, composite/wood joists and beams, and other wood-composite materials, such as oriented strandboard (OSB), flakeboard, medium density fiberboard (MDF), and particleboard. The use of engineered wood-composite materials facilitates the production of lightweight structural components, such as composite/wood joists and beams, with substantially reduced mass and cross-sectional area. For example, composite/wood joists and beams provide superior structural strength with reduced mass, allowing greater design flexibility and economy. There may be occasions where these engineered wood-composite products behave very differently than their primary wood precursers (Figure 6.4.6).

The introduction of glues and resins into the structural materials changes the chemistry of those materials. The relatively simple combustion chemistry of cellulose is complicated by the presence of petroleum-derived plastic resins, some of which may contain aromatic rings, halogens, epoxies, and other unsaturated hydrocarbon constituents. This affects heat output, flame spread rate, smoke composition, and smoke density during a fire involving these materials.

The more serious concern is the structural performance of engineered wood products, especially composite/wood joists and beams, under exposure to a fire. The reduced cross-sectional area of a composite/wood joist or beam provides a larger surface area for a given mass (weight) of material. Since both pyrolysis and combustion are surface phenomena, the increased surface area provides for a more rapid consumption of the fuel. As a result, the engineered wood-composite components burn faster than their solid, sawn lumber equivalents[26] (Figure 6.4.7).

The elevated rate of combustion on a mass consumed per unit time basis would predict earlier structural failure of a building supported by composite/wood components than one constructed of equivalent solid sawn lumber. However, there is the additional factor of the engineered distribution of mass in the composite/wood component. The mass of the composite/wood beam is concentrated in those areas where it is structurally significant, resulting in a cross section similar to an I-beam. This places the web and top flange in compression, and the bottom flange in tension (Figure 6.4.8). As the wood-composite material begins to char, the pyrolysis of the wood fibers leads to a more rapid deterioration of the structural properties than one encounters with dimension sawn lumber of equivalent design capacity. This effect combined with the greater rate of combustion due to the increased surface area and the greater heat release rate due to the petroleum-derived resins can create an expectation of earlier-than-expected failure of structures during fires.

When engineered wood-composite components were first introduced, there were also concerns that the heat of a fire might cause the adhesives to soften, allowing the component to fail. This notion might have come from anecdotal experience with casein adhesives. This does not seem to be the case with current wood-composite components using modern phenolic thermoset resins. The available research has not identified structural failures that are attributable to adhesive/resin failure.[26]

The Fire Protection Research Foundation has been instrumental in the investigation of these questions.[26] As the use of

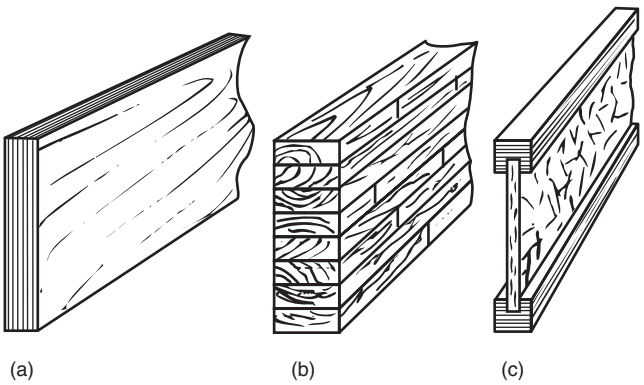

FIGURE 6.4.6 (a) Laminated Veneer Lumber; (b) Glu-Lam Beam; and (c) Composite Wood Joist

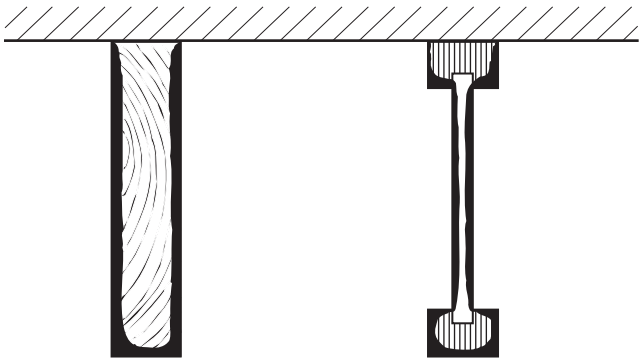

FIGURE 6.4.7 Charring of a Composite/Wood Joist (Right) Compared with a Sawn Joist (Left) After the Same Fire Exposure

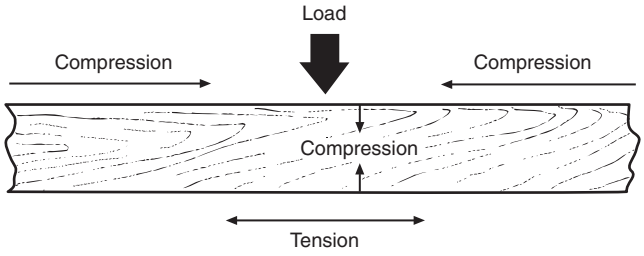

FIGURE 6.4.8 Orientation of Load Forces on a Beam or Joist

composite/wood beams and joists continues, the fire service will probably find it necessary to rethink the length of time a structure can be involved before it is deemed structurally unsafe for interior fire fighting.

The implications of the use of engineered lightweight construction components on the fire safety and fire endurance of structures continues to be an area of research. As wood has become more expensive and as structural engineers continue to make structures more efficient and lighter in weight, lightweight wood trusses may become more common. This demands that their behavior in a fire be better understood.

A solid sawn lumber joist or beam endures both compression and tension stresses under design loads, as shown in Figure 6.4.8. Since the mechanical properties of wood vary with the orientation of the stress to the grain of the wood fibers, greater stresses can be supported by an engineered wood assembly of less weight if the orientation of the grain of the wood fibers is "adjusted" to employ the wood in an orientation relative to the applied stress, which takes maximum advantage of its mechanical properties. This approach yields a structure shown in Figure 6.4.9.

These lightweight assemblies have two features that are considered important. First, the surface area-to-mass ratio of the lightweight truss assembly is much greater than that of the solid sawn plank. Since burning rate is proportional to the surface area, this could mean that the lightweight truss assembly will fail sooner under fire conditions. Second, lightweight truss assemblies are assembled from individual members that are attached to each other with steel gusset plates. There is currently some concern that the transmission of heat through the steel gusset plate will accelerate charring beneath the plate, leading to early failure of the attachment. Since the loss of an attachment threatens the load-bearing capacity of the entire truss, this could provide a mechanism for premature failure of a roof supported by lightweight truss assemblies.[27]

The Fire Protection Research Foundation has been the coordinator of research into these questions. There is considerable research yet to be conducted to develop the answers addressing the above concerns.[27]

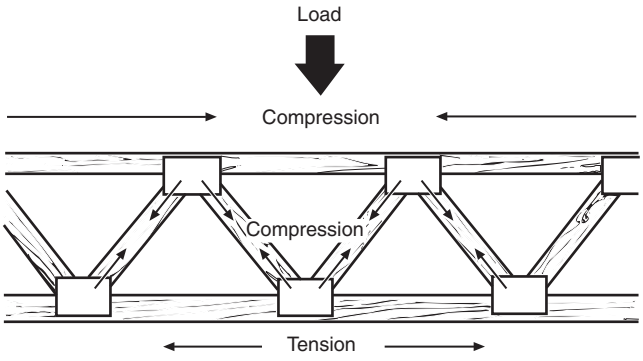

FIGURE 6.4.9 Stresses in the Lightweight Wood Truss Assembly, with Both Compression and Tension Stresses Oriented Along the Wood Grain

SUMMARY

Wood is, by its very nature, a nonuniform and variable material. Its chemistry and internal structure give it mechanical properties that we rely on to produce a wide range of products and structures. However, that same chemistry demands that water play an important role in the behavior of wood, both from a structural point of view and from the point of view of the fire protection engineer.

Unless green wood is involved, moisture content will have limited effect on the ignition temperature and heat release from combustion. Again, unless green wood is involved, the ignition of wood can be modeled as a four-phase process, beginning with drying, progressing to endothermic pyrolysis, then to exothermic pyrolysis, and culminating in flaming combustion. There is some concern, however, that this simple progressive model might not be appropriate when heating occurs at lower temperatures over very long time frames.

The fire protection engineer must be mindful of the effect a working fire can have on wooden structural components. Although it is well known that heavy timber construction provides considerable fire endurance due to char formation, the recent trends in construction, including the use of lightweight wood trusses and light-weight engineered wood beams, necessitates a reassessment of the fire endurance of structures where lightweight components are used. The surface combustion behavior of wood components predicts a loss of structural strength in earlier stages of a fire than would be expected if traditional sawn beams were used. How much earlier has not yet been quantified.

Consequently, despite the fact that wood has been humanity's first choice in structural materials for shelter and implements, there remains much to be learned from this most wonderful of materials.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on wood and wood-based products discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*

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Chapter 5

Fibers and Textiles

Jeffrey O. Stull ■ Salvatore A. Chines

Chapter Contents

Fibers
Textile Manufacturing
Textile Combustibility
Flame-Retardant Treatments
Relationship of Flammability and End Use
Textile Flammability Tests
Textiles in Special Environments

Key Terms

cellulosic fiber, combustible fiber, flame-retardant fibers, flammable fabric, Flammable Fabrics Act, limiting oxygen index, manufactured fiber, oxygen-enriched atmosphere, protective clothing

Fibers and textiles are an integral part of daily life. Clothing, furniture, carpets, and curtains are examples of textile materials produced with fibers. Almost all fibers are combustible. This characteristic results in problems when the fibers are manufactured, while they are stored, while they are made into fabrics, while they are collected as waste, and while they are worn as apparel or used as furnishings. Fiber combustibility combined with the prevalence of textile products explains the frequency of textile-related fires and the many deaths and injuries that result.

This chapter discusses commonly used fibers and textiles, their manufacturing, combustibility, end use, and fire-retardant treatments. Also detailed in this chapter are special environments where textiles are used and the testing methods employed in evaluating and creating standards for the use of fibers and textiles.

More information can be found elsewhere in this handbook, especially in the following chapters: Section 6, Chapter 6, "Upholstered Furniture and Mattresses"; Section 6, Chapter 11, "Medical Gases"; Section 9, Chapter 17, "Oxygen-Enriched Atmospheres"; Section 12, Chapter 9, "Fire and Emergency Services Protective Clothing and Protective Equipment"; and Section 18, Chapter 2, "Interior Finish."

FIBERS

Role of Fibers in Fires

Studies of fatal fires continue to show that textiles provide the initial fuel for the largest share of fatal structure fires, typically 40 percent or more (Table 6.5.1). These fires also typically accounted for one-sixth of structure fire incidents. There has been no clear trend in shares of fires and deaths, but the trends for the totals have been clearly and significantly down. Many fires start with the ignition of textile products then rapidly involve other combustibles, such as foam plastics used as filling materials in textile-covered upholstered furniture.

Table 6.5.2 shows the types of *fabric or textile* ranked by number of fires, number of civilian deaths, and dollars of direct property damage occurring in structure fires, where the fabric or textile was the material first ignited; the data are for 1994 through 1998. Table 6.5.3 presents data for 1999 through 2003 and includes civilian injuries. The differences between the tables are the result of different data definitions in Versions 4.1 and 5.0 of the National Fire Incident Reporting System (NFIRS). Chapters 3 and 4 of Section 3 contain additional information about NFIRS.

Table 6.5.4 shows the types of *product* (composed wholly or partly of fabric or textile) ranked by number of fires, number of civilian deaths, and dollars of direct property damage for structure fires, where the product was the first item ignited, for the years 1994 through 1998. Table 6.5.5 shows basically the same information for the years 1999 through 2003, but also includes civilian injuries. Again, the differences between the presentations of the two sets of data have to do with different data definitions between Versions 4.1 and 5.0 of NFIRS.

Fibers are the basic components of all textiles and may be either natural or manufactured. Natural fiber sources include cellulosic, protein, and mineral fibers. Cellulosic fibers come from a

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TABLE 6.5.1 Structure Fires with Fabrics or Textiles as the Type of Material First Ignited, by Year Based on Data Collected in NFIRS Version 5.0 Only

Year	Fires	Percentage of All Fires	Percentage of All Nonconfined Fires	Civilian Deaths	Percentage of All Deaths	Civilian Injuries	Percentage of All Injuries	Direct Property Damage (in Millions of Dollars)		Percentage of All Damage
								As Reported	In 2003 Dollars	
1980	186,100	(17%)		2670	(47%)	8090	(33%)	831	1855	(15%)
1981	173,800	(17%)		2830	(49%)	8220	(32%)	795	1604	(13%)
1982	148,900	(16%)		2350	(45%)	7980	(31%)	634	1207	(11%)
1983	132,500	(15%)		1980	(39%)	7990	(31%)	765	1410	(13%)
1984	130,100	(15%)		2020	(45%)	6960	(30%)	777	1373	(13%)
1985	129,200	(15%)		2220	(42%)	7030	(30%)	830	1416	(13%)
1986	123,200	(15%)		2060	(41%)	6720	(30%)	837	1404	(14%)
1987	116,300	(15%)		1970	(40%)	7070	(30%)	776	1255	(12%)
1988	112,600	(15%)		2320	(44%)	7920	(30%)	911	1417	(13%)
1989	104,100	(15%)		1950	(42%)	7430	(31%)	842	1248	(11%)
1990	97,000	(16%)		1740	(40%)	7010	(29%)	917	1291	(14%)
1991	99,200	(15%)		1550	(41%)	7560	(30%)	1157	1561	(14%)
1992	98,100	(15%)		1670	(42%)	7490	(31%)	891	1168	(13%)
1993	96,400	(16%)		1580	(40%)	8010	(30%)	1050	1336	(14%)
1994	94,400	(15%)		1510	(42%)	7280	(31%)	987	1225	(14%)
1995	89,300	(16%)		1650	(41%)	6500	(30%)	1076	1297	(14%)
1996	90,700	(16%)		1760	(42%)	6640	(30%)	1074	1259	(14%)
1997	85,600	(16%)		1550	(44%)	6170	(30%)	1063	1217	(15%)
1998	82,800	(16%)		1360	(40%)	5840	(30%)	1019	1150	(15%)
1999	94,300	(18%)	*(18%)*	1370	(45%)	6440	(35%)	1375	1517	(16%)
2000	89,500	(18%)	*(19%)*	1740	(49%)	5910	(30%)	1483	1584	(17%)
2001	82,100	(16%)	*(19%)*	1620	(50%)	5340	(31%)	1431	1486	(16%)
2002	72,600	(14%)	*(19%)*	1290	(47%)	4410	(28%)	1468	1501	(17%)
2003	63,100	(12%)	*(18%)*	1660	(49%)	4650	(30%)	1463	1463	(17%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries to the nearest ten, and direct property damage is rounded to the nearest million. Sums may not equal totals due to rounding errors. This table includes a proportional share of structure fires in which the type of material first ignited was unknown or not reported when it should have been. Estimates for 1999–2003 are based on nonconfined structure fires collected originally in NFIRS Version 5.0 only. Italicized figures show percents of nonconfined structure fires these years; nonitalicized percents are based on total structure fires and losses.

"Nonconfined" means the fire is *not* one of several categories (e.g., cooking, chimney, heating appliance, or trash) that are considered "confined" and for which causal information is not routinely collected.

Source: National Fire Incident Reporting System (NFIRS) and NFPA survey.

variety of plants, the most common being cotton. Protein fibers come from a variety of animal hairs. Mineral fibers include mineral wool and fiberglass. Manufactured fibers are produced by chemical processes. All fibers come in a variety of lengths. Although natural fiber length can be slightly manipulated genetically, manufactured fiber can be produced in any length desired.

Natural Fibers

The most common cellulosic fiber used in textile manufacture is cotton, which consists of more than 90 percent cellulose $(C_6H_{10}O_5)_x$. Other plant fibers, such as jute, flax (linen), hemp, and sisal, are primarily cellulosic in composition. Cellulosic fibers are combustible; the ignition temperature of cotton fiber is 752°F (400°C). When ignited, these fibers produce heat, smoke, carbon dioxide, carbon monoxide, water, and numerous other organic compounds. Plant fibers char but do not melt. Many cellulosic fibers are hollow; thus, each fiber has its own air supply. This allows fire to burrow deeply into bales.

Protein fibers, such as silk, wool, and other hair fibers derived from animals, are chemically different from cellulosics because they consist of complex protein molecules containing high percentages of nitrogen as well as carbon, hydrogen, oxygen, and small amounts of sulfur. Wool, for example, supports combustion only with difficulty and, other factors being equal, is more difficult to ignite, burns more slowly, and is easier to extinguish than cotton. This is seen in wool's small share of the

TABLE 6.5.2 Structure Fires with Fabrics or Textiles as Type of Material First Ignited, 1994–1998 by Type of Fabric or Textile

Type of Fabric or Textile	*Fires*	*Percentage*	*Civilian Deaths*	*Percentage*	*Direct Property Damage (in Millions of Dollars)*	*Percentage*
Cotton or rayon fabric or finished goods	48,800	54.9	748	47.8	507.5	48.6
Manufactured fabric or finished goods	34,100	38.3	765	48.8	475.2	45.5
Wool fabric or finished goods	1,300	1.5	16	1.0	17.3	1.7
Fur, silk, or other fabric or finished goods	300	0.4	2	0.1	5.0	0.5
Other or unclassified fabric or textile	4,400	5.0	36	2.3	40.4	3.9
Total	89,000	100.0	1566	100.0	1045.3	100.0

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires are rounded to the nearest hundred, civilian deaths to the nearest one, and direct property damage to the nearest hundred thousand dollars. Damage has not been adjusted for inflation. Figures include a proportional allocation of fires with type of material first ignited unknown or unreported and a proportional allocation of fabric on textile fires with type of fabric or textile unknown.

Source: National estimates based on National Fire Incident Reporting System (NFIRS) and NFPA survey.

TABLE 6.5.3 Nonconfined Structure Fires with Fabrics or Textiles as the Type of Material First Ignited, by Type of Fabric or Textile Ignited, 1999–2003 Annual Averages Based on Data Collected in NFIRS Version 5.0 Only

Type of Material Ignited	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Fabric, fiber, yarn, or canvas made of cotton, blends, rayon, or wool	67,800	(84%)	1310	(85%)	4610	(87%)	1205	(83%)
Plastic-coated fabric	1,100	(1%)	0	(0%)	40	(1%)	18	(1%)
Goods of fur, silk, or fabrics other than those listed above	300	(0%)	0	(0%)	10	(0%)	2	(0%)
Unclassified fabric, textile, or fur	11,100	(14%)	230	(15%)	630	(12%)	221	(15%)
Total	80,300	(100%)	1550	(100%)	5290	(100%)	1447	(100%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries to the nearest ten, and direct property damage is rounded to the nearest million. Property damage has not been adjusted for inflation. Sums may not equal totals due to rounding errors. Fires in which the type of material first ignited was unknown or not reported were allocated proportionally among fires with known type of material first ignited.

Source: National Fire Incident Reporting System (NFIRS) and NFPA survey.

fire problem, as evidenced in Table 6.5.2, although the data may also reflect a smaller share of total fabric in use for wool versus cotton and manufactured fibers.

Manufactured Fibers

Manufactured fibers are produced by processing liquids through small holes (spinnerets) and allowing the emerging filaments to be immersed in a coagulating medium. Spinneret orifices generally range from 0.002 to 0.005 in. (0.05 to 0.13 mm) in diameter. Most spinnerets are made of iridium and platinum. The resulting fibers can be used as "filament yarns" or can be cut into shorter lengths and spun into "staple yarns." Staple yarns can contain more than one type of fiber, for example, blends of polyester and cotton. In this way, different textile properties can be attained by blending different fibers.

Manufactured fibers can be divided into two groups: (1) "regenerated" or "reconstituted" fibers and (2) fully synthetic fibers. The major regenerated fiber in use today is viscose rayon. Rayon is made from dissolved cellulose and is similar to cotton in its charring and burning properties. Acetate is made by the reaction of cellulose and acetic acid; it melts before burning. Its burning characteristics are more like thermoplastic fibers (nylon, olefin, and polyester) than cellulose.

TABLE 6.5.4 Structure Fires with Fabrics or Textiles as Type of Material First Ignited, 1994–1998 by Form of Material First Ignited

Product Composed of Fabric or Textile	*Fires*	*Percentage*	*Civilian Deaths*	*Percentage*	*Direct Property Damage (in Millions of Dollars)*	*Percentage*
Mattress, bedding, or pillow	26,000	29.2	520	33.2	327.3	31.3
Clothing, on or not on a person	17,700	19.9	235	15.0	168.1	16.1
Upholstered furniture	11,400	12.8	571	36.5	204.4	19.6
Linen other than bedding	5,400	6.1	12	0.8	32.8	3.1
Dust, fiber, or lint	4,800	5.4	4	0.3	19.3	1.8
Floor covering	4,400	5.0	50	3.2	65.7	6.3
Curtain, drapery, or tapestry	3,600	4.0	28	1.8	39.9	3.8
Unknown-type fabric or textile product	2,000	2.2	35	2.2	23.5	2.2
Unclassified fabric or textile product	1,200	1.4	6	0.4	10.9	1.0
Unclassified form of material	1,200	1.4	8	0.5	11.3	1.1
Trash	1,200	1.3	1	0.1	6.1	0.6
Cleaning supplies	1,000	1.2	0	0.0	9.3	0.9
Other known form of material	9,000	10.2	95	6.1	126.8	12.1
Total	89,000	100.0	1,566	100.0	1,045.3	100.0

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires are rounded to the nearest hundred, civilian deaths to the nearest one, and direct property damage to the nearest hundred thousand dollars. Damage has not been adjusted for inflation. Figures include a proportional allocation of fires with type of material first ignited unknown or unreported.

Source: National estimates based on National Fire Incident Reporting System (NFIRS) and NFPA survey.

TABLE 6.5.5 Nonconfined Structure Fires with Fabrics or Textiles as the Type of Material First Ignited, by Item First Ignited, 1999–2003 Annual Averages Based on Data Collected in NFIRS Version 5.0 Only

Item First Ignited	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Mattress or bedding	19,100	(24%)	460	(29%)	1890	(36%)	371	(26%)
Clothing or wearing apparel	14,100	(18%)	190	(12%)	720	(14%)	181	(13%)
Upholstered furniture or vehicle seat	11,900	(15%)	560	(36%)	1100	(21%)	312	(22%)
Unclassified soft goods or wearing apparel	5,800	(7%)	60	(4%)	250	(5%)	85	(6%)
Linen other than bedding	5,200	(6%)	20	(1%)	180	(3%)	63	(4%)
Floor covering, rug, carpet, or mat	4,900	(6%)	80	(5%)	240	(5%)	94	(6%)
Unclassified furniture or utensil	4,500	(6%)	90	(6%)	320	(6%)	92	(6%)
Curtain, blind, drapery, or tapestry	4,100	(5%)	30	(2%)	270	(5%)	71	(5%)
Dust, fiber, or lint, including sawdust and excelsior	2,000	(3%)	0	(0%)	30	(1%)	18	(1%)
Unclassified item first ignited	1,300	(2%)	0	(0%)	60	(1%)	18	(1%)
Goods not made up, including fabrics and yard goods	800	(1%)	10	(0%)	20	(0%)	12	(1%)
Appliance housing or casing	600	(1%)	10	(0%)	20	(0%)	5	(0%)
Interior wall covering	600	(1%)	10	(1%)	20	(0%)	9	(1%)
Electrical wire or cable insulation	500	(1%)	0	(0%)	10	(0%)	8	(1%)
Oily rags	500	(1%)	0	(0%)	20	(0%)	16	(1%)
Other known item first ignited	4,300	(5%)	30	(2%)	140	(3%)	93	(6%)
Total	80,300	(100%)	1550	(100%)	5290	(100%)	1447	(100%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries to the nearest ten, and direct property damage is rounded to the nearest million. Property damage has not been adjusted for inflation. Sums may not equal totals due to rounding errors. This table includes a proportional share of structure fires in which the type of material first ignited was unknown or not reported when it should have been. Fires in which the item first ignited was unknown or not reported were allocated proportionally among fires with known item first ignited.

Source: National Fire Incident Reporting System (NFIRS) and NFPA survey.

The major fully synthetic fibers are acrylics (which char, intumesce, and burn when exposed to heat) and the thermoplastic fibers, such as nylon, olefin (including polypropylene and the less popular polyethylene fibers), and polyester. There are also glass, metallic, and carbon fibers. Acrylics and nylon contain nitrogen atoms and, like wool, produce hydrogen cyanide when burned. The thermoplastics do not char but shrink away from heat sources and melt, form holes near the heat source, and/or ablate, absorbing the thermal energy and degrading the product at the same time. If such fabrics burn, the upward flame spread tends to be slow. Molten polymer runs downward, moving the flames sideways and downward, or forms drops that may or may not flame. Compared to fabrics containing cellulose, thermoplastics are generally more difficult to ignite and the flames tend to cover smaller areas, travel more slowly, or self-extinguish, depending on the nature of the specific fiber. Glass, metal, and carbon fibers have relatively high heat resistance and do not ignite.

TEXTILE MANUFACTURING

All yarn manufacturing innovations during the past 20 years have been to increase productivity and reduce labor cost. Better control and testing of fiber properties using computers has resulted in higher quality products with greater consistency. Fiber frequency distributions of the cotton bale population establish better processing schemes. Cotton bales are selected for a proper mix using a number of blending algorithms that meet different blending strategies. A consistent fiber profile fed to the textile process will produce a consistent yarn quality. Fiber information is available from the USDA's regional classing offices and other sources of data. The impact of fiber selection and blending can be witnessed in all areas of the textile process and in the quality of the end product.

Many fibers are spun into yarns and then woven or knitted into a variety of fabrics, for example, plain or patterned fabrics, or pile, such as flannels, terry cloth towels, artificial furs, and carpets. Fibers also can be processed directly into useful structures, such as nonwoven fabrics or battings. Fabrics are usually scoured, bleached, dyed, and/or finished with chemicals that give them a stiffer or softer feel, permanent press characteristics, luster, or flame or weather resistance.[1]

Figure 6.5.1 shows the steps in manufacturing woven cotton and cotton blend materials. Additional details for the manufacture of cotton fabrics, along with their respective hazards, are provided in the succeeding paragraphs. Many of these steps apply to other types of fabrics.

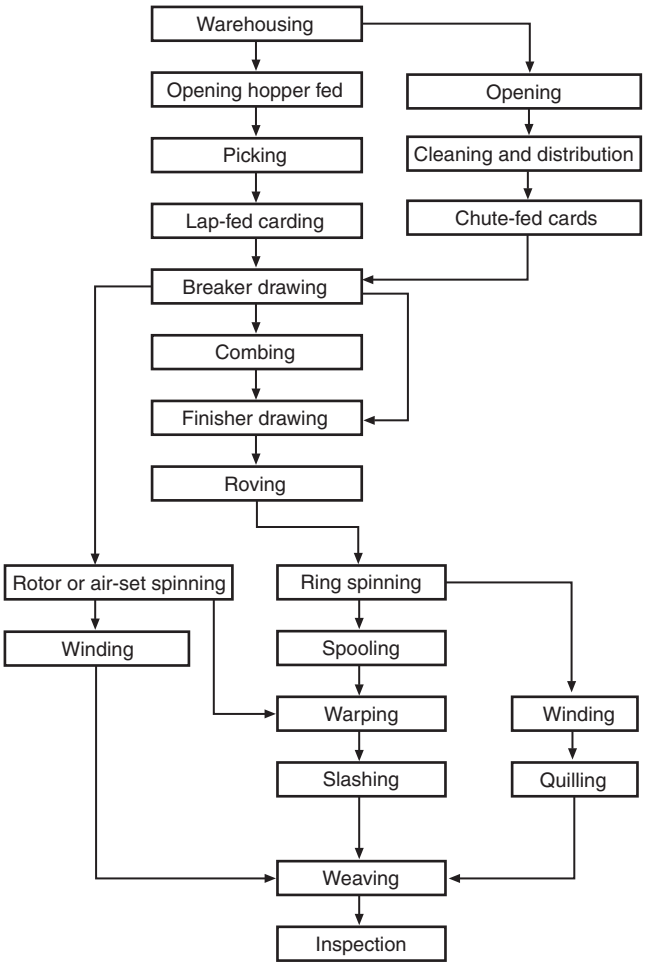


FIGURE 6.5.1 Cotton and Cotton Blend Woven Material Manufacturing

Opening, Picking, Cleaning, and Blending

Cotton received from the gin arrives in bales tightly matted and highly compressed. Debris in the form of dirt, leaf matter, grass, stones, baling wire, machine dust from the ginning process, and tool parts from the handling process can be present. When bales of cotton are brought from the warehouses into the opening rooms, bale ties and coverings are removed and bales are allowed to sit for several hours until they reach room temperature and adjust to the humidity of the area. To ensure uniformity in the end product, cotton must be blended from several bales to make the size, length, and color of the cotton as uniform as possible. This blending process, starting with opening, continues through most processing operations. Opening machinery loosens and separates the cotton into tufts, so it can be effectively cleaned and further processed.

Removing impurities, short fibers, and "dust" from the cotton fiber is essential to ensure product quality and to allow the use of high-speed spinning machines. The cleaning operations are performed pneumatically and mechanically, while the fibers are further separated by spiked and saw-toothed rollers. The dust and light impurities are sucked away, while heavy waste is removed by inertial traps. The efficiency and high speeds of these cleaning machines critically depend on the airflow within the equipment and within the dust-removal system.

In the chute-feed system, bales are automatically fed into openers connected to various mixers and blenders. The material is then air-driven through ductwork to the carding process, where card lines are fed from individual mixers/reserve hoppers. Usually, hand-fed waste-opener hoppers reintroduce usable waste to the process.

These chute-fed card systems could easily transport fires throughout the entire process, particularly with the high speed of the equipment. Causes of fires in these processes include foreign material in the stock being processed, friction, and defective electrical equipment. Fire in cotton can spread fast and flash over an entire group of open bales before it can be extinguished. Tramp metal in the cotton is a notable cause of fires in opener and picker rooms. The development of strong and reliable permanent magnets in the 1940s brought about the use of magnetic separators, which significantly contributed to reducing the risk of fire caused by foreign materials. Magnets, however, are not the complete answer to the problem. Nonferrous objects, such as stones, can still produce sparks if they strike any rapidly moving steel part of the opening or cleaning machinery. Gravity traps, which use gravity and inertia to separate heavy foreign materials from the cotton, can be strategically installed to remove these foreign materials.

Carding

Carding machines separate and lay the cotton fibers parallel to each other. During the carding process, two surfaces of wire or metallic card cloth, moving in the same direction but at different speeds on the card machine, comb the cotton into a fine web of generally parallel fibers. A rapidly vibrating vertical comb and a doffer roll remove the fibers from the main drum in a thin film known as the "web." The web is drawn through a tapered cylindrical device called a "trumpet," which condenses the web into a soft, fleecy, rope-like strand of cotton known as a "sliver." The sliver is coiled into storage cans and moved to subsequent equipment.

Fire hazards in a card room are not as great as in opener rooms. However, card room fires can occur and can be severe, as a result of higher operating speeds, insufficient maintenance, or insufficient cleaning.

Combing

Combing, an optional process used before drawing, produces a fine, high-quality product. Revolving or oscillating combs equipped with needles perform the combing operation. The purpose is to separate the shorter fibers from the longer ones for removal. The resulting combed fibers are more uniform.

Drawing and Roving

The purpose of "drawing" or "drafting" is to further straighten the cotton fibers, reduce the size of the sliver, and accomplish some degree of blending and additional paralleling of fibers. Usually six or more strands of "card sliver" are fed into the drawing frame and passed through many sets of rolls. The roving process is similar to drawing, except the end result is a condensed sliver about ⅛ in. (3.2 mm) thick.

Spinning

There are three spinning methods used by the textile industry:

- Conventional ring-spinning
- Rotor (or open-end) spinning
- Air-jet spinning

Each spinning system consists of:

- Drafting to reduce the size of the input material and deliver the proper yarn count
- Consolidating to provide the necessary coherence between fibers and strength
- Winding to form the yarn package

Rotor and air-jet spinning eliminate the need for combing, roving, and bobbin winding.

The yarn discharging from the spinning head can be wound directly onto spools to eliminate the need of a winding operation. Ring-spinning is performed on a spinning frame by reducing the roving strand to the desired size, imparting twist. The finished yarn or thread is wound on a bobbin. Although air-jet spinning is up to 10 times faster than ring-spinning, ring-spinning produces a stronger, more uniform yarn.[2]

Many mills have installed suspended ceilings above the spinning frames to better maintain temperature and humidity control. Unfortunately, cotton fiber and lint can accumulate above the ceiling tiles and create a potential fire hazard.

Warping

Warping is the first step in preparing for the weaving process. The end threads are tied into continuous lengths that are then threaded through guides and eyelets and wound in parallel on the "section beam." Warper beams are sometimes stored in a high-piled rack configuration consisting of cantilever beams.

Slashing

Before the warp yarns can be used in a loom, they must be treated and coated to prevent the yarns from breaking from tension forces and rubbing or chaffing during the weaving process. In this process, yarn is run through a hot solution of starch, gum, and a softening agent, then dried and wound on the "loom beam." The coating applied is called "sizing."

Loss exposure from fire in these areas is moderate due to combustible loading. However, improperly handled starch can result in a dust explosion. The use of starch has diminished greatly. Polyvinyl alcohol (PVA) is being used in its place.

Weaving

Weaving converts yarn into cloth by interlacing two sets of yarn on a loom. One set is the "warp," the long longitudinal threads; the other is the "filling" or "weft," which runs the width of the loom.

Fire losses in plain weave rooms, which are second only to cotton opening rooms, are usually small and contained in one machine. Two notable hazards are (1) defective electrical equipment and (2) excessive friction.

Knitting, Braiding, and Tufting

Knitting involves the interlooping of one yarn system that continuously connects vertical columns (wales) and horizontal rows (courses) of loops to form a knitted fabric structure. There are two general types of knitting: weft knitting and warp knitting.

In weft knitting, fabrics are made by feeding a multiple number of ends into the knitting machine and each loop is progressively made by the needle or needles. The previously formed yarn loop becomes an element of the knitting process with the latch needle. This process yields either flat knit fabrics or a circular tube, depending on how the equipment is set up. Warp knitting is accomplished by preparing a warp beam that contains several hundred ends. Stitch formation on a warp knit differs from weft knitting in that a complete course of loops is formed rather than individual needles acting on loops within a course. Knit fabrics offer relative high extension and recovery compared to woven fabrics; knit fabrics also generally involve a more open structure permitting greater air permeability but still at high levels of insulation.

Braiding involves diagonally overlaying different yarns and is used to produce narrow-width fabrics or cords and other three-dimensional fabrics. Tufting involves sewing a system of yarns into a fabric leaving the yarn loops to produce different surface effects on fabrics. These raised structures can result in greater flammability when ignitable fibers are used.

Nonwoven Fabrics

Nonwoven fabrics are textile structures produced by bonding and/or random interlocking of fibers. This can be accomplished mechanically, chemically, thermally, or by using solvents or adhesives. There are four common methods of making nonwoven fabrics: needlepunching, hydroentangled spunlacing, resin bonding, and thermoplastic bonding.

Needlepunched nonwovens work well with longer fiber length. Fiber finish is critical in needling. Bleached cotton or other fibers with good lubricity are needed to prevent fiber damage and needle breakage. Raw unbleached cotton can also be used with proper needle selection.

Hydroentangled spunlaced fabrics have many characteristics that are similar to woven fabrics. They are easily dyed and finished using conventional textile methods because they have good strength characteristics.

Resin-bonded webs can be bonded by spraying, foaming, gravure roll padding, or by aqueous dispersion equipment, depending on the end product performance desired. The newly formed web is dried, heat cured, and may be calendered. Some iron-on fabric adhesives are made in this manner.

Thermoplastic bonded nonwoven fabrics contain either cut staple or filament fibers with low melting points. Blends with natural fibers like cotton with polyolefin, polyester, or bicomponent fibers can be used. The fabric is produced by needle punching or other mechanical means. Once in mat formation, heated calenders or high-speed embosser calenders cause the fibers to bond by controlled melting and softening. Some materials use adhesives or latex to further stiffen the fabric. Unbleached cotton cannot be effectively bonded due to natural waxes on the raw fiber, which interfere with adhesion. The higher the cotton content, the lesser the bonding, thereby reducing the fabric strength.

Nonwoven fabrics are widely used in many ways, for example, as hazmat protective clothing, medical clothing, disposable clothing, stiffeners, and backings in clothing and rugs.

Nonwoven fabrics generally do not include paper or wool felt materials, even though the processes are somewhat similar. Loose, highloft fibers are used as filling materials and personal hygiene products.

TEXTILE COMBUSTIBILITY

There are 27 generic manufactured fibers and over 100 trade names. See Table 6.5.6 for common fiber types. Some trade names are as common as the generic names due to overuse. Some trade names refer to more than one generic fiber. One such fiber, Nomex®, can be nylon or aramid. Nylon is a long-chain polyamide in which less than 85 percent of the amide linkages are attached directly to two aromatic rings. If more than 85 percent are linked, it becomes an aramid fiber.

The ignitability, flame spread and heat release rates, total heat produced, heat shrinkage, and ease of fire extinction in textiles depend on the type of fibers used, their percent content, the configuration of the fabric, its weight, and its construction. The finish generally does not alter these properties significantly, unless the fabric is treated with a flame retardant. Flame-retardant treatments can be either durable or nondurable. Normal laundering and dry cleaning may reduce flame retardancy.

Characteristics of common textile fibers, including their burning behavior and end uses, are listed in Table 6.5.7. Table 6.5.8 provides burn characteristics and fire residue characteristics for selected fabrics.[2] The data have been collected from a variety of sources.[3,4] The descriptions of burning behavior in Tables 6.5.7 and 6.5.8 and the discussions throughout this chapter are based on small-scale tests and may be misleading when large fires or strong radiation sources are encountered. In such cases, even fabrics that are considered flame retardant may burn readily.

The orientation of a fabric also influences its combustibility. Fabrics generally burn faster in the vertical position than in the horizontal position. The edge of the fabric will also ignite much more easily than the surface, given the ability of the flame to contact more than one side. Some fabrics melt when burned,

TABLE 6.5.6 Common Natural and Manufactured Fibers

	Manufactured		
Natural	*Cellulosics*	*Noncellulosics*	
Cotton	Acetate	Acrylic	Nylon
Linen	Rayon	Anidex	Olefin
Silk	Triacetate	Aramid	PBI
Wool		Azlon	Polyester
		Glass	Rubber
		Lastrile	Saran
		Lyocell	Spandex
		Metallic	Sulfar
		Modacrylic	Vinal
		Novoloid	Vinyon

TABLE 6.5.7 Fire Hazard Properties of Common Textile Fibers

Fiber Designation	*Decomp. Temp. °F (°C)*	*Melting Temp. °F (°C)*	*Ignition Temp. °F (°C)*	*Burning Temp. °F (°C)*	*Burning Behavior*	*End Uses*
A. *Natural Fibers*						
Cellulosic: cotton, hemp, jute, linen, sisal, etc.	580–610 (305–320)	— —	490–750 (255–400)	1560 (850)	Chars, burns, sometimes afterglow	Apparel, furnishings, towels, cordage
Protein: wool, mohair, cashmere, camel hair, etc.	450 (230)	— —	1060–1110 (570–600)	1720 (940)	Chars, intumesces, burns less readily than cellulosics	Apparel, blankets, carpets, furniture covers
B. *Manufactured Fibers*						
Acetate	570 (300)	500 (260)	842 (450)	1720 (940)	Shrinks, melts, and burns	Apparel, lingerie, furnishings
Acrylic	540–590 (280–310)	420–490 (215–255)	860–1050 (460–565)	1560 (850)	Chars, intumesces, burns, and drips	Apparel, furnishings, carpets, blankets, pile fabrics
Nylon	600–790 (315–420)	420–490 (215–255)	840–1060 (450–570)	1600 (870)	Melts, ablates, burns	Apparel, lingerie, furnishings, carpets, cordage, industrial uses
Anidex	—	—	—	—	—	Elastic fiber used in apparel, home furnishing, and laces
Aramid	660 (370–400)	3700 (2040)	800–1040 (427–560)	—	Does not melt (decomposes)	—
Lyocell	350 (175)	450–500 (230–260)	860 (460)	—	—	Dresses, slacks, coats, jeans
Modacrylic	500 (287)	—	1025 (550)	—	—	Children's sleepwear, carpets, blankets, draperies
Novoloid	—	Nonmelting	—	—	—	Protective equipment
Rubber	200 (93)	—	—	—	—	—
Triacetate	>572 (>300)	550 (288)	>842 (>450)	1560 (850)	Shrinks, melts, and burns	—
Vinal	Similar to nylon	—	—	—	—	Good chemical resistance
Vinyon	—	—	—	—	—	Good chemical resistance
Olefin (polypropylene)	750 (400)	330 (165)	930–1060 (500–570)	1540 (840)	Melts, ablates, burns	Knitted sportswear, carpets, cordage, furniture covers, industrial uses
Polyester	680–750 (360–400)	480–570 (250–300)	840–1040 (450–560)	1290–1330 (700–720)	Melts, ablates, burns	Apparel, lingerie, furnishings, carpets, blankets, fiberfill, cordage, industrial uses
Rayon (viscose)	550 (290)	—	790 (420)	1560 (850)	Chars, burns	Apparel, lingerie, furnishings
Spandex	581–671 (305–355)	446–482 (230–250)	780 (415)	—	Melts, burns	In apparel and lingerie where stretch is desired

TABLE 6.5.8 Textile Identification by Burning Characteristics

Fiber	*Burn Characteristics*	*Residue*
Acetate	Shrinks, melts, and burns	Dark, hard, solid bead; acrid odor (hot vinegar)
Acrylic	Shrinks, melts, and burns	Hard, irregularly shaped bead; black smoke; acrid odor
Aramid	Shrinks, melts, and burns	Hard, black bead; self-extinguishing
Cotton	Burns	Fine, feathery gray ash; odor similar to burning paper
Flax, hemp, jute, ramie	Burns	Fine, feathery gray ash, odor similar to burning paper
Glass	Shrinks slowly, melts at very high temperature	Flame-resistant fiber, heat from lighter will not cause fiber to melt
Modacrylic	Shrinks, melts, and burns	Hard, black, irregular bead; self-extinguishing; acrid chemical odor
Novoloid	Shrinks, burns at high temperature	Retains shape but turns black; heat from lighter will not cause fiber to burn
Nylon	Shrinks, melts, and burns	Hard, cream-colored bead; if fibers are overheated, bead will become dark; flaming usually caused by finish present; drops of melted fiber may fall from heated portion of sample; celery odor
Olefin	Shrinks, melts, and burns	Hard, tan bead; black smoke; chemical odor
Polyester	Shrinks, melts, and burns	Hard, cream-colored bead; if fibers are overheated, bead will become dark, drops of melted fiber may fall from heated portion of sample; black smoke; chemical odor
Rayon	Burns	Fine, feathery gray ash
Rubber	Shrinks, melts, and burns rapidly	Tacky, soft black residue
Saran	Shrinks, melts, and burns	Hard, black, irregular bead; self-extinguishing; chemical odor
Silk	Shrinks and burns	Black, hollow, irregular bead which crushes easily to a gritty black powder
Spandex	Burns and melts	Soft, black ash
Triacetate	Shrinks, melts, and burns	Dark, hard, solid bead; chemical odor
Vinal	Shrinks, melts, and burns	Hard, tan bead; chemical odor
Vinyon	Shrinks, melts, and burns	Hard, black, irregular bead; acrid odor
Wool, mohair, cashmere, alpaca	Shrinks and burns	Black, hollow, irregular bead which crushes easily to a gritty black powder

form a pool, and require other combustibles to act as a wick before their full combustibility can be exhibited.

All common natural fibers, except glass, contain organic compounds and the elements carbon and hydrogen and often also oxygen and nitrogen. Coating added to textile fabrics can greatly alter their combustibility. A number of other coatings are commonly applied to fabrics or bonded to fabrics to create laminates. Coated or laminated fabrics exhibit combustibility characteristics of the coating or film and the fiber(s) used. Chlorine is found in vinyl-coated fabrics.

Thermoplastics are hard to ignite. There are, however, many situations in which thermoplastics can burn readily. This occurs when they are stiffened by finishes or heavy dye application, causing them to lose their ability to evade flames and ablate. It also occurs in blends of thermoplastic and char-forming fibers (even when the latter are flame-retardant), for example, in the popular polyester/cotton blends, which burn more like 100 percent cotton than 100 percent polyester. A thermoplastic fiber fabric in contact with a char-forming fabric, for example, a polyester/cotton skirt in contact with a nylon slip,[5] or a polyester curtain in contact with a foam lining, can burn readily. If a burning outer garment is not in contact with a nylon or polyester undergarment, the latter may not ignite, but it may become limp, shrink, make close contact with, and possibly stick to, the skin, causing injury even without burning. Finally, if an ablated thermoplastic fabric still flames when it falls, it can ignite garments or furnishings near it.

However, with such noted exceptions, many thermoplastics can be considered relatively safe with respect to small-flame ignition, as compared to cellulosics and if used as single-layer apparel. Thus, incidents in which children's nightwear was the first item to ignite were significantly reduced by the introduction of the children's sleepwear standard,[6] and the subsequent change from cotton to primarily thermoplastic nightwear, at no additional cost of the garment.[7] Modacrylic fiber is used for fire-retardant sleepwear. Its characteristics include the following:

- Low heat conductivity
- Weaker strength than acrylic
- Good elastic recovery
- Extremely sensitive to heat
- Inherently flame retardant (self-extinguishing)

The revision of the children's sleepwear standard to allow untreated cotton sleepwear if it passes a test for "snug" fit has reraised concerns about the risks to small children from these products. On the other hand, thermoplastics, even if they are hard to ignite, should not be used in garments that are intended to protect against heat, such as fire fighter or industrial uniforms,

because of their tendency to shrink, melt, and stick when exposed to elevated temperatures.

In addition to the burn behavior, Table 6.5.7 lists temperatures that have been cited for onset of decomposition, melting, ignition, and the burning temperature of the flames. The ranges are often quite wide for any one fiber because of the differences in methods for measuring such temperatures, as well as the variety of polymer compositions used in each fiber group for various end uses. In the case of nylon, there are two major types, Nylon 6 and Nylon 66, which vary in the structure of the base molecule. For the ignition temperature of cotton, one finds two values in the literature, that is, 490 and 750°F (255 and 400°C); it is possible that the lower value was obtained with aged cotton. (It is well known that the ignition temperature of wood decreases with aging, and that may hold for cotton as well.) The ignition temperature of blends tends to be similar to that of the component with the lower ignition temperature. Thus, measured by one method, the ignition temperature for 14 different fiber types ranged from 750°F (400°C) for cotton to 1110°F (600°C) for wool; 50/50 blends of cotton and another fiber ranged from 770 to 860°F (410 to 460°C).

Noncombustible Textiles

Noncombustible fabrics, listed in Table 6.5.9, include those made entirely from inorganic materials. Glass-based fabrics listed by testing laboratories for use as draperies are woven from uncoated glass yarns that do not burn or propagate flame. If a sufficient quantity of combustible coating or decorative material is applied to glass fabrics or to other noncombustible fabrics, however, the fabrics will support continued flaming. The inherent brittleness of glass and the other fibers listed in Table 6.5.9 eliminates them from use in clothing fabrics. They are used as reinforcement for plastics and, in the case of relatively low-priced glass fibers, for curtains and draperies.

High-Temperature and Flame-Retardant Textiles

Some fibers are engineered to be flame retardant for industrial purposes. Fabrics made from glass, aramid, novoloid, sulfar, and saran fibers do not burn with a flame and can withstand high temperatures but may char and degrade. Because of their high cost, texture, and appearance, they are used in specialty gear and industrial applications but are not commonly found in consumer clothing and household textiles.

TABLE 6.5.9 Noncombustible Fibers

Beta Fiber	*Stainless Steel*
E-glass	Super alloy
Quartz	Refractory-whiskers
Carbonaceous residue	Alumina
Carbon	Zirconia
Graphite	Boron

PBI (polybenzimidaxozole) fabric and its blends are used for firefighters' turnout gear, space suits, and aluminized crash/fire and rescue suits. (See Section 12, Chapter 9, "Fire and Emergency Services Protective Clothing and Protective Equipment.")

Aramid has excellent strength and low flammability. It does not melt but decomposes at temperatures above 660°F (349°C). Several of the fibers that resist high temperatures and are used in textiles are listed in Table 6.5.10[8,9] and in Table 6.5.11, along with their ignition temperatures, limiting oxygen index (LOI), and some other physical properties.

The LOI is a way to measure the tendency of a fabric, once ignited, to continue burning after the ignition source is removed. LOI is defined as the minimum volume concentration of oxygen in a mixture of oxygen and nitrogen that will just support sustained combustion of the material when ignited in a vertical position at its uppermost edge.[10] Cotton fabrics, for example, have a LOI of 19 percent, which means that, if the oxygen is reduced below 19 percent, the cotton will not continue to burn after the ignition source is removed. The higher the LOI of a fabric, the greater the probability that it will cease to burn once the ignition source is removed. Fabrics with high ignition temperatures and high LOIs can be expected to be safe for clothing and furnishings, since they will not ignite readily and will not continue to burn after an ignition source is removed. However, it should be noted that the use of the LOI test for textiles has abated in recent years; full-scale tests of the various items are considered more reliable.

As previously discussed, many synthetic fabrics shrink when exposed to temperatures approaching their melting or decomposition temperatures. When shrinkage brings the fabric into contact with the skin, the insulating layer of air is eliminated and the amount of heat transferred to the skin is increased significantly. Thermal shrinkage is a particularly important property to consider when selecting fabric for use in protective clothing. Another important property of fabrics used in protective clothing is the ability to maintain integrity during a fire. Fabrics that weaken by charring may split apart and fall away, leaving the skin directly exposed to heat.

FLAME-RETARDANT TREATMENTS

The flame-retardant treatment of theater scenery, curtains, and draperies in places of public assembly is commonly required by local fire authorities. Treated fabrics are used in hotels, hospitals, and other occupancies in the interest of preservation of lives and property.

Many businesses specialize in the flame-retardant treatment of theater scenery, draperies, and other fabrics, using standard chemicals. However, some of these businesses may not treat fabrics properly or may use relatively ineffective or nonpermanent chemicals. It is, therefore, advisable to deal only with businesses of known reliability or, if dealing with an unknown concern, to have treated fabrics tested for adequacy of treatment.

The resistance of such treatments to aging, laundering, and dry cleaning must be ensured. Also, it must be emphasized that such treatments are only expected to make fabrics resistant

TABLE 6.5.10 High-Temperature, Flame- and Chemical-Resistant Fibers

	Ryton	*Ultrate*	*Nomex*[a,b]	*Kevlar*[a,b]	*PBI*[b]	*P-84 Polyimide*	*Kynol*[b,c] *Phenolic*
Softening point °F (°C)	545 (285)	>600 (>315)	Decomposes[d]	Decomposes[d]	Decomposes[d]	Decomposes[d]	NA
Upper use temp. (50% tenacity) °F (°C)	400 (205)	500 (260)	450 (230)	500 (260)	>600 (>315)	>550 (>290)	NA
Strength (g/denier)	2–4	4–6	3–5	18–20	3–5	3–4	1.5
Elongation (%)	20–40	20–40	20–40	3–4	25–40	30–40	35
Chemical resistance							
Hot acid	VG	G	P	P	VG	VG	P
Hot base	VG	VG	P	F	G	P	P
Hydrolysis	VG	VG	F	F–P	VG	VG	NA
Solvents	VG	VG	G	VG	VG	VG	VG
Dry heat resistance	G	VG	G	G	VG	VG	VG
Flammability (LOI)[e]	34	26	30	29	38–49	37	29–31
Smoke density[f]	NA	NA	5	5	3	7	low

[a]Generic name: Aramid.
[b]Presently used in structural fire fighter's protective gear.
[c]Generic name: Novoloid.
[d]Decomposes rather than melts.
[e]LOI: Limiting oxygen index; for example, non-flame-retardant wool = 28 and cotton = 19.
[f]Smoke density is a relative scale where, for example, wool = 46 and cotton = 26.
VG = very good; G = good; F = fair; P = poor; NA = not available.
Table, with minor additions, reproduced by courtesy of Albany International Research Co., Mansfield, MA.

TABLE 6.5.11 Flame-Retardant (FR) Fibers

Fiber Type	*LOI*	*Ignition Temp °F (°C)*	*Burning Behavior °F (°C)*	*Trade Names*
PVC	37	930 (500)	Chars, shrinks at low temperatures	Rhovyl, Leavyl, Teviron
FR rayon	31	—	Chars	PFR
Matrix	29–32	930–1000 (500–540)	Chars at 430 (220), shrinks	Kohjin, Cordelan
Modacrylic	27–30	600 (315)	Chars, shrinks at 280–360 (140–180)	SCF
FR polyester	28	—	Melts at 480 (250)	Trevira 271, Heim
FR wool	32–34	1060–1100 (570–595)	Chars, intumesces	—
FR cotton	28–32	450 (230)	Chars	—

to ignition by small flames, and that they may burn readily in larger fires.

The effects of chemical treatments in reducing the flammability of combustible fabrics are varied and complex, and all phases are not fully understood. There are five different ways in which chemicals or mixtures retard spread of flame and afterglow: (1) they generate noncombustible gases that tend to exclude oxygen from the burning surface; (2) radicals or molecules from degradation of the flame-retardant chemical react endothermically and interfere with chain reactions in the flame; (3) the flame-retardant chemical decomposes endothermically; (4) a nonvolatile char or liquid is formed by the chemical, which reduces the amount of oxygen and heat that can reach the fabric; and (5) finely divided particles are formed that change the combustion reactions. Usually a flame-retardant chemical or mixture affects flammability in more than one of these ways. A review of flame-retardant treatments for textiles can be found in *Fire Safety Journal.*[11] Flame-retardant treatments can increase the LOI of cotton from 19 to 28 or 32, and of wool from 28 to 32 or 34.

Hundreds of different chemicals have been suggested as flame-retardants for textiles. It must be emphasized that no one system works for all fibers, as can be seen from Table 6.5.12. In addition, some chemical systems change textile properties, for example, resistance to sunlight, absorption, color, and flexibility, or lose some of their effectiveness when exposed to high temperatures or repeated launderings. Much progress has been made in overcoming most of these undesirable effects. Loss of strength, for example, has become a minor problem in correctly treated flame-retardant cotton fabrics. However, concern that some flame-retardants may be skin irritants, carcinogens, or too expensive can deter wider use.

TABLE 6.5.12 Flame-Retardant Chemicals for Textiles

Fiber	*Typical Flame-Retardant Chemical*
Cotton	Tetrakis (hydroxymethyl) phosphonium salt insolubilized with ammonia gas
Cotton-rayon (disposable, nondurable finish)	Diammonium phosphate; ammonium sulfamate; boron compounds
Rayon (modified fiber)	Hexapropoxy phosphazene
Polyester (modified fiber)	Oligomeric phosphonate decabromodiphenyl ether (DBDPE) and antimony oxide
Polyester, acetate, nylon	Oligomeric phosphonate decabromodiphenyl ether (DBDPE) and antimony oxide
Nylon (nondurable finish)	Thiourea
Wool	Ti, Zr compounds, dibromoterephthalic acid
Modacrylics (modified fibers)	Vinylchloride, vinylidene chloride, vinylbromide as comonomer

It must be emphasized that treatments that protect against ignition of textiles by small flames do not necessarily impart resistance to smoldering ignition by cigarette. For example, flame-retardant treatment of cotton generally lowers the charring temperature of cotton but often decreases the cigarette ignition resistance.

RELATIONSHIP OF FLAMMABILITY AND END USE

Understanding the characteristics of fibers and textiles provides a foundation for determining their behavior when contacted by heat or flame in end items. The specific application of a textile fabric will affect how the end item is evaluated for flame and heat properties.

Clothing

Congress passed the *Flammable Fabrics Act of 1953,*[12] after a rash of serious fire incidents in which rayon-pile fabric made into children's cowboy chaps and sweaters was involved. All wearing apparel sold since 1953 has had to pass a test described in the Consumer Product Safety Commission's (CPSC) "Standard for the Flammability of Clothing Textiles."[13] The test excluded the rayon-pile fabrics and other extremely flammable fabrics, such as very high-pile cotton flannels, stiffened nylon nets, and very light fabrics. However, all normal apparel fabrics must pass this test.

Several studies indicated that additional protection of young and old populations would be desirable. For example, in a study of 463 fire fatalities that occurred from 1972 through 1977 in the State of Maryland,[14] deaths from clothing ignitions comprised 5.5 percent of the fatalities. Of those victims, 21.6 percent were 9 years old or younger, and 20.5 percent were 60 years old or older. Persons aged 50 years and older were more likely to become fire casualties. The number of fire deaths in this age group was approximately twice the predicted number, based on 1970 census data for Maryland. Factors that contributed to the increased proportion of fire fatalities at both ends of the age spectrum were inability to rapidly and successfully cope with the fire situation and lowered tolerance to toxic combustion products. This applied especially to the older population, where increased cardiopulmonary weakness contributed to lower tolerance to toxic exposures. In addition, it was shown that many victims of garment fires wore sleepwear at the time of the incident.

Consequently, a children's sleepwear standard was promulgated for sizes 0 through 6x in 1971, followed by a standard for sizes 7 through 14, three years later.[5] At the time of promulgation, this standard strained the state of the art, but thermoplastic and flame-retardant garments were soon produced that passed this rather severe test. The results have been unexpectedly beneficial. As noted earlier, however, changes to the standard to allow untreated cotton sleepwear for children based on a test for snugness when sold raised the possibility that the problem of hazardous children's sleepwear might be introduced, but no evidence of this problem has surfaced.

Since the introduction of the children's sleepwear standard, the number of burn deaths among children under age 15 due to ignitions of any type of clothing has dropped to five or fewer a year. However, a serious problem still exists for older adults. From 1983 through 1985, for example, clothing-ignition burn deaths accounted for roughly one fire death of every 20 fire deaths overall, but for one of every eight fire deaths for people age 65 and over. Since people age 65 and over also have twice the fire death rate of the whole population, this means that they have five times the rate of death due to burns from clothing ignition fires.[15]

The style or type of garment is an important factor in evaluating its fire hazards. For example, a full-length gown containing several yards of flammable fabric could be quite hazardous, whereas a tightly fitting blouse or shirt made of the same material might be far less dangerous. Not only would the gown present much more fuel for burning, but its size and loose shape would make it far more vulnerable to contact with typical ignition sources. The wearer is unaware that an ignition source is in contact with the garment. Flared skirts, large bows, and full-sleeved kimonos are other examples of easily ignitable garments. The availability of oxygen on both sides of loosely fitting garments accelerates flame spread. This fact was the principle behind the recent change to the children's sleepwear requirements, but there is no guarantee that a garment sold as snug will still be snug after multiple wearings, washings, and hand-me-downs.

Heat- and Flame-Resistant Protective Clothing

Protective clothing used to protect against thermal hazards (flame, heat, and molten metal exposure) spans a range of required performance depending on the specific application. Common applications requiring special clothing with flame and heat protective properties include the following:

- Chemical processes and refining
- Electrical utilities
- Fire fighting
- Welding
- Smelting and foundry operations

Protective clothing for these and other applications is distinguished between primary protective clothing, where the clothing is specifically required to protect against a thermal hazard in which exposure is likely, and secondary protective clothing, where exposure might be incidental and accidental. For example, uniform clothing worn by workers at a petrochemical facility would be considered secondary protective clothing whereas the turnout clothing worn by firefighters is considered primary protective clothing.

In general, all forms of heat- and flame-resistant protective clothing must demonstrate some level of heat and flame resistance based on standardized test methods. Heat resistance indicates that materials used in the construction of clothing resist adverse effects from exposure to heat, such as ignition, melting, dripping, and separation. Quantitative effects from heat exposure can be determined by measuring the amount of shrinkage and weight loss. The temperature at which this testing is performed will discriminate performance among different materials. The level of flame protection required is usually sufficient to either indicate resistance to ignition by flame contact or to show that materials will not continue to burn once the flame source is removed.

Additional types of thermal performance will depend on the intended end use. Primary protective clothing is generally required to provide insulation from heat exposure, whether the heat exposure is through convection, conduction, radiation, or a combination of these forms of heat transfer. In addition, primary protective clothing might be required to resist the effects of contact with molten metal that can range from droplets (welding splatter) to splashes of molten metals in significant volumes (during smelting operations). For example, clothing materials used around molten aluminum must not only limit the amount of heat transfer through accidental contact but also permit the molten metal to run off and not ignite during the exposure.[16] Some intrinsically flame-resistant clothing materials are unsuitable for this application because the molten aluminum adheres to the fabric, causing localized damage to the fabric and high levels of heat transfer.[17]

Fire-fighting protective clothing is often called on to provide multiple forms of heat insulation performance because of the variety of hazards that can be encountered during emergency response operations. All materials used in this multilayered clothing must individually be resistant to flame and heat. As a composite, the materials must provide a sufficient amount of insulation to relatively high heat and flame exposures to offer a sufficient level of protection to the wearer. The relative protection will depend on the level of exposure and will be a function of energy level and time of exposure. Abbott characterized three distinct ranges of heat exposure to structural firefighters including routine, ordinary, and emergency conditions based on ranges of air temperature and thermal radiation.[18] Veghte further characterized these fire-fighting conditions by estimating the tolerance times that exist for firefighters working under these exposure conditions, including 10–20 minutes for routine conditions, 3–5 minutes for ordinary conditions, and 10–30 seconds for emergency conditions.[19] The type of heat environment will further vary with the type of fire fighting. Fire fighters in wildland situations are expected to have lower levels of heat exposure but must wear their protective clothing for much longer periods of time. On the other hand, fighting fires involving aircraft or bulk flammable fuels or gases, can produce extremely high levels of radiant heat and dictate the use of reflective or aluminized materials.

Secondary protective clothing involves use of flame-retardant-treated or intrinsically flame-resistant clothing materials. For petrochemicals workers, this type of clothing is required because of the potential for flash fire. Early studies indicated that the principal injuries to workers exposed to flame fire was the continued burning of their clothing as opposed to the flash fire exposure itself.[20,21] Therefore, this clothing in resisting ignition over the relative short duration of a flash fire provides a much larger level of safety for the wearer. Utility workers who can come into contact with high-voltage sources in electrical power generation stations must be protected from the thermal impulses associated with electrical arcs. These arcs are capable of generating 1.6 MW/m^2 in a fraction of a second.[22]

Table 6.5.13 is a list of specifications providing requirements for various types of heat and flame protective clothing. Each of these specifications cites specific test methods for evaluating clothing heat and flame resistance. Currently, there are no specifications for some types of protection including welding and fire entry suits.

Mattresses and Upholstery

The ignition of mattress and upholstery textiles is a well-documented cause of fires, particularly from cigarettes. Mattresses and bedding are a leading first product ignited in many house fires according to NFPA statistics.[23] Mattresses and bedding were the items first ignited in 17,490 home structure fires, 413 civilian deaths, 1990 civilian injuries, and $357.4 million in direct property damage per year between 1999 and 2002. These fires have declined steadily since 1980, mirroring the overall trend in home fires. Two of the major causes of mattress and bedding fires—heat source too close to combustibles and careless discarding of materials—can probably be explained by the high percentage of mattress and bedding fires initiated by cigarettes. Twenty-two percent of all mattress and bedding fires were the result of cigarette ignition. Matches and lighters caused another 28 percent of these fires. Similar, but proportionally less, statistics have been posed for upholstered furniture.

TABLE 6.5.13 Specifications for Heat- and Flame-Protective Clothing

			Requirements for Heat- and Flame-Resistance							
Specification	*Application*	*Type of Clothing*	*Flame Resistance*	*Heat Resistance*	*Radiant Heat Resistance*	*Thermal Shrinkage Resistance*	*Thermal Insulation (convection/radiation)*	*Thermal Insulation (conductive)*	*Thermal Insulation (electrical arc)*	*Molten Metal Resistance*
ASTM F1002	Molten metal protection	Primary, secondary	X							X
ASTM F1506	Electrical arc protection	Secondary	X						X	
ASTM F2302	General heat and flame protection	Secondary	X	X						
CGSB 155.1	Fire fighting	Primary	X	X		X	X			
CGSB 155.20	Industrial flash fire protection	Secondary	X	X		X	X			
CGSB 155.22	Wildland fire fighting	Primary	X	X	X	X	X			
EN 531	General heat and flame protection	Primary, secondary	X		X		X	X		X
EN 533	Flame protection	Secondary	X							
EN 469	Fire fighting	Primary	X	X	X	X	X			
EN 1086	Specialized fire fighting	Primary	X	X	X	X	X			
ISO 11611	Welding protection	Primary	X	X						X
ISO 11612	General heat and flame protection	Primary, secondary	X		X	X	X	X		X
ISO 11613	Fire fighting	Primary	X	X	X	X	X			
ISO 15384	Wildland fire fighting	Primary	X	X	X	X				
ISO 15538	Specialized fire fighting	Primary	X	X	X	X	X			
NFPA 1951	Technical rescue operations	Primary	X	X	X	X	X			
NFPA 1971	Structural fire fighting	Primary	X	X		X	X	X		
NFPA 1975	Station/work uniforms	Secondary	X	X						
NFPA 1977	Wildland fire fighting	Primary	X	X	X	X				
NFPA 2112	Industrial flash fire protection	Secondary	X	X		X	X			

ASTM = American Society for Testing and Materials.
EN = Committee on European Standardization.
CGSB = Canadian General Standards Board.
ISO = International Standards Organization.
NFPA = National Fire Protection Association.

A mattress or upholstery fire poses two main dangers. The materials used to make mattresses and upholstered furniture allow fire to penetrate deeply and smolder for a long period of time, and they tend to be slow burning. Both result in production of the toxic gases and difficulty in extinguishment that are associated with slowly burning materials.

The overall decline of mattress and upholstery fires has been due in part to regulations that introduced the use of improved flame-resistant materials in these products. The U.S. government and some states have had standards regarding the flammability of mattresses exposed to smoldering cigarettes found in 16 CFR Part 1632.[24] More recently, California has introduced testing to limit the peak heat release of mattresses or mattress sets during fires. When mattresses have a limited contribution to the fire, the available time for occupants to discover the fire and escape substantially reduces the risks associated with mattress fires. The federal government has adopted similar procedures as part of new regulations in 16 CFR Part 1633.[25]

Curtains, Draperies, and Wall Coverings

Curtains, draperies, and wall coverings can ignite from such ignition sources as electrical malfunction or wastepaper-basket fires. Flames can rapidly spread to walls and ceilings. It has been shown that large differences exist between the potential of various domestic curtain materials to ignite wall-covering materials and the production of heat and smoke this creates.[26] Curtains in public occupancies are regulated by local authorities and conforming materials do not seem to present major problems during the initial stages of a fire. The test most prescribed by regulatory authorities for curtains and draperies is NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films.* NFPA 701 recently addressed that, even if single layers of curtain fabrics pass the requirements of the standard, the combination of two or three layers, often found in motels, may burn vigorously. This was illustrated in a full-scale test.[27] Other improvements in test methodology have been incorporated into recent revisions.

Carpets and Rugs

Until 1960 there was very little fire experience to indicate that carpets were a significant factor in fires. Consequently, floor coverings were customarily exempted from coverage in building codes regulating life safety from fire. Since 1960, although there were only a small number of fires reported in which carpets spread fire, those that have been reported indicate that carpets can be the prime material involved in the development or spread of a fire. In 1970 a fire in a California dwelling was first seen by an occupant when it was a few feet in diameter on carpeting in front of the fireplace.[28,29] As the occupant applied water with a garden hose to the burning carpet, the fire spread rapidly on the carpet and, within ten minutes after discovery, enveloped the entire room including furniture and wood paneling. Because of such experiences, carpet flammability has been for some time regulated at the federal, state, and municipal levels. The persistence of fatal carpet and rug fires noted in Table 6.5.4 primarily occurs in the much less regulated home environment.

Among the many factors in carpet construction that may affect ease of ignition and ability to spread fire are fiber type, area unit weight density (or, loops per square inch), pile height, backing material, padding, type of adhesive, single versus double back, and type of dye. (Carpet flammability tests for residential and special occupancies are discussed later in this chapter.)

TEXTILE FLAMMABILITY TESTS

The severity of the hazard of a fabric in a particular type of product, such as a dress, curtain, or carpet, depends greatly on the ease of ignition of the product, the speed with which flame spreads, the amount of heat generated and the rate at which it is released, susceptibility to melting, and the quantity and composition of the smoke and gaseous products of combustion. No individual test method gives a complete evaluation of the hazard, and there are no nationally recognized test methods to measure some of the hazards. Many of the more important test methods for textile products have been summarized.[30–32] With the exception of the test methods for mattresses and upholstered furniture, those in common use in the United States are described below. Table 6.5.14 provides a list of several methods used for flammability of textile materials.

Clothing

The federal Flammable Fabrics Act of 1953 was signed into law in 1953 and amended in 1967.[12] The act prohibits the sale of all wearing apparel and fabrics subject to the act that are classified "highly flammable" when tested according to 16 CFR Part 1610, which was formerly designated Commercial Standard CS 191-53.[13] The specified test is designed to measure ease of ignition and rate of flame spread. It does this by impinging a ⅝ in. (16 mm) long gas flame for 1 second against the lower end of the upper face of a 2 by 6 in. (51 by 152 mm) specimen that is suspended at a 45-degree angle from the horizontal in a test chamber. Figure 6.5.2 shows a schematic diagram of the fabric flammability tester. If the fabric is ignited by the 1-second exposure, the time required for the flame to spread 5 in. (127 mm) on the fabric is used to classify the fabric (ASTM D1230, *Test Method for Flammability of Apparel Textiles,* embodies the same procedures but uses a slightly different classification system). This test has been successful in excluding inordinately flammable garments from interstate commerce. However, it neither discriminates nor is it intended to address differences in the burning characteristics of various apparel fabrics. For example, pile fabrics, such as cotton/polyester terry fabrics and cotton flannels cut into gowns, robes, and pajamas, gave considerably higher burn injury estimates (percentage of body surface burned weighted by depth of burn) than estimates obtained with almost 60 other common apparel fabrics when burned on an instrumented mannequin.[33,34] The same fabrics ranked high on the flammability scale when tested in 12 laboratory fabric flammability tests, but easily passed the Part 1610 requirements. One-hundred percent nylon and polyester fabrics also passed the test, as well as some blends containing wool or modacrylic fibers, which produced very low injury estimates on the mannequin and low flammability results in the other laboratory tests.

The test method in the 1980 edition of NFPA 702,* *Classification of the Flammability of Wearing Apparel,* is the same as that in Part 1610,[12] with two important exceptions. The committee that drafted the NFPA-wearing apparel standard noted that many fabrics, particularly those without raised fiber surfaces, were not ignited when the top surface was touched by a small test flame for 1 second. Those fabrics could not be evaluated for rate of flame spread. Furthermore, the committee concluded that the lower edge of a fabric should be easier to ignite than the surface. Consequently, the test flame in NFPA 702 was brought in contact with the lower edge of all samples and, in the case of those without raised fiber surface, was held there until ignition occurred. Many fabrics that do not ignite in Part 1610[14] ignite in the NFPA 702 test.[34]

*NFPA 702 was withdrawn as an NFPA document and is no longer available.

TABLE 6.5.14 Comparison of Flame-Resistance Test Methods for Textile Materials

Test Method	*Material Orientation*	*Flame Type*	*Exposure Type*	*Exposure Length*	*Measurements*	*Application*
16 CFR Part 1610	45 degrees	16 mm butane	Fabric face	1 sec	Rate of flame spread	Clothing textiles
16 CFR Part 1615	Vertical	38 mm butane	Cut edge	3 sec	Char length	Childrens' sleepwear
16 CFR Part 1616	Vertical	38 mm butane	Cut edge	3 sec	Char length	Childrens' sleepwear
16 CFR Part 1630	Horizontal	Methenamine pill	Fabric face	Varies	Char distance	Carpets, rugs
ASTM D1230	45 degrees	16 mm butane	Fabric face	1 sec	Rate of flame spread	Clothing, textiles
ASTM D2859	Horizontal	Methenamine pill	Fabric face	Varies	Char distance	Carpets, rugs
ASTM D3659	Vertical	38 mm methane (fan burner)	Cut edge (loose)	3 sec	Burn time Loss of mass	Clothing textiles, curtains, drapes
ASTM D4151	Horizontal	16 mm butane	Fabric face	1 sec	Observation of ignition Condition of test paper	Blankets
ASTM D6413	Vertical	38 mm methane (bunsen burner)	Cut edge	12 sec	Afterflame Afterglow Char length	FR textiles
ASTM E84	Horizontal	Series of gas burners	Fabric face	10 min	Flame spread index	Interior textiles
ASTM F1358	Vertical	38 mm methane (bunsen burner)	Folded edge	3 sec, 4 sec wait, then 12 sec	Afterflame Afterglow Burn distance	Multilayered non-FR clothing
NFPA 255	Vertical	Gas fee flame (1.2 m)	Wall-mounted	10 min	Flame spread index	Wall textiles
NFPA 256	Vertical	Gas burner	Wall-mounted	5 min @ 40 kW 10 min @ 150 kW	Flame spread index and smoke development index	Wall textiles
NFPA 286	Vertical	Gas burner	Wall-mounted	5 min @ 40 kW 10 min @ 160 kW	Flame spread index and smoke development index	Wall textiles
NFPA 701 Method 1	Vertical	Tapered Meker burner	Cut edge	45 sec	Char length	Building fabrics
NFPA 701 Method 2	Vertical	Burner meeting ASTM D5025 criteria	Cut edge	2 min	Char length	Outdoor fabrics
NFPA 702	45 degrees	16 mm butane	Cut edge	1 sec or greater	Rate of flame spread	Clothing textiles

Stringent standards were introduced for children's sleepwear in the early 1970s; Parts 1615 and 1616[5] are much more restrictive than Part 1610.[13] Fabric samples 10 by 3 in. (254 by 89 mm) are suspended vertically in a cabinet and subjected to a test flame along the bottom edge (Figure 6.5.3). A fabric passes the test if the average char length of five specimens does not exceed 7 in. (178 mm), and no specimen has a char length of 10 in. (254 mm). The barrel of the test flame burner is ¾ in. (19 mm) below the lower edge of the sample and the test flame is adjusted to extend 1½ in. (38 mm). The sample is exposed for 3 seconds. Char length is the distance from the fabric's lower edge to the end of the void or tear in the charred, burned, or damaged area. The tear is made by lifting the sample by one of the corners near the lower edge after weights had been attached to the opposite corner near the lower edge. Note again that this test is no longer required for U.S. children's sleepwear.

The United States thus has two apparel flammability standards: (1) the children's sleepwear standard, which has greatly reduced the incidence of accidents but restricted the

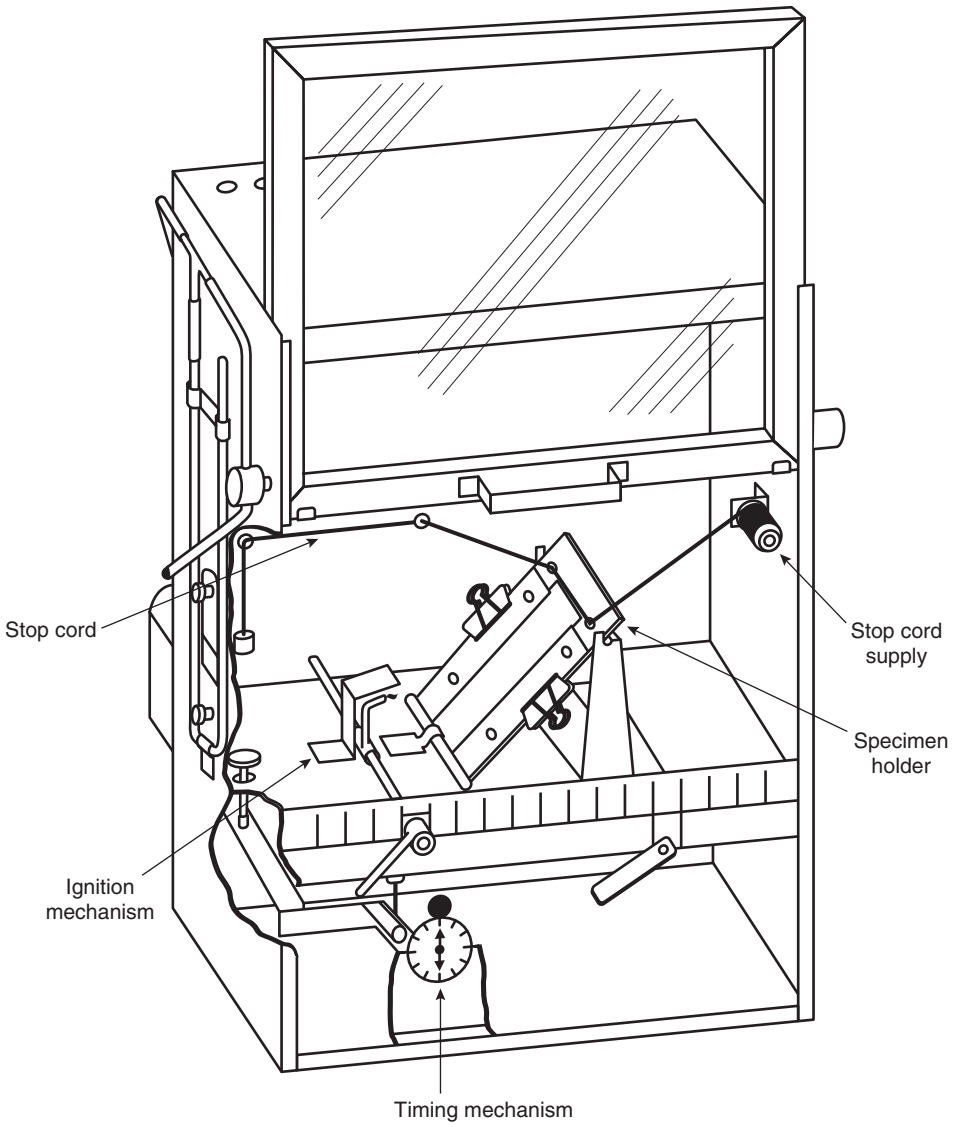


FIGURE 6.5.2 NFPA 702 Flammability Tester (Source: Adapted from NFPA 702, *Classification of the Flammability of Wearing Apparel,* 1980 edition, Figure 2-1.1)

choice of fabrics and which has been withdrawn and (2) the general apparel standard, which has eliminated inordinately flammable, limited-use fabrics, but does not significantly affect fabric choice. Attempts to further categorize fabric flammability hazards have been made; some have based such categorization on flame-spread rate measurements.[34,35] Flame-spread rate measured on remainders of garments involved in fire incidents, however, did not correlate with the size of the victim's burn injury.[36] Researchers have developed methods for measuring the rate of heat release from burning fabrics.[37–38] Braun et al.[39] suggested that fabrics with a low rate of heat release could be used in all garments; those with short ignition times and higher rate of heat release could be used only in tightly fitting garments; and finally suggested the elimination of fabrics with short ignition time (½ sec or less) and high-heat release rate.

Heat- and Flame-Protective Clothing

The types of test methods used to demonstrate the performance of heat- and flame-protective clothing fall into four general categories:

- Flame resistance tests
- Heat resistance tests
- Heat insulation tests
- Molten metal tests

The principal flame resistance test used in the protective clothing industry to demonstrate the adequacy of resistance to ignition and acceptable burning characteristics is ASTM D6413, *Standard Test Method for Flame Resistance of Textiles (Vertical Test).*[40] This test was developed based on Federal Test Method Standard (FTMS) 191A, 5903.1.[41] The test involves suspending

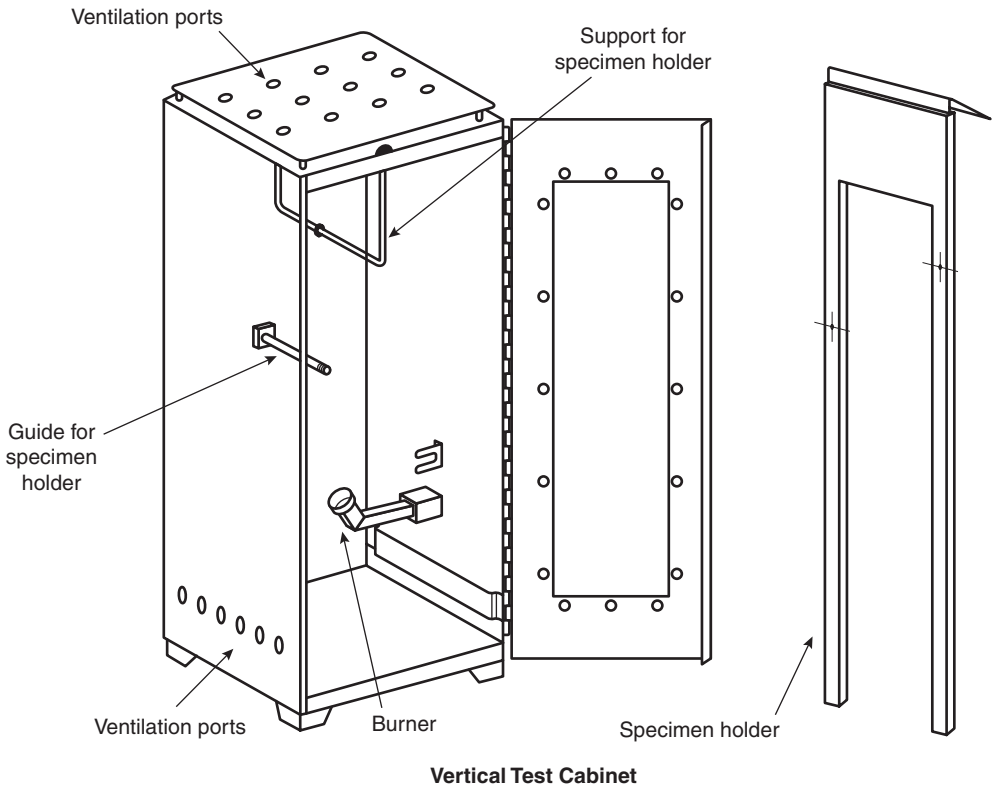


FIGURE 6.5.3 Apparatus for Testing Children's Sleepwear

the edge of a 3 in. by 12 in. (76 mm 305 mm) specimen vertically within a cabinet ¾-in. (19-mm) into a 1.5-in. (38-mm) high, methane-fueled flame for 12 seconds (Figure 6.5.4). The specimen is then removed from the flame and observed for afterflame and afterglow as measured in seconds. The damaged length of the specimen is determined as char length, where a specific weight is hung on a corner of the fabric causing a tear in the charred portion of the specimen. The length of this tear becomes the char length. Typically, afterflame time, afterglow time, and char length are used as criteria for establishing minimum acceptable performance. In the case of most primary protective clothing, a maximum char length of 4 in. (100 mm) is used in conjunction with the afterflame time being 2 seconds or less. A few specifications permit longer char lengths, up to 6 in. (150 mm). Acceptable material performance is often also based on burning behavior. Many protective clothing standards prohibit the use of fabrics that show evidence of melting and dripping when tested according to ASTM D6413.

A related flame-resistance test is ASTM F1358, *Standard Test Method for Effects of Flame Impingement on Materials Used in Protective Clothing Not Designated Primarily for Flame Resistance.*[42] This test method was developed for evaluating protective clothing that is used in nonthermal applications but may accidentally be exposed to a flame source.[43] The test method uses the same cabinet and burner as ASTM D6413 but presents a folded edge of the specimen to the flame. The test is conducted in two parts with an initial 3-second exposure, followed by reapplication of the flame to the same specimen for 12 seconds. The method reports afterflame time, afterglow, and burn distance (like char length, but without the use of a weight to tear the specimen). The test is particularly useful for composite clothing materials where the inner layers may not be flame resistant.

European and international approaches for measuring flame resistance typically use a horizontal or angled burner to contact the fabric face or edge. The fabric specimen is vertically held in place by stand-off pins. Common measurements applied to protective clothing include afterflame times, afterglow times, and specific observations of specimen damage. Char length or related measures are not used to characterize material performance because of concerns with measurement precision.

Heat resistance testing assesses a material's resistance to degradation when exposed to heat. In this testing, a 6-in. (150-mm) or 15 in. (380 mm) specimen is placed in a forced air convection oven set at a specific temperature. The material is then removed and examined for visual evidence of ignition, melting, dripping, and separation. In the United States, the testing is most commonly performed on materials at 500°F (260°C) for a 5 minute duration. In Europe, a 5-minute 355°F (180°C) exposure is used. The determination of dimensional changes in specimens after the heat exposure can also assess heat damage (to provide an indication of thermal shrinkage resistance). Although a part of several NFPA standards on emergency responder protective clothing, this method is embodied in ISO 17493, *Clothing for Protection against Heat and Flame: Test*

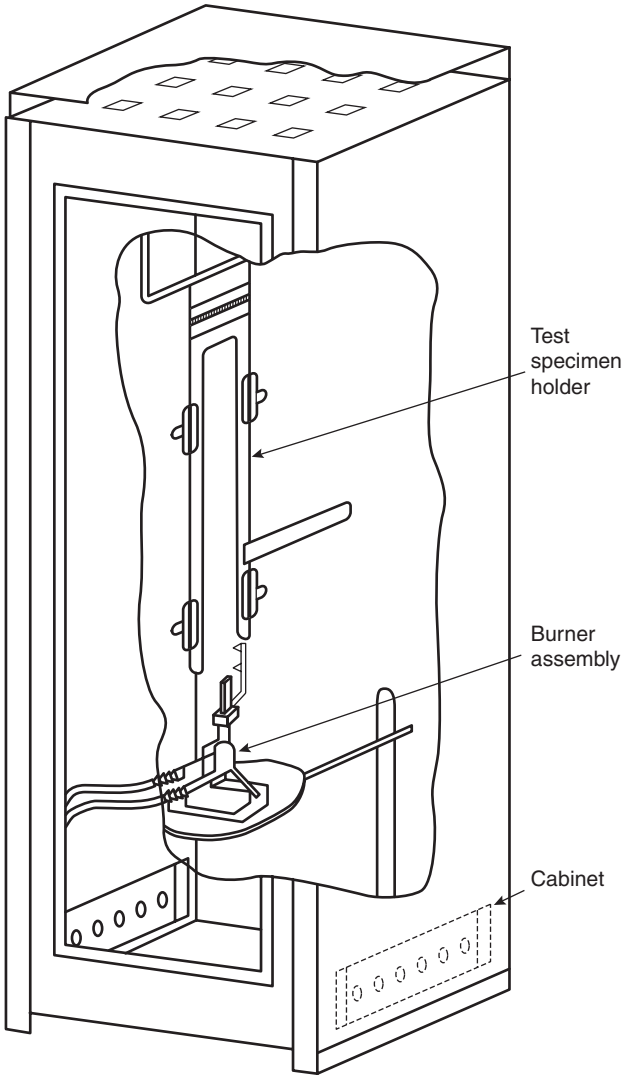


FIGURE 6.5.4 Test Apparatus Used by ASTM D6413 (Source: Copyright ASTM International. Reprinted with permission.)

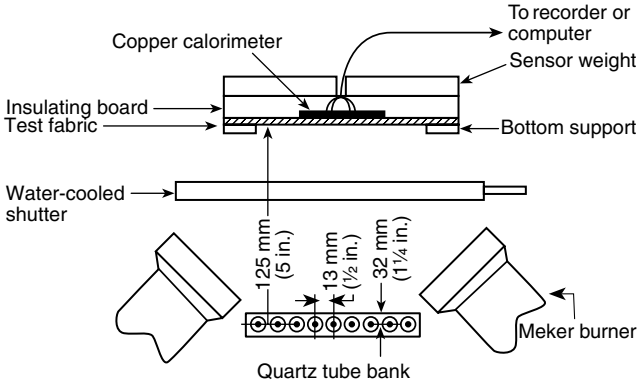


FIGURE 6.5.5 Thermal Protective Performance Test. Note: When used, the spacer is positioned between the material specimen and the sensory assembly. (Source: NFPA 2112, *Standard on Flame-Resistant Garments for Protection of Industrial Personnel Against Flash Fire,* 2007 ed., Figure 8.2.4.1.5)

Method for Convective Heat Resistance Using a Hot Air Circulating Oven.[44]

Many types of protective clothing are used for protecting workers from continued exposure to heat. The type of environments where heat exposure occurs will vary with the type and levels of heat. The Thermal Protective Performance (TPP) test was developed to simulate the types of exposure encountered in a flash fire.[45,46] This test exposes a horizontally positioned specimen over a combined convective and radiant heat source with a heat flux of 7.4 Btu/ft^2/sec (2.0 cal/cm^{2}s or 84 kW/m^2), as shown in Figure 6.5.5. Heat transfer through the specimen is measured with a copper calorimeter and the rate of temperature rise is then related to empirical human skin tolerance data to predict the times to sensation of pain and development of a second degree burn injury.[45,47] Different methods have been used for configuring the sample, but generally single layer materials are tested either in contact with the sensor or with a spacer that separates the sensor and interior material surface by ¼ in. (6 mm), whereas multiple layer specimens are tested in contact with the specimen. The test is extensively used, but some controversy has arisen over its predictive capabilities for whole clothing.

A full manikin test was developed to provide a complete evaluation of protective garments in simulated flash fire. The thermal manikin testing, developed by DuPont, employs a full human-form manikin that is outfitted with over 100 calorimeter-like sensors. In the test, the clothed manikin is subjected to flame and heat from multiple propane-fueled burners from 3 to 12 seconds.[48,49] The response of the individual sensors is then evaluated to determine those areas of the manikin where second- and third-degree burn injury would be predicted (Figure 6.5.6). This approach has been standardized as ASTM F1930, *Standard Test Method for Evaluation of Flame Resistant Clothing for Protection against Flash Fire Simulations Using an Instrumented Manikin.*[50] Due to some inconsistencies between TPP testing ranking of materials and performance of garments on manikins, this testing has led to investigation of other approaches for measuring material performance to short duration, extreme flame/heat exposures.[51]

Two other types of heat exposure are evaluated in other standardized tests. Heat transfer through contact with hot objects is measured using ASTM F1060, *Standard Test Method for Thermal Protective Performance of Materials for Protective Clothing for Hot Surface Contact.*[52] In this test, a weighted block with a copper calorimeter measures the heat transfer through a protective clothing composite set on a hot plate at a specified temperature. Calorimeter output is used to measure the time to pain sensation and time to second-degree burn injury. Radiant heat transfer through clothing material samples is evaluated with ASTM F1939, *Standard Test Method for Radiant Protective Performance of Flame Resistant Clothing Materials.*[53] Again the same principle is used as in TPP and conductive heat

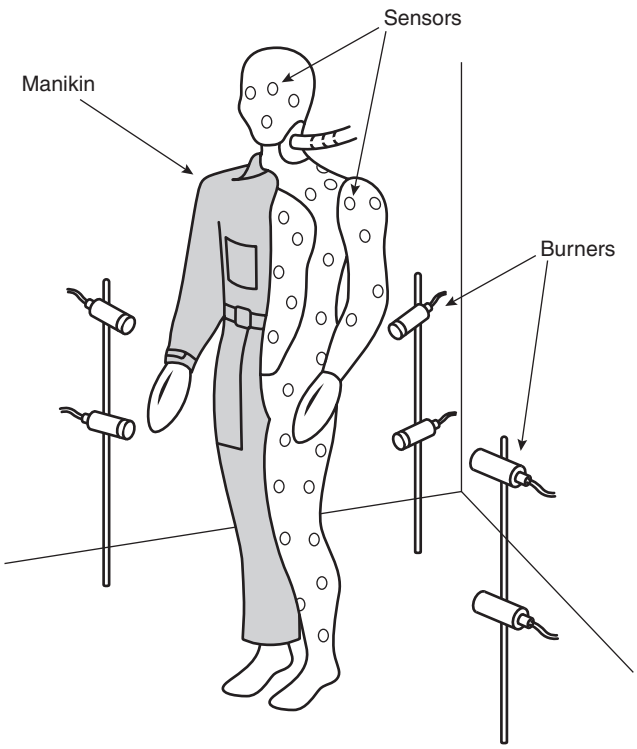


FIGURE 6.5.6 Instrumented Manikin Used in ASTM 1930 (Source: Copyright ASTM International. Reprinted with permission.)

transfer tests; however, in this case, the specimen is vertically oriented with a primarily radiant heat source. Both tests have been applied to various types of protective clothing with success in ranking materials or determining material acceptability for protective applications.[54,55]

Molten metal protection is measured using ASTM F955, *Standard Test Method for Evaluating Heat Transfer through Materials for Protective Clothing upon Contact with Molten Substances.*[56] The test involves pouring 1 kg of molten metal (e.g., aluminum, copper, iron) onto an inclined material specimen and observing the effects of the molten metal on the fabric. Calorimeters under the molten metal also measure heat transfer. While the test is useful for visualizing effects on materials, the large amount of molten metal is considered excessive and prevents quantitative comparison of heat transfer effects for some fabrics.[57,58] Analogous methods have been developed in Europe and internationally.

A summary of test methods for protective clothing heat properties other than flame resistance are provided in Table 6.5.15. This table also includes European and international test method standards. Many of the European methods are similar if not identical to the analogous international standard.

Blankets

In ASTM D4151, *Test Method for Flammability of Blankets,*[59] a small flame is brought down on the center of a specimen for 1 second. The specimen is covered with a paper monitor with a 2-in. (50-mm) circular cutout. If the paper monitor does not char or become discolored, the material is Class 1, and is considered acceptable.

Mattresses and Upholstery

Test methods for mattresses are provided in Consumer Product Safety Commission regulations, 16 CFR 1632 and 1633. In 16 CFR 1632, the test method measures the ignition resistance of a mattress or mattress pad by exposing the surface to lighted cigarettes in a draft-protected environment. The surfaces to be tested include smooth, tape edge, and quilted or tufted locations, if they exist on the mattress or mattress pad surface. A two-sheet test is also conducted on similar surface locations. In the latter test, the burning cigarettes are placed between the sheets (Figures 6.5.7 and 6.5.8). Criteria provided in 16 CFR 1632 require that individual cigarette test locations pass the test if the char length is not more than 2 in. (50 mm) in any direction from the nearest point of the cigarette. The newer 16 CFR 1633 is a full-scale method where a twin or larger size mattress is exposed to a pair of T-shaped burners, intended to simulate burning bedclothes, which are placed on the top and side of the mattress respectively. The peak heat release rate is measured for 30 minutes and cannot exceed 200 kW, whereas the total heat released during the first 10 minutes cannot exceed 15 MJ.

Upholstery flammability is commonly measured according to NFPA 260, *Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture,* where individual components of the upholstery, including the cover fabric, padding, under fabrics, and welting, are subjected to cigarettes held in a test fixture relative to the test fabric. Fabric performance classification is based on whether ignition occurs and, if ignited, the length of the vertical char. The method is based on a similar protocol established by the Upholstered Furniture Action Council (UFAC). NFPA 261, *Standard Method of Test for Determining Resistance of Mock-Up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes,* uses a similar protocol but specifies different test locations to simulate furniture geometry such as horizontal crevices in seat cushions and arm rests. This standard similarly classifies upholstery material performance on the basis of ignitability and char length.

Curtains, Draperies, and Wall Coverings

Curtains and draperies for public occupancies are generally regulated by local or state fire authorities, but the most widely used tests are described in NFPA 701. This standard has undergone significant changes over the years. Whereas the standard used to employ both a small- and large-scale test, there are now Methods 1 and 2. Method 1 is used for fabrics with a weight of 21 oz/yd^2 (700 g/m^2) or less. In this test, a 45-second tapered Meker burner exposure is used. Test 2 uses a longer, 2 minute exposure and is intended for heavier fabrics and those used in outdoor applications.

ASTM D3659, *Standard Test Method for Flammability of Apparel Fabrics by Semi-Restraint Method,*[60] has been suggested as a possible small-scale test for evaluating curtain and

TABLE 6.5.15 Test Methods for Evaluating Protective Clothing Properties Other Than Flame Resistance

Test Method	*Property Evaluated*	*Type of Exposure*	*Measurements*
ASTM F955	Molten metal resistance	1 kg molten metal	Time to second-degree burn Visual ratings
ASTM F1060	Conductive heat resistance	Hot plate (temperature user selected)	Time to pain Time to second-degree burn
ASTM F1930	Full manikin flame/heat	Simulate flash fire (84 kW/m^2)	% predicted body burn (second and third degree)
ASTM F1939	Radiant heat exposure	21 to 84 kW/m^2 (radiant burner)	Time to pain Time to second-degree burn
EN 348	Molten metal resistance (small droplets)	Simulated welding splatter	Time to 40°C rise
EN 366	Radiant heat transfer	5 to 80 kW/m^2 (radiant burner)	Visual effects or time to 10°C rise
EN 367	Flame heat transfer	80 kW/m^2 (flame)	Heat transfer index
EN 373	Molten metal resistance	50 g increments of molten metal	Damage to skin simulant
EN 702	Conductive heat resistance	Hot plate (temperature user selected)	Time to 10°C rise
ISO 6942	Radiant heat transfer	5 to 80 kW/m^2 (radiant burner)	Visual effects or time to 10°C rise
ISO 9150	Molten metal resistance (small droplets)	Simulated welding splatter	Time to 40°C rise
ISO 9151	Flame heat transfer	84 kW/m^2 (flame)	Heat transfer index
ISO 9185	Molten metal resistance	50 g increments of molten metal	Damage to skin simulant
ISO 12127	Conductive heat resistance	Hot plate (temperature user selected)	Time to 10°C rise
ISO 17492	Thermal protection	80 kW/m^2 (flame and radiant panel)	Time to burn; TPP rating
ISO 17493	Heat resistance	Oven heat (180 or 260°C)	Visible effects

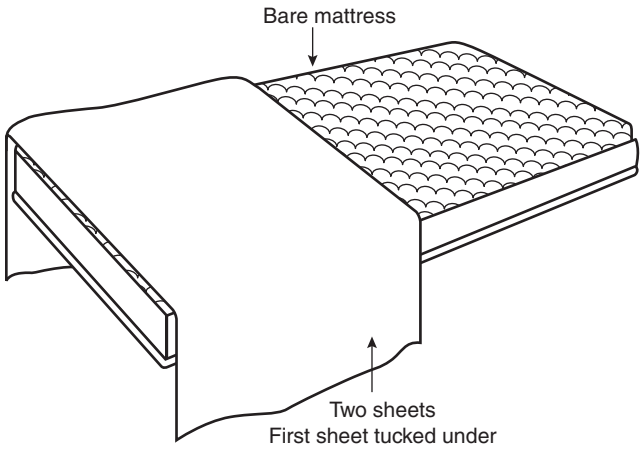


FIGURE 6.5.7 Arrangement of Sheets on Mattress to Be Tested for Cigarette Ignition

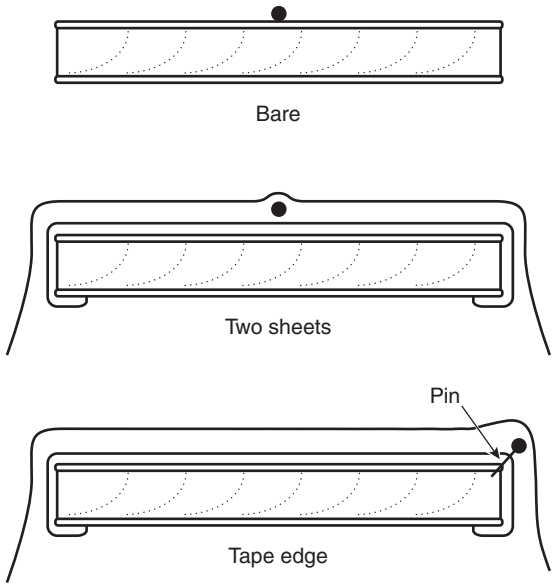


FIGURE 6.5.8 Location of Cigarette on Mattress to Be Tested for Cigarette Ignition

drapery fabrics. In this test, the 15 in. by 6 in. (380 mm by 150 mm) specimens are attached to a bar on the top of the test apparatus and are lightly restrained from movement by use of chains to the corners of the specimen. The method measures burn time and loss of mass.

Many jurisdictions require that wall coverings including fabrics be tested by ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials,*[61] or NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials.* A study was undertaken to compare the burning characteristics of a number of textile wall coverings in full-scale tests, yielding results of two bench-scale tests—the cone calorimeter and the lateral ignition flamespread test (LIFT).[62] In this test, specimens approximately 32 in. by 6 in. (800 mm by 150 mm) are mounted on an inert insulating material, with the longer dimension horizontal. A radiant panel is mounted at an angle to the specimen so that the heat flux over the specimen is varied. Flame spread and heat flux at which ignition occurs are measured. Use of such tests may eventually obviate the use of the more complex tunnel tests in which the materials—unrealistically for wall coverings—are mounted horizontally in a tunnel.

NFPA has developed several useful tests for understanding the burning characteristics or contributions of wall coverings and building materials. NFPA 255 provides procedures for comparing the surface burning characteristics of a material by evaluating flame spread over the surface when exposed to a test fire. Testing is conducted in a chamber that consists of a horizontal duct that has an induced draft. Specimens are exposed to a gas feed flame for 10 minutes. Afterwards, the distance of the flame front is measured. The material's flame spread results are compared to two other materials—cement board and red oak. Material acceptability is determined based on its flame spread index (FSI < 25) and smoke development index (SDI < 450). NFPA 265, *Standard Method of Fire Test for Evaluating Room Fire Growth Contribution of Textile Coverings on Full Height Panels and Walls,* determines the contribution of textile wall coverings to room fire growth. A 12 ft by 8 ft by 8 ft (3.7 m by 2.4 m by 2.4 m) room is used with the specimen mounted on two or three walls. A gas burner placed in a corner exposes the specimens to an open flame for 5 minutes at 38 Btu/s (40 kW) and 10 minutes at 142 Btu/sec (150 kW). Passing performance occurs when flame spread to the ceiling does not occur during the 38-Btu/sec 40-kW exposure. The specimen also cannot spread to its outside edge, form burning droplets, or cause a flashover in the room. A related standard, NFPA 286, *Standard Method for Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth,* uses a slightly higher second exposure at 152 Btu/s (160 kW) for the last 10 minutes and also quantifies the smoke release rate.

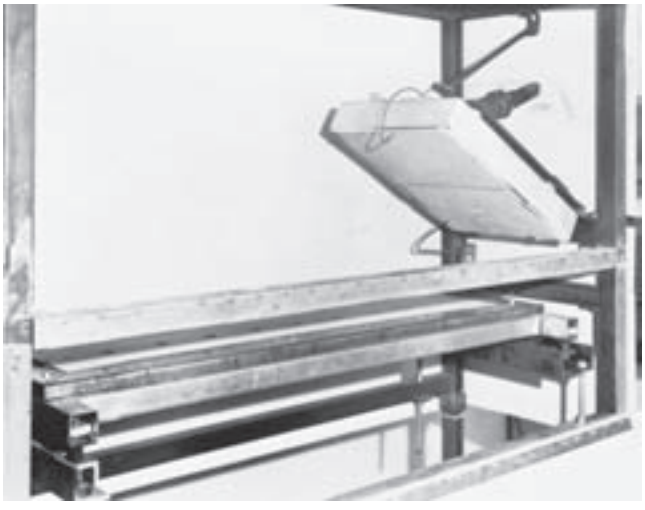
Carpets and Rugs

Carpets and rugs are currently regulated in the United States by federal regulations.[63] Separate parts of the regulations apply to particular sizes. In testing these carpets and rugs, a 9 in. by 9 in. (230 mm by 230 mm) sample is placed on the floor of a test chamber, and a flat steel plate with an 8-in. (203-mm) diameter hole in the center is placed on the sample. A methanamine tablet is placed in the center of the hole and ignited. The sample passes the test if the charred portion does not extend to within 1 in. (25 mm) of the edge of the hole at any point. Seven of eight specimens of other-than-small carpets and rugs must pass if carpets made of the tested material are to be sold. In the case of small carpets and rugs, those that do not pass the test may be sold if they carry a permanent label stating that they failed to pass and should not be used near an ignition source. This requirement eliminated only a small percentage (usually low quality) of the carpets on the market at the time the standard was introduced. A similar testing approach is provided in ASTM D2859, *Standard Test Method for Flammability of Finished Textile Floor Covering Materials.*[64]

Hospitals and other institutions receiving federal financial aid are required to comply with flammability limits for carpets and other floor coverings used on patient-occupied areas and exit ways. The flame spread rating of floor coverings must not exceed 75, as determined by ASTM E84.[61] This test is similar to NFPA 255 and is commonly referred to as the Steiner Tunnel Test.

NFPA *101®*, *Life Safety Code®*, suggests that where limitations are to be placed on the flammability of floor coverings, the test method in NFPA 255 is to be used. Objections have been raised regarding its use to evaluate floor coverings, because positioning the test specimen on top of the tunnel bears no resemblance to its position when in place in a building. The method is also criticized because it may result in delamination, melting, and dripping of test specimens, which removes combustible material from the reach of the burner. The Canadian carpet test places the specimen on the floor of a tunnel.[65]

In an effort to more correctly assess the flame spread hazard of flooring materials, the concept of critical radiant flux was de-



FIGURES 6.5.9 Flooring Radiant Panel Test Apparatus Showing Carpet Specimen and Gas-Fueled Panel (Source: NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source,* Figure 4.1(b))

veloped. In their work on model corridor fire tests, the National Bureau of Standards (now NIST) found that the radiant energy impacting on a floor covering had a significant influence on the propagation of flame across the floor covering. This work led to the development of the flooring radiant panel test (FRPT).

The flooring radiant panel test as embodied in NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source,* subjects a horizontal floor-covering specimen to a radiant energy flux from a gas-fired panel at a 30-degree angle (Figures 6.5.9 and 6.5.10). The radiant energy flux decreases along the length of the specimen according to a standard energy flux versus distance profile. A pilot flame ignites the specimen at the end with the higher radiant energy flux. The flame front is allowed to travel until it is no longer reinforced by the radiant energy flux and extinguishes. The heat flux at this point of the specimen is called the "critical radiant flux." For corridors and exitways in such occupancies as hospitals and nursing homes, a minimum of 0.45 W/cm^2 is recommended (except one- and two-family houses—where the recommendation is 0.22 W/cm^2).[66] The critical heat flux of carpets then is believed to have aggravated the initial fire conditions; for example, the Baptist Tower fire was found to be 0.1 W/cm^2.[67] However, the above requirements are well within the state of the art of carpet manufacture.

Textiles in Aircraft

The flammability of textiles in the crew and passenger compartments of aircraft is regulated by the Federal Aviation Administration (FAA). The vertical test method 5903.1 is used;[41] average char length for three specimens must not exceed 8 in. (203 mm), afterburn time must be less than 15 seconds, and the time that drippings may continue to flame must be less than 5 seconds. In addition, the FAA has specified a new test for passenger seats.[68] For the purpose of this test, a unique oil burner that has the following specifications is used: (1) kerosene consumption, 2 gal per hour (7.57 L/h); (2) nozzle diameter, 6 in. (152 mm); (3) distance of nozzle from side of seat to be tested,

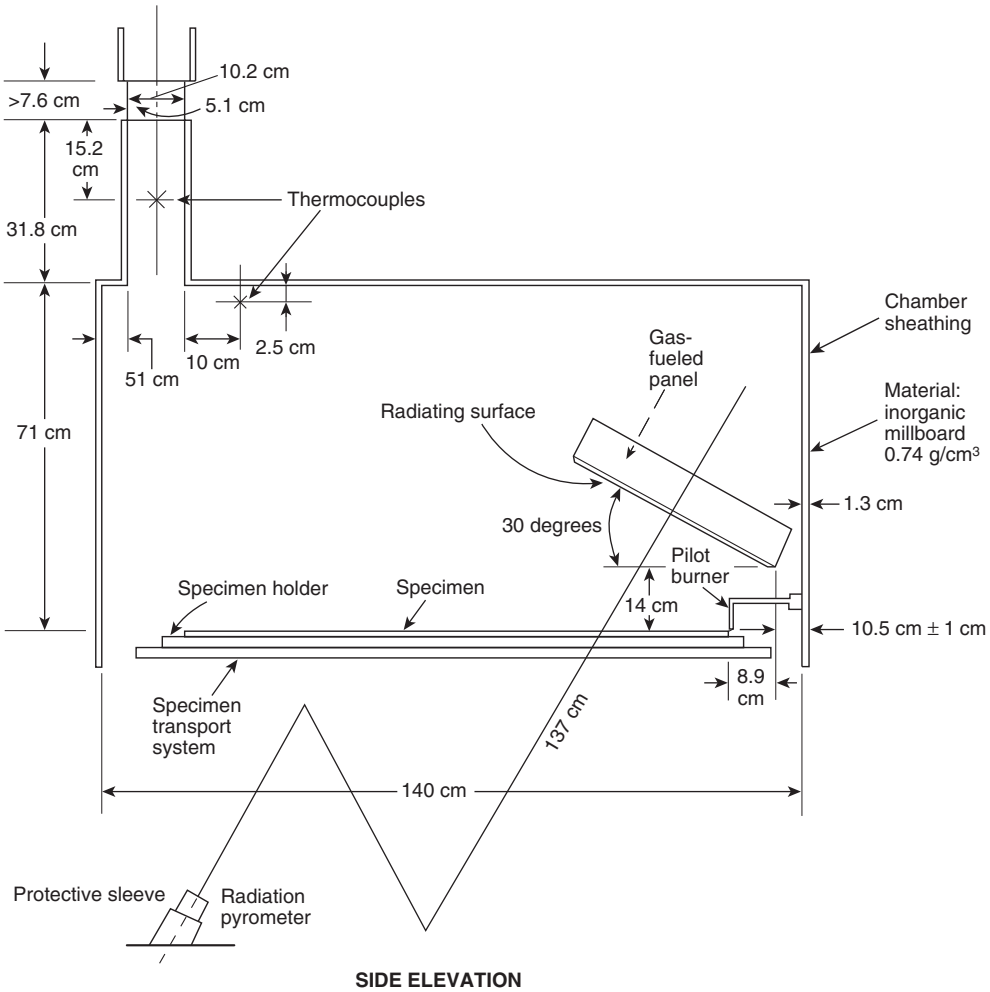


FIGURE 6.5.10 Flooring Radiant Panel Test Apparatus (Source: NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source,* Figure 4.2.1(a))

4 in. (102 mm); (4) heat delivery to seat specimen, 10 Btu per ft^2 per second (115 kW/m^2 per second); and (5) temperature at specimen, 1850°F (1010°C). At least three seats must be tested. For at least half of the number tested, the flame spread must not reach the side of the cushion opposite the burner, the average weight loss must not exceed 10 percent, and there must be no flaming melt drip below the cushion. Among the seat assemblies that pass this test are (1) those that contain the widely used wool/nylon fabric; (2) interlayers consisting of aluminized or ordinary Nomex® or PBI fabrics, which prevent pyrolysis gases from venting toward the flames; and (3) polyurethane foam. An interliner made from Vonar® neoprene-type foam sheet also makes it possible to pass this test, but the lighter fabrics are more cost effective in this application. Other interliner materials are under development, and the use of interliners has spread to institutional furniture as well.

Textiles in Motor Vehicles

Materials used in the occupant compartments of passenger cars, multipurpose passenger vehicles, trucks, and buses in the United States must not burn or transmit a flame front across the surface at a rate of more than 4 in. (100 mm) per minute when tested according to the motor vehicle safety standard of the Department of Transportation (DOT).[69] In that standard, a specimen is suspended in a horizontal position in a test chamber, and one end is ignited by a Bunsen burner flame. The specimen is held in a U-shaped clamp and the assembly is suspended so that the top of the barrel of the burner is ¾ in. (17 mm) below the exposed edge of the specimen. The burner flame is adjusted to 1½ in. (38 mm) high, and the flame temperature to that of a natural gas flame. The specimen is exposed to the test flame for 15 seconds. Timing begins when the flame from the burning specimen reaches a point 1½ in. (38 mm) from the open end of the specimen, and timing ends when the flame has progressed to 10 in. (250 mm) or self-extinguishes. As previously mentioned, burn rate must not exceed 4 in. (100 mm) per min. This test can be considered to provide only minimum protection, and work is in progress to develop a more realistic test, especially for school buses.

Tents, Tarpaulins, Air-Supported Structures

NFPA 102, *Standard for Grandstands, Folding and Telescopic Seating, Tents, and Membrane Structures,* requires that the textiles used in these structures meet the appropriate flame-resistance requirements when tested in accordance with NFPA 701. NFPA 102 covers (1) tents and air-supported structures used for assembly, (2) tents and air-supported structures in which animals are stabled, (3) tents and air-supported structures located in a portion of the premises used by the public, (4) tents and air-supported structures in places of assembly in or about which fuel-burning devices are located, and (5) all tarpaulins used in connection with (1) through (4).

The test method in NFPA 701 uses specimens 7 ft (2.1 m) long and 5 in. or 25 in. (127 mm or 635 mm) wide, depending on whether the specimen is to be tested as a flat sheet or is to be hung in folds. The flat specimen is suspended vertically in an open-ended metal stack and its lower edge is exposed to a 11-in. (280-mm) high flame from a Bunsen burner, the top of whose barrel is 4 in. (100 mm) below the bottom of the specimen. A folded specimen is tested with its folds ½ in. (12.5 mm) apart in the same metal stack and with the same burner arrangement. For both single-sheet and folded specimen, the test flame is applied for 2 minutes, then withdrawn, and the duration of flaming combustion recorded. Length of char, that is, the distance from the top of the test flame to the top of the charred area resulting from spread of flame or afterglow, is also recorded. To pass the test, afterflame time cannot exceed 2 seconds, and the char length cannot exceed 10 in. (250 mm). For specimens in folds, maximum afterflame time cannot exceed 2 seconds, and maximum char length cannot exceed 35 in. (890 mm), but afterglow may spread in the folds.

In addition, the Canvas Products Association International (CPAI) has developed CPAI, *A Specification for Flame-Resistant Materials Used in Camping Tentage.*[70] The test for wall and top material is essentially the same as the 5903.1 test;[41] and for flooring, the methanamine tablet carpet test is prescribed. Maximum char length for walls and tops varies from 4.5 in. (110 mm) for light fabrics to 9 in. (225 mm) for heavy fabrics. For floors, the Part 1630 criteria apply.[63] Provisions for leaching, weathering, and simulated sunlight exposure are part of this voluntary standard. Conforming tents carry the CPAI label.

A comprehensive specification for tentage materials is provided in ASTM D4372, *Standard Specification for Flame-Resistant Materials Used in Camping Tentage.*[71] As with carpets and rugs, flooring material flame resistance is measured using a methenamine pill as the ignition source. Tent wall and top material are evaluated using a vertical flame resistance test similar to ASTM D6413.[40] Floor criteria are based on extent of damage from the edge of the hole for the flattening frame, while wall/top requires afterflame times to be less than 40 seconds and damaged length as based on the weight of the fabric.

International Testing Methods

Different testing methods are used in Europe and internationally for the evaluation of textile flammability, heat resistance, and thermal insulation. The majority of these test methods are based on ISO standards, which use different approaches in testing. For example, most international textile flame resistance tests use a different burner, burner/specimen orientation, and exposure time, as well as measure different textile characteristics than the analogous tests used in the United States. Some representative procedures used in other countries to test for flame resistance and other characteristics include the following:

- EN 533, Protective clothing—Protection against heat and flame—Limited flame spread material and material assembles
- EN 1101, Textiles and textile products—Burning behavior—Curtains and drapes—Detailed procedure to determine the flame spread of vertically oriented specimens
- EN 1625, Textiles and textile products—Burning behavior of industrial and technical textiles—Detailed procedure to determine the ignitability of vertically oriented specimens
- ISO 6940, Textiles and textile products—Burning behavior—Determination of ease of ignition of vertically oriented specimens

- ISO 9150, Protective clothing—Determination of behavior of materials on impact of small splashes of molten metal
- ISO 12127, Clothing for protection against heat and flame—Determination of contact heat transmission through protective clothing or constituent materials
- ISO 17493, Clothing and equipment for protection against heat—Test method for convective heat resistance using a hot air circulating oven

TEXTILES IN SPECIAL ENVIRONMENTS

Certain ambient atmospheric conditions influence the behavior of treated textiles in fire situations. They are (1) oxygen-enriched atmospheres, (2) compressed-air atmospheres, (3) atmospheres where flammable inhalation anesthetizing agents may be present, and (4) exposure to weather.

Action of Treated Textiles in Oxygen-Enriched Air

Some industrial processes require work in atmospheres enriched above the normal oxygen content. Such atmospheres present a high fire hazard, particularly to the clothing worn by the workers. The effect of flame-retardant treatments on the combustibility of the fabrics has been studied.[72]

An indication of the resistance to burning of flame-retardant textiles in oxygen-enriched atmospheres can be inferred from the limiting oxygen indices in Table 6.5.10.

Nomex® high-temperature-resistant nylon fiber in both high-pressure air environments and oxygen-enriched atmospheres at greater-than-normal pressures retains its flame-retardant qualities under air pressure of four atmospheres (59 psig or 400 kPa). At this pressure and in higher oxygen concentrations (40 percent and greater), Nomex® did support combustion, but at a substantially slower rate than did untreated, readily combustible fabrics. NASA has further improved the state of the art in this area and uses materials such as PBI, flame-retardant cotton, etc., in the oxygen-rich atmospheres.

Fabrics used for hospital operating room garments, or in other atmospheres with flammable gas contamination, should be electrically conductive to prevent accumulation of static electricity. Such accumulations, if discharged to ground, could provide a spark of sufficient energy to ignite the gas.

Weather-Exposed Textiles

Flame-retardant treatments for tents, awnings, tarpaulins, and other fabrics exposed to the weather must not leach out over a period of time. If water-soluble chemicals are used, the treatments must be renewed at frequent intervals. The NFPA 701 and CPAI[70] and ASTM[71] tests for tentage specify methods for determination of the effects of weathering.

A wide variety of chemicals can be used for treating fabrics exposed to the weather. Many of the formulas used include chlorinated paraffin, chlorinated synthetic resins, or chlorinated rubber, in combination with various water-insoluble metallic salts, plasticizers, stabilizers, synthetic resins, pigments, binders, mildew inhibitors, and so on. Such mixtures are not water soluble and are used with hydrocarbon solvents or are suspended in aqueous emulsions. The effective application of such treatments calls for techniques and equipment ordinarily available only for factory processing or to businesses specializing in flame-retardant applications. Application of paint to these treated fabrics may lessen their flame resistance.

SUMMARY

Almost all textiles are combustible. Fibers, which may be natural or manufactured, are the basic components of all textiles. Many fibers are spun into yarns and then woven and knitted into fabrics. This type of textile manufacturing involves many processes, including opening, picking, cleaning, blending, carding, combing, drawing and roving, spinning, and so on.

The ignitability, flame spread and heat release rate, total heat produced, heat shrinkage, and ease of fire extinguishment vary among different types of fibers. The finish generally does not alter these properties significantly unless the fabric is treated with a flame retardant.

The end use of a textile (e.g., clothing, curtains, draperies, wall coverings, and carpets and rugs) is very important when evaluating its flammability. There are several commonly used test methods for textile products.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fibers and textiles discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA *101®, Life Safety Code®*
NFPA 102, *Standard for Grandstands, Folding and Telescopic Seating, Tents, and Membrane Structures*
NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 258, *Recommended Practice for Determining Smoke Generation of Solid Materials* (withdrawn—'06 Annual)
NFPA 259, *Standard Test Method for Potential Heat of Building Materials*
NFPA 260, *Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture*
NFPA 261, *Standard Method of Test for Determining Resistance of Mock-Up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes*
NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Coverings on Full Height Panels and Walls*
NFPA 269, *Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling*
NFPA 270, *Standard Test Method for Measurement of Smoke Obscuration Using a Conical Radiant Source in a Single Closed Chamber*
NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*
NFPA 272, *Standard Method of Test for Heat and Visible Smoke Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter*
NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*
NFPA 1951, *Standard on Protective Ensemble for Technical Rescue Operations*
NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*
NFPA 1975, *Standard on Station/Work Uniforms for Fire and Emergency Services*
NFPA 1977, *Standard on Protective Clothing and Equipment for Wildland Fire Fighting*
NFPA 2112, *Standard on Flame-Resistant Garments for Protection of Industrial Personnel Against Flash Fire*

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Chapter 6

Upholstered Furniture and Mattresses

Vytenis Babrauskas

Chapter Contents

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Key Terms

cigarette ignition, Consumer Product Safety Commission (CPSC), fire resistance, fire-safe cigarette, flame spread, flame spread rating, flammability standard, heat release rate (HRR), mattress, upholstered furniture

Upholstered items, such as furniture and mattresses, play a special role in fire hazard. This hazard was first identified many years ago in a statistical study that determined that these items constitute the classes of burnable items accounting for the largest share of fire deaths in the United States.[1] However, there has been a substantial and fairly steady decline in reported U.S. home structure fires originating with upholstered furniture and with mattresses or bedding respectively.[2] Upholstered furniture and mattresses can be ignited by cigarettes, flames, or other means, with the ignition source having a direct bearing on test methods. This chapter addresses the performance of upholstered furniture and mattresses when exposed to cigarette and flaming sources of ignition.

The need for upholstered items to resist cigarette ignition is distinctive—other furnishings, such as carpets or curtains, are ignited by cigarettes comparatively less often. Unfortunately, resistance to cigarette ignition and resistance to flames are not necessarily achievable by the same means. Among common upholstery fabrics, medium and heavyweight synthetic thermoplastic fabrics (e.g., nylon, olefin, and polyester) generally resist cigarette ignition but do not resist flame ignition. Cellulosic materials (e.g., cotton, hemp, jute, linen, and rayon fabrics) have poor cigarette ignition resistance, but burn more slowly when used as covering for polyurethane foam. Only a smaller selection of fabric/padding combinations—such as wool fabric over advanced foams—combine good cigarette ignition resistance with relatively high resistance to flames. In specialized applications (e.g., aircraft seating, certain institutional furniture), interliners—also called barriers—have been used for several decades to improve fire performance.

For related topics, see also Section 6, Chapter 5, "Fibers and Textiles"; and Section 6, Chapter 7, "Fire-Retardant and Flame-Resistant Treatment of Cellulosic Materials."

STATISTICAL BACKGROUND

Tables 6.6.1 and 6.6.2 demonstrate the decline in reported U.S. home structure fires originating in upholstered furniture and mattresses or bedding.[2]* Tables 6.6.3 and 6.6.4 demonstrate similar declines, but much lower numbers for reported U.S. fires in structures other than homes.[2]* During 1999 to 2002, fires originating in upholstered furniture accounted for 19 percent of home fire deaths (the largest share for any burnable item), 3 percent of home fire incidents, 7 percent of home fire injuries, and 5 percent of direct property damage in home fires. In the same period, fires originating in mattresses or bedding accounted for 14 percent of home fire deaths (the second largest share for any burnable item), 5 percent of home fire incidents, 13 percent of home fire injuries, and 7 percent of direct property damage in home fires. Together, they accounted for nearly 1000 home fire deaths, 27,000 reported home fire incidents, more than 3000 home fire injuries, and roughly $640 million in direct property damage in home fires, all per year in 1999 to 2002.

Fires starting with both products were dominated by cigarettes, candles, matches and lighters, and radiated heat from nearby equipment, such as space heaters (Tables 6.6.5 and 6.6.6).[2]*

*Rohr[2] and previous reports in the series, and special National Fire Incident Reporting System (NFIRS) analysis by National Fire Protection Association (NFPA) staff.

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TABLE 6.6.1 Upholstered Furniture Fires in U.S. Homes,[a] by Year, Structure Fires Reported to U.S. Fire Departments, 1980–2002[b]

Reporting Year	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage (in Millions of Dollars)
1980	36,850	1356	2972	219
1981	33,800	1360	2626	218
1982	27,500	1185	2532	272
1983	24,600	1099	2698	200
1984	24,100	1093	2313	217
1985	23,100	931	2331	225
1986	22,100	1068	2197	234
1987	20,800	1030	2145	196
1988	20,200	1098	2291	223
1989	18,100	883	2116	229
1990	16,400	867	2052	257
1991	16,200	676	2053	290
1992	15,200	631	1657	188
1993	14,300	653	1955	231
1994	14,000	669	1708	234
1995	13,300	659	1676	239
1996	12,800	652	1608	249
1997	11,800	655	1444	213
1998	11,600	543	1425	225
1999	11,000	472	1225	276
2000	10,300	632	1189	293
2001	9,500	639	1098	276
2002	8,800	502	984	282
Annual Average				
1980–2002	18,100	841	1926	239
1999–2002	9,900	561	1124	282

[a]"Homes" include one- and two-family dwellings, duplexes, manufactured homes, apartments, tenements, flats, townhouses, and condominiums. The home category does not include rooming, boarding, or lodging houses; hotels or motels; dormitories or fraternity or sorority houses; barracks or bunk houses; or any institutional property providing lodging.

[b]These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred; civilian deaths and injuries are rounded to the nearest one; and direct property damage is rounded to the nearest million dollars. Fires reflect a proportional share of fires in which item ignited was unknown or unreported.

Source: National Fire Incident Reporting System and NFPA survey.

TABLE 6.6.2 Mattress and Bedding Fires in U.S. Homes,[a] by Year, Structure Fires Reported to U.S. Fire Departments, 1980–2002[b]

Reporting Year	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage (in Millions of Dollars)
1980	61,100	937	2988	237
1981	57,100	824	2919	234
1982	48,900	697	2992	223
1983	45,600	696	3124	243
1984	43,700	665	2830	251
1985	43,100	855	2877	283
1986	41,600	725	2775	275
1987	38,400	718	3147	235
1988	37,400	922	3266	290
1989	34,500	650	3195	334
1990	30,700	622	2926	287
1991	31,000	623	3216	408
1992	30,100	620	3406	258
1993	29,700	620	3420	369
1994	28,700	465	3013	316
1995	25,100	525	2644	320
1996	24,600	662	2502	339
1997	22,600	488	2307	338
1998	21,400	398	2309	292
1999	20,700	336	2311	341
2000	18,700	486	2400	378
2001	16,300	389	1888	381
2002	14,300	442	1360	330
Annual Average				
1980–2002	33,300	625	2775	303
1999–2002	17,500	413	1990	357

[a]"Homes" include one- and two-family dwellings, duplexes, manufactured homes, apartments, tenements, flats, townhouses, and condominiums. The home category does not include rooming, boarding, or lodging houses; hotels or motels; dormitories or fraternity or sorority houses; barracks or bunk houses; or any institutional property providing lodging.

[b]These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten; civilian deaths and injuries are rounded to the nearest one; and direct property damage is rounded to the nearest hundred thousand dollars. Fires reflect a proportional share of fires in which item was ignited was unknown or unreported.

Source: National Fire Incident Reporting System and NFPA survey. Inflation adjustments have been made based on Table No. 697, "Purchasing Power of the Dollar: 1950 to 2003," U.S. Census Bureau's *Statistical Abstract of the United States: 2004–2005,* 124th Edition, 2004.

Not surprisingly, the cited factors contributing to these kinds of ignitions were led by abandoning of materials (such as improper disposal of a lit cigarette or used match), children playing with fire, and heat sources too close to the combustible products (Tables 6.6.7 and 6.6.8).[2]* Also significant, but not shown on these tables, because they are now recorded under different data elements, are intentional fires (typically juvenile firesetters too old to be called children playing with fire) and human factors

*Rohr[2] and previous reports in the series, and special National Fire Incident Reporting System (NFIRS) analysis by National Fire Protection Association (NFPA) staff.

TABLE 6.6.3 Upholstered Furniture Fires in U.S. Structures Other than Homes,[a] by Year, Structure Fires Reported to U.S. Fire Departments, 1980–2002[b]

Reporting Year	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
1980	7200	30	211	42.3
1981	6800	91	255	57.4
1982	6000	24	194	37.3
1983	4600	20	115	26.0
1984	4800	42	139	40.9
1985	4300	36	101	34.8
1986	4400	16	111	31.1
1987	3700	21	96	39.2
1988	3100	32	136	40.2
1989	2900	24	79	26.9
1990	2700	24	151	25.6
1991	2800	31	73	40.3
1992	2900	19	132	34.6
1993	2500	15	71	33.8
1994	2400	10	94	21.8
1995	2200	32	101	37.8
1996	2200	2	88	29.6
1997	2100	12	105	38.9
1998	1800	7	72	28.2
1999	1900	7	76	27.0
2000	1800	23	46	32.0
2001	1700	18	51	34.0
2002	1500	9	35	34.0
Annual Average				
1980–2002	3400	24	122	35.0
1994–2002	1700	15	92	32.0

[a]Includes all structures except homes as defined in note *a* of Table 6.6.1.

[b]These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten; civilian deaths and injuries are rounded to the nearest one; and direct property damage is rounded to the nearest hundred thousand dollars. Fires reflect a proportional share of fires in which item was ignited was unknown or unreported.

Source: Data from Rohr,[2] previous reports in series, and special National Fire Incident Reporting System analysis by NFPA staff.

TABLE 6.6.4 Mattress and Bedding Fires in U.S. Structures Other than Homes,[a] by Year, Structure Fires Reported to U.S. Fire Departments, 1980–2002[b]

Reporting Year	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
1980	16,100	78	702	50.0
1981	15,800	138	994	36.1
1982	12,900	51	705	27.7
1983	11,400	31	762	27.4
1984	10,600	60	584	27.1
1985	10,200	86	436	33.6
1986	9,600	98	511	33.6
1987	9,000	60	457	30.8
1988	7,800	49	535	38.4
1989	7,200	47	431	32.1
1990	6,400	65	464	44.0
1991	6,600	36	586	60.5
1992	6,300	48	413	39.9
1993	6,000	40	586	32.1
1994	5,700	43	418	33.9
1995	4,800	29	364	55.7
1996	5,100	39	298	35.6
1997	4,700	37	314	39.0
1998	4,300	33	265	31.4
1999	3,900	21	196	92.0
2000	3,100	9	172	38.0
2001	2,800	16	211	32.0
2002	2,300	49	155	30.0
Annual Average				
1980–2002	7,500	50	459	39.0
1994–2002	3,000	24	184	48.0

[a]Includes all structures except homes as defined in note *a* of Table 6.6.1.

[b]These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten; civilian deaths and injuries are rounded to the nearest one; and direct property damage is rounded to the nearest hundred thousand dollars. Fires reflect a proportional share of fires in which item was ignited was unknown or unreported.

Source: Data from Rohr,[2] previous reports in series, and special National Fire Incident Reporting System analysis by NFPA staff.

such as falling asleep, which lead to loss of control of the heat source.

Equipment heat sources were individually rare (Tables 6.6.9 and 6.6.10), but the leading equipment types for fatal fires starting with these products included portable and fixed space heaters, lamps or lightbulbs, and electrical cords or plugs.[2*]

*Rohr[2] and previous reports in the series, and special National Fire Incident Reporting System (NFIRS) analysis by National Fire Protection Association (NFPA) staff.

The victims of fires started by improper handling of a heat source are not always—or even usually—the people whose actions or errors started the fire. A majority of home fire deaths involve victims who were not in the room of fire origin. This fact is also true of a large minority of fire deaths started by smoking, open flame, or children playing with fire.[3] This circumstance also means that there is time and distance for fire protection measures, such as smoke alarms, sprinklers, and compartment barriers, to intervene and prevent these fires from causing fatal injury.

TABLE 6.6.5 Upholstered Furniture Fires in U.S. Homes,[a] by Heat Source Involved, Structure Fires Reported to U.S. Fire Departments, 1999–2002[b]

Heat Source	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Cigarette	3400	(34%)	277	(49%)	465	(41%)	85	(30%)
Radiated or conducted heat from operating equipment	900	(9%)	34	(6%)	60	(5%)	26	(9%)
Candle	900	(9%)	17	(3%)	149	(13%)	32	(11%)
Arcing	800	(8%)	23	(4%)	67	(6%)	26	(9%)
Cigarette lighter	700	(7%)	46	(8%)	126	(11%)	19	(7%)
Match	600	(6%)	13	(2%)	54	(5%)	22	(8%)
Unclassified hot or smoldering object	400	(4%)	14	(3%)	32	(3%)	10	(4%)
Hot ember or ash	400	(4%)	16	(3%)	34	(3%)	7	(2%)
Heat from other open flame or smoking materials	400	(4%)	27	(5%)	18	(2%)	13	(5%)
Heat from undetermined smoking material	300	(3%)	39	(7%)	44	(4%)	8	(3%)
Unclassified heat from powered equipment	300	(3%)	23	(4%)	12	(1%)	12	(4%)
Unclassified heat source	200	(2%)	6	(1%)	6	(1%)	9	(3%)
Spark, ember, or flame from operating equipment	100	(1%)	0	(0%)	8	(1%)	5	(2%)
Unclassified heat spread from another fire	100	(1%)	2	(0%)	9	(1%)	2	(1%)
Incendiary device	100	(1%)	0	(0%)	4	(0%)	1	(0%)
Pipe or cigar	100	(1%)	13	(2%)	18	(2%)	2	(1%)
Other known heat source	300	(3%)	10	(2%)	19	(2%)	7	(3%)
Total	9900	(100%)	561	(100%)	1124	(100%)	282	(100%)

[a]"Homes" include one- and two-family dwellings, duplexes, manufactured homes, apartments, tenements, flats, townhouses, and condominiums. The home category does not include rooming, boarding, or lodging houses; hotels or motels; dormitories or fraternity or sorority houses; barracks or bunk houses; or any institutional property providing lodging.

[b]These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred; civilian deaths and injuries are rounded to the nearest one; and direct property damage is rounded to the nearest million dollars. This table includes a proportional share of fires in which the item first ignited was unknown or unreported. Upholstered furniture fires in which the heat source was undetermined or not reported were allocated proportionally among fires of known heat source. Sums may not equal totals due to rounding errors.

Source: National Fire Incident Reporting System and NFPA survey.

MATERIALS USED IN UPHOLSTERED FURNITURE

The fire characteristics of combustible goods are determined in part by the materials from which they are made. Apart from wood frames, furniture construction materials have changed greatly during the last 50 years. Most upholstered furniture continues to be hand-built on a wood frame. An industry interest in molded plastics during the 1970s was short lived, and the frames made today differ only slightly from frames made decades ago. In a few cases, manufacturers use molded plastic portions in conjunction with a frame otherwise made from wood. Polyurethane foams, which became common in the 1960s, were initially used plain. Today they often have a "topper" layer of polyester batting. Fabrics are a fashion item and change over the years. The last decade has seen an upsurge in the popularity of leather upholstery, whereas prior to that there was a trend for using loosely sewn, puckered fabrics. Loose fabrics showed some adverse flammability effects (though not extensively studied), but the trend appears to be currently diminishing.

In 1997, the U.S. Consumer Product Safety Commission (CPSC) published statistics on the fabrics (Table 6.6.11) and paddings (Table 6.6.12) used in upholstered furniture.[4] Recently, it has become common to use mixed-fiber fabrics for furniture upholstery, but the CPSC tabulation does not reflect this.

Small-scale tests on retail furniture indicate that only about 39 percent of items upholstered in cellulosic fabrics are resistant to cigarette-caused smoldering, but about 95 percent of thermoplastic-fabric upholstered furniture is resistant.[5–9]

Apart from modest use of fire-retardant-treated (FR) cotton batting in mattresses, there is currently little use of fire-retarded or flame-resistant materials in the U.S. consumer market. Although FR furniture is presently not available in retail showrooms in the United States, it is available for specialty markets such as hospitals, correctional facilities, and other

TABLE 6.6.6 Mattress and Bedding Fires in U.S. Homes,[a] by Heat Source Involved, Structure Fires Reported to U.S. Fire Departments, 1999–2002[b]

Heat Source	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Cigarette	3,800	(22%)	180	(44%)	493	(25%)	65	(18%)
Cigarette lighter	2,800	(16%)	44	(11%)	425	(21%)	58	(16%)
Radiated or conducted heat from operating equipment	2,200	(13%)	29	(7%)	143	(7%)	41	(11%)
Match	2,000	(12%)	16	(4%)	175	(9%)	35	(10%)
Candle	1,700	(10%)	33	(8%)	318	(16%)	46	(13%)
Arcing	1,400	(8%)	9	(2%)	122	(6%)	27	(8%)
Unclassified heat from powered equipment	700	(4%)	16	(4%)	66	(3%)	15	(4%)
Heat from other open flame or smoking materials	600	(3%)	20	(5%)	60	(3%)	14	(4%)
Unclassified hot or smoldering object	500	(3%)	7	(2%)	27	(1%)	7	(2%)
Unclassified heat source	300	(2%)	9	(2%)	22	(1%)	10	(3%)
Heat from undetermined smoking material	300	(2%)	17	(4%)	35	(2%)	10	(3%)
Hot ember or ash	300	(2%)	10	(2%)	28	(1%)	6	(2%)
Spark, ember, or flame from operating equipment	200	(1%)	9	(2%)	31	(2%)	6	(2%)
Unclassified heat spread from another fire	200	(1%)	8	(2%)	13	(1%)	6	(2%)
Other known heat source	500	(3%)	6	(1%)	30	(2%)	12	(3%)
Total	17,500	(100%)	413	(100%)	1990	(100%)	357	(100%)

[a]"Homes" include one- and two-family dwellings, duplexes, manufactured homes, apartments, tenements, flats, townhouses, and condominiums. The home category does not include rooming, boarding, or lodging houses; hotels or motels; dormitories or fraternity or sorority houses; barracks or bunk houses; or any institutional property providing lodging.

[b]These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred; civilian deaths and injuries are rounded to the nearest one; and direct property damage is rounded to the nearest million dollars. This table includes a proportional share of fires in which the item first ignited was unknown or unreported. Mattress and bedding fires in which the heat source was undetermined or not reported were allocated proportionally among fires of known heat source. Sums may not equal totals due to rounding errors.

Source: National Fire Incident Reporting System and NFPA survey.

institutional uses. A different situation is found in the United Kingdom, where regulations passed in the late 1980s[10,11] mandated that upholstered furniture and mattresses (apart from tickings*) be resistant both to small flames and to cigarettes. The consequence has been that furniture on the U.K. market generally uses advanced, fire-retardant polyurethane foams and FR-treated fabrics. The official U.K. government survey[12] concluded that use of the improved materials raised costs by $24 to $32 per furniture item, but provided a 40:1 benefit/cost ratio. The U.K. analysis, however, was rebutted by a U.S. statistician whose reanalysis did not support the optimistic U.K. view.[13] The situation in the United States is expected to change rapidly with regards to mattresses, however, due to the enactment by CPSC in early 2006 of drastically new flammability regulations for mattresses, as discussed below.

*Mattress tickings were excluded from the regulation, but UK Product Safety Regulations in effect make manufacturers follow British Standards in this matter, which do encompass ticking performance.

SIMILARITIES OF AND DIFFERENCES BETWEEN UPHOLSTERED FURNITURE AND MATTRESSES

Ease of Ignition

Many aspects of flammability are similar for upholstered furniture and mattresses. However, some distinctions must be made: mattresses have predominantly flat surfaces that are not as likely to ignite by cigarettes as are crevices in furniture, such as the juncture of seat cushion and armrests and back of upholstered furniture. (In a similar vein, horizontal flat furniture surfaces are not as easily ignited by flame ignition sources as are vertical surfaces.)

On the other hand, cigarettes on mattresses may be inadvertently covered with sheets, blankets, or pillows. This increases the probability of ignition. Also, these intermediary materials may ignite from flames more readily than mattresses and then expose the mattress to a much more severe fire. Consequently, it

TABLE 6.6.7 Upholstered Furniture Fires in U.S. Homes,[a] by Factor Contributing to Ignition, Structure Fires Reported to U.S. Fire Departments (in NFIRS 5.0 Only), 1999–2002[b]

Factor Contributing to Ignition	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage*
Abandoned or discarded materials or products	29%	35%	35%	28%
Heat source too close to combustibles	18%	21%	15%	19%
Unclassified misuse of material or product	14%	12%	17%	13%
Playing with heat source	10%	14%	16%	11%
Unclassified factor	8%	9%	8%	13%
Unclassified electrical failure or malfunction	4%	3%	2%	4%
Unspecified short circuit arc	3%	2%	2%	2%
Short circuit arc from defective or worn insulation	3%	2%	0%	2%
Equipment unattended	2%	0%	0%	1%
Exposure fire	1%	1%	0%	1%
Collision, knock down, run over, or turn over	1%	0%	1%	1%

[a]"Homes" include one- and two-family dwellings, duplexes, manufactured homes, apartments, tenements, flats, townhouses, and condominiums. The home category does not include rooming, boarding, or lodging houses; hotels or motels; dormitories or fraternity or sorority houses; barracks or bunk houses; or any institutional property providing lodging.

[b]These are percentages of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Percents are used without numbers, because the fraction of data reported directly in Version 5.0, not converted from Version 4.1, is still small and may not be representative. Multiple entries are allowed under Factor Contributing to Ignition. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. This table includes a proportional share of fires in which the item first ignited was unknown or unreported. Upholstered furniture fires in which the factor contributing to ignition was undetermined were allocated proportionally among fires of known factor contributing to ignition.

Source: National Fire Incident Reporting System and NFPA survey.

TABLE 6.6.8 Mattress and Bedding Fires in U.S. Homes,[a] by Factor Contributing to Ignition, Structure Fires Reported to U.S. Fire Departments (in NFIRS 5.0 Only), 1999–2002[b]

Factor Contributing to Ignition	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage*
Playing with heat source	24%	13%	24%	24%
Heat source too close to combustibles	24%	25%	29%	28%
Abandoned or discarded materials or products	16%	32%	16%	16%
Unclassified misuse of material or product	12%	25%	14%	13%
Unclassified factor	5%	6%	5%	5%
Unclassified electrical failure or malfunction	4%	0%	2%	3%
Unspecified short circuit arc	3%	0%	3%	3%
Equipment unattended	2%	1%	1%	2%
Short circuit arc from defective or worn insulation	2%	0%	1%	2%
Collision, knock down, run over, or turn over	1%	1%	2%	1%
Unclassified mechanical failure or malfunction	1%	1%	1%	1%
Unintentionally turned on or not turned off	1%	0%	0%	4%
Exposure fire	1%	0%	0%	0%

[a]"Homes" include one- and two-family dwellings, duplexes, manufactured homes, apartments, tenements, flats, townhouses, and condominiums. The home category does not include rooming, boarding, or lodging houses; hotels or motels; dormitories or fraternity or sorority houses; barracks or bunk houses; or any institutional property providing lodging.

[b]These are percentages of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Percents are used without numbers, because the fraction of data reported directly in Version 5.0, not converted from Version 4.1, is still small and may not be representative. Multiple entries are allowed under Factor Contributing to Ignition. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. This table includes a proportional share of fires in which the item first ignited was unknown or unreported. Mattress and bedding fires in which the factor contributing to ignition was undetermined were allocated proportionally among fires of known factor contributing to ignition.

Source: National Fire Incident Reporting System and NFPA survey.

TABLE 6.6.9 Upholstered Furniture Fires in U.S. Homes,[a] by Equipment Involved, Structure Fires Reported to U.S. Fire Departments, 1999–2002[b]

Equipment Involved in Ignition	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
None	7900	(79%)	480	(85%)	962	(86%)	220	(78%)
Cord or plug	300	(3%)	16	(3%)	39	(3%)	9	(3%)
Portable heater	300	(3%)	28	(5%)	18	(2%)	10	(4%)
Unclassified equipment involved in ignition	300	(3%)	5	(1%)	23	(2%)	9	(3%)
Lamp, bulb, or lighting	300	(3%)	8	(1%)	19	(2%)	6	(2%)
Wiring, switch, or outlet	200	(2%)	2	(0%)	1	(0%)	7	(3%)
Fixed space heater	200	(2%)	9	(2%)	10	(1%)	5	(2%)
Unclassified heating, ventilating, and air conditioning equipment	100	(1%)	2	(0%)	8	(1%)	2	(1%)
Unclassified portable appliance designed to produce heat	100	(1%)	2	(0%)	2	(0%)	2	(1%)
Fireplace or chimney	100	(1%)	0	(0%)	4	(0%)	2	(1%)
Other known equipment	300	(3%)	10	(2%)	37	(3%)	9	(3%)
Total	9900	(100%)	561	(100%)	1124	(100%)	282	(100%)

[a]"Homes" include one- and two-family dwellings, duplexes, manufactured homes, apartments, tenements, flats, townhouses, and condominiums. The home category does not include rooming, boarding, or lodging houses; hotels or motels; dormitories or fraternity or sorority houses; barracks or bunk houses; or any institutional property providing lodging.

[b]These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred; civilian deaths and injuries are rounded to the nearest one; and direct property damage is rounded to the nearest million dollars. This table includes a proportional share of fires in which the item first ignited was unknown or unreported. Upholstered furniture fires in which the equipment involved was undetermined or not reported were allocated proportionally among fires of known equipment involved. Sums may not equal totals due to rounding errors.

Source: National Fire Incident Reporting System and NFPA survey.

is more difficult to develop relevant ignition tests and standards for mattresses than for upholstered furniture.

Materials

Upholstered furniture can contain well over a dozen materials: for example, cover fabrics and fabrics between the cover fabric and the padding (interliners); different padding materials in the seat, sides, and back; weltcords; another fabric and type of padding below the seat cushion (decking); and frames, springs, stiffening for the sides, and so on. Mattresses are complex but contain fewer materials. In the ignition process, whether from a cigarette or a small flame, the cover fabric and material immediately below it—one or two layers of padding—are important. As the fire progresses, other materials, including the frame and springs, become involved, which can affect the manner in which the burning item collapses.

Another difference stems from industry practices. Until recently, it has been possible to find older materials (cotton batting, latex foam, vegetable-origin fibers, etc.) in mattresses from certain manufacturers. By contrast, these materials have become quite rare in upholstered furniture, wherein polyurethane foam is by far the dominant padding material. However, the new CPSC mattress regulation may cause the materials used in the mattress industry to become simplified across the board.

Radiant Heat Conditions

An important difference concerning mattresses is that radiant heat conditions can affect them more readily. This difference can mean that a mattress and a chair that show the same heat release rate when burned in a very large space will behave differently when placed in a small room. In the latter case, the mattress is likely to burn more severely than the upholstered chair.[14] More technical discussions of differences in mattress and upholstered furniture behavior have been published.[15]

SMOLDERING AND FLAMING

Smoldering of upholstered items, which is the typical consequence of exposure to a burning cigarette, can produce enough smoke and toxic gases to incapacitate and kill, but rarely does so before the fire transitions to flaming or, in the absence of such a transition, before the fire self-extinguishes or is put out.[16] Transition from smoldering to flaming does not occur in all cases; when it does, times from placement of the cigarette to flaming of 22 minutes to several hours have been reported.[17,18] In a closed room, flaming can revert to smoldering when the oxygen supply is exhausted. With sufficient oxygen, a single upholstered item of sufficient burning rate can lead to room flashover.

TABLE 6.6.10 Mattress and Bedding Fires in U.S. Homes,[a] by Equipment Involved, Structure Fires Reported to U.S. Fire Departments, 1999–2002[b]

Equipment Involved in Ignition	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
None	13,000	(74%)	330	(80%)	1614	(81%)	261	(73%)
Lamp, bulb, or lighting	600	(3%)	8	(2%)	40	(2%)	11	(3%)
Portable heater	500	(3%)	18	(4%)	71	(4%)	14	(4%)
Cord or plug	500	(3%)	10	(2%)	45	(2%)	11	(3%)
Unclassified equipment involved in ignition	400	(2%)	11	(3%)	38	(2%)	10	(3%)
Unclassified portable appliance designed to produce heat	400	(2%)	3	(1%)	21	(1%)	7	(2%)
Wiring, switch, or outlet	400	(2%)	0	(0%)	25	(1%)	7	(2%)
Clothes dryer	300	(2%)	2	(0%)	9	(0%)	2	(1%)
Fixed space heater	200	(1%)	4	(1%)	18	(1%)	7	(2%)
Range or cooking surface with or without oven	200	(1%)	2	(0%)	3	(0%)	2	(1%)
Unclassified heating, ventilating, and air conditioning equipment	100	(1%)	3	(1%)	11	(1%)	3	(1%)
Cigarette lighter or pipe lighter	100	(1%)	4	(1%)	22	(1%)	2	(1%)
Other known equipment	800	(4%)	19	(5%)	71	(4%)	18	(5%)
Total	17,500	(100%)	413	(100%)	1990	(100%)	357	(100%)

[a]"Homes" include one- and two-family dwellings, duplexes, manufactured homes, apartments, tenements, flats, townhouses, and condominiums. The home category does not include rooming, boarding, or lodging houses; hotels or motels; dormitories or fraternity or sorority houses; barracks or bunk houses; or any institutional property providing lodging.

[b]These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred; civilian deaths and injuries are rounded to the nearest one; and direct property damage is rounded to the nearest million dollars. This table includes a proportional share of fires in which the item first ignited was unknown or unreported. Mattress and bedding fires in which the equipment involved was undetermined or not reported were allocated proportionally among fires of known equipment involved. Sums may not equal totals due to rounding errors.

Source: National Fire Incident Reporting System and NFPA survey.

TABLE 6.6.11 Fabric Types Used in Furniture Upholstery, as Reported by CPSC

Fabric	*Percent*
Cellulosic (e.g., cotton, rayon, linen)	31
Thermoplastic (e.g., polypropylene, nylon)	51
Wool, leather	10
PVC-coated	5
Other	2

TABLE 6.6.12 Padding Types Used in Upholstered Furniture, as Reported by CPSC

Padding	*Percent*
Polyester batting over polyurethane foam	76
Polyurethane foam alone	17
Other materials	6

Another feature of upholstered furniture fires is the difficulty of ensuring extinction, because soaking or even immersion in water may not ensure extinguishment. Items should be removed from the premises, torn apart, and the pieces thoroughly wetted. Many fire victims have wetted down a smoldering area in an upholstered chair or sofa, retired for the night, only to be faced several hours later with impenetrable smoke or a full-scale fire.[17] This problem has been very serious with latex foam items, but must be addressed with other types of constructions as well.

A monograph on upholstered furniture flammability contains an in-depth discussion of cigarette and small flame ignition resistance and postignition behavior.[19]

UPHOLSTERED ITEM FLAMMABILITY STANDARDS

Some cigarette and flame ignition standards and tests for upholstered items are listed in Table 6.6.13. They can be classified as voluntary standards and tests, federally enforced standards, and state-imposed standards. A more extensive discussion of earlier

TABLE 6.6.13 Flammability Tests for Upholstered Furniture and Mattresses

	Ignition Source		Status			Specimen		Occupancy	
Test	*Cigarette*	*Flame or Radiant*	*Voluntary*	*Regulatory*	*Proposed*	*Small-Scale*	*Actual Item or Large-Size Mock-Up*	*Residential*	*Special*
				Upholstered furniture					
ASTM E1474		x	x			x			x
ASTM E1353 (UFAC)	x		x			x		x	
ASTM E1352 (BIFMA)	x		x			x			x
Calif. T.B. 116[a]	x		x			x		x	
Calif. T.B. 117[a]	x	x		x		x		x	x
UK BS 5852	x	x		x		x		x	x
ISO 8191	x			x			x	x	
Calif. T.B. 133; ASTM E1537		x		x			x		x
Nordtest NT FIRE 032[a]		x	x				x		x
ASTM E1822—stacking chair test		x					x		x
ASTM D3675[b]		x		x		x			x
MVSS 302[c] (ASTM D5132)		x		x		x			x
U.S. 13 CFR 25.1587 Appendix F Part II[d]				x			x		x
CPSC Test		x			x	x		x	
				Mattresses					
U.S. 16 CFR 1632.4	x			x			x	x	
Calif. T.B. 129; ASTM E 1590		x		x					
Calif. T.B. 121		x		x			x		x
UK BS 6807	x	x		x		x		x	
Nordtest NT FIRE 036	x	x	x			x		x	
U.S. 16 CFR 1633		x		x		x		x	

[a]Also applicable to mattresses.
[b]Only used for rail vehicle applications.
[c]Only used for road vehicle applications.
[d]Only used for aircraft seating.

standards and also of international standards was presented in 1989.[20]

Testing Resistance to Smoldering Heat Sources

In the United States, mattresses made since June 1973 have had to comply with a cigarette-ignition test method that is published in Title 16, Code of Federal Regulations, Part 1632.[21] Originally, the test method was developed by the National Bureau of Standards (now the National Institute for Standards and Technology [NIST]), but after the establishment of the Consumer Product Safety Commission (CPSC) it was taken over by that agency. The pertinent test is still often known by its original designation as FF 4–72. The test is on a full-size article and involves placing nine cigarettes on the bare mattress and nine more sandwiched in between two sheets placed on the mattress. (See Figures 6.5.7 and 6.5.8 in Section 6, Chapter 5, "Fibers and Textiles.")

Additional voluntary standards have been developed by trade organizations, such as the Upholstered Furniture Action Council (UFAC) for residential furniture and the Business and Institutional Furniture Manufacturers Association (BIFMA) for business products. Two of these standards have also been developed as ASTM E1353, *Standard Test Method for Cigarette Ignition Resistance of Components of Upholstered Furniture Assemblies,* and ASTM E1352, *Standard Test Method for Cigarette Ignition Resistance of Mock-Up Upholstered Furniture Assemblies.* What became the BIFMA standard was originally developed by NIST in 1976 for CPSC as a proposed test for the resistance of upholstered furniture to cigarette ignition.

However, the furniture industry requested CPSC to allow a voluntary standard instead, and residential upholstered furniture items since the early 1980s have been available with the UFAC

hangtag. The presence of the hangtag indicates the manufacturer's certification that the item was manufactured in accordance with UFAC standards.[22] By the mid-1990s, CPSC found that 86 percent of all upholstered seating in the retail marketplace met all of the UFAC requirements.[23] Such furniture, of course, is not 100 percent ignition resistant, but CPSC did determine that there was approximately an 85 percent likelihood that a cigarette placed on any mid-1990s vintage furniture item would fail to ignite it.

The cigarette used in all U.S. smoldering ignition tests is a filterless, 85-mm commercial cigarette (Pall Mall® brand). It is representative of many other cigarette brands in its propensity to ignite. Cigarette tests generally specify placement of the cigarette in the most vulnerable configuration, which is the crevice formed by the horizontal and vertical upholstered surfaces except, of course, for mattress tests. The cigarette is covered with a piece of sheeting. This makes the test slightly more severe and more reproducible, presumably because of exclusion of air currents from the smoldering area. Pass/fail criteria are generally expressed in terms of char length or obvious ignition (i.e., sustained, expanding smoldering) for cigarettes.

For upholstered furniture, the state of California has a voluntary smoldering-resistance standard, Technical Bulletin 116, which is similar to the UFAC test methods but entails testing of the actual fabric/padding composites. The UFAC procedure, by contrast, while involving minimockups of composite material, tests only fabrics over "standard" foams and vice versa. For reasons not entirely clear, compliance with voluntary provisions for cigarette ignition resistance have been more successful in California than nationally. It is estimated that about 90 to 95 percent of the furniture sold in California is resistant to cigarette ignition.[5] California's T.B. 117 and the large-scale California tests—T.B. 121, T.B. 129, and T.B. 133—are discussed later. Most other states do not have any regulatory requirements.

Fire-Safe Cigarettes

Another strategy to reduce the risk of fires due to cigarette ignition of upholstered items is to regulate the cigarette itself, rather than the target fuel. CPSC asked NIST to examine the practicability of such "fire-safe" cigarettes as a consequence of two Congressional Acts, the Cigarette Safety Act of 1984 and the Fire Safe Cigarette Act of 1990. A fire-safe cigarette has a reduced propensity to continue burning when left unattended. In both cases, NIST produced voluminous studies on the topic, which elucidated many details of the problem. More important, at the end of the second study, the conclusion was that such cigarettes are not only feasible but also practicable.[6] NIST also developed a test method specifically for this purpose, which has become ASTM E2187, *Standard Test Method for Measuring the Ignition Strength of Cigarettes.*

In July 2000, the Philip Morris company started producing fire-improved Merit-brand cigarettes by using a patented cigarette paper, PaperSelect, that has thin bands of less porous paper that act as "speed bumps" to periodically slow down the burning rate. NIST tests[7] indicated that the cigarette does indeed show a reduced ignition potential, but the probability of ignition was still 3 to 50 percent, depending on the test substrate.

New York was the first state to adopt regulations requiring that cigarettes sold in New York State comply with the ASTM standard. New York Fire Safety Standards for Cigarettes[8] went into effect June 28, 2004. After that, the entire country of Canada adopted regulations using the same ASTM standard; this regulation[9] came into effect October 1, 2005. Similar regulations have gone into effect in Vermont (effective May 1, 2006) and California (effective January 1, 2007), and it is likely that additional states will follow.

In March 2006, the NFPA launched the Coalition for Fire-Safe Cigarettes with the stated goal of establishing country-wide adoption of similar legislation. The coalition, coordinated by NFPA, has called for cigarette manufacturers immediately to produce and market only cigarettes that adhere to an established standard based on ASTM E2187 and for all states to file legislation adopting such standards in their next legislative session. As an indicator of the coalition's success, three states adopted such laws within the four months following the coalition's establishment (Table 6.6.14). For current information, see http://www.firesafecigarettes.org.

TESTING RESISTANCE TO FLAMING HEAT SOURCES

Small-Scale Tests

There are three testing strategies for determining the resistance of upholstered items to flaming heat sources: (1) component testing, (2) small-scale composite or mock-up testing; and (3) full-scale testing. A full-scale test is obviously definitive, subject only to the specification that the ignition source be well thought out. A small-scale composite or mock-up may capture much of the same behavior, but this—by itself—is unproven. For a small-scale test to be a reasonable reflection of what happens in real fires, it is necessary that a research program be conducted wherein full-scale performance and small-scale results are directly compared.[24] This is not a trivial task, because even the engineering units needed are not the same. For full-scale performance, peak heat release rate (HRR) is often considered to be

TABLE 6.6.14 Fire-Safe Cigarettes: State Legislation

State	*Percent of U.S. Population Covered*	*Legislation Signed*	*Effective Date*
New York	6.5	December 31, 2003	June 28, 2004
Vermont	0.2	July 17, 2005	May 1, 2006
California	12.2	October 7, 2005	January 1, 2007
Illinois	4.3	May 19, 2006	January 1, 2008
New Hampshire	0.4	May 31, 2006	October 1, 2007
Massachusetts	2.2	July 8, 2006	January 1, 2008
	25.9		

the governing variable that best describes the real-life hazard;[25] but for small-scale results another metric needs to be found, which can be, for example, the 3 minute average HRR, divided by the specimen's area, giving units of kW/m^2. Component tests involve testing of foam, fabrics, etc., in isolation, without considering their interactions in the actual item. Such tests usually have little merit, because the interaction between the layers of an upholstered item is highly complex, both thermally and chemically; ignoring it does not lead to reliable conclusions. The one known exception to this generalization has been the component testing scheme studied in the European CBUF research project.[14] However, to become reliable, the scheme had to become so highly complex that it was no longer a practical, simpler alternative to composite testing. Consequently, its use was not even espoused for that project's objectives.

For flame ignition component tests, ignition is often by a gas flame at the bottom of a vertical specimen, such as foam or fabrics.[10,26] Flaming ignition in furniture mock-ups is generally at the crevice location.

Some of the newer tests described in Table 6.6.13 are more severe than the state standards such as T.B. 116 and T.B. 117 in that they employ larger ignition sources or heating with radiative sources. These tests often include heat release rate, flame spread, and smoke measurements, and are frequently used for research, product development, and regulation of special occupancies by some state and local authorities.

There is also a hybrid possible of strategies 1 and 2, whereby a composite is tested, but not the actual composite. Instead, a "standard" foam is placed underneath the to-be-tested fabric, or a "standard" fabric is placed on top of the to-be-tested foam. Various other component combinations can also be constructed in similar manner. This arrangement has the benefit of reducing testing costs but also introduces uncertainty. Furthermore, there has not been any broad-based scientific study to validate this type of approach.

The hybrid testing approach is found in a few sections of the (old) California T.B. 117 standard (see below) and was also used in the regulations issued by the United Kingdom for upholstered furniture during 1988–1989.[10,11] The U.K. regulation is a complex scheme that involves cigarette, small-flame, and wood-crib tests for various materials, depending on the material. The test methods themselves are a slightly modified version of British Standard BS 5852, *Methods of Test for Assessment of the Ignitability of Upholstered Seating by Smouldering and Flaming Ignition Sources.*

California T.B. 117

California became a unique state in the regulation of furniture when it put into effect a mandatory regulation for furniture flammability in 1975. Furniture makers wishing to sell products in California became subject to the requirements of California standard T.B. 117.[26] The standard was quite complex and covered both smoldering performance and small-flame resistance of upholstered furniture. The smoldering portions became moot in the 1980s, when the UFAC procedures became the nationwide norm. Because the test requirements for smoldering within T.B. 117 were so weak that they did not even cover the fabric, manufacturers generally made furniture according to the UFAC requirements and such furniture was then suitable for all 50 states.

The unique small-flame resistance requirements in T.B. 117 entailed component testing of padding materials (i.e., naked foams) using a vertical Bunsen burner test. Adding a small amount of fire-retardant chemicals to foams normally suffices to produce a dramatic improvement in performance in this test and allows the product to meet the California regulation. Unfortunately, testing by CPSC indicated that furniture meeting the test requirements of California T.B. 117 will very often not meet the intended purpose of the test—actually to make the furniture resist ignition when presented with a small ignition flame.[23] This finding is not surprising, because an external flame will expose the fabric first, and only then will the padding be subjected to ignition. But T.B. 117 specified the CS-191-53 test procedure[27] for fabrics, which will essentially never fail a fabric that is sufficiently thick to be viable for upholstery purposes. By 1994, the former head of the California Bureau of Home Furnishings[28] that developed this test method acknowledged most of these shortcomings. In 1999 the bureau announced that the standard would be revised and strengthened. A draft version of an entirely new T.B. 117 was publicized in 2002, but then California suspended further development due to CPSC's renewed efforts to establish a federal standard for the resistance of upholstered furniture to small-flame ignition sources.

CPSC Proposed Small-Flame Ignition Test for Upholstered Furniture

In the early 1980s, U.S. fire deaths due to smoldering ignitions of upholstered furniture were about 1000 per year (Figure 6.6.1).[4] By the mid-1990s, the rate dropped down to around 600 per year. This can be attributed to the reasonable effectiveness of the UFAC program, a reduction in smoking, improved fire safety education, and more widespread use of home smoke alarms. By contrast, the number of deaths due to flaming ignitions of upholstered furniture had declined less substantially and less steadily, and multiyear averages showed a decline in deaths from 110–120 to 90–100.

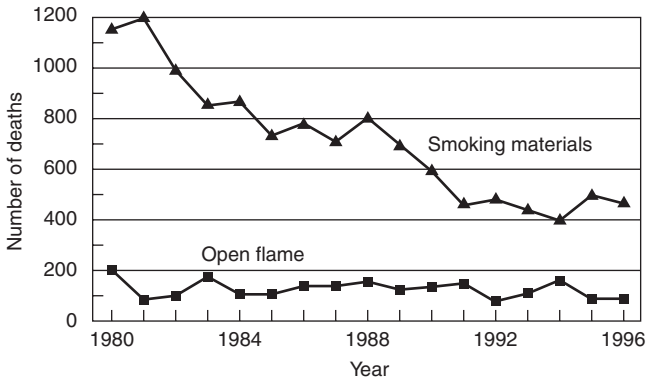

FIGURE 6.6.1 Annual U.S. Fire Deaths Due to Ignitions of Upholstered Furniture, as Estimated by CPSC

Statistics also indicate that although the number of upholstered furniture fires ignited by open flames has decreased (Figure 6.6.2), the risk of injury, given an ignition, has increased (Figure 6.6.3).

In view of the fact that deaths in open-flame fires were not clearly decreasing, the National Association of State Fire Marshals petitioned CPSC in 1992 and 1993 to establish some new national flammability standards for upholstered furniture. CPSC responded in 1994 by granting the part of the petition asking for a small-flame ignition test. The request for large open-flame resistance was not granted. CPSC first investigated the merits of California T.B. 117, which has been used since 1975. After a laboratory investigation of the method, CPSC concluded[29] that "T.B.-117 component results were not predictive of full scale performance," and that "T.B.-117 . . . would not, if federally mandated, ensure a substantial reduction in the risk of small open-flame ignition of finished articles of furniture." The same conclusion had emerged from earlier, private-sector studies on T.B.-117 complying furniture.[30,31]

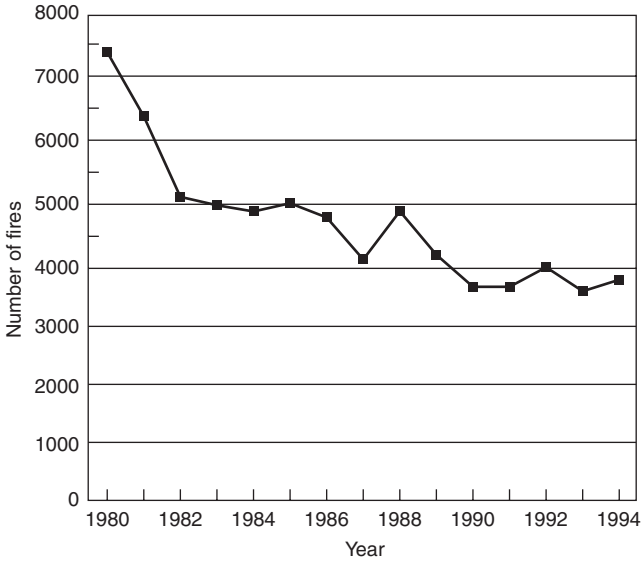

FIGURE 6.6.2 Annual Number of Furniture Fires Caused by Open Flames, as Estimated by CPSC

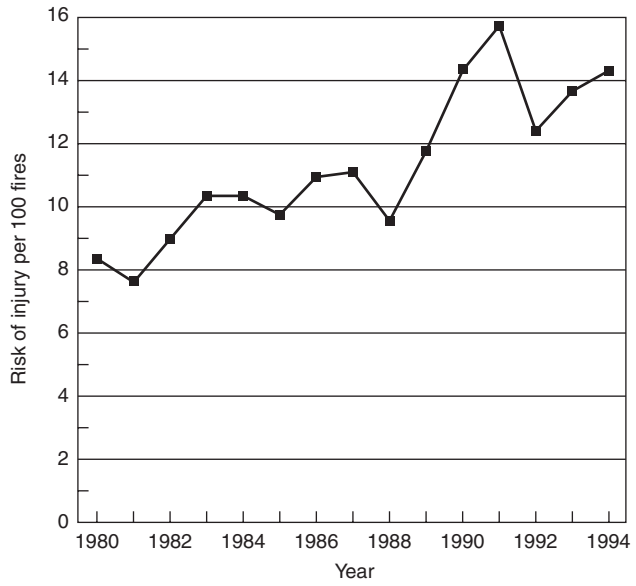

FIGURE 6.6.3 Risk of Injury, per 100 Upholstered Furniture Fires Ignited by Open Flames, as Estimated by CPSC

Consequently, CPSC then looked to the British approach for testing furniture, because it was considered that furniture complying with British regulations was better than the U.S.-marketplace furniture generally available to retail consumers.[4] The British regulations are both complex and discriminatory (e.g., latex foam is held to a lower standard than polyurethane foam). Thus, CPSC actively considered only the basic test setup and not the entire regulation and, over the next few years, developed a draft method that evolved from one of the mock-up tests used in the United Kingdom. A draft of this method was published in 1997[23] and elicited numerous comments from industry, primarily concerning the statistical reliability of the test.[32] The main test was a hybrid test of the fabric/foam composite used for the seat and back cushions, whereby a "standard" foam would be used in place of the actual foam. In addition, CPSC noted that a fire hazard also exists from flammable dust covers (a nonwoven fabric typically present below the seat cushion area), because children playing with fire sometimes ignite those from underneath. Thus, it proposed a separate dust-cover test. CPSC did offer limited support for its particular version of hybrid testing by conducting some preliminary testing[29] that found that "fabric ignition times were essentially the same when tested with and without . . . FR foams." The main CPSC test setup (Figure 6.6.4) uses a metal frame to create a seat and a back. The rig then holds a simulated back cushion of 305 by 458 by 76 mm, and a seat

FIGURE 6.6.4 Specimen Being Tested in the Proposed 1997 CPSC Open-Flame Test for Upholstered Furniture (Source: Photo courtesy K. Reimann, BASF)

cushion of 83 by 458 by 76 mm. A butane flame, about 35 mm tall, is applied for 20 seconds at the seat/back juncture.

During 1999–2000, CPSC conducted a round-robin study of the proposed test method, with nine test laboratories participating. The round-robin involved five upholstery fabrics and two types of dust cover. Generally, the laboratories were able to agree on "pass" or "fail" results for the test specimens. Two of the five fabrics were deliberately selected as borderline samples and, as expected, returned mixed results. Despite its long-term activity, CPSC did not publish much data on the performance of various materials in their draft test. Such an effort was undertaken by Reimann,[33] who examined 219 fabrics and conducted 408 mock-up tests. Of untreated fabrics only 4 out of 75 passed the test requirements at that time. Of fabrics stated to comply with BS 5852 (but not certified), 22 out of 52 passed. Of 11 cotton fabrics treated with a proprietary FR agent, 100 percent passed. Although not a part of the draft test method, testing with highly fire-retardant foams did not show an anticipated improvement in performance, presumably because advanced foam formulations cause improvements in heat release rate, not ignitability. Reimann also found a number of technical difficulties or shortcomings, especially that tensioning of the fabric is critical and may not be controlled adequately in the test method. In other industry testing,[34] it was found that only 17 out of 31 fabrics certified to meet BS 5852 met the CPSC requirements.

CPSC's development of a flaming-ignition standard was delayed when the furniture industry persuaded Congress to suspend its research on a test method and to focus on the question of whether fire-retardant chemicals to be used for making test-complying furniture might be hazardous from a toxicologic point of view. CPSC was consequently directed to cooperate with the National Research Council (NRC) in conducting a review of the literature on the topic. The focus was on fire-retardant agents used for fabrics, rather than foams, because (1) the CPSC test development effort focused on fabric improvements; and (2) the state of California had required FR-treated (or equivalent) furniture foams since 1975. Consequently, there is a wide database of consumer experience with FR-treated furniture foams. NRC studied in detail 16 FR agents deemed to be most likely used for treating furniture fabrics and published its findings in 2000.[35] The philosophy of the investigators was to examine whether there was an adverse health effect without considering at the same time the possibility of enhanced health effects due to the prevention of injuries from fire. This thinking is a conservative philosophy, yet the investigators found that 8 of the 16 chemicals warranted no further study, because they were clearly non-injurious to consumers. In their view, data were not sufficient to make the same statement about the other 8 chemicals, so they recommended that further research be done on those.

A government-sponsored study in the United Kingdom did set out to assess FR agents in a risk/benefit context.[36] The authors of that study concluded that "the benefits of many flame retardants in reducing the risk from fire far outweigh the risks to human health." But they too pointed out that FR agents need to be studied individually (or by chemical families)—it is clearly impossible to make a general statement about any and all chemicals proposed for use in a certain application.

Once the toxicity issue was settled, CPSC proceeded to issue new proposals in quick succession during 2001, 2003, 2005, and 2006.[37–41] The 2006 document proposes separate tests for flaming and smoldering resistance of upholstery composites, along with several variations and options that are still to be considered. Open-flame exposure specimen performance in the 2006 draft test method is illustrated in Figure 6.6.5. The specimens are identical except that an interliner was included in the specimen on the right, enabling it to pass the test criteria. Unlike for mattresses, there are no indications that CPSC would adopt HRR-based testing for upholstered furniture.

Large-Scale and Full-Item Tests

Testing for cigarette ignitability can be done satisfactorily on small samples (although reliability will perforce be higher if done on the full-scale item). However, for flaming behavior of

FIGURE 6.6.5 Performance of Two Specimens in the 2006 Draft Version of the CPSC Upholstered Furniture Test for Open-Flame Resistance of Upholstery Composites: Without Interliner (left); with Interliner (right)

fires, the situation is different. A small Bunsen burner or similar type of test cannot predict what will happen to real furniture. Thus, it had been recognized for a number of years that large-scale tests may be crucial.

The first large-scale fire test for upholstered furniture to gain widespread acceptability was California T.B. 133.[42] The test comprises a room in which an actual furniture item (or a full-scale mock-up) is fire tested. The original ignition source comprised 3.2 oz (90 g) of balled-up newspaper held in a wire cage placed into the crevice of the furniture. The criteria included room temperature rise, carbon monoxide (CO) concentration, and smoke density in several locations, and the weight loss of the test item. Following a research program at NIST,[43] the test method was revised in 1990 in three fundamental respects: (1) for improved reproducibility, the ignition source was replaced with a gas burner; (2) the main pass/fail criterion was set as a heat release rate value, taken at the 80 kW level; and (3) a new option was added for running tests in the hood of a large-scale furniture calorimeter, rather than inside of a burn room.

The California T.B. 133 test was originally voluntary. In 1992 it was made mandatory in California for certain public occupancies (but not for residential use). Its influence, however, extends beyond these limited applications. Most of the larger manufacturers of contract furniture now offer a significant selection of T.B. 133–complying furniture. Much of this acceptance has come from concerns about product liability litigation. The test has been adopted by ASTM International as ASTM E1537. An Underwriters Laboratories method (UL 1056) was originally published and entailed quite different test conditions. However, the UL method was changed to make it rather similar to the methods of ASTM. For actual testing, reference should be made to the ASTM method, because guidance to the laboratory is much more extensive there than in the California bulletin.

To meet T.B. 133 requirements, manufacturers have most often turned to using an interliner fabric (e.g., vinyl-coated glass fabric, or Nomex® or PBI (polybenzimidaxozole) nonwoven or woven fabrics) between the cover fabric and the padding. Foam improvements might be needed and care in selecting fabrics is also necessary. It is especially difficult to pass the T.B. 133 test with polyolefin (polypropylene) fabrics. It is important to realize that the test is a system test and not a materials test. Thus, using the same construction materials, it can be possible to pass the test with a smaller chair and fail it with a larger one. A number of other design variables, in addition to combustible mass, also enter into the picture.

For prison mattresses, California has long had a special large-scale test, T.B. 121. This test is run in the same test room as for the T.B. 133 test, but with a different ignition source, which is a wastebasket placed underneath the test specimen.[44] More recently, California developed a less severe mattress test suitable for other institutional occupancies. This test, T.B. 129,[45] uses a gas burner located alongside the edge of the specimen, with other test features being essentially identical to those of the T.B. 133, except for the pass/fail limit. For the California T.B. 129 test, this limit is set at 100 kW. The test has been adopted as ASTM E1590. The latest development is the new CPSC mattress test and regulation, discussed below.

A special category of concern is stacking chairs. These types of chairs are normally used in hotel ballrooms, churches, and other public assembly rooms. This chair type, when upholstered (some types are of solid molded plastic, without upholstery), usually has only a small amount of padding. Thus, it would seem that dangers associated with them would be small. After some significant fires, most notably the 1978 Cathedral Hill Hotel fire in San Francisco, California, however, attention was focused on the fact that such chairs are often found in their stacked configuration, where they can be many units high. Under these conditions, the hazards are much increased. This concern has led to a large-scale fire test method, ASTM E1822, *Standard Test Method for Fire Testing of Stacked Chairs.*[46]

In the area of transportation seating, there is a large-scale regulatory test promulgated by the FAA for airplane seats.[47] It specifies a 115 kW, 6 in. (152 mm) diameter kerosene burner flame directed for 2 minutes on the side of the seat. The flames must not spread across the seat, no flaming drips must fall, and a maximum weight loss is specified. This challenging test serves to ensure that airplane seats would not burn with a fierce fire. The other U.S. federal test for transportation seating is remarkable for its laxness. Motor Vehicle Safety Standard No. 302 uses a horizontal specimen and has minimal flame-spread requirements.[48] The consequence is that seating in automobiles is commonly easily ignitable and produces rapidly growing, high-heat-release-rate fires.

CPSC Open-Flame Ignition Test for Mattresses

In February 2006, CPSC issued new regulations governing the resistance of mattresses to open-flame ignition. The agency considers this the first regulation in that agency's history that has an impact of over $100 million on the national economy. The new federal standard, which went into effect on July 1, 2007, is described in a Federal Register notice.[49] This regulation has had a long and convoluted history. In 1991, California's Bureau of Home Furnishings and Thermal Insulation reported on extensive full-scale testing[50] of various bare mattresses (no bedding). Some of these specimens, however, easily passed the test, whereas the supposition was that in a real-life situation they might not have behaved similarly. An extensive study at NIST[51] in the 1970s had demonstrated that the bedding on a bed is the "driving force" causing flame spread and sustained combustion of the mattress. In the absence of bedding, a mattress fire may die out, yet the same specimen may burn vigorously when covered with bedclothes. Thus, presenting modest-sized flames to a bare mattress may produce unrealistically benign test results. Consequently, a few years later, the industry trade group International Sleep Products Association (ISPA) sponsored a new research project at NIST to develop a mattress test that duly recognizes the role of bedding on a mattress. Because of difficulties in ensuring a long-term supply of identical bedclothes, the NIST work focused on developing a substitute, which took the form of two "T-head" gas burners, one applied to the side of the mattress and one to the top. The top burner is run at a power of 18 kW, and the side burner receives 9 kW (Figure 6.6.6). This research work by Ohlemiller et al. has been documented in a series of NIST reports.[52–55]

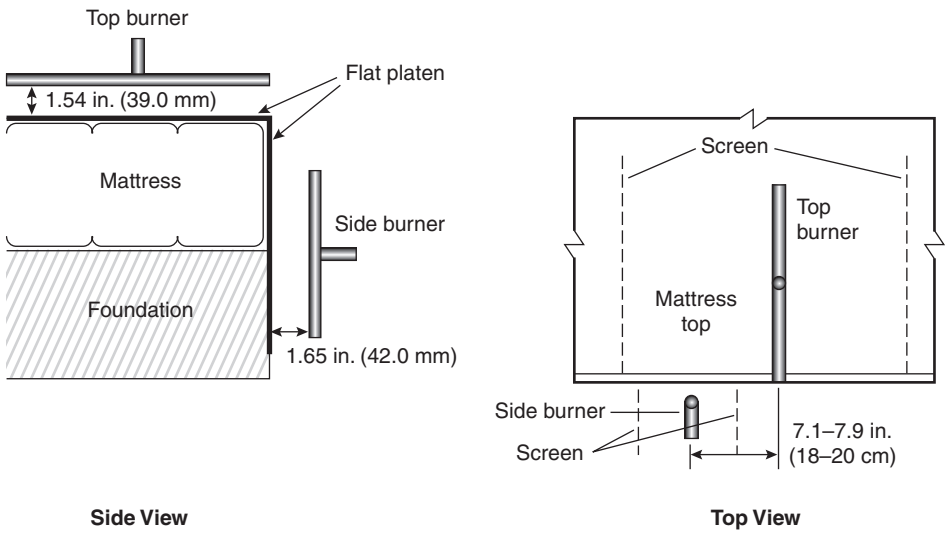

FIGURE 6.6.6 Two Burners Used to Provide a Simulated-Bedclothes Exposure to a Mattress Specimen in the CPSC Open-Flame Mattress Test

Even at this stage of development, the mattress test was of a substantially different nature than the small-flame tests for upholstered furniture used in California or investigated by CPSC. The latter simulate the application of a cigarette lighter, whereas the NIST procedures are based on a large open-flame ignition source. Similarly, the criterion is not nonignition (although a specimen that would resist ignition would obviously pass) but rather low heat release rate. In terms of material response, this criterion is a more difficult requirement, because it is easier to resist ignition from a small flame than to show very low fire development when presented with sizable flames from the ignition source.

The next step in the development took place when California passed a law in August 2001 (T.B. 603) that required all mattresses sold in California after January 1, 2004, to be effectively fire resistant so that they resist open-flame ignition sources, not just smoldering cigarettes. The California Bureau of Home Furnishings and Thermal Insulation was asked to develop regulations and a suitable test method. In response, it issued a standard, T.B. 603[56], that is essentially an implementation of the ISPA/NIST protocol. CPSC had, at the same time, ongoing work to develop a regulation for controlling the flammability of mattresses under open-flame conditions. Because the primary research being done at NIST was already adopted into the California regulation, CPSC decided to adopt essentially the same test method, but with certain modifications.

The California regulation permits testing in an open calorimeter, in the California-configuration burn room (10 × 12 ft [3.05 × 3.66 m]), or in the ASTM-configuration test room (8 × 12 ft [2.44 × 3.66 m]). CPSC reduced these options to two, either the open calorimeter or the California-configuration room. Because radiant heating from the upper portions of a room greatly exacerbates the burning of a mattress, however, it is clear that these configurations are not equivalent and, presumably, manufacturers will select to do testing in an open calorimeter. CPSC also slightly tightened the conditions for passing. The peak HRR value permitted is still 200 kW, but the 10-minute total heat release was reduced from 25 MJ to 15 MJ. The new CPSC test is in addition to the existing requirements for cigarette ignition resistance. Presumably, the California standard will become moot when the federal standard goes into effect, because it is slightly less restrictive than the federal version.

At this stage, it is not yet known what technologies manufacturers will use to meet these new regulations. Because the regulation was developed on the basis of the industry-sponsored research at NIST, it is reasonable to assume that the manufacturers do not foresee serious difficulties in meeting the requirements. It is likely that a common solution will be to use an interliner "bag," whereby a fire barrier material is used to encapsulate the padding.

Reducing the flammability of mattresses may not sufficiently reduce the risk of injury or death from a mattress fire, if the bedding burns with a high HRR. Thus, the California legislature also instructed the Bureau of Home Furnishings and Thermal Insulation to develop a companion regulation for the open-flame behavior of bedding. The Bureau issued a draft proposal, T.B. 604[57] in 2004, but thus far, a regulation has not been finalized. Somewhat unexpectedly, the draft regulation is not based on HRR, but rather on simple weighing of the specimen.

CHARACTERISTICS OF IGNITION SOURCES

The choice of the ignition source is crucial to fire testing. A test item that shows essentially no response under a given source may exhibit a runaway fire with just a slightly greater ignition source. Thus, the simulated source selected must be a realistic approximation of the actual fire conditions that may be encountered.

Table 6.6.15 shows the characteristics of some ignition sources that have been used in flammability experimentation with upholstered furniture items. The sources range over four orders of magnitude: from 0.05 to 500 kW. The maximum heat fluxes for the sources, except the methenamine pill, range between 18 and 42 kW/m^2. This range is rather small, and it can be generalized[58] that an "incidental" ignition source shows a typical flame flux of 35 kW/m^2. What varies when the ignition source strength is increased is not the flame flux, but rather the area over which the flux is applied. In the case of the polyethylene wastebasket, the area over which fluxes exceed 20 kW/m^2 is about 2.36 by 27.55 in. (60 by 700 mm); for a wood match this would be approximately 0.39 by 1.18 in. (10 by 30 mm). This relationship is generalized in Figure 6.6.7. It is seen that there is a linear relationship between the power output of the ignition source and its flame coverage area. It should be noted that the above data are all for "incidental" fire sources. Heat fluxes from specialized sources, such as oxyacetylene torches, may be much higher, for example, 140kW/m^2.

The reason the flame coverage area of the ignition source is important is that higher heat fluxes are required to raise small target areas to their ignition temperature than large areas. This coverage is especially true for fire-retardant-treated materials. Unfortunately, no theoretical guidance is yet available on this

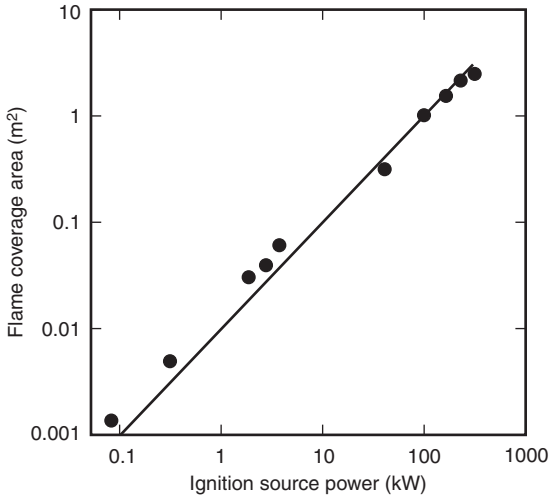

FIGURE 6.6.7 Flame Area as a Function of Ignition Source Power (for U.S. units: 1 ft = 0.305 m)

TABLE 6.6.15 Characteristics of Furniture Ignition Sources

	Typical Heat Output (W)	*Burn Time*[a] *(sec)*	*Maximum Flame Height (mm)*	*Flame Width (mm)*	*Maximum Heat Flux (kW/m^2)*
Cigarette 1.1 g (not puffed, laid on solid surface)					
Bone dry	5	1200	—	—	42
Conditioned to 50% R.H.	5	1200	—	—	35
Methenamine pill, 0.15 g	45	90		4	
Match, wood (laid on solid surface)	80	20–30	30	14	18–20
Wood cribs, BS 5852, Part 2				15[b]	
No. 4 crib, 8.5 g	1,000	190		17[b]	
No. 5 crib, 17 g	1,900	200		20[b]	
No. 6 crib, 60 g	2,600	190		25[b]	
No. 7 crib, 126 g	6,400	350			
Crumpled brown lunch bag, 6 g	1,200	80			
Crumpled wax paper, 4.5 g (tight)	1,800	25			
Crumpled wax paper, 4.5 g (loose)	5,300	20			
Folded double-sheet newspaper, 22 g (bottom ignition)	4,000	100			
Crumpled double-sheet newspaper, 22 g (top ignition)	7,400	40			
Crumpled double-sheet newspaper, 22 g (bottom ignition)	17,000	20			
California T.B. 133, Crumpled newspaper, 95–105 g	15,000	110	710	610	80[c]
Polyethylene wastebasket, 285 g, filled with 12 milk cartons (390 g)	50,000	200[d]	550	200	35[e]

Note: For U.S. Units: 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 oz = 28.4 g.
[a]Time duration of significant flaming.
[b]Measured from 25 mm away.
[c]Wide scatter.
[d]Total burn time in excess of 1800 seconds.
[e]As measured on simulation burner.
Source: Krasny, J. F., Parker, W. J., and Babrauskas, V., *Fire Behavior of Upholstered Furniture and Mattresses,* William Andrew Publishing, Norwich, NY, 2001.

point, which is one reason why ignition source selection must be done on an empirical basis. Too-small ignition sources can be misleading for an additional reason. Many materials shrink or melt away from a small ignition source; this can lead to passing of a Bunsen-burner-type test. When presented with a larger ignition flame area, however, the same item may be unable to shrink back and can ignite and burn vigorously. Bunsen-burner-type tests are considered the appropriate simulation of residential accidents involving matches or lighters. But such tests should never be utilized for high-risk occupancies (e.g., health care) where acceptable performance under exposure from much larger flames is required.

FLAME SPREAD

Flame spread has long been the basis of flammability evaluation of building materials; however, little quantitative work has been done on the flame spread over upholstered items. Cotton and rayon cover fabrics by themselves were shown to have flame spread rates inversely proportional to their "basis weight" (i.e., oz/yd^2 or g/m^2);[59] however, when tested over polyurethane padding, the differences between flame spread rates were small. This result is another case whereby component tests can give rise to misleading results, as mentioned earlier.

In another experimental series, the flame spread over seat cushions of chair mock-ups was measured by counting the number of 3.93 in. (100 mm) squares covered by flames as a function of time from ignition.[60] This flame spread rate was found to correlate fairly well with bench-scale measurements on the same fabric/padding composites. There were major differences, however, in the behavior of charring and melting thermoplastic fabrics. Cotton and rayon, the cellulosic fabrics, charred ahead of the flame, and on the side of the chair opposite to the one that was burning. Eventually the char burst into flame. The thermoplastic fabrics initially shrank away from the ignition source, but being supported by the foam, the shrunken material bead burned and presented a relatively large ignition source for the foam padding. The fabric on the chair side opposite the burning side ablated, exposing the foam to the radiation. Thus, flames spread more rapidly over the thermoplastic fabric-covered mock-ups, even when the foam was neoprene and did not significantly flame during the test.

General flame spread theory has not been much applied to upholstered items, primarily because of the variety of configurations and interaction between fabrics and padding. Dimensions in these items are sufficiently large so flame spread and heat-release behavior are dominated by radiative, rather than convective, mechanisms. Recently, some studies of furniture flame spread in the "against the wind" mode, that is, in the opposite direction to the draft induced by the buoyancy of the flame, have been conducted.[61] These tests may find an application in advancing the theory of furniture fires.

HEAT RELEASE RATE (HRR)

Measuring the HRR

Heat release rate (HRR) is recognized as the single most important variable describing fire hazard.[25] The reason for this is not hard to understand. When confronted with a fire, normally the first question that arises is: how big is the fire? The HRR is simply the quantitative rephrasing of that question. It is important to note that by knowing the HRR of the full-scale object one does not separately need to inquire as to its flame spread characteristics. Items showing slow or incomplete flame spread reflect this in their HRR curves, which are low or slow growing.

In earlier days, it was not possible to discuss the HRR of burning items, simply because measuring tools did not exist for it. This situation was changed in 1982 when the present author and co-workers at NIST developed the furniture calorimeter,[62] which allowed simple, low-cost testing of whole furniture articles under realistic burning conditions. The HRR (measured in kilowatts [kW]) was measured, along with smoke and toxic gas evolution from the burning object. Subsequently, a European standard based on furniture calorimeter testing was published.[63] This standard was followed by the U.S. standards discussed earlier, wherein the furniture calorimeter testing methodology is further developed (ASTM E1537 and E1590). Furniture calorimeters are now available in many U.S. and foreign test laboratories and manufacturers' laboratories.

The furniture calorimeter is based on the *oxygen consumption* principle, which states that the combustion heat released is proportional to the amount of oxygen consumed to within about 5 percent. The proportionality constant is 13.1 10^3 kJ per kg of O_2 consumed. Note that the *heat of combustion* of a fuel can vary widely and the oxygen consumption principle does *not* require that this be known or be constant. The details of this principle, along with extensive additional information on HRR applications, are available.[64]

Measurements of HRR also use the identical oxygen consumption principle when performed in room fire tests, for example, in the room test option of the CPSC's new open-flame mattress regulation.

In recent years, most small-scale HRR testing has been done with the cone calorimeter[65] (Figure 6.6.8). The name *cone calorimeter* comes from the cone-shaped heater used to irradiate the specimen. The basic apparatus is standardized by ASTM as ASTM E1354 and by the International Organization for Standardization as ISO 5660.

The cone calorimeter standards describe the basic equipment and test procedures. As such, they are pertinent to applications ranging from spacecraft to trash containers. Upholstered furniture, however, presents a special issue in that the samples are intrinsically composites, often comprising many layers. Thus, special specimen preparation instructions must be carefully followed in order to obtain reliable and reproducible results. These instructions, first developed in the mid-1980s, were incorporated in the 1990 edition of NFPA 264A, *Standard Method of Test for Heat Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter,* now obsolete. In subsequent years, furniture on the market came more to encompass fire-improved formulations and special constructions. Fire barriers (interliners) have come into widespread use in contract furniture as a consequence of T.B. 133 requirements. The earlier specimen preparation techniques proved to be insufficient for these new products. Also, with the widespread use of cone calorimeters in

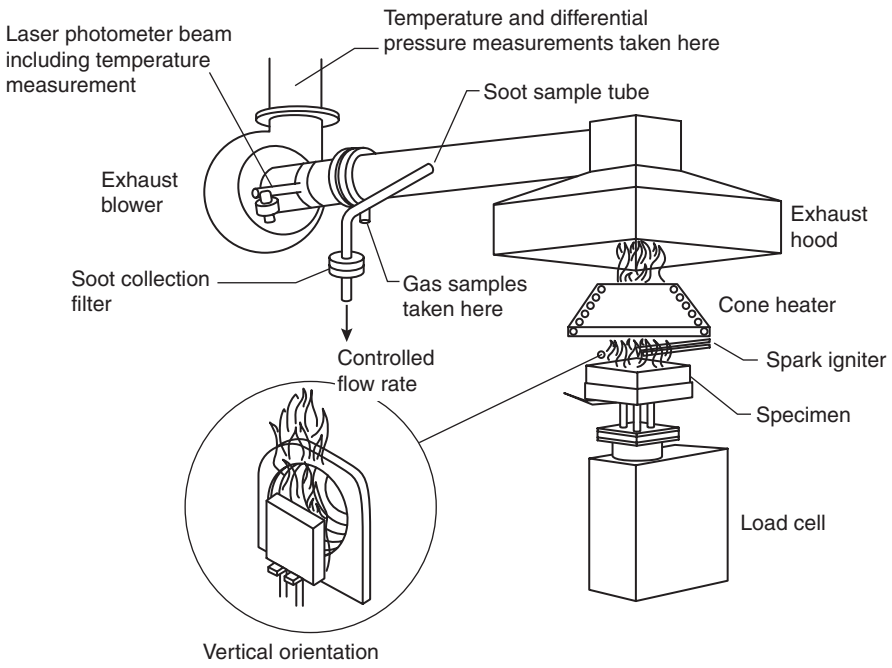

FIGURE 6.6.8 Cone Calorimeter Used for Small-Scale HRR Testing

various laboratories, emphasis on quality assurance procedures needed to be increased, because testing was not always being done by specialists. Consequently, a new, highly detailed specimen preparation protocol was developed in 1994.[66] This protocol was extensively validated in round-robin testing and formed the basis for updating the ASTM E1474 standard, which governs the furniture-specific details of conducting cone calorimeter tests.

Predicting the HRR Performance of Furniture

The HRR of a medium-sized sofa can reach values of around 2000 to 3000 kW (2 to 3 MW) in a very short time, only 3 to 5 minutes after ignition, with HRR around 5000 kW being common for large or sectional sofas. The context for interpreting this value is that it takes less than 2 MW to reach flashover in a room with a normal-sized door opening.[67] For health care, detention, and other high-risk occupancies, such large HRR values are not acceptable, and T.B. 133–complying (or similar) furniture should be used, as described in NFPA *101*®, *Life Safety Code*®, under the individual occupancy sections. In the consumer retail market, however, consumers traditionally have not been willing to pay the extra costs that would be incurred with T.B. 133–type furniture. Such furniture is not restricted to institutional sales and can be ordered by consumers. However, there is essentially no demand for furniture meeting these tougher regulations in the consumer sector.

In the T.B. 133 methodology, the furniture item is to be tested in full size, either in the furniture calorimeter or in a room fire test. Such a methodology should always be available, but it does have drawbacks: costs and effort in full-scale testing can be much greater than in testing small specimens. Thus, as with the fire performance of many other categories of products, bench-scale equivalents have been sought. A *predictive* bench-scale test can provide nearly as good information as a full-scale test, yet be much easier and simpler to conduct.

An initial method for predicting the HRR performance of full-size furniture items on the basis of cone calorimeter results was presented in 1985.[68] Since then, additional research took place to enhance the state of the art. The most significant such advance was embodied in the European research program, Combustion Behavior of Upholstered Furniture (CBUF). This massive study,[14] completed in 1995, yielded a new generation of predictive methods, based on very extensive testing and on advanced fire modeling work. Figure 6.6.9 shows the general design flowchart, as developed in the CBUF research; as mentioned above component-level is feasible in principle, but is not practicable. The simplest model, based on direct correlation, can be summarized as follows.

Determination of Propagating/Nonpropagating Behavior. The most important factor in determining the flaming combustion hazard of furniture for high-risk occupancies is whether the item will or will not support the propagation of fire over its surface. *Propagating* chairs spread fire over most of the surface of the item. Such behavior means that the chair was largely consumed at the end of the fire, although substantial portions of hard combustibles (wood, particleboard) may remain. *Nonpropagating* chairs show a very different behavior. With such items, once the ignition source dies out or is removed, the fire does not sustain itself. Thus, most of the padding and fabric still remains after the fire is over. Combustible materials are usually gone directly under the fire source and in its immediate vicinity; but from a short distance farther, the furniture item can appear essentially undamaged.

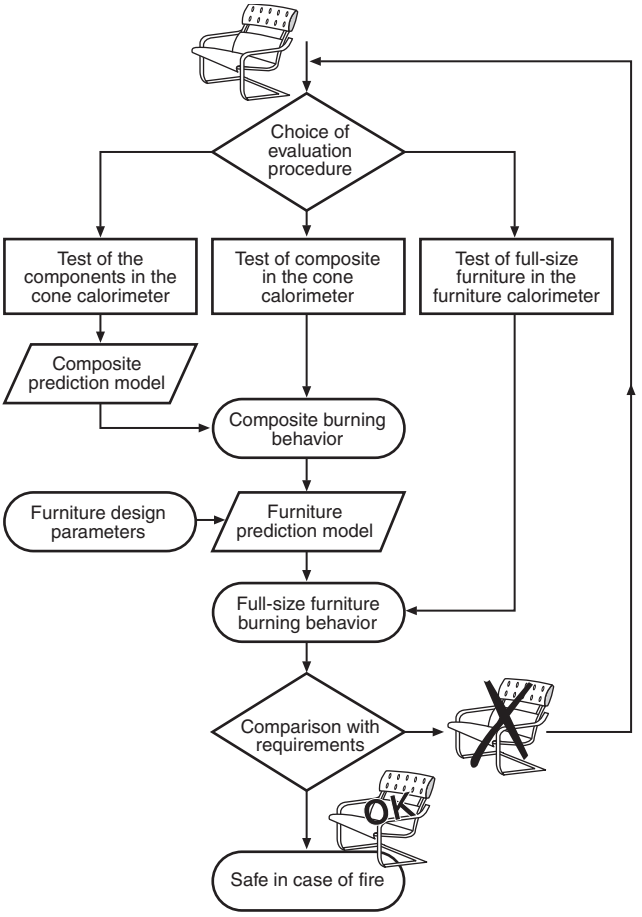

FIGURE 6.6.9 Procedure for Fire Safety Design of Upholstered Furniture

It is experimentally observed that nonpropagating full-scale chair fires normally show peak HRR values of 20 to 100 kW. One can compare this to the 80 kW level that California has selected as the pass/fail limit for T.B. 133. The propagating/nonpropagating behavior is only slightly affected by small variations in the type of ignition source used.

For a nonpropagating fire, the total HRR (and the emissions of toxic gases) is essentially identical to what is measured for the chair itself. For chairs that lead to propagating fires, however, the HRR (and toxic gas emissions) measured during a fire test represents only the *lower bound* to what may occur in a real fire. The reason is that for fires that are propagating fires, it is readily possible to ignite additional items in the room, including items that are not included in a test such as the room-test alternative of T.B. 133. The heat and radiation levels coming from a 100 kW fire are not sufficient to cause serious injury to an occupant, unless the occupant is very close to the fire, because of the room's small size or for other reasons. Thus, it can be concluded that nonpropagating fires are as *intrinsically safe* as a combustible item can ever be deemed to be.

Earlier studies[68] suggested that a propagation/nonpropagation criterion can be set as $\dot{q}'' = 75$ kW/m^2, where $\dot{q}''$ is defined as the cone calorimeter HRR average for the period starting with ignition and ending 180 seconds later. This limit was based on early experience with cone calorimeter testing, and both the irradiance and the test protocol were different from what was found necessary during the CBUF program. As a result of the CBUF study, a criterion value of $\dot{q}'' = 65$ kW/m^2 was determined.

Prediction of the Peak HRR. Analysis of the large amount of full-scale and bench-scale data collected within the CBUF program allowed equations to be developed to predict the peak HRR of the furniture (chair or sofa) item. Prediction of the peak HRR requires the use of Equations 1 through 5.

$$x_1 = (m_{soft})^{1.25}(\text{Style factor } A)(\dot{q}''_{pk} + \dot{q}''_{300})^{0.7}(15 + t_{ig})^{-0.7} \quad (1)$$

$$x_2 = 880 + 500(m_{soft})^{0.7}(\text{Style factor } A)(\Delta h_{c,eff}/q''_{tot})^{1.4} \quad (2)$$

$$\text{If } (x_1 > 115) \text{ or } (q''_{tot} > 70 \text{ and } x_1 > 40)$$
$$\text{or (Style factor} = \{3,4\} \text{ and } x_1 > 70)$$
$$\text{Then } \dot{Q} = x_2 \quad (3)$$

else,

$$\text{If } x_1 < 56$$
$$\text{Then } \dot{Q} = 14.4\, x_1 \quad (4)$$

else,

$$\dot{Q} = 600 + 3.77\, x_1 \quad (5)$$

For the above equations, the following cone calorimeter data are used:

$\dot{q}''_{pk}$ = Peak HRR (kWm^{-2}) at 35 kWm^{-2} exposure

$\dot{q}''_{300}$ = 300 seconds average HRR (kWm^{-2}) at 35 kWm^{-2} exposure

t_{ig} = Ignition time (seconds) at 35 kWm^{-2} exposure

$\Delta h_{c,eff}$ = Effective heat of combustion (MJ kg^{-1})

q''_{tot} = Total heat release (MJ m^{-2}) at 35 kWm^{-2} exposure

In addition, the total mass and the style factor of the full-scale item must be known:

m_{soft} = Mass of upholstery (fabric, filling, interliner, etc.) materials (kg)

Style Factors. Furniture style was already known to be an important variable affecting fire development from the earlier NIST studies, but the data available at that time were not adequate to derive suitable numeric expressions covering the range of commercial furniture styles. The CBUF study, by contrast, was able to include a wide variety of commercially important furniture styles. Table 6.6.16 shows the furniture styles adopted. These styles are obviously not exhaustive of the market possibilities but do include the majority of common types. Style factors are used for two purposes: (1) for predictions of peak HRR values and (2) for predictions of time to peak. Style factor A is pertinent to calculations of peak HRR, whereas style factor B pertains to calculations of time to peak.

TABLE 6.6.16 Furniture Styles Defined in the CBUF Predictive Model

Code	Style Factor A	Style Factor B	Type of Furniture
1	1.0	1.00	Armchair, fully upholstered, average amount of padding
2	1.0	0.80	Sofa, 2-seat
3	0.8	0.80	Sofa, 3-seat
4	0.9	0.90	Armchair, fully upholstered, highly padded
5	1.2	0.80	Armchair, small amount of padding
6	1.0	2.50	Wingback chair
7	—	—	Office swivel chair, plastic arms (unpadded), plastic, rear-back shell
8	—	—	High-back office swivel chair, plastic arms (unpadded), plastic back and bottom shell
9	—	—	Mattress, without innersprings
10	—	—	Mattress, with innersprings
11	—	—	Mattress and box spring (divan base) set
12	0.6	0.75	Sofa-bed (convertible)
13	1.0	0.80	Armchair, fully upholstered, metal frame
14	1.0	0.75	Armless chair, seat and back cushions only
15	1.0	1.00	Two-seater, armless, seat and back cushions only

The accuracy of the prediction of the earlier model (Equations 1 through 5) for peak HRR is shown in Figure 6.6.10.

Prediction of Total Heat Release. The total heat release is a measure of the effective fire load from the furniture item. The following equation was found to represent well the total heat:

$$Q = 0.9m_{\text{soft}} \cdot \Delta h_{c,eff} + 2.1[m_{\text{comb,total}} - m_{\text{soft}}]^{1.5} \qquad (6)$$

The effective heat of combustion comes from cone calorimeter tests of the composite (soft parts). For the full-scale article, $m_{\text{comb,total}}$ denotes the entire combustible mass—that is, all except metal frame parts or other noncombustible pieces—and m_{soft} is the mass of the upholstery system. The results of this prediction are shown in Figure 6.6.11.

Prediction of Time to Untenability. The time to untenability is defined as starting at the time when the full-scale HRR first exceeds 50 kW and ending when the smoke layer (100°C isotherm) is at 1.2 m above floor height. The measurement conditions correspond to the standard fire test room defined in ISO 9705. The untenability time, t_{UT}, is predicted by the following equation:

$$t_{UT} = 1.5 \times 10^5 \,(\text{Style factor } B)(m_{\text{soft}})^{-0.6} (\dot{q}''_{\text{trough}})^{-0.8} (\dot{q}''_{pk\#2})^{-.05} (t_{pk\#1} - 10)^{0.15} \qquad (7)$$

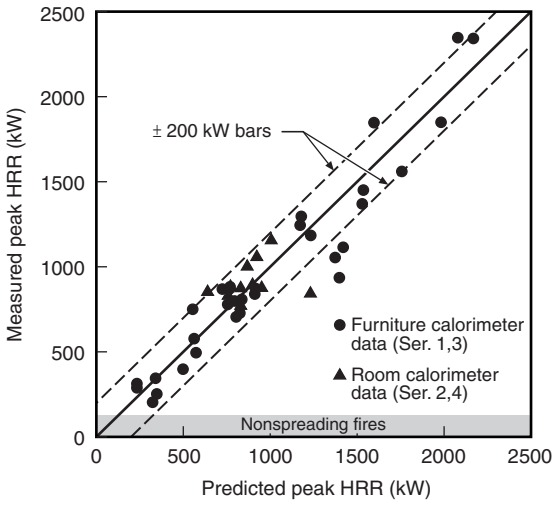

FIGURE 6.6.10 Prediction of Peak HRR of Upholstered Furniture, According to Equations 1 Through 5

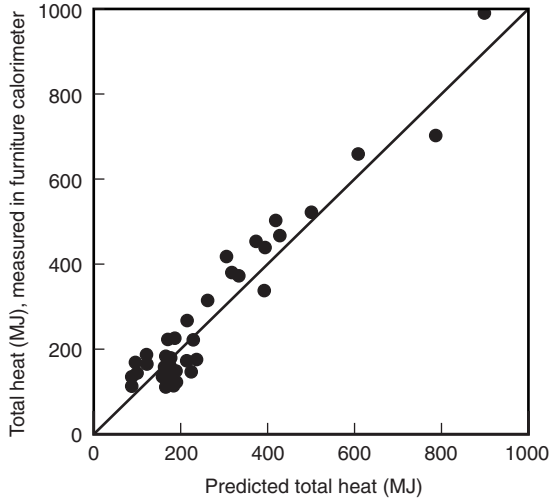

FIGURE 6.6.11 Prediction of Total HRR of Upholstered Furniture, According to Equation 6

The prediction results are indicated in Figure 6.6.12. Here, $\dot{q}''_t$ is the HRR in the cone calorimeter at the trough following the first peak; $\dot{q}''_{pk2}$ is the HRR at the second peak; and $t_{\text{pk\#1}}$ is the time to the first peak. These concepts are illustrated in Figure 6.6.13.

Prediction of Time to Peak. The time to peak is considered an important modeling parameter of a fire. This time is defined to occur when the peak value of HRR is recorded. Generally, all other hazard variables are also at or near their peak values when the HRR peak occurs. Because the ignition period of a fire can be highly varied and refers only to individual circumstances, one can consider the starting point for analysis to be the time that sustained burning first occurs, that is, when a fire level of

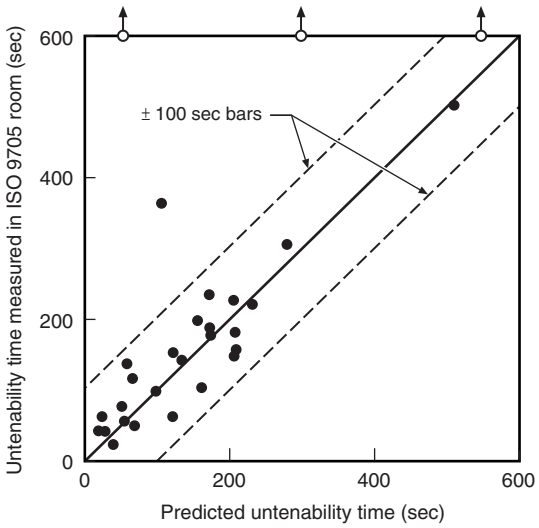

FIGURE 6.6.12 Prediction of Untenability Time, According to Equation 7

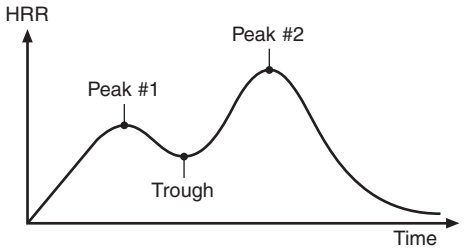

FIGURE 6.6.13 Peak and Trough Values on the Cone Calorimeter HRR Curve

50 kW is first reached. Thus, it is of interest to be able to predict the time interval starting with the time that sustained burning first occurs until the peak is reached. A predictive relationship was developed for estimating this time to peak as

$$t_{pk} = 30 + 4900(\text{Style factor } B)(mass)^{0.3} (\dot{q}''_{pk\#2})^{-0.5}(\dot{q}''_{\text{trough}})^{-0.5}(t_{pk\#1} + 200)^{0.2} \quad (8)$$

Here,

t_{pk} = Time to peak burning, from start of sustained burning (seconds)

Style factor B = Style factor B, as given in Table 6.6.16

$mass$ = Mass of upholstery (soft components only) of full-scale item (kg)

$\dot{q}''_{pk\#2}$ = Second peak of cone calorimeter HRR curve (kWm^{-2})

$\dot{q}''_{\text{trough}}$ = Trough of cone calorimeter HRR curve (kWm^{-2})

$t_{pk\#1}$ = Time to first peak of cone calorimeter HRR curve, from start of test (seconds)

The predictive results are shown in Figure 6.6.14.

Prediction of Smoke Production. The following correlation was established for predicting the smoke:

If

$$p_2 < 1800 \quad (9)$$

then,

$$SmP = p_2 \quad (10)$$

else,

$$SmP = p_1 \quad (11)$$

where

$$p_1 = 0.7 \cdot \frac{Q_{tot} \cdot \sigma_f}{\Delta h_{c,eff}} \quad (12)$$

$$p_2 = s_o - 0.15 s_o^{1.13} \quad (13)$$

with

$$s_o = \frac{Q_{tot} \cdot \sigma_f \cdot (1.25 - 0.00188 \dot{q}''_{35-60})}{\Delta h_{c,eff}} \quad (14)$$

and

$\dot{q}''_{35-60}$ = 60-second average HRR value from the cone calorimeter (kWm^{-2})

where

SmP = Full-scale smoke production (m^2)

Q_{tot} = Full-scale total heat release (MJ)

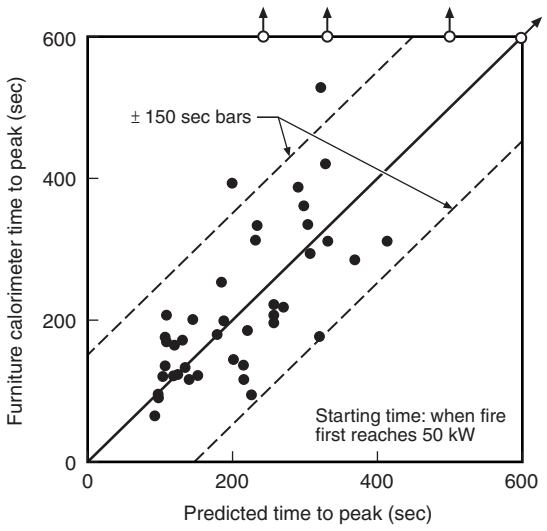

FIGURE 6.6.14 Prediction of Time to Peak Full-Scale HRR, According to Equation 8

σ_f = Cone calorimeter average specific extinction area (m^2kg^{-1})

$\Delta h_{c,eff}$ = Cone calorimeter average effective heat of combustion (MJ kg^{-1})

The results are plotted in Figure 6.6.15. The agreement for fires showing moderate smoke development (less than about 1500 m^2) is remarkably good. Even for fires with extremely large smoke production, the actual measurements are either close to predicted values or lower; thus, the model is a conservative estimate under all circumstances.

Toxic Gases. Human incapacitation and fatalities in fires are much more often due to toxic gas effects than to direct burn injuries. This circumstance would seem to suggest that test methods should, first and foremost, measure toxic gases. However, this oversimplified view does not reflect actual fire behavior realities. To understand this, it is best to consider the options to reduce the hazard of upholstered furniture from toxic fire gases. One could (1) reduce the "per-gram" toxicity of the combustion products or (2) reduce the *rate* at which combustion products are emitted. The effects of fire toxicity could be equally well mitigated by the first strategy or the second. In practice, it has been found that the first strategy is not feasible.[69] That is, materials are simply not to be found in the marketplace that show much reduced per-gram toxicities. In fact, most common materials available for constructing furniture exhibit very similar values. What is more viable, however, may be to design the furniture in such a way that the HRR is reduced. This strategy is taken by T.B. 133 for institutional furniture. More detailed bases of these conclusions are also discussed in the CBUF study.[14]

IMPROVEMENTS IN FIRE PERFORMANCE OF FURNITURE

In occupancies such as health care, incarceration, and public transportation, it is accepted that highest-level fire safety should be provided, even though such products then cost significantly more than consumer goods. For such uses, the fire behavior of upholstered furniture can be optimized by careful material selection, design considerations, and other factors. To accomplish this, materials should be selected that are resistant to cigarette ignition, resistant to small-flame ignition, and produce only limited fire involvement when confronted with a large-source ignition. Some qualitative guidance on cigarette and small-flame ignition resistance is summarized in Table 6.6.17. For fire performance once an item *is* ignited, some of the more important available strategies are summarized below. More comprehensive advice is available.[14]

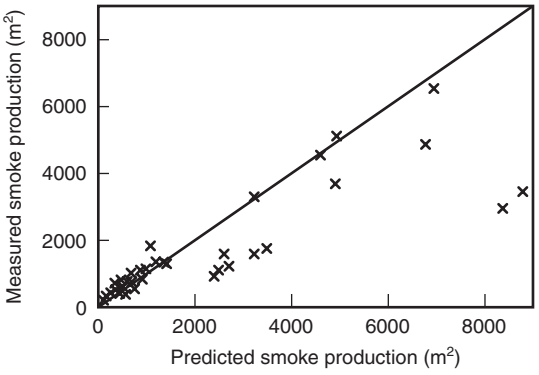

FIGURE 6.6.15 Prediction of Smoke Production, According to Equations 9 Through 14

Improving the Fabric

Fire behavior can be improved by selecting well-performing fabric categories. These include use of wool, modacrylic, FR-treated fabrics, and fabrics that do not show a strong melting tendency. For such fabrics, increased fabric weight usually corresponds to improved fire behavior. Thermoplastic fabrics are often troublesome; especially, the use of polyolefin (polypropylene) fabrics is to be avoided. Other thermoplastics usually perform better in flaming fires when they are of lighter rather than heavier weights. Loosely woven or lofted fabrics are usually less desirable than flat, tight weaves.[70] In many cases, fabric backcoatings can be successfully used. Backcoatings may not be as effective as an interliner or as a substantially improved foam; nonetheless, they can significantly improve the fire performance of many fabrics without creating adverse usability or aesthetic effects. Backcoatings have been especially favored by U.K. manufacturers.

Fabrics comprising 100 percent cellulosic fibers (cotton, rayon, linen) usually show difficulties in passing cigarette ignition tests. Cellulosic/thermoplastic blends, where the cellulosic component is less than 80 percent of the fabric weight, prove to be significantly more smolder resistant than pure cellulosics.[71] For a 100 percent cellulosic fabric to meet cigarette ignition requirements, it is very difficult if the fabric weight is greater than 13 oz/yd^2 (440 g/m^2), but is significantly less difficult[71] for fabrics lighter than 13 oz/yd^2 (440 g/m^2). Thermoplastic fabrics of any weight rarely show any problems in meeting cigarette resistance requirements. One development that has a potential to reduce ignition likelihood when presented with flaming sources or with cigarettes is a patented yarn-spinning process that is being introduced by a number of fabric manufacturers. Patent 6,287,690 describes a yarn with a two-ply core that comprises fiberglass and nylon. This core is sheathed with an inner sheath of modacrylic and melamine fibers, then with an outer sheath that comprises decorative fibers of choice. No chemical fire-retardant agents are added, yet fabrics made of this yarn may prove an attractive replacement for double-upholstering (outer fabric, plus interliner) systems.

Improving the Foam

Polyurethane (PU) foam is very widely used in upholstered furniture as well as in mattresses. In fact, consumers can find it difficult to find upholstered furniture without PU foam. Because of the combustible nature of PU foam, the simplest strategy to increase fire safety is to decrease the amount of foam used. As shown above, the peak HRR of a fire is highly dependent on

TABLE 6.6.17 Upholstered Furniture Components Listed in Approximate Order of Descending Ignition Resistance

Ignition Resistance	*Cover Fabric*	*Padding*	*Interliner Fabric*	*Weltcords*	*Construction Parameters*
A. Cigarette Ignition Resistance					
HIGH	Wool, PVC	Specialty foams[a]	Aluminized fabrics	Aluminized	Flat areas
↑	Heavy thermoplastics	Polyester batting	Neoprene sheets	PVC	Flat areas near weltcord
	Cellulose/thermoplastics blends (depending on thermoplastic percentages)	SR PU	Vinyl coated glass fab.	Thermoplastics	
		SR cellulosic batting	Novoloid felts	SR-treated cellulosics	Tufts
		Untreated PU	Thermoplastic fabrics	Cellulosics	Crevices
	Light thermoplastics	Mixed fiber batting	Cellulosic fabrics		
LOW	Light cellulosics	Cellulosic batting			
	Heavy cellulosics				
B. Small-Flame Ignition Resistance and Fire Growth					
HIGH	FR wool	Specialty foams[b]	Aluminized, gas impermeable fabrics	Effect of weltcord has not been investigated, believed minor	Flat areas
↑	Wool, PVC-coated cellulosics[b]	FR cellulosic batting	Neoprene sheets[b]		Vertical areas
	Cellulosics[b]	FR PU	Novoloid fabrics[c]		Corner areas
	Thermoplastics	Cellulosic batting	Aramid fabrics[b,c]		
		Polyester batting	Vinyl-coated glass fabrics[b]		
		Untreated PU	FR cellulosic fabrics[b,c]		
		Latex foam	Cellulosic fabrics[a,c]		
LOW			Thermoplastic fabrics		

Note: SR = smolder resistant; FR = flame resistant; PU = polyurethane foam. Data on the behavior of acrylic are sparse but it seems to act more like cellulosics (smolder) than thermoplastics.
[a]Neoprene; combustion modified, high-resiliency PU.
[b]Heavier materials have higher flame ignition resistance and generally higher heat release and lower flame-spread rate.
[c]Fabrics here include woven, knitted, and nonwoven structures.

the mass of the upholstery. Another strategy involves substituting ordinary grades (HR) of PU foam with an improved foam, possibly CMHR or one of the newer improved types. One solution in this area has been commercialized, whereby polyols with substantially improved fire performance[72]; it provides a way of increasing furniture fire performance without requiring fundamental changes in furniture-making techniques. Composite foam strategies can be explored. An inexpensive base foam is in some way covered or coated with a foam that has FR properties. Early efforts in this vein have not yet shown significant improvement, but the general strategy is still considered promising. In rail-car seating, neoprene foam is often used. Although neoprene foam shows excellent fire performance, it is usually too costly and too dense for other applications.

Using Interliners

Fire barrier types of interliners are among the most promising of the strategies to increase the fire performance of upholstered furniture. Considered here are only modern interliners that are lightweight, typically 70 to 170 g/m^2, and commercially available. They can be woven, knitted, or nonwoven. Nonwoven interliners, however, often have the drawback that local density cannot be well controlled. Thus, the performance may not be consistent, due to existence of thin spots. Several dozen different materials have been invented and proposed for interliner use. Commercially, the most common ones are glass fiber, aramid (e.g., Kevlar®), and a proprietary glass fiber/FR cotton construction. Apart from cost, the primary drawback to interliners is that they make the upholstery stiffer. This result would be inconsequential in, for example, subway car seating, but could be problematic in sofas where comfort is important.

The interliner offers protection, because as the PU foam underneath begins to melt, its upper surface moves steadily downward and away from the interliner, which stays in place and acts as a thermal radiation shield. It also acts as a flame barrier, preventing the flame from reaching the foam. In a noninterliner system, the retreating surface of the foam is often "chased" by the burning fabric. By using an interliner, however, the burning fabric stays where it is while the foam melts away from it. This stability decreases the heat transfer to the foam and thus slows the melting and reduces the HRR. An interliner can also release flame-retardant chemicals into the gas phase and thus reduce flaming. Most of the common interliners, including the aramid and glass-fiber types, are purely nonreactive systems. At least one proprietary interliner, however, is heavily loaded with flame retardants. "Best-quality" interliner-containing chairs show only limited burning of the fabric. The foam is fully protected. However, in some cases, the interliner provides protection to the foam only for a certain amount of time; eventually the foam burns up.

One way to use interliner technology is when the fabric supplier already laminates (attaches by fully gluing on) the interliner to the back of the upholstery fabric prior to delivering it

to the furniture manufacturer. The average chair requires the use of about 4 m^2 of interliner.

Testing[73,74] of several types of barriers for mattresses showed that impressive gains in fire safety can be achieved. In one case, a commercial mattress that showed a peak HRR of 1900 kW was retrofitted with an add-on barrier-type mattress cover, such as could be bought and fitted by the householder. The protected mattress gave an HRR of only 100 kW. Mattresses that were factory made with a barrier showed HRR values of 20 kW to 40 kW.

The general term *interliner* sometimes is taken to encompass a polyester fiber batting *topper,* which is an intermediate layer placed below the fabric and on top of the foam. Such polyester toppers are mainly a comfort feature but sometimes function to improve the cigarette resistance of furniture. They can have undesirable effects on flaming-fire behavior, however, because the low-density polyester material is readily combustible.

Improvements Due to Design

A powerful strategy is the use of panel mounting rather than webbing to support chair cushioning. Any strategies that reduce the tendency to pool burning can cause a major reduction of fire hazard. Studies in England[75] demonstrated that, in some cases, about 50 percent of the peak HRR from an upholstered chair can be accounted for by pool burning.

The effects of button tufting are not fully resolved,[14,76] but some evidence suggests that they may be problematic in certain cases.

Fire performance will be improved if cushions are tightly upholstered and not sewn in a loose or floppy fashion.[76]

A fabric skirt along the lower edge of an upholstered chair is an easily combustible feature that can add to fire severity;[76] such skirts should be avoided where possible.

Wide gaps (greater than 75 mm) between seat and back cushions and between arm cushions and seat cushions will improve the fire performance.[76]

Improvements Due to Frames

It is important to make sure that wood frame joints are strong and that metal joining plates that could fail early in a fire are not used. Thermoplastic material frames and frameless chair designs have generally unfavorable fire properties. For office chairs, it is vital to make sure that the hard-plastic materials used do not melt or ignite readily and that they have adequate HRR properties.

SUMMARY

The fire behavior of upholstered furniture is very different when presented with a smoldering ignition source (a cigarette) versus an open flame. Thus, testing or regulations cannot combine these two performance aspects. In the United States, the majority of both mattresses and upholstered furniture has been manufactured to be resistant to cigarette ignitions for several decades now. Until recently, however, CPSC has not regulated the open-flame performance of either product category. Beginning in 2007, however, mattresses will be subject to a new CPSC regulation whereby open-flame performance will be controlled. It is expected that flaming ignition of such new-generation mattresses will produce significantly less severe fires. CPSC has also been actively considering some open-flame standards (albeit much less severe) for upholstered furniture, but such regulation does not appear to be imminent.

Manufacturers of mattresses and upholstered furniture for institutional (health care, incarceration, public transport, etc.) occupancies have always been held to a much higher standard of care than is applicable to the retail consumer market. For a number of decades now, such institutional items have been expected to be produced so that they not only resist ignition from small flames but also, even if presented with a large-flame ignition source, will show appropriately low HRR values. Most manufacturers and suppliers are aware of this standard of care. But, because the regulation in these occupancies is complex, nonuniform, and sometimes self-regulated, some producers and suppliers have been supplying goods for such occupancies that do not show a fire safety level suitable for that occupancy. For mattresses, however, because the new CPSC regulations governing residential products are almost as strict as expected for institutional items, it is anticipated that inappropriate mattresses will soon no longer be offered in the institutional sector.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on upholstered furniture and mattresses discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 260, *Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture*

NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*

NFPA 272, *Standard Method of Test for Heat and Visible Smoke Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter*

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Chapter 7

Fire-Retardant and Flame-Resistant Treatment of Cellulosic Materials

James R. Shaw

Chapter Contents

Definitions of Terms
Basic Principles
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Practical Limitations of Treatments
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Misuse of Fire Retardants

Key Terms

cellulosic material, fire endurance, fire resistant, fire retardant, fire-retardant coating, flame spread rating, pressure impregnation, rate of heat release

This chapter discusses the basic principles of fire-retardant and flame-resistant treatments, their uses and limitations, and methods of treatment for wood, wood-based composite panels, paper, and miscellaneous decorative materials. Whereas the demand for fire-retardant and flame-resistant chemicals is highest in the plastics industry, there are important markets for these chemicals in treating nonplastic materials, especially for building construction materials.

Related information can be found in the following chapters: Section 6, Chapter 4, "Wood and Wood-Based Products"; Section 6, Chapter 5, "Fibers and Textiles"; Section 6, Chapter 13, "Polymeric Materials"; Section 13, Chapter 5, "Wildland Fire Management"; and Section 18, Chapter 2, "Interior Finish."

DEFINITIONS OF TERMS

Cellulosic materials are an integral part of the living environment. Homes, schools, factories, offices, shops, and so on use large quantities of cellulosic products in construction, furnishings, and decorations. Fire-retardant and flame-resistant treatments for these cellulosic materials can increase fire protection.

Popular use has created a variety of terms associated with this subject, resulting in misunderstanding, misuse, and an undesirable degree of ambiguity. Terms such as *fire resistant, fire retardant, flame resistant, flame retardant, fireproof,* and *flameproof* are often used indiscriminately and incorrectly.

The term *fire resistant* should not be used in reference to the fire-retardant treatment of combustibles. Fire resistant is used properly only to signify the ability of a structure, material, or construction assembly to resist the effects of a large-scale severe fire exposure. ASTM defines fire resistance as "the property of a material or assembly to withstand fire or give protection from it."[1] Fire-resistance rating or fire endurance is the time, in minutes or hours, that materials or assemblies have withstood a fire exposure, as established in accordance with the test procedures of NFPA 251 (ASTM E119), *Standard Methods of Tests of Fire Resistance of Building Construction and Materials.* Likewise, *fireproof* is misleading and should not be used synonymously with *fire resistant.*

Fire retardant signifies a lesser degree of protection than fire resistant. It should be used in reference to chemicals, treatments, or coatings used to reduce the combustibility of building materials and other such treated materials. ASTM International (ASTM) suggests *fire retardant* be used as a modifier only with defined compound terms, such as fire-retardant barrier, fire-retardant chemical, fire-retardant coatings, and fire-retardant treatments.[1] *Flame spread rating* refers to indices or classifications obtained according to NFPA 255 (ASTM E84), *Standard Method of Test of Surface Burning Characteristics of Building Materials,* or other flame spread tests. *Flame retardant* and *flame resistant* may be used more or less interchangeably for decorative materials that, due to

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chemical treatment or inherent properties, do not ignite readily nor propagate flaming under small-to-moderate fire exposure. *Flame retardant* is the preferred term to denote chemicals, processes, or coatings used for the treatment of decorative materials, including fabrics, foliage, Christmas trees, and similar materials used as decorations or furnishings. *Flameproof* and similar descriptors are misleading and subject to misunderstanding and abuse; they should not be used.

Fire retardants and flame-retardant treatments frequently have been misused. They have a widespread appeal due in part to a general lack of understanding about the limitations of the treatments and a failure to differentiate between those that are effective and those that are not. One popular misconception is that all fire-retardant treatments give a fire-resistance rating. This is not true. Although some fire-resistant coatings may improve the fire endurance of combustible materials and assemblies, other treatments are only effective in retarding the rate of burning and the rate at which fuel is contributed by the treated material. This action, however, can reduce the fire intensity of some materials that otherwise might be very fast burning. This burning rate property is measured and reported as the *rate of heat release.*

In other words, there are practical limits to fire-retardant treatments. They are not all permanent, they are not capable of making cellulosic materials noncombustible, they affect other properties of the treated material, and they add expense. They do, however, provide protection and utility on a competing basis with non-fire-retardant treatments and coatings. For example, fire-retardant paints have been improved to the point where many provide a colorful, protective coating with comparable wear resistance and strength of normal oil- and water-based paints.

BASIC PRINCIPLES

Treatments to reduce the combustibility of wood, fabrics, and other natural materials have a long history reaching back to at least the time of Moses. The early use and development of chemical retardants was limited to materials that were accidentally found to be effective. Research in basic combustion processes and action of retardants was greatly expanded during World War II due to increased military needs for flame-resistant fabrics and fire-retardant wood. This expansion continued for several years, leading to new-generation fire-retardant formulations for wood. Because cotton textiles and wood products have by far the longest history of use and are of great economic importance, much of the research has historically been directed toward these cellulosic materials. In the past few years, the research activity in the United States has stabilized.

Burning of Cellulose

Since cellulose is the major component of wood and other cellulosic materials and the major source of combustible volatiles that fuel flaming combustion, it is appropriate to focus on its reactions in the thermal degradation process.

The chemical reactions and the mechanisms involved in the combustion of untreated cellulose are, by themselves, highly complex and not yet fully understood.[2] The complexity is magnified by the addition of fire-retardant chemicals.

Wood or cellulose normally does not burn directly. The initial reaction to high heat exposure is pyrolysis, in which some of the products given off are gases, vapors, or mists that can form flammable mixtures with air. On ignition, the combustion of these products is evidenced by visible flames. The solid residues include charcoal, which can undergo a different form of combustion by combining directly with oxygen, as evidenced by glowing. This is an important distinction, because many chemicals that are effective flame inhibitors have little or no effect in retarding flameless combustion, or afterglow. For most applications, flame retardance is more important, but there are some instances where glow resistance is equally necessary.

Theories of Fire-Retardant Mechanisms

Four general theories have evolved to explain the mechanisms by which chemicals retard flaming or glowing of cellulosic materials. It is agreed that no single theory is adequate to explain these mechanisms and that, in most cases, more than one mechanism is involved. The four theories that offer the most satisfactory explanations for the function of fire-retardant chemicals are as follows.

Thermal. There are three possible ways that fire-retardant materials work to reduce the buildup of thermal energy in the treated combustible: (1) they increase thermal conductivity to dissipate the heat of combustion, (2) they increase thermal absorption to reduce the amount of heat available for pyrolysis, and/or (3) they provide thermal insulation to reduce heat access to the substrate. Thermal insulation is the most important mechanism and is also discussed under coating theories.

Coating. Some retardants melt or fuse at relatively low temperatures and it is believed that they form an insulating coating over the fibers of the treated material, acting to exclude oxygen and inhibit the escape of combustible gases. More effective retardants exhibit a bubbling or foaming action, creating an insulating barrier. Intumescent paints and coatings protect substrates by this mechanism.

Gas. Some chemicals function by releasing nonflammable gases, such as water, ammonia, and carbon dioxide, that dilute the combustible gases sufficiently to render the mixture nonflammable in air. Other retardants catalytically inhibit the free radical chain reactions that occur in the gas phase (flaming combustion). Halogen-containing retardants exhibit this type of mechanism and, when combined with antimony, a synergistic (more than additive) effect is observed.

Chemical. Simplified representations of the chemical mechanism are shown in Figures 6.7.1 and 6.7.2. In both figures, the size of the circle is representative of the volume of product. Note the predominance of liquid and flammable gas products in Figure 6.7.1 and the predominance of solids and the severe reduction in liquids and flammable gases emanating from the liquids in Figure 6.7.2. These diagrams illustrate the different effects of fire on untreated and treated cellulose and are diagramatically explained in "Flameproofing Textile Fabrics."[3] Untreated cel-

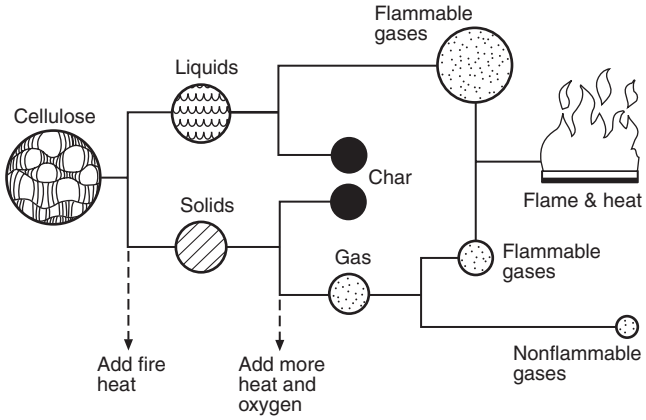

FIGURE 6.7.1 Burning Sequence of Untreated Cellulose

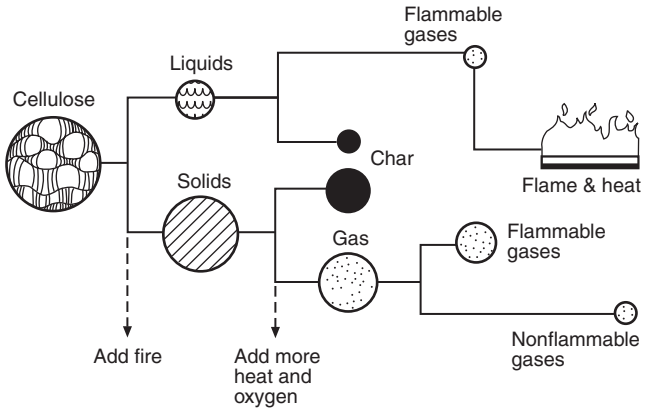

FIGURE 6.7.2 Burning Sequence of Treated Cellulose

lulose breaks down into liquids and a smaller amount of solids. The liquids, in turn, break down into flammable gases and char and the solids decompose into char and gases, some of which are flammable, some not. The flammable gases volatilized from the liquids combine with those from the solids to cause flaming and the emission of additional heat, which continues the reaction.

With treated cellulose, fewer liquids and more solids are formed and more of the solids become char. The reduced amount of liquids creates some char and some flammable gases. Because the amount of flammable gases from both the liquid and solid phases is now significantly less with treated cellulose, ignition is delayed and less heat is released. Therefore, flame resistance and a reduced burning rate is achieved. Another postulate, an expansion of the chemical theory known as the catalytic dehydration theory, has been advanced.[4]

Studies at the U.S. Forest Products Laboratory[5] have shown that pyrolysis reactions (without the presence of oxygen) for the lignin component of wood start at approximately 428°F (220°C), whereas that for the cellulose fraction starts near 518°F (270°C). However, once pyrolysis for the cellulose fraction has started, its decomposition is primarily an endothermic reaction and is nearly completed when 752°F (400°C) is reached. The lignin decomposes more slowly, in an almost entirely exothermic reaction, and loses less than half its weight in pyrolysis up to 1112°F (600°C).

Fire-retardant chemicals greatly influence the pyrolysis reaction of the cellulose fraction, frequently reducing the temperature at which decomposition starts from 518 to 446°F (270 to 230°C). As a result, the decomposition of the cellulose is promoted directly to form char and water, instead of forming intermediate flammable gases and tar products, and the char yield from the cellulose at 680°F (360°C) is increased from 15 percent up to 30 to 35 percent. The chemical treatment also increases the char yield from the lignin component from 49 percent up to 57 percent, but here the significance is less.

It was further shown that the combustion reactions for wood can be divided primarily into two exothermic stages: (1) one near 626°F (330°C) associated with flaming as the cellulose fraction of the wood undergoes decomposition into flammable gases and tars and becomes ignited and (2) a second reaction near 806°F (430°C) associated with glowing as the lignin fraction of the wood, which has been changed to charcoal, undergoes oxidation. Fire-retardant chemicals greatly reduce the intensity of the first exotherm and some chemicals also reduce the intensity of the second exotherm, thus reducing the heat released by the treated wood over a wide temperature range. Other chemicals reduce the first exotherm and intensify the second, thus requiring a second chemical to result in maximum fire-retardant performance. Heat release during the pyrolysis reactions for wood was found to be less than 5 percent of that released during the combustion reactions.

All of this data tended to prove that one of the principal reactions of fire-retardant chemicals impregnated into wood is to accelerate chemical reactions at certain temperature ranges. This reduces the release of certain intermediate products, such as levoglucosan tars and flammable gases, which may contribute to the flaming of wood, and also results in the formation of greater percentages of charcoal and water. Some chemicals are then further effective in reducing the oxidation rate for the charcoal residue. An excellent discussion of these basic principles is contained in the Forest Products Laboratory report, "Theories of the Combustion of Wood and Its Control."[6]

FIRE-RETARDANT TREATING METHODS AND LIMITATIONS

There are four basic methods of treatment to produce fire retardance in materials: (1) chemical changes (substitutions, admixtures), (2) impregnation (saturation, absorption), (3) pressure impregnation, and (4) coating. Chemical changes and pressure impregnation are limited to manufacturing processes and procedures and are not adaptable for field use. Impregnation and coating methods may be used in the field. Generally, methods employed in manufacturing processes are to be preferred, because they provide greater uniformity, permanence, and dependability. Applications in the field or subsequent to manufacture of the basic material are more subject to variation in skill and integrity of the processor or applicator. Treatments of the coating-

and pressure-impregnation type are covered in NFPA 703, *Standard for Fire Retardant–Treated Wood and Fire-Retardant Coatings for Building Materials.*

Chemical Changes

Fire-retardant chemical changes are primarily effective with plastics and with synthetic fibers, because different elements and compounds can be chosen that will alter the burning characteristics of the final product. Because the fire-retardant elements are an integral part of the chemical composition, these materials are said to be "inherently" fire retardant. Naturally occurring polymers, such as cellulose, cannot be made fire retardant by this method. However, another type of chemical fire-retardant treatment, known as chemical grafting, can be applied to natural polymers. In chemical grafting, the material is treated by a multistage process in which the material is chemically activated so that molecules of fire-retardant chemical are bonded to molecules of the material being treated. A follow-up curing step ensures permanence. This approach has not developed into a commercially viable method of producing fire-retardant-treated cellulosic products. Research efforts on chemical modification of wood continue, but the primary focus is on wood preservation and enhanced dimensional stability of wood.[7]

Impregnation

Impregnation refers to a technique for treating absorbent materials. The flame-retardant chemicals are either dissolved or dispersed in a solvent, usually water, and the material to be treated is thoroughly wetted or saturated with the solution. The solution may be applied by spraying or by immersion of the material. The latter process is used for treatment of large volumes of fabric yardage. The excess solution is extracted by passing the saturated material through squeeze rollers before drying.

In the simple water-soluble salt impregnation processes, the result is merely to deposit minute crystals of the salts within or on the surface of the fibers. The process is purely physical, that is, no chemical reaction is involved. With durable treatments, insoluble deposits are formed by chemical reactions or other means.

Certain cellulose-based products, such as paper, acoustical tile, and wood-based compositions, incorporate a wet pulp stage during the manufacturing process. It is possible to add fire-retardant chemicals at the wet pulp stage, resulting in even distribution of the chemicals through the entire mass of the finished product. This practice is prevalent in manufacturing treated papers of many types and is currently in use by several producers of building materials. Wood-fiber acoustical tile and building panels processed by this method have a NFPA 255 (ASTM E84) flame spread rating of less than 25.

Pressure Impregnation

Fire-retardant pressure impregnation is used for treating relatively dense nonabsorbent materials such as wood. This process replaces the air in the wood cells with fire-retardant chemical solutions. (The chemicals are deposited as the solutions dry.) The treating solution is usually forced into the wood by the standard vacuum pressure methods used in the wood preserving industry.[8] Compared to simple impregnation techniques, pressure impregnation provides deeper penetration and much greater chemical retention.

Coating

Several types of fire-retardant coatings are useful in treating many materials. Coatings may be applied at any stage from manufacture to use. They may either actively inhibit flame spread to some degree or present a noncombustible surface over which flame cannot spread. They are used predominantly on nonabsorbent building materials that cannot be treated by any other method; on Christmas trees and similar decorative materials; and, to a limited extent, on paper and fabrics that for various reasons cannot be treated effectively by impregnation.

The effectiveness of a coating depends on the chemical and physical properties of the material to which the coating is applied, the capability of the applier, and the thoroughness of the treatment. Because types of coatings and their effects vary depending on the material treated, they are discussed in the subsections of this chapter that cover materials.

PRACTICAL LIMITATIONS OF TREATMENTS

Ideally, a fire-retardant treatment would permanently eliminate all flame spread and smoke generation characteristics from a material; the color, feel, strength, weight, and other key characteristics of the basic material would not suffer from the treatment; and the method would be inexpensive, easy, and safe. No present-day treatments meet all these qualifications. As the different materials are discussed, the limitations of fire-retardant treatments will be identified.

WOOD

Wood can be made fire retardant by either pressure impregnation or coatings. Although both of these treatments will reduce the flame spread of wood, only some fire-retardant coatings are significantly effective in increasing the resistance of wood to degradation under sustained fire exposure or in delaying reduction of its load-bearing capacity.

Although the fire-retardant treatment that would make wood noncombustible does not exist, the spread of flame from the immediate area of an incipient fire can be retarded and, in some cases, prevented by present-day treatments, with a corresponding substantial reduction in smoke contribution. Also, the fire-resistance rating of wood structural members in buildings may be improved through the use of fire-resistant coatings.[9–11]

Fire-Retardant Pressure Impregnation

Pressure impregnation treatments deposit chemicals within the fibrous passages of wood. Many chemicals exhibit fire-retardant properties, but because of cost limitations or various other objectionable characteristics, comparatively few are considered practical. Chemicals commonly used in the past include monobasic and dibasic ammonium phosphates, ammonium sulfate, borax, boric acid, zinc chloride, and sodium dichromate, usually

in various combinations. Newer formulations tend to exclude hygroscopic salts, such as ammonium sulfate and zinc chloride, and, in some cases, include organophosphorus compounds and amino resins. Figure 6.7.3 shows the effect of some inorganic salts on the flame spread of Douglas fir. The most significant improvements in the new formulations are the high tolerance for high relative humidity conditions (up to 95 percent RH) and exterior application due to their nonleachability. The impregnation operation can be controlled to secure a predetermined absorption of solution. The important considerations are the depth of penetration and the amount of chemical deposited per unit volume of the wood.

Because the fire-retarding effect of the treatment is directly related to the amount of the chemical deposited within the wood, it is interesting to compare the effect of an ordinary brush treatment with a pressure-impregnation treatment. A 10-ft (3-m) high fence 50 ft (15.25 m) long of nominal 1-in. (25-mm) pine boards would absorb about 4 gal (15 L) of treating solution if applied by brush. The effect on flame spread would be minor (flame spread index [FSI] remains between 130 and 195, Class III). When the same boards are pressure impregnated to refusal (i.e., the point at which no more solution is absorbed by the wood), they absorb about 225 gal (852 L) of chemical and the flame spread is cut to one-fourth or less of the original (FSI less than 25, Class I).

A load or "charge" of wood is locked in a large cylinder that can be up to 8 ft (2.5 m) in diameter and over 140 ft (43 m) long. The air is then withdrawn and the resulting vacuum draws much of the entrapped air from the wood cells. After a delay to allow the vacuum to stabilize, the fire-retardant chemical solution is bled into the cylinder. After the cylinder has been filled with the treating solution, additional chemicals are forced into it under pressure. As the pressure is raised (up to 200 psi [1379 kPa]), the chemicals are forced into the empty wood voids. The process can be run to refusal and the unabsorbed salt solution drained from the cylinder. A slight vacuum may then be drawn to remove surface chemicals that would cause dripping and slow drying. After the charge is removed and dried, it is ready for shipment and use. Additional details are available from the American Wood Preservers Association (Figure 6.7.4).

This treating process has become an integral part of the definition of fire-retardant treated wood (FRTW) which is, per NFPA 255 (ASTM E84),

> any wood product impregnated with chemicals by a pressure process or other means during manufacture, and which, when tested in accordance with ASTM E84 for a period of 30 minutes, shall have a flame spread of not over 25 and show no evidence of progressive combustion. In addition, the flame front shall not progress more than 10½ ft (3.2 m) beyond the centerline of the burner at any time during the test.

Advantages. Pressure impregnation permits a large amount of fire-retardant chemical to be deposited in the wood under close control and with uniform and predictable results. Samples for tests are readily available. Of primary importance, the treatment can be considered permanently effective under normal and proper conditions of use. Since both water-soluble and nonleachable fire retardants are available, it is important that nonleachable treatments be chosen for exterior use. Treatments with low hygroscopicity should be used for interior applications where high humidity conditions exist.

Disadvantages. Early formulations of fire-retardant treatments for wood were very hygroscopic and corrosive to metal fasteners. In the late 1980s, the fire-retardant chemical producers changed to "new generation," low-hygroscopicity formulations that dramatically improved the resistance to corrosion of metal fasteners. However, there were reports of structural failures with some of these chemical formulations in fire-retardant treated plywood roofs where high temperature and humidity

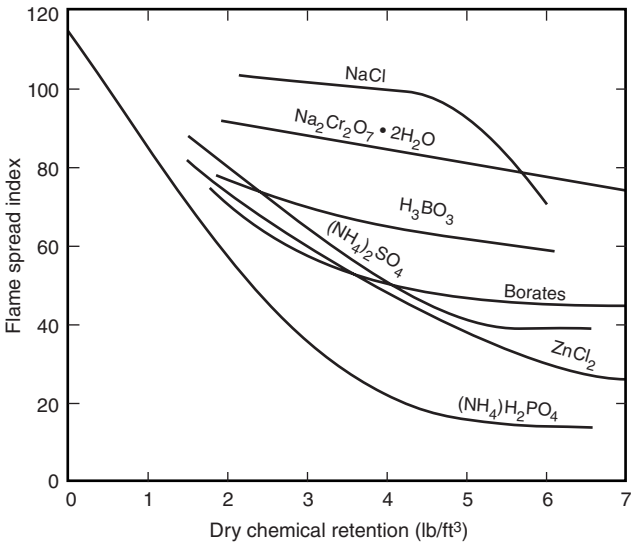

FIGURE 6.7.3 Effect of Inorganic Additives on Flame Spread Index of Douglas Fir, Measured in 8-ft (2.4-m) Tunnel[12]

FIGURE 6.7.4 Impregnated Plywood Sheets Being Removed from Pressure Cylinder

conditions exist.[13] Research efforts at the Forest Products Laboratory have shown that acidic fire-retardant chemicals, such as monoammonium phosphate, can cause premature degradation and simultaneous loss of strength at elevated temperatures [greater than 150°F (66°C)] and humidities. These conditions may be found in attics and can affect fire-retardant treated plywood sheathing and other treated structural components. It is important to note that not all fire-retardant formulations being used for wood during the eighties showed the same degree of loss of strength under the chosen laboratory conditions or field experience.

Formulations that experienced this problem in actual use were modified and retested according to developing ASTM standards, which ultimately became ASTM 5516, *Standard Test Method for Evaluating the Properties of Fire-Retardant Treated Softwood Plywood Exposed to Elevated Temperatures,* and ASTM 5564, *Standard Test Method for Evaluating the Mechanical Properties of Fire-Retardant Treated Softwood Plywood Exposed to Elevated Temperatures.* These reformulation efforts have been very successful in reducing the strength losses under these adverse conditions. At least one new formulation shows excellent flame spread performance without the use of phosphates.

Consumers should review the available literature on this subject and products, including the information available from the American Plywood Association (APA), the Engineered Wood Association, and the fire-retardant chemical producers before purchasing fire-retardant treated wood and plywood. Many technical reports on this problem published by the Forest Products Laboratory provide performance characteristics for most or all of the chemicals being used to treat wood.[14] Pressure impregnation must be done by a licensed treater after the wood has been dimensioned.

Fire Performance Characteristics. The pressure impregnation process can substantially improve the fire performance characteristics of wood, as measured by the tunnel test, the room fire test, and heat release rate tests. The effect can be illustrated by data shown in Tables 6.7.1 through 6.7.4.

Testing. The effectiveness of fire-retardant pressure impregnation treatments is tested by several methods. The Steiner tunnel test, described in Section 6, Chapter 3, "Concepts and Protocols of Fire Testing" (also see NFPA 255 [ASTM E84]), is used to determine the flame spread and smoke characteristics of pressure treated wood and many other products used in construction.[15] The *Design for Code Acceptance 1* published by the American Forests and Paper Association provides an extensive list of wood products with their flame spread index values. The *Underwriters Laboratories Building Products Directory* has listings for fire-retardant-treated wood products.

A standard room fire test of wall and ceiling materials was developed at the National Institute of Standards and Technology Center for Fire Research and is used to evaluate treated panel products. This room test method has been standardized by the International Organization for Standardization (ISO) as ISO 9705, *Fire Tests—Full-Scale Room Test for Surface Products.* (See Figure 6.3.10 in Section 6, Chapter 3.) The test uses the oxygen consumption method for calculating the rate of heat release. Data collected by this method are also used in the validation of fire mathematical models. Rate of heat release tests, such as the cone calorimeter (ASTM E1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*) and the intermediate scale calorimeter (ICAL) (ASTM E1623, *Standard Test Method for Determination of Fire and Thermal Parameters of Materials, Products, and Systems Using an Intermediate Scale Calorimeter [ICAL])* are being used successfully in distinguishing burning rate characteristics of fire-retardant-treated and untreated wood products. The ICAL test, due to the specimen size, can be used to measure the heat release from assemblies and materials. Efforts to establish correlations among the cone calorimeter results, room fire results, and tunnel results have been somewhat successful. (See Section 6, Chapter 3 for a discussion of fire test methods.)

Model codes allow the use of fire-retardant-treated wood in noncombustible construction, with some limitations. As shown in Table 6.7.1, lumber and plywood for construction can be treated by pressure impregnation to achieve a flame spread

TABLE 6.7.1 Surface Burning Characteristics of Pressure-Treated and Untreated Wood

Species[a]	*FSI*[b] *(Untreated)*	*FSI*[b] *Pressure-Impregnated*	*Smoke-Developed Pressure Impregnation*
Douglas fir (lumber)	70–100	≤25	≤25
Hemlock (lumber)	60–70	≤25	≤25
Southern yellow pine (lumber)	130–195	≤25	≤25
Western red cedar (lumber)	70	≤25	≤25
Redwood (lumber)	65–70	≤25	≤25
Red oak (lumber)	91	≤25	≤25
Western spruce (lumber)	100	≤25	≤25
Douglas fir (plywood)	115–130	≤25	≤25
Southern yellow pine (plywood)	95	≤25	≤25
Particleboard	140–200	≤25	≤25

[a]As tested by NFPA 255 (ASTM E84), selected species only. (See bibliography.)
[b]Flame spread index.

TABLE 6.7.2 Heat Release Rates of Pressure-Treated and Untreated Wood

Species (Product)	*Irradiance (kW/m^2)*	*Average Peak HRR[b] (kW)*	*Average HRR (kW)*
Southern yellow pine (plywood)[a]	50	237	156
Southern yellow pine (fire-retardant treated plywood)[a]	50	151	55

[a]Unpublished data generated at Weyerhaeuser Company.
[b]HRR = Heat release rate.

TABLE 6.7.3 Effect of Pressure Impregnation on Douglas Fir Plywood in the Room Fire Test[a]

	Untreated	*Pressure Impregnated*
Flashover time	3.3 min	None
Maximum heat release rate	7.3 mW	0.6 mW
Maximum smoke generation (O.D.[b])	1.11	0.76

[a]The ignition exposure was 40 kW (net) for 5 min, 160 kW (net) for 5 min, and 0 kW (net) for 5 min.
[b]Optical density.

index below 25 and to perform well in fire-resistant-rated assemblies.

Plywood. Fully treated plywood is satisfactory only when surface appearance is unimportant. For decorative purposes where the face veneer must have the beauty of natural wood, untreated face veneers of various species are laminated to treated cores. The flame spread classification of these treated plywood products varies in approximately inverse proportion with the density of the face veneer and ranges generally from 20 to 75, satisfying all but the most restrictive requirements. Fully treated plywood generally has a flame spread index less than 25 (Class I).

Relative Toxicity. Combustion toxicity testing of treated and untreated wood suggests that smoke from treated wood is "no more toxic than untreated Douglas fir."[16] This is true even though minor amounts of toxicants other than carbon monoxide are liberated from some treatments when burned.

Treated and untreated wood products tested by the University of Pittsburgh Test Method range in LC_{50} values from 7 to 72 g.[17] Many treated and untreated wood products have also been tested by the radiant furnace method. These results also indicate that smoke from treated wood is slightly less toxic than from untreated wood.[18]

Fire-Retardant Coatings

In existing structures of untreated wood or in cases where fire-retardant pressure impregnations are impracticable, fire-retardant coatings can be used. Coatings can be applied to any exposed surface of structural members, interior finish, or contents. They may be applied by means of brush, roller, sprayer, or trowel. As in the case of pressure impregnations, the degree of the flame spread reduction secured by a coating is dependent on the original combustibility of the surface to be protected, the effectiveness of the coating material used, the amount of coating used, the thoroughness of the application, and the size and severity of the exposing fire.

With normal paints, the usual aim is to get maximum coverage with minimum material. The approach is different in the application of fire-retardant coatings. Here, the objective is to provide the needed amount of coating per unit area required to ensure a definite degree of protection. Film thickness for intumescent coatings is a very important factor in their ultimate performance.

Among the many proprietary fire-retardant coatings, several have been listed by testing laboratories. Beware of any so-called fire-retardant or "fireproof" paint that has not been certified as to its flame spread characteristics by an independent

TABLE 6.7.4 Variations in Effect of Different Fire-Retardant Coatings on Unprimed Douglas Fir

	Untreated	*Painted with Coating X[a]*	*Painted with Coating Y[a]*	*Painted with Coating Z[a]*
Total coverage	—	100	100	200
(ft^2 per gal [L/m^2])	—	2.45 L/m^2	2.45 L/m^2	1.23 L/m^2
Flame spread[b]	100	60	10	25
Fuel contributed[b]	100	35	15	10
Smoke developed[b]	100	40	5	10
Rate per coat	—	300	200	200
(ft^2 per gal [L/m^2])	—	0.82 L/m^2	1.23 L/m^2	1.23 L/m^2
Number of coats	—	3	2	1

[a]Each coating is listed by Underwriters Laboratories Inc. as meeting the minimum requirements for a fire-retardant coating.
[b]If a range of values was obtained, the figure given here is the highest obtained.

testing laboratory. There are four types of fire-retardant coatings for wood, as follows:

1. *Intumescent paints.* These coatings, on the action of heat, expand from a thin, paintlike coating to a thick, puffy, burnt-marshmallow-type coating. The puffy coating results in one or all of the following effects: insulation of fuel from heat, exclusion of oxygen from fuel, production of diluent gases, and reduction of flammable gases. It will retain its effectiveness until broken up either by high heat or by sustained heat.
2. *Mastics.* These materials are applied by trowel or by heavy-duty spray equipment and form a thick coating on the surface of the combustible material. They vary from hard, ceramic-like materials to soft, tarlike coatings. All withstand significant amounts of heat and inhibit flame spread by the impervious noncombustible membrane they form.
3. *Gas-forming paints.* These coatings, when heated, release quantities of noncombustible gas that dilute the oxygen at the protected surface so there is not sufficient oxygen to support combustion.
4. *Cementitious and mineral-fiber coatings.* Limited research has been conducted on the potential use of cementitious and mineral-fiber coatings on wood to improve its fire endurance characteristics. These coatings are commonly used on structural steel to enhance fire resistance by protecting the steel from the intense heat of a fire. Some researchers feel that structural wood systems may be protected in the same manner.

The customary finishing materials for wood, such as ordinary stains, oil paints, enamels, varnishes, shellac, lacquer, and waxes, are of no appreciable value in protecting wood against fire and, in some cases, increase combustibility. Paint, however, may be of value in preventing absorption of oil and in promoting cleanliness. It should also be noted that dry, decayed wood is more susceptible to ignition by small sparks from cigarettes than is sound wood and that paint coatings tend to prevent surface decay.

Water-based gels have been evaluated for efficacy in preventing ignition of combustible siding on residential structures during a wildland fire. Tests conducted at Omega Point Laboratories showed an increase in the time-to-ignition from 30 seconds for untreated wood siding to approximately 300 seconds for the treated wood siding when exposed to 25 kW/m^2.[19] These water-based gels are applied with a garden hose and an aspirator system and are intended for temporary protection only.

Standard test methods are being developed by ASTM to assess the fire resistance of materials and assemblies in structures exposed to wildland fires. These test methods will apply to areas in the high-hazard category. NFPA 1144, *Standard for Protection of Life and Property from Wildfire,* which provides "minimum requirements for planning, construction, maintenance, fire prevention, and management to parties responsible for fire protection, land use planning, property development, property maintenance, and others responsible for or interested in improving fire and life safety in areas where wildland fire could threaten lives, property, and other values" should be consulted for additional information.

Advantages. Fire-retardant coatings have the following advantages: (1) they can be used on combustible materials already in place, (2) they are relatively inexpensive, (3) they are easily applied, and (4) they do not cause strength loss at high temperatures and humidities.

Disadvantages. Fire-retardant coatings have the following disadvantages: (1) ease of application can lead to thin and ineffective treatments, (2) unexposed surfaces cannot be treated, (3) limited life and durability, (4) susceptibility to damage, and (5) required maintenance.

Fire Performance Characteristics. The fire performance of wood can be improved through the use of fire-retardant coatings. The amount of improvement is determined by the effectiveness of the treatment. Underwriters Laboratories Inc. has established a minimum standard of effectiveness for listed coatings to be a flame spread rating of 50 or less in the Steiner tunnel test or a 50 percent reduction in flame spread as compared to the untreated surface, whichever is lower.

Listed coatings, when properly applied, are effective in improving fire performance characteristics, some to a point well below the limits noted above. The variations in effect of listed fire-retardant coatings on Douglas fir are shown in Table 6.7.4.

Permanence. Some fire-retardant paints and coatings have good permanence when used in interior locations of relatively normal humidity and temperatures. Water-resistant, oil-based, intumescing fire-retardant coatings have been developed.[20] But the use of fire-retardant coatings in exterior locations, in areas of relatively high humidity, and in areas of high temperature has not been thoroughly tested. One difficulty in testing these exterior paints is the problem of weathering samples. Samples for small-scale tests can be placed in a weather accelerator or weatherometer and the results measured. These small-scale tests, however, do not produce significant flame spread results. There is also doubt as to the comparability of weatherometer exposure and actual long-term weathering. The samples required for the acceptable large-scale tests are too large for accelerated weathering and thus must be exposed to actual weathering, which requires long periods of time. Until this testing problem can be solved, the use of fire-retardant coatings in exterior locations is questionable.

Strength and Deterioration. Strength and deterioration of both the materials coated and their fastenings is not a problem with most fire-retardant coatings.

Moisture. Only those coatings that use hygroscopic fire-retardant chemicals are vulnerable to absorbing moisture, with consequent reduction in effectiveness.

Toxicity. The reactive toxicity of the total products of combustion of the coated material as compared to the uncoated material should be considered when examining fire-retardant coatings.

Preservative Treatments

Where subject to decay, insect attack, or attack by marine borers, timber and lumber are commonly pressure treated with coal tar creosote, pentachlorophenol, chromated copper arsenate, ammonical copper arsenate, or one of the newer, environmentally friendly chemicals, such as alkaline copper quat, copper azole, and borates. These preservative-treated products are used in piers, bridges, trestles, decks, fences, boardwalks, railroads, and some locations in buildings.

Oil-type preservatives, such as creosote, can cause an increase in fire hazard as compared with untreated wood. Fire-retardant chemicals that use the proper ratio of phosphorus–halogen mixture are effective in reducing the combustibility of the treated wood to that of untreated wood. There is, however, an initial flash of "light ends" not observed in untreated wood.[21] Neither creosote nor pentachlorophenol-treated wood is used in residential applications.

Fire can spread more rapidly and generate higher surface temperature in structures containing newly creosoted wood than in structures of untreated wood, particularly where general fire temperatures are sufficiently high to vaporize the creosote oils. Any unusual fire risk in creosoted pier substructures, however, will be due primarily to the excessive areas of wood construction without firebreaks, which are inaccessible for manual fire fighting and lack automatic sprinkler protection. As the construction industry shifts to new waterborne treatments, this concern is expected to lessen in new structures.

Waterborne salt preservatives can provide some fire-retardant effect, but normal preservative retentions are not sufficient as effective fire-retardant treatments. Conversely, some fire-retardant formulations combine fire retardancy and preservation. Borates are a good example of this dual effect.

Christmas Trees

Christmas trees can become extremely flammable when cut long in advance of use and then brought indoors where heat and low humidity accelerate drying. To reduce the hazard, the tree should be kept indoors only as long as absolutely necessary, the trunk sawed off at an angle at least 1 in. (25 mm) above the original cut end, and the tree placed in water while it is indoors. Water should be added at intervals to the pail, tub, or tree stand in which the tree is placed so that the water level is always above the cut. To achieve a satisfactory degree of flame resistance in any combustible material, including Christmas trees, it is essential to get a certain minimum quantity of effective flame-retardant chemical either into or on the surface of the material to be treated. Since Christmas trees by their nature are not absorbent, the only way to effectively treat them is to apply a surface coating. Treating Christmas trees with simple solutions of water-dissolved chemicals, such as borax-and-boric acid, diammonium phosphate, or ammonium sulfate, is not effective. To provide a significant flame-retardant value, the testing solution or coating must be thick or syrupy enough to form a fairly heavy coating.

Much misunderstanding in this area results from tests of fresh trees treated with simple water-thin solutions of the type described above. Such tests lead to the erroneous conclusion that the treatment is effective, when the fact is that the tree was naturally flame resistant due to its water content.

Pressurized aerosol containers of flame-retardant Christmas tree coatings may be convenient, but their value is questionable due to the very limited quantity of the contents. Many cans would be necessary to adequately treat all parts of larger trees, but the high cost leads the user to apply only a token (and useless) coating.

WOOD-BASED COMPOSITE PANELS

The group of materials referred to here as "wood-based composite panels" includes products such as insulation boards, hardboards, particleboards, oriented strand boards, medium-density fiberboard, and laminated paper boards. They consist of a mixture of fibers, particles, or flakes and binder formed under pressure into boardlike panels or tiles. These board or panel materials in final form retain some of the properties of the original wood but, because of the manufacturing methods, gain new and different properties from those of the wood.

Wood-based composite panels can be fire-retardant treated by chemical admixtures, impregnations, and coatings. These treatments vary in their effectiveness and are somewhat limited in their use by their effect on the physical properties of the untreated panel.

Admixtures

When mineral fibers, such as glass or rock wool, are added to a mixture of organic fibers, they will reduce the combustibility of the mixture, depending on the amount of mineral fiber used. If mineral fibers completely replace the organic fibers, the product becomes noncombustible, provided the binder used to join the fibers is noncombustible or has a sufficiently high ignition temperature. Mixtures of alumina trihydrate, boric acid, and wood fibers have been successfully combined into panel products with very low flame spread and smoke-developed values. Fire-retardant particleboard and oriented strand board are prepared by adding the fire-retardant chemicals prior to board making. These products give very consistent flame spread and smoke-developed values if chemical retentions are consistent.

Impregnations

Attempts have been made to reduce the combustibility of organic composite boards by pressure impregnation of the finished product and by treatment of the raw fiber product itself. Treatments have included soluble salts, insoluble complexes, and chemical reactions with the organic materials themselves. The effect of these treatments on combustible composite boards varied with respect to the type of treatment and type and quantity of chemicals used. Treatment by pressure impregnation has not yet proved to be commercially feasible, due in part to losses in physical properties and inadequate fire retardancy. At least one manufacturer has developed a successful wood pulp treatment process for both composite boards and acoustical tile. Similarly treated wood fiber acoustical tile is produced by other manufacturers.

Coatings

The treatments previously discussed are made during the manufacture of the material. Coatings can be applied during manufacture or to material already in use. Factory-applied coatings are usually fire-retardant paints; however, many are of questionable effectiveness when exposed to severe fire conditions. Their main effect is to cover the fuzzy surface of the untreated material.

The application of fire-retardant paints of the intumescent variety to existing composite board will provide good protection for the exposed side of the board, provided the coatings are maintained. Some composite boards exhibit considerable dimensional instability, expanding when damp and contracting when dry. This movement may expose cracks and gaps in the material that will open untreated areas to the action of heat and rapid flame spread.

Fire Performance Tests of Wood-Based Composites

The effectiveness of the treatments of composite boards can be shown with a fire test. Most of the methods listed under the section on wood can be used to evaluate their fire performance characteristics.

PAPER

Paper can be treated by impregnation to make it flame and glow retardant after the ignition source has been removed. In addition to treating various forms of paper, for example, building paper, wrapping, packing, and decorative paper, these same treatments can be used to preserve foliage, leaves, grass skirts, broom straw, excelsior, and similar materials if they are sufficiently absorbent. Adequate wetting may be achieved by dipping or spraying with some materials, whereas others may require soaking for several hours or even days.

The development of flame-retardant products has been given impetus by the code requirements for nonflammable display and decorative material in hotels, theaters, schools, hospitals, nursing homes, and other high-occupancy buildings. Decorative crepe paper, corrugated display cardboard, textiles, and window-shade materials may be made flame resistant during manufacture, which is the most reliable method. Field treating paper is difficult due to variations in paper finishes, sizing, and color fastness. It is preferable to purchase factory-treated materials.[22]

CELLULOSIC INSULATION

Cellulosic fiber such as shredded newsprint can be treated with fire-retardant chemicals to make a safe building insulation. It is one of the most important construction products using fire-retardant chemicals. Boric acid, borax, and disodium octaborate tetrahydrate are three of the most common fire-retardant chemicals used for this purpose.[23]

MISUSE OF FIRE RETARDANTS

Fire-retardant treatments are used for reduction of flame spread on structural wood members and combustible interior finish, such as wood paneling, acoustical tile, and wood-based composite panels. Flame-retardant treatments are used for reducing the flammability of contents, furnishings, and decorative materials, such as curtains, draperies, upholstery, crepe and corrugated papers, Christmas trees, and miscellaneous dried or artificial plants and foliage. In all these applications, there are opportunities for misuse or misrepresentation. Some of the more prevalent kinds of misuse are described, as follows:

1. Promoting pressure-impregnated wood for uses where noncombustible materials are absolutely required. Such substitutions are appropriate in certain limited applications, but even the most effective treatments cannot entirely eliminate some contribution of fuel and smoke. The concept of a "limited combustibility classification" is being considered in ASTM and ISO on the basis of heat release rate characteristics. Fire-retardant-treated wood is an example of a material that could be so classified.
2. Using pressure-impregnated or coated materials that are not intended for use in locations that are exposed to the weather or unusually high humidity conditions.
3. Attempting to treat the newer synthetic fiber fabrics with common water-soluble-salt flame-retardant solutions. Such solutions are effective only on cellulose fibers, such as cotton and rayon, and the common animal fibers, such as wool and silk. They are not effective for the treatment of nylon, acetate, Orlon®, Dacron®, Acrilan®, or any of the similar synthetics presently in wide use.
4. Marketing flame-retardant solutions in small aerosol spray containers for home use. This practice is subject to many abuses, including the lack of product labels to indicate the limitations of the contents and instructions for proper application. Some advertising contains wildly exaggerated claims for the product's utility, giving the impression that the contents of one can will "flameproof" virtually everything in the home. The product itself may be excellent and convenient to use, but there is a great risk that the average user will not achieve an effective degree of flame resistance. With few exceptions, flame-retardant treatments should be left to skilled persons.
5. Advocating the use of ordinary water-soluble-salt solutions for the treatment of nonabsorbent materials. Effective treatment of nonabsorbent materials can be achieved only by means of a substantial surface coating, requiring that the treating solution be of a syrupy or paintlike consistency.

The technology of flame-retardant treatment is highly useful and can do much to increase fire safety. But because it is also a field vulnerable to entry by unskilled entrepreneurs and charlatans, the buyer should be alert to its limitations. Products that have been tested, rated, and labeled by reputable, independent testing laboratories are the consumers' best safeguard against the pitfalls listed above.

SUMMARY

Cellulosic materials common in the living environment include wood, wood-based composite panels, paper, and miscellaneous decorative materials. Fire-retardant treatment is used to reduce

flame spread on structural wood members and combustible interior finish. Flame-resistant treatment is used to reduce the flammability of contents, furnishings, and decorative materials. Treatments are able to retard flaming or glowing by several different mechanisms, including reducing thermal buildup or excluding oxygen and inhibiting the escape of combustible gases. The four basic methods of treatment are chemical changes, impregnation, pressure impregnation, and coating. Chemical changes and pressure impregnation are limited to manufacturing processes and procedures. Impregnation and coating methods are used in the field. The method applied depends on a number of factors, including the chemical and physical characteristics of the material being treated. Flame-retardant and flame-resistive treatments must be applied properly by a skilled person and tested in order to ensure effective fire protection.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire-retardant and flame-resistant treatments of cellulosic materials discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA *101®, Life Safety Code®*
NFPA 220, *Standard on Types of Building Construction*
NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 272, *Standard Method of Test for Heat and Visible Smoke Release Rates for Upholstered Furniture Components of Composites and Mattresses Using an Oxygen Consumption Calorimeter*
NFPA 703, *Standard for Fire-Retardant–Treated Wood and Fire-Retardant Coatings for Building Materials*
NFPA 1144, *Standard for Protection of Life and Property from Wildfire*

Chapter 8

Dusts

Richard F. Schwab

Chapter Contents

Factors Influencing the Explosibility of Dusts
Dust Cloud Ignition Sources
Deflagration Characteristics of Selected Combustible Dusts
Factors Influencing the Destructiveness of Dust Explosions
Dust Explosion Test Apparatus and Procedures

Key Terms

combustible dust, deflagration, dust, dust cloud, dust explosion, explosibility index, explosion pressure, explosion severity, ignition sensitivity, ignition temperature, inert material, lower explosive limit, lower flammable limit, upper explosive limit

Most finely divided combustible materials are hazardous. When suspended in air and ignited, they can cause severe explosions. This phenomenon has been known for well over 200 years. The first recorded dust explosion—a flour dust explosion in a warehouse in Turin, Italy—occurred on December 14, 1785. The entire industrial spectrum, including agricultural, chemical, metallurgical, mining, plastics, and woodworking industries, continues to be plagued by this problem.[1–5] Although the basic principles for controlling dust explosions have been understood for many years, knowledge is becoming increasingly sophisticated as incidents continue to occur.[2,3–7]

This chapter looks at the factors influencing the explosibility of dusts, such as particle size, dust concentration, and moisture in dust particles. It continues with an examination of ignition sources of dust clouds and the deflagration characteristics of selected combustible dusts. The chapter also discusses factors influencing the destructiveness of dust explosions, such as the effects of rate of pressure rise, of maximum explosion pressure, of duration, of excess pressure, and of confinement. It concludes with a discussion of dust explosion test apparatus and procedures.

For related topics see also Section 2, Chapter 8, "Explosions"; Section 6, Chapter 2, "Combustion Products and Their Effects on Life Safety"; and Section 17, Chapter 8, "Explosion Prevention and Protection."

FACTORS INFLUENCING THE EXPLOSIBILITY OF DUSTS

The chance of a dust cloud igniting is governed by the size of its particles, dust concentration, impurities present, oxygen concentration, and the strength of the source of ignition. Dust explosions usually occur as a series. Frequently, the initial deflagration is rather small in volume but intense enough to jar dust from beams and ledges or even rupture small pieces of equipment within buildings, such as dust collectors or bins. Subsequently, a much larger dust cloud develops, through which a secondary explosion can propagate. It is not unusual to have a series of explosions propagating from room to room or building to building.[7]

Hazards of Dusts

The hazard of any given dust is related to its ease of ignition and the severity of the ensuing explosion. The Bureau of Mines of the U.S. Department of the Interior has developed an arbitrary scale based on small-scale tests, which is quite useful for measuring the hazard. The ignition sensitivity (IS) is a function of the ignition temperature (of the dust cloud) and the minimum energy of ignition; the explosion severity (ES) is a function of the maximum explosion pressure and the maximum rate of pressure rise. To facilitate comparisons of explosibility data in U.S. Bureau of Mines tests, all test results[8] are related to a standard Pittsburgh coal dust taken at a concentration of 0.50 oz per ft^3 (500 g/m^3), with the exception of some metal dusts.[9]

The ignition sensitivity and explosion severity of a dust are defined as:

$$IS = \frac{(T_i \times E_m \times C_m)_{\text{Pittsburgh coal dust}}}{(T_i \times E_m \times C_m)_{\text{Sample dust}}}$$

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$$ES = \frac{(P_{max} \times R_{max})_{Sample\ dust}}{(P_{max} \times R_{max})_{Pittsburgh\ coal\ dust}}$$

where

T_i = Ignition temperature of a dust cloud

E_m = Minimum ignition energy of a dust cloud

C_m = Minimum concentration for a combustible dust cloud

P_{max} = Maximum explosion pressure

R_{max} = Maximum rate of pressure rise in the test apparatus

The explosibility index (EI) is the product of the ignition sensitivity and explosion severity. This method allows one to rate the relative hazard of the dusts as shown in Table 6.8.1. The concept of using this scale to measure the hazard of a combustible dust has in recent years been found to be outdated though it is still widely used.[10]

Table 6.8.2 gives the explosibility index, ignition sensitivity, explosion severity, maximum explosion pressure, maximum rate of pressure rise (not necessarily at the concentration of 0.50 oz per ft^3 [500 g/m^3]), ignition temperature of both the dust cloud and a layer, the minimum ignition energy of the dust cloud, minimum explosion concentration, and the limiting oxygen concentration in a spark-ignition chamber.

Particle Size

The smaller the size of the dust particle the easier it is to ignite the dust cloud, insofar as the exposed surface area of a unit weight of material increases as the particle size decreases. It is also true that particle size has an effect on the rate of pressure rise. For a given weight concentration of dust, a coarse dust will show a lower rate of pressure rise than a fine dust. The lower explosive limit (LEL) concentration, ignition temperature, and the energy necessary for ignition will decrease as the dust particle size decreases. Numerous studies by various investigators show this effect for a variety of dusts.[11]

Decrease in particle size also increases the capacitance of dust clouds, that is, the size of electrical charges that can accumulate on particles in the cloud.[12,13] Because capacitance of solids is a function of surface area, the possibility of developing electrostatic charges of sufficient intensity to ignite a dust cloud increases as average particle size decreases. However, to produce such electrostatic charges requires, among other things, large quantities of dust in large volumes, with relatively high dielectric strengths and consequent long relaxation times. Because of the high ignition energies required for dust clouds to ignite in comparison with ignition energies of gases, attributing the cause of dust explosions to static electricity should be held suspect unless definite evidence exists to show that static electricity was a likely cause.[3,7]

TABLE 6.8.1 Relative Hazard of Dusts

Type of Explosion	*Sensitivity*	*Severity*	*Index*
Weak	<0.2	<0.5	<0.1
Moderate	0.2–1.0	0.5–1.0	0.1–1.0
Strong	1.0–5.0	1.0–2.0	1.0–10
Severe	>5.0	>2.0	>10

Concentration

As with flammable gases and vapors, there is a specific range of dust concentration within which a dust explosion can occur. It is customary to express the concentration figures in terms of weight per unit volume; however, without knowledge of the particle size distribution of the sample, this expression is meaningless. The results presented in Table 6.8.2 were developed by the U.S. Bureau of Mines and were obtained with dusts small enough to pass through a 200-mesh screen (74 microns or smaller). In data published in Germany,[4,14,15] based on the data shown in Table 6.8.3, the median particle size was shown for every test. These German tables were condensed from far more extensive tables,[14] which also included the particle size distribution for most of the reported tests.

Variations in minimum explosive concentration will occur with changes in particle diameter; that is, the minimum explosive concentration is lowered as the diameter of particles decreases. Sample purity, oxygen concentration, strength of ignition source, turbulence of dust cloud, and uniformity of dispersion also affect the lower explosive limits (LEL) of dust clouds.

Upper explosive limits for given cloud combustible dust cloud have been determined for very few samples. There are many experimental difficulties associated with gathering this information and, from a practical point of view, this information is of questionable use.[16]

Curves formed by plotting explosion pressures and rates of pressure rise against concentration show that explosion pressures and rates of pressure rise are at a minimum at the lower explosive limit, then rise to a maximum value at a given optimum concentration, and then slowly decrease from this point. It is to be noted that the maximum pressure and the maximum rate of pressure rise do not always occur at precisely the same concentration. The destructive effect is determined primarily by the rate of pressure rise.

It appears that the most violent explosion occurs at a concentration slightly above that required for reaction with all of the oxygen in the atmosphere. At lower dust concentrations, less heat is generated and smaller peak pressures are developed. With dust concentrations greater than those causing the most violent explosions, absorption of heat by unburned dust is apparently the reason for less-than-maximum explosive pressures.

Moisture

Moisture in dust particles raises the ignition temperature of the dust because of the heat absorbed during heating and vaporization of the moisture. The moisture in the air surrounding a dust particle has no significant effect on the course of a deflagration once ignition has occurred. There is, however, a direct relationship between moisture content and minimum energy required for ignition, minimum explosive concentration, maximum

TABLE 6.8.2 Explosion Characteristics of Various Dusts

Type of Dust	*Explosibility Index*	*Ignition Sensitivity*	*Explosion Severity*	*Maximum Explosion Pressure (psig)*[a]	*Maximum Rate of Pressure Rise psi/sec*[a]	Ignition Temperature[b] *Cloud (°C)*	Ignition Temperature[b] *Layer (°C)*	*Minimum Cloud Ignition Energy (joules)*	*Minimum Explosion Conc. (oz/ft³)*[c]	*Limiting Oxygen Percentage*[d] *(Spark Ignition)*
Agricultural Dusts										
Cellulose, alpha	>10	2.7	4.0	117	8,000	410	300	0.040	0.045	—
Cornstarch commercial product	9.5	2.8	3.4	106	7,500	400	—	0.04	0.045	—
Lycopodium	16.4	4.2	3.9	75	3,100	480	310	0.04	0.025	C13
Wheat starch, edible	17.7	5.2	3.4	100	6,500	430	—	0.025	0.045	C12
Wood flour, white pine	9.9	3.1	3.2	113	5,500	470	260	0.040	0.035	—
Carbonaceous Dusts										
Charcoal, hardwood mixture	1.3	1.4	0.9	83	1,300	530	180	0.020	0.140	—
Coal, Pennsylvania, Pittsburgh (experimental mine coal)	1.0	1.0	1.0	90	2,300	610	170	0.060	0.055	—
Chemicals										
Adipic acid	1.9	1.7	1.1	84	2,700	550	—	0.060	0.035	—
Bis-phenol A	>10	11.8	2.8	89	8,500	570	—	0.015	0.020	C12
Phthalic anhydride	6.9	11.9	1.4	72	4,200	650	—	0.015	0.015	C14
Stearic acid, aluminum salt (aluminum tristearate)	>10	21.3	1.9	87	6,300	420	440	0.015	0.015	—
Sulfur	>10	20.4	1.2	78	4,700	190	220	0.015	0.035	C12
Drugs										
Aspirin, acetylsalicylic acid, $C_9H_8O_4$	>10	2.4	4.3	88	>10,000	660	Melts	0.025	0.050	—
Vitamin C, ascorbic acid, $C_6H_8O_6$	2.2	1.0	2.2	88	4,800	460	280	0.060	0.070	C15, N12
Metals										
Aluminum flake, A 422 extra fine lining, polished	>10	7.3	10.2	127	20,000+	610	326	0.010	0.045	—
Magnesium, milled, Grade B	>10	3.0	7.4	116	15,000	560	430	0.040	0.030	—
Alloys and Compounds										
Aluminum-cobalt alloy (60–40)	0.4	0.1	3.5	92	11,000	950	570	0.100	0.180	—
Thermoplastic Resins and Molding Compounds										
Acrylamide polymer	2.5	4.1	0.6	85	2,500	410	240	0.030	0.040	—
Methyl methacrylate polymer	6.3	7.0	0.9	84	2,000	480	—	0.020	0.030	C11
Cellulose acetate	>10	8.0	1.6	85	3,600	420	—	0.015	0.040	C14
Polycarbonate	8.6	4.5	1.9	96	4,700	710	—	0.025	0.025	C15
Phenol formaldehyde molding compound, wood flour filler	>10	8.9	4.7	94	9,500	500	—	0.015	0.030	C14

[a]1 psi = 6.894 kPa.
[b]°F = 9/5 (°C + 32).
[c]0.1 oz/ft³ = 100 g/m³.
[d]Numbers in this column indicate percentage whereas the letter prefix indicates the diluent gas. For example, the entry "C13" means dilution to an oxygen content of 13 percent, with carbon dioxide as the diluent gas. The letter prefixes are C = carbon dioxide and N = nitrogen.

Sources: Compiled from the following reports of the U.S. Department of Interior, Bureau of Mines: RI 5753, "The Explosibility of Agricultural Dusts"; RI 6516, "Explosibility of Metal Powders"; RI 5971, "Explosibility of Dusts Used in the Plastics Industry"; RI 6597, "Explosibility of Carbonaceous Dusts"; RI 7132, "Dust Explosibility of Chemicals, Drugs, Dyes, and Pesticides"; and RI 7208, "Explosibility of Miscellaneous Dusts."

pressure, and maximum rate of pressure rise. For example, the ignition temperature of cornstarch may increase as much as 122°F (50°C), with an increase of moisture content from 1.6 percent to 12.5 percent. As a practical matter, however, moisture cannot be considered an effective explosion preventive, since most ignition sources provide more than enough heat to vaporize the moisture and to ignite the dust. In order for moisture to prevent ignition of a dust by common sources, the dust would have to be so damp that a cloud could not be formed.

Inert Material

The presence of an inert solid powder reduces the combustibility of a dust because it absorbs heat, but the amount of inert powder necessary to prevent an explosion is usually higher than concentrations that would normally be found or could be tolerated as foreign material. The addition of inert material reduces the rate of pressure rise and increases the minimal dust concentration. Rock dusting of coal mines is a practical application of the use of inert dust to prevent explosion of combustible dust. For general rock dusting of coal mine entries, enough rock dust is usually added to provide an inert dust concentration of at least 65 percent of the total dust.[4,7] In industries other than mining, adding inert dust is seldom applicable due to contamination and other problems.

Inert gas is effective in preventing dust explosions because it reduces the oxygen to a concentration too low to support combustion. In selecting a suitable inert gas, care must be taken to choose one that is not reactive with the dust. Certain metallic dusts, for example, react with carbon dioxide or nitrogen.[9] Helium and argon are suitable diluents in such instances.[17]

Oxygen Concentration, Turbulence, and Effect of Flammable Gas

Variations in oxygen concentrations affect the ease of ignition of dust clouds and the explosion pressures. With a decrease in the partial pressure of oxygen, the energy required for ignition increases, ignition temperature increases, and maximum explosion pressures decrease. The type of inert gas used as the diluent for reduction of the oxygen concentration also has an effect apparently related to molar heat capacity.

The combustion of dust takes place at the surfaces of the dust particles. The rate of reaction, therefore, depends on intimate mixing of the dust and oxygen. It is for this reason that turbulent mixing of dust and air results in more violent explosions than those obtained by ignition in more relatively quiescent mixtures.[1,18,19] The data presented in Table 6.8.2 were gathered by igniting the dust under violently turbulent conditions; thus, they cannot be compared to explosion data for flammable gases that were gathered under comparatively quiescent conditions.

Addition of a small amount of flammable gas to a dust cloud and igniting the resultant aerosol greatly increases the violence of the explosion, particularly at lower dust concentrations. The resultant rates of pressure rise are very much higher than usually anticipated. Without the dust, the remaining fraction of the total combustible in air, represented by the flammable vapor, would be in itself below the lower flammable limit (LFL). In certain drying operations, involving the evaporation of a flammable vapor from a combustible powder with entrainment of the combustible dust along with the flammable vapor, explosions occurred that were far more violent than anticipated when only the fraction represented by the flammable vapor alone was considered.[1,3,4,20] Indeed, explosions occurred in such flammable vapor-combustible dust-air mixtures when the flammable vapor-air portion was below the LFL. When encountered, these situations need special safeguards, such as inert gas dilution, explosion suppression, very large explosion vents, and careful static electricity elimination designs. (See Figure 18.6.1 in Section 18, Chapter 6.)

When the oxygen content is reduced by the addition of an inert gas, ignition of the subsequent dust cloud reduces the maximum pressure and the rate of pressure rise obtained from the ignition of the dust cloud in addition to requiring an increase in the minimum ignition energy. This also has the effect of reducing the K_{St} value and results in a reduction of the amount of vent area needed to effectively vent a dust explosion. It has been suggested by Eckhoff[21] that this can be used as a protection technique to design appropriate control measures to protect against the dust explosion hazard.

DUST CLOUD IGNITION SOURCES

Dust clouds have been ignited by open flames, lights, smoking materials, electric arcs, hot filaments of lightbulbs, friction sparks, high-pressure steam pipes and other hot surfaces, spontaneous heating, welding and cutting torches and sparks from these operations, and other common sources of heat for ignition. The dust cloud ignition temperatures given in Table 6.8.2 for the most part fall between 300 and 600°C, and a large majority of the reported minimum spark ignition energies were between 10 and 40 mJ. This can be contrasted to flammable vapor ignition energies with a range for the most part between 0.2 and 10 mJ. As a general rule, combustible dusts require 20 to 30 times the ignition energies of flammable vapors.[3]

Because ignition temperatures and ignition energies for dust explosions are much lower than the temperatures and energies of most common sources of ignition, it is not surprising that dust explosions have been caused by common sources of ignition. For this reason, the elimination of all possible sources of ignition is a basic principle of dust explosion prevention. Ignition sources in dust-handling operations are identified and recommendations for their elimination are described in various NFPA standards for the prevention of dust explosions (see bibliography).

DEFLAGRATION CHARACTERISTICS OF SELECTED COMBUSTIBLE DUSTS

Table 6.8.3 is based on information obtained from *Forschungsbericht Staubexplosionen: Brenn und Explosions Kenngrossen von Stauben*[14] and *Brenn und Explosions Kenngrossen von Stauben.*[15] For each dust, the tables show the median particle size of the material tested, as well as the following test results obtained in a 1 m^3 vessel: minimum explosible concentration, maximum pressure developed by the explosion (P_{max}), and the maximum rate of pressure rise $(dP/dt)_{max}$. Also shown are the

TABLE 6.8.3 Dust Explosion Test Data

Dust Type	*Particle Size (m)*	*1 m^3 or C_{min} (g/m^3)*	*20 liter P_{max} [Bar (g)]*	*Vessel K_{St} (Bar m/sec)*	*Dust Ignition G.G. (°C)*	*Cloud Temperature BAM (°C)*	*VDI MIE (mJ)*	*Glow Temperature (°C)*	*Flammability <250:m Class*
Pharmaceuticals/ Cosmetics/Pesticides									
Acetyl salicylic acid		15	7.9	217		550			2(5)
Ascorbic acid, L+	14	60	6.6	48	490			Melts	2(2)
Ascorbic acid	39	60	9	111	460			Melts	2(2)
Caffeine		30	8.2	165		>550		Melts	2(5)
Digitalis leaves	46	250	8.5	8.5	73				
Methionine	<10	30	8.7	128	390		100	Melts	5
Intermediate Chemical Products									
Adipinic acid	<10	60	8	97	580			Melts	2(5)
Anthracene	235	15	8.7	231	600			>450	
Anthrachinone	<10		10.6	364					
Calcium acetate	92	500	5.2	9	730			>460	2
Casein	24	30	8.5	115	560			>450	
Methyl cellulose	22		10	157	400		12	380	3
Methyl cellulose	37	30	10.1	209	410		29	450	5
Ethyl cellulose	40		8.1	162	330			275	
Cyanoacrylicacid methyl ester	260	30	10.1	269	500			>450	5
Fumaric acid	215	–100							5
Cellulose ion exchange resin	<10	60	10	91	410			>450	5
Hexamethylene tetramine	27	30	10.5	286					
Melamine	<10	1000	0.5	1	>850			>450	2
Barium/lead stearate		15	8.1	180					2(2)
Paraformaldehyde	23	60	9.9	178	460			>480	5
Lead stearate	12	30	9.2	152	630			Melts	5
Calcium stearate	145	30	9.2	155	550		12	>450	
Sodium stearate	22	30	8.8	123	870			Melts	2
Zinc stearate	13				520		5	Melts	
Metal dusts									
Aluminum powder	<10	80	11.2	515	560			430	
Aluminum/iron	21	250	9.4	230	760			>450	2
Aluminum/nickel	<10		11.4	300					
Aluminum powder	29	30	12.4	415	710			>450	4
Bronze powder	18	750	4.1	31	390			260	4
Iron carbonyl	<10	125	6.1	111	310			300	3
Magnesium	28	30	17.5	508					
Manganese (electrolyte)	16		6.3	157	–330			285	
Zinc dust from collector	<10	250	6.7	125	570			440	3
Other Inorganic Products									
Sulfur	20	30	6.8	151	280				5
Cotton/Wood/Peat									
Cotton	44	(100)	7.2	24	560			350	3
Cellulose	51	60	9.3	66	500		250	380	5
Wood dust	33				500		100	320	
Lignin dust	18	15	8.7	208	470			>450	5
Paper dust	<10		5.7	18	580			360	
Peat (15% moisture)	58	60	10.9	157	480			320	4
Food/Feed									
Dextrose (ground)	22								2
Dextrose (ground)	80	60	4.3	18	500			570	3

(continued)

TABLE 6.8.3 Continued

Dust Type	*Particle Size (m)*	*1 m^3 or C_{min} (g/m^3)*	*20 liter P_{max} [Bar (g)]*	*Vessel K_{St} (Bar m/sec)*	*Dust Ignition G.G. (°C)*	*Cloud Temperature BAM (°C)*	*VDI MIE (mJ)*	*Glow Temperature (°C)*	*Flammability <250:m Class*
Food/Feed *(continued)*									
Fructose (from filter)	150	60	9	102	430		<1	Melts	
Wheat grain dust	80	60	9.3	112				290	3
Coffee (from filter)	<10	60	9	90	470			>450	
Potato flour	65	125	9.1	69	480			>450	
Milk powder (low fat, spray dried)	46	30	7.5	109			>100		
Rye flour	29		8.9	79	490			>450	
Potato starch	32		–9.4	–89	520		>3200	>450	
Corn starch	16	60	9.7	158	520			40	2
Rice starch	18		10	190	530			420	3
Tea, black from dust collector	76	125	8.2	59	510			300	4
Wheat flour	57	60	8.3	87	430			>450	
Milk sugar	27	60	8.3	82	490			460	2
Coal/Coal Products									
Activated carbon	18	60	8.8	44	790			>450	
Anthracite (filter dust)	<10	60	9.1	59	510			260	
Bituminous coal (high volat)	4	60	9.1	59	510			260	
Bituminous coal	<10		9	55	590			270	
Brown coal	41		9.1	123	420		160	230	4
Charcoal	19	60	8.5	117	540			270	
Asphalt	29	15	8.4	117	550			Melts	
Other Natural Organic Products									
Dextrin	55		8.8	109	40–			350	3
Lycopodium	30		7.6	179		370	4.7	280	
Plastics/Resins/Rubber									
Acrylonitrile–Butadiene–Styrene Copolymer	200	60	9.2	147	480			>450	5
Rubber	34	–100	7.4	106					5
Epoxy resin	26	30	7.9	129	510			Melts	2
Epoxy resin with Al	34		8.9	208	570			Melts	
Melamine resin	18	125	10.2	110	840			>450	2
Melamine resin	57	60	10.5	172	470			>450	2
Phenol resin	<10	15	9.3	129	610			>450	2
Polymethylmethacrylate		15	8	199					(2)
Methylmethacrylate–butadiene–styrene	135	30	8.6	120	470		11	Melts	5
Polyester	<10		10.1	194	570			Melts	
Polyethylene (high pressure)	26		8.7	104	490			>450	
Polyethylene (low pressure)	<10	–30	6	156	420			Melts	2(5)
Polymethylmethacryimide	105	30	9.6	125	530			Melts	5
Polypropylene	25	(30)	8.4	101	410			Melts	3(5)
Polystyrene (hard foam)	760		8.4	23					
Polyurethane	3	<30	(7.8)	(156)					5
Polyvinylalcohol	26	60	8.9	128	460			Melts	5
Shellac		15	7.6	144					
Miscellaneous Products									
Toner	<10	60	8.9	196		520	4	Melts	

Note: This table is derived from the data published in Eckhoff,[4] which in turn were condensed from data published by the BIA.[15]

K_{St} value, which is the equivalent to $(dP/dt)_{max}$ because of the size of the test vessel, dust hazard class, cloud and layer ignition temperatures, combustibility rating, and test number.

The dust explosion test data presented in Table 6.8.3 are only a qualitative indication of the dust explosion hazard of a particular dust. It should not be used for design purposes. The dust explosion hazard depends on the size of the dust particles (particle size distribution), the method of grinding or pulverization affecting the particle shape, moisture content of dust sample, and possible solvent content of the dust sample. An evaluation of the hazard of a specific combustible dust is needed to design appropriate protection features such as deflagration (explosion) venting, explosion prevention methods such as provision of inert gas blankets, and explosion suppression techniques. Each of these protection features depends on test data of the specific representative dust sample.

The median particle size gives a median or average value of the dust sample particle size. Most of the samples listed in Table 6.8.3 were tested on the "as received" basis and in some cases were passed through a No. 200 mesh screen.

Most of the tabulated data in Table 6.8.3 were determined in a 1-m^3 sphere ISO vessel or in the 20-L Siwek sphere. Experience has shown that the latter value gives lower values than the 1 m^3 sphere often by a factor of two. The C_{min} in brackets is the concentration of the dust determined in the 1.2-L Hartmann bomb. These values tend to be higher than the true C_{min} determined in the 1-m^3 test vessel.

The P_{max} is the maximum pressure if the dust is ignited at the optimum concentration in a nonvented test vessel and is reported in bar (gauge). The numbers in brackets were obtained with a 20 L vessel using a simplified test procedure.

The K_{St} [bar meter/s] is defined as the maximum rate of pressure rise in a nonvented vessel times the cube root of the volume. The data were determined in a standard in a 1-m^3 test vessel or a 20-L Siwek spherical test vessel calibrated to give the same results as the 1-m^3 test vessel.

Minimum Ignition Temperature of Dust Clouds

The minimum ignition temperature data in Table 6.8.3 were acquired using the Godbert-Greenwald furnace or the BAM furnace. The data in brackets were obtained using a modified elongated version of the Godbert-Greenwald furnace yielding somewhat lower values than the version proposed as an IEC standard.

Minimum Ignition Energy (MIE)

The values reported in Table 6.8.3 are the so-called soft values, those with long discharge times (high inductance) based on the experimental technique described by Berthold (1987) (VDI method) and Eckhof (1976) (CMI method). The VDI and CMI methods differ from the earlier U.S. Bureau of Mines method. It has been found that the MIE determined by the U.S. Bureau of Mines included an appreciable fraction of the $\frac{1}{2} CV^2$ energy that was lost in the transformer supplying energy to the spark igniting the dust clouds, as a result, the U.S. Bureau of Mines MIE data are generally higher than those determined by the newer VDI and CMI methods. The U.S. Bureau of Mines values are high capacitance (short time) sparks.

Glow Temperature

The glow temperature data were obtained with a 5-mm-thick layer of dust resting on a hot plate of known controllable temperature (equivalent to proposed standard IEC method for determining the minimum ignition temperature of a dusty layer on a hot surface).

Flammability

The dusts are classified according to their ability to propagate a combustion wave when deposited as a layer. Ignition is accomplished using either a gas flame or a glowing platinum wire at 1000°C. The test sample is a 2-cm wide by 4-cm long dust ridge resting on a ceramic plate. Ignition is performed at one end. The definitions are:

- Class 1: No self-sustained combustion
- Class 2: Local combustion of a short duration
- Class 3: Local sustained combustion, but no propagation
- Class 4: Propagating smoldering combustion
- Class 5: Propagating open flame
- Class 6: Explosive combustion

The class numbers refer to a modified test procedure according to which 20 weight percent diatomaceous earth is mixed with the powder or dust to be tested. By this means some materials that otherwise would not propagate a flame because they melt may show sustained flame propagation.

FACTORS INFLUENCING THE DESTRUCTIVENESS OF DUST EXPLOSIONS

Although the destructiveness of a dust explosion depends primarily on the rate of pressure rise, other contributing factors are the maximum pressure developed, the duration of the excess pressure, the degree of confinement of the explosion (deflagration) volume, and the oxygen concentration.

Effect of Rate of Pressure Rise

The rate of pressure rise can be defined as the ratio of the increase in explosion pressure to the time interval of that increase. It is the most important single factor in evaluating the hazard of a dust and principally determines the destructiveness of a deflagration.

The rate of pressure rise is also an important consideration in the design of explosion (deflagration) vents, since it largely determines the size of the vent. In many cases, an extremely rapid rate of pressure rise indicates that an explosion vent design is either impractical or, at best, extremely difficult. In those cases, alternate protective schemes, such as use of inert gases,[21] explosion suppression, or containment, should be considered. (See NFPA 69, *Standard on Explosion Prevention Systems.*)

Effect of Maximum Explosion Pressure

The maximum explosion pressures reported by recognized test procedures are, for the most part, in excess of 50 psig (345 kPa) and, sometimes, in excess of 100 psig (690 kPa). These figures are valid only for test conditions and are subject to changes by variation in particle size, concentration, and other variables. Considering that an ordinary brick wall 12 in. (0.3 m) thick can be destroyed by less than 1 psi (6.89 kPa) pressure, it is evident that it is not practical to construct a building strong enough to resist the maximum pressures resulting from a dust deflagration. One reason why the degree of destruction is not greater in many dust explosions is that the dust is not uniformly dispersed throughout the explosion volume. A dust cloud is rarely ignited under optimum concentration conditions with respect to the development of maximum explosion pressures.

Effect of Duration of Excess Pressure

Closely associated with maximum pressure and rate of pressure rise as indications of the destructiveness of dust explosions is the length of time the excess pressure is exerted on the surroundings. The area under the time-pressure curve determines the total impulse exerted. It is this total impulse rather than the force exerted at any moment that will determine the amount of destruction. This is shown in Figure 6.8.1, where the pressure-time history of a gas explosion is compared with that of a dust explosion in identical vented enclosures and with the same vent opening pressure. Note that the faster burning gas develops a higher maximum peak pressure than does the dust, but the overpressure decreases more quickly. The area under the dust explosion curve is larger than the area under the gas explosion curve, indicating a greater total impulse and, therefore, potentially more damage. This relationship between destructiveness and total impulse explains why dust explosions, which generally have slower average rates of pressure rise than gas explosions, can be more destructive than gas explosions.

Effect of Confinement

When a dust explosion occurs, gaseous products are formed and heat is released, which raises the temperature of the air in the enclosure. Since gases expand when heated, destructive pressures will be exerted on the surrounding enclosure, unless enough vent area is provided to release the gas pressure before dangerous pressures are reached.

Bartknecht,[1,22] Nagy and Verakis,[23] Field,[24] Palmer,[7] Cross and Farrer,[12] and Hartmann et al.[11] have examined the effect in some detail. The work of Bartknecht and his associates is generally considered to be the most comprehensive, leading to basic design methods for deflagration vents, and is the basis for the procedures shown in NFPA 68, *Standard on Explosion Protection by Deflagration Venting.* Generally his procedures relate to vessels or enclosures that are capable of withstanding 1.5 psig (10.4 kPa) or more. The work of Swift and Epstein[25] is the basis of the design procedures for low-strength structures (weaker than 1.5 psig [10.4 kPa]) in NFPA 68.

In some instances, it may be impractical to provide sufficient vent area to reduce pressures to a safe level. In these situations, the dust-producing operation can be conducted in the open, under an inert atmosphere, or protected by an explosion suppression system. The explosion suppression system consists of a flame or pressure detector and a flame-quenching agent that is expelled rapidly during the incipient stage of a deflagration.

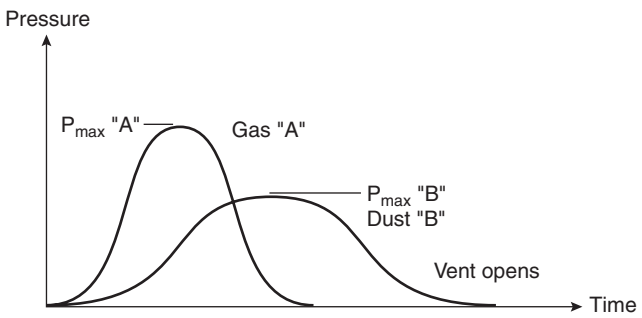

FIGURE 6.8.1 Total Impulse of Gas Explosion Compared to Total Impulse of Dust Explosion

Effect of Inerting on Explosion Pressures and Rates of Pressure Rise

Data published by the U.S. Bureau of Mines[26] and Bartknecht[22] show that reduction in the oxygen concentration in the atmosphere, and mixture of inert powder (Fuller's earth or rock dust) or moisture with the combustible dust, reduces the maximum explosion pressure and rates of pressure rise. These data are shown in Figures 6.8.2 and 6.8.3 for explosions of 0.50 oz per ft^3 (500 g/m^3) of cornstarch. A slight reduction in the atmospheric oxygen concentration or slight additions of inert powder or moisture have little effect on the explosion pressure. The effect of the inerting on the dust explosion becomes marked only when limiting values are approached. The maximum rate of pressure rise developed by the explosion (deflagration) appears to decrease almost linearly with use of inerting.

DUST EXPLOSION TEST APPARATUS AND PROCEDURES

There are a number of different types of dust explosion test chambers and even more procedures for using them, each of which can profoundly affect the test results for any given dust sample. For example, the result of the dust explosion test in a closed chamber is affected by the geometry of the chamber, that is, interior dimensions (cubical, spherical, cylindrical, etc.), and by the method of creating the dust cloud in the chamber (the method affects the turbulence of the cloud and uniformity of particle dispersion). This situation causes considerable difficulty in attempting to compare results obtained by various methods. In fact, unless several test results on the same dust sample are made in different chambers, and a consequent correlation is developed between the test methods, it can be said without reservation that any comparison of data obtained by different

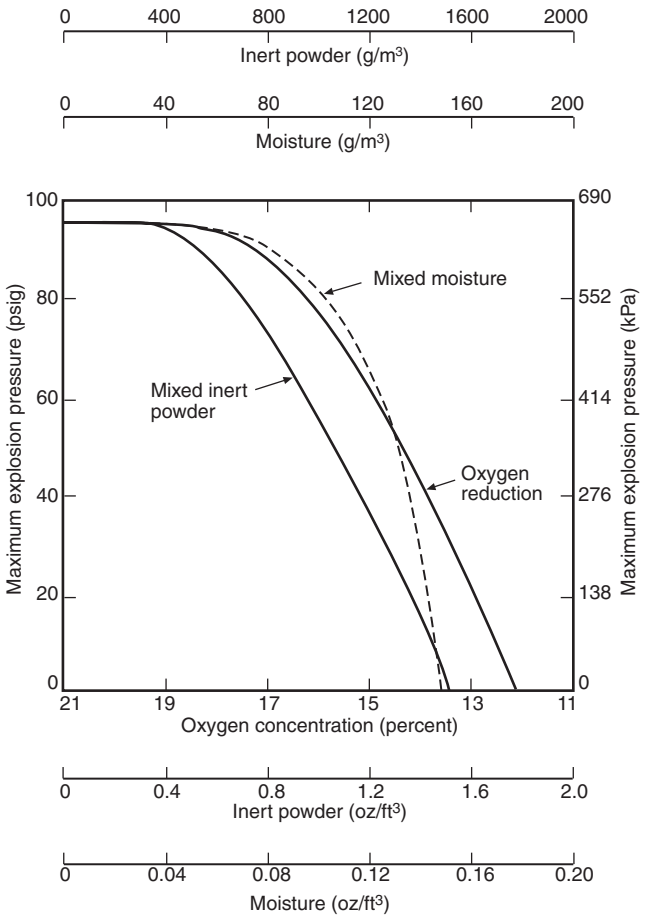

FIGURE 6.8.2 Effect of Inerting on Maximum Pressure Developed by Explosion of 0.50 oz/ft^3 (500 g/m^3) of Cornstarch

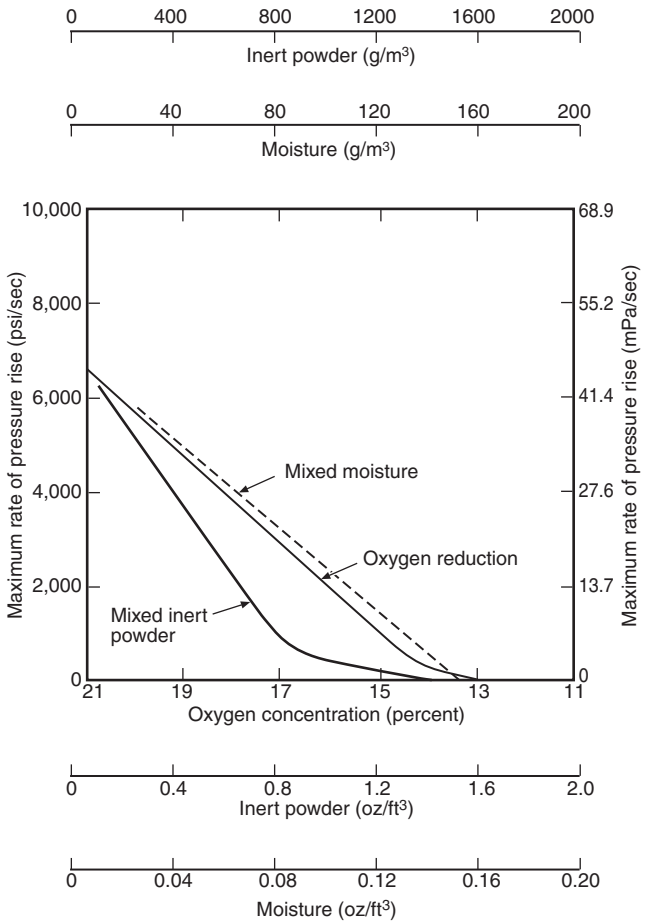

FIGURE 6.8.3 Effect of Inerting on Maximum Rate of Pressure Rise Developed by Explosion of 0.50 oz/ft^3 (500 g/m^3) of Cornstarch

test methods is, at best, only qualitative. For example, attempts to correlate test results obtained in the Hartmann bomb with the 5.29 gal (20 L) spherical bomb developed by Bartknecht have been unsuccessful.

Lack of uniformity in test procedures also rules out any attempt to compare the pressures and rates of pressure rise resulting from tests on flammable vapors and dusts. By far, the largest amount of dust explosion test data has been obtained from tests conducted by the U.S. Bureau of Mines. The U.S. Bureau of Mines' test equipment and procedures are described in RI 5624.[27] The test equipment used by the U.S. Bureau of Mines is a cylindrical vessel of about 75 in.^{3} (1.2 L), standing about 13 in. (0.33 m) high, referred to as the Hartmann apparatus[28] (Figure 6.8.4). All of the data recorded in Table 6.8.2 has been collected in this type of test apparatus. This type of data is not satisfactory for designing explosion (deflagration) relief vents.

Recent data, particularly that intended for use in designing explosion (deflagration) vents, were collected in spherical vessels. Bartknecht and his associates developed a 20-L (about 5-gal) spherical bomb[29,30] (Figure 6.8.5). Data collected in these containers tend to give more consistent results and follow

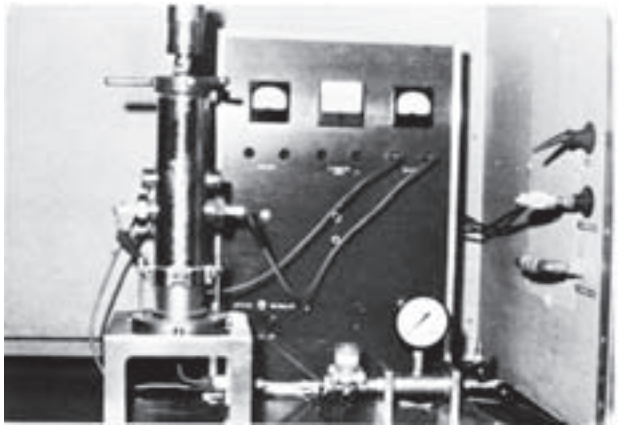

FIGURE 6.8.4 Hartmann Apparatus (Source: U.S. Bureau of Mines)

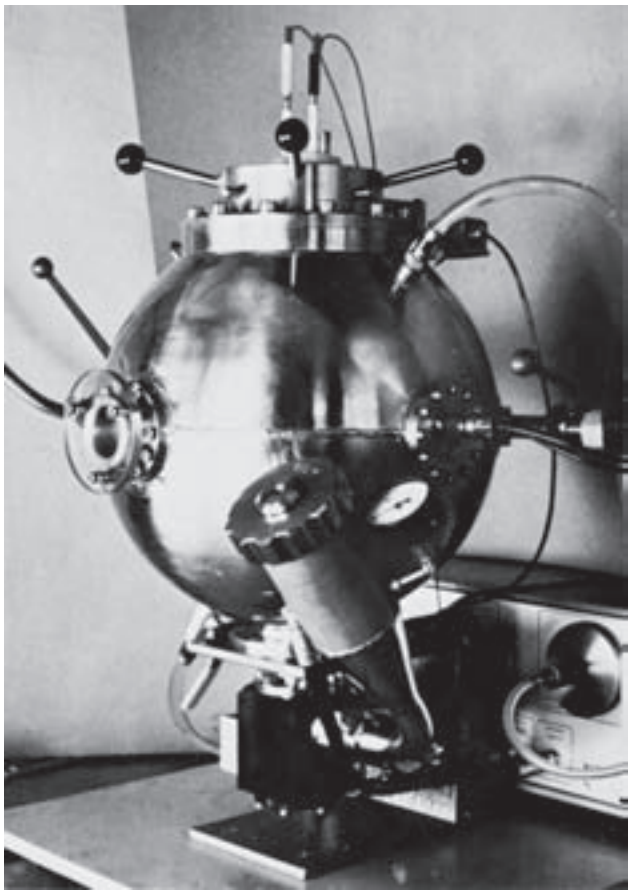

FIGURE 6.8.5 Bartknecht Apparatus (Source: W. Bartknecht)

the "cubic law" (described later). Data collected in a spherical bomb, properly calibrated, have been shown to generally follow the "cubic law" over a range from 20 L to 250 m^3. The data obtained in this vessel can be used as a basis for the design of explosion vents. Data obtained from test results obtained in the Hartmann apparatus cannot be used for this purpose.

Interpretation and Application of Dust Explosion (Deflagration) Test Data

Dust explosion test data are gathered in a variety of chambers, from a highly turbulent dust cloud to a practically stagnant cloud. Most modern test data are gathered in calibrated spherical test vessels that follow the "cubic law," which is represented for dusts as follows:

$$\left(\frac{dP}{dt}\right)_{\max} \times V^{1/3} = K_{St}$$

where

P = Pressure (bar)

t = Time (sec)

V = Volume (cu. meters)

K_{St} = Dust characterization factor (bar meter/sec)

This can also be expressed by the following relationship:

$$\frac{R_l}{R_s} = \left(\frac{V_s}{V_l}\right)^{1/3} = \frac{A_l}{A_s}$$

where

R_l = Rate of pressure rise in the large chamber

R_s = Rate of pressure rise in the small chamber

V_l = Volume of the large chamber

V_s = Volume of the small chamber

A_l = Vent ratio of the large chamber

A_s = Vent ratio of the small chamber

(All variables must be in consistent units.)

This law indicates that the test data gathered in small chambers can be extrapolated to larger chambers with some degree of confidence, though care must be taken to keep the shape of small chambers and large chambers within reasonable limits. If the test is done in small spheres, the results cannot be expected to hold up in the design of explosion (deflagration) relief for a long, narrow vessel.

Ignition Temperature

One piece of apparatus developed at the U.S. Bureau of Mines consists essentially of an electrically heated vertical cylindrical tube at the top of which is a small container holding a weighed amount of dust. The dust is projected down through the tube as a uniform cloud by a controlled blast of compressed air directed at the dust sample. The ignition temperature is considered to be the lowest temperature at which flame issues from the open bottom end of the tube. Differences in results are due to differences in the size and shape of test containers.[27] This test is used to determine the ignition temperature of the dust cloud.

The furnace is also used to determine the ignition temperature of a dust layer sample, ½ in. (12.5 mm) deep, 1 in. (25.4 mm) diameter, in a container suspended in the furnace heated by a stream of hot air flowing at 30 $in.^3$ per min (½ L/min) past the sample.[27] Other recognized testing agencies use hot plates with the dust layers ¾ in. (19 mm) deep.[14,15] Other researchers have reported test data using different test procedures[31,32] designed to investigate ignition sources encountered under industrial conditions.

Ignition in Inert Atmospheres

For the determination of the ignitability of dust in various inert gas-air mixtures, the apparatus consists of a vertical cylindrical tube containing tungsten electrodes to produce a spark for ignition. The tube is designed so that it can be flushed with the inert gas-air mixture prior to the test. The dust sample in a container near the top of the tube is projected downward as a cloud by a controlled blast of the inert gas-air mixture. Flame issuing from the open bottom of the tube signifies ignition.[31,32] Bruderer[31] has also investigated limiting oxygen concentrations for various ignition sources in his work.

Minimum Energies for Ignition

Apparatus developed at the U.S. Bureau of Mines, used to determine minimum energies needed to cause ignition of dust clouds, consists of a vertical cylindrical lucite tube. In this test, the dust is dispersed upward in the tube by controlled discharge of compressed air into the dust chamber at the bottom of the tube. A spark discharged by an electrical condenser is used as the ignition source, and by using condensers with different capacities, spark energy can be varied. Discharge of the condenser is synchronized with the formation of the dust cloud. Visible flame in the tube signifies ignition.

The data presented in Table 6.8.2 for cloud ignition energies has been gathered in this fashion. Recent work [27,33,34] has shown that, if the spark is generated in a different fashion with a high resistance in series with the capacitance discharge, it is possible to obtain ignition of the dust cloud considerably below that reported by the U.S. Bureau of Mines technique. Generally speaking, the data reported by the U.S. Bureau of Mines might be expected to be a factor of 3 to 5 times too high.[12]

Eckhoff[33] has managed to ignite some of the more sensitive dusts, such as aluminum (5 μm) and sulfur, at energies of 1 mJ or less. The U.S. Bureau of Mines quotes 15 mJ for these materials. It is questionable whether a circuit that produces such a low-level spark of the nature required would occur naturally. Ignitability is not solely a function of spark energy but also a function of spark duration, with long-duration sparks igniting dusts more easily than short-duration sparks.[12]

Explosion Pressures

Apparatus described by the U.S. Bureau of Mines[27] for determining maximum explosion pressures and rates of pressure rise consists of a vertical cylindrical steel bomb into which a weighed sample of dust can be dispersed upward by a jet of compressed air. Pressures are measured by a strain gauge transducer mounted in the top of the bomb. A pressure-time record is obtained on an oscillograph using a light beam galvanometer system.

SUMMARY

Dust cloud explosions are a hazard common to a number of industries, including agricultural, chemical, metallurgical, mining, plastics, and woodworking. The chance of a dust cloud igniting is governed by the size of its particles, dust concentration, impurities present, oxygen concentration, and the strength of the source of ignition. Measures that can reduce the risk or damage of explosions include inert material or gas dilution, elimination of sources of ignition, explosion suppression, very large explosion vents, and careful static electricity elimination designs. The U.S. Bureau of Mines has conducted many tests on the properties and explosibility of dusts; the data collected will continue to aid in designing safeguards.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on dusts discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 484, *Standard for Combustible Metals*
NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*
NFPA 655, *Standard for Prevention of Sulfur Fires and Explosions*
NFPA 664, *Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities*

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Chapter 9

Metals

Revised by
Tom Christman

Chapter Contents

Overview
Fire Prevention and Protection
Magnesium
Titanium
Alkali Metals: Sodium, Potassium, NaK, and Lithium
Zirconium and Hafnium
Calcium and Zinc
Aluminum
Radioactive Metals
Metals Not Normally Combustible

Key Terms

alkali, calcium, combustible metal, dust, explosibility, hafnium, magnesium, process hazard, radioactive metal, titanium, zinc, zirconium

Combustible metals are those metals that are either combustible or explosive. The hazards of combustible metals can occur while the metals are being produced, processed, finished, handled, or stored. The hazards also exist in related processes such as process ventilation systems. This chapter covers the fire hazard properties of combustible metals and the means to prevent their ignition or explosion.

For information on the hazards of metal dusts see Section 6, Chapter 8, "Dusts."

OVERVIEW

General

Nearly all metals will burn in air under certain conditions. Some oxidize rapidly in the presence of air or moisture, generating sufficient heat to reach their ignition temperatures. Others oxidize so slowly that heat generated during oxidation is dissipated before the metals become hot enough to ignite. Certain metals, notably calcium, hafnium, lithium, magnesium, niobium, plutonium, potassium, sodium, tantalum, thorium, titanium, uranium, zinc, and zirconium, are referred to as combustible metals because of the ease of ignition of thin sections, fine particles, or molten metal. However, the same metals in massive solid form, with the exception of the alkali metals, are very difficult to ignite.

The alkali metals (cesium, francium, lithium, potassium, rubidium, sodium, and alloys of these metals, such as NaK) are water reactive. They react with water to generate hydrogen. The amount of metal or its particle size does not contribute to the risk of ignition. Generally, contact with water will result in a reaction that may include fire or explosive forces. Metals such as lithium, sodium, potassium, and NaK react with water at room temperature. Other alkali metals may only react when they are heated or involved in a fire.

Fire and Life Safety Requirements

Requirements for specific metals can be found in NFPA 484, *Standard for Combustible Metals.* This standard covers the significant combustible metals, with each metal having its own chapter covering the specifics of that metal. Two important changes have been made to NFPA 484. First, a chapter has been added on the assessment of whether the materials of concern should be treated as combustible metals. The assessment is composed of two tests, one for combustibility and the other for explosivity, as described in Figure 6.9.1. When a material fails either test, the material in question is considered a combustible metal and the precautions of NFPA 484 are applicable. The second major change to NFPA 484 is the addition of a chapter that provides some general precautions for combustible metals not specifically addressed by any individual chapter.

Tom Christman began working with combustible metals in 1976. In 1994 Mr. Christman was appointed as a principal member of the Combustible Metals Committee, which had the responsibility for individual standards on aluminum, lithium, magnesium, titanium, and zirconium. He presently is the chair of NFPA 484, *Standard for Combustible Metals.*

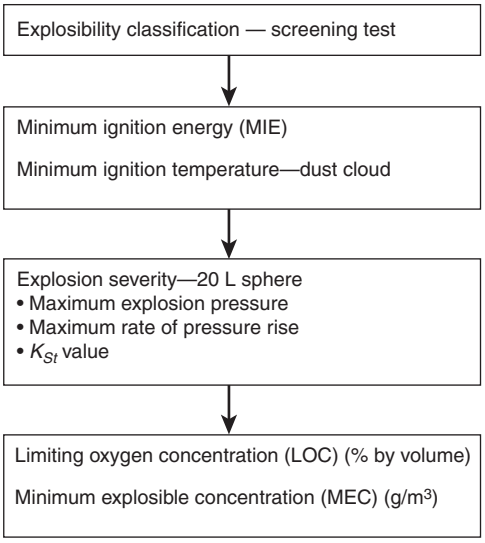

FIGURE 6.9.1 NFPA 484 Determination of Explosibility (Source: NFPA 484, *Standard for Combustible Metals,* 2006 ed., Figure 4.3.1)

Combustibility Factors and Hazards

Some metals, such as iron and steel, which are not normally thought of as combustible, can ignite and burn when finely divided or when in contact with other burning materials. Clean, fine steel wool, for example, can be ignited fairly easily. Particle size, shape, quantity, and alloy are important factors to consider when evaluating metal combustibility.

Clouds of most metal dusts in air are explosive. Therefore, fugitive dusts must be controlled to prevent a fire or explosion. Housekeeping must be especially good in areas where fugitive dust is present to ensure against the buildup of dust. In general, if the layer of dust is thick enough to obscure the color of the surface below or is thick enough to write your name in it, it *is* an explosion hazard.

Alloys, which are essentially mixtures of different metals combined in varying proportions, may differ widely in combustibility from their constituent elements. Metals tend to be most reactive when finely divided and some powders may require shipment and storage under inert gas or in liquid or might have to be coated to reduce fire risks.

Hot or burning metals may react violently on contact with other materials, such as certain extinguishing agents or agents normally used on fires involving ordinary Class A combustibles or flammable liquids. A few metals, such as thorium, uranium, and plutonium, emit ionizing radiation (e.g., gamma rays or beta and alpha particles) that can complicate fire fighting and introduce a contamination problem.

Temperatures produced by burning metals are generally much higher than temperatures generated by burning flammable liquids. Some hot metals can continue burning in atmospheres of carbon dioxide, nitrogen, or steam where combustion of ordinary combustibles or flammable liquids would not be sustained.

Properties of metal fires cover a wide range. For example, burning titanium produces little smoke, whereas burning lithium smoke is dense and profuse. Some water-moistened metal powders, such as zirconium, burn with near-explosive violence; the same powder wet with oil burns quiescently. Sodium melts and flows while burning; calcium does not. Some metals (e.g., uranium) acquire an increased tendency to burn after prolonged exposure to moist air, whereas prolonged exposure to dry air may make it more difficult to ignite the metal.

Another hazard of combustible metals is the possible formation of eutectics. A eutectic is an alloy that has a melting point below any of its constituent metals and that has the potential for reaction at lower temperatures than that of its constituents. Often this reaction can be vigorous and exothermic. Practical examples of catastrophic occurrences involving eutectic mixtures have been heating a titanium plate in a furnace where a large excess of steel scale (iron oxide) might contact a thin edge or corner of the plate or heating a niobium base alloy on a nickel base plate, even in a vacuum furnace. Pressure and finely divided forms of either material can help trigger such reactions. One particularly unpleasant consequence is that the eutectic composition will liquefy at a temperature below the melting point of either material and the hot liquid will spread by flow.

In general, all particulate forms of combustible metals, especially thinner chips and fine powders, should be stored in individual sealed metal containers rather than in bulk-type storage. Above 80 mesh or thicknesses greater than 0.015 in. (381 microns), the reactivity and resultant hazard is somewhat reduced. Finer particulates or thinner cross sections represent an increasing hazard.

Storage of some powders and fines can be done under the cover of water, but care must be taken if the fine particulates begin to dry out. At some critical moisture level, particularly with fine powders, spontaneous combustion may occur. Sometimes, personnel may not realize that a wet grinding or polishing operation is creating wet metal fines that can become very sensitive as the water or other liquid carrier dries out. A good informal rule is to tailor packaging sizes to quantities utilized in processing as opposed to bulk packaging. Where product contamination is not a concern, bagging in polyethylene under the cover of argon and then placing inside a metal container is recommended.

Thin sheet, strip, or foil in pickle baths or hot, caustic descaling vats can ignite or be ignited due to heat of reaction and this phenomenon may be exacerbated by stray electrical currents, which may cause arcing.

In the case of "fluffy," light, loosely packed turnings or powders, care must be exercised not to disperse the burning particulates with forceful application of an extinguishing agent. Another concern with fine particulates is trails in corners and crevices, which can permit sparks to travel some distance to other areas. Frictional forces can also cause ignition of fines due to pinch points and rubbing in machinery.

A good basic philosophy when handling thin section products of these materials and their alloys is to assume that at some time a fire will occur. Good housekeeping and careful logistics of material handling can limit the damage when a fire does occur.

One particularly insidious aspect of working with fine particulates of these materials is the inconsistency of reaction. There will be times when they seemingly cannot be ignited and others when the static from a poly bag or scuffing of a foot on hard surface will generate enough energy to cause ignition. A long period of "being lucky" can lead to a false sense of security.

FIRE PREVENTION AND PROTECTION

Extinguishment

Extinguishing a combustible metal fire is a difficult task when significant quantities of metals are involved. Portable Class D fire extinguishers or extinguishing agents specifically for the combustible metal involved may be used to control small fires. The basic principle of extinguishment is that the burning metal will have to be completely covered with a compatible agent. Given that portable fire extinguishers and wheeled fire extinguishing units have a limited quantity of agent, the amount of burning metal must be significantly less than the agent on hand can handle to achieve an effective extinguishment.

Most fires will involve multiple classes of burning material. Fire-fighting efforts to extinguish Class A materials with water will significantly increase the amount of fire and reactions with the combustible metals. The reaction from applying water to a combustible metal fire is exothermic and will result in violent reactions with potential explosions. The paradigm of applying water to a combustible metal fire to speed of the reaction is akin to applying gasoline to a house fire. The molecular structure of the water is broken down when applied to combustible metal releasing quantities of hydrogen and oxygen that contribute to the fire.

Application of water to combustible metals fires is, therefore, very risky and must be fully understood. The risk of applying water to a motor block that was machined out of magnesium is clearly not worth the risk of getting any fire fighter or bystander injured by the molten magnesium that will be thrown through the air. Putting the fire in perspective is a key element in the size-up of the fire scene.

Some combustible metals are processed with combustible liquids during machining or in packaging. A fire under these conditions will involve both Class B and Class D material burning simultaneously. The fire will likely continue to burn unless both classes of fire are extinguished together. Caution must be used if the combustible liquid in the fire has already been preheated to a temperature that will continue to produce vapors after the flame front has been extinguished. The resulting vapors have the potential to cause an explosion or flash fire.

Training and Planning

Inasmuch as the extinguishment of fires in combustible metals involves techniques not commonly encountered in conventional fire-fighting operations, it is good practice for those responsible for controlling combustible metal fires to gain experience in this area prior to an actual fire emergency. Fire fighters should practice extinguishing fires in those metals in an isolated outdoor location. Part of the practice should include the controlled application of water to a combustible metal fire to acquaint emergency responders with the risks associated with the application of water to a Class D fire.

A key element in being able to control a combustible metals fire is prefire planning. Fire departments responsible for protecting businesses or industries that use combustible metals need to be aware of the conditions that may be present on their arrival. A small machine shop in the jurisdiction may machine small quantities of combustible metals that would result in chips and fines in relatively small quantities. A manufacturing plant that uses very fine aluminum powder may have a significant fugitive dust problem throughout the processing area that could result in an explosion and total destruction of the building or processing area. Emergency response organizations, usually the fire department, must be aware of hazards prior to arrival at an emergency.

MAGNESIUM

Properties

The ignition temperature of massive magnesium is very close to its melting point of 1202°F (650°C) (Table 6.9.1). However, ignition of magnesium in certain forms may occur at temperatures well below 1202°F (650°C); magnesium ribbons and shavings can be ignited under certain conditions at about 950°F (510°C), and finely divided magnesium powder can ignite below 900°F (482°C).

TABLE 6.9.1 Melting, Boiling, and Ignition Temperatures of Pure Metals in Solid Form

	Temperature					
	Melting Point		Boiling Point		Solid Metal Ignition	
Pure Metal	*°F*	*°C*	*°F*	*°C*	*°F*	*°C*
Aluminum	1220	660	4445	2452	1832[a,b]	1000[b]
Barium	1337	725	2084	1140	347[a]	175[a]
Calcium	1548	842	2625	1441	1300	704
Hafnium	4032	2222	9750	5399	—	—
Iron	2795	1535	5432	3000	1706[a]	930[a]
Lithium	367	186	2437	1336	356	180
Magnesium	1202	650	2030	1110	1153	623
Plutonium	1184	640	6000	3316	1112	600
Potassium	144	62	1400	760	156[a,c]	69[a,c]
Sodium	208	98	1616	880	239[b]	115[b]
Strontium	1425	774	2102	1150	1328[a]	720[a]
Thorium	3353	1845	8132	4500	932[a]	500[a]
Titanium	3140	1727	5900	3260	2900[a]	1593
Uranium	2070	1132	6900	3816	6900[a,d]	3816[a,d]
Zinc	786	419	1665	907	1652[a]	900[a]
Zirconium	3326	1830	6470	3577	2552[a]	1400[a]

[a]Ignition in oxygen.
[b]Above indicated temperature.
[c]Spontaneous ignition in moist air.
[d]Below indicated temperature.

Metal marketed under different trade names and commonly referred to as "magnesium" may be one of a large number of different alloys containing principally magnesium, but also significant percentages of aluminum, manganese, and zinc. Some of these alloys have ignition temperatures considerably lower than that of pure magnesium, and certain magnesium alloys will ignite at temperatures as low as 800°F (427°C). Flame temperatures can reach 2500°F (1371°C), although flame height above burning metal is usually less than 12 in. (305 mm).

Thin, small pieces of magnesium, such as ribbons, chips, and shavings, may be ignited by a match flame, whereas castings and other large pieces are difficult to ignite even with a torch because of the high thermal conductivity of the metal. In order to ignite a large piece of magnesium, it is usually necessary to raise the entire piece to the ignition temperature. Magnesium melts as it burns and may form puddles of molten magnesium, which present explosion hazards in the presence of water.

Scrap magnesium chips or other fines may burn as the result of ignition of waste rags or other contaminants. Chips wet with water, water-soluble oils, and oils containing more than 0.2 percent fatty acid may generate hydrogen gas. Chips wet with animal or vegetable oils may burn if the oils ignite spontaneously. Fines from grinding operations generate flammable hydrogen when submerged in water, but the metal particles themselves cannot be ignited if kept immersed. If fines from grinding operations are stored in drums, adequate ventilation must be provided to prevent a buildup of hydrogen gas, which could explode when the drum is opened. Holes can be made in the lid or a nonsealing lid can be used. Grinding fines that are slightly wetted with water may generate sufficient heat to ignite spontaneously in air, burning violently as oxygen is extracted from the water with the release of hydrogen, which can also ignite.

Storage and Handling

The more massive a piece of magnesium, the more difficult it is to ignite. Once ignited, however, magnesium burns intensely and is difficult to extinguish. The storage recommendations in NFPA 484 take these properties into consideration. Recommended maximum quantities of various sizes and forms to be stored in specific locations are covered in this standard. The storage building should be noncombustible and the magnesium should be segregated from combustible material.

With easily ignited lightweight castings, segregation from combustible materials is especially important. In the case of dry fines and fine magnesium scrap, storage in noncombustible covered containers in separate fire-resistive storage buildings or rooms provided with explosion venting is preferable. For combustible buildings or buildings containing combustible contents, NFPA 484 recommends automatic sprinkler protection to ensure prompt control of a fire before the magnesium becomes involved.

Because of the possibility of hydrogen generation and of spontaneous heating of fines wet with coolants (other than neutral mineral oil), it is preferable to store wet scrap fines outdoors. Covered noncombustible containers should be vented.

Magnesium in powder, pellet, or ribbon form is shipped as a flammable solid and must be appropriately labeled according to U.S. Department of Transportation (DOT) requirements. Massive pieces or castings do not require special shipping safeguards.

Process Hazards

In machining operations involving magnesium alloys, sufficient frictional heat to ignite the chips or shavings may be created if the tools are dull or deformed. If cutting fluids are used (machining of magnesium is normally performed dry), they should be mineral-oil types that have high flashpoints. Water or water-oil emulsions are hazardous, since wet magnesium shavings and dust liberate hydrogen gas and burn more violently than dry material when ignited. Machines and the work area should be frequently cleaned and the waste magnesium kept in covered, clean, dry steel, or other noncombustible drums, which should be removed from the building at regular intervals. Magnesium dust clouds are explosive if an ignition source is present. Grinding equipment should be equipped with a liquid precipitation separator (Figures 6.9.2, 6.9.3, and 6.9.4) and should be interlocked with the liquid precipitation system so that it can operate only if the exhaust blower and water spray are functioning properly. The equipment should be restricted to magnesium processing only. Because the disposal of wet sludge presents a problem, NFPA 484 permits the use of dry cyclone collectors that are located and protected in accordance with that standard. Collection media are required to be located outside the building and protected in such a manner that an explosion or fire in the media collector will not injure personnel in the area.

Molten magnesium presents a serious fire problem if not properly handled. Sulfur dioxide or melting fluxes are commonly used to prevent oxidation or ignition of magnesium during foundry operations. The action of sulfur dioxide is to exclude air from the surface of the molten magnesium; it is not an extinguishing agent.

Pots, crucibles, and ladles that may contact molten magnesium must be kept dry to prevent steam formation or a violent

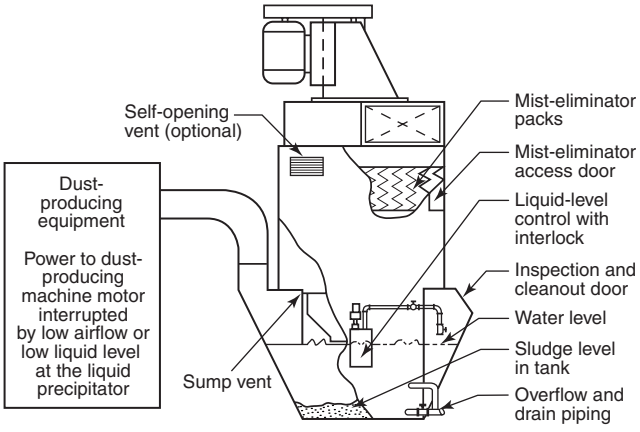

FIGURE 6.9.2 Typical Liquid Precipitation Collector for Fixed Dust-Producing Equipment (Source: NFPA 484, *Standard for Combustible Metals,* 2006 ed., Figure A.6.3.4.4(a))

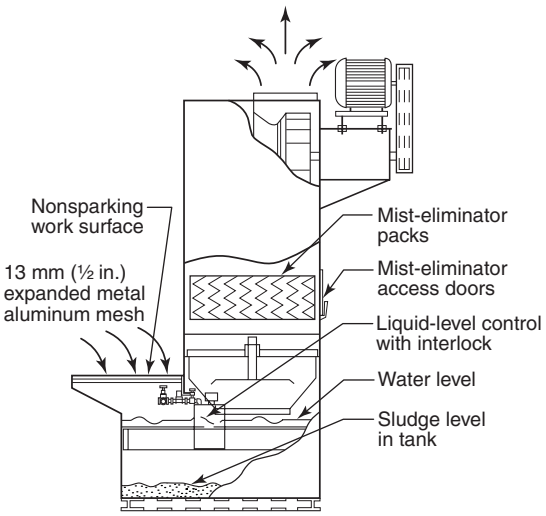

FIGURE 6.9.3 Typical Liquid Precipitation Collector for Portable Dust-Producing Equipment (Source: NFPA 484, *Standard for Combustible Metals,* 2006 ed., Figure A.6.3.4.4(b))

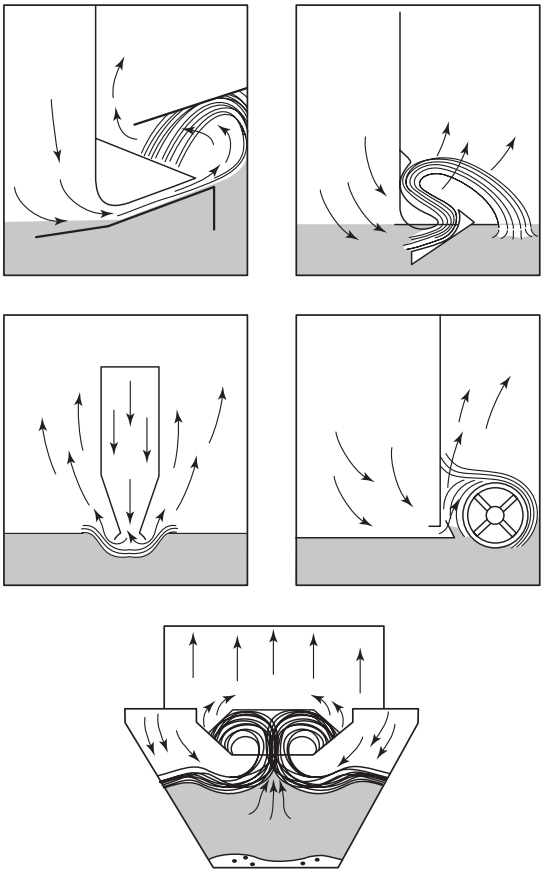

FIGURE 6.9.4 Five Methods of Precipitating Dust in Precipitators (Source: NFPA 484, *Standard for Combustible Metals,* 2006 ed., Figure A.6.3.4.4(c))

metal-water reaction. Containers should be checked regularly for any possibility of leakage or weak points. Steel-lined runoff pits or pits with tightly fitting steel pans should be provided, and the pans must be kept free of iron scale. Leaking metal contacting hot iron scale results in a violent thermite reaction. Use of stainless steel pans or linings will eliminate this possibility.

Heat-treating ovens or furnaces, where magnesium alloy parts are subjected to high temperatures to modify their properties, present another special problem. Temperatures needed to secure the desired physical properties are often close to the ignition temperatures of the alloys themselves and careful control of temperatures in all parts of the oven is essential. Hot spots leading to local overheating are a potential cause of these fires. Large castings do not ignite readily, but fine "casting fins" and sprues, as well as chips or dust, more readily ignite. For this reason, castings should be thoroughly cleaned before heat-treating. Magnesium castings in contact with aluminum in a heat-treating oven will ignite at a lower temperature than when placed on a steel car or tray.

Magnesium should not be heat-treated in nitrate salt baths. Certain commonly used molten mixtures of nitrates and nitrites can react explosively with magnesium and magnesium alloys, particularly at temperatures over 1000°F (538°C).

Fighting Magnesium Fires

Magnesium and its alloys present special problems in fire protection. Magnesium combines so readily with oxygen that, under some conditions, water applied to extinguish magnesium fires is decomposed into its constituent elements (i.e., oxygen and hydrogen). The oxygen combines with the magnesium and the released hydrogen burns and adds to the intensity of the fire. With the exception of the noble gases, such as helium and argon, none of the commonly available inert gases is suitable for extinguishing magnesium fires. The affinity of magnesium for oxygen is so great that it will burn in an atmosphere of carbon dioxide. Magnesium may also burn in an atmosphere of nitrogen to form magnesium nitride. For these reasons, any of the common extinguishing methods that depend on water, water solutions, or inert gases (other than the noble gases) are not effective on magnesium chip fires.

Halogen-containing extinguishing agents (halons and many halon replacement agents) react violently with burning magnesium, the chlorine or other halogen combining with the magnesium. However, inerting with noble gases (e.g., helium or argon) will extinguish burning metal.

The method of extinguishing magnesium fires depends largely on the form of the material. Burning chips, shavings, and small parts must be smothered and cooled with a suitable dry extinguishing agent (e.g., graphite and dry sodium chloride). Where magnesium dust is present, care must be taken to prevent a dust cloud from forming in the air during application of the agent because this may result in a dust explosion.

Fires in solid magnesium can be fought without difficulty if attacked in their early stages. Often it may be possible to remove surrounding material, leaving the small quantity of magnesium to burn itself out harmlessly. Considering the importance of prompt attack on magnesium fires, automatic sprinklers are

desirable because they provide automatic notification and control of fire. Although the water from the sprinklers may have the immediate effect of intensifying magnesium combustion, it will serve to protect the structure and prevent ignition of surrounding combustible material.

Magnesium fires in heat-treating ovens can best be controlled with powders and gases developed for use on such fires. By using melting fluxes to exclude air from the burning metal, fires in heat-treating furnaces can be successfully extinguished. Boron trifluoride gas is an effective extinguishing agent for small fires in heat-treating furnaces.

TITANIUM

Properties

Titanium, like magnesium, is classified as a combustible metal, but here again the size and shape of the metal determine to a great extent the ease of ignition. Castings and other massive pieces of titanium are not combustible under ordinary conditions; however, they can burn in the presence of other burning fuels or in high-oxygen atmospheres. Small chips, fine turnings, and dust ignite readily and, once ignited, burn with the release of large quantities of heat. Tests have shown that very thin chips and fine turnings can be ignited by a match, and heavier chips and turnings can be ignited by a Bunsen burner. Coarse chips and turnings 1/32 in. by 3/28 in. (0.79 mm by 2.7 mm) or larger may be considered as difficult to ignite, but, unless it is known that smaller particles are not mixed with the coarser material, it is wise to assume that easy ignition is possible.

Dry titanium fines collected in cyclone separators can ignite spontaneously when allowed to drop freely through the air. Ignition temperatures of titanium dust clouds in air range from 630 to 1090°F (332 to 588°C) and of titanium dust layers from 720 to 950°F (382 to 510°C). Titanium dust can be ignited in atmospheres of carbon dioxide or nitrogen. Titanium surfaces that have been treated with nitric acid, particularly with red fuming nitric acid containing 10 to 20 percent nitrogen tetroxide, become pyrophoric and may be explosive.

Fine titanium chips coated with water-soluble oil have spontaneously ignited. The unusual conditions under which massive titanium shapes will ignite spontaneously include contact with liquid oxygen, in which case they can detonate on impact. It has been found that under static conditions, spontaneous ignition will take place in pure oxygen at pressures of at least 350 psi (2413 kPa). If the oxygen was diluted, the required pressure increased, but in no instance did spontaneous heating occur in oxygen concentrations less than 35 percent. Another requirement for spontaneous heating is a fresh surface that oxidizes rapidly and exothermically in an oxygen atmosphere.[1]

Storage and Handling

Titanium castings and ingots are so difficult to ignite and burn that special storage recommendations for large pieces are not included in NFPA 484. Titanium sponge and scrap fines, on the other hand, do require special precautions, such as storage in covered metal containers and segregation of the containers from combustible materials. Because of the possibility of hydrogen generation in moist scrap and spontaneous heating of scrap wet with animal or vegetable oils, a yard storage area remote from buildings is recommended for scrap that is to be salvaged. Alternate recommended storage locations are detached scrap storage buildings and fire-resistant storage rooms. Buildings and rooms for storage of scrap fines should have explosion vents.

Process Hazards

Contact of molten metal with water is the principal hazard during titanium casting. To minimize this hazard, molds are usually thoroughly predried and vacuum or inert gas protection is provided to retain accidental spills.

The heat generated during machining, grinding, sawing, and drilling of titanium may be sufficient to ignite the small pieces formed by these operations or to ignite mineral-oil-based cutting lubricants. Consequently, water-based coolants should be used in ample quantity to remove heat and cutting tools should be kept sharp. Fines should be removed regularly from work areas and stored in covered metal containers. To prevent titanium dust explosions, any operation that produces fugitive dust should be equipped with a dust collecting system discharging into a liquid precipitation separator (see Figures 6.9.2, 6.9.3, and 6.9.4).

Descaling baths of mineral acids and molten alkali salts may cause violent reactions with titanium at abnormally high temperatures. Titanium sheets can ignite upon removal from descaling baths. This hazard can be controlled by careful regulation of bath temperatures.

Titanium melting furnaces use an electric arc to melt a consumable electrode inside a water-cooled crucible maintained under a high vacuum. Stray arcing between the consumable electrode and crucible, resulting in penetration of the crucible, permits water to enter and react explosively with the molten titanium. Indications are that such explosions can approach extreme velocities. The design and operation of these furnaces require special attention in order to prevent explosions and to minimize damage when explosions do occur.

Fighting Titanium Fires

Carbon dioxide, foam, and dry chemical extinguishers are not effective on titanium fires, but good results can be obtained with extinguishing agents developed for use on magnesium fires. The safest procedure to follow with a fire involving small quantities of titanium powder is to ring the fire with a Class D fire extinguishing agent or materials that have been found to be effective in the control of combustible metal fires and allow the fire to burn itself out. Care should be taken to prevent formation of a titanium dust cloud by the application of high velocity extinguishing agents.

ALKALI METALS: SODIUM, POTASSIUM, NaK, AND LITHIUM

Properties

Sodium. At room temperature, sodium oxidizes rapidly in moist air, but spontaneous ignitions have not been reported except when the sodium is in a finely divided form. When heated

in dry air, sodium ignites in the vicinity of its boiling point (1616°F [880°C]). Sodium in normal room air and at a temperature only slightly above its melting point (208°F [98°C]) has been ignited by placing sodium oxide particles on its surface. This indicates the possibility of ignition at temperatures below the boiling point. Once ignited, hot sodium burns vigorously and forms dense white clouds of caustic sodium oxide fumes. During combustion, sodium generates about the same amount of heat as an equivalent weight of wood.

The principal fire hazard associated with sodium is its rapid reaction with water. It floats on water (density 0.97), reacting vigorously and melting. The hydrogen liberated by this reaction may be ignited by the heat of the reaction. Sodium (like other burning, reactive metals) reacts violently with halogenated hydrocarbons, with halogens (e.g., iodine) and with acids.

Potassium. The fire hazard properties of potassium are very similar to those of sodium, with the difference being that potassium is usually more reactive. For example, the reaction between potassium and the halogens is more violent and, with bromine, a detonation can occur. There is also an explosive reaction with sulfuric acid. Unlike sodium, potassium forms some peroxides during combustion. These peroxides may react violently with organic contaminants. Unreacted potassium may form an oxide known as potassium superoxide, KO_2. This oxide is bright yellow in color and can be shock sensitive in the presence of organics.

NaK (Sodium-Potassium Alloys). "NaK" is the term used when referring to any of several sodium-potassium alloys. The various NaK alloys differ from each other in melting point, but all are liquids or melt near room temperature. NaK alloys possess the same fire hazard properties as those of their component metals, except that the reactions are more vigorous. Under pressure, NaK leaks have ignited spontaneously.

Lithium. Lithium undergoes many of the same reactions as sodium. For example, both react with water to form hydrogen, but whereas the sodium-water reaction can generate sufficient heat to ignite the hydrogen, the far less violent lithium-water reaction does not. On the other hand, the lack of ignition may cause a buildup of hydrogen gas in the area, which could lead to an explosive cloud of hydrogen. Therefore, adequate ventilation must be ensured.

Lithium ignites and burns vigorously at a temperature of 356°F (180°C), which is near its melting point. Unlike sodium and potassium, it can burn in nitrogen. Noble gases, such as helium and argon, are used for inerting in equipment and storage containers involving lithium. The caustic (oxide and nitride) fumes accompanying lithium combustion are more profuse and dense than those of other alkali metals burning under similar conditions. Lithium is the lightest of all metals. During combustion, it tends to melt and flow.

Storage and Handling

Because of their reactivity with water, alkali metals require special precautions to prevent contact with moisture. Drums and cases should be stored in a dry fire-resistant room or building used exclusively for alkali metal storage. Since sprinkler protection would be undesirable, no combustible materials should be stored in the same area. However, if exposure fires could jeopardize equipment containing alkali metals, sprinkler protection should be considered and is permitted by NFPA 484 for lithium storage. It is good practice to store both empty and filled alkali metal containers in the same area, and all containers should be on metal skids. There should be no water or steam pipes, but sufficient heat should be maintained to prevent moisture condensation due to atmospheric changes. Ventilation at a high spot in the room is desirable to vent any hydrogen that may be released by accidental contact of alkali metal with moisture.

Large quantities of alkali metal are often stored outdoors in aboveground tanks. In such installations weatherproof enclosures should cover tank manholes and the free space within the tank should contain a nitrogen atmosphere. Argon or helium atmospheres should be substituted for nitrogen in the case of lithium.

Lithium is routinely stored and shipped with a light coating of mineral oil over the ingot. In some cases, the lithium is submerged in dry mineral oil for long-term storage or transportation.

Dry alkali metal is customarily shipped in watertight steel barrels or drums. It is also shipped as a solid in tank-car quantities. The DOT specifies the type of barrels, drums, and tank cars that are to be used in interstate transportation.

Transfer of an alkali metal to and from tank cars and storage tanks requires heating the metal to its melting point. This is accomplished by circulating hot oil through pipes within the tank. The alkali metal is transferred by evacuating a receiver with a vacuum pump and, as the metal is removed from the tank, it is replaced by nitrogen. An alkali metal-level indicator should be provided and a low-pressure warning device should be part of the nitrogen system.

An alkali metal covered with an organic solvent may be shipped in 1 qt (946 mL) metal cans, each can placed in another can and cushioned with soda ash. The cans are shipped in wood boxes of 100 lb (45.4 kg) maximum gross weight. Liquid alkali metal alloys may be shipped in pressure-tested metal vessels that are purged with an inert cover gas.

For small-scale transfer of solid alkali metal from a storage area to its area of use, a metal container with a tight cover is recommended. Alkali metal should be removed from storage in as small quantities as practicable. When stored on workbenches, it should be kept under kerosene or oil in a closed container. Alkali metal, with its great affinity for moisture, may react at the time it is sealed in a container with any atmospheric moisture. Due to the possible presence of hydrogen, containers should not be opened by hammering on the lid.

Process Hazards

Liquid alkali metals are valuable as high-temperature heat transfer media. For example, they are used in hollow exhaust valve stems in some internal combustion engines and in the transfer of heat from one type of nuclear reactor to a steam generator.

In the latter process or in other large-scale uses of molten alkali metal, any equipment leak may result in a fire. Where molten alkali metal is used in process equipment, steel pans are located underneath to prevent contact and violent reaction of burning sodium with concrete floors.

Processing of alkali metal involves essentially melting it to form sticks or bricks or to add it as a liquid to closed transfer systems. During this handling, contact with moist air, water, halogens, halogenated hydrocarbons, and sulfuric acid must be avoided.

Fighting Sodium, Potassium, NaK, and Lithium Fires

The common extinguishing agents, such as water, foam, and vaporizing liquids, should never be used because of the violent reactions of alkali metals with these agents. Special dry powders (essentially graphite) developed for metal fires, dry sand, dry sodium chloride, dry lithium chloride, and dry soda ash can be effective. These finely divided materials blanket the fire while the metal cools to below its ignition temperature. Alkali metal burning in an apparatus can usually be extinguished by closing all openings.

For sodium, potassium, and NaK, blanketing with nitrogen is also effective. In the case of lithium, argon or helium atmospheres should be used instead of nitrogen. Copper powder is a very effective extinguishing agent for lithium fires.

When alkali metals are handled in solidified form in tanks or drums and hot oil heating is required, the extinguishing agents to be used for any hot oil spill fire must be compatible with the alkali metal. Usually, large dry powder systems are used.

Fire residue can contain unburned alkali metal and must be promptly cleaned up and disposed of.

ZIRCONIUM AND HAFNIUM

Properties

Zirconium. The combustibility of zirconium appears to increase as the average particle size decreases, but other variables, such as moisture content, also affect its ease of ignition. In massive form, zirconium can withstand extremely high temperatures without igniting, whereas both clouds and layers of dust in which the average particle size is about 3 microns can spontaneously ignite at room temperature. Spontaneous heating and ignition are also possibilities with scrap chips, borings, and turnings if fine dust is present.

Dust clouds of larger particle size can be readily ignited if an ignition source is present and such explosions can occur in atmospheres of carbon dioxide or nitrogen just as well as in air. Zirconium dust will ignite in carbon dioxide at approximately 1150°F (621°C) and in nitrogen at approximately 1450°F (788°C). A cloud of zirconium dust in air presents a serious flash-fire hazard, in addition to its potential explosion hazard. Combustion of zirconium dust in air is stimulated by the presence of limited amounts (5 to 10 percent) of water. When very finely divided zirconium powder is completely immersed in water, it is difficult to ignite, but once ignited it burns more violently than in air. With respect to layers of the dust, the depth of the layer and its moisture content are important variables for ignition. Layers of 6-micron-diameter dust can ignite when heated to 374°F (190°C).

Massive pieces of zirconium do not ignite spontaneously under ordinary conditions, but ignition will occur when an oxide-free surface is exposed to sufficiently high oxygen concentrations and pressure. The explanation for this reaction is the same as that cited for a similar titanium reaction. Zirconium fires (like fires involving titanium and hafnium) attain very high temperatures but generate very little smoke.

Explosions can occur while zirconium is being dissolved in a mixture of sulfuric acid and potassium acid sulfate. Zirconium can explode during and following pickling in nitric acid, and also during treatment with carbon tetrachloride or other halogen-containing materials. Spontaneous explosions can occur during handling of moist, very finely divided, contaminated zirconium scrap.

Hafnium. Hafnium has combustion properties similar to those of zirconium. Hafnium burns with very little flame, but it releases large quantities of heat. Unless inactivated, hafnium in sponge form may ignite spontaneously.

Hafnium is generally considered to be somewhat more reactive than titanium or zirconium of similar form. Damp hafnium powder reacts with water to form hydrogen gas, but at ordinary temperatures this reaction is not sufficiently vigorous to cause the hydrogen to ignite. Under some conditions, however, ignition of the hydrogen may be expected to proceed explosively.

Storage and Handling

Special storage precautions are not required for zirconium castings because of the very high temperatures massive pieces of the metal can withstand without igniting. Zirconium powder, on the other hand, is highly combustible; consequently, it is customarily stored and shipped in 1 gal (3.8 L) containers with at least 25 percent water by volume. For specific details, refer to NFPA 484.

Zirconium powder storerooms should be of fire-resistant construction equipped with explosion vents. Cans should be separated from each other to minimize the possibility of a fire in one can spreading to others and to permit checking of the cans periodically for corrosion. Some manufacturers of zirconium have established the practice of disposing of cans containing powder that have been on the shelf for six months.

Process Hazards

In general, processing recommendations for zirconium and hafnium are the same. Whenever possible, handling of zirconium powder should be under an inert liquid or in an inert atmosphere. An inert atmosphere of argon or helium in equipment and storage containers is a method used to prevent flash fires and explosions. If zirconium or hafnium powder is handled in air, extreme care must be used because the small static charges generated may cause ignition.

To prevent dangerous heating during machining operations, a large flow of mineral oil or water-based coolant is required. In some machining operations, the cutting surface is completely immersed. Turnings should be collected frequently and stored under water in cans. Where zirconium dust is a by-product, dust-collecting equipment that discharges into a liquid precipitation separator is a necessity (see Figures 6.9.2, 6.9,3, and 6.9.4).

Fighting Zirconium and Hafnium Fires

Zirconium and hafnium fires can be fought in the same way. Fires exposing massive pieces of zirconium, for example, can be fought with water. The discharge of water as a spray has no adverse effect on burning zirconium turnings. When a sprinkler opens directly above an open drum of burning zirconium scrap, there is a brief flare-up, followed by continued quiet burning. When a straight stream of water at a high rate of flow is discharged into the drum, water overflows and the fire is extinguished.

Where small quantities of zirconium powder or fines are burning, the fire can be ringed with a Class D extinguishing agent or other agents that have been shown to be effective with zirconium to prevent its spread. After the fire has been contained, the fire can be allowed to burn out. Special extinguishing powders can be effective in extinguishing small zirconium fires. When zirconium dust is present, the extinguishing agent should be applied gently, so that a dust cloud is not formed. If the fire is in an enclosed space, it can be smothered by introducing argon or helium.

CALCIUM AND ZINC

Properties

Calcium. The flammability of calcium depends considerably on the amount of moisture in the air. If ignited in moist air, it burns without flowing and at a somewhat lower rate than sodium. It decomposes in water to yield calcium hydroxide and hydrogen, which may burn if ignited by the heat of the reaction. Finely divided calcium will ignite spontaneously in air. It should be noted that barium and strontium are similar to calcium in their fire properties.

Zinc. Zinc does not introduce a serious fire hazard in sheets, castings, or other massive forms because of its difficulty of ignition. Once ignited, however, large pieces burn vigorously. Moist zinc dust reacts slowly with the water to form hydrogen, and, if sufficient heat is released, ignition of the dust can occur. Zinc dust clouds ignite in air at 1110°F (599°C). Burning zinc generates appreciable smoke.

Storing, Processing, and Fighting Calcium and Zinc Fires

The requirements of NFPA 484 for magnesium can be applied to calcium and zinc.

ALUMINUM

Properties

The usual forms of aluminum have a sufficiently high ignition temperature so that its burning is not a factor in most fires (see Table 6.9.1). However, aluminum can burn vigorously in the presence of other burning materials. In particular, aluminum in contact with magnesium burns readily, perhaps due to the formation of an alloy at the interface. Very fine chips and shavings are occasionally subject to somewhat the same type of combustion as described for magnesium.

Aluminum pastes are subject to fires, especially where the paste is solvent-wet and the solvent vapors have a low ignition temperature. Dry aluminum powder or flake is capable of exploding under some conditions, if the surface of the particles has not oxidized sufficiently. The degree of explosivity increases as the particle size decreases. NFPA 484 provides requirements for the storage and handling of aluminum powders, flakes, and pastes.

Aluminum processing and finishing operations, such as machining, sawing, grinding, or buffing, produce fines and dust that are highly explosive. The dust collection systems for such operations are also subject to fires or explosions. Wet or dry collectors can be used. Requirements for collector installation are provided in NFPA 484. Collectors for aluminum must be dedicated to the collection of aluminum since the collection of iron or steel can lead to a thermite-type reaction in the system. Dust collections systems are located outdoors to help in the mitigation of damage should an explosion occur.

Fire Suppression

Extinguishing agents for aluminum fires depend on the form of the aluminum. For example, a fire in other combustible materials usually ignites large castings. These fires can be extinguished with large quantities of water or other typical fire-extinguishing agents. Fires involving aluminum fines or powder, however, must be treated carefully to prevent the dispersal of the material into the air where it often explodes. Such fires are best handled by hand application of dry sand or a Class D extinguishing agent. Water, dry powder, carbon dioxide, or halogen-containing agents must not be used.

RADIOACTIVE METALS

Radioactivity does not influence nor is it influenced by the fire properties of a metal. Radioactive metals include those few that occur naturally (e.g., uranium and thorium) and those produced artificially (e.g., plutonium and cobalt-60). Since radioactivity cannot be altered by fire, radiation will continue wherever the metal is spread during a fire. Smoke from fires involving radioactive materials can cause more property damage than the fire. The damage, however, is not physical, but results from radioactive contamination that must be cleaned up to avoid exposure.

Naturally occurring radioactive metals consist of a mixture of atoms having slightly different mass. These are called isotopes. For example, the radioactivity of each uranium isotope is different and it follows that the radiation hazards from any given

piece of uranium will change with its isotopic composition, which can be varied by special processing. Change of isotopic content of a piece of uranium alters the nature and magnitude of its radiation hazard but does not alter its chemical or fire properties. The same is equally true of thorium and plutonium.

Uranium, thorium, and plutonium are easily ignited in the form of chips, turnings, and fines. They will react slowly with water to form hydrogen. In addition, collection of fines under water in containers larger than 1 gal (3.8 L) can result in a fire as the water is not able to cool the fines at the center of the containers. The fines at the center of the mass produce heat and hydrogen. The heat is sufficient to boil off the water and ignite the remaining fines in the container. Limiting collection of fines to quantities less than 1 gal (3.8 L) in volume has been shown to be effective in preventing spontaneous ignition.

Uranium

Normal uranium is a radioactive metal that is also combustible. Its radioactivity does not affect its combustibility but can have a bearing on the significance of the fire loss. Most metallic uranium is handled in massive forms that do not present significant fire risk unless exposed to a severe and prolonged external fire. Once ignited, the massive metal burns very slowly. A 1-in. (25.4-mm) diameter rod requires about one day to burn out after ignition. In the absence of strong drafts, uranium oxide smoke, due to its density, tends to deposit in the immediate area of the burning metal. Unless covered with oil, massive uranium burns with virtually no visible flame. Burning uranium will react violently with carbon tetrachloride, 1,1,1 trichloroethane, the halons, and many halon replacements. For power reactors, uranium fuel elements are always encased in a metal jacket (usually zirconium or stainless steel).

Uranium in finely divided form is readily ignited, and uranium scrap from machining operations is subject to spontaneous ignition. This reaction can usually be avoided by storage under a coolant (oil- or water-based). Moist dust, turnings, and chips react slowly with water to form hydrogen. Containers used to store uranium with water-based coolants, water, or stored underwater, must be vented to prevent the buildup of hydrogen. Grinding dust can ignite even under water and fires can occur spontaneously in drums of coarser scrap after prolonged exposure to moist air. Disposal of chips and fines in a timely manner is essential to managing the fire risk. Larger pieces generally have to be heated en masse to their ignition temperature before igniting. Uranium surfaces treated with concentrated nitric acid are subject to explosion or spontaneous ignition in air.

Thorium

Thorium, like uranium, is a naturally occurring element. Both are known as "source materials," the basic materials from which nuclear reactor fuels are produced. The powdered form of thorium requires special handling techniques because of its low ignition temperature. In the dry state, it must be handled under a helium or argon atmosphere. The dry metal powder should not be in air because even the friction of the particles falling through the air or against the edge of a glass container may produce electrostatic ignition of the powder.

Powdered thorium is usually compacted into solid pellets weighing about 1 oz (28 g) each. In this form it can be safely stored or converted into alloys with other metals. Improperly compacted thorium pellets have been known to slowly generate sufficient heat through absorption of oxygen and nitrogen from the air to raise a steel container to red heat.

Thorium is handled by remote control due to the toxicological effects of the metal.

Plutonium

Plutonium is somewhat more susceptible to ignition than uranium and is normally handled by remote control in an inert gas. In finely divided form, such as dust or chips, plutonium is subject to spontaneous ignition in air.

Plutonium metal is generally not exposed to water, in part because of fire considerations. The massive metal ignites at about 1112°F (600°C) and burns in a manner quite similar to uranium, except that plutonium oxide smoke damage (i.e., airborne radioactive contamination) is more difficult to control and also more hazardous. The steam generated by the use of water on a plutonium fire significantly increases the spread of contamination. Because of certain nonfire hazard considerations, it is necessary to limit the quantity of plutonium kept at one location, thus limiting the maximum size of a fire in this metal. Plutonium, which ignites spontaneously, is normally allowed to burn under conditions limiting both fire and radiological contamination spread.

Fire Suppression

Prefire planning is particularly important where radioactive materials are involved. Automatic sprinkler protection is generally provided for facilities containing radioactive materials. However, in general, the use of water to control a radioactive metal fire is not recommended due to the generation of steam that is likely to spread contamination throughout the area of the fire and beyond. Fires involving uranium, thorium, and plutonium burn relatively quickly through fines and turnings. Limiting the amount of turnings throughout the machining area is important so that a small, localized fire does not propagate to other turnings or combustible materials that may be located in the machining area. Fire tests have shown that providing an air gap of approximately 4 in. (100 mm) between containers used to collect chips and turnings can prevent propagation of a fire from one container to another.

Due to the radioactive contamination that is produced during a fire, manual intervention is not recommended unless a self-contained breathing apparatus (SCBA) is worn. The worst type of exposure to the radioactive metals is inhalation and ingestion.

METALS NOT NORMALLY COMBUSTIBLE

Iron and Steel

Iron and steel are not usually considered combustible; in massive form, as in structural steel and cast-iron parts, they do not

burn in ordinary fires. In the form of fine wool or dust, however, they can be ignited by the flame of a torch or the sparks from a grinding operation. Fires can occur in piles of steel turnings and fines that contain some oil and other materials that might facilitate combustion. Spontaneous ignition of water-wet borings and turnings in closed areas, such as in the cargo hold of a ship, can also occur.

SUMMARY

Combustible metals are metals that have either combustible or explosive properties because of their inherent properties or because of their physical form. Nearly all metals will burn in air under certain conditions. Metals, such as magnesium, titanium, sodium, potassium, sodium-potassium alloys, lithium, zirconium, hafnium, calcium, and zinc, are easily ignited and have certain properties that impact their storage, handling, and processing. The processing of aluminum can generate dusts that are highly explosive. Other metals, such as iron and steel, are not normally considered combustible. Radioactive metals present special hazards because their radioactivity is not altered by fire and the effects of radioactive contamination must be a consideration during fire-fighting activities.

Good housekeeping, removal of turnings, chips and fines, and the collection of fugitive dust are essential in the processing, machining, and handling of combustible metals. Failure to follow the basic principles of handling combustible metals is likely to result in significant fire loss and the potential of personal injury.

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NFPA 484, *Standard for Combustible Metals*

NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*

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Chapter 10

Gases

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Chapter Contents

Gases Defined
Classification of Gases
Basic Hazards of Gases
Gas Emergency Control
Specific Gases

Key Terms

boiling liquid expanding vapor explosion (BLEVE), compressed gas, corrosive gas, cryogenic gas, deflagration, explosion, flammable gas, gas, liquefied gas, nonflammable gas, overpressure, pyrophoric gas, reactive gas, toxic gas

The term *gas* describes the physical state of a substance that has no shape or volume of its own but will take the shape of and fill the entire volume of whatever container or other enclosure it occupies. This state is in contrast to a liquid, which has no shape of its own but does have volume, and to a solid, which has both its own shape and volume. Gases are composed of extremely minute particles in constant motion. This motion affects the properties and behavior of gases, for example, the higher the temperature, the more rapid the motion.

The categories of gases described in this chapter are consistent with those found in NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks,* which was first issued in 1993. The categories in NFPA 55, in turn, are the same as those used by the U.S. Department of Transportation for labeling requirements for shipments of gases.

The goal of this chapter is to provide information on the properties of gases, their classification, and the equipment needed to store gases safely, including key safety devices. It explains boiling liquid expanding vapor explosion (BLEVE), an important and frequently misunderstood failure mode of liquefied compressed gases, and other types of gas explosions. Information is provided on the properties of selected gases. The chapter also provides information on the properties, storage, and hazards of gases for fire safety professionals. The hazards that gases present in storage differ from those presented when gases escape—both kinds of hazards are discussed along with the control measures to follow in an emergency. The chapter concludes with a summary of the properties and behavior of some common gases. For each gas, information is provided about its classification, chemical properties, physical properties, usage, hazards inside containers, hazards when released from containment, and emergency control.

For additional information see Section 2, Chapter 8, "Explosions"; Section 7, Chapter 3, "Storage of Gases"; Section 9, Chapter 17, "Oxygen-Enriched Atmospheres"; Section 17, Chapter 4, "Foam Extinguishing Agents and Systems"; and Section 17, Chapter 8, "Explosion Prevention and Protection."

GASES DEFINED

Because all substances can exist as gases, depending on the temperature and pressure applied to them, the term *gas,* as used in this chapter, is applied only to substances that exist in the gaseous state at normal temperature and pressure (NTP) conditions—approximately 70°F (21°C) and 14.7 psia (an absolute pressure of 101 kPa). However, even at normal or near NTP conditions, many substances can exist as either liquids or gases. The terms *gas* and *flammable liquefied gas* are defined in NFPA 55 as follows:

> *Flammable Gas.* A material that is a gas at 20°C (68°F) or less at an absolute pressure of 101.325 kPa (14.7 psia), that is ignitable at an absolute pressure of 101.325 kPa (14.7 psia) when in a mixture of 13 percent or less by volume with air, or that has a flammable range at an absolute pressure of 101.325 kPa (14.7 psia) with air of at least 12 percent, regardless of the lower limit.

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Flammable Liquefied Gas. A liquefied compressed gas that, when under a charged pressure, is partially liquid at a temperature of 20°C (68°F) and is flammable.

These definitions are the same as those used in U.S. Department of Transportation regulations and, therefore, are identical to the definitions used for labeling of gases in transportation in the United States. These definitions are essentially identical to those used in United Nations protocols for international gas shipments.

CLASSIFICATION OF GASES

Classification According to NFPA 55

The classifications of gases from NFPA 55 are as follows:

1. Physical hazards, which include the following:
   - Flammable gas
   - Nonflammable gas
   - Oxidizing gas
   - Pyrophoric gas
   - Unstable reactive (detonable) gas, Class 3 or Class 4
   - Unstable reactive (nondetonable) gas, Class 2 or Class 3
2. Health hazards, which include the following:
   - Corrosive gas
   - Cryogenic fluids
   - Highly toxic gas
   - Toxic gas
   - Irritant gas

Flammable Gases. The definition of *flammable gas* has been provided previously. Every flammable gas has a lower and upper flammable limit. Mixtures of a flammable gas and air will ignite only within this range of flammability and when the minimum ignition energy is provided. In a few cases, the narrow width of the flammable range or a high lower limit of flammability, or both, results in classification of a gas that can be made to burn in air as nonflammable because the chances of ignition of the gas in air is low under most conditions. Anhydrous ammonia is an example of such a gas. Although it is a flammable gas in the context of the previous paragraph, it is classified by the U.S. Department of Transportation (DOT) as a nonflammable gas for purposes of transportation in interstate commerce.

The term "explosive range" is sometimes used as a synonym for flammable range for flammable gases. With the extensive work done on the use of hydrogen as a vehicle fuel, it has been determined that hydrogen has an explosive range that is different from the flammable range. (The explosive range is narrower than the flammable range.) Because of this difference, care must be taken to use the correct terms, and although to date hydrogen is the only gas with a recognized, published explosive range, the term should not be used except when dealing with hydrogen.

Although flammable liquid vapors and flammable gases exhibit similar combustion characteristics, the term *flashpoint,* which describes a common and useful combustion property of flammable liquids, has no practical significance for flammable gases. The flashpoint is the temperature at which a flammable liquid produces sufficient vapors for ignition to occur. This temperature is always below the normal boiling point. A flammable gas exists normally at a temperature exceeding its normal boiling point, even when the gas is in the liquid state (as it often is in shipment and storage). Therefore, a flammable gas exists at a temperature that not only exceeds its flashpoint but also that is usually well above it. In other words, a flammable liquid must be above a certain temperature (flashpoint) to produce sufficient vapors to ignite while flammable gases can always ignite.

Nonflammable Gases. Nonflammable gases are those that will not burn in any concentration of air or oxygen. Among the most common are nitrogen, argon, helium, and other rare gases in the atmosphere, as well as carbon dioxide and sulfur dioxide. (There are some metals, however, that are combustible and can react vigorously in carbon dioxide or nitrogen atmospheres, e.g., magnesium.) Although oxidizing gases are nonflammable, they are categorized separately by NFPA 55.

Pyrophoric Gases. Pyrophoric gases are flammable gases that spontaneously ignite in air. Examples are silane and phosphine. Their storage is of special concern, as they do not require a source of ignition to burn. They are not used widely but are most likely to be found in semiconductor manufacturing facilities.

Oxidizing Gases. Oxidizing gases support combustion. They are generally either oxygen or mixtures of oxygen and other gases, such as oxygen-helium or oxygen-nitrogen mixtures, or certain gaseous oxides, such as nitrous oxide. These mixtures contain considerably more oxygen than is present in the oxygen-nitrogen mixture that comprises air. Oxygen and nitrous oxide are examples of oxidizing gases.

Unstable Reactive Gases. Unstable reactive gases are gases that, in the pure state or as commercially produced, will vigorously polymerize, decompose, or condense, become self-reactive, or otherwise undergo a violent chemical change under conditions of shock, pressure, or temperature.

Class 2 Unstable Reactive Gas. A Class 2 unstable reactive gas is a material that readily undergoes violent chemical change at elevated temperatures and pressures.

Class 3 Unstable Reactive Gas. A Class 3 unstable reactive gas is a material that is itself capable of detonation or explosive decomposition or explosive reaction but that requires a strong initiating source or that must be heated under confinement before initiation.

Class 4 Unstable Reactive Gas. A Class 4 unstable reactive gas is a material that is itself readily capable of detonation or explosive decomposition or explosive reaction at normal temperatures and pressures.

Corrosive Gases. Corrosive gases are gases that causes visible destruction of or irreversible alterations in living tissue by chemical action at the site of contact.

Cryogenic Gases. Cryogenic gases are liquefied gases that exist in their container at temperatures below –130°F (–90°C). A principal reason for this distinction with respect to a liquefied gas is that a cryogenic gas cannot be retained indefinitely in a container. Heat from the atmosphere, which can be slowed but not prevented from entering the container, continually raises the container pressure. If the gas is confined, the resulting pressure could greatly exceed any feasible container strength.

These descriptions of gas classifications by physical properties pertain only to usage in context of this chapter. Somewhat different descriptions of the terms *compressed gas, liquefied gas,* and *cryogenic gas* can be found in codes and regulations, particularly the DOT hazardous materials regulations applicable to interstate transportation. For example, in the United States, many liquefied gases are classified as compressed gases by DOT. Some pertinent physical properties of cryogenic gases, are given in Table 6.10.1.

Toxic Gases. Certain gases can present a serious life hazard if they are released into the atmosphere. These gases, which are poisonous or irritating when inhaled or contacted, include chlorine, hydrogen sulfide, sulfur dioxide, ammonia, carbon monoxide, and arsine. The presence of these gases may complicate fire-fighting efforts by exposing fire fighters to a toxicity hazard. Toxic gases are labeled "poison gas" for shipment.

Toxic Gas. A toxic gas is a gas with a median lethal concentration (LC50) in air of more than 200 ppm, but not more than 2000 ppm by volume of gas or vapor, or more than 2 mg/L, but not more than 20 mg/L of mist, fume, or dust, when administered by continuous inhalation for 1 hour (or less if death occurs within 1 hour) to albino rats weighing between 0.44 and 0.66 lb (200 and 300 g) each.

Highly Toxic Gas. A highly toxic gas is a chemical that has a median lethal concentration (LC50) in air of 200 ppm by volume or less of gas or vapor, or 2 mg/L or less of mist, fume, or dust, when administered by continuous inhalation for 1 hour (or less if death occurs within 1 hour) to albino rats weighing between 0.44 lb and 0.66 lb (200 g and 300 g) each.

Irritant Gas. An irritant gas is a chemical that is not corrosive but that causes a reversible inflammatory effect on living tissue by chemical action at the site of contact. A chemical is a skin irritant if, when tested on the intact skin of albino rabbits by the methods of 16 CFR 1500.41, for an exposure of 4 or more hours or by other appropriate techniques, it results in an empirical score of 5 or more. A chemical is classified as an eye irritant if so determined under the procedure listed in 16 CFR 1500.42, or other appropriate techniques.

Classification by Physical Properties

Physical properties are of primary fire protection concern because they affect the physical behavior of gases while they are inside containers and after any accidental release from containers. Until they are used, gases must be completely confined in containers. This includes transportation, transfer, and storage. It is a matter of economic necessity and the ease of usage that gases be packaged in containers that contain as much gas as is practical. These requirements have resulted in transportation and storage of gases in the liquid as well as the gaseous state. Distinguishing between gases in a liquid or gaseous state is important for the application of sound fire prevention and protection practices.

TABLE 6.10.1 Physical Properties of Cryogenic Gases

	Normal Boiling Point								Normal Conditions 70°F, 14.7 psi (21°C, 101 kPa)			
	Temperature		Liquid Density		Gas Density		Latent Heat		Gas Density			
Name	*°F*	*°C*	*lb/ft³*	*kg/m³*	*lb/ft³*	*kg/m³*	*Btu/lb*	*kJ/kg*	*lb/ft³*	*kg/m³*	*ft³ Gas from 1 ft³ Liquid*	*m³ Gas from 1 m³ Liquid*
Air	–317.8	–194.3	54.6	87.5	—	—	88.2	205.1	0.075	0.120	728	726
Argon	–302.6	–158.9	86.98	139.3	0.356	0.570	70.2	163.3	0.103	0.165	842	842
Carbon monoxide	–312.7	–191.5	51.12	81.9	—	—	92.8	215.8	0.073	0.117	706	706
Ethylene	–154.8	–103.7	35.4	56.7	0.130	0.208	208.0	483.8	0.072	0.115	487	487
Fluorine	–306.6	–188.1	94.1	150.7	0.363	0.581	74.1	172.3	0.098	0.160	961	961
Helium	–452.1	–268.9	7.8	12.5	0.106	0.170	10.3	23.9	0.01	0.016	754	754
Hydrogen	–423.0	–252.8	4.43	7.1	0.084	0.134	192.7	448.2	0.005	0.008	850	850
Methane	–258.7	–161.5	26.5	42.4	0.111	0.178	219.2	509.8	0.042	0.067	636	636
Nitrogen	–320.4	–195.8	50.46	80.8	0.288	0.461	85.7	199.3	0.072	0.115	696	696
Oxygen	–297.4	–183.0	71.27	114.2	0.296	0.474	91.7	213.3	0.083	0.133	861	861

Source: Compiled from data in the *Handbook of Compressed Gases,* Compressed Gas Association.

Compressed Gases. A compressed gas is defined in NFPA 55 as follows:

> *Compressed Gas.* A material, or mixture of materials, that (1) is a gas at 68°F (20°C) or less at an absolute pressure of 14.696 psia (101.325 kPa) and (2) that has a boiling point of 68°F (20°C) or less at an absolute pressure of 14.7 psia (101.325 kPa) and that is liquefied, nonliquefied, or in solution, except those gases that have no other health or physical hazard properties are not considered to be compressed gases until the pressure in the packaging exceeds an absolute pressure of 40.6 psia (280 kPa) at 68°F (20°C).

This definition means that a compressed gas is one that exists solely in the gaseous state under pressure at all normal atmospheric temperatures inside its container. The pressure depends on the pressure to which the container was originally charged, how much gas remains in the container, and the gas temperature. There are no universally defined lower or upper limits to the container pressure. In the United States, the lower limit is customarily considered 25 psi (273 kPa) at normal temperatures (70 to 100°F [21 to 38°C]). The upper limit is restricted only by the economics of container construction and is usually in the range of 1800 to 3600 psi (12,512 to 24,923 kPa).

A container of compressed gas is limited in the weight of gas it can hold. For example, the largest common portable cylinder of compressed oxygen contains only about 20 lb (9 kg) of oxygen or about 245 standard ft^3 (SCF) (6.9 m^3) of oxygen measured at NTP of 70°F (21°C) and 14.7 psia (101 at absolute pressure of kPa).

Liquefied Gases. A liquefied gas is one that, at 68°F (20°C) inside its closed container, exists partly in the liquid state and partly in the gaseous state and is under pressure as long as any liquid remains in the container. The pressure depends on the temperature of the liquid, although the quantity of liquid can affect this under some conditions.

A liquefied gas is much more concentrated than a compressed gas. For example, the compressed oxygen cylinder mentioned previously could hold about 116 lb (53 kg) of liquefied oxygen or about 1400 ft^3 (39.6 m^3) of oxygen measured at NTP, which is about six times greater. This comparison is valid for illustrative purposes only, because compressed oxygen and liquefied oxygen will not be found in the same type of container.

Classification by Usage

Historically, some common gases have been categorized by their principal use. This is reflected in some codes, such as NFPA 54, *National Fuel Gas Code.* This classification scheme is not as precise as classification by physical property and there is much overlap in uses with the gases.

Fuel Gases. Fuel gases include those flammable gases customarily burned in appliances with air to produce heat (and sometimes light), which in turn is used as a source of heat (comfort and process), power, or light. By far the principal and most widely used fuel gases are natural gas and the liquefied petroleum gases (butane and propane).

Industrial Gases. Industrial gases include the entire range of gases classified by chemical properties customarily used in industrial processes for welding and cutting, heat treating, chemical processing, refrigeration, water treatment, and so on.

Medical Gases. By far the most specialized usage classification, medical gases are used for medical purposes, such as anesthesia and respiratory therapy. Oxygen and nitrous oxide are common medical gases.

BASIC HAZARDS OF GASES

An evaluation of gas hazards distinguishes between the hazards presented by a gas when it is confined in a container and the hazards presented when it escapes from a container—even though both of these hazards may be simultaneously present in a single incident.

Hazards Within Containers

Gases expand when heated, producing an increase in pressure on a container. This can result in release of the gas through an overpressure-relief valve or can cause container failure. In addition, containers can lose their strength and fail during a fire. Compressed and liquefied gases are affected somewhat differently when heated.

A compressed gas (solely in the gaseous state) simply attempts to expand and follow the classic gas behavior laws. No actual gas follows these laws exactly, but the laws of Boyle and Charles are sufficiently accurate to predict the behavior of compressed gases under commonly encountered conditions. A consistent set of measurement units, either U.S. customary or SI units, must be used in calculations. Temperature and pressure must be given in "absolute" values, not in the units commonly used. In the formulas that follow, T is the absolute temperature, expressed in degrees Rankine or degrees Kelvin (°F + 459 = °R; or °C + 273 = °K), P is the absolute pressure (gauge pressure in $lb/in.^2$ + 14.7 psi; or kPa), and V volume in ft^3 or m^3 or any other suitable unit of volume.

Boyle's Law

Boyle's law states that the volume occupied by a given mass of gas varies inversely with the absolute pressure if the temperature is not allowed to change, or

$$PV = \text{Constant}$$

Charles's Law

Charles's law states that the volume of a given mass of gas is directly proportional to the absolute temperature if the pressure is kept constant. Thus,

$$V/T = \text{Constant}$$

Therefore, for most gases, within practical working limits, the relation among temperature, pressure, and volume may be closely approximated by the following formula:

$$\frac{T_1}{T_2} = \frac{P_1 V_1}{P_2 V_2}$$

T_1, P_1, and V_1 refer to initial conditions; T_2, P_2, and V_2 refer to changed conditions to be determined.

EXAMPLE 1: Assume a 10 ft^3 cylinder of compressed gas at 70°F at sea level has a gauge pressure of 1000 psi. Assume that the temperature is increased to 150°F. What will be the pressure?

T_1 = 70°F + 459 = 529°R

P_1 = 1000 psi (gauge)
+ 14.7 (atmospheric pressure at sea level)
= 1014.7 psi (absolute)

V_1 = 10 ft^3

T_2 = 150°F + 459 = 609°R

P_2 = to be determined

V_2 = 10 ft^3

Substituting in the formula,

$$\frac{529}{609} = \frac{1014.7 \times 10}{P_2 \times 10}$$

$$P_2 = 1014.7 \times \frac{609}{529} = 1170$$

Therefore, gauge pressure will be 1170 psia – 14.7, or 1155.3 psig.

EXAMPLE 2: Assume a 2.0 m^3 cylinder of compressed gas at 20°C at sea level has a gauge pressure of 1200 kPa. Assume that the gas is further compressed into a 1.0 m^3 cylinder and maintained at 50°C. What will be the gauge pressure?

T_1 = 20°C + 273 = 293 K

P_1 = 1200 kPa
+ 101 (atmospheric pressure at sea level)
= an absolute pressure of 1301 kPa

V_1 = 2.0 m^3

T_2 = 50°C + 273 = 323 K

P_2 = to be determined

V_2 = 1.0 m^3

Substituting in the formula,

$$\frac{293}{323} = \frac{1301 \times 2.0}{P_2 \times 1.0}$$

P_2 = 2868 kPa absolute, or 2767 kPa gauge

A liquefied gas, including a cryogenic gas (which is partly in the liquid state), exhibits a more complicated behavior because the net result of heating is the combination of the following three effects:

1. The gas phase is subject to the same effect as for a compressed gas.
2. The liquid attempts to expand, compressing the vapor.
3. The vapor pressure of the liquid increases as the temperature of the liquid increases.

The combined result of these effects is an increase in pressure when the container is heated.

A steep pressure rise can occur if the liquid expansion results in the container becoming full of liquid (the initial gas-phase condensing). If this happens, a small amount of additional heating results in a large increase in pressure. For this reason, it is vital never to place more liquefied gas in the liquid phase into a container than can be accommodated—leaving a vapor space—if the liquid temperature is raised to a level commensurate with the expected ambient temperatures. The proper quantity varies with the liquefied gas and the factors that affect expected temperature rises, such as the temperature of the liquid when placed into the container, the size of the container, and whether the container is insulated or installed above or below ground. The quantities permitted are commonly expressed as "filling densities" or "loading densities" and are specified for individual gases (in some cases, groupings of similar gases) by codes, standards, and regulations. Filling densities expressed in terms of weight are absolute values; that is, the designated weight of gas may always be placed into the container. Filling densities expressed in terms of volume, however, must always be qualified by specifying the liquid temperature.

Table 6.10.2 shows an example of how filling densities are expressed for liquefied gases—in this case, liquefied petroleum gases stored at normal temperatures in uninsulated containers. Note that larger quantities of higher specific gravity materials are permitted (reflecting the fact that these liquids tend to expand less) and that larger containers can be filled more than smaller ones can (reflecting the fact that it takes longer for them to absorb heat from atmospheric temperatures or solar radiation). Also, underground containers can be filled even more (reflecting the fact that their ambient temperatures are relatively constant and well below summer atmospheric temperatures).

Containers of compressed or liquefied gases can represent high levels of potential energy release due to the concentration of matter by compression or liquefication. Container failure releases this energy—often extremely rapidly and violently—with a simultaneous release of gas to the surroundings and propulsion of the container or container pieces. Compressed gas container failures are distinguished more by the flying missile hazard than by the results of gas release, because these containers contain lesser quantities of gas. Liquefied gas container failures can release larger quantities of gas.

Overpressure-Relief Devices

In the United States, Canada, and other countries, spring-loaded pressure-relief valves, bursting discs, or sometimes both, are provided on most compressed and liquefied gas containers to limit container pressure to a level the container can safely withstand. Fusible plugs are sometimes used on smaller containers. The start-to-discharge pressure settings of pressure relief

TABLE 6.10.2 Maximum Permitted Filling Density (LP-Gas Stored at Normal Temperatures in Uninsulated Containers)

Specific Gravity at 60°F (15.6°C)	Aboveground Containers				All Underground Containers	
	0 to 1200 gal[a]		Over 1200 gal[a]			
	% of WWC[b]	*Vol. % at 60°F*[c]	*% of WWC*[b]	*Vol. % at 60°F*[c]	*% of WWC*[b]	*Vol. % at 60°F*[c]
0.496–0.503	41	82.0	44	88.0	45	90.0
0.504–0.510	42	82.6	45	88.5	46	90.5
0.511–0.519	43	83.5	46	89.4	47	91.3
0.520–0.527	44	84.3	47	90.0	48	91.8
0.528–0.536	45	84.7	48	90.3	49	92.2
0.537–0.544	46	85.2	49	90.7	50	92.5
0.545–0.552	47	85.6	50	91.2	51	93.0
0.553–0.560	48	86.4	51	91.8	52	93.6
0.561–0.568	49	87.0	52	92.3	53	94.1
0.569–0.576	50	87.5	53	92.7	54	94.4
0.577–0.584	51	87.9	54	93.1	55	94.8
0.585–0.592	52	88.3	55	93.5	56	95.1
0.593–0.600	53	88.9	56	94.0	57	95.6

[a]Total water capacity, U.S. gallons (1200 U.S. gallons equals 4.54 m^3).
[b]WWC = water weight capacity.
[c]60°F = 15.6°C.

devices are determined by the strength of the container. In most cases, the relieving capacity (in terms of gas flow rate through them) is based on the maximum heat input rates resulting from fire exposure, because this is generally the largest anticipated source of heat. In some installations, such as underground or insulated containers, other sources of overpressure may be the dominant effect, such as overfilling of the container.

As noted, the relieving capacity of these devices is based on discharge of the gas. In the case of liquefied gas containers exposed to fire, it is possible to have conditions such that liquid will be discharged instead of gas, for example, when the container is tipped over. Under such conditions, the relieving capacity will be reduced—in some cases as much as 60 to 70 percent because liquids are more viscous than gases and flow more slowly through valves. With the possible exception of the fire exposure condition, this reduction is of little practical significance. Even in the case of fire exposure, this situation is not as critical as it may appear because prevention of container failure under fire exposure conditions requires other safeguards in addition to the overpressure relief device. Inspection, maintenance, and replacement of these devices are essentially unregulated and they are subject to potentially harmful influences.

Containers of certain poisonous and highly toxic gases do not have overpressure relief devices because the overall hazard of a prematurely operating or leaking relief device outweighs the hazard of container failure from overpressure. Overpressure safety is accomplished by a lowered filling limit.

It is also the practice in some countries, especially in Europe and countries using European standards, not to provide overpressure protection on liquefied gas containers. This practice reflects the widespread use and installation of such containers inside buildings, including homes, and commercial and institutional buildings. In such cases, the hazard of gas release indoors due to operation of the relief device is believed to outweigh the hazard of container failure due to overpressure.

Liquefied Gas BLEVE

Instances where containers of liquefied gases fail and break into two or more pieces when exposed to fire are common enough to warrant treatment in some detail. This failure is termed *boiling liquid expanding vapor explosion* (BLEVE), a type of pressure-release explosion.

All liquefied gases are stored in containers at temperatures above their boiling points at NTP and remain under pressure only so long as the container remains closed to the atmosphere. This pressure ranges from less than 1 psi (6.9 kPa) for some cryogenic gas containers to several hundred psi for noncryogenic liquefied gas containers at normal storage temperatures. If the pressure is reduced to atmospheric pressure, such as through container failure, the substantial heat that is in effect "stored" in the liquid causes very rapid vaporization of a portion of the liquid. This vaporization occurs to a degree directly proportional to the temperature difference between that of the liquid at the instant of container failure and the normal boiling point of the liquid. For many liquefied flammable gases, this temperature difference at normal atmospheric temperatures can result in vaporization of about one-third of the liquid in the container.

Because overpressure-relief devices are set to discharge at pressures above the operating pressure of the pressure vessel, the liquid temperature will be well above the normal atmospheric boiling point. For example, propane at 275 psig (gauge pressure of 1.9 mPa)—the maximum pressure-relief valve setting—has a boiling point of about 135°F (57°C), well above the atmospheric boiling point of about –40°F (–140°C). Therefore, the liquid temperature is higher than this if container failure oc-

curs when a relief device is functioning. More liquid is vaporized under these conditions—often over one-half of the liquid in the container—than in a BLEVE caused by something other than fire exposure. The remaining unvaporized liquid is cooled by the "self-extraction" of heat when the pressure is reduced to atmospheric and is cooled to near its normal boiling point. In the event of a BLEVE caused by other than fire exposure, the amount of liquid vaporized will be less. A significant hazard still exists.

Liquid vaporization is accompanied by a large liquid-to-vapor expansion. It is this expansion process that provides the energy for propagation of cracks in the container structure, propulsion of pieces of the container, rapid mixing of the vapor and air resulting in the characteristic fireball upon ignition by the fire that caused the BLEVE, and atomization of the remaining cold liquid. Many of the atomized droplets burn as they fly through the air. However, it is not uncommon for the cold liquid to be propelled from the fire zone too quickly for ignition to occur and fall to earth still in liquid form.

Reduction of internal pressure to atmospheric level in a container results from the container losing its ability to hold the pressure it was designed to contain. This failure is most often due to weakening of the container metal from flame contact but can also be the result of mechanical failure of the container due to wall thinning from corrosion, puncture, or gouging. It is important to remember that a BLEVE is what happens after the container fails, not how the container fails.

As shown in Figure 6.10.1, the strength of carbon steel steadily decreases with temperature increases above about 400°F (204°C). Figure 6.10.1 is based on a typical low-carbon steel. The curves will vary quantitatively with other steels, but

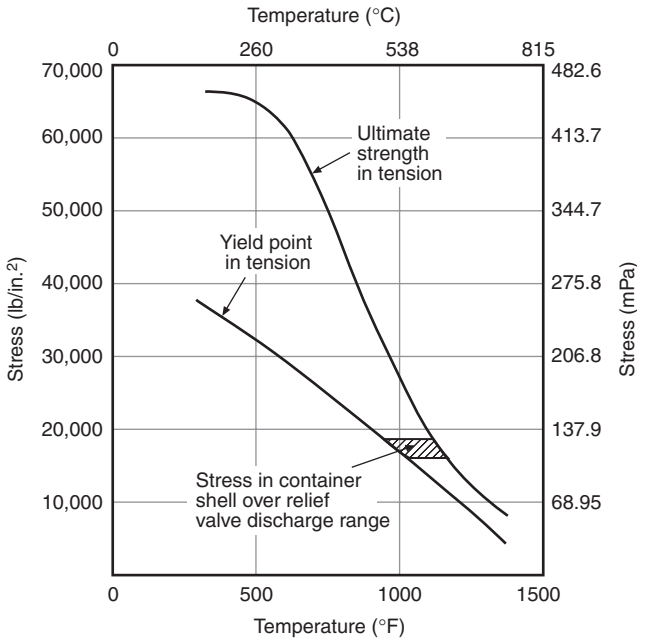


FIGURE 6.10.1 Behavior of Liquefied Gas Container Metal (Carbon Steel) When Exposed to Fire

the loss of strength with increasing temperature is valid for all common metals, and the critical temperatures are well below those attainable in a fire.

Figure 6.10.1 also shows why entirely satisfactory performance of a spring-loaded relief valve to design parameters cannot prevent a BLEVE. By its nature, such a valve cannot reduce the pressure to atmospheric but only to a point somewhat below its start-to-discharge pressure. Therefore, the liquid will always be at a temperature above its normal boiling point, pressure will remain inside the container, and the container structure will be stressed in tension. This stressed area is shown as the shaded portion in Figure 6.10.1 for a common type of LP-gas container having a pressure-relief valve set for 250 psi (172 kPa). Although this area will vary for different metals or pressure vessel relief valve design characteristics, it is evident that if the metal is heated above this range (which is quite possible in the event of direct flame contact), the metal will not withstand the stress and the container will fail.

It is extremely difficult to significantly heat the container metal where it is in contact with liquid because liquid conducts the heat away from the metal and acts as a heat absorber as the liquid is converted to vapor. For example, when the relief valve cited in this example is discharging, the propane liquid stays in the 120 to 140°F (49 to 60°C) range. As a result, the metal temperature is well within safe limits. This situation does not exist for the metal in the vapor space of the container, as vapor is a relatively poor heat conductor and has little heat-absorbing capacity. This is regularly demonstrated in most kitchens, when a tea kettle with water is placed on a heating element to boil water. If water is in the kettle, the kettle bottom will not melt and can be used indefinitely. If the kettle becomes dry, the bottom will overheat and can melt.

In BLEVEs where the failure is due to metal overheating, the container failure typically originates in the metal in contact with the vapor space. The heated tank metal shell stretches and thins out at the point of flame impingement. As the metal stretches and thins, a longitudinal tear begins and gets longer until a critical length is reached. When the critical length is reached, the metal becomes brittle and the tear propagates at sonic velocity through the metal tank shell in both the longitudinal and circumferential directions. As a result, the container typically comes apart in two or more pieces.

Most liquefied gas BLEVEs that involve container failure result from fire exposure. However, a few BLEVEs have occurred due to container failures from other causes, such as corrosion or impact from an outside force. Impact failures are particularly noticeable in transportation accidents involving railcars and cargo vehicles. In these cases, the BLEVE generally occurs simultaneously with impact. In one instance, however, a 30,000 gal (113.5 m^3) tank car of LP-gas was only severely weakened by impact during derailment and did not BLEVE until more than 40 hours later.[1] The tank car had been lifted and moved without incident in the interim. At the time of failure, however, the internal pressure was increasing as the ambient temperature was rising.

Magnitude of a BLEVE. The size of a BLEVE depends on the weight of the container pieces and on how much liquid vaporizes

when the container fails. This is analogous in many respects to the performance of rockets, as far as propulsion of container parts is concerned. Most liquefied gas BLEVEs occur when containers are from slightly less than one-half to about three-fourths full of liquid. The liquid vaporization-expansion-energy to container-piece weight ratio is such that pieces are propelled for distances up to approximately ½ mile (0.8 km). Deaths from such missiles can occur as far as 800 ft (244 m) from larger containers. Fireballs several hundred feet in diameter can occur, and fatal burns can be suffered by persons as much as 250 ft (76 m) from the larger containers.

A major LP-gas disaster with multiple BLEVEs occurred on November 19, 1984, near Mexico City, Mexico.[2] According to a Swedish investigator who cooperated with NFPA, this incident occurred at about 5:00 a.m. on a Monday while the terminal was being filled by pipeline from a refinery in another part of Mexico. According to information provided to NFPA, a failure in a component of the 12-in. (25.4-mm) fill line resulted in a line break and the development of a large LP-gas cloud that ignited upon reaching a ground-level flare about 20 minutes later. The resulting explosion and fire are believed to have been the major factor in the 500 deaths reported. The flame issuing from the broken pipeline impinged on one of the four 10,000 barrel (1590 m^3) spheres that caused a BLEVE about 10 minutes later. In all, approximately 15 BLEVEs were noted on seismic charts among the four 10,000 barrel (1590 m^3) spheres and 48 horizontal tanks.

The two 15,000-barrel (2384 m^3) spheres remained on their foundations but were severely damaged (Figure 6.10.2). (Note how far out of vertical they are due to partial failure of the container supports.) The four 10,000 barrel (1590 m^3) spheres were found in pieces both on and off the terminal site. All 48 horizontal tanks were damaged in varying degrees with major sections as far as 3600 ft (1.1 km) from the site. Figure 6.10.3 illustrates the spectacular dimensions a BLEVE can reach.

Time Intervals for Fire-Caused BLEVEs. The time between initiation of flame contact and a BLEVE varies because it depends on such widely varying factors as the size and nature of the fire as well as the container itself. Uninsulated containers located aboveground can be subject to a BLEVE in the absence of water cooling in a matter of a very few minutes in the case of small containers to a few hours for very large containers. Data on insulated containers are meager because only cryogenic containers, some reactive-gas containers, and a few propane containers are usually insulated. However, there is no doubt that insulation designed for fire-exposure conditions can delay BLEVE times significantly. In one case involving an insulated LP-gas railroad tank car, the BLEVE did not occur until 20½ hours of fire exposure—undoubtedly an extreme example. In comparison, using fire tests on LP-gas railroad tank cars, a BLEVE occurred in 93 minutes in the insulated case, as opposed to 25 minutes for the uninsulated tank.

FIGURE 6.10.2 Two 15,000 Barrel Spheres (2384 m^3) Involved in the Mexico City LP-Gas Disaster

FIGURE 6.10.3 Fireball Formed in a BLEVE Involving LP-Gas Railroad Tank Cars. The elevated water tank at center is a point of reference in visualizing the dimensions of the fireball.

Protection Against a BLEVE. Protection for an uninsulated liquefied gas container that may be exposed to fire is provided by the application of water so that a film of water coats portions of the container not in internal contact with the liquid. The methods used can range from hose streams to installation of fixed water spray systems.

The preceding data on BLEVE magnitude, time intervals, and protection apply only to unreactive liquefied flammable gases. The additional chemical energy in reactive gases introduces chemical factors not present in the purely physical and combustion phenomena just described, even though the outward appearance and general effects are similar. The hazard can be increased by evolution of internal heat of chemical reaction (which adds to the heat from the exposing fire) and the inability of externally applied cooling water to cool the liquid inside the container.

Prevention of BLEVE. NFPA 58, *Liquefied Petroleum Gas Code,* provides requirements for the installation of propane and

other LP-gas containers. The requirements have evolved over time based on evaluation of BLEVE incidents at propane storage facilities. The incidents had one common feature: the fuel for the fire that caused a BLEVE came from the propane container being threatened or from an adjacent propane container. An example of this type of incident that occurred in Albert City, Iowa, on April 9, 1998.[3] In that incident an 18,000 gallon (68 m^3) propane container exploded following exposure to fire from a broken pipe that fed propane from the tank that ignited and was pointed at the tank following an impact. The tank shutoff valve was located under the tank and was not accessible.

NPFA 58 has been evolving to prevent BLEVEs, using a number of required safety components collectively called *product control.* The key concept of product control is the ability to remotely close container valves in a fire. All larger propane containers are required to have an internal valve, shown in Figure 6.10.4, for all liquid and vapor openings above a minimum size that provide the following safety features:

- *Excess flow valves.* A valve that closes when the flow of liquid or gas exceeds a preset value. Excess flow valves provide a level of safety as they are sized to close upon a clean "guillotine" of a pipe. If a pipe breaks in such a manner that the opening is not round, the area of flow is reduced, and the resulting flow may not be sufficient to operate the excess flow valve. If the ambient temperature is low at the time of a pipe break, the container pressure is reduced and the flow from the container is correspondingly reduced and may not be sufficient to operate the excess flow valve.
- *Remote shutoff.* A remote shutoff can be operated to close the flow of propane from a container to stop fire or the potential of fire either at the valve or between 20 and 100 ft (6 and 30 m) from the valve. Experience has shown that most incidents occur with trained personnel in attendance.

FIGURE 6.10.4 Internal Valve (Source: NFPA 58, *Liquefied Petroleum Gas Code,* 2004 ed., Figure 3.13; Courtesy of Engineered Controls International, Inc.)

All new propane containers have been required to have internal valves since 2001, and all existing propane containers larger than 4000 gal (15 m^3) are required to have internal valves by July 2011.

Combustion Within Containers

Another significant hazard of gas stored in containers is the danger of container failure from overpressure, resulting from combustion of the gas while inside the container. Flammable gas-air or gas-oxygen mixtures are seldom provided in containers intentionally but can be established inadvertently. This type of explosion can occur in industrial and medical gas applications where oxygen or compressed air is often used in conjunction with flammable gases. They can also occur in piping systems delivering both oxygen and a flammable gas, as is common in industrial cutting and welding operations and other applications such as jewelry manufacture. Where such a possibility is inherent in a process, for example, an oxygen-fuel gas metal cutting system, provisions are made to prevent the occurrence of such mixtures in containers by installing special backflow prevention devices. More generally, most explosions can be prevented by education and training in proper container-filling procedures. Consumers of industrial and medical gases seldom have the expertise needed to fill containers safely.

Hazard of Gases Released from Containers

When gases are released from their containers, the hazards vary according to the chemical and physical properties of the gases and the nature of the environment into which the gases are released. All gases, with the exception of air, present a hazard to life if they displace the breathing air. Nitrogen, helium, argon, and other odorless and colorless gases are particularly hazardous because they are not detectable by the human senses. At reduced oxygen concentrations, judgment and coordination are affected.

Toxic or Poisonous Gases. These gases present obvious life hazards. They are especially dangerous when released during a fire because they can impede fire-fighting efforts by either preventing or delaying access to the site by fire fighters.

Oxygen and Other Oxidizing Gases. These gases are nonflammable, but they make combustibles ignite at lower temperatures, accelerate combustion, and start fires by causing flames in fuel-burning appliances to extend beyond their combustion chambers.

Liquefied Gases (Including Cryogenic Gases). Because of their low temperatures, these gases present a hazard to persons and property when they escape as liquids. Contact with cold liquid can cause frostbite, which can be severe if the exposure is prolonged. The properties of many structural materials, particularly carbon steel and plastics, are affected by low temperatures and embrittlement can occur, which could lead to structural failure.

Flammable Gases. Because of their prevalence, the behavior of flammable gases when released from their containers is of

major interest. Released flammable gases present two basic hazards: (1) combustion explosions and (2) fire. Failure to distinguish between the circumstances surrounding these two hazards can result in misapplication of protective measures.

Combustion Explosions

It is useful to consider a flammable gas combustion explosion as occurring in the following sequence:

1. A flammable gas or the liquid phase of a liquefied flammable gas is released from its container, piping, or equipment (including the normal operation of an overpressure relief device). If liquid escapes, it rapidly vaporizes and produces the potentially large quantities of vapor associated with this liquid-to-vapor transition.
2. The gas mixes with the air.
3. With certain proportions of gas and air (in the flammable or combustible range), the mixture is ignitable and will burn (Table 6.10.3).
4. When ignited, the flammable mixture burns rapidly and produces heat rapidly.
5. The heat is absorbed by everything in the vicinity of the flame and by the very hot gaseous combustion products.
6. Nearly all materials expand when they absorb heat. The one material in the vicinity of the flame or hot gaseous combustion products that expands most when it is heated is air. Referring to the gas laws cited earlier in this chapter, it will be noted that air expands to double its original volume for every 459°F (237°C) it is heated.
7. If the heated air is not free to expand (i.e., it is confined in a room), the pressure in the room will rise.
8. If the room structure is not strong enough to withstand the pressure, some part of the room will suddenly and abruptly move and depart from its original position. A bang, woosh, boom, or other noise will be heard.

This sequence of events partly describes an explosion. Because the source of pressure is combustion, this kind of explosion is called a *combustion explosion.* It is also called, less accurately, a room explosion or vapor-air explosion.

A combustion explosion requires that a quantity of flammable gas-air mixture be present in an enclosure. In addition, the quantity/strength-of-enclosure relationship must be such that the strength of some part of the enclosure must be exceeded by the pressure-building potential of the mixture. If the enclosure is strong enough to withstand the pressure, a combustion explosion cannot occur because it is the manner in which the

TABLE 6.10.3 Combustion Properties of Common Flammable Gases

Gas	*Btu per ft³ (Gross)*	*mJ/m³ (Gross)*	Limits of Flammability Percent by Volume in Air		*Specific Gravity (Air = 1.0)*	*Volume of Air Needed to Burn 1 ft³ of Gas (ft³)*	*Volume of Air Needed to Burn 1 m³ of Gas (m³)*	Ignition Temperature	
			Lower	*Upper*				*°F*	*°C*
Natural gas									
High inert type[a]	958–1051	35.7–39.2	4.5	14.0	0.660–0.708	9.2	9.2	—	—
High methane type[b]	1008–1071	37.6–39.9	4.7	15.0	0.590–0.614	10.2	10.2	900–1170	482–632
High Btu type[c]	1071–1124	39.9–41.9	4.7	14.5	0.620–0.719	9.4	9.4	—	—
Blast furnace gas	81–111	3.0–4.1	33.2	71.3	1.04–1.00	0.8	0.8	—	—
Coke oven gas	575	21.4	4.4	34.0	0.38	4.7	4.7	—	—
Propane (commercial)	2516	93.7	2.15	9.6	1.52	24.0	24.0	920–1120	493–604
Butane (commercial)	3300	122.9	1.9	8.5	2.0	31.0	31.0	900–1000	482–538
Sewage gas	670	24.9	6.0	17.0	0.79	6.5	6.5	—	—
Acetylene	1499	55.8	2.5	81.0	0.91	11.9	11.9	581	305
Hydrogen	325	12.1	4.0	75.0	0.07	2.4	2.4	932	500
Anhydrous ammonia	386	14.4	16.0	25.0	0.60	8.3	8.3	1204	651
Carbon monoxide	314	11.7	12.5	74.0	0.97	2.4	2.4	1128	609
Ethylene	1600	59.6	2.7	36.0	0.98	14.3	14.3	914	490
Methylacetylene, propadiene, stabilized[d]	2450	91.3	3.4	10.8	1.48	—	—	850	454

[a]Typical composition CH_4 71.9–83.2%; N_2 6.3–16.2%.
[b]Typical composition CH_4 87.6–95.7%; N_2 0.1–2.39%.
[c]Typical composition CH_4 85.0–90.1%; N_2 1.2–7.5%.
[d]MAPP® gas.

enclosure performs that basically determines whether such an explosion occurs. However, few enclosures are strong enough to withstand such pressure.

If an enclosure was full of a flammable gas-air mixture at atmospheric pressure, the enclosure would have to withstand about 60 to 110 psi (400 to 750 kPa) in order to remain intact to prevent a combustion explosion. If a reactive flammable gas is involved or oxygen enrichment occurs, even higher pressures are possible. Conventional structures are capable of withstanding pressures only in the order of 0.5 to 1.0 psi (3.5 to 7.0 kPa). This wide pressure disparity shows clearly that conventional structural enclosures are vulnerable even if they are not full of a flammable gas-air mixture. Most combustion explosions of conventional structures typically occur with less than 25 percent of the enclosure occupied by the flammable mixture. This fact should not be overlooked—it is erroneous to assume that a flammable gas-air mixture needs to completely fill a room or building before an explosion can occur.

The mechanics of gas accumulation in a structure are affected by the rate of gas release, whether the gas is in the liquid or gas phase, the density of the gas, and the ventilation in the structure. Classic diffusion laws are of little significance under actual conditions because the combination of extremely slow release rates and airtight structures seldom happens. For this reason, and the fact that most flammable gas-air mixtures are about 90 percent air, the density of the gas itself (i.e., whether it is lighter or heavier than air) is less often a significant factor in gas combustion explosions involving structures than one might expect.

Due to the large and rapid flammable gas-air mixture potential of liquefied gases, codes and standards impose severe limitations on the handling of such gases indoors. Considering the fireball aspect of the BLEVE, it is evident that an indoor fireball behaves similarly to an ignited gas-air mixture accumulation; the results of a BLEVE of a container located indoors can be very similar to a combustion explosion.

Combustion Explosion Safeguards

Basic combustion explosion prevention safeguards are designed to limit the development of a flammable gas-air mixture in a structure. Fundamental safeguards are the use of rugged storage containers and equipment that minimize the chance of leakage, the minimal quantity of gas released by emergency flow control devices, and the use of limiting orifices to minimize the quantity released. Burners are often equipped with flame failure devices that shut off the flow of gas if the flame is extinguished for any reason.

Many gases are colorless and odorless. It is, therefore, common to odorize the more widely used fuel gases to increase chances of leak detection. Odorization of both natural gas and LP-gas is required by codes, standards, and regulations so that these gases can be detected by humans with a normal sense of smell at concentrations in air not exceeding one-fifth of the lower limit of flammability. This is common practice throughout the world today. The odorants are usually volatile organic liquids containing chemically combined sulfur and have a characteristic "gassy" or "rotten egg" odor.

Although it is an effective safeguard, odorization has limitations. The functioning detector, that is, a human's sense of smell, is not always present, such as when the premises are vacant or the occupants are asleep. In addition, all odors deaden the sense of smell if inhaled long enough, and senses of smell vary. Odorants can be scrubbed from the gas by some soils, a factor where leakage stems from underground piping. Mixture accumulations can also be limited by ventilation systems in structures. These systems, however, are usually in industrial operations, and even then only rather nominal release rates can be handled by practical ventilation systems because of the necessity to condition the makeup ventilation air for comfort purposes. Additional information on the odorization of gases can be found in the *National Fuel Gas Code Handbook.*

Control of ignition sources is also fundamental to combustion explosion prevention. This safeguard is limited mainly to industrial operations where the conduct of employees can be controlled. It is impossible to prevent smoking, use of candles, and so on in residential occupancies.

In addition to combustion explosion prevention safeguards, the severity of the explosion can be reduced by special structural design whereby some elements of the structure are designed to dislocate at lower pressures, and other elements are designed to stay in place at the lower pressures that result. This is known as "deflagration venting" and is covered in some detail in NFPA 68, *Standard on Explosion Protection by Deflagration Venting.* Such a building design is not practical for most ordinary buildings, and this practice is applied to industrial structures.

Flammable Gas Fires

The flammable gas fire can be considered as an aborted combustion explosion wherein an explosive quantity of flammable gas-air mixture does not accumulate because the mixture is either ignited too quickly or a confining structure is not present. As would be expected when flammable gas escapes outdoors, fires are more likely than explosions. If a massive release occurs, it is possible for the air or surrounding buildings to comprise enough confinement to lead to a type of combustion explosion known as an open-air explosion or space explosion. Liquefied noncryogenic gases are subject to this phenomenon, as are hydrogen, ethylene, and some reactive gases that have a high flame speed. An example of the intentional provision of prompt ignition to achieve a fire instead of a combustion explosion is the use of pilots in gas-burning equipment, such as range ovens, water heaters, boilers, and furnaces.

Gas fire prevention safeguards include many of the combustion explosion prevention safeguards. Unlike the combustion explosion, the destructive effects of the gas fire can be minimized by control measures applied after the fact.

GAS EMERGENCY CONTROL

Controllable gas emergencies resulting from the escape of gas from containers present the following two basic forms of hazard:

1. Toxic, inert, or oxidizing gases can present hazards to persons or property and unignited flammable gases can be ignited, possibly explosively ("no fire" emergencies).
2. Gas fires can present thermal hazards to persons or property ("fire" emergencies) and, if such fires expose gas

containers, introduce the possibility of container failure and a BLEVE.

A fire in any combustible material also presents the hazard of container failure from fire exposure.

Control of "No Fire" Emergencies

Control consists of directing, diluting, and dispersing the gas to prevent contact with persons, preventing it from infiltrating structures if release is outdoors, and avoiding its contact with ignition sources while, if possible, simultaneously stopping the flow of escaping gas. Gas direction, dilution, and dispersion require the use of a carrier fluid; air, steam, and water have proved to be practical. The use of air, for all practical purposes, is limited to indoor situations and is an extension of the ventilation safeguards against a combustion explosion. Steam has been distributed through systems of fixed nozzles around outdoor ethylene processing equipment and where the large quantities of needed steam are available.

Water in the form of a spray, applied from hoses or monitor nozzles or by fixed water spray systems, is the most common carrier fluid. The use of hose streams is largely a fire department operation because of the personnel requirements. Fixed water spray systems for this purpose are designed differently from the more conventional spray systems used to control fire. To date, such systems have been provided at a few outdoor ethylene and liquefied natural gas (LNG) facilities. When water is used on cryogenic liquid containers, care must be taken to ensure that water does not contact the pressure-relief valve, as it can easily freeze and defeat the operation of this important safety device.

The physical properties of the escaping gas affect control techniques. The density of compressed gases is an important factor. Control tactics for compressed gases that are colorless and odorless can be complicated because instruments are needed to define the extent of the hazardous area.

Liquefied gases possess an inherent visible indicator of their location; the refrigerating effect of their vaporization condenses water vapor from the air that produces a visible fog. The fog roughly defines the gas area, but invisible ignitable gas-air mixtures often extend for several feet (1 ft = 0.3 m) beyond the extremities of the visible fog.

Because noncryogenic liquefied gases contain considerable heat for vaporization (because they are above their atmospheric boiling temperature), they often vaporize so rapidly from contact with the air or ground that they do not exist in the liquid phase once they escape—at least not to the extent that a pool will form. The lower vapor pressure noncryogenic liquefied gases, such as butane and chlorine, are exceptions. Even the higher vapor pressure gases, such as propane, pool when ambient temperatures are well below freezing.

Cryogenic liquefied gases, on the other hand, must obtain nearly all the heat for vaporization from ground or air contact and, therefore, characteristically form a pool if the leak continues for a long enough time. In such cases, application of a carrier fluid increases the vaporization rate if applied to the liquid—an often undesirable effect.

The gas produced near the source of vaporization of a liquefied gas is always heavier than air at normal temperatures because of the low temperature of the gas at that point. This fact, together with the associated water fog, tends to cause even normally tighter-than-air gases to hug the ground for some distance.

The use of foam, particularly high-expansion foam, to control the flow of gas produced by a vaporizing cryogenic gas, which is lighter than air at ambient temperatures, has been investigated to some extent. A sufficiently thick blanket of foam can warm the gas to the point where it will rise above the blanket instead of flowing horizontally near the ground. However, this applies only to established pools of vaporizing liquid and not to the initial high vaporization rate escape phase.

Some gases react chemically with the carrier fluid—particularly if the carrier is steam or water. Chlorine is a notable example—the reaction produces hydrochloric acid. However, the principal problem in this respect is enlargement of the leak as the metal container reacts with the acid.

A special type of "no fire" control for indoor application to flammable gases is the explosion suppression system. Actually, such systems do permit ignition to occur but arrest the combustion of the flammable gas-air mixture before the pressure needed for a combustion explosion is obtained.

Control of "Fire" Emergencies

Control of fire emergencies is generally the control of heat from the fire by the application of water while, if possible, stopping the flow of escaping gas. Many gas fires can be extinguished by conventional extinguishing agents, including carbon dioxide, dry chemical, and the halogenated agents. However, the potential conversion of a gas fire into a combustion explosion if gas continues to escape after extinguishment must be recognized. The generally accepted practice is to limit actual extinguishment by agent application to small leaks that will not present a hazard if they reignite. In addition, the use of halogenated agents is being phased out because of their detrimental effect on the earth's ozone layer. (See Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems.")

Methods of water application are the same as described for the "no fire" emergencies, that is, hose streams, monitor nozzle streams, and fixed water spray systems, as well as sprinkler systems. The selection of the particular application method, or combination of methods, requires a sound fire protection analysis of the existing conditions. This is particularly true where water is used to prevent a BLEVE because of the limited time available if uninsulated containers are involved. This fact, together with the specialized tactics needed for safety of emergency personnel, has been shown to severely tax the capabilities of hose stream application in many instances. Manual actuation of fixed systems (water spray or sprinkler) that have nozzles and dry piping in the fire area is questionable because the immediate intensity of a gas fire can quickly damage the piping before the water is turned on.

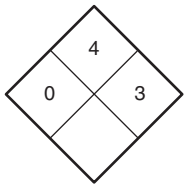
Conventional automatic sprinkler protection is limited to indoor or roofed-over areas. However, sprinklers have been effective in greatly reducing the number of overpressure relief devices on cylinders that operate during a fire. In turn, the number of cylinders that may fail from contact with the burning gas

discharged from pressure relief devices is reduced; sprinkler spacing and water density must be tailored to this hazard.

Foam can control a fire in a pool or tank of cryogenic gas but cannot extinguish it. The degree of control depends on the extent to which the foam can cover the liquid and the length of time the foam application can be maintained.

SPECIFIC GASES

Acetylene



UN 1001

Classifications. Acetylene is classified as reactive, flammable, compressed, and industrial.

Chemical Properties. Acetylene consists of two carbon atoms that are connected to each other by a triple chemical bond and to a hydrogen atom by a single bond. The triple bond, which is easily broken, is responsible for acetylene's reactivity. In the liquid or solid state, or in the gaseous state at moderate or high pressure, acetylene can decompose rapidly with the formation of carbon and hydrogen and the evolution of heat. Decomposition can be initiated by heat. Decomposition of liquid or solid acetylene also can be initiated by mechanical impact. In a confined space, the heated decomposition gases can cause overpressure and container, piping, or equipment failure.

As an indication that a hazardous, heat-producing reaction can occur in the absence of air, an upper flammable limit of 100 percent may sometimes be found in the literature rather than the 81 percent given in Table 6.10.3. This technical misapplication of the flammable range concept has caused confusion.

Acetylene can react with certain metals to produce metallic acetylides, extremely shock-sensitive explosive compounds that, if detonated even in small quantities, can initiate acetylene's decomposition. Copper and some copper alloys are notable in this respect, and their use must be avoided in most acetylene piping and equipment. However, these metals can be used in some components of acetylene systems under conditions that reflect the reaction kinetics involved. Torch tips, for example, fall into this category. Brass containing less than 65 percent copper can be used for acetylene piping systems.

Acetylene is not toxic and many years ago was mixed with oxygen for use as an anesthetic. Pure acetylene is odorless, but acetylene in general use has a characteristic odor due to minor impurities inherent in its generation from calcium carbide or derivation from other hydrocarbons.

Physical Properties—Autoignition Temperature (581°F [305°C]). Although acetylene is considered a compressed gas, the usual acetylene container used in transportation and storage does not exclusively contain acetylene in the gaseous phase and is unique in this respect. To ensure stability under reasonably anticipated shipping and use conditions, acetylene cylinders are filled with a porous-mass carbon or carbon-based packing material containing very small pores or cellular spaces so that any volume of gas therein is correspondingly small. This limits the decomposition energy available and restricts communication between spaces. In addition, the mass is saturated with acetone or dimethylformamide (DMF), a flammable liquid in which acetylene is very soluble. In this manner, acetylene gas can be compressed in solution in a manner similar to that of carbon dioxide in water to produce carbonated water. When the pressure is reduced, for example, by opening a cylinder valve, the gas escapes from solution and thus leaves the container in the gaseous state. Currently, a charging pressure maximum of 250 psig at 70°F (1724 kPa at 21°C) is recognized by DOT and Transport Canada (TC) regulations. The pressure inside an acetylene cylinder will rise or fall 2.5 psig per 1°F of temperature change (9 kPa per 1°C). For each atmosphere (14.7 psi or 101.3 kPa) of pressure, acetone or DMF will dissolve about 25 times its own volume of acetylene so that at 250 psig (1724 kPa) acetone will dissolve about 425 volumes of acetylene. An acetylene cylinder is illustrated in Figure 6.10.5.

Usage. Acetylene is used primarily in chemical processing and as a fuel gas in oxygen-fuel gas cutting and welding operations. Occasionally it is manufactured at the consuming location by reacting calcium carbide (a solid) and water in acetylene generators and piped directly to gas holders or to the point of use.

Hazards Inside Containers. Acetylene is shipped in DOT and TC cylinders as described previously and stored in these or in low-pressure gas holders. It is either handled in hoses or piping systems.

Acetylene cylinders are indirectly protected against overpressure by heat-actuated devices, usually fusible metal plugs of eutectic alloys, which have low melting points similar to those alloys employed in automatic sprinklers. These may be threaded plugs, or the fusible metal can be incorporated into the construction of the cylinder valve. Unlike spring-loaded pressure-relief valves, operation of fusible plugs results in complete reduction to atmospheric pressure because both the compressed gas and acetone or DMF are released at the same time. Due to this mode of overpressure protection, acetylene cylinders are not subject to a BLEVE, which by definition cannot occur if the liquid contents are not above their boiling points at NTP. Under fire exposure conditions and during charging operations in acetylene cylinder charging plants, however, internal decomposition has occurred, which has resulted in BLEVE effects, such as cylinder rupture and propulsion, accompanied by small fireballs.

Because susceptibility to decomposition is directly related to pressure, that is, the higher the pressure, the easier it is to initiate decomposition and the more violent the effects, an acceptable degree of stability in most piping systems containing gaseous acetylene is achieved by limiting or regulating the pressure. In general, this pressure must not exceed 15 psi (103 kPa). In applications requiring higher pressures, particularly in acetylene cylinder charging plants, special piping design features

FIGURE 6.10.5 Cutaway of a Typical Acetylene Cylinder Showing Porous Filler Material. Cylinder valve and packing for well at top of cylinder are not shown.

can be employed to control this hazard. The use of acetylene in either the liquid or solid phases is extremely hazardous and is prohibited by standards and codes covering conventional applications.

Hazards When Released from Containment. When acetylene is released from containment, it presents combustion explosion and fire hazards. Because of its reactivity, it is easier to ignite than most flammable gases and burns more rapidly. The latter effect increases the severity of combustion explosions and increases the difficulty of providing explosion venting. Acetylene is only slightly lighter than air and does not readily dissipate (see Table 6.10.3).

Because of acetylene's reactivity, the design of electrical equipment for use in acetylene atmospheres is unique to this material, and Group A electrical equipment (see NFPA 70, *National Electrical Code®*) is devoted exclusively to acetylene. In practice, electrical equipment is avoided in the more likely acetylene release areas. As a result, available Group A equipment is extremely limited in variety.

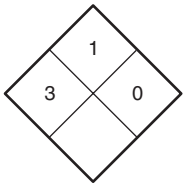
Emergency Control. Because of the limited quantities of acetylene in conventional shipping modes and storage practices, emergencies seldom occur. Fire control measures are similar to those involved with any flammable, nontoxic gas—that is, application of water to containers for cooling and dissipation of leakage and stopping the flow of escaping gas if possible.

Hazards of Acetylene Cylinders Exposed to Fire. Special precautions are needed when acetylene cylinders are exposed to fire. If an acetylene cylinder is exposed to fire, the fusible-metal pressure-relief devices will function when the metal reaches about 212°F (100°C). The nature of acetylene presents hazards that may not be present with other gases. Acetylene will decompose into hydrogen and carbon at temperatures in excess of 570°F (300°C). This property can present a danger when cylinders are involved in fire and heated locally above 570°F (300°C). When this occurs, cylinders can become overpressured and can, in some cases, rupture violently. The decomposition of acetylene can be so rapid that the pressure relief provided by a plug(s) cannot always prevent rupture. Rupture can occur in as soon as a few minutes or up to several hours after exposure.

Acetylene cylinders in the United States and Canada have fusible-metal pressure-relief devices incorporated into the cylinder or cylinder valve. Small cylinders incorporate the fusible metal into the valve. Medium and large cylinders incorporate the fusible metal in a plug(s) in the top head or bottom head. Most acetylene cylinders in Europe and other parts of the world do not have pressure-relief devices and are more susceptible to overpressure and rupture. When part of an acetylene cylinder is exposed to fire and is heated over 570°F (300°C), the acetylene will begin to decompose into carbon and hydrogen. Decomposition is rapid and liberates large quantities of energy. Cylinders exposed to fire should be sprayed with water from a protected location, and persons should not approach an acetylene cylinder that has been exposed to fire. Cylinders exposed to fire can explode even 24 hours after the exposure.

A common hazard of acetylene cylinders happens when a small leak occurs and ignites, resulting in a small flame. This small flame can cause heating of the fusible metal, resulting in the release of a torchlike flame that can be as much as 12 ft (3.6 m) in length. This sudden flame can be a danger to people in the area and to other cylinders.

Anhydrous Ammonia



UN 1005

Classifications. Anhydrous ammonia is classified as flammable, liquefied, and industrial.

Chemical Properties. Anhydrous ammonia is composed of a nitrogen atom bonded to three hydrogen atoms. Although often referred to simply as *ammonia,* this term is more appropriately used to describe a solution of anhydrous (meaning "without water") ammonia in water. The nitrogen component is inert in the combustion reaction and accounts for the somewhat limited flammability of anhydrous ammonia as manifest by its high lower-flammability limit and low heat of combustion (see Table 6.10.3).

Moist ammonia will vigorously attack copper and zinc and many of their brass or bronze alloys, which has caused some problems in agricultural areas where, because of their similar vapor pressures, anhydrous ammonia and propane are often handled in the same storage tanks, transport containers, and associated equipment at different times of the year, with ammonia being used as a fertilizer in the spring and summer, and

propane in the fall and winter as a fuel. LP-gas equipment customarily utilizes brass, bronze, copper, and zinc extensively for valves, gauges, piping, regulators, and so on. This equipment, if converted to anhydrous ammonia service, must be changed to steel. Subsequently, anhydrous ammonia must be carefully purged from a container when it is reconverted to LP-gas service to avoid corrosion of copper and brass components in building piping systems and appliances.

The characteristic pungent odor and irritant properties of anhydrous ammonia serve as warnings for this relatively toxic gas. However, the effectiveness of the warning depends on the rate of release. Large clouds of ammonia gas can be rapidly produced from large liquid leaks, so that people can be trapped and killed before they can evacuate the area. Another important factor is that human sense of smell can become accustomed to the odor of ammonia (and other pungent odors) over time. This is especially important in ammonia production plants and facilities that use large quantities of ammonia, such as many large refrigerated warehouses.

Physical Properties. At its normal boiling point of –28°F (–33°C), anhydrous ammonia has a liquid density of 42.6 lb/ft^3 (682.4 kg/m^3), a gas density of 0.055 lb/ft^3 (0.88 kg/m^3), and a latent heat of vaporization of 589.3 Btu/lb (1371 kJ/kg). At NTP, the gas has a density of about 0.045 lb/ft^3 (0.72 kg/m^3), and vaporization of 1 ft^3 (0.3 m^3) of liquid will produce about 885 ft^3 (25 m^3) of gas.

When vaporized it becomes a colorless gas, with a penetrating suffocating characteristic odor. Liquid released under pressure floats and boils on water.

Usage. Anhydrous ammonia is used primarily as an agricultural fertilizer, as a refrigerant, and as a source of hydrogen for metal heat treating. It is also used to provide special atmospheres in semiconductor manufacturing.

Hazards Inside Containers. Anhydrous ammonia is shipped in DOT and TC cylinders, DOT-specification cargo trucks, railroad tank cars, and barges. It is stored in cylinders, American Society of Mechanical Engineers (ASME) code tanks, and, in cryogenic form, in insulated American Petroleum Institute (API) tanks.

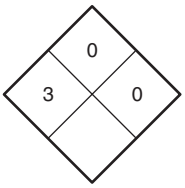
Anhydrous ammonia containers with a capacity of less than 165 lb (79 kg) are not required to be equipped with overpressure protection devices. This reflects the toxicity of the gas and is a safety trade-off between the hazards of container rupture from overpressure and gas release due to operation of an overpressure protective device, especially indoors where the smaller containers are often found. The limited flammability of the gas minimizes the probability of it supplying the exposing fire.

Hazards When Released from Containment. Anhydrous ammonia presents combustion explosion and fire hazards (as well as a toxicity hazard) when released from containment. However, its high lower limit of flammability and low heat of combustion reduce these hazards substantially.

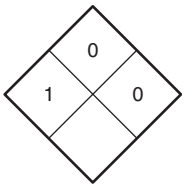
If anhydrous ammonia is released outdoors, it is difficult for it to reach the lower flammability limit concentration except for small zones in the immediate vicinity of the leak. Even where large quantities of liquid are released, ignitable concentrations tend to be in discontinuous pockets and this fact, together with the low heat of combustion, reduces the possibilities of sustained burning. Experience indicates that similar circumstances apply when the release occurs indoors in conventional and reasonably well-ventilated buildings. In unusually tight rooms, such as refrigerated process or storage areas, however, the release of liquid or large quantities of gas can result in the accumulation of sufficient quantities of a flammable mixture to result in a combustion explosion. In such cases, even though the low heat of combustion produces lower pressures than most flammable gases, the pressure is enough to do major structural damage. As a result of these factors, anhydrous ammonia fires are infrequent and, where ignition does occur, a combustion explosion is the likely result.

Emergency Control. At normal temperatures, anhydrous ammonia gas weighs about 0.6 times as much as air. Because of its pronounced solubility in water, the spread of escaping anhydrous ammonia gas can be readily controlled by water spray. If hose streams are used, the toxic and inerting properties of anhydrous ammonia require fire fighters to use protective breathing apparatus. Where liquid contact is likely, full protective clothing should be worn. If release of liquid in cryogenic form occurs, pooling is possible and application of water to pools should be avoided, unless the vapors can be controlled, in order to prevent increasing vaporization rate.

Carbon Dioxide



UN 2187
Cryogenic Liquid



UN 1013
Compressed Gas

Classifications. Carbon dioxide is classified as nonflammable (inert), liquefied, and industrial.

Chemical Properties. Carbon dioxide is composed of a carbon atom bonded to two oxygen atoms. The ability of carbon to chemically link with as much oxygen as possible prohibits its further oxidation (combustion), making it nonflammable. Although nontoxic, carbon dioxide is a "simple asphyxiant," which can cause asphyxiation due to the displacement of air.

Physical Properties. Carbon dioxide exhibits some unique physical properties. At a temperature of –69.9°F (–56.6°C) and a pressure of 60.4 psig (416.4 kPa), it can exist in a container simultaneously as a liquid, solid, and gas (the triple point). At temperatures and pressures above these and below 87.8°F (30.8°C), it exists as both liquid and gas. Above 87.8°F (30.8°C), it exists only in the gaseous phase. At normal temperatures, the gas is about 1½ times heavier than air.

Usage. Carbon dioxide is used primarily to carbonate beverages, to provide an inert atmosphere, and to extinguish fires.

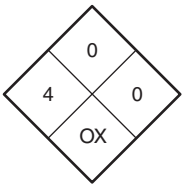
Hazards Inside Containers. Carbon dioxide is shipped in DOT and TC cylinders and insulated DOT-specification cargo trucks and railroad tank cars. It is stored in cylinders at a pressure of about 850 psi at 70°F (5861 kPa at 21°C) or in insulated ASME-code tanks at pressures of about 200 to 312 psi (1380 to 2150 kPa) and temperatures of –20 to 40°F (–28.8 to 4.4°C).

Cylinders are provided with overpressure protection in the form of frangible (bursting) discs. Insulated tanks are equipped with pressure-relief valves. Carbon dioxide cylinders can BLEVE as a result of corrosion with enough energy to nearly demolish small cargo vehicles.

Hazards When Released from Containment. In addition to the hazard of asphyxiation, contact with cold vaporizing carbon dioxide can cause frostbite. For these reasons, actuation of automatic room-flooding extinguishing system applications should incorporate a time delay if personnel occupy the protected area.

Emergency Control. Carbon dioxide emergencies are "no fire" emergencies involving potential asphyxiation hazards. Structure ventilation indoors and water spray control outdoors are applicable. Self-contained breathing apparatus should be used.

Chlorine



UN 1017
Chlorine

Classifications. Chlorine is classified as reactive, nonflammable, liquefied, toxic, and industrial.

Chemical Properties. Chlorine is a basic chemical element. It is a strong oxidizer. Although it is nonflammable, chlorine can react with many organic materials corrosively and, in some instances, explosively, particularly with acetylene, turpentine, ether, gaseous ammonia, hydrocarbons, most fuel gases, and finely divided metals.

The reactivity of chlorine necessitates special attention to the container, piping, and equipment materials of construction. Below 230°F (110°C), steel, copper, iron, and lead are widely used. In contact with water, chlorine forms hypochlorous and hypochloric acids, which are corrosive to most metals.

Physical Properties. The normal boiling point of chlorine is about –30°F (–34.4°C). At 32°F (0°C), the liquid density is 91.7 lb/ft^3 (1468 kg/m^3) and the gas density is 0.2 lb/ft^3 (3.2 kg/m^3). The latent heat of vaporization at the normal boiling point is 123.7 Btu/lb (287.7 kJ/kg). At 32°F (0°C), the vaporization of 1 ft^3 of liquid will produce about 458 ft^3 of gas (1 m^3 of liquid will produce about 458 m^3 of gas). Chlorine has a greenish-yellow color.

Usage. Chlorine is used primarily in chemical processing, bleaching, purification of drinking water and swimming pools, and sanitation of industrial and sewage wastes.

Chlorine has been used in warfare as a poison gas. Liquid chlorine can burn skin. Its sharp odor serves as a warning.

Hazards Inside Containers. Chlorine is shipped in DOT and TC cylinders, in DOT-specification portable tanks (so-called "one-ton containers"), and in insulated railroad tank cars.

Chlorine cylinders and 1-ton (1016-kg) containers are provided with overpressure protection by fusible plugs. Tank cars are protected by pressure-relief valves. Because the operation of fusible plugs results in complete depressurization, the probability of a BLEVE is low.

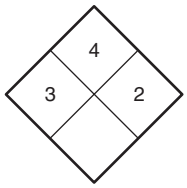
Steel is a suitable material for a chlorine container at normal temperatures; however, it is rapidly attacked at temperatures above approximately 230°F (110°C), and leaks can develop upon fire exposure. For this reason, as well as for BLEVE protection, water should be applied to fire-exposed containers. Application of water directly on a leak should be avoided because it may enlarge the leak from acid corrosion.

Hazards When Released from Containment. Chlorine presents primarily toxicity and corrosion hazards when released from containment. Since chlorine gas is about 2½ times heavier than air, it will hug the ground.

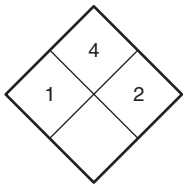
Emergency Control. The gas can be controlled by water spray. If hose streams are used, fire fighters should wear full protective clothing. Water applied to liquid chlorine will accelerate vaporization.

The chlorine industry has developed an extensive leak-control program that includes strategic siting of trained emergency personnel and special equipment kits for stopping the more common leaks in cylinders, ton containers, and tank cars. Information on this program is available from the Chlorine Institute, 1300 Wilson Blvd. Arlington, VA 22209 (http://www.chlorineinstitute.org).

Ethylene



UN 1038
Cryogenic Liquid



UN 1962
Compressed Gas

Classifications. Ethylene is classified as flammable, compressed, cryogenic, and industrial.

Chemical Properties. Ethylene is composed of two carbon atoms connected to each other by a double bond and each connected to two hydrogen atoms. The double chemical bond imparts a degree of reactivity. Except at very high pressures normally encountered only in chemical processing, it is a stable material. It has a wide flammable range (see Table 6.10.3) and

high burning velocity, reflecting its reactivity. Although it is nontoxic, ethylene is an anesthetic and asphyxiant.

Physical Properties. See Table 6.10.1.

Usage. Ethylene is principally used in chemical processing, for example, manufacture of polyethylene plastic. It is also used to ripen fruit.

Hazards Inside Containers. Ethylene is shipped as a compressed gas in DOT and TC cylinders and as a cryogenic gas in insulated cargo trucks and railroad tank cars in accordance with DOT specifications and regulations. It is stored in cylinders or in insulted ASME-code or API tanks.

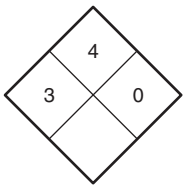
Ethylene cylinders (except for medical cylinders that may have fusible plugs or combination safety devices) are protected against overpressure by frangible (bursting) discs. Insulated truck tanks and tank cars are protected by pressure-relief valves. Cylinders are subject to failure from fire exposure but not to BLEVEs because they do not contain liquid. Insulated containers are subject to BLEVEs, but such incidents are rare.

Hazards When Released from Containment. Ethylene presents combustion explosion and fire hazards when released from containment. A wide flammable range and high burning rate accentuate these hazards. Given a large outdoor release, an open-air or open-space explosion can occur.

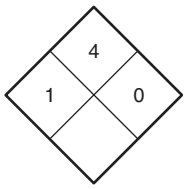
Emergency Control. Escaping ethylene presents both "no fire" and "fire" emergency situations. At normal atmospheric temperatures, ethylene gas is very slightly lighter than air. Ethylene gas vaporizing from the cryogenic liquid near its normal boiling point is heavier than air at 70°F (21°C) and can spread along the ground. Escaping liquid will also pool on the ground. Although the visible fog created is a rough indication of the extent of the hazardous area, the hazard can extend beyond the visible area.

Escaping gas can be controlled by water spray. Contact between water and pooled ethylene should be avoided to prevent increased vaporization, unless the vapors can be controlled. Water should be applied to fire-exposed containers and the flow of escaping gas should be stopped if possible.

Hydrogen



UN 1066
Cryogenic Liquid



UN 1049
Compressed Gas

Classifications. Hydrogen is classified as flammable, compressed, cryogenic, and industrial.

Chemical Properties. Hydrogen is a basic chemical element. Hydrogen has an extremely wide flammable range and the highest burning velocity of any gas. Its ignition temperature is reasonably high, but its ignition energy is very low. Because hydrogen contains no carbon, it burns with a nonluminous flame that is often invisible in daylight. Hydrogen is nontoxic.

Physical Properties. See Table 6.10.3.

Usage. Hydrogen is principally used in chemical processing for hydrogenation of edible oils, in welding and cutting, as a metal heat-treating special atmosphere, as a coolant in large electrical generators, and in the manufacture of semiconductors. It is also being used as a vehicle fuel.

Hazards Inside Containers. Hydrogen is shipped as a compressed gas in uninsulated DOT and TC cylinders, as a cryogenic gas in insulated DOT and TC cylinders, and in insulated cargo trucks and railroad tank cars according to DOT specifications and regulations. It is stored in cylinders or in ASME-code insulated tanks.

Compressed hydrogen cylinders are protected against overpressure by frangible (bursting) discs or such discs in combination with fusible plug devices. Insulated cylinders, trucks and railroad tank cars, and storage tanks are protected by pressure-relief valves and frangible disks. Compressed gas cylinders are subject to failure but not to BLEVEs because they do not contain liquid. Insulated cryogenic containers are theoretically subject to BLEVEs, but the probability is low.

Hydrogen is also shipped as a refrigerated liquid at about its normal atmospheric boiling point of –423°F (–253°C) in insulated containers. These are pressure vessels with reclosing pressure-relief valves, which will open to relieve the pressure that develops when heat leakage into the container results in boiling of some of the stored hydrogen. When this occurs, a visible cloud will develop as the air is cooled. Do not spray water in the vicinity of the discharge point, as it can freeze and block this important safety procedure.

Hazards When Released from Containment. Hydrogen presents both combustion explosion and fire hazards when released from containment. Although its wide flammable range and high burning rate accentuate these hazards, its low ignition energy, low heat of combustion on a volume basis, and its nonluminous (low thermal radiation level) flame exert counteracting influences in many instances.

Because of its low ignition energy, when gaseous hydrogen is released at high pressure, nominally small heat-producing sources, for example, friction and static generation, can result in prompt ignitions. On this basis, hydrogen may be frequently thought of as self-igniting under these circumstances. Typically, in high-pressure applications, fires rather than combustion explosions occur. When hydrogen is released at low pressures, however, self-ignition is unlikely. Rather, hydrogen combustion explosions occur that are characterized by very rapid pressure rises that are extremely difficult to vent effectively. Open-air or open-space explosions can occur from large releases of gaseous hydrogen.

Because of its very low boiling point, contact between liquid hydrogen and air can result in condensation of air and its oxygen and nitrogen components. A mixture of hydrogen and

liquid oxygen is potentially explosive, even though the quantities involved are likely to be small.

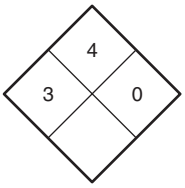
At ordinary temperatures, hydrogen is very light, weighing only about 1/15 as much as air. The accordingly high diffusion rate makes it difficult for hydrogen to accumulate in conventional structures, unless the escape rate is high. This tends to reduce its combustion explosion hazard.

Emergency Control. Escaping gaseous hydrogen seldom presents a "no fire" emergency situation because it either ignites promptly or rises in the atmosphere rapidly. Hydrogen gas vaporizing from the cryogenic liquid near its normal boiling point is slightly heavier than air at 70°F (21°C); this fact, together with the visible fog of condensed water vapor created, causes it to spread along the ground for sizable distances (depending on leak size and meteorological conditions). Because of the low gas density of vapors produced from vaporizing cryogenic hydrogen liquid, impounding or diked areas have not been required.

Ignitable mixtures can extend well beyond the visible cloud. Such escapes can be controlled by water spray. Contact between water and pooled hydrogen should be avoided to prevent increased vaporization, unless the vapor can be controlled.

Water should be applied to fire-exposed containers and the flow of gas stopped, if possible. Because hydrogen burns with a flame that is often invisible in daylight and because its flames produce low levels of thermal radiation, people can walk into its flames unaware. When approaching hydrogen fires, a useful technique is to hold a broom out in front, while progressing slowly and at the same time throwing dirt ahead. The combustibles in the dirt will incandesce and locate the edge of the fire.

Liquefied Natural Gas (LNG)



UN 1972

Classifications. Liquefied natural gas is classified as flammable, cryogenic, and fuel.

Chemical Properties. LNG is a mixture of materials all comprising carbon and hydrogen. The principal component is methane, with lesser amounts of ethane, propane, and butane. The composition will vary, depending principally on whether the source of the natural gas (which has been liquefied) is a transmission pipeline or gas wells. In the former instance, more of the propane and butane is removed prior to introduction into the pipeline (Table 6.10.4). LNG is nontoxic but is a simple asphyxiant, which can cause asphyxiation due to the displacement of air.

Physical Properties. See Table 6.10.4.

Usage. LNG is used as a source of natural gas to augment pipeline supplies during periods of extreme demand (peak shaving), to supply gas distribution systems in areas remote from central distribution systems, and as a basic supply of natural gas. To a small extent, it is used as a vehicle propulsion fuel.

TABLE 6.10.4 Approximate Properties of LNG

Composition	
Methane	83–99%
Ethane	1–13%
Propane	0.1–3.0%
Butane	0.2–1.0%
Physical properties	
Normal boiling point (NBP)	–250 to –260°F (–160 to –164°C)
Density liquid at NBP	3½ to 4 lb per gal (0.42 to 0.48 g/cm^3)
Density vapor at NBP (compared with air at 70°F or 21°C)	1.47
Liquid to vapor expansion	600 to 1
Heat of vaporization	220–248 Btu/lb (512–577 kJ/kg) 770–990 Btu/gal (215–276 mJ/m^3)
Combustion properties	
Flammable range	5–14% (methane at normal temperatures) 6–13% (methane near –260°F or –127°C)
Heat of combustion	22,000 Btu/lb (51.2 mJ/kg)
Burn rate, steady-state pool	0.2–0.6 in. (5 to 15 mm) per min

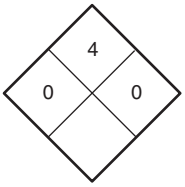
Hazards Inside Containers. LNG is shipped as a cryogenic gas in insulated cargo trucks built to DOT specifications and regulations and in marine vessels under DOT authorization. It is stored in insulated ASME code or API tanks. LNG containers are protected against overpressure by pressure-relief valves. Such containers are theoretically subject to BLEVEs, but the probability is low.

Hazards When Released from Containment. LNG presents both combustion explosion and fire hazards when released from containment. At the present time, LNG is seldom used indoors and when so used the structure is designed for a combustion explosion hazard in accordance with national standards and regulations.

Emergency Control. Escaping LNG presents both "no fire" and "fire" emergency situations. LNG gas vaporizing from the cryogenic liquid near its normal boiling point is about 1½ times heavier than air is at 70°F (21°C) and will spread along the ground accompanied by the visible fog created by condensed water vapor. This distance will depend on the leak size and meteorological conditions and on the geometry of the required liquid-impounding area provided. Ignitable areas are roughly

defined by the visible cloud but can extend beyond the visible area. Such escape can be controlled by water spray. Contact between water and pooled LNG should be avoided to prevent increased vaporization, unless the vapor can be controlled. Water should be applied to fire-exposed containers and the flow of gas stopped, if possible.

Liquefied Petroleum Gases (LP-Gas)



UN 1075

Classifications. Liquefied petroleum gas is classified as flammable, liquefied, and fuel.

Chemical Properties. LP-gas is a mixture of hydrocarbon materials. In commerce, LP-gas is predominantly either propane or normal butane or mixtures of these with smaller amounts of ethane, ethylene, propylene, iso-butane, and butylene (including isomers). Principal variations in composition occur depending on whether the source is gas wells or petroleum refineries. LP-gas is nontoxic but is a simple asphyxiant, which can cause asphyxiation due to the displacement of air.

Physical Properties. See Table 6.10.5.

Usage. LP-gas is used principally as a domestic, commercial, agricultural, and industrial fuel gas in chemical processing and as vehicle fuel. In domestic and recreational applications, it is sometimes known as bottled gas.

Hazards Inside Containers. LP-gas is shipped as a liquefied gas in uninsulated DOT and TC cylinders and in ASME tanks and in DOT-specification cargo trucks, railroad tank cars, and marine vessels. It is also shipped at low temperatures near its normal boiling point of about –40°F (–40°C) at atmospheric pressure in insulated marine vessels. It is stored in cylinders, ASME-code tanks, and insulated API tanks.

LP-gas containers are generally protected against overpressure by pressure-relief valves, although some cylinders are protected by fusible plug devices and, occasionally, by a combination of these. Most containers are subject to BLEVEs.

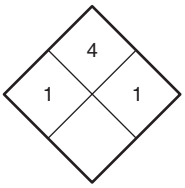
Hazards When Released from Containment. LP-gas presents both combustion explosion and fire hazards when released from containment. This hazard is accentuated when LP-gas is used indoors—reflecting the fact that 1 gal (3.8 L) of liquid propane or butane will produce about 245 to 275 gal (927 to 1041 L) of gas. For this reason, standards and codes severely restrict the uses of liquid-phase LP-gas indoors. Large releases of LP-gas outdoors will most likely result in a deflagration rather than a detonation.

TABLE 6.10.5 Approximate Properties of LP-Gases

	Commercial Propane	*Commercial Butane*
Vapor pressure in psig at		
70°F	127	17
100°F	196	37
105°F	210	41
130°F	287	69
Vapor pressure in kPa at		
20°C	895	103
40°C	1482	285
45°C	1672	345
55°C	1980	462
Specific gravity of liquid at 60°F (15.5°C)	0.509	0.582
Initial boiling point at 14.7 psia	–44°F	15°F
Initial boiling point at 101 kPa	–42°C	–9°C
Weight per gal of liquid at 60°F, lb	4.20	4.81
Weight per m^3 of liquid at 15.5°C, kg	504 kg	582 kg
Specific heat of liquid, Btu/lb 60°F	0.630	0.549
Specific heat of liquid, kJ/kg at 15.5°C	1.46	1.28
ft^3 of vapor per gal at 60°F	36.38	31.26
m^3 of vapor per L at 15.5°C	0.271	0.235
ft^3 of vapor per lb at 60°F	8.66	6.51
m^3 of vapor per kg at 15.5°C	0.534	0.410
Specific gravity of vapor (Air = 1) at 60°F (15.5°C)	1.50	2.01
Ignition temperature in air	920–1120°F (493–549°C)	900–1000°F (482–538°C)
Maximum flame temperature in air	3595°F (1980°C)	3615°F (1990°C)
Limits of flammability in air, percent of vapor in air-gas mixture		
(a) Lower	2.15	1.55
(b) Upper	9.60	8.60
Latent heat of vaporization at boiling point		
(a) Btu/lb	184	167
(b) Btu/gal	773	808
(c) kJ/kg	428	388
(d) kJ/L	216	226
Total heating values after vaporization		
(a) Btu/ft^3	2,488	3,280
(b) Btu/lb	21,548	21,221
(c) Btu/gal	91,547	102,032
(d) kJ/m^3	92,430	121,280
(e) kJ/kg	49,920	49,140
(f) kJ/m^3	25,140	28,100

Emergency Control. Escaping LP-gas presents both "no fire" and "fire" emergency situations. LP-gas vapor is 1½ times heavier than air, and the vapor produced as LP-gas vaporizes from the liquid at its normal boiling point is even heavier. As a heavier-than-air gas, it will tend to spread along the ground but is affected by wind and air currents. When released under pressure, the velocity of a jet release will overcome the weight of the gas. Escaping liquid LP-gas is accompanied by the created visible fog of condensed water vapor. Ignitable mixtures extend beyond the visible area. Such escape can be controlled by water spray. When propane is stored and handled at atmospheric temperatures, it is unlikely to pool, except near the normal boiling point of about –40°F (–40°C). Butane stored and handled at atmospheric temperatures and low-temperature LP-gas are likely to pool at temperatures near the normal boiling point of about 31°F (–0.5°C). Contact between water and pooled LP-gas should be avoided to prevent increased vaporization, unless the vapor can be controlled. Water should be applied to fire-exposed containers and the flow of gas stopped, if possible.

Methylacetylene-Propadiene, Stabilized (MPS)



UN 1060

Classifications. Methylacetylene-propadiene, stabilized (or MPS), is classified as flammable, liquefied, and industrial.

Chemical Properties. Methylacetylene-propadiene, stabilized, is a mixture of materials all composed of carbon and hydrogen. In commerce, and in compliance with standards covering its use as a metal-cutting gas, the composition of MPS is given in Table 6.10.6.

Methylacetylene (also known as "propyne") and propadiene (also known as "allene") contain double and triple chemical bonds and are unstable, reactive materials presenting hazards similar to acetylene. The achievement of an adequate degree of stability for this product depends on the existence of a sufficient quantity of the propane, butane, and iso-butane components of the mixture.

MPS has a degree of chemical reactivity with metals, similar to acetylene—especially as it pertains to the use of copper and copper alloys. (See "Acetylene" in this chapter.)

MPS is nontoxic but has some anesthetic and narcotic effects. It has a strong odor detectable at concentrations as low as 100 ppm in air (Tables 6.10.3 and 6.10.7).

Physical Properties. See Table 6.10.7.

Usage. MPS is principally used as a metal-cutting fuel gas with oxygen.

TABLE 6.10.6 MPS Composition

Methylacetylene-propadiene (in combination with a maximum ratio of 3.0 moles of methylacetylene per mole of propadiene in the initial liquid phase in a storage container)	68 mole percent *maximum*
Propane, butane, isobutane (in combination)	24 mole percent *minimum,* of which at least one-third (8 mole percent of total mixture) shall be butane and/or isobutane
Propylene	10 mole percent *maximum*
Butadiene	2 mole percent *maximum*

Hazards Inside Containers. MPS has physical properties very similar to propane and is shipped as a liquefied gas in uninsulated DOT and TC cylinders and in DOT-specification cargo trucks and tank cars. It is stored in cylinders and ASME-code tanks. Its hazards inside containers are analogous to propane. The pressure of MPS in piping systems is not restricted.

Hazards When Released from Containment. MPS presents combustion explosion and fire hazards when released from containment. It is easier to ignite (due to a lower ignition energy) than propane and burns more rapidly; thus, it is similar to eth-

TABLE 6.10.7 Selected Properties of MPS*

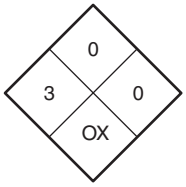
Molecular weight (average-stabilized mixture)	42.3
Heat of vaporization	227 Btu/lb (528 kJ/kg)
Gross heat of combustion	21,700 Btu/lb (50.5 mJ/kg)
Normal boiling range, 1 atm	–36 to –4°F (–37.8 to –20°C)
Flame temperature in oxygen	5301°F (2927°C)
Specific heat, liquid Cp—70°F, (21°C) 1 atm	0.362 Btu/lb°F [1.5 J/(kg/K)]
Specific heat, liquid Cv—70°F, (21°C) 1 atm	0.277 Btu/lb°F [0.9 J/(kg/K)]
Critical temperature	245°F (118°C)
Critical pressure	752 psi (5.2 MPa)
Burning velocity	15.4 ft/sec (4.7 m/sec)
Explosive limits in oxygen	2.5 to 60%
Vapor pressure at 70°F (21°C)	94 psi (648 kPa)
Specific gravity of the liquid (60/60°F)	0.576
Specific volume of the gas at 70°F (21°C), 1 atm	8.85 ft^3/lb (0.55 m^3/kg)
Heat of formation	1075 Btu/lb (2.5 mJ)
Minimum ignition energy	0.2–0.25 mJ

*MAPP gas (Dow Chemical Company).

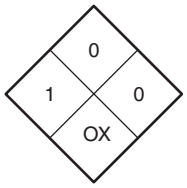
ylene in these respects. MPS is classified as a Group C material for purposes of suitability of electrical equipment installed in classified hazardous areas.

Emergency Control. See "Liquefied Petroleum Gases" in this chapter.

Oxygen



UN 1073
Cryogenic Liquid



UN 1072
Compressed Gas

Classifications. Oxygen is classified as nonflammable (oxidizing), compressed, cryogenic, industrial, and medical.

Chemical Properties. Oxygen is a basic chemical element. It reacts with practically all materials, and the general reaction is known as oxidation. Combustion is a particular type of oxidation reaction. In most combustion reactions, the oxygen is accompanied by nitrogen in a mixture known as air. Nitrogen contributes nothing to the combustion reaction and actually inhibits it. Therefore, concentrations of oxygen in excess of its concentration in air increase most combustion hazards to a degree directly related to the concentration, which affects all basic combustion parameters, except for the heat of combustion. For example, ignition temperatures and energies are lowered, the flammable range is widened, and the burning rate is increased as the oxygen concentration increases—the ultimate effects occurring at an oxygen concentration of 100 percent. In consideration of these properties, the design of systems containing 100 percent oxygen requires particular attention to these factors from a compatibility standpoint.

Physical Properties. See Table 6.10.1.

Usage. Oxygen is primarily used in the production of steel, in metal welding and cutting, in medical applications, in life-support systems, in aeronautic and aerospace applications, and in chemical processing.

Hazards Inside Containers. Oxygen is shipped as a compressed or cryogenic gas in DOT and TC cylinders and in tank cars and trucks in accordance with DOT specifications and regulations. It is stored in DOT-specification cylinders (insulated or uninsulated) or in ASME-code insulated tanks.

Compressed-oxygen cylinders are protected against overpressure by frangible (bursting) discs or a combination of these with fusible plugs. Insulated cryogenic containers are protected with pressure-relief valves. Metals for containers and piping must be carefully selected, depending on service conditions. The various steels are acceptable for many applications, but some service conditions may call for other materials (usually copper or its alloys) because of their greater resistance to ignition and lower rate of combustion.

Similarly, materials that can be ignited in air have lower ignition energies in oxygen. Many such materials may be ignited by friction at a valve seat or stem packing or by adiabatic compression produced when oxygen at high pressure is rapidly introduced into a system initially at low pressure.

Oxygen container failures from fire exposure are rare—probably reflecting standards that require separation of containers from flammable gases and other combustibles. Oxygen system components can fail due to accumulations of grease, oil, and so forth on the surfaces of these components in contact with oxygen, reflecting poor housekeeping practices. Since materials such as grease are easily ignited in air, they are especially ignitable in 100 percent oxygen. Their ignition often results in combustion of system components that are noncombustible in air, including metallic components. Such incidents usually involve only small portions of such components but may occur in a spectacular way, causing property damage and personal injury. They are referred to conventionally as "flashes."

Hazards When Released from Containment. Release of compressed or liquefied oxygen is usually observed by acceleration of the fire in whatever is burning. Release of liquid oxygen in the absence of fire presents an increased possibility that an oxygen-fuel mixture may occur prior to ignition. If ignition delay occurs under these circumstances, an explosion may result. Almost any combination of liquid oxygen and a combustible material is potentially explosive due to the rapid combustion circumstances produced. Some commercial explosives have been derived in this manner. Oxygen is slightly heavier than air at the same temperature, but its density is sufficiently close to that of air that the oxygen will not sink.

Emergency Control. Escaping oxygen presents basically a "no fire" situation but can create a "fire" situation in the vicinity of fired equipment or arcing electrical equipment by causing these to get out of control. For example, metallic components of internal combustion engines have burned in the oxygen-rich atmospheres produced by escaping oxygen. Oxygen gas vaporizing from the cryogenic liquid near its normal boiling point is approximately four times heavier than air is at 70°F (21°C) and will spread along the ground accompanied by the visible fog of condensed water vapor that has been created. Such escape can be controlled by water spray. Contact between water and pooled liquid oxygen should be avoided to prevent increased vaporization, unless the vapor can be controlled. Water should be applied to fire-exposed containers and the flow of gas stopped, if possible.

Liquid oxygen spilled from containers will remain in liquid form for some time while slowly boiling. If it is in contact with any organic material, such as asphalt paving, the combination is shock sensitive and can detonate. The hazard exists only when liquid oxygen is present, and extreme caution is advised.

Utility Gases

Classifications. Utility gases are classified as flammable and fuel.

Chemical Properties. The term *utility gas* applies to any flammable gas distributed by gas utilities as a fuel gas. Natural gas dominates this field today. Some LP-gas is distributed by gas utilities. Many utilities use LP-gas to augment natural gas supplies during short periods of peak demand that occur in unusually cold weather.

The creation of natural gas is the result of decomposition of organic material by heat, pressure, and bacteriological action in the absence of air, usually below ground. As it is evolved underground, natural gas consists of both flammable and nonflammable gases. The flammable gases are composed of carbon and hydrogen and are principally methane and ethane, with some propane, butane, and pentane. The nonflammable gases are principally nitrogen and carbon dioxide. In commerce, most of the nonflammable gases are removed prior to distribution so that the natural gas consists of about 70 to 90 percent methane, with the remainder mostly ethane (see Table 6.10.3).

Natural gas is nontoxic but is a simple asphyxiant. This is in marked contrast to the manufactured gas formerly widely distributed as utility gas and that contained quantities of poisonous carbon monoxide.

Utility natural gas has no odor of its own and is generally odorized as distributed.

Physical Properties. With the exception of liquefied natural gas (LNG), utility natural gas is distributed in piping as a compressed gas at pressures ranging from approximately 0.25 to 1000 psi (1.72 to 6895 kPa) and in cylinders at pressures up to 3600 psi (24.8 MPa). The gas has a density of about ⅔ that of air.

Usage. Utility natural gas supplies about one-fifth to one-fourth of the total fuel energy of the United States for domestic, commercial, and industrial heating and power.[4] It is also being used as a motor fuel and is known as compressed natural gas (CNG). Natural gas (usually supplied from a gas utility distribution piping system) is compressed to 2400 to 3600 psi (16.5 to 24.8 MPa), stored in a fueling station, and dispensed into vehicle containers at the same pressure.

Hazards Inside Containers. Utility natural gas is distributed nearly exclusively by a network of about 1.5 million miles (2.5 million km) of underground pipeline in the United States. It is transported from gas wells in producing areas in large-diameter transmission pipelines at pressures up to approximately 1000 psi (6895 kPa). These pipelines are tapped by utility gas companies, and pressures are reduced for distribution—generally to around 0.25 to 60 psi (1.72 to 414 kPa). Regulators and safety relief devices are used to control pressures.

Steel and cast-iron pipe are used extensively. In recent years, thermoplastic and thermosetting plastic piping have been used extensively in distribution piping at pressures up to approximately 100 psi (689.5 kPa).

SUMMARY

The term *gas* describes the physical state of a substance that has no shape or volume of its own but will take the shape and fill the entire volume of whatever container or other enclosure it occupies. The classfications of gas are flammable, nonflammable, pyrophoric, oxidizing, and toxic.

Gas hazards include both a gas in a container and a gas when it escapes from a container. Hazards within containers include overpressurization, the liquid gas BLEVE, and combustion. Basic combustion explosion prevention safeguards limit flammable gas-air mixture accumulation in a structure.

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3. U.S. Chemical Safety Board Investigation Report, *Propane Tank Explosion,* Report No. 98-007-I-IA, USCSB, Washington, DC, 1998.
4. *Statistical Abstract of the United States 2000,* Bureau of the Census, Washington, DC, Dec. 2000.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on gases discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 51, *Standard for the Design and Installation of Oxygen-Fuel Gas Systems for Welding, Cutting, and Allied Processes*
NFPA 51A, *Standard for Acetylene Cylinder Charging Plants*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 52, *Vehicular Fuel Systems Code*
NFPA 54, *National Fuel Gas Code*
NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 59, *Utility LP-Gas Plant Code*
NFPA 59A, *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 70, *National Electrical Code®*
NFPA 99, *Standard for Health Care Facilities*
NFPA 302, *Fire Protection Standard for Pleasure and Commercial Motor Craft*
NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*

Chapter 11

Medical Gases

Revised by
Mark Allen

Chapter Contents

Types and Hazards of Medical Gases
Distribution Systems for Centrally Piped Medical Gases
Oxygen and Compressed Air
Helium-Oxygen Mixtures and Carbon Dioxide
Vacuum Systems
Respiratory Therapy
Anesthetic Agents
Health Care Facility Laboratories
Fire Prevention and Fire Response
Hyperbaric Chambers
Ambulatory Care Facilities

Key Terms

gas and vacuum systems, health care facility, hyperbaric chamber, medical gas, respiratory therapy, waste anesthetic gas disposal (WAGD)

Medical gases are important from the viewpoint of fire safety not so much because of what they are, but, rather, because of where they are used, namely, in areas where patients are present. Since many patients cannot be readily moved, either because they depend on life-support equipment or because they are not mobile, a fire becomes a more lethal threat than it would be in other environments. The increased use of oxidizers, such as oxygen and nitrous oxide (N_2O), and the increased reliance on potential ignition sources—for example, electrical appliances—places the hospitalized patient at increased risk. This chapter discusses those parts of the health care fire safety problem that are related to the storage and use of medical gases.

Fires directly related to medical gases are fortunately rare; it is primarily the effects of medical gases being near a fire originally caused by other factors that is of greatest concern. The fires most directly associated with medical gases have been related to use of lasers near endotracheal tubing which contains medical gas, with consequent ignition of the gases or tubing, and ignition of catheters (typically for oxygen) because a patient tried to smoke. Some fires are thought to have resulted from ignition of anesthetic waste gases passing through oil-lubricated pumps. Other incidents, injuries, and fatalities associated with medical gases have been the result of construction problems (e.g., failure to test for cross connections in piping systems), cylinder and container misuse (e.g., unsafe handling of cylinders, presence of cylinders filled with the wrong gas, mislabeling, theft), and inadequate training of maintenance personnel.

The safe practices and hazards discussed in this chapter apply to all health care facilities that use medical gases, for example, hospitals, ambulatory health care centers, nursing homes, dental offices, and so on; they also have relevance to the home health care environment. Pertinent information on the problem and hazard of medical gases and equipment can be found in the following chapters: Section 6, Chapter 1, "Fire Hazards of Materials"; Section 6, Chapter 10, "Gases"; Section 6, Chapter 12, "Flammable and Combustible Liquids"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 7, Chapter 3, "Storage of Gases"; Section 9, Chapter 12, "Fire Protection of Laboratories Using Chemicals"; and Section 9, Chapter 17, "Oxygen-Enriched Atmospheres."

TYPES AND HAZARDS OF MEDICAL GASES

Types of Medical Gases

In a typical medical facility, there are a variety of gases used for life support, therapy, medical analysis, and mechanical power. These include oxygen, medical air, nitrous oxide, nitrogen, carbon dioxide, blood gas mixtures, helium, and mixtures of these gases. In addition, two vacuum systems are usually present—medical vacuum and waste anesthetic gas disposal (WAGD). The presence of these gas supplies and vacuum systems, combined with the fact that patients may depend on their uninterrupted supply or operation for life support, complicates the fire picture inside any medical facility.

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Hazards of Medical Gases

Medical gases can present several specific hazards. The first and most significant hazard is the fact that the supply of one or more of these gases may be the only thing keeping a patient alive or ensuring that a treatment or procedure can be successfully completed.

The second hazard is that some of these gases are oxidizers and others are asphyxiants. Oxygen is the most important of these, as a little pure oxygen will increase the intensity of any fire and cause items that are normally considered noncombustible in air to burn very well indeed. Nitrous oxide has a similar character when heated to disassociation—that is, when the nitrogen and oxygen atoms in the N_2O molecule separate, pure oxygen becomes available and the reaction is exothermic, increasing the temperature. Even when not heated to disassociation, nitrous oxide will act as an asphyxiant. Medical air is simply a purified compressed air and will support fire as well as any air, but it is also under pressure. In contrast, nitrogen, helium, and carbon dioxide will slow or stop a fire but at the price of making an anoxic environment, where there is not enough oxygen for breathing and anyone nearby risks asphyxiation.

The third hazard is that these gases are present in cylinders and containers, which, if subjected to overheating from a fire, will vent their contents and, in extreme circumstances, may explode. There are also the simple mechanical hazards of having cylinders fall over, possibly complicating evacuation or presenting the risk of knocking off the cylinder valve and creating a high speed torpedo.

The first way to reduce these hazards is to remove cylinders and containers from the occupied space. This is done simply by locating all the sources remotely and piping the gases and vacuum to the bedside. Centrally piped medical gas systems are found in most hospitals and larger medical facilities. Only in small facilities or facilities that do not use medical gases routinely are there likely to be cylinders at the bedside. An example frequently encountered is nursing homes. However, even in the largest and best-equipped hospital, cylinders for specialized gases will be encountered, most notably in laboratories.

DISTRIBUTION SYSTEMS FOR CENTRALLY PIPED MEDICAL GASES

Components

Distribution systems for medical gases consist of the following components:

- Centrally located supply systems with appropriate controls
- Piping systems, including control valves and alarm
- Terminal units (outlets) in patient care areas and laboratories

The terminal units may be mounted in the wall or in a variety of substructures (manufactured assemblies) located in patient care areas.

Piping System

Each gas and vacuum system will pass through its own dedicated network of copper pipe. All joints, except those at the source of supply, must be brazed or otherwise joined to ensure they can withstand a fire exposure of 1000°F (588°C) or greater. The piping must be pressure tested prior to being filled with the intended gas to ensure there are no leaks and must be tested for purity, cleanliness, and absence of cross connections to other systems before being placed in service, as set forth in detail in NFPA 99, *Standard for Health Care Facilities.*

All piping systems are zoned to allow the gas supply to any specific area to be shut off. In this way, medical gases can be isolated from the piping in a fire area to allow for a "defend in place" fire attack without shutting off the supply of gases or vacuum to patients in other areas who are dependent on these systems (Figure 6.11.1).

Valves

Although zone valves are provided primarily for isolation in case of a fire, extreme care must be exercised before any valve in a medical facility is closed. Valves should only be closed after verifying that all patients are stable and that the supply of gases can be safely cut off. It is also important to note that many valves are poorly labeled and closing one can affect areas not described on the label. Although there are many other valves in a medical gas system, no valve other than the zone valves should be closed by other than facility staff. It is rare to completely evacuate a medical facility and there may be patients in an area not affected by a fire who are still dependent on the medical gases for life.

FIGURE 6.11.1 Typical Enclosure for Gas System Shutoff Valve

TABLE 6.11.1 Standard Designation Colors and Operating Pressures for Gas and Vacuum Systems

Gas Service	*Abbreviated Name*	*Colors (Background/Text)*	*Standard Gauge Pressure*
Medical air	Med Air	Yellow/black	345–380 kPa (50–55 psi)
Carbon dioxide	CO_2	Gray/black or gray/white	345–380 kPa (50–55 psi)
Helium	He	Brown/white	345–380 kPa (50–55 psi)
Nitrogen	N_2	Black/white	1100–1275 kPa (160–185 psi)
Nitrous oxide	N_2O	Blue/white	345–380 kPa (50–55 psi)
Oxygen	O_2	Green/white or white/green	345–380 kPa (50–55 psi)
Oxygen/carbon dioxide mixtures	O_2/CO_2 *n*% (*n* is % of CO_2)	Green/white	345–380 kPa (50–55 psi)
Medical-surgical vacuum	Med Vac	White/black	380 mm to 760 mm (15 in. to 30 in.) HgV
Waste anesthetic gas disposal	WAGD	Violet/white	Varies with system type
Other mixtures	Gas A%/Gas B%	Colors as above Major gas for background/ minor gas for text	None
Nonmedical air (level 3 gas-powered device)		Yellow and white diagonal stripe/ black	None
Nonmedical and level 3 vacuum		White and black diagonal stripe/ black boxed	None
Laboratory air		Yellow and white checkerboard/ black	None
Laboratory vacuum		White and black checkerboard/ black boxed	None
Instrument air		Red/white	1100–1275 kPa (160–185 psi)

Source: NFPA 99, *Standard for Health Care Facilities,* 2005 ed., Table 5.1.11.

Station Outlets

Station outlets for medical gas supply systems must be equipped with noninterchangeable fittings that are keyed to the specific gas handled. Station outlets also require a label with the name of the gas supplied to the outlet. It is allowed to connect breathing apparatus, such as supplied air respirators, to medical air systems, but be aware that the connections are often different and not interchangeable. If medical air is intended to be used for these purposes, for instance in the event of a disaster involving chemical or biohazardous agents, ensure that the connections are compatible.

Medical gases are color coded for quick identification. These colors are used throughout the systems from the source to the outlets and even may carry through the equipment that is plugged into the outlets (Table 6.11.1).

Medical Gas Supplies

Cylinder weights, sizes, pressures, and contents are shown in Table 6.11.2, which is taken from NFPA 99. Oxygen is usually supplied from either a bulk oxygen system or a manifold system of cylinders. Safety requirements for both are contained in NFPA 99. Nitrous oxide, carbon dioxide, and nitrogen are commonly supplied through a manifold system of cylinders (Figure 6.11.2). Medical air systems are typically supplied from a compressor, but occasionally a manifold system is used.

Manifold rooms and rooms used to store cylinders should be identified and labeled as containing medical gases. The labeling must indicate if the room contains oxygen or if it contains only asphyxiants. Care should always be exercised when entering a room containing quantities of medical gases.

Medical air compressors and vacuum pumps are typically located in the same mechanical rooms with other equipment. Because these systems can be life supporting, ensure that

FIGURE 6.11.2 Typical Manifold Medical Gas Supply

TABLE 6.11.2 Typical Medical Gas Cylinders—Volume and Weight of Available Contents[a]

			Name of Gas								
								Mixtures of Oxygen			
Cylinder Style & Dimensions	*Nominal Volume[b] (in.³/L)*	*Contents*	*Air*	*Carbon Dioxide*	*Cyclo-Propane*	*Helium*	*Nitrogen*	*Nitrous Oxide*	*Oxygen*	*Helium*	*CO_2*
B	87/1.43	psig		838	75				1900		
3½" od × 13"		liters		370	375				200		
8.89 × 33 cm		lb-oz		1-8	1-7¼				—		
		kilograms		.68	.66				—		
D	176/2.88	psig	1900	838	75	1600	1900	745	1900	[c]	[c]
4½" od × 17"		liters	375	940	870	300	370	940	400	300	400
10.8 × 43 cm		lb-oz	—	3-13	3-5½	—	—	3-13	—	[c]	[c]
		kilograms	—	1.73	1.51	—	—	1.73	—	[c]	[c]
E	293/4.80	psig	1900	838		1600	1900	745	1900	[c]	[c]
4¼" od × 26"		liters	625	1590		500	610	1590	660	500	660
10.8 × 66 cm		lb-oz	—	6-7		—	—	6-7	—	[c]	[c]
		kilograms	—	2.92		—	—	2.92	—	[c]	[c]
M	1337/21.9	psig	1900	838		1600	2200	745	2200	[c]	[c]
7" od × 43"		liters	2850	7570		2260	3200	7570	3450	2260	3000
17.8 × 109 cm		lb-oz	—	30-10		—	—	30-10	122 ft³	[c]	[c]
		kilograms	—	13.9		—	—	13.9	—	[c]	[c]
G	2370/38.8	psig	1900	838		1600		745		[c]	[c]
8½" od × 51"		liters	5050	12,300		4000		13,800		4000	5330
21.6 × 130 cm		lb-oz	—	50-0		—		56-0		[c]	[c]
		kilograms	—	22.7		—		25.4		[c]	[c]
H or K	2660/43.6	psig	2200			2200	2200	745	2200		
9¼" od × 51"		liters	6550			6000	6400	15,800	6900		
23.5 × 130 cm		lb-oz	—			—	—	64-0	244 ft³		
		kilograms	—			—	—	29.1	—		

[a]These are computed contents based on nominal cylinder volumes and rounded to no greater variance than ± 1%.
[b]All volumes at 70°F (21.1°C).
[c]The pressure and weight of mixed gases will vary according to the composition of the mixture.
Source: Reprinted with permission from the Compressed Gas Association, Inc.

patients are under proper alternate care whenever the systems are deactivated.

Specifications for the design, installation, testing, and operation of nonflammable medical piped gas systems for health care facilities are covered in NFPA 99.

OXYGEN AND COMPRESSED AIR

Oxygen and Nitrous Oxide Use

Oxygen is routinely used for many therapeutic purposes. This relates to the simple fact that oxygen is essential to life and getting enough oxygen is the first essential for survival. Thus, recognizing that oxygen-enriched atmospheres are present in various therapeutic applications, fire or explosion prevention in health care facilities must take into account the control of potential fuels and ignition sources.

The problem of oxygen enrichment must be extended to encompass the other commonly used oxidant, nitrous oxide. Since nitrous oxide vigorously supports combustion and also releases heat of decomposition, the fire hazard of N_2O is compounded. The widespread use of oxygen and nitrous oxide in operating rooms, in conjunction with the "wet environment" of the operating room, along with a wide array of potential electrical ignition sources, makes the operating room a particularly hazardous fire location.

Oxygen Compression and Storage

Most oxygen for medical use is prepared by compression and liquefaction of air, followed by fractional distillation. Once purified, it is transported to and stored at the site of consumption as a compressed gas or as a liquid. Because of the economies of scale, almost all medium to large hospitals rely on bulk oxygen storage on site. NFPA 55, *Standard for the Storage, Use, and*

Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks, includes information on the design and operation of such bulk oxygen storage units.

Oxygen concentrators, which separate air into its major components, nitrogen and oxygen, and then deliver oxygen of purity approaching 90 percent, can also be used. Oxygen concentrators are particularly useful when used on-site in facilities such as mobile military hospitals, hospitals in inaccessible geographic areas, and home health care environments.

Compressed Air

Compressed air has a wide variety of uses in medicine. It can be mixed with oxygen for ventilation of a patient's lungs, thus avoiding the complications of breathing pure oxygen over prolonged periods of time. Compressed air is also used in various laboratory apparatus. NFPA 99 includes provisions for the installation of a central piping system for compressed air for medical purposes.

Atmospheric air compressed to greater than ambient pressure (i.e., greater than 14.7 psi [101 kPa]) constitutes an oxygen-enriched atmosphere. Although not as hazardous as pure oxygen, the ease of ignition of combustible substances is nevertheless increased, and flame spread rate is greater than in air at ambient pressures. The fire hazard created by compressed air is thus significant; fire extinguishment in a compressed air atmosphere is difficult. Fire blankets and dry chemical agents are ineffective, since the burning continues in gas pockets that require the burning material be cooled by water.

If a fire occurs in electrically powered equipment in a compressed air atmosphere, the equipment must first be deenergized. The fire can then be extinguished with water.

Compressed air is supplied from compressors or from manifolded gas cylinders. If a compressor is used to supply a piped medical air system in a health care facility, the compressor must not add impurities, such as hydrocarbons, carbonaceous particulates, or carbon monoxide. To meet these specifications, at minimum, the air intake for the compressor must not take suction from the building in which the compressor is located. In addition, the air supplied by the compressor must be free of any contaminant lubricants or products resulting from the breakdown of lubricants. Some lubricants release contaminants such as carbon monoxide under the pressure and temperature generated in an air compressor, which could be distributed in the compressed air system. In a health care facility using a compressor to furnish air to the operating room and as an adjunct to respiratory therapy, electric power to the compressor must be wired to the critical branch of the essential electrical system of the facility. The specifications for this electric system are set forth in NFPA 99.

If a health care facility is located in an area in which the atmosphere is highly contaminated, it may be desirable to use compressed air from cylinders rather than compressing it on site. Some suppliers of cylinders may not have a pure source of atmospheric air to compress and oxygen-nitrogen mixtures may then be used. This so-called synthetic air is purer than ambient air, because it is made up of pure oxygen and nitrogen and so contains no atmospheric pollutants.

Because of the risks of backfeeding and overdrawing the system, the medical compressed air system should not be used for any nonpatient purpose. Medical air may also be used in hyperbaric chambers.

HELIUM-OXYGEN MIXTURES AND CARBON DIOXIDE

Helium-Oxygen Mixtures

Helium-oxygen mixtures are occasionally used in treating certain forms of respiratory distress and in anesthesia for laser airway surgery. This gas mixture should be treated as an oxygen-enriched atmosphere and precautions noted in the previous section should be followed. It should also be noted that helium delays ignition of combustibles due to its higher thermal conductivity compared to nitrogen. However, if combustion does occur, this higher thermal conductivity creates a more rapid flame spread rate in helium than in nitrogen. In addition, since helium possesses a lower specific heat than that of nitrogen, the flame temperature will be higher in helium dilution than in nitrogen dilution. Thus, although helium can delay ignition, if ignition does occur, the fire in a helium atmosphere is more destructive than in a nitrogen atmosphere.

Carbon Dioxide

Carbon dioxide is seen in more hospitals than previously because the gas is a vital part of "keyhole" surgery, in which it is used to balloon the body (insufflation) to allow space for endoscopes to pass through the body to perform surgery.

VACUUM SYSTEMS

Operation of Medical Vacuum Systems

In addition to centrally piped gas systems for pressurized gases, central vacuum systems are a standard feature in most health care facilities. They will appear the same as the gas systems in most respects, but the flow is into the wall or ceiling rather than out. Station inlets for the vacuum system are commonly installed in emergency rooms, operating rooms, recovery rooms, intensive care units, delivery rooms, nurseries, and patient rooms. Although portable individual vacuum pump units have been used in the past, and are still sometimes available for backup, most large health care facilities use central systems. A central vacuum system requires both collection bottles and trap bottles at the station inlets. The collection bottles collect the fluids. The trap bottles ensure that none of the material so collected enters the suction line. In dealing with vacuum systems, the additional presence of biological contamination must be expected and precautions similar to those employed for blood borne pathogens should be considered.

Vacuum System Uses and Hazards

Medical and surgical vacuum systems are also life supporting. Although it is less likely to be instantly fatal than loss of

oxygen or medical air, loss of vacuum can be deadly to a patient whose condition depends on the vacuum. Medical vacuum systems should be treated with the same precautions as any piped system as regards valve closures or source interruption. A central vacuum system may also be used in laboratories and other hospital facilities. Such systems should not be connected to the medical-surgical vacuum system piping. However, a common receiver tank is permitted.

In the operation of a central vacuum system, it is important to avoid drawing flammable gases or liquids into the system. At the discharge end, the system should avoid contaminants returning into the facility. Requirements for vacuum systems in health care facilities are included in NFPA 99.

Waste Anesthetic Gas Disposal (WAGD) (Scavenging)

Accepted anesthesia practice dictates that waste anesthetic gas disposal (WAGD) be incorporated in anesthetizing locations. Anesthesia techniques can result in a portion of the excess gases being vented to the operating room atmosphere, polluting the operating room and possibly creating an occupational hazard for personnel.

Waste anesthetic gas disposal systems include the collection system for the excess anesthesia gases, the system that transports the gases, and the vacuum producer (typically a pump or blower). The medical vacuum system is permitted to be used for WAGD and if used in this way must have a capacity greater than that for conventional operating room requirements. There have been reports of fires that appear to have resulted from waste anesthetic gases being passed through oil-lubricated pumps; this practice should be discouraged. For more details on WAGD, ANSI Z79.11, *Anesthetic Equipment—Scavenging Systems for Excess Anesthetic Gases,* should be reviewed.

Housekeeping Vacuum Systems

In some health care facilities, a vacuum system for housekeeping purposes may exist. It is used in conjunction with vacuum equipment for cleaning corridors, drapes, and other related housekeeping chores. This system must be separate from the central vacuum system used for medical purposes.

RESPIRATORY THERAPY

Respiratory Therapy Equipment and Uses

Respiratory therapy began with the use of oxygen-enriched atmospheres in oxygen tents. Subsequently, various methods for the use of oxygen in medical care were developed, including oxygen hoods, incubators for newborns, oronasal or nasal masks, nasal catheters, and devices that mechanically assist or control breathing while delivering medical gases via tracheal tubes.

This equipment, which intermittently generates pressure, delivers oxygen, air-oxygen mixtures, or oxygen mixed with therapeutic agents. These devices may be powered by a pressurized oxygen supply or by an electrically operated motor and pump system. Controls for such ventilators are pneumatic, fluidic, or electronic. One type of respiration unit is shown in Figure 6.11.3. The unit shown is connected to the hospital compressed air and oxygen distribution system via quick-connect couplers on hoses at rear. The desired air-oxygen mixture is typically delivered to the patient through a filter and through the attached corrugated tubing. The above-mentioned combination of oxygen-enriched atmosphere and an electrically operated power supply, in addition to the proximity of potential fuels, can contribute to fires in the equipment.

Respiratory Therapy Equipment Hazards

In oxygen-enriched atmospheres, combustible substances possess a lower ignition temperature and burn more rapidly than in air. Flame spread can be extremely rapid, especially if bedding or clothing is saturated with oxygen. The safe practices for the use of respiratory therapy equipment are detailed in NFPA 99.

Handling of Cylinders

Transfilling gas from cylinder to cylinder is a hazardous procedure and should be performed only by qualified personnel. It is

FIGURE 6.11.3 Respirator Typically Used for Intensive-Care Patients

not permitted in patient care areas of health care facilities (see NFPA 99). The Compressed Gas Association publishes safety guides for transfilling cylinders (see Bibliography). In addition to bulk storage of liquid oxygen, liquid oxygen within a medical facility may also be distributed by portable liquid oxygen units.

Oxygen is sometimes used in emergency service vehicles. Generally, small cylinders are employed. The same precautions must be exercised in emergency service vehicles as in a permanent facility.

Medical gases are encountered in home health care usually in the form of smaller containers or concentrators for oxygen. The oxygen is used by the patient for breathing support, sometimes during exercise (a "walker"), or to deliver medications. Fires from smoking around oxygen may occur in these situations.

ANESTHETIC AGENTS

Development of Anesthetic Agents

The introduction of diethyl ether as an anesthetic in 1846 led to dramatic changes in surgical practice. Its benefits were so obvious that general anesthesia rapidly became an accepted technique. Diethyl ether had many drawbacks, however, including flammability, and the search for better methods led to the development and introduction of many other agents, including some that were true gases (e.g., nitrous oxide and cyclopropane). Enrichment of anesthetic atmospheres with oxygen occurred nearly simultaneously with the introduction of nitrous oxide and allowed anesthetists to administer appropriate concentrations of anesthetic to patients while, at the same time, maintaining adequate levels of oxygenation. The practice of using oxygen as a component of inhalation anesthesia persists to this day.

Flammability of Anesthetics

Anesthesiologists have almost completely abandoned the use of flammable anesthetic agents. This includes both ether and cyclopropane. A large number of nonflammable anesthetic agents have replaced them, including halothane, enflurane, isoflurane, desflurane, and sevoflurane. Nitrous oxide continues to be used widely as an adjuvant (i.e., a pharmacological agent added to a drug to increase or aid its effect). Nitrous oxide and oxygen, both oxidants, vigorously support combustion. The oxygen in the nitrous oxide molecule is released under flame conditions, contributing to the oxidation-reduction reaction and the released heat of dissociation contributes to the damage created by the fire.

Anaesthetic agents are considered nonflammable under usual anesthetic conditions of use. However, given that these agents are often mixed with oxygen and nitrous oxide, they can become flammable. Sevoflurane is reported to have a lower flammability limit of 11 percent in oxygen and 10 percent in nitrous oxide. In oxygen, desflurane is reported to have a lower flammability limit of 11 percent and an upper flammability limit of 21 percent. In nitrous oxide, the reported lower flammability limit is 18 percent, and the upper flammability limit is 27 percent.

Safe Practices in Using Anesthetics

A consideration of safe practices in anesthesia begins with understanding the basic chemistry and physics of oxygen and the anesthetic gases, as well as the vapors produced by the volatile liquid agents. Nitrous oxide is stored in cylinders and typically piped through the facility to outlets in all anesthetizing locations. Similarly, oxygen is stored in containers or cylinders and piped to the anesthetizing areas. Medical air is produced on site through compressors and purification apparatus and then piped to the area of use. In contrast, liquid anesthetic agents, such as halothane and isoflurane, are stored as liquids that then volatilize in vaporizers during use. The oxygen, nitrous oxide, and air are carrier gases that transport the vaporized molecules of the volatile anesthetic agent through the anesthesia circuit.

HEALTH CARE FACILITY LABORATORIES

Health care facility laboratories may use a wide variety of gases and gaseous mixtures for chemical analysis, the generation of flames, and other purposes. NFPA 99 sets forth the design features and practices required for the safe operation of such a laboratory.

Gas Sterilization

For many years, sterilization by either dry heat or steam was standard practice for the eradication of bacteria and other pathogens from reusable medical equipment. Ethylene oxide, an extremely volatile liquid that vaporizes readily at room temperatures, was then introduced. It is an effective bactericidal and virucidal agent.

To sterilize objects by this method, the sterilizer chamber is first evacuated of air, then filled with ethylene oxide gas. The gas penetrates the material contained in the chamber and destroys bacteria, viruses, and other pathogenic organisms. Ethylene oxide is highly flammable and chemically reactive. Proper operation of the equipment is required to avoid the danger of unintentional ignition or explosion. The liquid is delivered to the facility in cylinders that must be stored properly, as is the case with any container of flammable liquid or gas. It also can be delivered mixed with other gases to reduce flammability. Ethylene oxide is toxic to humans, and proper venting of the ethylene oxide sterilizer to the outside of the building is mandatory. Ethylene oxide is not considered a medical gas in the sense that oxygen and nitrous oxide are medical gases, and it has no role in patient treatment. This means that it is not covered under the rules that govern the design and installation of medical gases. Safe practices applicable to ethylene oxide storage, handling, and use can be found in NFPA 560, *Standard for the Storage, Handling, and Use of Ethylene Oxide for Sterilization and Fumigation.*

Other Disinfecting Agents

Other chemical sterilizing and disinfecting agents have been used in the past, including chlorine, ozone, sulfur dioxide, and formaldehyde gas. Because of the problems in handling these

agents, their corrosive nature, and the greater efficacy and safety associated with heat and ethylene oxide sterilization, these agents are no longer used for medical sterilization purposes.

FIRE PREVENTION AND FIRE RESPONSE

Fire and Explosion Prevention

Potential ignition sources in hospital oxygen-enriched atmospheres include electrosurgical units, lasers, fiberoptic light sources, heat of adiabatic compression of gases, electric sparks, friction sparks, heated objects (including open flame), static electricity, short circuits, defibrillators, and others. In view of the hazards involved, fire prevention methods generally strive for redundancy to establish built-in safeguards of a multifaceted nature so that an explosion or fire will not occur even if one element of the safety recommendations fails or is omitted.

To prevent dangerous adiabatic compression heating of oxidizing gases, it is recommended that cylinder valves be opened slowly to allow only gradual introduction of the high-pressure gas downstream from the cylinder valve. This allows a slow buildup of pressure and, hence, temperature buildup is minimized, thus allowing the mass of the metal of the regulator or other gas-containing component to dissipate the heat rapidly enough to prevent the buildup of dangerously high temperatures. Under the conditions of oxygen-enrichment and high pressure, certain metals can burn. Aluminum is particularly susceptible to ignition under such conditions. This phenomenon has been held responsible for a number of fires that have occurred in aluminum cylinder regulators used by first responders. Generally, the use of aluminum regulators in this service should be avoided and brass regulators substituted.

The elimination of electric sparks requires the proper design, application, and maintenance of electrical equipment. Specifications for this electrical equipment, as well as for line cords and power supplies, are set forth in NFPA 99. Recommendations for the proper use of this equipment by facility personnel are also spelled out in NFPA 99.

Cylinders, regulators, pipeline systems, and other systems containing compressed air, oxygen, and nitrous oxide must be cleaned specifically for such use and maintained free of hydrocarbon contaminants (solvents, lubricants, etc.) that may act as fuels. Combustion of such fuels contributes to the fire hazard and creates increased pipeline pressure and the release of potentially toxic pyrolysis and combustion products.

Other fuels include mattresses, bed and operating-room table sheets and drapes, patient hair, anesthesia and respiratory care equipment, cleaning and prepping solutions, rubber gloves, oxygen-delivery tubing and masks, gauze pads and sponges, and the intestinal gases hydrogen and methane.

Fire-Fighting Problems

Oxygen-enriched atmospheres are encountered during practically every inhalation anesthetic and respiratory therapy procedure. Nitrous oxide, an anesthetic, is also considered an oxygen-enriched atmosphere. When bedding and clothing become saturated with oxygen and a fire occurs, flame spread will be extremely rapid and large quantities of water are required for extinguishment. Dry chemical fire extinguishers and fire blankets are ineffective. If the fire involves electrical equipment, such equipment must first be deenergized. The fire may then be extinguished with water. Halon and carbon dioxide fire extinguishers are also appropriate. Safe practices for the prevention of fires during the use of respiratory therapy are covered in NFPA 99. Also included is a recommended response in the event of a fire involving respiratory therapy equipment.

Flammable liquids are present in most health care facilities in pharmacy storage, hospital laboratories, housekeeping, and other areas. Special fire problems are created if any of these substances are allowed to enter drains, the central suction system, or ventilation ducts.

Mechanical hazards are created by the potential energy contained in compressed gas cylinders. For some surgical procedures, an operating room meets the definition of a "wet location." Although high-voltage electrical equipment (e.g., radiological) and electronic equipment (e.g., medical monitoring and computer) do not alone usually create a fire hazard, combustibles stored in their vicinity may be involved in a fire. The free use of water is inadvisable because of the electric shock hazard to the fire fighter or damage to the equipment. The presence of radioisotopes may also hamper fire suppression methods. Fire service personnel must be made aware of all special problems created by equipment or supplies in any health care area.

An aid to the identification of hazards associated with medical gases and agents is the NFPA hazards identification symbol system (see NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*). This identification scheme, based on the "704 diamond," can visually present information on flammability, health, and self-reactivity (instability) hazards, as well as special information associated with the hazards of the materials being identified. NFPA 99 requires application of the NFPA hazards identification symbols to laboratories. It is also prudent policy to apply the system throughout a facility in such areas as general stores, housekeeping, pharmacy, operating rooms, gas and flammable liquid storage rooms, and any other location where volumes of combustible or flammable materials are stored or used, or where certain special fire-fighting problems exist.

Fire-fighting personnel are trained to recognize and understand the relative hazard potential identified by the 704 diamond. Adoption of the 704 hazard identification system affords enhanced fire protection. Fire personnel are instantly apprised of the hazards they face. In addition, employees are educated about the hazardous nature of the materials they employ daily, enhancing prevention. It is also possible that, in deploying the system, personnel discover hazardous materials no longer in use that should be removed from the hospital premises, thus eliminating potential problems.

HYPERBARIC CHAMBERS

The operation of hyperbaric chambers is another use of an oxygen-enriched atmosphere. Typically, the percentage of oxygen is deliberately increased in the chamber. Some chambers may be small and accommodate only a single patient. Others

may be designed to allow the performance of an operative or other procedure and are thus large enough to accommodate one or more patients and several attendants. Because the pressure of the gas in the chamber is elevated, an increased partial pressure of oxygen results. Safety standards for hyperbaric chambers and facilities are detailed in NFPA 99.

The number of hyperbaric chambers in the United States increased during the latter part of the twentieth century. Most hyperbaric facilities are located in hospitals or other health care facilities and operate under NFPA 99. However, with the recent increase in the number of hyperbaric chambers there has been a corresponding increase in the number of freestanding hyperbaric facilities that operate independently of health care facilities. These independent facilities must also follow safety codes and operational safeguards that are essential with these units.

AMBULATORY CARE FACILITIES

Many requirements for the safe use of oxygen-enriched atmospheres in ambulatory care facilities, dental offices, and other facilities are identical to those for hospitals. Individual vacuum units rather than a central system are commonly used because of the relatively small amount of suction needed in dental offices. In larger dental offices or ambulatory care facilities in which surgery is performed under general anesthesia, it is necessary to incorporate a central vacuum system for the operating rooms and the recovery rooms, as well as for central piping of oxygen and nitrous oxide. Requirements for inhalation anesthesia in such facilities are contained in NFPA 99.

SUMMARY

The storage and use of oxidizing gases in hospitals and other health care facilities represent a unique fire safety problem, since many patients cannot be easily evacuated in a fire emergency. Effective fire prevention measures include minimizing potential ignition sources, such as cigarette smoking and electrical sparks. Cylinders, regulators, pipeline systems, and other systems containing compressed air, oxygen, and nitrous oxide must be cleaned, handled, and maintained properly.

Fire service personnel must be made aware of all special problems created by equipment or supplies in any health care area. An aid to the identification of hazards associated with medical gases and agents is the NFPA hazards identification symbol system, which visually presents information on flammability, health, and self-reactivity (instability) hazards. The use of an oxygen-enriched atmosphere in hyperbaric chambers and the use of inhalation anesthesia in ambulatory care facilities are covered by NFPA 99.

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NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres*
NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks*
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 99, *Standard for Health Care Facilities*
NFPA *101®*, *Life Safety Code®*
NFPA 115, *Standard for Laser Fire Protection*
NFPA 560, *Standard for Storage, Handling, and Use of Ethylene Oxide for Sterilization and Fumigation*
NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*
NFPA 801, *Standard for Fire Protection for Facilities Handling Radioactive Materials*

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CGA V-1, *Compressed Gas Cylinder Valve Outlet and Inlet Connections*
CGA V-5, *Diameter—Index Safety System (Non-Interchangeable Low-Pressure Connections for Medical Gas Applications)*
CGA V-6, *Cryogenic Liquid Transfer Connections*

Chapter 12

Flammable and Combustible Liquids

Orville M. Slye, Jr.

Chapter Contents

Hazards of Flammable and Combustible Liquids
Classification of Flammable and Combustible Liquids
Physical Properties of Liquids
Physical Characteristics of Flammable and Combustible Liquids
Fire Characteristics of Liquids That Burn
Ignition Temperature (Autoignition Temperature, Autogenous Ignition Temperature)
Burning Characteristics of Liquids That Burn
Fire Prevention Methods

Key Terms

boiling point, combustible liquid, evaporation rate, flammable limit, flammable liquid, flashpoint, ignitable mixture, ignition temperature, specific gravity, vapor density ratio, vapor pressure, viscosity

This chapter focuses on the fire hazards of flammable and combustible liquids and includes a review of the NFPA classification system for these liquids. The physical and fire characteristics of liquids are discussed with a special emphasis on the burning characteristics of these materials. Fire prevention methods for the use, handling, and storage of flammable and combustible liquids complete the chapter.

For more information about flammable and combustible liquids not contained here, see the following chapters: Section 2, Chapter 1, "Physics and Chemistry of Fire"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 7, Chapter 4, "Storage and Handling of Chemicals"; Section 8, Chapter 1, "Air-Moving Equipment"; Section 11, Chapter 5, "Control of Electrostatic Ignition Sources"; and Section 17, Chapter 8, "Explosion Prevention and Protection."

Flammable and combustible liquids fires can be controlled and extinguished using foam, dry chemical agents, carbon dioxide, halogenated agents, or water, as covered in the following chapters: Section 16, Chapter 9, "Water Spray Protection"; Section 17, Chapter 1, "Carbon Dioxide and Application Systems"; Section 17, Chapter 2, "Chemical Extinguishing Agents and Application Systems"; Section 17, Chapter 4, "Foam Extinguishing Agents and Systems"; and Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems."

HAZARDS OF FLAMMABLE AND COMBUSTIBLE LIQUIDS

The fire hazard of a flammable or combustible liquid comes from its vapors, rather than from the liquid itself. When a flammable or combustible liquid is heated, vapors are evolved from the liquid's surface; this is called *evaporation*. If the liquid is heated to its flashpoint, the vapors evolved will be concentrated enough to be ignited and burn. Because, by definition, most flammable liquids are stored and handled above their flashpoint temperature, vapors are continuously released by the liquid resulting in an ignitable mixture of vapor and air over its surface.

Ignitable mixtures occur when concentrations of vapors in air are within a definite percentage range, commonly referred to as the flammable range. The lower limit of the range is known as the lower flammable limit (LFL). The upper limit of the range is known as the upper flammable limit (UFL). For example, the proportions (flammable range) for carbon disulfide are from about 1 to 44 percent carbon disulfide vapors in air by volume; for ethyl alcohol, from about 4 to 19 percent by volume; and for gasoline, from about 1.4 to 7.6 percent by volume. Therefore, storing flammable and combustible liquids in the proper closed containers and minimizing the exposure of the liquid to air while in use are fundamental safety measures.

Accumulations of flammable vapor-air mixtures can occur in a confined space, such as containers, tanks, rooms, or buildings. The violence of a flammable vapor explosion is dependent on the nature of the vapors, the enclosure containing the mixture, the quantity of the mixture, and the concentration of vapor in the mixture with air. Flammable vapor-air mixtures that have vapor

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concentrations near the lower or upper limits of the flammable range are less intense than those that occur in a well-mixed "stochiometric" concentration.

Distinct from an explosion of a flammable vapor-air mixture inside a tank or container is overpressuring of a tank or container, which results in a rupture. As with vapor explosions, pressure ruptures vary in intensity. Any closed container may rupture violently when exposed to a severe fire.

Fire and explosion prevention measures are based on one or more of the following techniques or principles: (1) exclusion of sources of ignition, (2) exclusion of air (oxygen), (3) storage of liquids in closed containers or systems, (4) ventilation to prevent the accumulation of vapor within the flammable range, and (5) use of an atmosphere of inert gas instead of air. Extinguishing methods for flammable and combustible liquid fires involve shutting off the fuel supply, excluding air by various means, cooling the liquid to stop evaporation, or a combination thereof.

Gasoline is the most widely used flammable liquid. Gasoline generates flammable vapors at ambient temperatures. However, there are many other volatile flammable products. A comprehensive list of the more commonly used flammable or combustible liquids, including the characteristics of each, appears in NFPA's *Fire Protection Guide to Hazardous Materials,* 13th Edition.

Flashpoint is the most commonly used means to determine the relative hazard of flammable and combustible liquids. Other factors that influence the hazard of a liquid are ignition temperature, flammable range, rate of evaporation, reactivity when contaminated or exposed to heat, density, and rate of diffusion of the vapor. The flashpoint and other factors that determine the relative susceptibility of a flammable or combustible liquid to ignition have minimal influence on the burning characteristics of the liquid once the fire has burned for a short period of time.

Although many flammable and combustible liquids are chemically stable (i.e., their primary fire hazard is that they burn), others introduce the problem of instability or reactivity.

The storage, handling, and use of unstable (reactive) flammable or combustible liquids require special attention. It may be necessary to increase the distances to property lines from storage tanks and between adjacent tanks or to provide extra fire protection. For example, it would be poor practice to locate heat-reactive and water-reactive flammable or combustible liquids tanks adjacent to each other. In the event of a ground fire, water applied to the heat-reactive tank for protection might penetrate the tank of water-reactive liquid and cause a violent reaction.

CLASSIFICATION OF FLAMMABLE AND COMBUSTIBLE LIQUIDS

For fire protection purposes, an arbitrary division between liquids and gases has been established, based on the definition of a flammable liquid found in NFPA 30, *Flammable and Combustible Liquids Code.* Liquids are defined as those fluids with a vapor pressure not exceeding 40 psia (2068 mm Hg) at 100°F (37.8°C). Another arbitrary division also has been established between liquids and solids for the purposes of this classification system. A liquid is additionally defined as one which has a fluidity greater than that of 300 penetration asphalt.

The following classification system for flammable and combustible liquids (from NFPA 30) is based on the division of flammable liquids into three categories. It is anticipated that, in most areas, the indoor temperature could reach 100°F (37.8°C) at some time during the year. Therefore, all liquids with flashpoints below 100°F (37.8°C) are called Class I liquids. In some areas, the ambient temperature could exceed 100°F (37.8°C), requiring only a moderate degree of heating to bring the liquid to its flashpoint. Based on this concept, an arbitrary division of 100 to 140°F (37.8 to 60°C) was established for liquids in this flashpoint range, to be known as Class II liquids. Since liquids with flashpoints higher than 140°F (60°C) would require considerable heating from a source other than ambient temperatures, they have been identified as Class III liquids.

Flammable Liquids

1. Flammable liquids have flashpoints below 100°F (37.8°C) and vapor pressures not exceeding 40 psia at 100°F (2,068 mm Hg at 37.8°C).
2. Class I liquids include those with flashpoints below 100°F (37.8°C) and may be subdivided as follows:
   (a) Class IA liquids includes those with flashpoints below 73°F (22.8°C) and with boiling points below 100°F (37.8°C).
   (b) Class IB liquids includes those with flashpoints below 73°F (22.8°C) and with boiling points at or above 100°F (37.8°C).
   (c) Class IC liquids includes those with flashpoints at or above 73°F (22.8°C) and below 100°F (37.8°C).

Combustible Liquids

Liquids with flashpoints at or above 100°F (37.8°C) are referred to as combustible liquids and may be subdivided as follows:

1. Class II liquids have flashpoints at or above 100°F (37.8°C) and below 140°F (60°C).
2. Class IIIA liquids have flashpoints at or above 140°F (60°C) and below 200°F (93°C).
3. Class IIIB liquids have flashpoints at or above 200°F (93°C).

Other Classification Systems

There are other classification systems for flammable and combustible liquids. In some, the breakpoints between classes of liquids are different, or the open-cup flashpoint tester is used to determine the flashpoint. In some classification systems, the solubility of the liquid with water is considered. Check with local authorities to determine alternative classification systems that might be used.

Solids with Flashpoints

Many combustible chemicals that are solids at 100°F (37.8°C) or above are classified as solids. When heated, the solid becomes

liquid and gives off flammable vapors; flashpoints can then be determined. In their liquid state, these solids should be treated as liquids with similar flashpoints. Some manufactured solids, such as paste waxes or polishes, may contain varying amounts of flammable liquids. The flashpoint and amount of liquid in such manufactured solid materials will indicate the degree of hazard.

PHYSICAL PROPERTIES OF LIQUIDS

In liquids, molecules move freely among themselves, but they do not tend to separate from one another in the way that molecules in gases do. Liquids, unlike gases, are only slightly compressible and are incapable of indefinite expansion. They differ from solids in the ease with which their molecules move against one another, causing them to adapt to the shape of the containing vessel. Some liquids are very viscous (i.e., have a relatively high resistance to flow), however, and no sharp definition can be drawn between these liquids and solids. Neither is there a sharp line of demarcation between liquids and gases. Materials can exist in either state, depending on temperature and pressure conditions. Liquids tend to become gases as their temperatures increase or their pressures decrease. On the other hand, gases tend to become liquids as their temperatures decrease or their pressures increase. However, a material can only exist as a gas, regardless of pressure, if its temperature is above the so-called critical temperature. (The critical temperature is an intrinsic property of a material and is the temperature above which the material can exist only in the gaseous state.) In all cases, the actual state of a liquid is determined by the combination of temperature and pressure.

PHYSICAL CHARACTERISTICS OF FLAMMABLE AND COMBUSTIBLE LIQUIDS

Specific Gravity

Specific gravity is the ratio of the density (weight per unit volume) of a material to that of some reference standard. For liquids, the reference standard is water, which is assigned a specific gravity of 1.0. Because the specific gravity of water equals one, a liquid with a specific gravity of less than one will float on water (unless it is water soluble). A specific gravity greater than one indicates that water will float on the liquid. Because fire-fighting foams are water-based extinguishing agents, this is an important consideration in fighting a flammable or combustible liquids fire.

Vapor Density Ratio

Vapor density is the weight per unit volume of a pure gas or vapor. For fire protection purposes, vapor density is reported in terms of the ratio of the weight of a volume of vapor to the weight of an equal volume of air, under the same conditions of temperature and pressure. In this respect, the vapor density ratio is similar to the specific gravity of a liquid, except that air is used as the reference standard in place of water. Air is taken as unity and the vapor density is reported as a ratio. A vapor density of 3 (i.e., 3:1) indicates that the vapor is three times as dense, or heavy, as air.

$$\text{Vapor density ratio} = \frac{\text{Molecular weight (MW) of the material}}{\text{Composite molecular weight of air}}$$

$$= \frac{\text{MW}}{29}$$

Vapor density ratios are reported at conditions of equal temperature and atmospheric pressure. Unequal or changing conditions will appreciably change the density of any vapor.

Generally, pure vapors are seldom found, except when the liquid is normally stored above its boiling point. For those liquids that are stored or handled below their boiling points, the vapor located above the liquid will be a mixture of vapor and air.

For liquids with boiling points above the prevailing ambient temperature at atmospheric pressure, the vapor density may be a misleading figure. For example, the boiling point of ethyl acetate is 171°F (77°C). At 70°F (21°C) its vapor pressure is about 2.35 psi (16.2 kPa) or 0.16 atm (atmospheres). Thus, an equilibrium mixture of ethyl acetate vapor and air at 70°F (21°C), as might be found in a closed vessel, would have a composition of 16 percent ethyl acetate vapor and 84 percent air. The "theoretical" vapor density of ethyl acetate is 3.0. The "actual" density of the "vapor-air mixture" that is produced by ethyl acetate at 70°F (21°C) and at atmospheric pressure is

$$0.16 \times 3.0 + 0.84 \times 1 = 1.32$$

Vapor densities are ordinarily used as an indication of the settling or rising tendency of a vapor. Thus, a density greater than air indicates that the vapor will accumulate in low areas of a room or outdoor facility. A density less than air indicates that the vapor will rise to the top of an enclosure or is likely to dissipate more readily than heavier vapors. The increased density associated with a substance heavier than air can make vapors released from a spill or similar emergency travel upwind or significant distances to unprotected ignition sources.

Vapor Pressure

The percentage of vapor in the atmosphere of a closed container of liquid can be determined from the vapor pressure of the liquid. The percentage of vapor is directly proportional to the relationship between the vapor pressure of the liquid and the total pressure of the mixture. For example, acetone at a temperature of 100°F (37.8°C) has a vapor pressure of 7.6 psia (52 kPa). Assuming total pressure at 14.7 psia (101 kPa), the proportion of acetone vapor present will be 7.6 divided by 14.7, or 52 percent. Vapor pressures of petroleum liquids usually are determined by the Reid method, as described in ASTM D323, *Standard Test Method for Vapor Pressure of Petroleum Products.*[1] This method gives the vapor pressure in psia (kPa) at 100°F (37.8°C), which differs slightly from the true vapor pressure. Vapor pressure figures for many substances can be found in chemical handbooks. If the closed-cup flashpoint of a liquid and the vapor pressure

at the flashpoint temperature are known, the lower flammable limit for the vapor (at the flashpoint temperature), in percent by volume at normal atmospheric pressure, can be calculated as follows:

$$\text{LFL} = \frac{V}{0.147} \left(\text{in SI: LFL} = \frac{V}{1.01} \right)$$

where LFL is percent vapor by volume at the lower flammable limit, and V is vapor pressure in psia (kPa) at flashpoint temperature. At other pressures,

$$\text{LFL} = \frac{100V}{P}$$

where P is the ambient pressure in psia (kPa).

In a mixture of volatile flammable liquids, the effects of the two vapor pressures, one upon the other, generally depend on whether the two liquids are completely miscible, partly miscible, or completely immiscible. If the two liquids are completely miscible, they lower each other's vapor pressures; if they are nearly completely immiscible, the vapor pressure of the mixture is the sum of the partial pressure of each liquid layer (Dalton's Law of Partial Pressure); if both liquids are partially miscible, the relationships are more complex.

Evaporation Rate

Evaporation rate is the rate at which a liquid is converted to the vapor state at any given temperature and pressure. The differing rates of mixture evaporation is of primary concern in fire protection. In general, as the boiling point decreases, the vapor pressure and the evaporation rate increases.

Viscosity

The viscosity of a liquid is a measure of its resistance to flow resulting from the combined effects of adhesion and cohesion, that is, a measure of internal friction in a fluid. Although there are several recognized devices for determining viscosity, the measurement principles are generally the same. These involve measuring the time required for a predetermined quantity of liquid at a specified temperature to flow into a receiving flask or through an orifice of a prescribed size.

Latent Heat of Vaporization

Latent heat of vaporization is the heat that is absorbed when one pound or gram of liquid is transformed into vapor at the boiling point under one atmosphere pressure and is expressed in Btu per lb or calories per gram (cal/g).

Solubility in Water and Surface Tension

Solubility in water and surface tension are other characteristics of a liquid that concern the fire protection field. Fires in liquids that are water soluble can be extinguished by dilution of the liquid with water, or by use of "alcohol-type" foams for extinguishment. The use of wetting agents affects the surface tension of a liquid and, in some cases, aids in fire extinguishment.

FIRE CHARACTERISTICS OF LIQUIDS THAT BURN

Fire Point

Fire point is related to flashpoint and is defined as the lowest temperature to which a liquid must be heated in order to evolve sufficient vapor to allow sustained burning for at least 5 seconds after application of a test flame.[2] Fire point is the minimum temperature at which the liquid evolves vapor as fast as it is consumed by flame, indicating the temperature for indefinite burning of a pool of liquid. Fire point is at least equal to the flashpoint, but, for high flashpoint liquids, is typically reported as 10°F to 27°F (5°C to 15°C) higher than the flashpoint.[3]

Fire point has application where codes such as NFPA 30 exempt requirements for storage limitations due to liquids having a flashpoint but not being capable of sustained burning. Fire point is typically determined by the Cleveland open-cup apparatus, ASTM D92. The use of an open cup allows liquid, as it is heated slowly, to lose volatile components before the liquid has been heated to the point of ignition. The test therefore may not recognize the ability of large volumes of such mixtures to burn rather than just flash.[4]

Flashpoint

A vapor mixed with air in proportions below the lower limit of flammability may burn at the source of ignition, that is, in the zone immediately surrounding the source of ignition, without propagating (spreading) flame away from the ignition source. The flashpoint of a liquid corresponds roughly to the lowest temperature at which the vapor pressure of the liquid is just sufficient to produce a flammable mixture at the lower limit of flammability. Figure 6.12.1 shows liquid, vapor, and air in equilibrium in a closed container at normal atmospheric pressure.

There are several types of test apparatus used for determining flashpoint (Figure 6.12.2). The material to be tested is slowly heated, and at periodic intervals a test flame is applied to the vapor space. Flashpoint is the temperature at which a

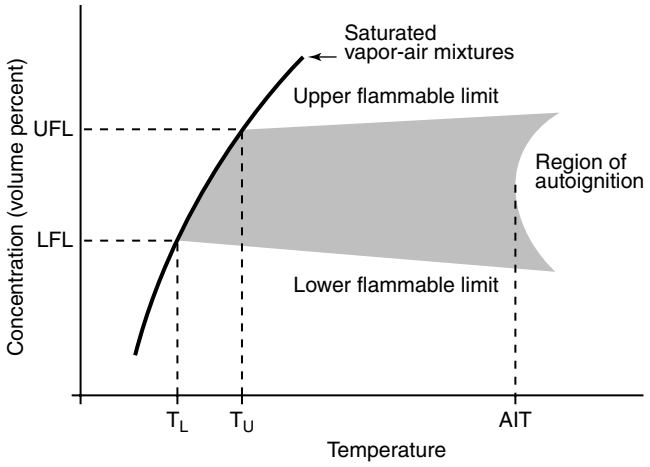

FIGURE 6.12.1 Range of Flammability for a Flammable Vapor

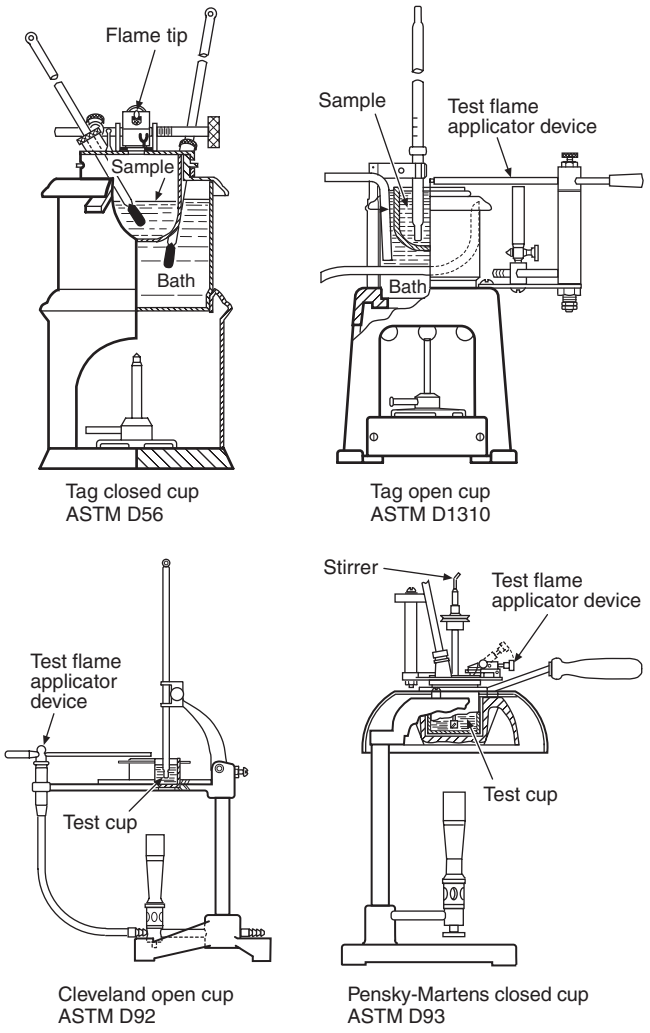

FIGURE 6.12.2 Four of the Commonly Used Testers for Determining Flashpoints of Flammable or Combustible Liquids

flash of fire is seen when the test flame is applied. The full details of conducting tests for each type of testing apparatus are given in the applicable standards of the ASTM or by the manufacturer.

The tag closed tester is described in ASTM D56, *Standard Test Method for Flash Point by Tag Closed-Cup Tester.*[5] The Pensky-Martens closed tester, as described in ASTM D93, *Standard Test Methods for Flash Point by Pensky-Martens Closed-Cup Tester,*[6] is specified for testing liquids with flashpoints above 200°F (93°C) or for certain viscous or film-forming materials.

ASTM D3278, *Standard Test Methods for Flashpoint of Liquids by Small Scale Closed-Cup Apparatus,*[7] is used for testing paints, enamels, lacquers, varnishes, and related products and their components with flashpoints between 32 and 230°F (0 and 18°C).

Open-cup flashpoints are sometimes used in grading flammable liquids in transportation and are determined by ASTM D1310, *Standard Test Method for Flashpoint and Fire Point of Liquids by Tag Open-Cup Apparatus,*[8] or ASTM D92, *Standard Test Method for Flash and Fire Points by Cleveland Open-Cup Tester.*[9] Open-cup flashpoints represent conditions with the liquid in the open and are generally higher than the closed-cup flashpoint figures for the same substances. However, closed-cup flashpoint figures are generally higher than the actual lower temperature limit of flammability (flashpoint) when tested in a vertical tube, using the principle of upward flame propagation.

It is essential to realize that flashpoint varies with pressure and with the oxygen content of the atmosphere, as well as with the purity of the product being tested, the method of test, and the skill of the operator conducting the test. It is quite possible to have a flammable mixture far below the stated flashpoint value if the pressure is considerably less than 1 atm.

IGNITION TEMPERATURE (AUTOIGNITION TEMPERATURE, AUTOGENOUS IGNITION TEMPERATURE)

The autoignition temperature of a liquid is the temperature of the external environment that will initiate combustion without the presence of an obvious ignition source, such as a spark or flame. The autoignition temperature is determined in a closed or nearly closed container that is heated until the vapor in the container spontaneously ignites and burns. Frequently, there is a lag time before ignition occurs. The standard test procedure used to determine autoignition temperature is ASTM E659, *Standard Test Method for Autoignition Temperature of Liquid Chemicals.*[10]

Within a given hydrocarbon series, such as the straight-chain series running from normal methane through normal decane, ignition temperature decreases as molecular weight or carbon chain length increases, all other factors being equal (Figure 6.12.3). Thus, pentane [$CH_3(CH_2)_3CH_3$; molecular weight 72.1] has a higher ignition temperature than hexane [$(CH_3CH_2)_4CH_3$; molecular weight 86.2].

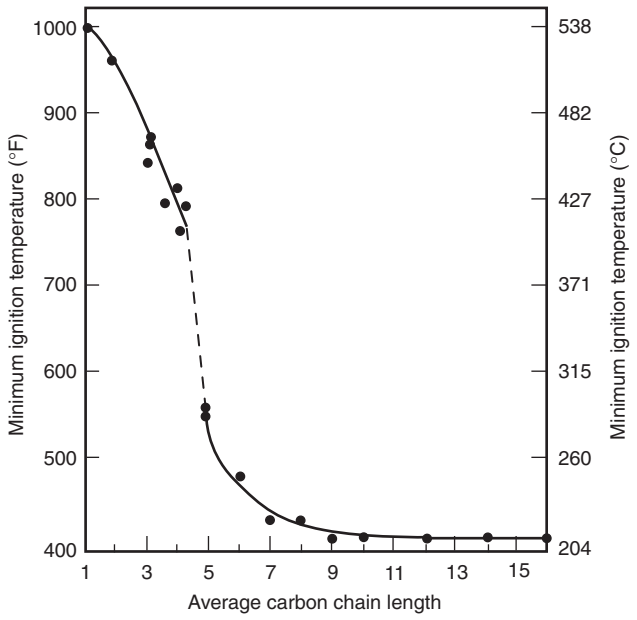

FIGURE 6.12.3 Minimum Ignition Temperatures of Hydrocarbons of Various Carbon Chain Lengths

Boiling Point

The temperature at which the equilibrium vapor pressure of a liquid equals the total pressure on the surface is known as the boiling point. The boiling point is entirely dependent on the total pressure. (Boiling point increases with an increase in pressure.) Theoretically, any liquid may be made to boil at any desired temperature by sufficiently altering the total pressure on its surface. Similarly, unless decomposition takes place, any liquid may be made to boil at any desired pressure by sufficiently changing its temperature.

The temperature at which a liquid boils when under a total pressure of 1 atm (14.7 psia or 101 kPa) is termed the normal boiling point.

This statement applies to pure materials or constant boiling mixtures. Most flammable liquids and gases on the market today are mixtures and do not follow the physical laws governing pure materials. The boiling points of mixtures are reported as distillation curves. The 10 percent point of a distillation performed in accordance with ASTM D86, *Standard Test Method for Distillation of Petroleum Products at Atmospheric Pressure,*[11] is used as the boiling point for most NFPA standards.

Flammable (Explosive) Limits

The term *lower flammable limit* (LFL) describes the minimum concentration of vapor to air below which propagation of a flame will not occur in the presence of an ignition source. The *upper flammable limit* (UFL) is the maximum vapor-to-air concentration above which propagation of flame will not occur. If a vapor-to-air mixture is below the lower flammable limit, it is described as being "too lean" to burn, and if it is above the upper flammable limit, it is "too rich" to burn.

The concept of the flammable range is best illustrated by Figure 6.12.1. This figure illustrates the flammable limits compared with vapor concentration in air and also illustrates the changes to flammable range as temperature increases. Concentrations of vapor that are below the shaded area are less than the LFL line and are, therefore, too lean to be ignited. Conversely, concentrations of vapor above the shaded area are above the UFL line and are too rich to be ignited. The effect of change in temperature is illustrated by the temperature limits T_L and T_U, where T_L is the temperature limit of flammability and T_U corresponds to the upper flammable limit concentration for saturated vapor-air mixtures.

When the vapor-to-air ratio is somewhere between the LFL and UFL, fires and explosions can occur. The mixture is then said to be within its flammable or explosive range. When the mixture happens to be in the intermediate range between the LFL and UFL (synonymous with lower explosive limit [LEL] and upper explosive limit [UEL], respectively), the ignition is more intense and violent than if the mixture were closer to either the upper or lower limits.

Calculating Vapor Volume and Flammable Mixtures

The volume of air necessary to provide sufficient dilution to prevent the formation of an ignitable mixture frequently must be determined when designing ventilation for a drying oven or similar hazard. This can be readily calculated when the quantity of solvent supplied is known or can be reasonably estimated. Examples of such calculations can be found in NFPA 86, *Standard for Ovens and Furnaces*, and in Section 17, Chapter 8, "Explosion Prevention and Protection."

For example, consider a process in which acetone vapor is released. The flammable range for acetone vapor in air is from 2.6 to 12.8 percent by volume. Any mixture containing more air than 100 minus 2.6, or 97.4 percent of air—equivalent to 97.4 divided by 2.6, or approximately 37 volumes of air to 1 volume of vapor—will be too lean to be ignitible. Hence, if the volume of vapor can be estimated, it is a simple matter to determine the required air volume.

The volume of vapor produced from 1 gal of solvent can be calculated from the specific gravity (Sp.G.) of the liquid and the vapor density (V.D.) as follows:

$$\frac{\text{ft}^3 \text{ of vapor from}}{1 \text{ gal of liquid}} = \frac{8.33 \times \text{Sp.G. of liquid } (H_2O = 1)}{0.075 \times \text{V.D. of vapor (air} = 1)}$$

where 8.33 is the weight of 1 gal of water (lb), and 0.075 is the weight of 1 ft^3 of air (lb).

Stated more simply,

$$\text{Vapor equivalent of 1 gal: } 111 \times \frac{\text{Sp.G.}}{\text{V.D.}}$$

If the V.D. is not known, it can readily be calculated from the molecular weight.

Again, taking acetone as an example (Sp.G. = 0.792; V.D. = 2) yields:

$$\text{Vapor equivalent of 1 gal: } 111 \times \frac{0.792}{2} = 44 \text{ ft}^3$$

The volume of air required to dilute vapor from 1 gal of acetone to below the lower flammable limit is

$$44 \times 37 = 1628 \text{ ft}^3$$

If the rate of evaporation of acetone into a given space (oven, etc.) should be 1 gpm, it would require 1628 cfm of uncontaminated ventilating air to keep the vapor concentration below the lower flammable limit.

For SI units, the volume of vapor (m^3) produced by 1 L of solvent can also be calculated from the Sp.G. of the liquid and the vapor density as follows:

The m^3 vapor equivalent of 1 L of liquid is

$$L = 0.83 \times \frac{\text{Sp.G.}}{\text{V.D.}}$$

For acetone, vapor equivalent of 1 L is

$$L = \frac{0.83 \times 0.792}{2} = 0.33 \text{ m}^3$$

In SI units, the volume of air required to dilute 1 L of acetone to below the lower flammability limit is

$$0.33 \times 37 = 12.2 \text{ m}^3$$

Based on the evaporation rate of the flammable liquid, the quantity of air would be proportional. In practice and as a safety

factor, a substantial excess of air ventilation would be applied because of the inevitable lack of uniformity of the atmosphere within the enclosure. Where it is desirable to keep a space "too rich" to be ignitable, a similar procedure (using the UFL) may be used to determine the maximum quantity of air that can be tolerated. This procedure is not, however, recommended, since it is necessary to enter and pass through the flammable range during operation.

Variation in Hazard with Temperature and Pressure

The temperature and pressure to which a particular liquid is subjected must often be considered in the practical application of the flammable limits of that liquid. It can be shown that these factors have a pronounced effect on the fire and explosion hazard and are as important in safe handling as are the flammable limits themselves. A liquid that has a flashpoint above room temperature and, therefore, is not expected to produce flammable vapors, will do so if its temperature is raised to its flashpoint or higher.

The extent of liquid vaporization varies as the pressure in the vapor space over the liquid is increased or lowered. More vapor is released as pressure is lowered and less vapor as pressure is increased. In the same manner, at a higher temperature the liquid will have a higher vapor pressure and will tend to vaporize in greater amounts. When at a given temperature and pressure the liquid has vaporized to the point where no further vaporization will occur unless conditions are changed, a state of equilibrium is said to have been reached. It is evident that equilibrium cannot exist in other than a closed system. In the open air, a vaporizing liquid would continue to vaporize until the supply was exhausted. The pressure-temperature effect, therefore, is applicable only in tanks, pipes, and processing equipment, in which the liquid and vapor-air mixture approach equilibrium.

The lower limits of flammability of vapors are also affected by the temperature. This is a safety factor in installations, such as industrial ovens, where pressure is not a factor, but where temperature needs to be taken into account in hazard evaluation. In such industrial ovens, mechanical or forced ventilation is usually employed to dilute the concentration of the vapors below their lower flammable limits in air and to remove them from the oven. Information on the lower flammable limits of the vapors at elevated temperatures is needed in order to determine the amount of ventilation required for safe operation of an oven[12] (Table 6.12.1). Figures 6.12.4 and 6.12.5 show the effect of temperature and pressure on flammable limits, as determined by Mitchell and Vernon.[13]

Figure 6.12.4 is applicable only to flammable liquids or gases in equilibrium in a closed container. Mixtures of vapor and air will be too "lean" to burn at temperatures below and at pressures above the values shown by the line on the chart for any substance. Conditions represented by points to the left and above

TABLE 6.12.1 The Effect of Elevated Temperature on the Lower Flammable Limit of Combustible Solvents as Encountered in Industrial Ovens

		Lower Flammable Limit Percent Vapor by Volume at Initial Temperature, °F (°C)						
Solvent	*Flashpoint Closed Cup*	*Room Temp.*	*212 (100)*	*392 (200)*	*437 (225)*	*482 (250)*	*572 (300)*	*662 (350)*
Acetone	3	2.67	2.40	2.00[a]	—	—	—	—
Amyl acetate, iso	77	—	1.00	0.82	—	0.76[a]	—	—
Benzene	–4	1.32	1.10	0.93	—	—	0.80[a]	—
Butyl alcohol, normal	100	—	1.56	1.27	1.22[a]	—	—	—
Cresol, meta-para	202	—	1.06[b]	0.93	—	0.88[a]	—	—
Cyclohexane	–4	1.12	1.01	0.83[a]	—	—	—	—
Cyclohexanone	111	—	1.11	0.96	0.94	0.91[a]	—	—
Ethyl alcohol	54	3.48	3.01	2.64	—	2.47	2.29[a]	—
Ethyl lactate	131	—	1.55	1.29	—	1.22[a]	—	—
Gasoline	–45	1.07	0.94	0.77[a]	—	—	—	—
Hexane, normal	–15	1.08	0.90	0.72[a]	—	—	—	—
High-solvency petroleum naphtha	36	1.00	0.89	0.74	0.72	0.69[a]	—	—
Methyl alcohol	52	6.70	5.80	4.81	—	4.62	4.44[a]	—
Methyl ethyl ketone	21	1.83	1.70	1.33[a]	—	—	—	—
Methyl lactate	121	—	2.21	1.86	1.80	1.75[a]	—	—
Mineral spirits, No. 10	104	—	0.77	0.63[a]	—	—	—	—
Toluene	48	1.17	0.99	0.82	—	—	0.72[a]	—
Turpentine	95	—	0.69	0.54[a]	—	—	—	—
V. M. & P. Naptha	28	0.92	0.76	0.67[a]	—	—	—	—

[a]Rapid and extensive thermal decomposition and oxidation reactions in vapor-air mixture at this temperature.
[b]Lower limit determined at 302°F (150°C).

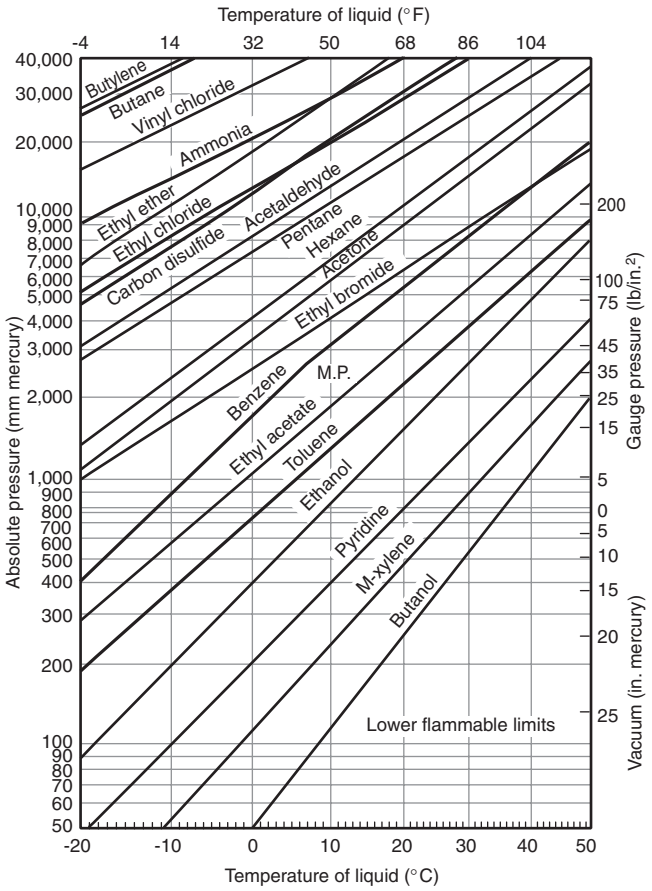

FIGURE 6.12.4 Variation of Lower Flammable Limits with Temperature and Pressure

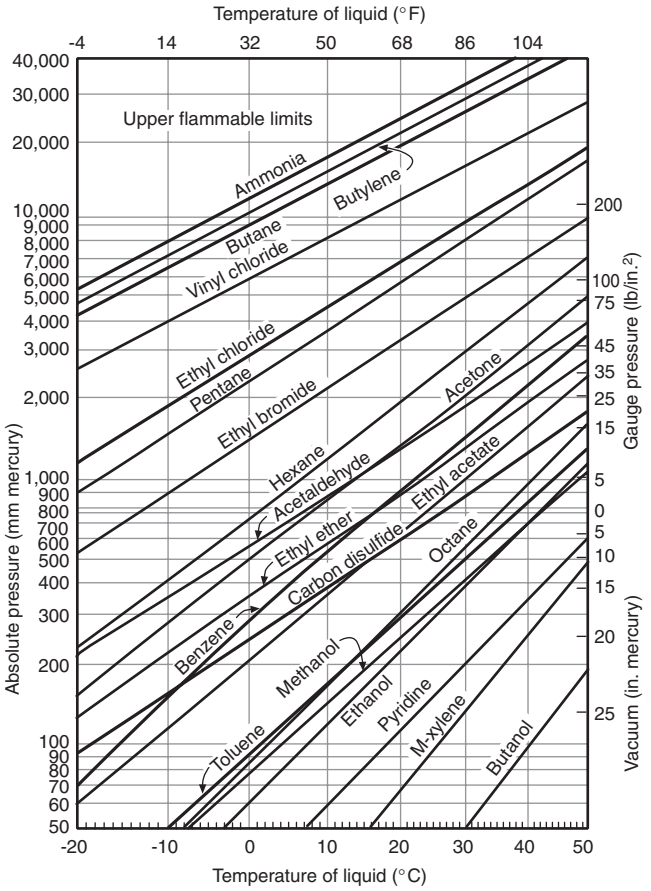

FIGURE 6.12.5 Variation of Upper Flammable Limits with Temperature and Pressure

the respective lines are accordingly nonflammable. Points where the diagonal lines cross the zero gauge pressure line (760 mm of mercury, absolute pressure) indicate flashpoint temperatures at normal atmospheric pressure. Figure 6.12.5 is applicable only to flammable liquids or gases in equilibrium in a closed container. Mixtures of vapor and air will be too "rich" to be flammable at temperatures above and pressures below the values shown by the line on the chart for any substance. Conditions represented by points to the right of and below the respective lines are accordingly nonflammable. In using Figures 6.12.4 and 6.12.5, it should be noted that they represent equilibrium conditions and that, prior to the establishment of equilibrium, values may be different.[13] For example, when a liquid is introduced into a pressure container with air at a temperature such that the resultant vapor-air mixture will be above the UFL (according to the chart), some time will elapse before sufficient evaporation has taken place to reach this condition; meanwhile, the mixture may be flammable or explosive.

It should also be noted that the pressures developed, or the intensity of an explosion, will vary with the initial pressure of the vapor-air mixture. With high initial pressures, the pressures are greater, as in the familiar example of the gasoline engine. With low initial pressures, the pressures are relatively lower.

Energy Required for Ignition of Vapors

The principal sources of ignition of flammable liquids include flames; electrical, static, or frictional sparks; hot surfaces; and adiabatic compression.

Flames. Except for extremely small examples produced under laboratory conditions, flames are unfailing sources of ignition for flammable vapor-air mixtures that are within the flammable range. Flames must be capable of heating the vapor to its ignition temperature in the presence of air in order to be a source of ignition. For some liquids and solids, it will be necessary for the flame to be of sufficient duration and heat to volatilize the fuel and to ignite the released vapors. Once ignited, the radiated heat from the burning vapors perpetuates the burning process.

Electrical, Static, and Frictional Sparks. These sparks must have sufficient energy to ignite flammable vapor-air mixtures. Electrical sparks from most commercial electrical supply installations are above flame temperatures and can ignite flammable mixtures. However, friction sparks might fail to ignite a flammable mixture because the spark may be of such short duration as to fail to heat the vapor to its ignition point. Also, not only

must an electrical spark have sufficient intensity and length, but also some variable conditions must exist within certain limits before ignition will occur. The nature of the ignition points and surfaces, as well as the composition, temperature, and pressure of vapor-air mixtures, are the principal variables in calculating ignition. Most of these same factors and variables also apply to static electrical sparks and frictional sparks as a source of ignition because, in either case, the spark must be of sufficient duration, intensity, or both, to create sufficient heat to cause ignition.

Hot Surfaces. Hot surfaces can be a source of ignition if they are large enough and hot enough. The smaller the heated surface, the hotter it must be to ignite a mixture. The larger the heated surface in relation to the mixture, the more rapidly ignition will take place and the lower the temperature necessary for ignition. A flammable liquid, however, must remain in contact with a hot surface for a sufficient length of time to form a vapor-air mixture within its flammable range. For example, a single drop of a low-viscosity, highly volatile flammable liquid that falls on the surface of an electric hotplate at 2000°F (1093°C) may ignite. A hot exhaust pipe in the open seldom ignites a flammable mixture, even though the surface temperature may be considerably above the environmental ignition temperature test method.

Adiabatic Compression. Adiabatic compression has been the cause of several destructive explosions. When controlled, adiabatic compression is the basis of diesel engine operation. A rapidly compressed flammable mixture will be ignited when the heat generated by the compressing action is sufficient to raise the flammable vapor to its ignition temperature.

Behavior of Mixed Liquids

The behavior of mixed liquids varies considerably, depending on physical characteristics of the liquid and environmental conditions. However, the vapor pressure or evaporation rate of mixed liquids is particularly important in the prevention of fires. These factors are significant when a mixture of liquids is listed as nonflammable or has a high flashpoint but becomes flammable under conditions of use. As a specific example, sufficient carbon tetrachloride can be added to gasoline so that the mixture has no flashpoint. However, while standing in an open container, the carbon tetrachloride will evaporate more rapidly than the gasoline. Over a period of time, therefore, the residual liquid will first show a high flashpoint, then a progressively lower one, until the flashpoint of the final 10 percent of the original sample will approximate that of the higher boiling fractions of gasoline.

To evaluate the fire hazard of such liquid mixtures, fractional evaporation tests can be conducted at room temperature in open vessels. After evaporation of appropriate fractions, such as 10, 20, 40, 60, and 90 percent of the original sample, flashpoint tests can be conducted on the residue. The results of such tests indicate the class into which the liquid should be placed if the conditions of use are such as to make it likely that appreciable evaporation will take place. With other liquid mixtures, the flashpoint may increase as evaporation occurs.

Noncompatible Materials

Noncompatible materials of construction or equipment are those materials with which an unstable flammable liquid or its normal reaction products will combine, or whose products of corrosion are contaminants. For example, if mercury is a harmful contaminant, then mercury thermometers should not be used. If a chlorinated compound slowly releases hydrochloric acid, aluminum should not be used. The aluminum chloride formed by this acid may act as a catalyst. There are many materials that will chemically react with each other; when there is a question, reference should be made to NFPA's *Fire Protection Guide to Hazardous Materials,* 13th edition.

BURNING CHARACTERISTICS OF LIQUIDS THAT BURN

Because it is the vapors from flammable liquids that burn, the ease of ignition as well as the rate of burning can be related to such properties as the vapor pressure, flashpoint, boiling point, and evaporation rate. Liquids with vapors in the flammable range above the liquid surface at the stored temperature will have a rapid rate of flame propagation. Flammable and combustible liquids with flashpoints above temperatures at which they are stored have a slower rate of flame propagation, because it is necessary for the heat of the fire to sufficiently heat the liquid surface and form a flammable vapor-air mixture before the flame will spread through the vapor. There are many variables affecting the rate of flame propagation and burning, including environmental factors, wind velocity, temperature, heat of combustion, latent heat of vaporization, and barometric pressure.

Liquid hydrocarbons normally burn with an orange flame and emit dense clouds of black smoke. Alcohols normally burn with a clean blue flame and produce very little smoke. Certain terpenes and ethers burn with considerable ebullition (boiling) of the liquid surface, making it difficult to extinguish fires involving these substances.

Boilover, Slopover, and Frothover

Three specific conditions—boilover, slopover, and frothover—deserve special mention in regard to fires in open-topped tanks containing various types of oils.

Boilover. Boilover is a phenomenon that may occur spontaneously during a fire in an open-top tank containing certain types of crude oils. This may occur when the roof of a tank is blown off by an explosion, or when a floating roof is sunk to expose the crude. After a long period of quiescent burning, there is a sudden overflow or ejection of some of the residual oil in the tank. It is caused by boiling water that forms a quickly expanding steam-oil froth. The frothing results from the existence of the following three conditions, the absence of any one of which will prevent the occurrence:

1. The tank must contain free water or water-oil emulsion at the tank bottom. This situation will normally prevail in tanks storing crude oil.

2. The oil must contain components having a wide range of boiling points, such that when the lighter components have been distilled off and burned at the surface, the residue, with a temperature of 300°F (149°C) or over, is more dense than the oil immediately below. This residue sinks below the surface and forms a layer of gradually increasing depth which advances downward at a rate substantially faster than the rate of regression of the burning surface. This sets up the so-called heat wave, which is the result of localized settling of a part of the hot surface oil until it reaches the colder oil below. There is no heat conduction from the burning surface downward.
3. Sufficient content of heavier oils are present in the oil to produce a residue that can form a tough persistent froth of oil and steam.

NFPA records indicate the most serious loss-of-life tank fire in history occurred on December 19, 1982, in Tacoa, Venezuela. The storage tank, located a few miles northwest of Caracas in the small seaside village of Tacoa, supplied fuel to an electric generating plant. Two workers died upon ignition of the tank. After 6 hours of intense burning, the contents of the tank erupted into an extremely violent boilover. The final toll—160 people dead, hundreds more injured, others still unaccounted for, and damage estimated at $50 million. Fifty of those who died were fire fighters, which also makes the Tacoa incident the gravest of its kind in terms of loss of life of fire personnel (Figure 6.12.6).

Slopover. Slopover can result when a water stream is applied to the hot surface of a burning oil, provided the oil is viscous and its temperature exceeds the boiling point of water. Since only the surface oil is involved, a slopover is a relatively mild occurrence.

FIGURE 6.12.6 Emergency Personnel on the Scene of Storage Tank Fire Boilover in Tacoa, Venezuela, December 19, 1982. At this moment, the fire had been declared under control. Note the fire fighters on the top of the dike and the other personnel along the roadway fence. The boilover occurred minutes after this photo was taken, and all of the people shown above were reportedly killed.

Frothover. Frothover refers to the overflowing of a container not on fire when water boils under the surface of a viscous hot oil. A typical example would be when hot asphalt is loaded into a tank car containing some water. The first asphalt is cooled by contact with the cold metal, and, at first, nothing may happen. But when the water becomes heated and starts to boil, the asphalt may overflow the tank car.

A similar situation can arise when a tank containing a water bottom or wet emulsion is used for storing oil slops or residium at temperatures below 200°F (93°C), and the tank receives a substantial addition of hot residium at a temperature of 300°F (149°C) or higher. After enough time has elapsed for the effect of the hot oil to reach the water in a tank, a prolonged boiling action can take place, which can remove a tank roof and spread froth over a wide area.

Burning Rates of Liquids That Burn

The burning rate of flammable liquids will vary somewhat similar to the rate of flame propagation. Gasoline, a compound of light and heavy fractions, will burn more rapidly at first while the lighter fractions are burning, whereas the heavier fractions will burn at a rate approaching that of kerosene. The burning rate for gasoline is 6 to 12 in. (150 to 300 mm) of depth per hour, and for kerosene the rate is 5 to 8 in. (130 to 200 mm) of depth per hour. For example, a pool of gasoline ½ in. (12.7 mm) deep could be expected to burn itself out in 2½ to 5 minutes.

In a series of tests conducted at the U.S. Bureau of Mines,[14] the burning rates of several liquids and gases were determined and found to approach "a maximum and constant value with increasing pool diameter. This constant burning rate is proportional to the ratio of the net heat of combustion to the sensible heat of vaporization."[14]

Based on these observed burning rates in petroleum tank fires, an estimate can be made of the extent of area that will be involved in fire from a petroleum spill. When a spill is burning, the fire area will first be small and then spread to a point of equilibrium where it will burn as fast as it is released. At a burning rate of 1 ft/hr (0.3 m/hr), 1 gal/min (3.8 L/min) of spillage will reach an equilibrium burning area of about 8 ft^2 (0.74 m^2). Thus, a 10 gpm (38 L/min) spill rate will be in equilibrium with 80 ft^2 (7.4 m^2) of burning area; 100 gpm at 800 ft^2 (380 L/min at 74 m^2); and so on. For liquids having higher burning rates, the area would be smaller; and for those liquids having lower burning rates, the area would be larger. Also, the terrain will have an influence on the shape of the burning area.

FIRE PREVENTION METHODS

When flammable and combustible liquids are stored or handled, the liquid is usually exposed to the air at some stage in the operation, except where the storage is confined to sealed containers that are not filled or opened on the premises or where handling is in closed systems and vapor losses are recovered. Even when the storage or handling is in a closed system, there is always the possibility of breaks or leaks, which permit the liquid to escape. Therefore, ventilation is of primary importance to prevent the accumulation of flammable vapors. It is also good

practice to eliminate sources of ignition in places where low-flashpoint flammable liquids are stored, handled, or used, even though no vapor may ordinarily be present.

Whenever possible in manufacturing processes involving flammable or combustible liquids, equipment, such as compressors, stills, towers, and pumps, should be located in the open. This will lessen the fire potential created by the escape and accumulation of flammable vapors. Gasoline and almost all other flammable liquids produce heavier-than-air vapors, which tend to settle on the floor or in pits or depressions. Such vapors may flow along the floor or ground for long distances, be ignited at some remote point, and flash back. The removal of such vapors at the floor level (including pits) is usually the proper method of ventilation. Convection currents of heated air or normal vapor diffusion may carry even heavy vapors upward, and, in such instances, ceiling ventilation may also be desirable. Ventilation to eliminate flammable vapors may be either natural or artificial. Although natural ventilation, which depends on temperature and wind conditions, has the advantage of not being dependent on manual starting or on power supply, it is not so easily controlled as is mechanical ventilation. Mechanical ventilation should be used wherever there are extensive indoor operations involving flammable and combustible liquids.

Explosion Venting

In rooms or buildings where possible explosions of flammable vapors may occur, it is recommended that relief through explosion venting be provided for at least Class IA liquids and unstable liquids.

Substitution of Less Combustible Liquids

The hazard created by flammable liquids may be avoided or reduced by the substitution of relatively safer materials. Such materials should be stable, have a low toxicity, and either be nonflammable or have a high flashpoint. For example, trichloroethylene, though higher in price, is nonflammable at ordinary temperatures and may for some uses be substituted for a more hazardous flammable solvent. Tetrachloroethylene (perchloroethylene) is another nonflammable liquid. However, even though these products are less toxic than carbon tetrachloride, they should be used only in well-ventilated areas, with full vapor recovery and controls to prevent release to the atmosphere.

There are several commercial-type stable solvents available that have flashpoints from 140 to 190°F (60 to 88°C) and that have a comparatively low degree of toxicity.

Specially refined petroleum products, first developed as "Stoddard Solvent" but now sold by different companies under a variety of trade names, have solvent properties approximating gasoline, but with fire hazard properties similar to those of kerosene. A danger in their use lies in the possibility that persons believing that they are using a safe solvent without fire hazard may neglect ordinary precautions that would be observed with a liquid such as kerosene. When heated to above their flashpoint [about 100°F (37.8°C)], these solvents produce vapors as flammable as those of gasoline at its flashpoint temperature.

Several other types of commercial solvents which are mixtures of liquids with differing rates of evaporation are available. Some are mixtures of gasoline or one of the various naphthas and a chlorinated solvent having a different and often higher evaporation rate than the flammable solvent which, over a period of time, would leave the original low flashpoint solvent. These mixtures create a toxicity hazard, as well as a fire hazard, and their use in open containers should be discouraged.

Solvents and solvent vapors are toxic in varying degrees, and ventilation is almost always necessary to keep vapor concentration within safe limits.

SUMMARY

The hazards and fire protection of flammable and combustible liquids are a function of the liquids' physical properties and characteristics, as well as fire characteristics (flashpoint, ignition temperature, boiling point, and flammable limits). Effective methods for preventing fires in flammable and combustible liquids include preventing or reducing the accumulation of flammable vapors through ventilation, explosion venting, and substitution of less flammable liquids.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on flammable and combustible liquids discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*
NFPA 30B, *Code for the Manufacture and Storage of Aerosol Products*
NFPA 31, *Standard for the Installation of Oil-Burning Equipment*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 326, *Standard for the Safeguarding of Tanks and Containers for Entry, Cleaning, or Repair*
NFPA 385, *Standard for Tank Vehicles for Flammable and Combustible Liquids*

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Fire Protection Guide to Hazardous Materials, 13th ed., National Fire Protection Association, Quincy, MA, 2002.

Chapter 13

Polymeric Materials

Robert P. Benedetti ■ Guy R. Colonna

Chapter Contents

Terminology
The Family of Polymers
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Additives and Blends
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Natural and Synthetic Rubber
Cellulose Nitrate (CN)
Fire Behavior of Plastics
Fire Tests for Plastics
Installation Safeguards
Fire- and Flame-Retardant Treatments
Fighting Fires in Plastics

Key Terms

cellular plastic, cellulose nitrate, elastomer, fire-retardant treatment, flame-retardant treatment, plastic, polymeric material, rubber, rubber (natural), rubber (synthetic), thermoset

Since World War II, the types, variations, and uses of plastics have proliferated at a tremendous rate, producing a family of materials that is extraordinarily complex and varied. Each of the variations can be considered combustible. Some burn very rapidly and under certain conditions present extreme hazards to life and property. When such hazardous characteristics are identified, modifications can be made in manufacture and application that can reduce the hazard to acceptable levels. For example, cellulose nitrate motion picture film presents the hazard of flash burning. This hazard was controlled by phasing out the cellulose nitrate film and replacing it with slow-burning acetate "safety film." More recently, the hazards of cellular plastics, such as polyurethane and polystyrene, which were used for exposed interior finish in buildings, have been controlled by using flame-retardant additives during manufacture combined with thermal barriers installed in the field.

This chapter focuses on the fire behavior of polymeric materials that are used as building materials and on the characteristics of polymers in general. The tests that are used to identify the relative hazards from fire and smoke of plastics used in building applications are also discussed.

Although part of the family of polymers, natural and synthetic rubbers, technically, are not plastics. Yet, because of the many similarities and the formulations that intermix the traditional characteristics of plastics and elastomers, rubbers are included in this chapter. It should be understood, however, that rubber has a whole complex technology of its own—one that predates the modern plastics industry.

For related topics, see Section 6, Chapter 5, "Fibers and Textiles"; and Section 9, Chapter 4, "Plastics Industry and Related Process Hazards." See also Section 6, Chapter 2, "Combustion Products and Their Effects on Life Safety"; and Section 21, Chapter 10, "Marine Vessels."

TERMINOLOGY

The following terms are used in this chapter or are commonly encountered in the application, use, and storage of polymeric products.

Additive: Any material mixed with a resin or compounded with rubber to modify its processing or end-use properties. If the main ingredient is a resin, the resulting mix usually is called a *plastic* to distinguish it from the "resin." Additives may be dyes, pigments, powdered fillers for stiffening, plasticizers for flexibility, fibers to reinforce, antioxidants, lubricants to aid flow into or release from a mold, or flame retardants.

Binders: The resins in a plastic mixture that hold together all of the other ingredients. They are usually a product of polymerization or a naturally occurring substance of high molecular weight.

Blowing Agent: A material that releases gas upon heating so that the plastic in which it is mixed will expand into foam. The gas may result from boiling of a liquid or from decomposition of the blowing agent. (See also "Foaming Agent.")

Copolymers: High-molecular-weight compounds produced when two or more monomers are involved in a polymerization process.

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Cross-Linking: The process of establishing chemical bonds between adjacent molecules to make a network that will reduce solubility or resist flow on heating. The amount of cross-linking may be enough to render the plastic highly resistant to flow at temperatures up to thermal decomposition, in which case the plastic is said to be a thermoset.

Fillers: Materials that modify the strength and working properties of a plastic. Fillers may be used to increase heat resistance or alter the dielectric strength, for example. A wide variety of products are used, including wood, flour, cotton, sisal, glass, and clay.

Film: A general term for polymeric materials not more than 0.01 in. (0.25 mm) thick, regardless of the process used to make them.

Foam: Any polymeric material having a low-density, cellular structure. The cellular structure can be either open or closed.

Foaming Agent: Synonymous with "Blowing Agent."

Inhibitor: Any material added to prevent or retard an undesired chemical reaction.

Laminate: A composition of two or more layers of polymeric material firmly adhered either by partly melting one or more of the layers, by an adhesive, or by impregnation. High-pressure laminates are rigid stock made in presses at pressures above 400 psi (2760 kPa).

Monomers: The starting molecules, usually gaseous or liquid, used to produce polymer resin.

Plastic (ASTM Definition): A material that contains as an essential ingredient one or more organic polymeric substances of large molecular weight, is solid in its finished state, and at some stage in its manufacture or processing into finished articles can be shaped by flow.

Plasticizers: Organic materials added to plastics to make the finished product more flexible or to facilitate compounding. Some plasticizers increase the combustibility of the plastic whereas others serve as flame retardants.

Polymerization: The process by which molecules of a monomer are made to add to themselves or to other monomers in a repetitive way, forming a much longer chainlike molecule.

Polymers: Large molecules made by combining smaller molecules by chemical reaction.

Reinforced Plastic: A plastic with a filler that significantly increases flexural, impact, or tensile strength. Additives used for reinforcement include glass, asbestos, cotton, or nylon fibers.

Resin (ASTM Definition): A solid or pseudosolid organic material, often of high molecular weight, which exhibits a tendency to flow when subjected to stress, usually has a softening or melting range, and usually fractures conchoidally. *Note:* In a broad sense, the term is used to designate any polymer that is a basic material for plastics.

Sheet: A general term for plastics 0.01 in. (0.25 mm) and thicker, regardless of the method of manufacture.

Stabilizer: A material added to prevent or retard an undesired chemical reaction. When used to prevent polymerization, the preferred term is *inhibitor.* Stabilizers usually comprise less than 1 percent of the total weight. They may be antioxidants, screening agents for ultraviolet radiation, or chemicals to neutralize decomposition products during hot processing.

Thermoforming: The process of stretching or bending a plastic sheet that has been softened by heating.

Thermoplastic (ASTM Definition): A plastic that can be repeatedly softened by heating and hardened by cooling through a temperature range characteristic of the plastic and that in the softened state can be shaped by flow into articles by molding or extrusion.

Thermoset (ASTM Definition): A plastic that, after having been cured by heat or other means, is substantially infusible and insoluble.

THE FAMILY OF POLYMERS

In the classification of engineered materials, polymers are one division under the general category of nonmetals, which also includes ceramics, glasses, and materials such as oils, greases, lubricants, and papers. Polymers are further subdivided into three classes—elastomers, thermosets, and thermoplastics—as shown in Figure 6.13.1. Basically, polymers are characterized by their very large molecules, formed in chemical "polymerization" reactions, which link small molecules into larger molecules. These larger molecules contain repeating structural units of the original molecules. If the linkages result in a rigid "cross-linked" molecular structure, a thermosetting plastic results. If the molecular structure is more flexible, including side chains not rigidly linked to the other molecules, the resulting material is a thermoplastic.

The products known as "plastics" include the common types of thermosetting and thermoplastic polymers included

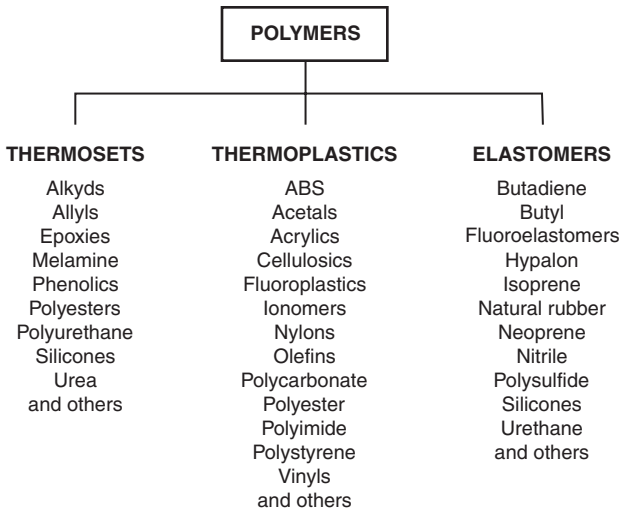


FIGURE 6.13.1 The Family of Polymers

in Figure 6.13.1, plus many more. In addition to the polymer constituent, most finished plastics contain plasticizers, colorants, fillers, stabilizers, reinforcing agents, lubricants, or other special additives. The variation of individual plastics-product formulations runs into the thousands. The ultimate form of each product, whether it appears in solid sections, films and sheets, foams, molded forms, synthetic fibers, pellets, or powders, has a significant effect on its fire properties. Additionally, fire properties are influenced by the environment, and the resultant hazard by the quantity of the product and the conditions of its use. For these reasons, it is important to conduct fire tests of products in their end-use configuration and under conditions that simulate the end-use environment.

Elastomers

Elastomers are commonly referred to as *synthetic rubbers* and are characterized by their elastic or rubberlike properties. As a whole, this class of polymers is intended to reproduce or surpass the best properties of natural rubber for particular applications. The fire characteristics of elastomers are usually similar to those of natural rubber. A discussion of both natural and synthetic rubbers is included in this chapter.

Thermosetting Plastics

Thermosetting plastics, or thermosets, are hardened into a permanent shape in the manufacturing process. These materials cannot usually be softened by heating. For those that can be softened, they cannot be remelted or restored to their original state before they were cured. The components of thermosets can be purchased in liquid form as either monomer/polymer mixtures or as partially polymerized molding compounds. Thermosets are usually formed into their final shape with heat (sometimes under pressure), although some are cured at room temperature.

Thermoplastics

Thermoplastics do not cure or set into a permanent shape under the application of heat, since heat will cause them to soften. They can be softened and rehardened repeatedly, although eventual thermal aging will cause a degradation of the material and limit the number of reheat cycles. When heated to a flowable state, thermoplastics can be transferred to a mold and cooled into the shape of the mold. Thermoplastics can be extruded through dies and solidified around other materials, such as insulation over electrical wiring. Generally, no chemical reaction takes place.

There is some overlap between thermosets and thermoplastics. Thermoplastics, after extrusion, can be cross-linked chemically or by irradiation to produce a thermoset product. The molding techniques typical of thermoplastics have been modified to permit injection molding of thermosets, such as phenolics.

USES OF PLASTICS

Plastics have wide-ranging and continuously expanding applications. In building construction applications, plastics can be found in thermal and acoustical insulation, roofing materials, decorative trims and imitation wood parts, ceiling and wall panels, resilient flooring, light fixture diffusers, electrical conduits, insulation on wiring, water and gas piping, bathtubs and sinks, and heating ducts. Plastics are found in the housings and parts of equipment and appliances. Entire pieces of furniture, seat cushions, mattresses, carpeting, wall coverings, and draperies are often plastics, as are countertops, desktops, and tabletops. Textiles in clothing today often are partially or totally plastics products. Other uses of plastics include major parts, trim, and interiors of automobiles, buses, airplanes, and trains; packaging materials, including plastic wrap; housewares; sports equipment; toys; photographic films; magnetic tapes; phonograph records; and luggage.

Lack of stability under high temperature and inherent combustibility so far have ruled out the use of plastics for applications where fire-resistance ratings are a requirement. One exception is the use of special silicone plastic foams for sealing openings in fire walls; the material retains its sealing and insulating properties while it slowly burns away during fire exposure.

ADDITIVES AND BLENDS

The physical properties of the basic types of polymers can be altered substantially during manufacturing by a variety of techniques. An extraordinary number of combinations of special properties are obtainable through the blending, or alloying, of one polymer with another. Additives, such as carbon black, glass fibers, flame retardants, and fillers ranging from cotton to clay, can alter not only the strength and other properties needed for the finished product but also the response to heat and flame.

Fiberglass and other threads added to plastics (usually, polyethylene) are used in the manufacture of fiber-reinforced plastic (FRP) products, such as boat hulls, motor vehicle body panels, fishing rods, skis, swimming pools, bathtubs, shower enclosures, building panels, and translucent roofing and siding. Although flame retardants can be added to lower the ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials,* flamespread index to a range of 20 to 75, general-purpose FRP panels and other products are likely to have much higher surface flamespread ratings, in the range of 150 to 400.[1]

MAJOR GROUPS OF PLASTICS

The major groups of plastics are briefly described in the following paragraphs. Hundreds of variations are sold under thousands of individual trade names. More detailed information can be obtained from consulting the standard reference works of the industry (see references at the end of this chapter).

Positive identification of the plastic used in a product is often very difficult. Guidelines are available to assist in the identification of the more common types. Braun[2] sets forth simple laboratory tests using heat (pyrolysis), flame, and melting, compiled in a small, easy-to-read reference volume. Saechtling's plastics identification material is included (Figures 6.13.2 through 6.13.5).[2,3] Figure 6.13.6 presents a number of simple

tests that take advantage of the unique characteristics that many common plastics possess.[4]

According to Saechtling,[3] plastics can be divided into four groups that reflect their derivation, method of synthesis, and historical development: (1) plastics from natural products, starting with vulcanized fiber in 1859, celluloid in about 1870, and artificial horn in 1897 as the oldest plastics (Figure 6.13.2); (2) "classical" condensation resins, including thermosets stemming from the discovery of Bakelite in about 1910 (Figure 6.13.3); (3) Staudinger polymerized plastics, deriving from foundations in 1922 for the polymerization of unsaturated monomers into long-chain macromolecules (Figure 6.13.4); and (4) plastics from multifunctional aliphatic and aromatic intermediate products, derived from work since the 1950s in combining various intermediates into a series of general-purpose and specially tailored engineering plastics (Figure 6.13.5).

Commonly accepted abbreviations have been developed for many plastics materials, and some of these have been standardized in ASTM D1600, *Standard Terminology for Abbreviated Terms Relating to Plastics*.[5] Manufacturers are being urged to offer the abbreviation along with trademark names to aid in the rapid identification of the material. This is particularly important for plastics products used in building construction. For the purposes of this text, the abbreviation is noted either in parentheses in the heading or after the name of the plastic in the descriptions that follow.

ABS Plastics: Developed to offset some of the shortcomings of polystyrene, ABS plastics are copolymers of acrylonitrile, butadiene, and styrene monomers in varying proportions. They are balanced for mechanical toughness, good service temperature for other-than-high temperature applications, and ease of fabrication. ABS materials have relatively good electrical insulating properties, good resistance to a wide range of chemicals, and good dimensional stability. Typical applications include automobile dashboards, pump impellers, refrigerator parts, appliance housings, luggage, protective helmets, battery cases, telephones, pipe and fittings, shoe heels, knobs, and tool handles.

Acetals (AR): Acetal resins are made primarily by the polymerization of formaldehyde. Copolymers of acetal are also produced. These materials form one of the strongest and stiffest thermoplastics. The products show good resistance to organic solvents; however, they do react with strong acids or bases. These plastics are widely used for equipment gears, automotive equipment, plumbing parts, and appliances. Two basic types are (1) a homopolymer and (2) a copolymer.

Acrylics: Acrylics are based on any of a number of acrylate and methacrylate monomers. One member of the family, polymethyl methacrylate (PMMA) is known for its excellent clarity, high transparency, good resistance to sharp blows, strength, and rigidity. It is odorless, tasteless, and nontoxic, but the surface scratches easily and contact with grit and harsh scouring agents must be avoided. Because it is a thermoplastic, it loses its shape in boiling water, although some cast acrylics have higher heat resistance. In sheets of varying thickness and color, PMMA is used for glazing, building panels, advertising displays, and protective shields. Solutions and emulsions of PMMA are produced for use as surface coatings, adhesives, and finishes. In rods and tubes, it is used for electric lighting and medical illuminating equipment, which utilize its capacity to transmit light along

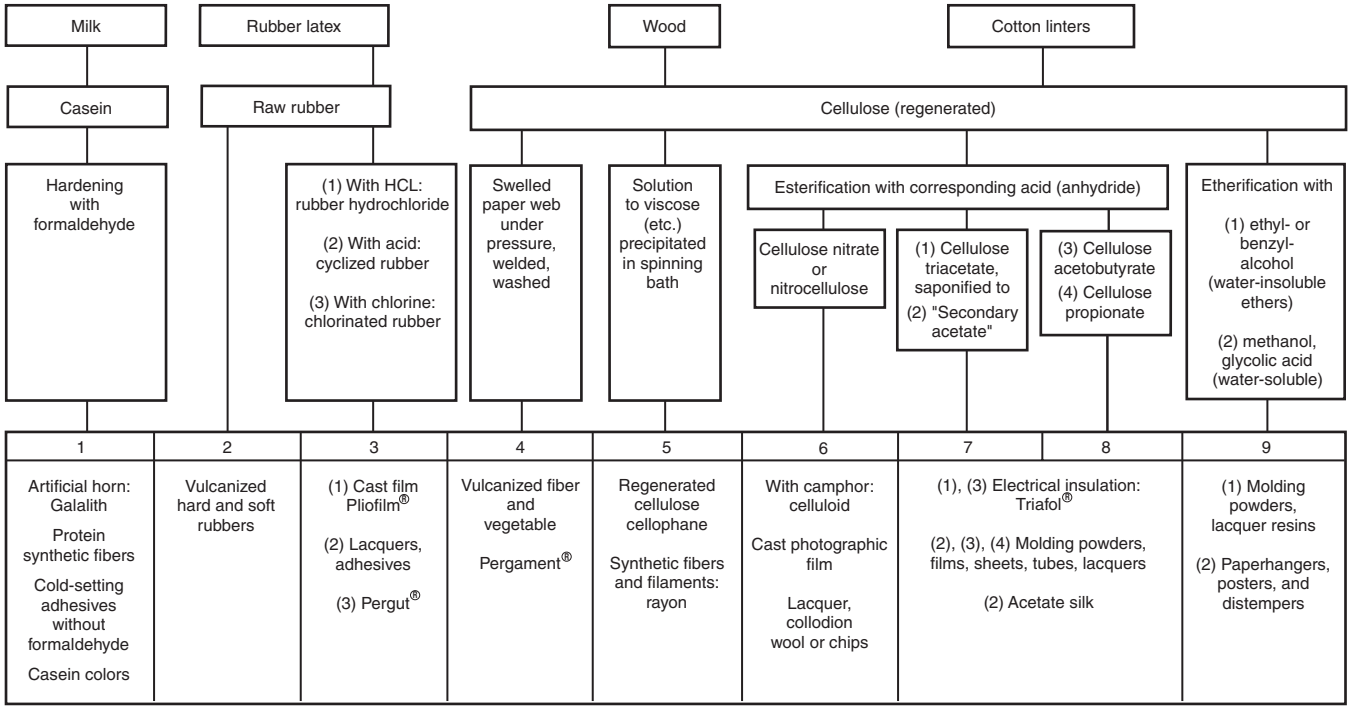


FIGURE 6.13.2 Plastics from Natural Products

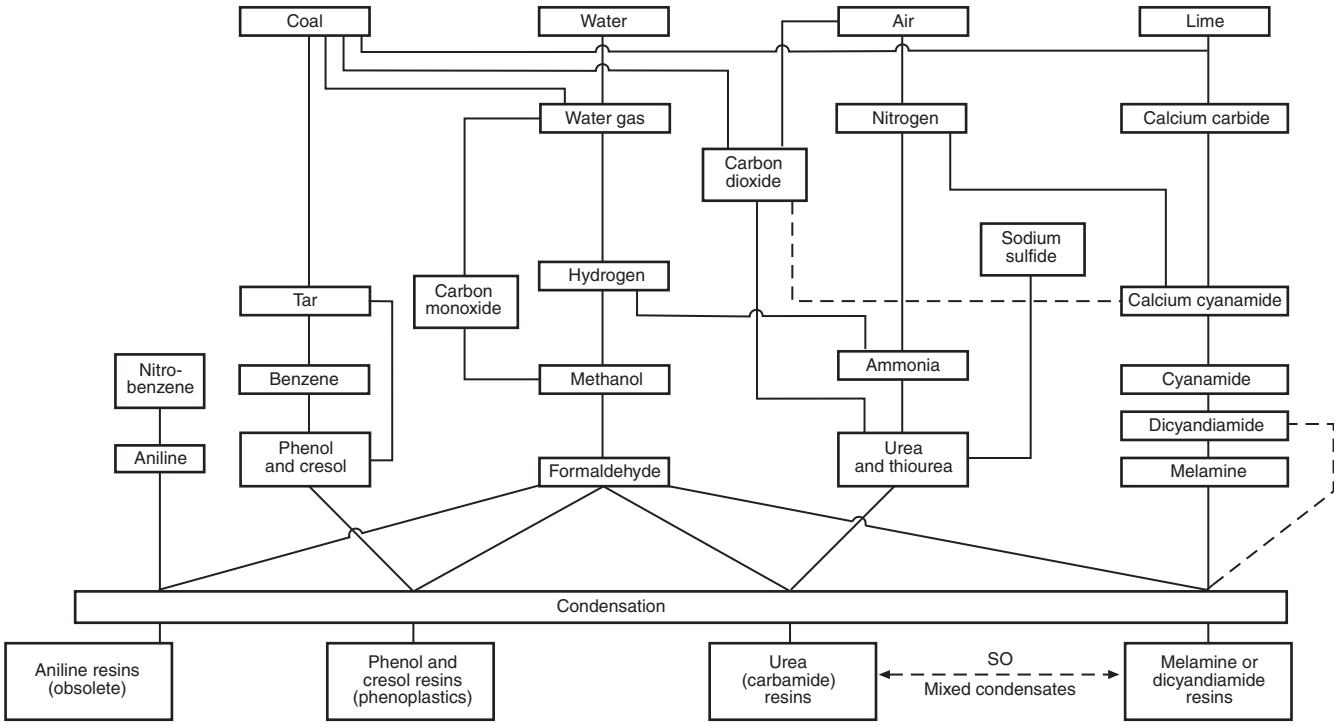


FIGURE 6.13.3 Condensation Resins—Thermosets

its length and around curves. In its molded form, it is used for lenses, dentures, toilet articles, and telephones.

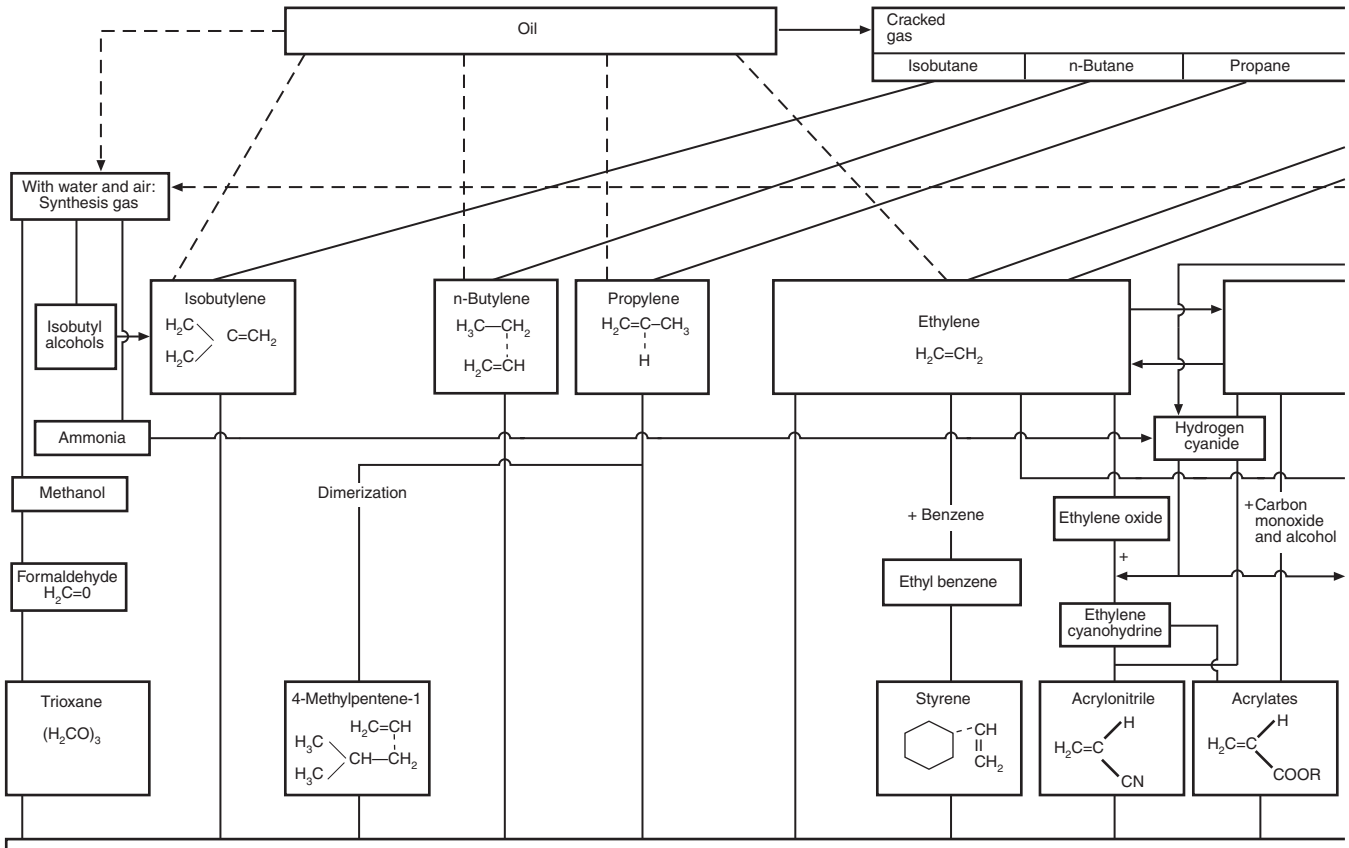
Alkyds: Good insulating properties, excellent moldability, short cure time, and low cost are primary reasons for the use of thermosetting alkyds in electrical materials, such as housings and cases for switchgear, encapsulation of capacitors and resistors, and parts for fuses, light switches, and insulators. Maximum use temperature of the molded parts is 250 to 300°F (120 to 150°C). Liquid resins are used for enamels and lacquers for cars, stoves, and refrigerators.

Allyls (Allylics): Allyl resins and monomers are thermosetting plastics that are commercially available as the diallyl esters of phthalic (DAP) and iso-phthalic (DAIP) acids. Other monomers in this grouping are diallyl maleate (DAM) and diallyl chlorendate (DAC). The latter is used for flame-resistant formulations because of the high chlorine content of the resins. Allyls can be polymerized by raising their temperature or by the use of peroxide initiators. The molding and electrical properties of these materials are excellent. They are primarily used for electrical components, decorative laminates, sealants, and coatings.

Cellulosics: Cellulosic plastics are produced by the chemical modification of cellulose, a natural polymer that is a major constituent of plant life. The primary sources of cellulose for this purpose are cotton linters and wood pulp. The term *cellulosic plastics* applies only to plastics whose resinous content is an ester or ether of cellulose. Included in this group are cellulose acetate, cellulose acetate butyrate, methyl cellulose, cellulose triacetate, cellulose propionate, ethyl cellulose, cellulose nitrate, cellulose films, and fibers.

Cellulose Acetate (CA): A thermoplastic made by treating cellulose with acetic acid and acetic anhydride, with sulfuric acid as a catalyst. It can be formed into molding powder, foamed by rapid evaporation of a solvent, dissolved for lacquers, cast into film, and spun from solution into fibers. It has replaced hazardous cellulose nitrate for photographic use under the name "safety film" (see also cellulose triacetate). Cellulose acetate molding compositions are tough and of good color and gloss; hardness is controlled by varying the ratio of plasticizer and ranges from rigid to flexible. Primary uses are in electronic components, insulation tapes, food packaging, toys, eyeglass frames, and video and sound recording tapes. Rigid cellulose acetate foam is used as the core in sandwich panels and marine floats. Variations in composition include the degree of esterification of cellulose and amount and choice of plasticizer, which is usually a phthalate ester. Molding stocks for general purposes ignite easily, give off burning drips, burn with a dark yellow flame, produce moderate smoke, and have an odor of vinegar unless masked by the odor of the plasticizer. Flame-resistant stocks are widely used for molding.

Cellulose Acetate Butyrate (CAB): A plastic made by treating cellulose with a mixture of acetic and butyric acids and anhydrides in the presence of a catalyst. The ratio of acetic and butyric components can be varied to produce the desired flexibility. CAB absorbs less water than cellulose acetate. Compositions with ultraviolet stabilizers are used for small outdoor and indoor signs. Major uses are for automobile steering wheels and taillights, telephone handsets, toothbrush handles, business machine keys, appliance housings, piping, and tubing.



1 Polyoxymethylene	2 Polyisobutylene	3 Polymethylpentene	4 Polybutene-1	5 Polypropylene	6 Polyethylene	7 Polystyrene	8 Acrylonitrile cop.	9 Polyacrylates
Delrin Tenac	Hyvis Vistanex Oppanol B	TPX resins	Shell PB	Profax, Tenite Hostalen PP, Novolen, Vestolen P, Moplen, Napryl, Poprolin, Propathene, Carlona, Stamylan, Daplen	Alathon, Escorene, Fortiflex, Marlex, Petrothene, Hi-zex, Sholex, Baylon, Hostalen, Lupolen, Vestolen, Fertene, Lacqtene, Carlona, Eltex, Stamylan, Ropol, Sclair	Styron, Hostyren, Vestyron, Edistir, Atcolene Lacqrene, Lustrex	with 7, 10: Barex Cycopak Soltan	Only important in copolymers

Copolymer, polymer mixes (blends) and derivatives

Celcon Kematal Duracon Hostaform Ultraform Tarnoform	Building sealing webs: Rhepanol			Copolymers 5 + 6 special types	Copolymers + 13 Evatate, Evaflex Lupolen V. Wacker VAE, Evatane Copolymers with acrylic acid salt Ionomere Surlyn A. Copolene, Himilan Blend with Bitumen Lucobit	Copolymers with butadiene: high impact PS Copolymers + 8, SAN Tyril, Sanrex, Luran Copolymers + 8 + Butadiene, Blends, ABS: Cycolac, Kralastic, Novodur, Terluran, Ravikral, Urtal Copolymers +8 + 9, ASA Luran S	Elevated temperature resistance with Copolymers 7, 9, 10, 12 Fibers: Orlon Dolan Dralon Craylor Anilana	Copoplymer dispersions with 7, 8, 10, 11, 13: Acronale Plextole
1	2	3	4	5	6	7	8	9

FIGURE 6.13.4 Double-Bond Polymerization Thermoplastics

Cellulose Propionate (CP): A thermoplastic molding composition made from cellulose and propionic acid. Molding compositions are usually supplied as granules or pellets, and finished articles can be fabricated by injection molding or extrusion. CP has uses similar to those of CA and CAB, but due to better surface hardness than that of CAB and less moisture sensitivity than that of CA, it is also used for mechanical pencils, telephones, and shoe heels.

Cellulose Triacetate (CAT): A thermoplastic made by reacting cellulose with acetic anhydride. It differs from cellulose acetate in chemical structure in that it consists of three acetate

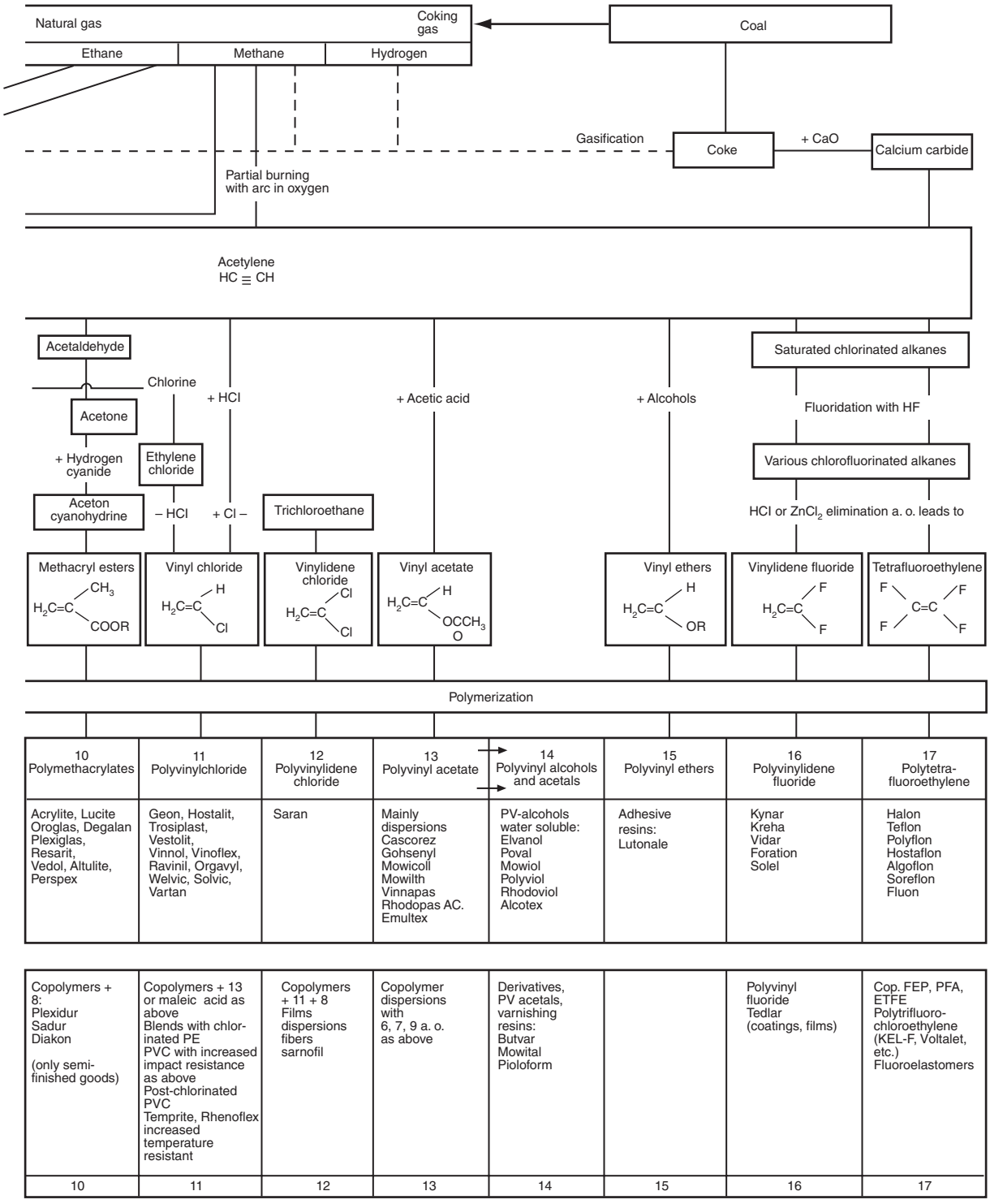


FIGURE 6.13.4 Continued

groups (instead of two) attached to each glucose unit of the cellulose molecule. Because of its high-softening temperature, it is not suitable as molding stock. It has lower water absorption than that of CA and is now the prevalent base for photographic safety film, drawing and printing film, magnetic tape, and transformer and capacitor dielectrics.

Cellulose Nitrate (CN): Because of the extreme fire hazards associated with cellulose nitrate in its processing, use, and storage, this plastic is discussed in detail later in this chapter.

Epoxies (EP): Epoxy resins are primarily produced by the reaction of epichlorohydrin and bisphenol-A in the presence of a

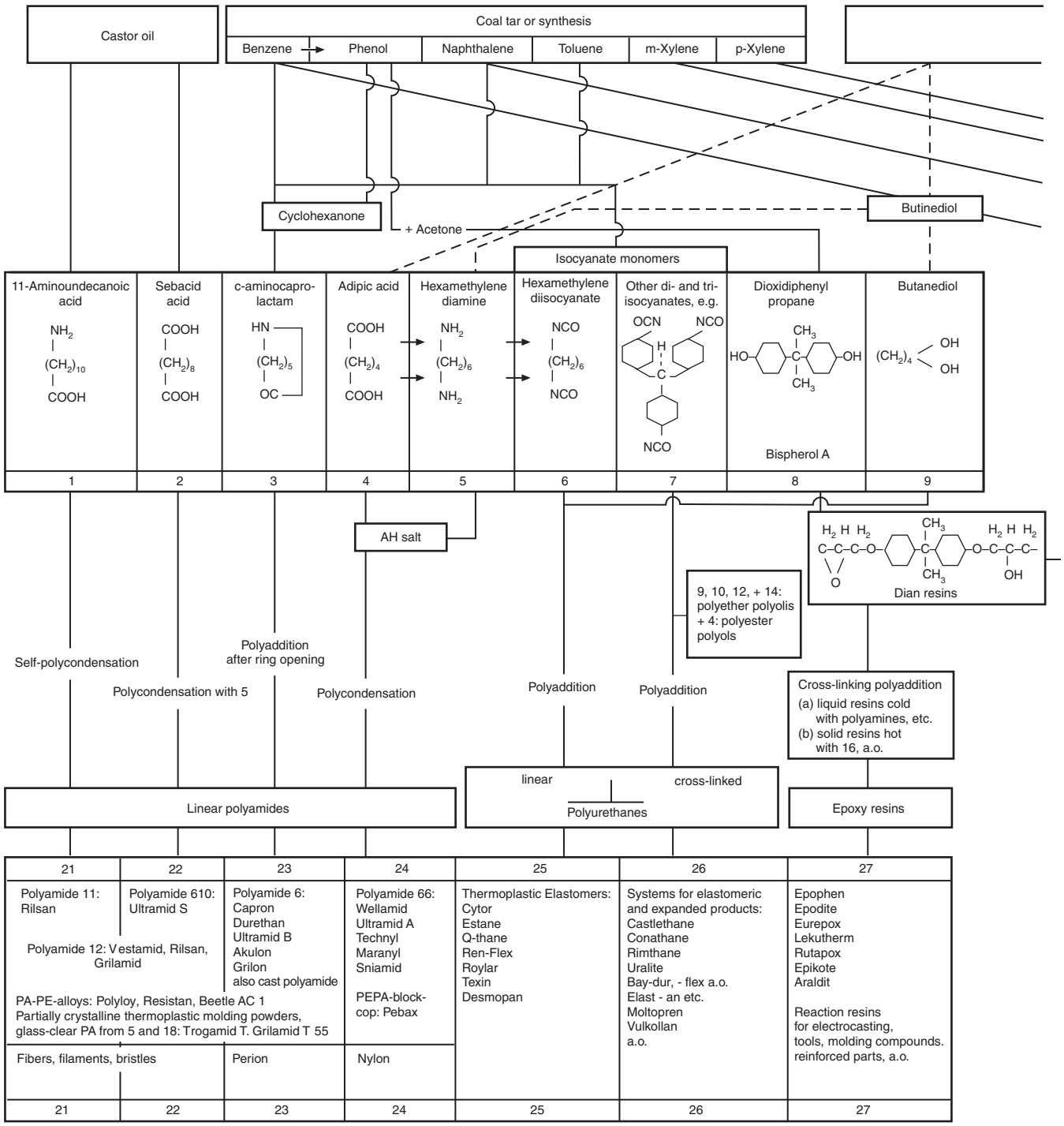


FIGURE 6.13.5 Plastics from Multifunctional Intermediate Products

catalyst. By varying the ratio of the ingredients, the resultant product may be a low-viscosity fluid or a high-melting solid. Two primary classes are available: (1) the liquid resins that are combined with curing agents for adhesives, potting, and tooling compounds, and (2) the solid resins that are modified with other resins to make coating materials. Epoxy resins also are used as "body solders" for automobile repair, as dies for forming sheet metal, as piping and tubing, and as foamed blocks for construction insulation.

Fluoroplastics: Fluoroplastics or fluorocarbons are commercially available in several major groups under the headings polyethylene-tetrafluoroethylene (ETFE), polyethylene-chlorotrifluoroethylene (E-CTFE), polytetrafluoroethylene (TFE), polyfluoroethylene-propylene (FEP), polychlorotrifluoroethylene (CTFE), polyvinyl fluoride (PVF), and polyvinylidene fluoride (PVF_2). All of these resins are characterized by resistance to solvents and chemical at-

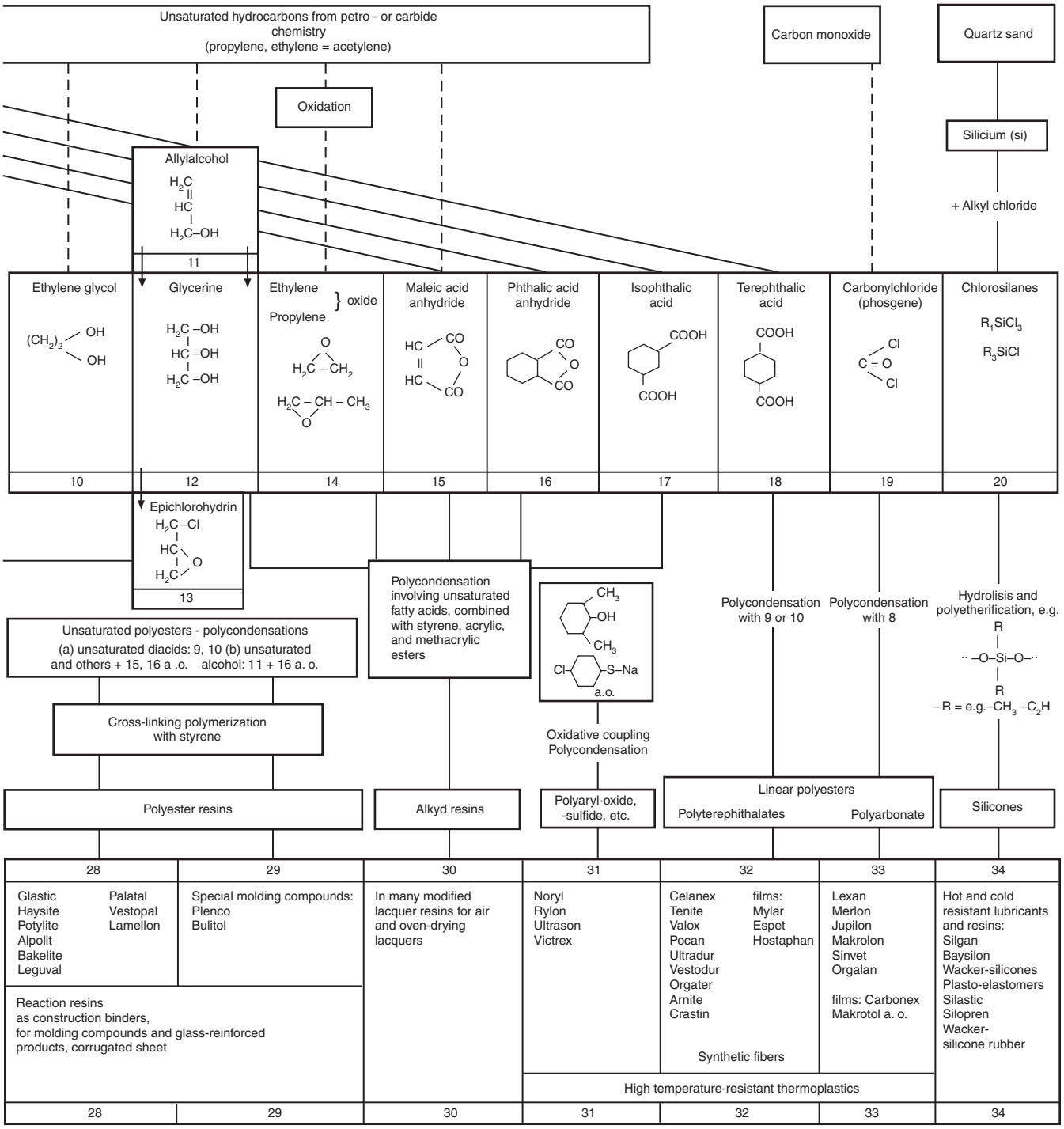
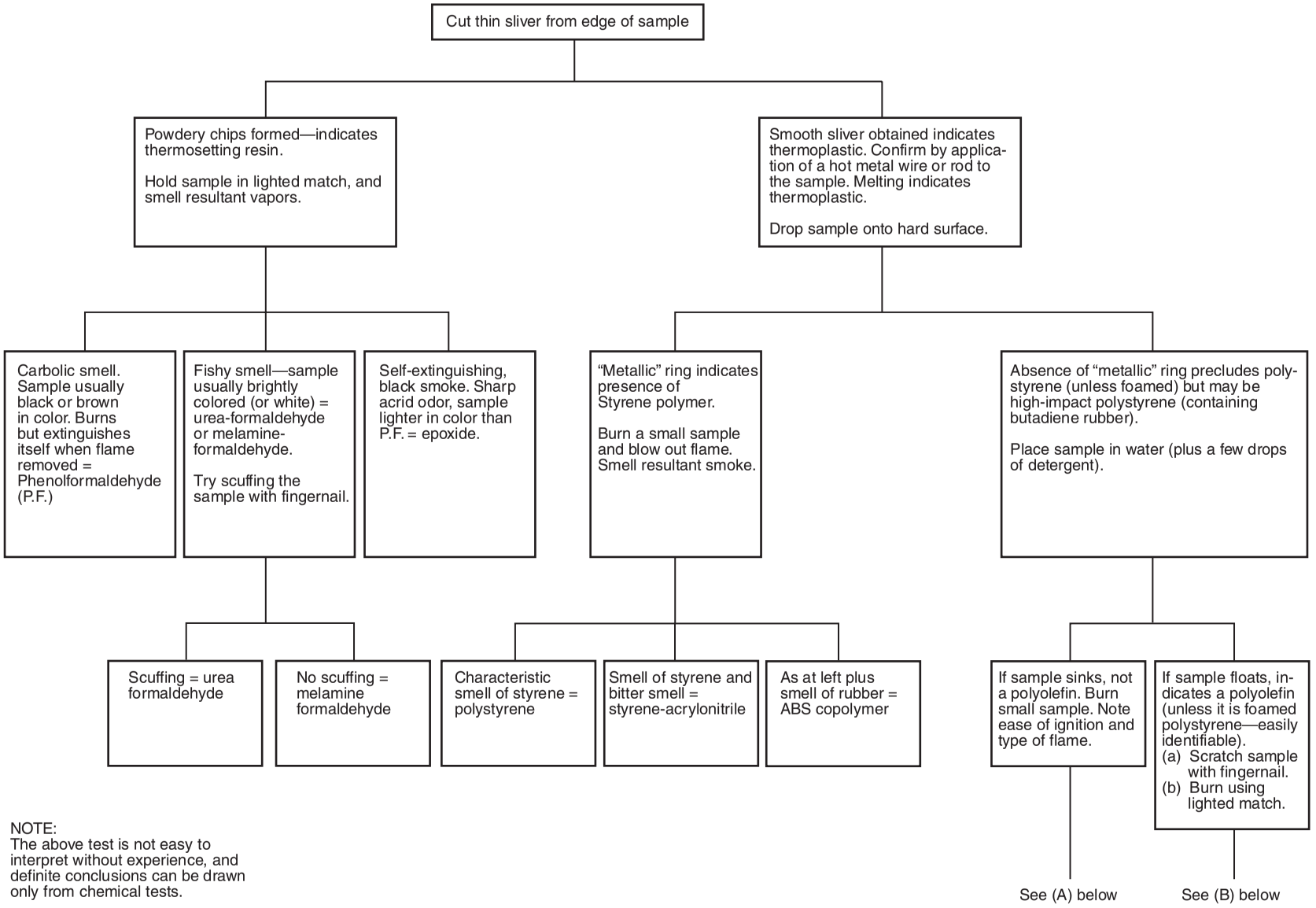


FIGURE 6.13.5 Continued

tack and good-to-excellent weatherability. Six are described below.

Polytetrafluoroethylene (PTFE): A representative of a group of completely fluorinated resins. It is handled as general-purpose molding powders, fine granules, and aqueous dispersions. The methods of processing include compression molding, extruding, dip coating, and film casting. PTFE has a very extended range of serviceable temperatures, from –450 to 500°F (–265 to 260°C). It is used as chemical gasketing, high-frequency and high-temperature electrical insulation, lubricants, and on molded bearings and coated cookware.

Polyfluoroethylene-propylene (FEP): A copolymer of tetrafluoroethylene and hexafluoropropylene. FEP can be handled through the melt-flow processes involved in extrusion and



NOTE:
The above test is not easy to interpret without experience, and definite conclusions can be drawn only from chemical tests.

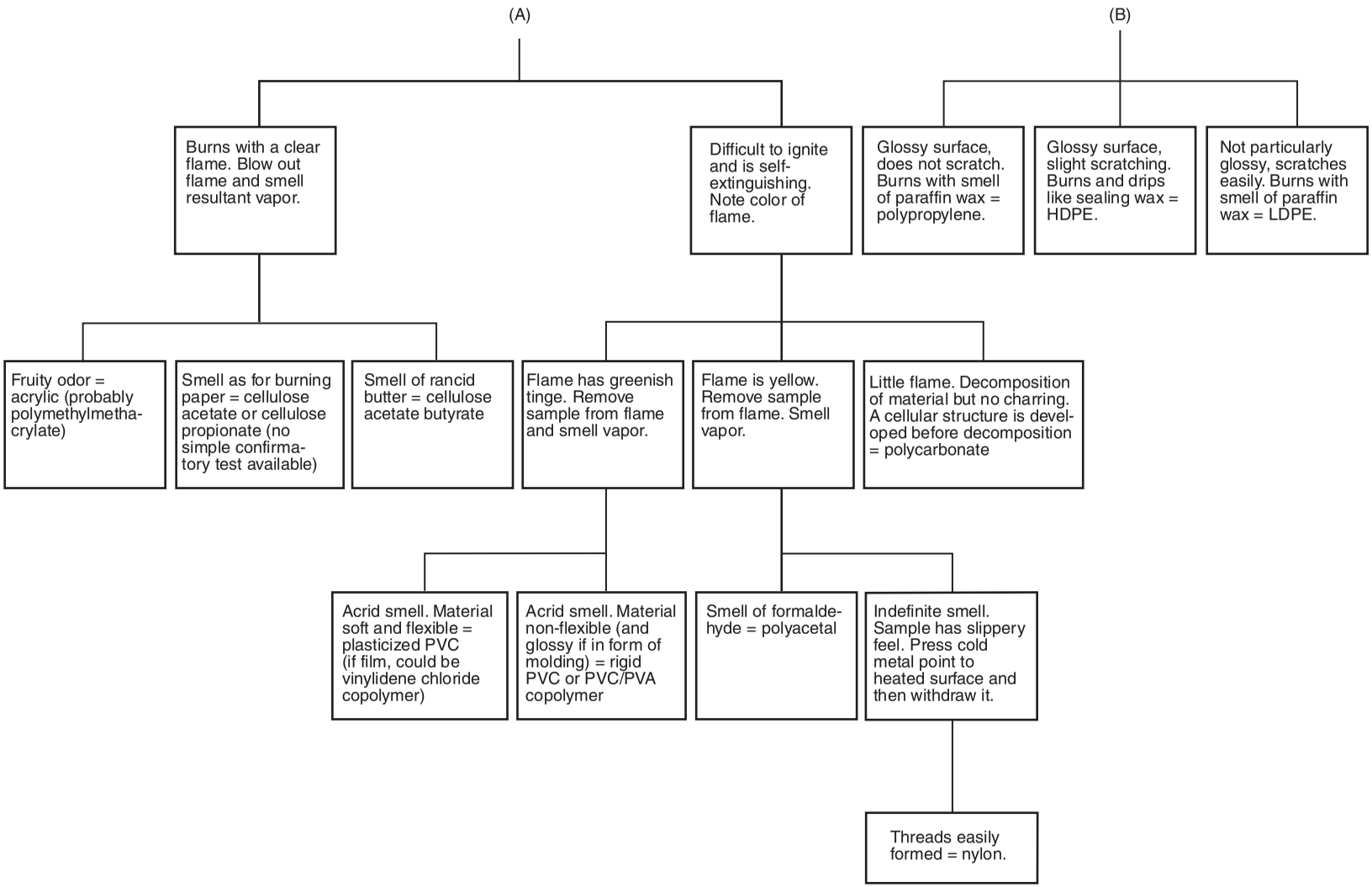


FIGURE 6.13.6 Simple Tests for Identifying the More Common Plastics

injection molding. It is widely used in industrial applications, particularly as insulation for process industries involving heat and corrosive atmospheres. It is also used as a lining for vessels, pipes, valves, and fittings handling corrosive fluids.

Polyethylene-tetrafluoroethylene (ETFE): A copolymer of ethylene and tetrafluoroethylene. It is processed by the conventional method of extrusion and injection molding. Its applications include use as gears, pump components, automotive parts, labware, valve linings, electrical connectors, and wire coatings. ETFE can be reinforced with glass fiber.

Polychlorotrifluoroethylene (CTFE): A thermoplastic resin produced in various formulations of fluoroplastics. It differs from the usual fluoroplastic in that its molecular structure contains chlorine. It flows like FEP for injection molding or extrusion, but is less thermally stable. It is chemically resistant to many corrosive liquids. Its serviceable temperatures range from –400 to 390°F (–240 to 200°C). Its electrical and thermal properties make it valuable for insulation, cable assemblies, printed circuits, and electronic components. It is also used in the chemical process industries in valves, fittings, and gaskets.

Polyethylene-chlorotrifluoroethylene (E-CTFE): A 1:1 copolymer of ethylene and chlorotrifluoroethylene. E-CTFE is processed by extrusion, molding, rotocast, and powder coating techniques. Applications include chemically resistant linings, coatings, containers, labware, moldings, wire coatings, fibers, and films.

Polyvinyl fluoride (PVF): A plastic produced through the polymerization of vinyl fluoride. Films are cast from selected hot solvents, and the major use is as a weather-resistant surface on building siding made of aluminum, wood, composite boards, or polyester glass fiber laminates.

Ionomers: The term *ionomer* is used to describe the class of thermoplastic polymers in which ionized carboxyl groups create ionic crosslinks in the intermolecular structure. Ionomer resin formulations are available in a wide variety of compositions. They are outstanding plastics, with regard to toughness, transparency, and solvent resistance, and they resist impact at temperatures as low as –160°F (–107°C). Articles made from these plastics include housewares, toys, containers, safety shields, tool handles, electrical insulation, and packaging. These plastics are also used in the lamination of various building construction materials.

Melamines (MF): Melamine, one of the members of the amino family, is a thermosetting plastic noted for its extreme hardness, permanent colors, and good electrical insulating characteristics. Alpha-cellulose filled, general-purpose grades are used for dishes and kitchenware, where their lack of taste and odor and resistance to food stains make them particularly desirable. Mineral-filled grades are used in electrical applications. The resin may be bonded with fabrics, paper, wood veneers, etc., to produce laminates for building applications.

Nylon: See polyamides.

Olefins: See polybutylene, polyethylene, polyallomers, and polypropylene.

Phenolics (PF): The discovery of phenol formaldehyde plastics (Bakelite™) in about 1910 marked the beginning of the plastics industry. Many varieties are now available, marked by low cost and good mechanical, electrical, and thermal properties. General-purpose, wood-filled grade phenolics are suitable for use up to about 300°F (150°C), but glass- or mineral-filled compounds have long-term retention of properties up to approximately 500°F (260°C). Some special, heat-resistant types are usable for up to 1 hour at temperatures as high as 1000°F (540°C).

Paper or fabric impregnated with phenolic resin in a water or organic solvent can be wound into tube form or pressed into flat sheets to make tough thermoset "laminates" with low water absorption and high service temperature capabilities. Laminates are used for electrical insulation and bearings for marine propellers and heavy rolling mills. Similar compositions are used as laminating adhesives for exterior-grade plywood and as impervious surfacing materials. Paper impregnated with phenolic resin and printed with wood grain is frequently the top surface for wall panels or furniture, with backing of other phenolic laminates or plywood. Phenolics are standard binders for brake shoes, sandpaper, grinding wheels, sand-casting foundry molds, and wood chip particleboard.

Two types of phenolic foam—reaction foam and syntactic foam—are used in construction or for thermal insulation. Reaction foam is made by curing the phenolic resin with agitation so rapid that water is produced as a byproduct, and is vaporized and trapped to make the voids in the foam. Syntactic foam is made from hollow spheres of phenolic resin with a phenolic or other resin binder. Each type is used for cores in sandwich panels and as buoyancy or a stiffening means in marine and aircraft structures. Cast phenolic resin is largely used for decorative applications.

Polyallomers: Polyallomers are made by polymerizing two monomers with catalysts so that blocks of each polymer are formed in the polymer chain. The most common polyallomer contains ethylene and propylene. Applications for polyallomers include films, bottles, appliance parts, automotive parts, toys, and closures.

Polyamides: Two aliphatic polyamides—nylon-6,6 and nylon-6—find their greatest uses in home furnishings and apparel, and account for most of the production in this family of polymers. The manufacture of nylon-6,6 started in 1938, and nylon-6 in 1939. The first major application was in the hosiery market. Nylon has become one of the leading polymers due to its high-impact strength, versatility, and ease of processing. Other forms of nylons are also commercially available and find application in ropes, fishlines, cable jacketing, gears, slide fasteners, boat propellers, and appliance parts.

Aromatic polyamides are more heat resistant. Their commercial production started in 1961 with Nomex™ and, more recently, Kevlar™ fiber. Nomex™ is found in items such as fire fighter's protective clothing, whereas Kevlar™ is ideally suited for tires and ballistic vests because of its strength. Kevlar™, together with graphite, is finding a use in superior composite materials, such as fiber-reinforced plastics (FRP). Polyamide imides and polyimides are other members of this grouping, typically used for heat-resistant electrical wire and cable insulation.

Polybutylene (PB): Polybutylene is flexible, has excellent creep resistance at room and elevated temperatures, and has higher long-term temperature resistance than other polyolefins. Other advantages include good toughness, high tear strength, and good moisture barrier and electrical insulation characteristics. Applications include film and sheeting, hot-melt coatings and adhesives, flexible pipe and tubing, and shrink film.

Polycarbonates (PC): Polycarbonates are thermoplastic polyesters of carbonic acid. The resin is available in several different forms, including pellets, powder, film, sheet, rod, plate, and tubing. High-impact strength, good electrical properties, clarity, and resistance to creep have caused this material to find many applications, such as in appliances, electrical and electronics equipment, food-handling systems, and sporting goods. Its transparency makes it useful for lenses, safety shields, and glazing.

Polyester, High-Temperature Aromatic: Important characteristics of this material are its dimensional stability at high temperatures (over 600°F [315°C]), self-lubricating properties, good stiffness, electrical insulating properties, and solvent resistance. It decomposes rapidly at approximately 1000°F (540°C). An unusual aspect of this thermoplastic is its very high thermal conductivity, which makes the material useful in applications, such as bearings and electrical insulation, where failure from localized hot spots is a problem with most plastics. Stick-free coatings for frying pans and encapsulation of electronic parts are among its other uses.

Polyesters, Thermoplastic: Unsaturated polyesters show good weathering resistance, light stability, and heat resistance. Their primary application is in the production of reinforced plastics. They are used to fabricate structures ranging in size from electrical components to large boat hulls. Saturated polyesters do not have the double bond that would permit further polymerization by treatment with initiators, such as organic peroxides. Saturated polyesters of high molecular weight, such as ethylene glycol terephthalate, are used principally in fiber and film production, for example, magnetic recording tapes, tough or boil-in-bag food packaging, and satellite balloons. They can be backplated with metals for decorative films and nameplates. The low-molecular-weight esters are used as plasticizers for vinyl and acrylic resins.

Thermoplastic polyester molding compositions are available. Besides poly (ethylene-terephthalate)—PET, there are poly (1,4-butylene-terephthalate)—PBT, poly (tetramethylene-terephthalate)—PTMT, and poly (cyclohexylenedimethylene-terephthalate-isophthalate)—PCDT. PBT and PTMT are the same chemically. Thermoplastic polyesters have engineering applications, including automotive parts, appliance parts, business machine parts, electrical and electronic parts, gears, bearings, pulleys, and pump components. The polyester PET, discovered in Britain during World War II, can be spun into a fiber that is commonly used in textiles.

Polyethylene (PE): Three major types of polyethylene are marketed: the low-, medium-, and high-density products. In addition, copolymers of ethylene-ethyl acrylate, ethylene-vinyl acetate, and ethylene-butylene are produced. The three density ranges are 56.8 to 57.7, 57.8 to 58.7, and 58.8 to 60.2 lb/ft^3 (90.9 to 92.4 kg/m^3, 92.5 to 94.0 kg/m^3, and 94.1 to 96.4 kg/m^3).

Low-density stocks are waxy, relatively limp, and are the toughest of the polyethylenes, with an upper service temperature of approximately 160°F (70°C). As density increases, so does surface hardness, stiffness, resistance to permeation by oils and water, and softening temperature. For polyethylenes of the highest density, the upper service temperature is 240°F (115°C) under no-load conditions.

The outstanding properties of polyethylenes are (1) good moldability, (2) good mechanical properties, (3) excellent electrical resistance, (4) low moisture vapor transmission, (5) resistance to solvents and chemicals, and (6) lightness in weight. Polyethylene is widely used for film, sheeting, plastic bottles, piping, tubing, dish pans, garbage containers, laundry baskets, electronic components, insulation, and textiles. Boat and motor vehicle fuel tanks are a recent application for high-density polyethylene. Polyethylene can be crosslinked chemically or by irradiation to form a thermoset with high heat resistance.

Polyphenylene Oxide (PPO): Polyphenylene oxide is a thermoplastic resin formed by the catalyzed oxidation of 2,6-xylenol. It is a specialized, highly engineered plastic with a wide temperature range, good mechanical and electrical properties, and resistance to corrosive materials. It has many electrical and electronic applications, and is used for packaging frozen foods and as a replacement for glass and stainless steel in hospital utensils and medical instruments.

Polyphenylene Sulfide (PPS): Excellent chemical resistance and high stiffness at elevated temperatures make polyphenylene sulfide useful as a coating for various metals, including aluminum, steel, cast iron, and brass, and in the petroleum and chemical processing industries. Other uses include cookware, pump impellers, pumps, conveyor rollers, and machine parts.

Polypropylene (PP): Polypropylene possesses the lowest density of the commercially available thermoplastics. In addition, it exhibits good rigidity, high yield strength, good surface hardness, exceptional flexural properties, resistance to chemicals, and excellent dielectric properties. Like all olefins, it has excellent resistance to water solutions that are highly damaging to many metals.

Primary areas of use include the usual categories of molding, as well as in film and piping. It is used for luggage, housewares, automobile and aviation components, and appliance parts. Because of its superior insulating properties, it is also used to make electronic components. Carpeting made of polypropylene fibers also is available. Polypropylene filled with asbestos offers high-impact strength, stiffness (up to 250°F [120°C]), and low friction.

Polystyrene (PS): A glassy transparent thermoplastic, primary characteristics of polystyrene are hardness, rigidity, clarity, and heat and dimensional stability. By varying the polymerization reaction, polystyrenes have been developed with higher heat distortion temperatures. Styrene polymers are marketed in granular and powder form for extrusion or molding. Beads of polystyrene that contain the flammable gas pentane as a blowing agent are sold for the production of polystyrene foam.

General-purpose and impact grades of polystyrene are used for refrigerator liners, appliance housings, automotive applications, films for wrapping, sporting goods, toys, and novelties. Heat-resistant polystyrene is used for television sets, radios, and illuminated signs. Glass-filled polystyrene is used for business machines, electronic equipment, and military hardware. Polystyrene foam is used to make toys, insulation, displays, shipping containers, and molded furniture. Construction panels, consisting of cores of polystyrene foam between sheets of plywood, plastic, or aluminum, and foamed-in-place polystyrene insulation are used in the building industry.

Polysulfone (PSU): Polysulfone is a thermoplastic resin that contains a diphenylene group. This group imparts certain desirable characteristics to the polymer, including thermal stability (over 300°F [150°C]), oxidation resistance, and rigidity. Glass fibers may be added for improved environmental stress crack resistance. Commercial applications include electronic units, electrical circuit breaker parts, automobile engine parts, aircraft interiors, kitchen range hardware, electroplating equipment, and appliance hardware.

Polyurethane (PUR): Polyurethanes consist of a group of polymers that are produced in the following two general forms: (1) foams, for example, flexible, semiflexible, and rigid; and (2) elastomers, for example, casting compounds and elastoplastic resins, adhesives, coatings, and spandex fiber. The basic reaction used to produce the urethane polymers involves isocyanates and reactive hydrogen-bearing materials, such as polyethers, castor oils, amines, carboxylic acid, and water. By varying the number of branchings, it is possible to make polyurethanes that are thermoplastic or thermosetting.

Polyurethane foams are widely used in the production of upholstered furniture, bedding, sponges, toys, wearing apparel, and medical dressings. Rigid urethane foams are used for insulation in building construction. Substantial quantities of the polyurethanes are used to produce coatings and adhesives. Their rubberlike qualities aid in the production of specialty fillers and elastomers. Gears, sprockets, and rolls are produced from urethanes. Very thin films are used to produce containers impermeable to gas and moisture.

Silicones (SI): Silicone resins comprise a large group of polymers consisting of chains of alternating silicone and oxygen atoms with organic groups, for example, methyl groups attached to the silicone atoms. They are stable at high and low temperatures, have good dielectric properties, resist weathering, do not react with most chemicals, and repel water.

Silicone emulsions are used as mold-release agents, defoamers, and waterproofing materials. A compound of liquid silicone and finely divided filler produces a grease suitable for high-temperature lubrication applications. Silicone paints, varnishes, and enamels have many uses, including cloth and wire coating. With inorganic fillers, such as glass or asbestos, silicones are molded into such products as connector plugs, coil bobbins, insulators on induction furnaces, and heat barriers in jet engine afterburners. Silicone glass laminate applications include rigid hot air ducts for aircraft, terminal boards, and transformer spools and spacers. Rigid silicone foams can be preformed or foamed in place. High-temperature insulation is the principal use of rigid silicone foams.

Styrene Acrylonitrile (SAN): Produced through the copolymerization of styrene and acrylonitrile, styrene acrylonitrile is a transparent thermoplastic with improved heat resistance, stiffness, and scratch and impact resistance. It finds application in decorative panels, food packages, "dishwasher-safe" housewares, battery cases, lenses, glasses, appliance parts, and automobile components.

Ureas (UF): Urea formaldehyde, as a thermosetting plastic, is especially suitable for any application that must resist heat. The material has excellent resistance to oils and greases, but is not recommended for high-humidity environments. Because urea formaldehyde is hard, strong, odorless, and tasteless, it has been frequently used in tableware, crockery, and decorative articles for the home. Other uses are for electrical parts, such as switches and outlet covers, bottle tops, toys, and as a laminate in building panels.

Vinyls: The vinyl resins are thermoplastics that exist in a wide variety of polymers and copolymers. Commercial production of the vinyl chloride monomer starts with acetylene or ethylene. Most vinyl plants use an oxychlorination process with ethylene to produce vinyl chloride. Copolymers of vinyl chloride and vinyl acetate account for a large part of vinyl production.

The major applications for flexible and rigid vinyls include automobile seat covers, floor mats, and moldings; shower curtains; window shades; wrappings; bottles; adhesives; flooring; siding; piping; wiring; swimming pools; records; and medical appliances.

Polyvinyl Chloride (PVC): This type of plastic is made as a rigid product for a number of building components and as a flexible plasticized stock for upholstery and wearing apparel. It exists in hundreds of individual formulations. It has good abrasion resistance. The unplasticized PVC softens as it burns, producing white smoke and acrid fumes, which can be corrosive. Most of the chlorine content of PVC is released as hydrogen chloride. The fire properties of plasticized PVC are determined to a large extent by the nature of the plasticizer. Building products should be tested individually.

Vinyl Chloride—Vinyl Acetate Copolymers (Polyvinyl Acetate) (PVAC): These contain from 5 to 20 percent vinyl acetate in the polymer. They are used for more flexible stocks than is PVC and are more readily softened by plasticizers. Their properties are essentially those of PVC.

Polyvinyl Dichloride (PVDC): Because this plastic is made by chlorinating PVC, its properties are essentially those of rigid PVC. It is used most where more toughness, stiffness, and heat resistance are needed than are offered by PVC.

Vinyl Acetate Polymer (VAC): Vinyl acetate polymer is a thermoplastic that is used in coatings, as a wood primer, and as an adhesive in a milky aqueous dispersion. It is not used as a molding or sheet plastic, as its upper service temperature is below 120°F (50°C).

Vinyl Alcohol Resins (PVA): Because they are made by hydrolysis of polyvinyl acetate, PVA products swell or dissolve completely in water. They are highly impervious to oils and many lacquer solvents. They are used in hoses for spray painting and as water-soluble film for dose-packaging detergents, and so on.

Polyvinyl Butyral (PVB): Polyvinyl butyral is produced by condensing butyraldehyde with polyvinyl alcohol. It has remarkable adhesive qualities and is primarily used as plasticized film for laminating automotive safety glass.

Polyvinyl Formal (PVFM): Polyvinyl formal is produced by condensing formaldehyde with polyvinyl alcohol to make a hard resin. Polyvinyl formal is then mixed with small amounts of phenolic resin to improve the bond and reduce creep. It is not to be confused with polyvinyl fluoride (see fluoroplastics). Its principal use is as standard insulation enamel for magnet wire in small motors and electronic equipment.

Vinylidene Chloride Polymer: This is a thermoplastic that as a film has low permeability to water vapor. A principal use is as a coating on cellophane. Filaments are used for webbing on garden furniture and for window screening.

Vinylidene Chloride-Vinyl Chloride Copolymer: This plastic is less rigid than PVC and flows more readily in extrusion and molding. Its major use is as a coating for metals and molded electrical parts.

NATURAL AND SYNTHETIC RUBBER

Like plastics, rubber appears in many shapes and forms, from very soft and pliable products to hard rubber that looks and feels like a molded plastic. Many polymers can be manufactured in elastomeric grades and are classified in that form as synthetic rubbers. Crepe soles fall in that category.

Natural Rubber (NR): Natural rubber is a constituent of latex, the white milky sap collected from the rubber tree. The processed rubber may be used in sheet form for items like shoe soles, extruded into products like inner tubes, or compression molded with heat to make items like tires and hot-water bottles. Liquid latex has a variety of applications. It is often coated on fabrics for waterproofing, mixed with cement for superior bonding qualities, included in water-based paints to produce a cohesive film after the paint dries, and expanded into the familiar foam latex, or foam rubber. The density of the foam is controlled by varying the ratio of foam to air and the size of the cavities.

Vulcanization is a curing process that causes rubber to crosslink. Rubber that has been vulcanized cannot be reshaped or remolded when reheated. By prolonging the vulcanization process, the degree of hardness can be varied, eventually resulting in "hard rubber" (known as ebonite or vulcanite in England). Hard-rubber tubes and rods have been popular products, valued for their resiliency, electrical insulating quality, and chemical inertness. Other common products have included automobile battery cases, combs, telephone receivers, castors, wheels, and bushings. In many of these applications, synthetics have replaced natural rubber.

Synthetic Rubber (SR): These materials are intended to imitate the elasticity of natural rubber and they can be vulcanized. They have similar long-chain molecular structures, built up from copolymerized synthetic monomers, such as butadiene with styrene, or butadiene with acrylonitrile. The former method produces styrene-butadiene rubber (SBR); styrene-butadiene rubber is used extensively in automobile tires. Nitrile rubber (NBS) is the product of the butadiene-acrylonitrile reaction, whereas butyl rubber is produced from an isobutylene-isoprene copolymer. Neoprene (GR) is a very strong and durable synthetic made from chloroprene.

Synthetic foam rubber usually means a soft flexible product of the polyurethane type and is either polyester (AU) or polyether (EU). However, new types are continually being developed, including ethylene-propylene rubber (EPR), polybutadiene (BR), and polyisoprene, the synthetic equivalent of natural rubber.

Silicone rubber (SI) incorporates the inorganic, inert element silicone, which gives it a number of unique properties. It is the only satisfactory soft material for human implants, and it is commonly used for breast implants and many other implants, including artificial ears, skull plates, and jawbones. In building applications, self-curing, water-repellent silicone rubber is used as a sealant, and it finds many applications where a nonstick surface is desired. Some formulations have been used successfully as firestops and to seal openings in fire walls, where its flexibility gives performance superior to grout or plaster.

Additional information sources on synthetic rubbers are *Plastics: Design and Materials,*[6] *Introduction to Industrial Polymers,*[7] and *Rubber Technology Handbook.*[8]

CELLULOSE NITRATE (CN)

Cellulose nitrate (also referred to as nitrocellulose and pyroxylin) is made by the action of nitric and sulfuric acids on cellulose materials, such as cotton. Pyroxylin plastic comprises the lower nitrated products and contains from 11 to 12 percent nitrogen. Cellulose nitrate material that has been subjected to heat, such as that salvaged from a fire, may be so altered in composition that it is subject to spontaneous ignition.

When cellulose nitrate products are heated to temperatures above 300°F (150°C), decomposition starts, which generates further heat and soon raises the material to its ignition temperature. Decomposition of cellulose nitrate generates heat and does not depend on an external air supply.

Cellulose nitrate, when in solution in acetone or any of the various solvents, has no greater hazard than that of the solvent. If the solvent is lost, the hazard reverts to that of cellulose nitrate.

Most articles formerly made of cellulose nitrate are now made from less hazardous plastics, but it is still used to some extent in industrial applications, for items such as shoe heels, some housewares, and as a pigment in lacquers.

Processing Cellulose Nitrate

Fire safety in plants processing cellulose nitrate plastic consists essentially of four parts: (1) segregation of hazards, (2) elimination of ignition sources, (3) good housekeeping, and (4) strong

fire control facilities. In some plants, finished cellulose nitrate plastic parts may be assembled with other articles that do not involve any special fire hazard, for example, toilet seats. In such cases, the hazard and necessary protection depend on the quantity of cellulose nitrate used. If the quantities used are large, the same safeguards should be followed as for plants in which the product is made entirely from cellulose nitrate.

Cellulose Nitrate Storage

Storage of cellulose nitrate plastics requires special facilities. Depending on the quantity to be stored, these facilities may be cabinets, vaults, storage rooms, or isolated storage buildings. Storage facilities are described in detail in two NFPA standards: NFPA 40, *Standard for the Storage and Handling of Cellulose Nitrate Film*, and NFPA 42, *Code for the Storage of Pyroxylin Plastic*.

Cellulose Nitrate Photographic Film

All photographic film made in the United States and Canada since 1952 is the safety-base type, usually cellulose acetate or triacetate or polyester. An engraving process used in some printing plants engraves on cellulose nitrate plates.

There is comparatively little storage of cellulose nitrate X-ray film, although some hospitals may still store X-rays made on cellulose nitrate film many years ago. However, appreciable quantities of old nitrate motion picture and aero film still exist. Small amounts of portrait, industrial, and amateur nitrate film probably exist, but the usual storage of this material (in paper envelopes) poses no serious hazard. Nitrate-based film manufactured in other countries may occasionally be found.

The existence of old nitrate motion picture and aero film does present a hazard, since persons handling this material may not be familiar with its serious hazards and the elaborate precautions necessary to handle it safely. Although it is unlikely that nitrate film will be projected in a theater handling present-day motion pictures, such material may be shown in small art or film society theaters. Unfortunately, projectionists may not be aware of the fact that a nitrate print is to be shown. For this reason, theater projection standards for nitrate film should still be kept in effect. Storage of nitrate film should be in accordance with NFPA 40.

The amounts of scrap-nitrate motion picture film have greatly decreased, and most of the agencies that formerly handled this material are no longer in existence. This has given rise to the possibility that scrap could accumulate in dangerous quantities. Prior to environmental concern with air pollutants from outdoor burning, the best procedure for disposing of scrap nitrate film was to burn it at a remote location in the open, with all personnel at a safe distance upwind (because toxic oxides of nitrogen are among the products of combustion of this film). If accumulations of scrap-nitrate film are a problem, the best course to follow would be to check with environmental authorities to learn if such open burning is permitted locally.

Transportation of Cellulose Nitrate

The U.S. Department of Transportation (DOT) regulates the interstate transportation of cellulose nitrate plastic by rail, land, or water. These regulations permit dry shipment of cellulose nitrate (pyroxylin) scrap when specially packaged, but if there is evidence or the possibility of decomposition, the cellulose nitrate must be packaged under water. Shipment of cellulose nitrate sheets, rolls, rods, and tubes is not subject to special DOT regulation, except when shipped by rail express or water.

Articles manufactured entirely of or containing cellulose nitrate plastic do not require special packaging when shipped by land, rail, or water. Special shipping regulations apply to cellulose nitrate wet with alcohol, solvent, or water.

Shipments of cellulose nitrate motion picture and X-ray films are permitted when certain packaging requirements are met, including inside containers made of light metal, cardboard, or fiberboard for individual reels of film. NFPA 40 places restrictions on the transportation of nitrate film in public vehicles so as to protect the public against the consequences of a possible fire involving the film.

Air transportation of cellulose nitrate plastic scrap is not permitted by regulations of the International Air Transport Association. Cellulose nitrate plastic rods, sheets, rolls, tubes, manufactured articles, and motion picture and X-ray films are permitted only when specially packaged.

Extinguishing Cellulose Nitrate Fires

Large volumes of water are required to extinguish cellulose nitrate fires. Automatic sprinklers constitute the best general protection for areas where cellulose nitrate materials are stored or handled. Water supplies should be particularly strong. Closer sprinkler spacing than for ordinary occupancies is required in order to supply sufficient water to absorb the heat. The water from sprinklers, in addition to its extinguishing and cooling effects, tends to absorb the poisonous oxides of nitrogen fumes but has no effect on carbon monoxide.

If hose streams are required, the objective should be to get large quantities of water on the fire as soon as possible. Fire fighters should be located upwind or protected by self-contained breathing apparatus (SCBA) to prevent inhalation of the products of combustion.

FIRE BEHAVIOR OF PLASTICS

Although there is no special fire hazard for most accepted usages of plastics, some exhibit burning characteristics that are considerably different from those encountered with the more traditional cellulosic building materials. Different fire conditions cause significantly different burning characteristics that pose unusual hazards to life and property, including the following.

Ignitability and Rate of Burning. Although plastics tend to have a higher ignition temperature than wood and other cellulosic products, some are easily ignited with a small flame and burn vigorously. Very high surface flame spread rates are possible—up to approximately 2 ft/sec (0.6 m/sec), or 10 times the rate of flame spread across most wood surfaces.

Smoke Produced. The burning of some plastics is characterized by the rapid generation of large amounts of very dense,

sooty, black smoke. Chemicals added to inhibit flammability may increase smoke production.

Toxic Gases. Any fire will generate lethal products of combustion, principally carbon monoxide. Depending on the plastic and the particular fire conditions, gases with much higher toxic potency, such as hydrogen cyanide and hydrogen chloride, may also evolve (see Section 6, Chapter 2, "Combustion Products and Their Effects on Life Safety").

Flaming Drips. Thermoplastic articles tend to melt and flow when heated. In a fire, this characteristic may cause the material to melt away from the flame front and inhibit further burning, or it may produce flaming and tar-like dripping, which is difficult to extinguish and may start secondary fires.

Deviation from Test Results. Small-scale "Bunsen burner" tests are used for product development and laboratory control purposes. In the past they were used to indicate that certain plastics were "self-extinguishing" or "nonburning" and, presumably, safe for use. Unfortunately, in real-life situations the same materials can show flash burning characteristics.

Corrosion. Severe corrosion damage to sensitive electronic equipment and to metal surfaces can occur following fires involving such plastics as polyvinyl chloride.

Smoke Generation

Smoke generation from a given polymer may vary widely, depending on the nature of the polymer, the additives present, whether fire exposure was flaming or smoldering, and the type of ventilation that was present. The following comments from Gaskill's[9] comprehensive study on smoke density are especially pertinent:

1. Woods and most polymeric material pyrolytically degrade, yielding smokes that are dense to very dense. Ventilation tends to clear the smoke, but in most cases it does not reduce the intensity to the point of satisfactory visibility. With fire retardants incorporated into the polymer (at least in the case of solid materials), heat and flame generally produce very dense smokes, and this occurs rapidly.

2. Woods and those polymeric materials that burn cleanly will yield smokes, under conditions of heat and flame, of somewhat less density.

3. Urethane foams under flaming or nonflaming exposures generally yield dense smokes, and, with few exceptions, obscuration occurs in a fraction of a minute. Flaming exposure usually causes the smokes to be generated in less than 15 seconds, and the intensities in this case are usually higher than in the nonflaming case.

Cellular Plastics

Cellular plastics (or foamed or expanded plastics) have been in widespread use since the 1960s. The low resistance of cellular plastics to excessive heat and their ease of ignition contrast sharply with their most valuable property in building construction—their excellent resistance to heat transfer. In a 1969 study of the flammability of cellular plastics,[10] Underwriters Laboratories Inc. (UL) reported on an analysis of 34 fires where rigid cellular plastics had been used as building materials. The report indicated the following:

1. The fire performance of cellular plastics can vary considerably depending on whether they are exposed or protected and/or flame resistant, along with the degree of flame resistance. But the reduction in flammability through the use of inhibitors or protective coverings is not conclusively demonstrated by the study.

2. In 8 of 21 fires, a high rate of flame spread was reported and appeared to be especially typical of sprayed-on polyurethane and rigid polyurethane boards. Flame spread ratings from NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials,* tunnel tests of some of the materials ranged from 5 to 1375 (red oak, 100).

3. The fire behavior of cellular plastics appears to be affected by the extent of foam application, that is, whether the foam is applied to the walls and ceiling or only to the walls.

4. The fire behavior of the flexible foam plastics appears to be similar to that of the rigid plastic foams. (Peculiar to the flexible foams, though, is the pool of liquid product that can be generated in a fire in the bulk storage of the foam "buns." The liquefied plastic burns like a high flashpoint flammable liquid.)

Whereas untreated rigid polyurethane burns rapidly and is readily ignited by common ignition sources found in the environment, fire-retardant grades have substantial resistance to localized, temporary ignition sources under most fire environments. Sustained application of heat and flame causes such foam to burn, but the burning rate tends to be retarded. Often, burning will cease entirely when the external flame source is removed. The production of dense smoke is a characteristic of both treated and untreated urethane.

Untreated rigid polystyrene foam, likewise, ignites easily and burns vigorously with the production of dense, black smoke and a very black, viscous melt product which can burn with the intensity of a flammable liquid. Fire-retardant treatments inhibit ignition; the plastic tends to shrink away from fixed heat sources without igniting. The heat of combustion of styrene is about 50 percent higher than that of urethane foam (18,000 Btu/lb versus 12,000 Btu/lb [42 mJ/kg versus 28 mJ/kg]).

At times, cellular plastics that exhibit good resistance to burning under most exposure conditions have shown a markedly different behavior when surfaces of the exposed plastic are arranged to cause a feedback of radiant heat between the surfaces.[11] The combination of low thermal conductivity, high rate of heat release, and rapid degradation under heat exposure appears to be responsible for a rapid upward propagation of the flame front occurring in a room corner configuration. When the ceiling is also insulated with the exposed foamed plastic, the corner configuration encourages rapid extension of the fire across the underside of the ceiling. This phenomenon has occurred even with ignition sources as small as a wastebasket fire. The laboratories of FM Global Research (formerly Factory Mutual

Research Corporation) devised the "corner test" to simulate this exposure condition.

Rubber

Burning rubber is notable for its smell and dense smoke. The material, as generally used, is not easily ignited and does not burn with unusual rapidity.

The bulk storage of rubber items, particularly rubber tires, is subject to hot, difficult-to-control, and very smoky fires. Surface application of water may be only marginally effective because the fire can easily burrow into the material. Special automatic sprinkler protection is required to help ensure control if the storage is more than 5 ft (1.52 m) high (see NFPA 13, *Standard for the Installation of Sprinkler Systems*).

Rubber or plastic jacketing on grouped electrical cables has provided the fuel for fires in the electrical and communications industries. Considerable work has been done to raise the operating temperature limits and ignition temperatures of insulation for electric power and control cables. An applicable standard is IEEE 383, *Standard for Type Test of Class IE Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations.* Butyl/neoprene and neoprene rubber insulation, for example, tend to burn readily and fail such small-scale tests.

No significant differences appear to exist in the ignition or combustion characteristics of natural rubber and the various synthetics. Silicone rubbers can be formulated to reduce combustibility to a minimum under ordinary conditions, but not all silicone rubbers have that quality: the material failed the requirement of no flashover in a quarter-scale room fire test conducted at the National Bureau of Standards.[12]

Test Results

The variation of the fire behavior of plastics when compared to that of other building materials was further demonstrated in tests conducted at Underwriters Laboratories Inc.[13] Thirty-one materials were subjected to the Steiner tunnel test (NFPA 255; ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials;* and UL 723, *Standard for Safety Test for Surface Burning Characteristics of Building Materials*) to establish flame spread and smoke-developed classifications. These materials were also subjected to a 20 lb (9.1 kg) wood crib exposure fire in a full-size corner configuration. Testing established that the 20 lb (9.1 kg) wood crib presented fire severity conditions about equal to the 5000 Btu/min (88 kW) burner in the tunnel test, generating a heat flux of about 0.97 Btu/sec·ft^2 (1.1 W/cm^2). Four materials in the test series achieved an identical flame-spread classification of 18 (cement asbestos, 0; red oak, 100), but the smoke that developed and the extent of burning were markedly higher for the flame-retardant grade of plastic foam (Table 6.13.1).

These four building materials were also subjected to exposures in the heat-release rate calorimeter test developed by NIST (National Bureau of Standards).[14] As reported by UL[13] in the document on the 1973–74 test series, the first three specimens, code letters E, I, and T, yielded identical heat release rates of 0.26 Btu/sec·ft^2 (0.3 W/cm^2) at an exposure energy level of 2.6 Btu/sec·ft^2 (3 W/cm^2). However, a heat release rate 25 times higher [6.6 Btu/sec·ft^2 (7.5 W/cm^2)] was recorded for the flame-retardant plastic, code letter Z.

TABLE 6.13.1 Test Results (Cellular Plastics) for a 20 lb (9.1 kg) Wood Crib Fire Test

Code Letter	*Material*	*FSC*[a]	*SDC*[b]	*Affected Area*[c]
E	3½-in. (89-mm) thick glass fiber blanket insulation, 6% resin by weight, unfaced, 0.65 pcf (10.4 kg/m^3) density	18	3	24%
I	½-in. (12.7-mm) thick wood fiberboard acoustic ceiling panels, integrally flame retardant treated, decorative finished, 18.8 pcf (301.2 kg/m^3) density	18	4	37%
T	½-in. (12.7-mm) thick wood particleboard, integrally flame retardant treated	18	37	25%
Z	2-in. (51-mm) polyurethane spray cellular plastic on ¼-in. (6-mm) asbestos cement board; 2.2 pcf (35.2 kg/m^3) density, flame retardant	18	935	85%

[a]Flame spread classification, tunnel test result.
[b]Smoke developed classification, tunnel test result.
[c]Percentage of 192 ft^2 (17.8 m^2) total wall and ceiling area affected in full-scale corner test (7 percent affected in control fires).

Another cellular plastic, 2 in. (51 mm) extruded polystyrene cellular plastic boardstock (1.8 lb/ft^3 [0.03 g/cm^3] density, flame retardant), obtained a flame spread classification of 3 in the tunnel test, but its smoke developed classification was 785 (red oak, 100), and 146 ft^2 (13.6 m^2), or 76 percent, of the wall-ceiling area of the corner test structure was adversely affected by the burning.

The fire problem associated with plastics was studied by the Products Research Committee (PRC), formed to administer a trust fund established by a number of companies engaged in the manufacture and sale of cellular plastics and their ingredients. The PRC issued its final report[15] in 1980 after a five-year effort, which included sponsoring a number of research programs. Highlights of conclusions reached by the PRC included the following:

1. Building codes today appropriately require that foam plastic insulation not be installed exposed within buildings unless covered by a 15 minute thermal barrier or unless the

insulation has met the provisions of the NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth,* room corner test.

2. Properly designed interlayers between furniture fabric and padding are one means of reducing the fire risk of upholstered furniture.
3. The use of results of many different small-scale fire tests to obtain an estimate of behavior of a material in fire is appropriate; however, the present state of the art does not allow regulatory decisions to be made without considerable expert judgment and, preferably, data from full-scale fire tests in which the most probable fire scenarios are simulated.

FIRE TESTS FOR PLASTICS

Combustibility characteristics and suitability for use should be determined for any material or assembly on the basis of tests that simulate the end-use condition as realistically as possible. The tests should be designed to show how the product will perform when it is subjected to the type of fire exposure that can be anticipated under the conditions of use. The most desirable tests, from the standpoint of fire protection, engineering, and codes, are those that are suitable for all products for a particular application and that treat all products equally. Separate tests for plastics, or any other group of materials, that do not allow comparison of the fire behavior under like test conditions are undesirable.

As explained previously, small-scale tests, such as the oxygen index test (ASTM D2863) and the UL 94, are now used mostly for product development and production control. Such tests, where the ignition source is small and of low intensity, are unsuitable for evaluating the fire characteristics of materials under room fire or other full-scale fire conditions.

Greater fire intensity exposures are produced by standard fire tests, such as the Steiner tunnel test (ASTM E84/NFPA 255). The tests need to be selected in a manner that is suitable for the application in which the material or product is intended to be used. Examples of such tests include NFPA 286, ISO 9705, and the FM Global Research corner test, and other specialized tests designed specifically for the application. Guidance on selection of large-scale tests for realistic applications is found in ASTM E603 and ASTM E2067.

Other tests that may be required by the authority having jurisdiction (AHJ) are used to determine, separately, ignition temperature, surface flame spread index, and the rate of smoke production. Potential heat (caloric value) of the plastic material may have to be determined, but this parameter is of little significance in fire protection engineering; more important is the rate at which heat is liberated and contributes to the intensity of the fire. A multiplicity of tests to qualify plastics, or any other material, for end-use applications may not be required in the future. Test apparatus that measure heat release and smoke development rates at varying radiant heat flux exposures provide more realistic assessments of probable fire response under real-life situations than some of the older test methods. The first standardized test for this analysis is ASTM E906, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products,* for use with the Ohio State University (OSU) heat and smoke release-rate apparatus (Figure 6.13.7). Typical of the curves generated by the OSU heat and smoke release rate apparatus shown in Figure 6.13.7 are (a) heat release rates for several specimens at an exposure level of 2.6 Btu/sec·ft^2 and

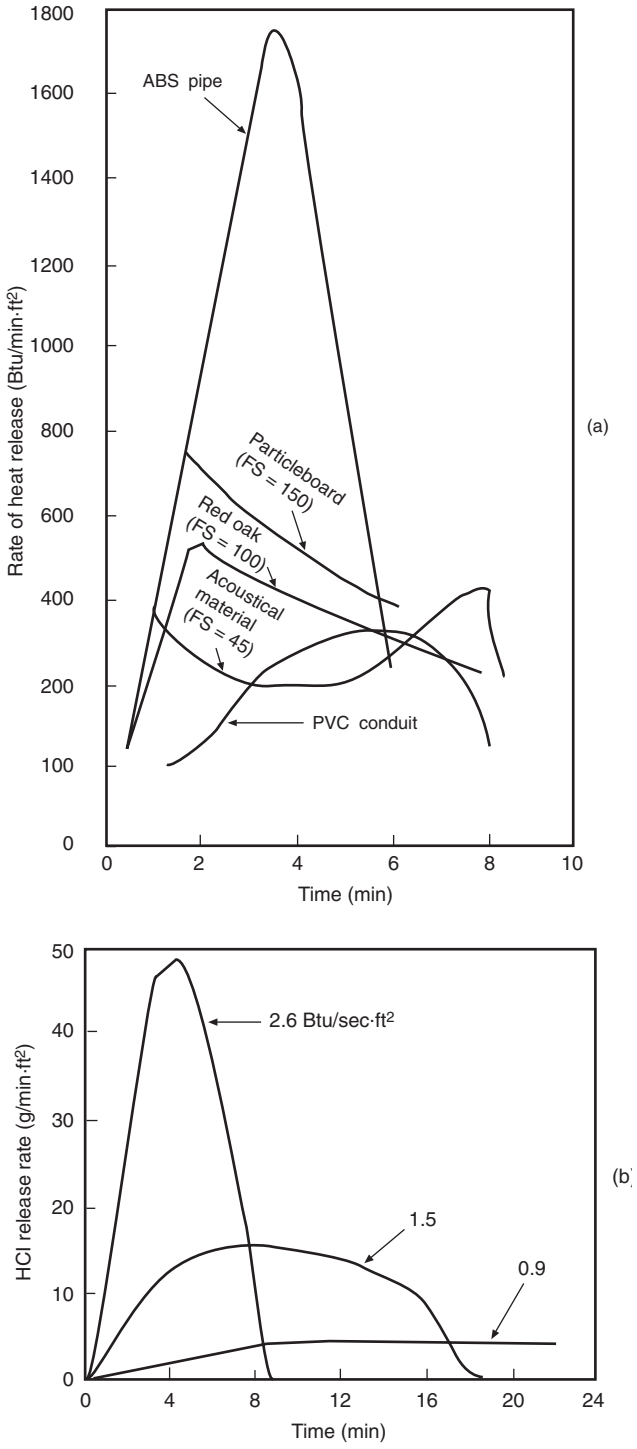


FIGURE 6.13.7 Curves Generated by the OSU Heat and Smoke Release Rate Apparatus (FS = flame spread rating, ASTM E84 [1 Btu/sec·ft^2 = 0.053 W/m^2])

(b) hydrogen chloride release rates from a sample of conduit at different exposure levels. Measurements include heat and smoke particles released by the test specimen per unit time and total during the test, toxic gases given off, ease of ignition, and flame spread rate. Procedures for similar analyses using an oxygen-consumption cone calorimeter developed at National Institute of Science and Technology (NIST) are standardized in ASTM E1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter,* and NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter.* FM Global Research also developed a small-scale calorimeter, which has since been standardized for use with materials in clean rooms (NFPA 287, *Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using a Fire Propagation Apparatus (FPA),* and ASTM E2058, *Standard Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus (FPA).*

In addition to the fire test methods for building construction materials and assemblies in general (i.e., not product related), a number of test methods have been developed to analyze flammability and other fire response characteristics of plastics, specifically. Almost all are small-scale tests intended primarily for research, product development, and manufacturing quality control. They are not intended for, and should not be used for, building or room fire hazard assessments, unless their scope is so noted. A number of such test methods have been issued by the American Society for Testing and Materials (ASTM); descriptions can be found in ASTM D3814, *Standard Guide for Locating Combustion Test Methods for Plastics.* Underwriters Laboratories Inc. (UL) has several standards for measuring ease of ignition and other characteristics of plastics that are used in products that have been tested and listed or classified by UL. One common test is UL 94, *Standard for Safety Tests for Flammability of Plastic Materials for Parts in Devices and Appliances* (Figure 6.13.8), which includes procedures for hot-wire and arc ignition and for rates of burning while the sample is positioned horizontally and vertically. Results of this test, like the ASTM plastics flammability tests, cannot be compared to the fire behavior of the materials under full-scale fire exposures.

A number of organizations have cooperated in producing test methods for evaluating the hazard of plastics and textiles in specific applications. Working with the U.S. Consumer Product Safety Commission, the Upholstered Furniture Action Council, NIST, and others, NFPA has prepared test methods NFPA 260, *Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture,* and NFPA 261, *Standard Method of Test for Determining Resistance of Mock-Up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes,* for determining the resistance to cigarette ignitions in upholstered furniture. Similarly, ASTM E1590, *Standard Test Method for Fire Testing of Mattresses,* covers the fire response of mattresses and bedding exposed to flaming ignition. NFPA 262, *Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces,* used for determining fire and smoke characteristics of plastic and other insulations on wires and cables, was derived from one of the UL tests. NFPA 272, *Standard Method of Test for Heat and Visible Smoke Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter,* addresses fire characteristics of upholstered furniture, mattresses, and bedding when material samples are tested in the cone calorimeter.

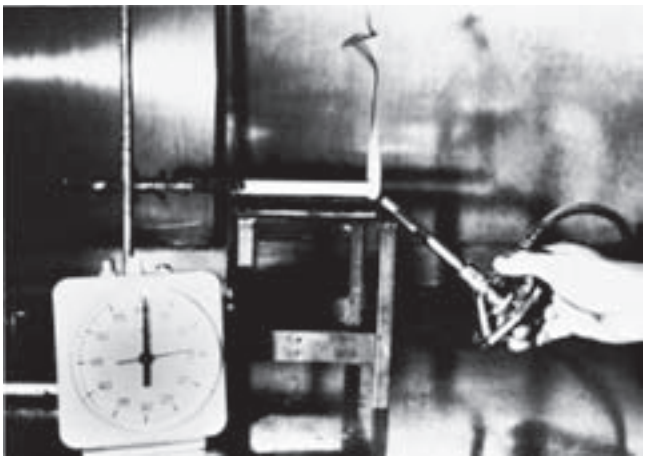


FIGURE 6.13.8 Specimen Being Tested Under the Horizontal Burning Test of UL 94 for Flammability of Plastics (Source: Underwriters Laboratories Inc.)

Some U.S. government agencies have promulgated regulations to control the flammability of plastics and textiles in certain applications. Under MVSS-302, the DOT regulates interior materials for automobiles, using a test for burning rate in the horizontal mode. The U.S. Coast Guard, under 46 CFR, Subchapter T, regulates materials used as resins for hulls in boats-for-hire carrying more than six passengers. The U.S. Coast Guard also uses a modified version of ASTM E136, *Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C,* to establish the "noncombustibility" of materials used in the interior of passenger-carrying ships. More detailed information on applications for marine vessels can be found in Section 21, Chapter 10, "Marine Vessels." Guidelines for the flammability of carpets, rugs, children's sleepwear, mattresses, and mattress pads are issued by the U.S. Consumer Product Safety Commission. CPSC has been involved since the 1990s in the development of potential test methods for upholstered furniture and mattresses. The U.S. Nuclear Regulatory Commission has issued guidelines for the ignitability and flammability of plastics used in the insulation of electrical cables requiring qualification under test procedures in IEEE 383, *Standard for Type Test of Class IE Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations.*

INSTALLATION SAFEGUARDS

In the current state of the art, large areas of cellular plastics left exposed in interior building construction or decoration must be considered to be extremely hazardous. Exposed foam on ceilings or walls, in air-handling plenums, in shafts, in other

flue-like vertical spaces inside walls, or above hung ceilings should be avoided. A low flame-spread classification (e.g., 25 or less) does not ensure that a product has limited combustibility under such conditions, nor can it be assumed that automatic sprinklers will control the hazard. Coating such surfaces with a fire-retardant paint, intumescent or otherwise, is not likely to produce satisfactory results.

Model building codes require that foamed plastic used as interior wall insulation be covered with a thermal barrier, such as ½ in. (12.5 mm) thick ordinary gypsum board, or another method that reduces the risk of ignition and the subsequent flash-fire propensity. The use of foamed plastics in the cavities of hollow masonry walls, such as perimeter insulation around the foundation of a building, insulation below concrete slabs on the ground, and for roof insulation under certain conditions, is generally accepted without thermal barrier protection. All such plastics in the thickness and density used must have a smoke-developed rating no greater than 450 and a flame-spread rating no greater than 75, under ASTM E84 (NFPA 255) tunnel test conditions.

In other than noncombustible or fire-resistant building types, foamed-plastic insulated steel or aluminum exterior building panels are permitted by the model building codes, provided the foam core has a flame-spread classification of 25 or less and the space is protected by automatic sprinklers.

When used as interior wall and ceiling finish, plastic materials other than foamed plastic generally are not subject to any special requirements. As for any other materials, plastics are subject to limitations on surface flame spread and often on the smoke generated, as measured by standard test procedures, such as the Steiner tunnel test or radiant panel test. These or other special limitations may be applied to plastics used as diffusers in lighting fixtures, where it is often acceptable to have a plastic that deforms and drops out of the fixture at an elevated temperature still well below its ignition point. Special limitations may also be set forth by building codes for the use of plastic glazing instead of glass in exterior walls of buildings, where the normal requirement for conformance to the limitations for interior finish may be waived.

Plastic laminates for countertops, kitchen cabinets, tabletops, and so on, are not usually included in the definition of interior finish, as regulated by building codes. Even when it is not regulated by local code, the flammability level should be limited to that encountered when natural products are used in these applications. Plastic laminates are commonly available with low surface flame-spread classifications, in the range of 25 to 75.

Further guidelines for the installation of plastics in various applications can be found in publications of the Society of the Plastics Industry[16] and FM Global Research.[17]

The packaging, storage, and shipping precautions that are customarily observed for ordinary combustible materials apply generally to most plastics. No special shipping requirements for plastics (other than cellulose nitrate) have been adopted by the DOT.

FIRE- AND FLAME-RETARDANT TREATMENTS

All organic and some inorganic materials burn under proper conditions. Fire and flame retardants can make a given material more difficult to ignite, and when ignited, cause it to burn more slowly. Retardants can be very effective in preventing ignition from low-level, short-duration flame and heat exposures. Even under moderate exposures, the burning characteristics can be greatly improved by fire retardants, depending on the product and the additive used. For severe exposures, such as from a fully developed room fire, treated and untreated plastics typically show similar fire behavior.

Fire- and flame-retardant chemicals are added to plastics during the manufacturing process. Because of the widely varying properties of plastics, no single, universal additive is available, nor is there only one effective mechanism for imparting flame resistance. Fire- and flame-retardant additives may be blended into the polymer mix during processing, or they may be reactants that change the molecular structure of the polymer. The additives can be chemically reacted throughout the polymer substrate or on the surface of finished or semifinished products. Surface treatments added after the manufacturing process, such as fire-retardant paints or coatings, are unreliable without test data to prove the effectiveness of the combination.

Additives blended into the mix may be organic or inorganic materials. Organic additives typically are chlorinated and brominated hydrocarbons or halogenated and nonhalogenated organophosphorous compounds. Among the inorganic flame retardants are the salts of antimony, zinc, molybdenum, and aluminum. Those classed as reactants include brominated aromatics, brominated aliphatic polyols, and phosphorous-containing polyols.

Phosphorous additives appear to improve flame resistance by (1) promoting formation of char to reduce concentration of carbon-containing gases; (2) forming a glassy, insulating layer; and (3) either entering into chemical reactions that remove heat from the combustion system, or chemically inhibiting the combustion process, or both. Compounds containing halogens, such as chlorine and bromine, tend to inhibit burning in the gas phase by interrupting chain reactions needed for continuous burning. Other flame retardants involve heat absorption reactions, for example, by providing a heat sink through evaporation of water of hydration.[18]

A complicating aspect of treating plastics and other materials is that a fire-retardant chemical that works on one substrate system will not necessarily work on other substrates. Thus, fire-retardant chemicals for polystyrene will not necessarily work on polyethylene, nylon, wood, or cotton. Fire-retardant chemicals often impair some other material properties. For example, fire-retardant treatments for cotton fabrics generally reduce fabric strength and wear life. Fire retardants in plastics may reduce allowable processing temperatures and impair physical properties. Costs are generally increased.

Smoldering, rather than free-burning, combustion is likely to increase the amount of total smoke produced, while reducing the rate of smoke production per unit time, and there tends to be more smoke when fire retardants are added to polymers, but this is not true in all cases. Comparisons were made among five different types of products in fire-retardant and non-fire-retardant versions in a series of tests sponsored by the Fire Retardant Chemicals Association at the National Institute of Science and Technology.[19] Included were polystyrene TV cabinets, polyphenylene oxide business machine housings, polyurethane

foam-padded chairs, electrical cable with polyethylene insulation and rubber jacketing, and polyester/glass electric circuit boards. Heat release, spread of flames, and the propensity for flashover were reduced when the fire-retardant products were tested. Smoke yields generally were similar, but fire-retardant TV cabinets produced twice the amount of total smoke than the non-fire-retardant versions. Potential escape times for occupants were reported to be 15 times greater when the fire-retardant products were used in the tests.

FIGHTING FIRES IN PLASTICS

Plastics other than cellulose nitrate are classified as ordinary combustibles. Consequently, extinguishing methods suitable for fires involving wood and other ordinary combustibles (Class A fires) should be used to extinguish a burning plastic. Some plastics, for example, flexible polyurethane, may form a pool of burning liquid during a fire, similar to a high-flashpoint combustible liquid (Class B) fire. Water from automatic sprinklers or spray nozzles on hoselines can be used for fire control, although the extent of a pool fire is likely to be overshadowed by the more generalized fire in the area.

Storage with a preponderance of plastics products or materials can develop into fires with extremely high temperatures that tremendously magnify the normal problem of radiant heat, structural damage, and exposure.[19] Rapid fire spread, high burning rates, and thick, dense smoke in heavy clouds can be anticipated. FM Global Research recommends a two-fold attack: (1) properly designed sprinkler protection, and (2) appropriate manual fire-fighting techniques. Large-orifice (17⁄32 in.) sprinklers have been found to be substantially better in controlling fires in plastics, and large-drop and early suppression fast response (ESFR) sprinklers were developed at FM Global Research specifically to address the high-challenge plastics fire.

The physical form of plastics will greatly influence their fire behavior. Molding pellets, which are shipped in bags, drums, or large cartons, provide little surface for access to air. These same plastics in such shapes as flashlight cases will have much more access to air and may burn vigorously until heat causes the shapes to melt, thereby reducing the surface area exposed to air. Melting may be a hazard if it causes burning drips to carry flame to a lower floor or spreads fuel for later ignition.

Although fire may develop more slowly in the more dense, unexpanded form than in foamed products, once established, the burning rate is comparable. For fires that have become well established in a large quantity of plastics products in a sprinklered warehouse, "buttoning up" the building to limit combustion air and letting the sprinklers do the work of fire control, for hours if necessary, before moving in for final mop-up by conventional means, is an approach recommended by FM Global Research.[19] Shutting off sprinklers to allow the smoke to rise and vent the building is dangerous because the high combustibility of the storage can cause the blaze to rapidly flash out of control.

Toxicity

Possibly because of the long chemical names of some plastics, combustion and thermal decomposition products of plastics have been a cause for concern among fire fighters. For plastics now in commercial use, the hazard of carbon monoxide from partial combustion greatly outweighs the toxic effects of other fire gases, both as to nature and amount.

On burning, some plastics, for example, polyvinyl chloride or ethylene sulfide rubbery caulking materials, generate hydrogen chloride or sulfur dioxide. Because these are strongly irritating, they ordinarily force evacuation long before their toxic effects become dangerous. These gases also are corrosive to metals and electrical equipment; therefore, such equipment should be ventilated, rinsed, or treated with dilute ammonia, and rinsed as soon as possible after exposure.

The need for a standard method for the development of data that could be used in toxic hazard modeling prompted the NFPA Technical Committee on Fire Tests to develop NFPA 269, *Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling.*

SUMMARY

Plastics and rubber belong to the varied and complex family of polymers, and all types are combustible to varying degrees. Special fire behavior problems associated with plastics include the emission of dense, sooty smoke and toxic gases. In building construction, plastics can be found in many applications, including thermal and acoustical insulation, roofing materials, decorative trims and imitation wood parts, ceiling and wall panels, resilient flooring, light fixture diffusers, electrical conduits, insulation on wiring, water and gas piping, bathtubs and sinks, and heating ducts. Combustibility characteristics and suitability for use should be determined for any material or assembly on the basis of tests that simulate the end-use condition as realistically as possible. Modifications can be made in the manufacture and application of plastics that can reduce hazards to acceptable levels, for example, by treating with fire- or flame-retardant additives. Large-orifice sprinklers and large-drop and early suppression fast response (ESFR) sprinklers have been found to be effective means of suppressing plastics fire.

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19. "Stored Plastics—The High-Challenge Risk," Pamphlet P7742, FM Global Research, Norwood, MA, 1987.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on polymeric materials discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 40, *Standard for the Storage and Handling of Cellulose Nitrate Film*
NFPA 42, *Code for the Storage of Pyroxylin Plastic*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 260, *Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture*
NFPA 261, *Standard Method of Test for Determining Resistance of Mock-Up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes*
NFPA 262, *Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces*
NFPA 269, *Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling*
NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*
NFPA 272, *Standard Method of Test for Heat and Visible Smoke Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*

References

American Society for Testing and Materials, W. Conshohocken, PA

ASTM D3814, *Standard Guide for Locating Combustion Test Methods for Plastics*
ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials*
ASTM E136, *Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C*
ASTM E800, *Standard Guide for Measurement of Gases Present or Generated During Fires*
ASTM E906, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products*
ASTM E1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*
ASTM E1590, *Standard Test Method for Fire Testing of Mattresses*

Institute of Electrical and Electronics Engineers, Inc., New York

IEEE 383, *Standard for Type Test of Class IE Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations* (Revised 1992)

The Society of the Plastics Industry, Inc., Washington, DC

Expanded Polystyrene Division

"Fire Safety Guidelines for Use of Expanded Polystyrene in Building Construction," EPS 301, Cat. No. AH-101
"Flammability of Expanded Polystyrene Insulation Used in Conjunction with Gypsum Wallboard"
"Flammability of Expanded Polystyrene Insulation when Used as Full-Scale Building Enclosure Ceiling Construction Material"
"Flammability of Expanded Polystyrene Insulation Used in Conjunction with Plywood Paneling"
"Flammability of Exposed Polystyrene Insulation (with and without Wooden Dividers)"
"Foamed Plastic, Full-Scale Corner Test, 7½-in. Thickness, EPS"
"Literature Review of the Combustion Toxicity of Expanded Polystyrene"

Polyurethane Division

U-100R2, "Fire Safety Guidelines for Use of Rigid Polyurethane Foam Insulation in Building Construction"
U-102R, "An Update Report on Findings of Fire Study of Rigid Cellular Plastic Materials for Wall and Roof Ceiling Insulation"
U-103, "Large-Scale Corner Wall Fire Tests of Spray-On Coatings over Rigid Polyurethane Foam Insulation"
U-105, "Evaluation of the Fire Performance of Carpet Underlayments"
U-106, "Fire Safety Guidelines on Flexible Polyurethane Foams Used in Upholstered Furniture and Bedding"
U-107, "Room-Scale Compartment Corner Tests of Spray-On Coatings over Rigid Polyurethane Foam Insulation"
U-110, "Flexible Polyurethane Foams and Combustibility"
U-111, "Using Flexible Polyurethane Foams Safely"
U-118, "Guide for Safe Handling and Use of Polyurethane and Polyisocyanurate Foam Systems"

Underwriters Laboratories Inc., Northbrook, IL

UL 94, *Standard for Safety Tests for Flammability of Plastic Materials for Parts in Devices and Appliances,* 1991
UL 723, *Standard for Safety Test for Surface Burning Characteristics of Building Materials,* 1993

Chapter 14

Pesticides in the Workplace

Revised by
Fred Whitford

Chapter Contents

Regulations and Guidelines
Hazard Identification and Labeling
Facility Planning for Risk Reduction
Emergency Plans
Security

Key Terms

emergency action plan, flammable liquid, hazardous material, pesticide, security, toxicity

FIFRA, the Federal Insecticide, Fungicide, and Rodenticide Act, defines a pesticide as a chemical or mixture of chemicals or substances used to repel or combat an animal or plant pest including insects, spiders, and other invertebrate organisms; vertebrate pests, such as rodents and birds; weeds; plant diseases; and microorganisms. Household germicides and plant growth regulators are also examples of chemicals that fall under FIFRA's definition of a pesticide. *Pesticides* is a general term that encompasses products that control pests and are subdivided into groups, depending on the pests being controlled. For instance, insecticides control insects, fungicides control plant diseases, bactericides control bacteria, herbicides control unwanted weeds, and rodenticides control mice and rats.

Pesticide products are diverse in chemical composition, formulation, and hazard. There are literally thousands of different pesticide products that reflect the enormous diversity of insect, weed, disease, rodent, bird, and other pests that they are intended to control. There are also many federal and state agencies that regulate their transportation, storage, use, and disposal. In some cases, local jurisdictions have established their own sets of standards for storage, handling, and use. Pesticide products are widely distributed through retail and wholesale outlets. Some communities are host to manufacturing operations and warehouses where large amounts of these products are stored awaiting shipment to regional distributors and retailers. A variety of state and county agencies store pesticides, including state and county parks, highway departments, and mosquito control units. Finally, there is a large number of service-oriented businesses (e.g., lawn care, pest control, right-of-way maintenance) and farms that store pesticides on-site.

In addition to being stored at manufacturing facilities, large volumes of pesticides are stored at farm supply stores, company-owned distribution warehouses, commercial (public) warehouses, and agricultural chemical warehouses. Fire protection education and safeguards have traditionally focused on pesticides stored in warehouses such as those just described, but it is important to be aware of hazards presented by the presence of pesticides in other locations. On the retail front, lesser amounts of pesticide products can be expected to be found at nurseries, supermarkets, discount stores, hardware stores, and other retail outlets. In transportation, expect them to be shipped in solid, liquid, and in a few cases, gaseous form. Emergency responders should always be prepared to deal with pesticides when responding to problems involving fires at these facilities or when reacting to a transportation accident.

This chapter provides an overview of the requirements and practices that reflect state-of-the-art philosophies in location, construction, and administration of facilities that handle pesticide products, from manufacturing facilities, to local businesses and farms. However, local, state, and federal laws need to be reviewed to determine specific measures that will have to be implemented.

For additional information relevant to the hazards of the storage and use of pesticides, see Section 3, Chapter 7, "Fire Hazard Analysis Techniques"; Section 3, Chapter 8, "Fire Risk Analysis"; Section 6, Chapter 1, "Fire Hazards of Materials"; Section 6, Chapter 12, "Flammable and Combustible Liquids"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 7, Chapter 3, "Storage of Gases"; Section 7, Chapter 4, "Storage and Handling of Chemicals";

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Section 7, Chapter 5, "Hazardous Waste Control"; Section 11, Chapter 4, "Fire Hazards of Construction, Alteration, and Demolition of Buildings"; Section 12, Chapter 8, "Effect of Building Construction and Fire Protection Systems on Fire Fighter Safety"; and Section 20, Chapter 16, "Storage Occupancies."

REGULATIONS AND GUIDELINES

Reducing Exposure of Personnel

Pesticide products are governed by numerous "standard of care" regulations and guidelines that address proper transportation, storage, handling, use, and disposal. These regulations and guidelines also address the need to reduce exposure to workers, emergency responders, the general public, and pesticide applicators, as well as the need to prevent release to the environment that might cause water contamination or wildlife injury. For example, state and federal governments have enacted laws that address concerns over the transportation and storage of pesticides through (1) formal, comprehensive planning for product management, as outlined by Occupational Safety and Health Administration (OSHA) regulations; (2) employee training documentation of competency; (3) planning for pesticide emergencies and sharing those plans with local and state authorities; (4) reporting inventories to local and state officials; and (5) management of transportation through safe driver training, proper inspection of trucks and trailers, and proper placarding. Figures 6.14.1 and 6.14.2 show emergency plans being put into action. Figure 6.14.1 shows local responders and medical personnel practicing procedures at a mock pesticide spill and mock injury on a farm. In Figure 6.14.2, a medical helicopter staff are attending a field day to explain their procedures for handling accident victims.

Preventing Release

Most modern regulations focus on what can be done to prevent the release of pesticides at the facilities that handle such products or from the vehicles that transport them. Secondarily, the regulations enforce training to deal with pesticide releases into the environment in the event of an accident. Much of this change by government at all levels has been supported by both the pesticide-use industry and the farming community. Everyone seems more aware today of the dangers and costs associated with the escape of a pesticide into the environment. Any release of pesticide product due to fire, natural disaster, or deliberate act can have consequent costs associated with the cleanup and remediation of the site where the release occurs and could conceivably include dealing with contamination of groundwater or surface water that renders a public drinking water supply unfit for use. Ground spills can lead to substantial costs associated with removing contaminated soil to an approved landfill that can accept such waste. Personal injuries can result that often lead to a decade or more of legal action. Even the cost of replacing the protective gear of emergency responders or the decontamination of ambulances and hospital rooms can reach thousands of dollars. All of these factors have added to a change in philosophy in which strategies and regulations that focus on prevention and communication have surpassed reaction measures.

Compliance with Regulations

Business owners must invest time and effort in training employees to deliver products and services in a safe, effective, professional manner. Managing a business now means more than just managing the bottom line and attracting new customers. Today's businesses must also comply with numerous regulations that deal with all aspects of licensing and hiring, pesticide storage, transportation, and use. Employee training is a part of nearly every federal and state pesticide regulation. Table 6.14.1 is a checklist that provides a starting point in maintaining compliance with federal and state regulations as it relates to the safe handling of pesticide products.

General Guidelines

Concise guidance is provided to facility managers and risk planners by the following documents:

FIGURE 6.14.1 Practicing Procedures Through a Mock Spill and Mock Injury

FIGURE 6.14.2 Explanation of Medical Helicopter Staff Procedures

TABLE 6.14.1 Matrix for Facility Planning

Management Sector	*General Categories*	*Specifics*
Licenses	General business permits Restricted-Use Pesticide Dealer Department of Agriculture pesticide certification Transportation regulations	PPP-65, *DOT Rules for the Road* PPP-68, *Carrying Farm Products and Supplies on the Road*
Insurance	Coverage amounts, limitations Pollution insurance	PPP-49, *The Insurance Policy*
Employment selection and retention	Minimum age Verification of I-9 employment eligibility Drug and alcohol testing	PPP-69, *The Hiring Process*
Communication to employees and to the community	Community Right-to-Know State pesticide notification requirements Material safety data sheets OSHA workplace logs (to employees only) Workplace safety plans	PPP-37, *Pesticides and Material Safety Data Sheets* PPP-32, *Pesticides and Community Right-to-Know* PPP-45, *The Quick Response Emergency Plan* PPP-55, *Company Bulletin Boards*
Worker protection	Personal protection equipment	Needs assessment Respirators Forklift training PPP-38, *Pesticides and Personal Protective Equipment*
	OSHA rules	Lock out/tag out Confined space entry OSHA injury/illness log
	First aid training	First aid kits Blood-borne pathogens
Fire protection and prevention	Fire protection plan	Clear means of egress Exit signs Emergency call list Evacuation plan and drills First aid training Safe handling of fuels PPP-41, *Pesticides and Planning for Emergencies* PPP-73, *Aboveground Pesticide Tanks*
	Fire-fighting equipment	Fire extinguishers: location and maintenance Sprinkler systems installation and maintenance
Dealing with spills	Spill response plan Notification of spill incidents Internal coordination and media communication	Spill kits Spill response materials Federal and state spill reporting Handling hazardous waste Disposal of hazardous waste PPP-60, *Communicating with the News Media* PPP-58, *Pesticides and Fleet Vehicles* PPP-52, *Pesticides and Risk Communication*

1. *The Crop Protection Handbook.* This document has an excellent comprehensive and detailed checklist for agricultural chemicals stored in warehouses. (See http://www.greenbook.net.)

2. *SARA Title III, List of Lists.*[1] This document presents a consolidated list of chemicals regulated by the Environmental Protection Agency (EPA) under the Comprehensive Environmental Response, Compensation, and Liability Act (otherwise known as "Superfund"), the Superfund Amendments and Reauthorization Act (SARA Title III), the Emergency Planning and Community Right-to-Know Act (EPCRA), and the Clean Water Act. It provides a chemical list of materials that are required to be reported when the facility's storage exceeds the published threshold quantities. In addition, this document provides the

threshold for chemicals that need to be federally reported during a spill.

3. *Survey Form for Public Warehousing of Crop Protection Products.* Mid America CropLife Association identifies eight key elements of facility location, structures, and management. It provides a series of questions that helps the manager to evaluate the relative risk of chemical accidents at a specific facility.[2]

National Fire Protection Guidelines

The introduction to this chapter lists chapters in this handbook that contain additional information on the hazards of storage and use of pesticides.

Purdue University Cooperative Extension Service Pesticide Programs Publications

The Purdue Pesticide Program publishes an extensive series of publications on storage and transportation of pesticide products and their regulation. Within this chapter, publications identified as PPP are those from Purdue Pesticide Programs. Information about each publication can be found at the following website: http://www.btny.purdue.edu/ppp. Extension pesticide specialists can be reached at each state's land grant university (see http://www.aapse.org) in order to determine the availability of state-specific printed and web-based safety and regulatory publications.

HAZARD IDENTIFICATION AND LABELING

Data Sheets

The hazards of any particular pesticide product can originate from the active ingredients, that is, the components that provide the pesticidal activity, or the inert ingredients used as the carrier, or both. (See the following Purdue Pesticide Program publication: PPP-31, *Pesticides and Formulation Technology.*) It can also be a flammable or combustible liquid solvent or a flammable gas. Obviously, the best method of determining the hazards of the active and inert materials is to access the product's material safety data sheet (MSDS). (See PPP-37, *Pesticide and Material Safety Data Sheets.*)

MSDSs should be available for reference in all emergencies. They provide quick access to information on the product, how to deal with the emergency, and access through the emergency phone number to other professionals who can help supply valuable information. Additional and current sets of the MSDS should be available in an easily reached off-site location. The MSDS should be made available to the fire department, local hospitals, and other associated parties. Figure 6.14.3 shows an emergency response information mailbox containing site maps, product inventories, contact numbers, and MSDSs.

The pesticide facility should also maintain an up-to-date site plan that shows the general classification and approximate quantities of products within the various storage areas. This site plan should also be available during an emergency and preferably given to the local emergency response services. Approved "lock boxes" and outside plastic tubes that can be mounted on a building exterior are available in sizes that accommodate MSDS binders, contract numbers, and site plans. These boxes limit access to all but authorized personnel and can protect against tampering when connected to security systems.

FIGURE 6.14.3 Emergency Response Information Mailbox

The intrinsic toxicity of the active ingredient in pesticides varies considerably. When considering together the hazards presented by the components of the pesticide formulation, including its active ingredients, carriers, and adjuvants, pesticides can be corrosive, reactive, flammable or combustible, or relatively benign. In a fire situation, however, products of combustion may present a significant health hazard to responding fire departments or to occupants of neighboring properties. MSDSs and all of the hazards used to identify single products are of little use when multiple products are engulfed in a fire. Incident commanders and fire fighters need to take extreme care when responding to a facility, farm, or transport vehicle where pesticides are involved in the accident.

Flammable and Combustible Liquids and Solids

Liquids. The majority of pesticide products stored in large volumes are in liquid form. Some of these formulations are considered flammable or combustible liquids by the U.S. Department of Transportation (DOT), and the outer packaging holding individual containers or the intermediate bulk container will have the appropriate transportation label. The pesticide products pictured in Figure 6.14.4, for example, are categorized as flammable liquids and are appropriately marked with DOT labels. The hazards of flammable or combustible liquids when released from containers can range from a manageable spill fire to near-explosive ignition of ignitable vapors in a confined area. Like all other products used in commerce, each pesticide must be reviewed individually to access what its flammable, combustible, and health risks are to the emergency responder, community, and employees.

FIGURE 6.14.4 DOT Marking on Cardboard Box Containing Pesticides

Solids. Solids are usually stored and handled as granules, dusts, and powders. The DOT marking on the package shown in Figure 6.14.5 indicates that it contains a solid pesticide product with its specific Class 6 hazard. If combustible, solids can present a dust explosion hazard when dispersed into the air. Most pesticide solids, however, are specific formulations absorbed into an inert material, such as clay. Hazards of "inerts" used in pesticide formulations need to be evaluated on a case-by-case basis during a release incident. Once again, inerts are not specifically identified on the product label or on its MSDS. However, some MSDSs will list the hazards of the inerts, which can provide valuable guidelines in dealing with a spill or other accident. A list of pesticides that should be kept away from ignition sources is provided in the Crop Protection Handbook at http://www.greenbook.net.

FIGURE 6.14.5 DOT Marking When Required Identifies the Hazards of a Pesticide Product

Labeling

The labels on packaged pesticides can provide emergency responders with quick, useful information. Labeling of pesticides reflects the fact that they are grouped according to their level of toxicity for humans. On the front panel of each product label are signal words that infer the level of acute toxicity of the material in the container or bag. These signal words are "Danger," Warning," and "Caution" in descending order of toxicity. (Figure 6.14.6 shows a signal word contained on a product label.) Normally, products labeled with the "Danger" identifier have more and stricter requirements for personal protective equipment.

Pesticides are grouped by the hazard they pose to the applicator and/or to the environment. Products that carry additional risks to human health, water, and wildlife are categorized as restricted-use pesticides. They are easily identifiable from the product label. Above the brand name of the product, a restricted-use pesticide will have a rectangle at the top of the container or bag that contains the restricted-use statement.

Pesticide labels are regulated by the EPA and provide specific directions and precautions directed to the end user (see PPP-24, *Pesticides and the Label,* and PPP-36, *Pesticides and the Law.)* Hazard information dealing with short-term effects provided on pesticide labels (e.g., signal word) is based on the combination of active ingredient and the inerts. The label in many aspects provides little information to the emergency responder for the community or the company. The label also does not typically address fire or reactivity hazards of the complete formulation as a whole, nor does it provide the details needed to respond to an emergency beyond very general statements for small spills. Information on the synergistic effects due to fire

FIGURE 6.14.6 Signal Word Warning Clearly Marked at the Lower-Left Edge of the Container

or due to releases involving a mixture of pesticide materials is not available from any source. This lack of information should cause emergency responders to consider in great detail their initial approach to a fire, the equipment worn, and the potential for evacuating the surrounding population. In many respects, the MSDS is the key source of information on how to deal with any emergency involving pesticides. Concentrations of active ingredients will vary widely in the various formulations. Table 6.14.2 lists the current EPA-required warning systems for labeling pesticide containers.

FACILITY PLANNING FOR RISK REDUCTION

Handling and Storing Pesticides

It is important to realize that most state and federal laws do not dictate how pesticides must be stored. There are laws that regulate how large volumes should be diked and bermed, but these laws basically focus on warehouses and large agricultural facilities. Most industries such as lawn care, golf course, pest control, and right-of-way that use pesticides as part of their service do, however, follow industry-specific best management practices when it comes to how products are stored on-site. Therefore, emergency responders should do on-site visits to determine the volume of material stored, when those quantities are at their highest inventories, and the manner in which they are stored.

In addition to routine housekeeping, special attention should be paid to accumulations of combustible materials in areas where pesticide products are stored and to the handling, storage, and prompt management of spills, leaks, and damaged and returned goods. NFPA 434, *Code for the Storage of Pesticides,* NFPA 30, *Flammable and Combustible Liquids Code,* and NFPA 13, *Standard for the Installation of Sprinkler Systems,* provide information relative to aisle space in the storage area. Other relevant NFPA standards should also be consulted as to pile size and storage height limitations for chemicals of other hazard classes. Storage area personnel and retail stock personnel should know the class and hazards of each product stored and displayed. Pesticide products should never be stacked to heights that exceed the structural strength of the packaging or the shelving units.

Flammable and restricted-use pesticides should be stored and displayed separately from other products. A system that recognizes not only the chemical hazard classes of the materials involved but also the potential loss to the facility should a fire or release occur must be used. Stored substances must be segregated according to accepted codes, standards, and industry best management practices. DOT tables for coshipment of incompatible materials in highway cargo vans can be used as an initial guide.

TABLE 6.14.2 EPA Toxicity Categories

Category 1: POISON/DANGER

All pesticide products meeting the following criteria:
- Oral LD_{50} up to and including 50 mg/kg
- Inhalation LD_{50} up to and including 0.2 mg/liter
- Dermal LD_{50} up to and including 200 mg/kg
- Eye effects—corneal opacity not reversible within 7 days, and skin effects corrosive.

Must bear on the front panel the signal word "Danger." In addition, if the product was assigned to Category 1 on the basis of its oral, inhalation, or dermal toxicity (as distinct from skin and eye local effects), the word "Poison" must appear in red on a background of distinctly contrasting color, and the skull and crossbones must appear in immediate proximity to the word "Poison."

Category 2: WARNING

All pesticide products meeting the following criteria:
- Oral LD_{50} from 50 through 500 mg/kg
- Inhalation LD_{50} from 0.2 through 2.0 mg/liter
- Dermal LD_{50} from 200 through 2000 mg/kg
- Eye effects—corneal opacity reversible within 7 days (irritation persisting for 7 days)
- Skin effects—severe irritation at 72 hr

Must bear on the front panel the signal word "Warning."

Categories 3 and 4: CAUTION

All pesticide products meeting the following criteria:
- Oral LD_{50} greater than 500 mg/kg
- Inhalation LD_{50} greater than 2.0 mg/liter
- Dermal LD_{50} greater than 2000 mg/kg
- Eye effects—no corneal opacity
- Skin effects—moderate irritation at 72 hr

Must bear on the front panel the signal word "Caution."

Facility Planning and Construction

Farms and businesses that do not warehouse pesticides should conduct their own environmental site assessments to determine how safe pesticides are being stored, used, and transported. (See PPP-42, *Pesticides and Environmental Site Assessments*.) The following criteria represent ideal storage facility conditions for pesticide products with significant hazards.

Location and Site Factors for New Construction

If siting a new building, this might be the most important decision that a business or farm can undertake. Often a well-positioned building can eliminate much of the risk to the surrounding environment. There are many factors that can affect the location of a business or warehouse that will store pesticides. Obviously, such a facility should be located in an area where exposure and risk are minimal should a fire or other disaster such as a tornado or flood occur. The first concern is what types of commercial, residential, and public buildings are located near the site under consideration. It is preferred that new construction be placed on the property as far away as possible from schools, hospitals, retirement homes, places of assembly, day care centers, or other buildings where large numbers of people congregate or are housed. In many cases, county zoning is quite helpful in that the building of a pesticide warehouse or service business

storing pesticides will be limited to certain areas. In older areas, buildings storing pesticides do pose a problem for emergency responders. In an emergency at these facilities, the occupants of such public and private buildings may have to be evacuated, thereby increasing the complexity of dealing with a pesticide emergency.

State and federal laws may require specific separation or set-back distances that will have to be followed. Guidance can be provided by the architect who will design the building and by local building and fire prevention officials. In some cases, actual separation distances can be determined by a realistic process hazards analysis developed on a site-specific basis.

Preferably, facilities storing large quantities of pesticides will be located in an area where the probability of a natural disaster, such as flood, earthquake, tornado, or hurricane, is low. When this is not the case, the design of the building and its contents needs to address the specific risk issues faced. The proposed site should be easily accessible to emergency responders. It is important to discuss this situation with local emergency responders to gather their recommendations about what can be done to address any concerns about the facility.

Easy access to and easy movement within the facility by the responding fire department is essential in the event of a fire or chemical release. The site plan should be devised to ensure that all areas of the facility can be easily reached.

Consideration should be given to providing multiple entry points to facilitate a safe, upwind approach to the facility for emergency response in the case of hazardous materials release. Separate storage areas for products with widely different hazards or characteristics may need to be considered. For example, products that are not chemically compatible with each other should be stored in separate rooms or buildings. Consideration may need to be given to separating flammable materials without a significant toxicity hazard from those materials that are flammable and have a significant health hazard, such as those that produce toxic products of combustion, are skin-contact poisons, or represent significant environmental hazards. Nonflammable materials that have a health hazard rating of "3" or "4" according to NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response,* should also be isolated from other materials. Generally speaking, however, small businesses do not segregate their products in inventory due to space limitations.

Facility Construction

The pesticide storage building will have to comply with local and state building codes. Very few jurisdictions beyond the building codes dictate how buildings that store pesticides are to be designed and constructed. The following are suggestions that might improve the safe storage of pesticides at facilities and farms that are smaller than warehouses:

- Single-story facilities without basements are preferred.
- Noncombustible construction is preferred when the choice of building materials presents itself. NFPA 220, *Standard on Types of Building Construction,* provides details for approved noncombustible or limited-combustible materials.
- Insulation, when required, should not be of a type that will contribute fuel to a fire; insulation should serve to contain a fire.
- Floors should be constructed of materials that are easy to clean and maintain. Floor sealers that can resist pesticides, solvents, and fuels should be considered, but they require considerable maintenance.
- Buildings should be well lighted to prevent accidents. A guideline is that lighting levels should be sufficient for personnel to read written materials without the need of an additional lighting source.
- Storage areas might need to have interior fire walls to prevent a fire from spreading from one area to another. These walls should be standard 4-hour-rated fire walls that extend 3 ft (0.9 m) above the roofline. They should also be liquid-tight with floor ramps or raised sills at openings.
- Fire doors should be appropriately rated for the opening protected and arranged to close automatically in the event of a fire. See NFPA 80, *Standard for Fire Doors and Other Opening Protectives,* for criteria and installation requirements for fire doors.
- The use of noncombustible walls or partitions should be considered where there needs to be an effective means of segregating incompatible materials within a building.
- All electric service should be in compliance with NFPA 70, *National Electrical Code®*.
- Heating appliances should be segregated from the storage areas.
- Ventilation is an essential component to safe storage. Ventilation system design should consider the handling of both materials and containers and the potential effects of odors from solvents and pesticide products, which can build up to irritating, if not unhealthy, levels. Professional guidance will be needed to specify proper design of the ventilation system, including flow rates, make-up air, location of vents, and so forth. Automatic systems that are preset for temperatures are preferred over the standard wall on-off switch.
- The floor of the pesticide storage area should be sloped into a "blind" drain to allow for easy cleanup in the event of a spill. All drains leaving the building should be temporarily or permanently sealed to prevent a spill from entering the sewer or septic system. All water sources entering the building should have air gaps or antisiphon devices to prevent the movement of pesticides into private or public wells.
- Storage in smaller businesses and farms should be located within a specifically designated area that will provide emergency responders with many options in dealing with a fire. In Figure 6.14.7, for example, pesticides are stored in a predesignated area within a barn.

Conventional precautions for fire protection of pesticide facilities and farms must be balanced with concerns for off-site exposures due to evolution of products of combustion during a fire situation and the potential for environmental damage due to fire water runoff. (See following subsection entitled "Environmental Impact and Containment.") The instructions printed next to a drain shown in Figure 6.14.8 show that local officials are concerned about waste entering drains.

FIGURE 6.14.7 Storage of Pesticides in Predesignated Area

FIGURE 6.14.8 Community Concern Demonstrated by Warning Against Dumping Products in Storm Drains

A pesticide facility should ideally have 100 percent sprinkler coverage, where needed, a sufficient number of fire extinguishers for preliminary response by employees, and a fire detection system that includes smoke and heat detectors. NFPA standards are referenced at the end of this chapter. See also appropriate chapters of this handbook as indicated at the start of the chapter.

Environmental Impact and Containment

In the event of atmospheric release of pesticide products or smoke and products of combustion from a fire, it is important to assess and plan for the effect on sensitive areas downwind. The facility should have the capability to contain any spills and water runoff within the facility boundary by means of a secondary containment system. It is important to note that most pesticides that will be encountered are not required to be placarded, nor are they found in the Emergency Response Guidebook. Response policies and previous experiences all help to shape what action is undertaken to bring the situation under control. One excellent source of information is the emergency phone number found on the product's MSDS. Often the persons answering the phone can provide quick and reliable information on what needs to be done in the specific example. With so few examples in which pesticides have been involved, getting personnel within a company to share their experiences and what ought to be done is a critical first step. The MSDS is the key to accessing such persons.

Internal Containment. If the nature of the material being contained permits, internal containment by means of curbs and sloped ramps at door openings provides a limited alternative to traditional methods of conducting spillage and runoff to an exterior impounding area. Advantages to internal containment include (1) greater control over the materials if spilled, (2) security against vandalism, (3) localized storage, and (4) prevention of rainwater from contacting any spilled material. Drawbacks to internal containment are (1) potential workplace exposure to the contaminants remaining in the building, (2) the presence of released chemicals that may pose the threat of flash fire, (3) potential for vapor explosion or other unacceptable occurrence, and (4) hindrance to emergency responders whose work will be made more difficult by the retention of large quantities of spilled materials. Although there are drawbacks, secondary containment in most cases offers too many advantages to be ignored. Secondary containment is required by state or federal law only when specific quantities of pesticides trigger containment.

External Containment. In some cases, especially in agriculture, pesticides may be contained outdoors in large tanks designed to contain concentrated pesticide products. Exterior containment areas should be secured from access and located away from important valves, building exits, incompatible materials, or environmentally sensitive areas. If exterior containment areas are not roofed, they should be adequately sized to contain additional volumes of rain.

Calculating Containment Volume. Adequate containment volume should be calculated, at a minimum, to include a reasonable and credible worst-case scenario release from (1) a single tank or vessel, and (2) potentially contaminated water from fire-fighting runoff and/or sprinkler operation. In many cases, the state Department of Agriculture has already mandated how much secondary containment is required for the volume being stored. Water utilized during fire control operations may dissolve chemicals, resulting in contaminated runoff from the fire scene. The volume of fire-fighting water runoff to be contained should be determined by the authority having jurisdiction. Overflow from secondary containment must not pose an immediate threat to people, property, or the environment.

Additional Tips. The following tips can help to reduce the threat of a fire or the negative consequences arising from a fire or transportation accident:

- Store all chemicals in one location, away from wells, ditches, animals, and equipment.
- Store chemicals in the smallest quantities possible.

- Use returnable/refillable containers or dry formulations with low use rates.
- Plan ahead. Develop a safety and environmental contingency plan. Share this with local authorities and emergency response services.
- Post emergency phone numbers throughout the facility.
- Post emergency phone numbers at the building entryway where they are easily visible to emergency response personnel.
- For remotely located facilities, such as farms, place large, reflective 9-1-1 numbers on the mailbox to help responders identify and reach the site in an emergency.
- Have emergency responders tour the facility on a regular basis.
- Put backflow preventers on all wells and other water sources.
- Never pump water directly from a well into spray equipment.
- Perform a walkaround inspection of all vehicles to check for potential problems.

Figure 6.14.9 shows a mailbox containing a site map and summary information that fire fighters can use during an emergency. The mailbox pictured in Figure 6.14.10 marks the entry to a county road and posts the number 7865, which is the emergency property identification number assigned by the county to help fire fighters quickly locate a fire or spill.

Additional recommendations for farms and businesses can be found in the following publications: PPP-50, *Managing Farm Chemicals;* PPP-57, *Managing Farm Emergencies;* PPP-58, *Pesticides and Fleet Vehicles: Transporting Pesticides Safely;* and PPP-61, *Pesticide Safety Tips for the Workplace and Farm.*

Detection and Extinguishment

Facility management, assisted by safety and supervisory personnel, should develop and implement a routine system for safety, health, and environment inspection of the facility. This creates a consistent system for maintenance, safe and compatible product storage, management of damaged and returned goods, and overall safe operation of the facility. Inspection tours should be supported by documentation. The aerial photo shown in Figure 6.14.11 is an example of documentation that fire fighters could use to gain a quick visual understanding of a site plan.

Detection System. If fire protection is to be provided by a sprinkler system, a detection system should also be installed to alert facility personnel of incipient fires, thus allowing time for response that may control the incident before sprinkler discharge is triggered. Consideration should be given to both automatic and manual alarm systems that can provide rapid notification of incipient fires or other emergency conditions to personnel. If the facility is not occupied on a 24 hour basis, supervision of these systems should be provided.

FIGURE 6.14.10 Glow-in-the-Dark County-Assigned Number Posted on a Mailbox

FIGURE 6.14.9 Fire Emergency Mailbox Containing Emergency Information

FIGURE 6.14.11 An Aerial Map Downloaded from the Internet Can Provide Important Layout Information

Inspection, Testing, and Warnings. Routine inspections and tests should be conducted to ensure fire protection systems are operable. The inspections and tests should cover sprinkler systems, valves, fire pumps, extinguishers, hose systems, fire doors, runoff containment structures and vessels, and runoff treatment systems, if any. A "no-smoking" policy is mandatory for any area where flammable and combustible materials are stored.

Indentification. Hazard warning signs using the NFPA 704 system should be posted on all structures and fixed tanks that house or store hazardous materials. The use of the NFPA 704 placards should be coordinated with the servicing fire jurisdiction.

Application of Water. The application of water to a building containing pesticides can lead to significant contamination of the property and of the environment if the pesticide-contaminated runoff is not controlled and contained. Given the right set of circumstances, contaminated runoff can kill large numbers of fish and other aquatic animals or can severely contaminate a drinking water supply. Matters are somewhat complicated in that many businesses and farms that store pesticides also store large amounts of fuels and anhydrous ammonia and other fertilizers. In some cases, facility operators should consider posting the W signal (Figure 6.14.12) (from NFPA 704) to warn emergency responders not to use water. The W signal should, of course, only be posted after consultation with the local authorities and with the insurance companies of facilities or farms.

Farmers are sometimes creative and generous in allowing responders to use their irrigation systems for fire emergencies. Figure 6.14.13 shows an irrigation system that has been modified by a farmer to enable fire departments from three districts with three different fitting sizes to connect to his irrigation system.

Alternative Means of Extinguishment. Due to the potential for spread of contamination via runoff from sprinkler systems or the water reactivity of some materials (e.g., fumigants), consideration should be given to alternative means of fire extinguishment and control. Dry chemical, carbon dioxide, or other extinguishing agents and systems may be effective means of fire protection in some pesticide facilities. However, compatibility of the products with these alternative fire extinguishing agents should be given careful consideration. It is important to have the local fire department review the products in storage to determine if appropriate extinguishing materials are on hand at the business, farm, or emergency response organization. In some cases, business owners may need to purchase the appropriate agents if the local emergency services do not have or lack the funds to purchase them. Figure 6.14.14 shows a trailer equipped by business owners with emergency response equipment and supplies.

FIGURE 6.14.12 The W Signal Posted on the Side of a Building

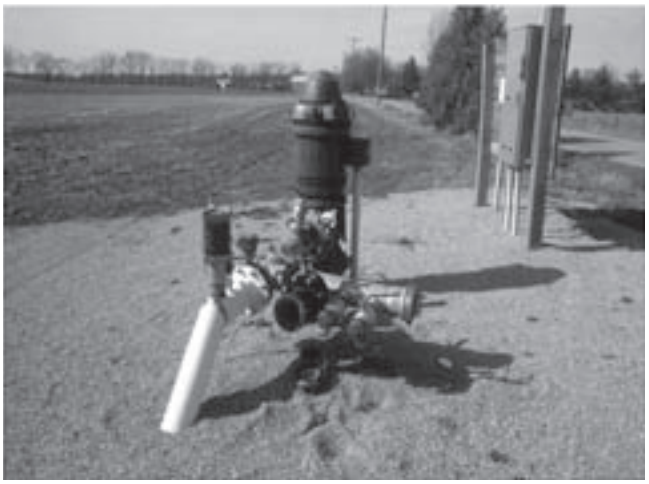

FIGURE 6.14.13 Irrigation System Modified to Accept Fire Department Hose Fittings

Training

Employee Training. Managers and supervisors of pesticide products facilities must be safety conscious and constantly on the lookout for means to reduce spills and injuries resulting from

FIGURE 6.14.14 A Pesticide Application Business Equipped with Emergency Response Supplies

the misuse or careless storage of pesticides. All facility personnel should be able to demonstrate a thorough knowledge of the regulations that are imposed on the facility and themselves, including training of employees under DOT, EPA, OSHA, and state agencies. The safety at the facility or on the farm will only be as good as the routine safety performance of the employees. Copies of relevant regulations, standards, and permits should be available at each facility. Initial and periodic refresher training should be provided as needed and all training and educational programs documented.

All facility personnel should be properly trained, on an annual basis, in the use of the fire extinguishers available at their location. It is recommended that training sessions be conducted with local fire and emergency services. This training should include identification and location of sprinkler control valves, so that emergency responders can control fire spread from the area of origin into adjoining areas of the facility, while allowing them to stop the discharge of water onto released chemicals. The training should also include procedures for notifying both fellow rescuers and personnel at the facility where the emergency occurs. Contact names of fire fighters and business owners should be listed in a hierarchy that enables callers to try one name after another on lists until they reach appropriate responders.

Management of Training for Emergency Response. Management must create, review, deliver, and keep records of effective training programs in all aspects of operations. OSHA's *Hazardous Waste Operations and Emergency Response Standard* (HAZWOPER, 29 CFR 1910.120) and PPP-44, *Pesticides and Planning for Emergencies,* provide detailed guidance for the management of training and specify the degree to which participants can respond to a spill. Participation in outside trade councils may be another important source of effective training materials. Training program documentation must include comprehensive initial technical as well as safety/health training, refresher programs, on-the-job training, and drills and exercises with local responders.

EMERGENCY PLANS

Regulations, Records, and Reports

Under SARA Title III/EPCRA and many other federal and state regulations, facilities may be required to prepare emergency plans. Detailed guidance for such plans is available in NFPA 434, *Code for the Storage of Pesticides,* and NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents,* as well as in other documents such as PPP-44, *Pesticides and Planning for Emergencies: Prevention, Reaction, and Response.* Because there are many regulations scattered across the Environmental Protection Agency, the Department of Transportation, the Department of the Interior, and the Department of Labor, the agencies agreed to a single, consolidated plan: The National Response Team's Integrated Contingency Plan. This consolidation allowed businesses that store pesticides to focus on a single plan. That plan can be found in the Federal Register, Volume 61, No. 109, Page 28642, and in PPP-44.

It is critical that the chemicals stored on-site be reviewed against the products on the SARA Title III/EPCRA listing of reportable products. If the pesticide is on that list and is stored above its reportable quantity, then the facility is required to report to local fire departments, the appropriate state emergency response commission (SERC), and any local emergency planning commissions (LEPC). Management at chemical storage and retail facilities should (1) have a thorough knowledge and understanding of the requirements, (2) file all necessary reports, (3) complete an effective emergency response preplan in concert with local fire authorities, and (4) be active in the local emergency planning committee (PPP-32, *Pesticides and Community Right-to-Know*).

Developing and Implementing Emergency Plans

Preplanning. Effective risk management for general operations and for emergency response is a joint responsibility of the facility owner/operator and the emergency response organizations serving the facility. Adequate preplanning requires evaluation of material safety data sheets (MSDSs) for each formulation. As is the case with all chemicals, the emergency response organization must have MSDSs available to them and must be capable of interpreting how the physical and chemical characteristics of the pesticide products in storage change or modify its approach to responding, reacting, and containing an emergency.

Developing the Plan. The plan should address product spills, medical emergencies, and other types of disasters that may occur at the facility. The plan should be prepared with the cooperation and consultation of local, state, and federal emergency response agencies and with their assistance, if possible. The emergency response plan should be viewed as an integral component of an overall chemical management plan for the facility. Once the plan has been completed, the various positions identified as participating actively in response (e.g., incident commander, technician, and specialist) must be trained to meet the requirements of the OSHA HAZWOPER regulations. NFPA 472, *Standard for*

Professional Competence of Responders to Hazardous Materials Incidents, provides competency standards for such training.

As part of emergency planning, facility management, the fire department, and other involved agencies should identify under which scenarios a fire will be fought versus letting it burn. Factors to be evaluated when making this determination by the responders should include (1) the presence of combustible loading in the form of flammable products, (2) combustible packaging materials, (3) the stage (intensity) of the fire at the time emergency responders arrive, (4) combustible construction, (5) the toxicity of the products involved, (6) the expected toxicity of smoke and products of combustion, (7) the direction of the smoke, (8) the surrounding population, (9) impact of fire water runoff on the environment, and (10) the location of drinking water sources. Other factors include the ability to contain fire-fighting water runoff and the proximity of people, property, or sensitive environmental areas to the products of pesticide combustion.

Insurance Coverage. Many insurance policies held by commercial businesses and farms have insurance clauses that exclude pollution remediation from the policy (see PPP-49, *The Insurance Policy*). A Let-It-Burn Policy is found in PPP-44, *Pesticides and Planning for Emergencies.* Before instigating such a policy, it is advisable to check with the insurance carrier and attorney to see what other legal ramifications are involved with taking such a position. No matter what an insurance policy for a facility stipulates, it is always the fire responders' responsibility to determine if the public is better protected by letting the fire burn or extinguishing it.

Figure 6.14.15 shows a barn being allowed to burn because of pesticides stored inside.

FIGURE 6.14.15 Letting a Barn Burn Due to Pesticide Storage

Implementing the Plan. The emergency plan should be exercised and reviewed annually to reflect changes in products handled, quantities handled, and operating methods, and this process should be documented. The plan should also be reviewed with local fire departments. To handle emergencies, it is important to have on hand a complete list of emergency contacts and phone numbers. These phone numbers should include both mandatory regulatory notification numbers as well as contacts for technical assistance and cleanup services. Examples of necessary phone numbers include those of the facility emergency coordinator, fire department, police, emergency medical transport and hospitals, CHEMTREC, and chemical suppliers, among others. This phone list should be updated whenever changes in contacts and personnel are made, and the list should be verified at least twice a year. (For a prototype list, see PPP-45, *The Quick Emergency Response Plan*, and PPP-28, *Pesticides and Spill Management.*)

SECURITY

Today security has become a serious issue that each farm and business must address. There are many types of threats that can have serious repercussions, not only to a facility's operations but to the community as well. Threats can come from a mischief-maker, trespasser, thief, narcotics entrepreneur, disgruntled employee, computer hacker, homegrown extremist, or terrorist. It is very important for those planning security to determine which one is a realistic threat and, then, to implement measures to deter their unwelcome work. This means deterring, detecting, and delaying the wrongdoer. Security issues are addressed in great detail in PPP-64, *Rural Security Planning: Protecting Family, Friends, and Farm.*

A pesticide facility should have good exterior lighting. Fencing and gates, as shown in Figure 6.14.16, can be effective deterrents to security breaches. Security alarms are also an effective method to deter unauthorized entry. Inbound and outbound shipments should be handled in a designated area. Patrolling the facility affords additional security with the benefit of providing early identification of chemical releases. Access to all hazardous pesticide storage areas must be controlled. In some cases in which there have already been problems, electronic security measures, such as alarms, access control, and video surveillance, might be warranted. Figure 6.14.17 shows electronic devices a farmer has installed on his grain bin. Facil-

FIGURE 6.14.16 Fencing Around a Commercial Agricultural Facility

FIGURE 6.14.17 A Farmer's Grain Bin Protected from Vandalism by Electronic Devices

ity managers can always turn to local police when they feel that increased surveillance is called for.

It is important to hire employees who are not only well qualified for the work but who have also been screened to identify those who might pose a security risk. In many companies, routine drug and alcohol testing as well as background checks are job requirements for drivers and warehouse employees (PPP-69, *The Hiring Process*).

Routine inventories reduce pilferage and help identify problems early. Inventories must be thorough with special attention given to visual inspection of each unit. In many cases, employees cannot access the pesticide products without first contacting a supervisor who actually handles the transfer of product to the employee.

SUMMARY

Pesticides are important products that produce tangible benefits to the public. However, like most technologies, the benefits come with some level of risk when the products are stored on site in large quantities or are transported on highways. The storage, transportation, and use of pesticides are controlled by state and federal regulations and locally through building codes and zoning. Business owners and farm managers must not only comply with these standards but also follow additional industry guidelines. It is important that emergency responders take the initiative to work closely with business owners and farm managers. By visiting facilities where pesticides are stored, emergency responders can become familiar with sites ahead of time and review emergency plans with owners. The goal is to put into practice measures that prevent the release of pesticides into the environment, whether through an accidental release, a fire, natural disaster, vandalism, or terrorism. Site-specific practices must be developed to ensure that the risks posed to employees, neighbors, community, and environment are minimized and controlled.

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2. *Survey Form for Public Warehousing of Crop Protection Products,* http://www.maca.org/edu/survey.pdf, St. Louis, MO, May 15, 2007.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on pesticides in the workplace discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 30B, *Code for the Manufacture and Storage of Aerosol Products*
NFPA 70, *National Electrical Code®*
NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA 220, *Standard on Types of Building Construction*
NFPA 434, *Code for the Storage of Pesticides*
NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents*
NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents*
NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*

Chapter 15

Explosives and Blasting Agents

Lon D. Santis

Chapter Contents

Overview
Nature of Explosive Materials
Types of Explosive Materials
Classes of Explosives
Manufacture of Explosive Materials
Transportation of Explosive Materials
Storage of Explosive Materials
Fire Protection for and Safety and Security Issues Involving Explosive Materials

Key Terms

blasting agent, explosive, low explosive, nuclear explosive, permissible explosive, primary explosive, propellant, secondary high explosive, storage magazine, two-component explosive

This chapter describes explosives and explosive materials, with emphasis on their fire and explosion hazards. Additional important data concerning the manufacture, transportation, storage, and use of explosive materials can be found in NFPA 495, *Explosive Materials Code,* and in other referenced material. NFPA 495 is a current and comprehensive code that should be studied by all who work with explosives.

See also Section 2, Chapter 8, "Explosions"; and Section 17, Chapter 8, "Explosion Prevention and Protection."

OVERVIEW

Hazard of Explosives

NFPA 495 provides a rule that must always be obeyed: *Do not fight fires involving explosive materials.* Always look for signs demarcating explosives storage. Never fight a fire that involves explosives; evacuate the area instead. In 1988, six fire fighters were killed in Kansas City, Missouri, fighting a fire in an ammonium-nitrate-based blasting agent storage facility.[1]

The hazardous nature of explosives has long been recognized, and their production and use throughout the United States and around the world make it necessary to point out those properties that contribute most to the inherent dangers of these very important industrial and military products. In the industrial field alone, over 7 billion pounds (3.2 million metric tons) of explosives and blasting agents were used in 2005. As shown in Figure 6.15.1, commercial explosives consumption has steadily increased in the last half century. Of these totals, approximately 90 percent were used in mining and the remainder principally in construction operations.[2]

History

An explosive is any chemical compound, mixture, or device, the primary or common purpose of which is to function by explosion. Black powder was the first explosive known, although fireworks and pyrotechnics were known and used many centuries earlier.[3] Roger Bacon described the preparation and properties of black powder in the thirteenth century, and it was first used for military purposes in the fourteenth century. The first use of black powder for mining operations occurred in the latter part of the seventeenth century, and it remained the dominant commercial explosive until the latter part of the nineteenth century. In 1846, the compound nitroglycerin was first prepared and its explosive properties studied. The extremely hazardous nature of this compound prevented its wide use until 1867, when Alfred Nobel made the discovery that nitroglycerin absorbed in an inert material, such as diatomaceous earth, produced a mixture that was relatively safe to handle. The best-known form of this mixture is dynamite. This explosive mixture, with many modifications and improvements, remained the predominant commercial explosive until the introduction of modern blasting agents in the mid-1950s. Meanwhile, the use of black powder decreased to an insignificant

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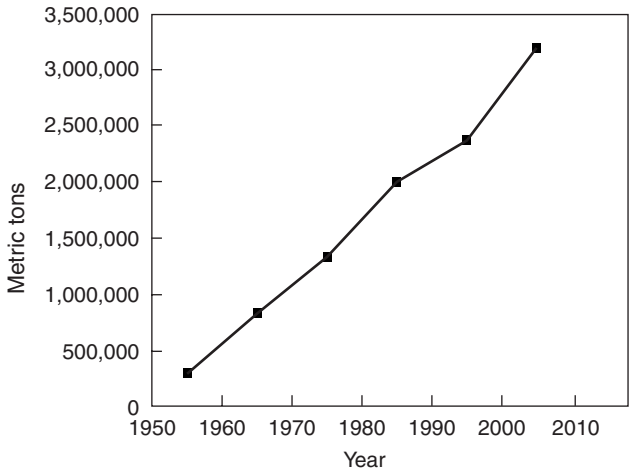

FIGURE 6.15.1 U.S. Commercial Explosives Consumption

quantity, largely because of its sensitivity to heat and flame. In the last 50 years, blasting agents composed principally of ammonium nitrate (AN) have taken over approximately 99 percent of the market.[2] Today, over 90 percent of blasting agents are delivered to the worksite in bulk. These changes are based largely on (1) economic considerations and (2) the greatly improved safety of water-based explosive materials.

NATURE OF EXPLOSIVE MATERIALS

Terminology

An understanding of the nature of explosive materials is essential before one can understand the fire and explosion potential of these hazardous products. A few general terms are defined to provide a background for future discussions.

Blasting Agents (Division 1.5 Materials): Materials that have been classified according to tests specified in Title 49 of the U.S. *Code of Federal Regulations,* Parts 170–189,[4] and found to be so insensitive that there is very little probability of accidental initiation to explosion or of transition from deflagration to detonation. Blasting agents cannot be detonated in the standard blasting cap sensitivity test.

Detonator: Any device containing an initiating or primary explosive that is used for initiating detonation. A detonator is not permitted to contain more than 154 grains (10 g) of explosive material per unit, excluding ignition or delay charges. The term includes, but is not limited to, electric detonators of the instantaneous and delay types, detonators for use with safety fuses, detonating cord delay connectors, and nonelectric detonators of the instantaneous and delay types that consist of a detonating cord, a shock tube, or any other replacement for electric leg wires.

Explosion: A chemical reaction involving an extremely rapid expansion of gases usually associated with the liberation of heat.

Explosive: Any chemical compound, mixture, or device, the primary or common purpose of which is to function by explosion. The term includes, but is not limited to, dynamite, black powder, pellet powder, initiating explosives, detonators, safety fuses, squibs, detonating cord, igniter cord, and igniters. The term includes any material determined to be within the scope of Title 18, United States Code, Chapter 40, "Importation, Manufacture, Distribution and Storage of Explosive Materials," and also includes any material classified as an explosive by the U.S. Department of Transportation, "Hazardous Materials Regulations," 49 CFR, Parts 100–199.

Explosive Material: Includes explosives, blasting agents, water gels (slurries), and detonators. A list of explosive materials is published annually by the Bureau of Alcohol, Tobacco, and Firearms (ATF) in the Federal Register.

Propellant: An explosive that normally functions by deflagration and is used for propulsion purposes. It is classified by the U.S. Department of Transportation, "Hazardous Materials Regulations" as Division 1.1 or 1.3, depending on its susceptibility to detonation.

Fires and Explosions

A distinction must be made between controlled and unwanted fires and explosions. Controlled combustion reactions are basic to the production of power and necessary for an industrial economy. Likewise, detonation reactions are essential for use by the mining and construction industries. On the other hand, the loss of life and natural resources from unwanted fires and explosions is a matter of international concern. Since fire is a major hazard associated with the utilization of explosives and blasting agents, this chapter discusses the basic nature of these materials and methods for reducing the loss from uncontrolled reactions in these materials.

TYPES OF EXPLOSIVE MATERIALS

This chapter mainly addresses commercial explosives, but some of the similarities and differences between commercial and military explosives are mentioned. Most military explosives have high shattering power and relatively high detonation velocities. Military explosives are often kept in storage for relatively long periods of time and therefore must have extremely good long-term stability. It is essential that these explosives detonate reliably even after storage in a wide variety of conditions. Although there are no truly military explosives equivalent to the blasting agents used in commercial operations, the military uses commercial-type explosives and blasting agents for operations such as road building, airstrip preparations, and a wide variety of similar operations.

Commercial explosives are designed to have a wide range of properties to meet the diverse needs of users. Explosives users consider factors such as water resistance, fume production, sensitivity, energy, shelf life, and ruggedness when choosing the right product for their application. For example, explosives used in underground operations should have relatively good postdet-

onation fume characteristics to minimize production of toxic gases that might adversely affect personnel.

Explosive materials can be divided into a number of specific types according to their characteristic properties.[4] The following types are generally recognized in industry.

Primary or Initiating High Explosives

Primary explosives are sensitive explosives that nearly always detonate by simple means such as spark, flame, impact, friction, or other primary heat sources of appropriate magnitude. These materials are quite hazardous, but they play a very important role in the utilization of explosive materials. Typical explosives of this type are mercury fulminate, lead styphnate, and lead azide. Because of their high sensitivity they are seldom, if ever, used alone, and their principal function is to initiate detonation in less-sensitive explosives. They are used almost exclusively as the initiating agent in detonators, and are classified by the Department of Transportation (DOT) as Division 1.1A materials. Unless shipped as a component of a manufactured article, initiating explosives normally must be wetted (desensitized) with water or alcohol for shipment.

Secondary High Explosives

These are materials that are relatively insensitive to mechanical shock and heat and yet are readily detonated by the shock from a primary explosive. They can be used for both military purposes and in commercial blasting operations. Secondary high explosives include such products as TNT, RDX, dynamite, nitroglycerin, and pentaerythrital tetranitrate (PETN). Because of nitroglycerin's sensitivity, it is normally not used alone. Secondary high explosives are generally detonator-sensitive, which distinguishes them from blasting agents, and are classified by DOT as Division 1.1D materials.

Low Explosives or Propellants

These are used primarily for propulsion purposes. They normally function by deflagration (rapid burning) rather than detonation, although some propellants are susceptible to detonation when confined. Black powder, smokeless powder, and solid rocket fuels fall into this category. Fire constitutes the greatest hazard in the handling and use of propellant explosives. Propellants can be Division 1.1 or 1.3 materials (Class A or Class B explosives).

Blasting Agents

The most commonly used explosive is a fuel/oxidizer system that consists primarily of ammonium nitrate and a fuel, such as No. 2 diesel fuel. The formulation is termed ANFO and is sold under a variety of trade names. The addition of approximately 6 percent fuel oil to specially prepared AN prills produces a very efficient blasting material. This combination has the advantages of low cost, high energy, satisfactory fume characteristics, and greatly increased safety over nitroglycerin dynamites. Although blasting agents and secondary explosives should simply burn in a fire, confinement may allow the burning to transition into a detonation. ANFO's use in wet conditions is limited, and ANFO does not have relatively strong shattering power. Therefore, many variations of the basic ANFO formulation have been developed and successfully used. Powdered aluminum or other fuels can be added to increase the energy and blasting efficiency of the basic ANFO formulation. AN solutions can be emulsified or slurried with other ingredients to make a semisolid type of blasting agent and mixed with AN or ANFO.

Water Gels, Slurries, and Emulsions

Operations where a very water-resistant explosive material is a necessity and where a higher shock energy than can be obtained with ANFO is desirable, have led to the development of water gels, slurries, and emulsions. These may be classed as either 1.5 (blasting agents) or 1.1 explosives, depending on their formulation and sensitivity. Ammonium nitrate is usually the basic oxidizer in this type of explosive, and it may be sensitized by a variety of materials, including paint-grade aluminum, monomethylamine nitrate (MMAN), TNT, and various gelling agents and emulsifiers. Water gels, slurries, and emulsions usually contain between 10 and 25 percent water.

Nuclear Explosives

Nuclear explosives are used for military purposes only.

CLASSES OF EXPLOSIVES

In 1991 the Department of Transportation (DOT) issued regulations for the transportation of hazardous materials based on the *United Nations Recommendations on the Transportation of Dangerous Goods*.[5] Use of the classification system previously in place (Class A, B, and C) is no longer permitted by DOT.

UN Recommendations for Classification

Under the United Nations recommendations, hazardous materials are assigned to a class according to their specific characteristics. Explosives are assigned to Class 1, and the explosives in Class 1 are divided into six divisions, as shown in Table 6.15.1. Class 1 divisions are further divided into compatibility groups.

Where the classification system in effect prior to January 1, 1991, is referenced in state or local laws, ordinances, or regulations not pertaining to the transportation of hazardous materials, Table 6.15.2 can be used to compare old and new hazard class names.

Other Classification Systems

The Department of Justice's ATF bureau has a classification system based on the type of explosive material involved. In their system, explosive materials are classified as high explosives, low explosives, and blasting agents. This classification is employed in the enforcement of Title 11, "Regulation of Explosives," of the *Organized Crime Control Act of 1970* (18 U.S.C., Chapter 40), which is intended to provide for the secure and safe storage of explosive materials.

TABLE 6.15.1 UN Recommendations for Classification of Explosives

Class 1 Division	*DOT Package Label*
Division 1.1. Consists of explosives that have a mass explosion hazard. A mass explosion is one that affects almost the entire load instantaneously. Division 1.2. Consists of explosives that have a projection hazard but not a mass explosion hazard. Division 1.3. Consists of explosives that have a fire hazard and either a minor blast hazard or a minor projection hazard, or both, but not a mass explosion hazard.	
Division 1.4. Consists of explosives that present a minor explosion hazard. The explosive effects are largely confined to the package, and no projection of fragments of appreciable size or range is to be expected. An external fire must not cause virtually instantaneous explosion of almost the entire content of the package.	
Division 1.5. Consists of very insensitive explosives. This division comprises substances that have a mass explosion hazard but are so insensitive that there is very little probability of initiation or of transition from burning to detonation under normal conditions of transport.	
Division 1.6. Consists of extremely insensitive articles that do not have a mass explosion hazard. This division comprises articles that contain only extremely insensitive detonating substances and that demonstrate a negligible probability of accidental initiation or propagation.	

Notes:
The "**" on the DOT package label must be replaced with the appropriate division number and compatibility group letter.
The "*" on the DOT package label must be replaced with the appropriate compatibility group.

Permissible Explosives

The term *permissible explosive* is used to describe a type of explosive that has been tested and approved by the Department of Labor's Mine Safety and Health Administration as meeting the minimum safety requirements for use in underground coal mines.[6] These materials are modified dynamites, water gels, or emulsions that exhibit reduced tendencies to ignite flammable gas-air and gas-air-coal dust mixtures.

TABLE 6.15.2 Comparison of Old and New Hazard Class Names as of January 1, 1991

Current Classification	*Class Name Prior to January 1, 1991*
Division 1.1	Class A explosives
Division 1.2	Class A or B explosives
Division 1.3	Class B explosives
Division 1.4	Class C explosives
Division 1.5	Blasting agents
Division 1.6	No applicable hazard class

Two-Component Explosives

Two-component, or binary, explosives consist of two or more unmixed, commercially manufactured, prepackaged chemicals, including oxidizing chemicals, flammable liquids, or solids that are not independently classified as explosives. When mixed, the chemicals exhibit explosive properties and must be stored, transported, and handled as explosives.

MANUFACTURE OF EXPLOSIVE MATERIALS

All manufacturers of explosive materials in the United States must obtain a license from ATF and must follow the ATF regulations as specified in Title 27 of the U.S. *Code of Federal Regulations,* Part 555. Additionally, state and local regulatory agencies may also have rules covering the manufacture of explosive materials and may license manufacturers.

Cartridged or packaged explosive materials are manufactured at fixed plant sites and are transported to the point of use or are shipped to storage/distribution facilities generally located in or near explosive-consuming areas. The production of explosive materials at fixed plant sites must be under the close super-

vision of qualified personnel. The safety record at such plants should be extremely good. Hazards should be well recognized and operating procedures designed to keep potential hazards to a minimum. Fire is the chief concern during manufacture, and plant layout should keep this hazard within reasonable limits. Smoking should never be allowed near the explosive operations, and use of flame-producing equipment must occur only in specific areas under strict safety procedures.

The use of bulk explosives dominates large mining, quarrying, and construction blasting operations. Bulk explosives are Division 1.5 materials (blasting agents) and can consist of ANFO, water gels, slurries, or emulsions, or blends of these materials. Bulk explosives can be plant-mixed and delivered to the blast site by bulk trucks or they can be mixed at the blast site in a bulk truck. Bulk explosives are normally moved by auger or pumped from the bulk truck directly into the blastholes.

Fire is a safety concern in the operation of any type of bulk truck, and the driver/operator must be thoroughly trained in the operation of the mixing, pumping, and/or augering equipment. Bulk transfer operations involving pumps should follow industry standards.[7] Equally important are the characteristics, safe handling, and emergency procedures for the explosive materials being handled. The driver/operator must have a DOT commercial driver's license (CDL), with a hazardous materials (H) endorsement.

TRANSPORTATION OF EXPLOSIVE MATERIALS

The DOT regulates the transportation of all explosive materials in accordance with regulations set forth in U.S. *Code of Federal Regulations,* Title 49, Chapter I, "Transportation," Parts 100–199.[8] Copies of these regulations can be obtained from the U.S. Government Printing Office in their bookstores or on the Internet at http://www.gpoaccess.gov.

DOT must approve and classify an explosive before it can be transported. Most commercial explosives are transported over public highways by truck. Military explosives are transported both by rail and by truck. Fire is the greatest concern in the transportation by motor vehicle over public highways. Although tire fires are less common since the introduction of tubeless tires, they are still a concern and represent a hazard that is difficult to control because the driver of a truck may be unaware of the fire until it has gained considerable headway. Detonators may be transported in limited quantities on the same vehicle with explosives and blasting agents, provided DOT regulations concerning quantity and type of container are observed.

Truck and rail transportation exposes the public to fire and explosion hazards. Unfortunately, fires and other types of accident situations can draw spectators, which increases the danger of casualties.

The DOT publishes an *Emergency Response Guidebook* (ERG),[9] which covers emergency response procedures for transportation incidents involving explosives or other hazardous materials. The publication is widely distributed and is normally carried on all hazardous materials transport vehicles and by emergency responders such as fire and police departments. Copies of the ERG can be purchased from the U.S. Government Printing Office in their bookstores. Electronic copies of the ERG and other ERG resources are available on the Internet at http://hazmat.dot.gov/pubs/erg/gydebook.htm.

Safe havens and interchange lots provide parking and interchange facilities for vehicles transporting explosives. Some explosives interchange lots also provide temporary holding facilities for less-than-truckload quantities of explosives. These terminals should be well controlled and are operated under strict safety regulations. Regulations for these terminals are contained in NFPA 498, *Standard for Safe Havens and Interchange Lots for Vehicles Transporting Explosives.*

STORAGE OF EXPLOSIVE MATERIALS

Objectives

A primary objective for the storage of most nonexplosive industrial materials is to provide protection for such materials from their surroundings. Because of the hazardous nature of explosive materials, the reverse must be considered. Safety to the industrial workers involved and to the general public in the vicinity of such storage must be of primary importance. Since most explosive materials are used by the mining and construction industries, these industries should train their employees to provide the maximum attainable safety. Employees of explosives manufacturing firms must be well aware of the hazards of their occupation and have safety be an integral part of their work.

Commercial explosives are usually consumed quickly, but occasionally, old or abandoned explosives are encountered in questionable condition. Commercial explosives can have shelf lives ranging from a few weeks to indefinite and can become unstable or even inert. Consult the manufacturer or local bomb squad if any uncertainty exists.

Storage Magazines

To provide proper storage for the wide variety of explosive materials now being produced, five different types of magazines are recognized. The requirements for these five types of magazines are given in the regulations developed by the ATF.[10] The specifications for these magazines and types of materials to be put in them can be obtained from ATF or can be found in NFPA 495.

The probability of unintentional initiation of an explosive while in an approved storage location is very small. To safeguard the general public, the *American Table of Distances for Storage of Explosive Materials* (ATD) has been prepared to indicate the isolation distances for stores of explosives from points of contact with the public[11] (Table 6.15.3). The Institute of Makers of Explosives periodically revises this table. Although Division 1.5 materials (blasting agents) are appreciably less sensitive than Division 1.1 materials, once they are initiated to detonation, the damage produced by such an accident is comparable, and the ATD is used to determine the safe distances of stores of Division 1.5 materials from inhabited buildings, public highways, and passenger railways. However, because of the lower sensitivity of Division 1.5 materials, the separation distances between stores

TABLE 6.15.3 American Table of Distances for Storage of Explosives

Quantity of Explosive Materials[b]		Distance (ft)[a,j,k]							
		Inhabited Buildings[c]		Public Highways Class A to D[d]		Passenger Railways—Public Highways with Traffic Volume of More than 3000 Vehicles/Day[d,e]		Separation of Magazines[f]	
Pounds[g] *Over*	*Pounds*[g] *Not Over*	*Barricaded*[h]	*Unbarricaded*	*Barricaded*[h]	*Unbarricaded*	*Barricaded*[h]	*Unbarricaded*	*Barricaded*[h]	*Unbarricaded*
0	5	70	140	30	60	51	102	6	12
5	10	90	180	35	70	64	128	8	16
10	20	110	220	45	90	81	162	10	20
20	30	125	250	50	100	93	186	11	22
30	40	140	280	55	110	103	206	12	24
40	50	150	300	60	120	110	220	14	28
50	75	170	340	70	140	127	254	15	30
75	100	190	380	75	150	139	278	16	32
100	125	200	400	80	160	150	300	18	36
125	150	215	430	85	170	159	318	19	38
150	200	235	470	95	190	175	350	21	42
200	250	255	510	105	210	189	378	23	46
250	300	270	540	110	220	201	402	24	48
300	400	295	590	120	240	221	442	27	54
400	500	320	640	130	260	238	476	29	58
500	600	340	680	135	270	253	506	31	62
600	700	355	710	145	290	266	532	32	64
700	800	375	750	150	300	278	556	33	66
800	900	390	780	155	310	289	578	35	70
900	1,000	400	800	160	320	300	600	36	72
1,000	1,200	425	850	165	330	318	636	39	78
1,200	1,400	450	900	170	340	336	672	41	82
1,400	1,600	470	940	175	350	351	702	43	86
1,600	1,800	490	980	180	360	366	732	44	88
1,800	2,000	505	1010	185	370	378	756	45	90
2,000	2,500	545	1090	190	380	408	816	49	98
2,500	3,000	580	1160	195	390	432	864	52	104
3,000	4,000	635	1270	210	420	474	948	58	116
4,000	5,000	685	1370	225	450	513	1026	61	122
5,000	6,000	730	1460	235	470	546	1092	65	130
6,000	7,000	770	1540	245	490	573	1146	68	136
7,000	8,000	800	1600	250	500	600	1200	72	144
8,000	9,000	835	1670	255	510	624	1248	75	150
9,000	10,000	865	1730	260	520	645	1290	78	156
10,000	12,000	875	1750	270	540	687	1374	82	164
12,000	14,000	885	1770	275	550	723	1446	87	174
14,000	16,000	900	1800	280	560	756	1512	90	180
16,000	18,000	940	1880	285	570	786	1572	94	188
18,000	20,000	975	1950	290	580	813	1626	98	196
20,000	25,000	1055	2000	315	630	876	1752	105	210
25,000	30,000	1130	2000	340	680	933	1866	112	224
30,000	35,000	1205	2000	360	720	981	1962	119	238
35,000	40,000	1275	2000	380	760	1026	2000	124	248
40,000	45,000	1340	2000	400	800	1068	2000	129	258
45,000	50,000	1400	2000	420	840	1104	2000	135	270
50,000	55,000	1460	2000	440	880	1140	2000	140	280
55,000	60,000	1515	2000	455	910	1173	2000	145	209
60,000	65,000	1565	2000	470	940	1206	2000	150	300
65,000	70,000	1610	2000	485	970	1236	2000	155	310
70,000	75,000	1655	2000	500	1000	1263	2000	160	320
75,000	80,000	1695	2000	510	1020	1293	2000	165	330
80,000	85,000	1730	2000	520	1040	1317	2000	170	340
85,000	90,000	1760	2000	530	1060	1344	2000	175	350
90,000	95,000	1790	2000	540	1080	1368	2000	180	360
95,000	100,000	1815	2000	545	1009	1392	2000	185	370
100,000	110,000	1835	2000	550	1100	1437	2000	195	390
110,000	120,000	1855	2000	555	1110	1479	2000	205	410
120,000	130,000	1875	2000	560	1120	1521	2000	215	430
130,000	140,000	1890	2000	565	1130	1557	2000	225	450
140,000	150,000	1900	2000	570	1140	1593	2000	235	470

TABLE 6.15.3 Continued

Quantity of Explosive Materials[b]		Distance (ft)[a,j,k]							
		Inhabited Buildings[c]		Public Highways Class A to D[d]		Passenger Railways—Public Highways with Traffic Volume of More than 3000 Vehicles/Day[d,e]		Separation of Magazines[f]	
Pounds[g] *Over*	*Pounds*[g] *Not Over*	*Barricaded*[h]	*Unbarricaded*	*Barricaded*[h]	*Unbarricaded*	*Barricaded*[h]	*Unbarricaded*	*Barricaded*[h]	*Unbarricaded*
150,000	160,000	1935	2000	580	1160	1629	2000	245	490
160,000	170,000	1965	2000	590	1180	1662	2000	255	510
170,000	180,000	1990	2000	600	1200	1695	2000	265	530
180,000	190,000	2010	2010	605	1210	1725	2000	275	550
190,000	200,000	2030	2030	610	1220	1755	2000	285	570
200,000	210,000	2055	2055	620	1240	1782	2000	295	590
210,000	230,000	2100	2100	635	1270	1836	2000	315	630
230,000	250,000	2155	2155	650	1300	1890	2000	335	670
250,000	275,000	2215	2215	670	1340	1950	2000	360	720
275,000	300,000[i]	2275	2275	690	1380	2000	2000	385	770

Explanatory Notes Essential to the Application of the American Table of Distances for Storage of Explosives

[a] 1 ft = 0.305 m.

[b] "Explosive materials" means explosives, blasting agents, and detonators. "Explosives" means any chemical compound, mixture, or device, the primary or common purpose of which is to function by explosion. A list of explosives determined to be within the coverage of Title 18, United States Code, Chapter 40, "Importation, Manufacture, Distribution and Storage of Explosive Materials," is issued at least annually by the Director of the Bureau of Alcohol, Tobacco, and Firearms of the Department of the Treasury. For quantity and distance purposes, detonating cord of 50 grains per foot should be calculated as equivalent to 8 lb (3.7 kg) of high explosives per 1000 ft (305 m). Heavier or lighter core loads should be rated proportionately. "Blasting agents" means any material or mixture consisting of fuel and oxidizer, intended for blasting, and not otherwise defined as an explosive, provided that the finished product, as mixed for use or shipment, cannot be detonated by means of a No. 8 test blasting cap where unconfined. "Detonator" means any device containing any initiating or primary explosive that is used for initiating detonation. A detonator may not be permitted to contain more than 154 grains (10 g) of total explosives by weight, excluding ignition or delay charges. The term includes, but is not limited to, electric blasting caps of instantaneous and delay types, blasting caps for use with safety fuses, detonating cord delay connectors, and nonelectric instantaneous and delay blasting caps that use detonating cord, shock tube, or any other replacement for electric leg wires. All types of detonators in strengths through No. 8 cap should be rated at 1½ lb (0.7 kg) of explosives per 1000 caps. For strengths higher than No. 8 cap, the manufacturer should be consulted.

[c] "Inhabited building" means a building regularly occupied in whole or part as a habitation for human beings, or any church, schoolhouse, railroad station, store, or other structure where people are accustomed to assemble, but does not include any building or structure occupied in connection with the manufacture, transportation, storage, or use of explosive materials.

[d] "Highway" means any public street, public alley, or public road.

[e] "Railway" means any steam, electric, or other railroad or railway that carries passengers for hire.

[f] "Magazine" means any building, structure, or container, other than an explosives manufacturing building, approved for the storage of explosive materials. Where two or more storage magazines are located on the same property, each magazine shall comply with the minimum distances specified from inhabited buildings, railways, and highways, and, in addition, they should be separated from each other by not less than the distances shown for "separation of magazines," except that the quantity of explosive materials contained in detonator magazines shall govern with regard to the spacing of said detonator magazines from magazines containing other explosive materials. If any two or more magazines are separated from each other by less than the specified "separation of magazines" distances, such magazines, as a group, shall be considered as one magazine, and the total quantity of explosive materials stored in such group shall be treated as if stored in a single magazine located on the site of any magazine of the group, and shall comply with the minimum specified distances from other magazines, inhabited buildings, railways, and highways.

[g] 1 lb = 0.454 kg.

[h] "Natural barricade" means natural features of the ground, such as hills, or timber of sufficient density that the surrounding exposures that need protection cannot be seen from the magazine when the trees are bare of leaves. "Artificial barricade" means an artificial mound or revetted wall of earth of a minimum thickness of 3 ft (0.9 m). "Barricaded" means the effective screening of a building containing explosive materials from the magazine or another building, a railway, or a highway by a natural or an artificial barrier. A straight line from the top of any sidewall of the building containing explosive materials to the eave line of any magazine or other building or to a point 12 ft (3.7 m) above the center of a railway or highway shall pass through such barrier.

[i] Storage in excess of 300,000 lb (136,200 kg) of explosive materials in one magazine generally is not necessary for commercial enterprises.

[j] This table applies only to the manufacture and permanent storage of commercial explosive materials. It is not applicable to the transportation of explosives or any handling or temporary storage necessary or incident thereto. It is not intended to apply to bombs, projectiles, or other heavily encased explosives.

[k] Where a manufacturing building on an explosive materials plant site is designed to contain explosive materials, the building shall be located at a distance from inhabited buildings, public highways, and passenger railways in accordance with the American Table of Distances based on the maximum quantity of explosive materials permitted to be in the building at one time.

Source: The American Table of Distances is reprinted from IME Safety Library Publication No. 2 with permission of the Institute of Makers of Explosives, as revised in June 1991.

of Division 1.1 materials and stores of Division 1.5 materials, or between stores of Division 1.5 materials, need not be as great as that required between stores of Division 1.1 materials (Table 6.15.4).

The ATD applies to the manufacture and storage of *commercial* explosive materials. The distances specified are those measured from the explosive materials storage facility to the inhabited building, highway, or passenger railway, irrespective of property lines.

The ATD covers all commercial explosive materials, including, but not limited to, high explosives, blasting agents, detonators, initiating systems, and explosive materials in process. The ATD is not designed to be altered or adjusted to accommodate varying explosive characteristics such as blast effect, weight strength, density, bulk strength, and detonation velocity.

The ATD should not be used to determine safe distances for blasting work, the firing of explosive charges for testing or quality control work, or the open detonation of waste explosive materials. It may, however, be used as a guide for developing distances for the unconfined, open burning of waste explosive materials where the probability of transition from burning to high-order detonation is unlikely.

Table 6.15.4 shows the recommended separation distances and the thickness of artificial barricades for the separation of Division 1.1 from Division 1.5 materials and AN. When barricades are *not* provided, the recommended distances must be increased by a factor of six, as shown in Table 6.15.4 (Note 2).

FIRE PROTECTION FOR AND SAFETY AND SECURITY ISSUES INVOLVING EXPLOSIVE MATERIALS

Fire is a principal cause of accidents involving explosive materials. Although explosives may vary in their sensitivity to fire, they always have the potential to produce a disastrous explosion when subjected to fire. The only effective method for fire protection with explosive materials is to eliminate the source of fire. This involves meticulous housekeeping standards. It is often a small fire in oily rags or wastepaper that triggers a major catastrophe. Smoking or the use of any fire-producing equipment should not be permitted where explosive materials are produced, handled, stored, or used. Because of the relative insensitivity of 1.5 materials (blasting agents), there is always a danger that personnel will become careless around these materials. A fire and subsequent explosion in a blasting agent mixing house near Norton, Virginia, illustrates the potential hazard from the careless use of heat-producing equipment.[12] Another fire and explosion in a blasting agent storage facility in Kansas City, Missouri, killed six fire fighters who were fighting the fire.[1]

Some of the materials used in making explosives and blasting agents may also be hazardous. Materials likely to be found include nitric acid, aluminum powder, AN, ammonium perchlorate, sodium nitrate, fuel oil, and corrosive gas. NFPA codes and standards should be consulted for proper storage and protection of these materials.

For all explosive materials, whether in manufacture, storage, transportation, or use, housekeeping should be of the highest order.

Fighting Fires Involving Explosives and Blasting Agents

No attempt should be made to fight a fire involving explosive materials. The area should be evacuated to a distance of at least 2000 ft (610 m).

Truck fires involving explosive materials pose a special threat to the public because of the potential for large numbers of occupants of other vehicles to be within the radius of effects of any blast. A study of DOT data showed there were 10 truck fires involving Class 1 materials in the six-year period from 1993 to 1998.[13] Although none of these incidents resulted in a mass detonation, the possibility always exists. To prevent loss of life, all sources of ignition should be controlled until the cargo can be transported away. Immediate evacuation in the event of a fire is imperative because although the possibility of a detonation always exists, DOT regulations should prevent it from occurring for some time.

Security

Long before the current threats existed, the element of security was integral to commercial explosives operations. Although commercial explosives are usually not the choice of terrorists or other criminals, nonetheless the public must be protected from the illicit use of commercial explosives. Security-related regulations of the DOT, ATF, and Department of Homeland Security (DHS) should be thoroughly understood and complied with. Copies of these regulations can be obtained from the U.S. Government Printing Office in their bookstores or on the Internet at http://www.gpoaccess.gov. Industry standards should be consulted for ways to increase security beyond the level that the regulations require or address.[14]

Destruction of Explosive Materials

At times it may be necessary to destroy commercial explosive materials. These may consist of explosives or blasting agents from containers that have been broken during transportation, or may be materials that have exceeded their recommended shelf life, are believed to be overage, or are no longer needed.

Before destroying any explosives product, one must be familiar with the regulatory requirements and properties of the product. The member companies of the Institute of Makers of Explosives have agreed to supply advice and assistance in destroying explosives. Assistance should be sought from the manufacturer, if known. If the manufacturer is not known, a member company of the Institute of Makers of Explosives may provide advice or assistance.

When improvised explosive devices or bombs, military ordnance, military explosives, or homemade or illegal explosive materials are involved, disposal should be under the supervision of trained bomb disposal experts from a governmental regulatory agency.

SUMMARY

Generally speaking, the greatest threat to unintentional initiation of explosives is fire. Every effort should be made to prevent

TABLE 6.15.4 Table of Recommended Separation Distances of Ammonium Nitrate and Blasting Agents from Explosives or Blasting Agents[a,b,h]

Donor Weight		Minimum Separation Distance of Acceptor when Barricaded[a] (ft)[c]		
Pounds Over[d]	*Pounds Not Over*[d]	*Ammonium Nitrate*[e]	*Blasting Agent*[b]	*Minimum Thickness of Artificial Barricades*[f] *(in.)*[g]
	100	3	11	12
100	300	4	14	12
300	600	5	18	12
600	1,000	6	22	12
1,000	1,600	7	25	12
1,600	2,000	8	29	12
2,000	3,000	9	32	15
3,000	4,000	10	36	15
4,000	6,000	11	40	15
6,000	8,000	12	43	20
8,000	10,000	13	47	20
10,000	12,000	14	50	20
12,000	16,000	15	54	25
16,000	20,000	16	58	25
20,000	25,000	18	65	25
25,000	30,000	19	68	30
30,000	35,000	20	72	30
35,000	40,000	21	76	30
40,000	45,000	22	79	35
45,000	50,000	23	83	35
50,000	55,000	24	86	35
55,000	60,000	25	90	35
60,000	70,000	26	94	40
70,000	80,000	28	101	40
80,000	90,000	30	108	40
90,000	100,000	32	115	40
100,000	120,000	34	122	50
120,000	140,000	37	133	50
140,000	160,000	40	144	50
160,000	180,000	44	158	50
180,000	200,000	48	173	50
200,000	220,000	52	187	60
220,000	250,000	56	202	60
250,000	275,000	60	216	60
275,000	300,000	64	230	60

[a]Where the ammonium nitrate or blasting agent, or both, is not barricaded, the distances shown in Table 6.15.4 must be multiplied by 6. These distances allow for the possibility of high-velocity metal fragments from mixers, hoppers, truck bodies, sheet-metal structures, metal containers, and the like that could enclose the donor. Where storage is in bullet-resistant magazines recommended for explosives or where the storage is protected by a bullet-resistant wall, distances and barricade thicknesses in excess of those prescribed in the American Table of Distances (see Table 6.15.3) are not required. Recommended separation distances are to prevent explosion of ammonium nitrate and ammonium-nitrate-based blasting agents by propagation from nearby stores of high explosives or blasting agents referred to in the table as the "donor." Ammonium nitrate, by itself, is not considered to be a donor where applying this table. Ammonium nitrate, ammonium nitrate-fuel oil, or combinations thereof are acceptors. If stores of ammonium nitrate are located within the sympathetic detonation distance of explosives or blasting agents, half the mass of the ammonium nitrate shall be included in the mass of the donor.

[b]These distances apply to blasting agents that pass the insensitivity test prescribed in regulations of the U.S. Department of Transportation and the U.S. Department of the Treasury, Bureau of Alcohol, Tobacco, and Firearms.

[c]1 ft = 0.305 m.

[d]1 lb = 0.454 kg.

[e]The distances in the table apply to ammonium nitrate and ammonium nitrate–based materials that show "negative" (–) result in the UN Test Series 2 Gap Test and show "positive" (+) result in the UN Test Series 1 Gap Test. Ammonium nitrate and ammonium–nitrate–based materials that are DOT hazard Class 1–sensitive shall be stored at separation distances determined by the American Table of Distances (see Table 6.15.3).

[f]Earth, sand dikes, or enclosures filled with the prescribed minimum thickness of earth or sand shall be permitted to be used as artificial barricades. Natural barricades, such as hills or timber of sufficient density that the surrounding exposures that need protection cannot be seen from the donor when the trees are bare of leaves, also shall be permitted to be used.

[g]1 in. = 2.54 cm.

[h]For determining the distances to be maintained from inhabited buildings, passenger railways, and public highways, Table 6.15.3, the American Table of Distances for Storage of Explosives, shall be used.

the start of fire near explosives. Equipment should be on hand to control fires and prevent them from involving the explosives in the fire. *If the explosives become involved in the fire, all fire fighting must stop and people must be removed to a distance of at least 2000 ft (610 m).*

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on explosives and blasting agents discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 490, *Code for the Storage of Ammonium Nitrate*
NFPA 495, *Explosive Materials Code*
NFPA 498, *Standard for Safe Havens and Interchange Lots for Vehicles Transporting Explosives*

References

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Internet Resources

http://www.gpoaccess.gov, official website of the U.S. Government Printing Office; provides access to federal laws, regulations, and court documents.

http://www.firstgov.gov, official portal website of the U.S. government; provides links to federal, state, and local government agencies and their programs.

http://www.nfpa.org, website of the NFPA.

http://www.ime.org, website of the Institute of Makers of Explosives, a nonprofit safety and security association of the commercial explosives industry.

http://www.isee.org, website of the International Society of Explosives Engineers, a professional society dedicated to promoting the safe and controlled use of explosives in commercial applications.

http://www.unece.org/trans/danger/danger.htm, official website of the United Nations' Committee of Experts on the Transport of Dangerous Goods (TDG) and the Globally Harmonized System of Classification and Labeling (GHS).

Chapter 16

Manufacture and Storage of Aerosol Products

David L. Fredrickson

Chapter Contents

The Aerosol Product
Classification and Fire Behavior of Aerosols
Aerosol Filling Plants
Product Storage

Key Terms

aerosol, aerosol (hazard classification), propellant, warehouse

A wide variety of products are packaged as aerosols for consumer and industrial uses. Applications of this packaging technique include lubricants, cleaning agents, personal care products, pharmaceuticals, food products, paints, and pesticides.

Prior to the issuance of the first edition of NFPA 30B, *Code for the Manufacture and Storage of Aerosol Products,* in 1990, fire protection of aerosol products was governed by NFPA 30, *Flammable and Combustible Liquids Code.* Under NFPA 30, aerosol products were considered to be equivalent to Class IA flammable liquids. This classification often led to fire protection strategies, particularly in aerosol storage facilities, that were considered by many users to be excessive.

Fire testing conducted in the early to mid-1980s by a consortium of aerosol product manufacturers, industry suppliers, distributors, and interested insurance companies indicated that the fire characteristics of aerosol products were more complicated than provided for under NFPA 30. Some products presented severe fire hazards, whereas others presented a much lower fire challenge than a Class IA flammable liquid, leading not only to the development of an aerosol product fire hazard classification system but to improved fire protection strategies for aerosol storage facilities and, later, to the development of NFPA 30B. Additional research in the late 1980s and early 1990s led to improved understanding and clearer identification of the three levels of aerosol products and their protection criteria.

This chapter reviews the components and manufacture of aerosol products, the fire hazard classification system associated with aerosol products, the fire behavior of aerosol products, and fire protection strategies for manufacturing and storage occupancies.

See also Section 6, Chapter 1, "Fire Hazards of Materials"; and Section 6, Chapter 2, "Combustion Products and Their Effects on Life Safety."

THE AEROSOL PRODUCT

Containers

The most common aerosol containers are high-strength metal units with capacities ranging from 10 milliliters (less than one-half fluid ounce) up to a liter (about one quart). The top and base of the container are generally domed to provide strength. Unit working pressure ranges between 965 to 1241 kPa (140 to 180 psi).

A finished aerosol product typically consists of the basic elements shown in Figure 6.16.1. A base product is dispensed into the aerosol container, an actuator assembly is fitted to the container body, and the container is pressurized with propellant. If a nozzle or tip assembly is not part of the previously installed actuator assembly, one is installed. Depending on actuator design, a protective outer cap (not shown in Figure 6.16.1) may be provided to prevent damage to the nozzle or premature discharge of product.

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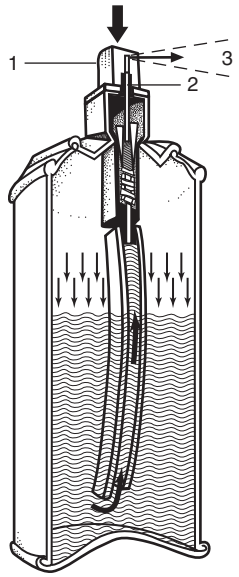

FIGURE 6.16.1 Aerosol Can (Cutaway View). When the plunger (1) is pressed, a hole in the valve (2) allows a pressurized mixture of product and propellant (3) to flow through the plunger's exit orifice.

Propellants

A variety of liquefied gas and compressed gas propellants are available to aerosol formulators. Hydrocarbon propellants are most widely used for a number of reasons, including their ability to maintain relatively constant pressure and resultant spray patterns throughout the life of the product. Characteristics of concern to formulators include odor, purity, stability, and toxicity. Often, to satisfy performance needs, blends of liquefied gases are selected. Although compressed gases are not often used, they do fill certain needs for the formulator. The compressed gases used include carbon dioxide, nitrous oxide, nitrogen, and air.

Liquefied gas propellants are typically blends of propane and butane. Specific blends of these gases are provided to aerosol fillers by propellant suppliers and are marketed as "aerosol"-grade gases. As with most consumer and industrial products, these gas blends are sold under specific manufacturer's product names.

Liquefied gas propellants are gaseous at ambient temperatures and pressures. They will condense to liquid form under moderate pressure or at low temperature. They maintain constant pressure within the aerosol container, at a given temperature, throughout the life of the unit.

Table 6.16.1 contains a summary of the fire hazard properties of the common liquefied propellant gases. The vapor pressure of these materials and the large quantities of gas they produce when vaporized makes them suitable propellants.

A particular gas or gas blend can be denoted by its vapor pressure at 70°F (21°C). For example, A-31 refers to aerosol-grade isobutane, which has a vapor pressure of 31 psig (214 kPa). A-108 refers to propane, with a vapor pressure of 108 psig (745 kPa). A particular desired vapor pressure can be achieved by blending gases.

Base Products

The material other than propellant dispensed from the aerosol container is referred to as the "base product" or the "concentrate." These base products run the full range of consumer and industrial products. The fire hazards of these materials can be minimal (e.g., a water-based liquid), to highly flammable, such as with many lubricants or coatings. An understanding of the physical properties and fire hazards of these materials is important. Each plays an important role in developing the proper fire plans for facilities that manufacture or store aerosol products.

CLASSIFICATION AND FIRE BEHAVIOR OF AEROSOLS

Classification

In order to determine appropriate fire protection measures for use with aerosol products, aerosol products are classified by NFPA 30B into one of three levels. The 1994 edition of the

TABLE 6.16.1 Fire Hazard Properties of Liquefied Gas Propellants

	Flammable Limits*		Flashpoint		Autoignition Temperature	
	Lower	*Upper*	°F	°C	°F	°C
Propane	2.1	9.5	–156	–104	940	504
Isobutane	1.8	8.4	–117	–83	890	477
n-Butane	1.8	8.4	–101	–74	806	430
iso-Pentane	1.4	7.6	–60	–51	788	420
n-Pentane	1.5	7.8	–40	–40	500	260
Difluoroethane	3.9	16.9	–58	–50		
Tetrafluoroethane			Nonflammable			
Dimethyl ether	3.4	18.0	–40	–40	662	350

*Present in air by volume.

standard first recognized a revised approach to aerosol hazard classification developed by Factory Mutual Research Corporation (FMRC).

This new classification method is based on the chemical heats of combustion of the aerosol products. The chemical heats of combustion calculation method accounts for the chemical heats of combustion of the propellant and the base product.

Based on the aerosol product's aggregate chemical heat of combustion, the following hazard levels have been established:

- *Level 1.* Those aerosol products with total chemical heat of combustion equal to or less than 8600 Btu/lb (20 kJ/g)
- *Level 2.* Those aerosol products with total chemical heat of combustion greater than 8600 Btu/lb (20 kJ/g) but less than or equal to 13,000 Btu/lb (30 kJ/g)
- *Level 3.* Those aerosol products with total chemical heat of combustion greater than 13,000 Btu/lb (30 kJ/g)

The 1998 edition first recognized a second classification method with fire testing of a 12-pallet test array.

Proper fire hazard classification of aerosol products is particularly important in storage areas used for aerosol products. The expected fire behavior and associated protection requirements will vary greatly with the level of aerosol product.

Fire Behavior

Fire tests of large amounts of aerosol products have demonstrated the importance of proper sprinkler protection of these products. In an out-of-control situation, Level 2 and Level 3 aerosol products can produce intense heat; rocketing of ruptured containers can make manual fire fighting extremely difficult. These tests have also shown that Level 1 aerosol products, even though they may contain flammable gas propellants, can be very easy to protect. Level 1 aerosol products can be protected in the same manner as Class III commodities, as defined by and in accordance with NFPA 13, *Standard for the Installation of Sprinkler Systems.*

Level 2 aerosol products are typically alcohol-based products, which means most of the base product is water soluble. Although they can produce a very intense fire, they are easier to protect than are Level 3 aerosol products due to the lower heat output of the burning ingredients and solubility in water of the base product.

Level 3 aerosol products are typically petroleum solvent–based products. The higher heat output and lack of water solubility produce an extremely intense fire when sprinkler protection is not adequate.

Both Level 2 and Level 3 aerosol products in warehouse settings have been shown to require rapid sprinkler response. Quick-response sprinklers, such as early suppression fast-response (ESFR) sprinklers or in-rack sprinklers, which are close to the product, demonstrate excellent protection for stored aerosol products, since they generally respond to the carton fire before the aerosol products themselves become involved. Fires involving properly protected Level 2 and Level 3 aerosol products are quite often extinguished by the sprinklers. They do not produce rocketing containers and, where manual fire fighting is required, it can be readily accomplished.

Annex B in NFPA 30B describes many of the small and full-scale tests run with aerosol products. Some full-scale tests had up to 64 pallets of product in the arrays.

Warehouse Fires Involving Aerosols

Prior to the research programs and development of NFPA 30B, aerosol products were involved in several large-scale and costly warehouse fires. One of the most notable fires involving aerosol products destroyed a 27 acre (10.9 ha) distribution center operated by the Kmart Corporation in Falls Township, Pennsylvania, in 1982.[1] A fire in palletized storage of Level 3 aerosol products overwhelmed the automatic sprinkler protection. The fire quickly spread beyond the aerosol storage area. The large volume of fire and failure of the automatic sprinkler protection led to the loss of structural integrity within the building. The loss, expressed in 1982 dollars, was estimated to be in excess of $100 million (Figure 6.16.2).

Aerosol products also were present in a fire that resulted in the loss of a large storage facility in Elizabeth, New Jersey, in 1985, and the loss of a coatings product distribution facility in Dayton, Ohio, in 1987.[2] These and similar incidents indicate that aerosol products storage arrangements should be maintained in configurations that are within the capability of the level of fire protection provided.

AEROSOL FILLING PLANTS

Fire and explosion hazards within aerosol product filling operations are controlled using a number of layers of protection. These layers are (1) incident prevention, (2) fire/explosion suppression, and (3) incident magnitude mitigation. Where not properly protected by these layers, aerosol filling operations have suffered explosions that destroyed facilities and injured employees. Some instances have even resulted in single or multiple deaths. Proper controls, interlocks, and safeguards are needed to prevent catastrophic scenarios.

FIGURE 6.16.2 Aerosol Cans Located in the Area of Fire Origin of the Kmart Fire

Incident Prevention

Aerosol product filling facilities, properly designed to minimize fire and explosion hazards, are subdivided into several areas. Propellant gases are stored in remotely located bulk storage facilities. Further subdivisions can occur in multiple-line filling operations and filling components, such as propellant pumps.

Charging of aerosol cans with propellant must take place in an area separated from the main manufacturing area. Many modern designs use a propellant charging house that is physically separate from the main aerosol production building.

Empty aerosol cans are placed on a conveyor and run through a product filling station where the base product is metered into the can. The actuator assembly is placed into the can and prepared for propellant charging. The actuator assembly may or may not be sealed to the can, depending on which of two methods is used to charge the propellant.

The through-the-valve pressure filling method involves sealing the actuator assembly to the can before the can enters the propellant charging station. There, the propellant is injected into the can through the stem of the actuator assembly, essentially in the reverse manner in which the aerosol product is used. Figure 6.16.3 shows a propellant-charging machine of this type. Figure 6.16.4 is a diagram of one of the charging heads.

In the undercup filling method, the aerosol can is conveyed to the propellant charging station with the actuator assembly in place but *not* sealed to body of the can. In the charging station, the aerosol can is mated to a filler head that lifts the actuator assembly, charges the propellant, then replaces and seals the actuator assembly. Figure 6.16.5 shows an under cup propellant charging machine. Figure 6.16.6 is a diagram of one of the charging heads.

As filled aerosol cans are returned from the filling area to the main production area, quality testing is performed. Cans are conveyed through hot water test baths and defective units removed to disposal containers. Reject-can containers should be provided with active ventilation to remove propellant gas and/or base-product vapors. Finished cans are cartoned and placed in storage.

The initial preparatory steps within the general manufacturing area typically present no unusual fire hazards. Combustibles in the area might include packaging materials, such as cardboard and plastic wrap. The area will also customarily include large quantities of metal containers.

Within the charging facility, several severe fire hazards might exist. The aerosol base product will be present. This material might be a combustible or flammable liquid. Most importantly, propellant gas will be present in the area. Small quantities of propellant might be lost to the atmosphere during charging operations. The propellant gas losses and any vapor evolved from the base product must be controlled by a properly maintained, dedicated ventilation system.

Several active prevention and protection systems should be provided. For prevention purposes, a flammable gas detection system should be installed and interlocked to the charging area's ventilation system, equipment controls, and alarm system.

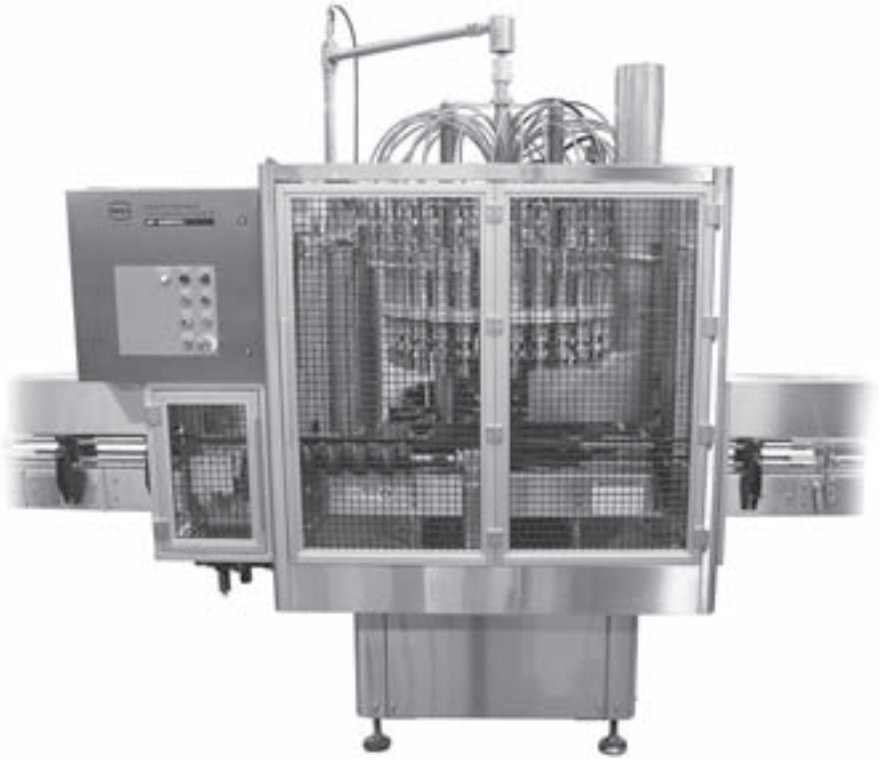

FIGURE 6.16.3 Through-the-Valve Propellant Pressure Filler (Courtesy Packaging Technologies, Inc., Davenport, IA)

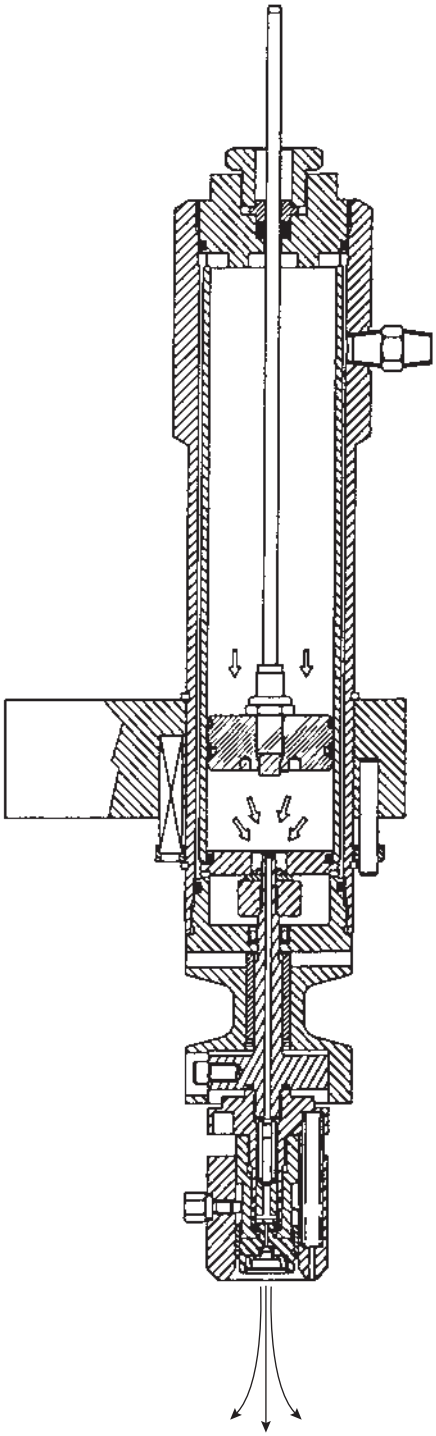

FIGURE 6.16.4 Detail of Through-the-Valve Propellant Pressure Filler Head (Courtesy Packaging Technologies, Inc., Davenport, IA)

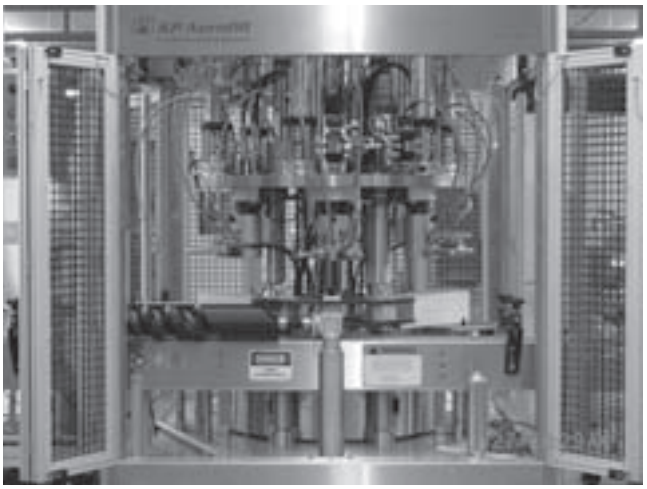

FIGURE 6.16.5 Undercup Propellant Filler (Courtesy Packaging Technologies, Inc., Davenport, IA)

The charging area ventilation system should be designed by experienced professionals and should account for anticipated propellant losses during filling operations. Furthermore, it must have the capability to provide high-volume air removal under emergency operations. When the combustible gas detection system senses conditions above 20 percent of the propellant's lower explosive limit (LEL), the ventilation rate in the charging area should be increased to at least 150 percent of the design airflow or two air changes per minute, whichever is greater. Audible and visual alarms should be activated to alert operators to the condition.

Automatic equipment controls should also be provided. When the gas detection system senses 40 percent of the propellant LEL, the aerosol line and the main propellant supply line should be shut down automatically. Audible and visual alarms should be activated to alert operators to the condition.

Fire/Explosion Suppression

In the event that prevention measures fail, an explosion suppression system should also be provided. Such a system will respond quickly to suppress an explosion in its earliest stages. Wet-pipe automatic sprinkler protection should also be provided in the area. All protective systems should be interlocked to aerosol production equipment, so that equipment is shut down in the event of protective system activation.

Mitigation

In the event that both prevention and suppression measures fail, the design of the charging facility should provide for relief of deflagrations. Structural elements in the charging area, located adjacent to major buildings or assets, should be designed to withstand the anticipated overpressure of a deflagration. Deflagration vents, directed away from buildings and personnel, should be provided at the charging area exterior walls.

PRODUCT STORAGE

Storage arrangements for aerosol products depend to a great degree on the amount of material stored by the manufacturer or distributor. NFPA 30B provides guidance for the storage of

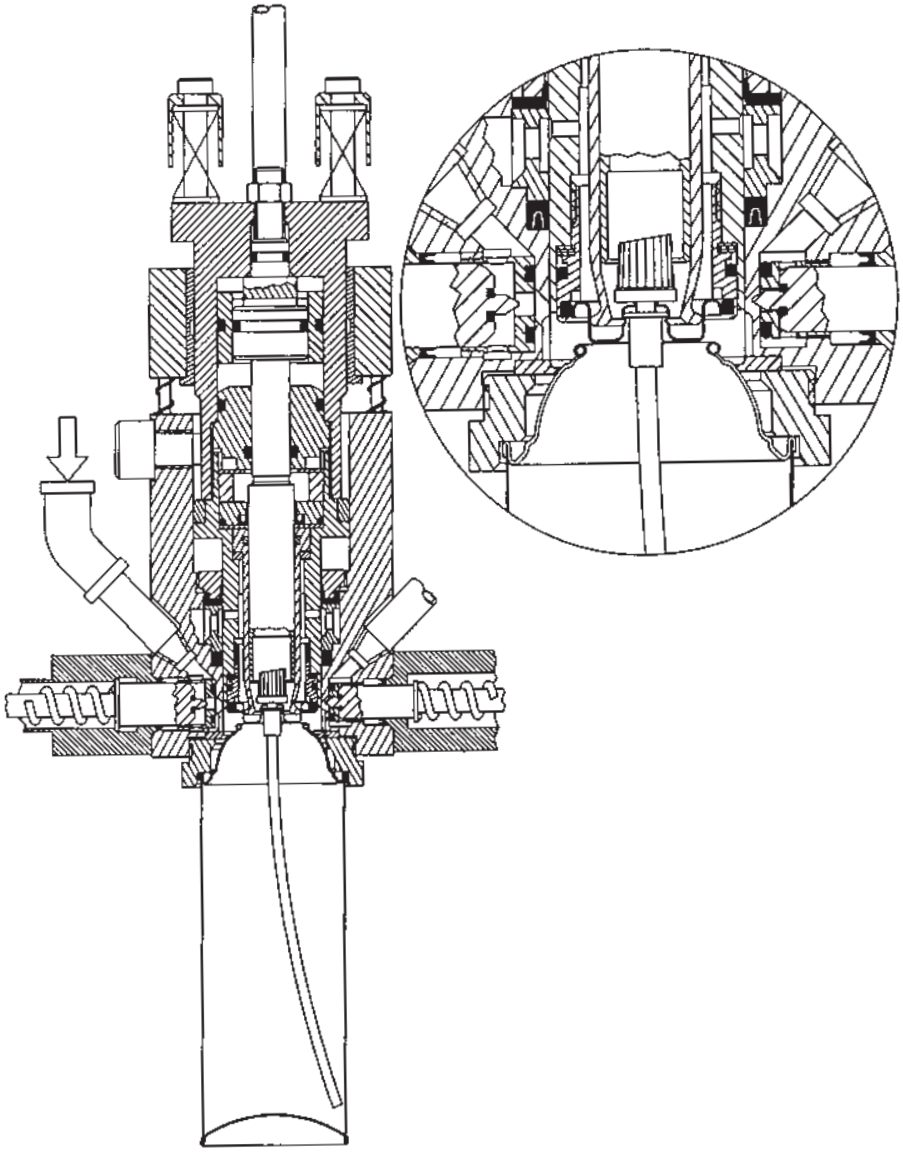

FIGURE 6.16.6 Detail of Undercup Propellant Filler Head (Courtesy Packaging Technologies, Inc., Davenport, IA)

limited amounts of aerosol products in assembly, business, educational, industrial, or institutional occupancies. Storage in a single fire area within these occupancies for Level 2 and Level 3 aerosol products should be limited to 1000 lb (454 kg) and 500 lb (227 kg), respectively. If larger amounts are required, storage should be in separate inside storage areas or flammable liquid cabinets.

NFPA 30B includes design criteria for sprinkler protection of palletized (solid pile) storage and rack storage of both cartoned and uncartoned aerosol products. The tables for uncartoned aerosols were developed based on research done by a consortium of aerosol manufacturers, suppliers, and insurance companies in the late 1990s. The ceiling sprinkler design criteria specify the sprinkler type and nominal orifice size, the sprinkler's response/nominal temperature rating, and the design density in terms of the number of sprinklers operating at a specified discharge pressure. For in-rack sprinkler protection, the appropriate tables also specify the sprinkler type and nominal orifice size, the sprinkler's response/nominal temperature rating, and the required discharge pressure. To assist the user, the tables are presented in pairs, one table in SI (metric) units and a corresponding table in English customary units.

The following tables are reproduced from the 2006 edition of NFPA 30B. Tables 6.16.2 and 6.16.3 show the sprinkler system design criteria for palletized storage of cartoned aerosol products. Tables 6.16.4 and 6.16.5 show the sprinkler system design criteria for rack storage of cartoned Level 2 aerosol products. Note that the figures referenced for in-rack sprinkler

TABLE 6.16.2 Sprinkler Design for Palletized Storage of Cartoned Level 2 and 3 Aerosol Products (SI Units)

			Ceiling Sprinkler Protection Criteria				
Aerosol Level	*Maximum Ceiling Height (m)*	*Maximum Storage Height (m)*	*Sprinkler Type/Nominal Orifice ($L/min/bar^{0.5}$)*	*Response/ Nominal Temperature Rating**	*Design (Density/Area) (# Sprinklers @ Discharge Pressure)*	*Water Supply Duration (hr)*	*Hose Stream Demand (L/min)*
2	7.6	5.5	Large drop K = 161	SR/Ordinary	15 @ 3.4 bar	2	1900
		6.1	ESFR-pendent K = 202	QR/Ordinary	12 @ 3.4 bar	1	950
			ESFR-pendent K = 235	QR/Ordinary	12 @ 2.4 bar	1	950
			ESFR-pendent K = 314	QR/Ordinary	12 @ 1.7 bar	1	950
			ESFR-pendent K = 363	QR/Ordinary	12 @ 1.7 bar	1	1900
	9.1	1.5	Spray K ≥ 115	SR/High	12 mm/min over 232 m^2	2	950
		4.6	ESFR-pendent K = 202	QR/Ordinary	12 @ 3.4 bar	1	950
			ESFR-pendent K = 235	QR/Ordinary	12 @ 2.4 bar	1	950
			ESFR-pendent K = 314	QR/Ordinary	12 @ 1.7 bar	1	950
			ESFR-pendent K = 363	QR/Ordinary	12 @ 1.7 bar	1	950
3	6.1	1.5	Spray K ≥ 115	SR/High	12 mm/min over 232 m^2	2	1900
		3.0	Large drop K = 161	SR/Ordinary	15 @ 5.2 bar	2	1900
	7.6	4.6	ESFR-pendent K = 202	QR/Ordinary	12 @ 3.4 bar	1	950
			ESFR-pendent K = 235	QR/Ordinary	12 @ 2.4 bar	1	950
			ESFR-pendent K = 314	QR/Ordinary	12 @ 1.7 bar	1	950
			ESFR-pendent K = 363	QR/Ordinary	12 @ 1.7 bar	1	950
	9.1	1.5	Spray K ≥ 161	SR/High	25 mm/min over 232 m^2	2	1900
		4.6	ESFR-pendent K = 202	QR/Ordinary	12 @ 5.2 bar	1	950
			ESFR-pendent K = 235	QR/Ordinary	12 @ 3.6 bar	1	950
			ESFR-pendent K = 314	QR/Ordinary	12 @ 3.1 bar	1	950
			ESFR-pendent K = 363	QR/Ordinary	12 @ 1.7 bar	1	950

*QR = Quick Response; SR = Standard Response.

Source: NFPA 30B, *Code for the Manufacture and Storage of Aerosol Products,* Table 6.3.2.7(a).

layout are NOT reproduced, due to space limitations. In general-purpose warehouses, Level 2 and Level 3 aerosol products must be segregated as described in NFPA 30B. Very large quantities should be stored in an aerosol warehouse that requires separation from other occupancies by either fire-rated assemblies or by distance.

Wet-pipe automatic sprinkler protection is required for Level 2 and Level 3 aerosol product storage. Live fire testing

TABLE 6.16.3 Sprinkler Design for Palletized Storage of Cartoned Level 2 and 3 Aerosol Products (English Units)

			Ceiling Sprinkler Protection Criteria				
Aerosol Level	*Maximum Ceiling Height (ft)*	*Maximum Storage Height (ft)*	*Sprinkler Type/Nominal Orifice (gpm/psi$^{0.5}$)*	*Response/ Nominal Temperature Rating**	*Design (Density/Area) (# Sprinklers @ Discharge Pressure)*	*Water Supply Duration (hr)*	*Hose Stream Demand (gpm)*
2	25	18	Large drop K = 11.6	SR/Ordinary	15 @ 50 psi	2	500
		20	ESFR-pendent K = 14.0	QR/Ordinary	12 @ 50 psi	1	250
			ESFR-pendent K = 16.8	QR/Ordinary	12 @ 35 psi	1	250
			ESFR-pendent K = 22.4	QR/Ordinary	12 @ 25 psi	1	250
			ESFR-pendent K = 25.2	QR/Ordinary	12 @ 25 psi	1	250
	30	5	Spray K ≥ 8.0	SR/High	0.30 gpm/ft^2 over 2500 ft^2	2	500
		15	ESFR-pendent K = 14.0	QR/Ordinary	12 @ 50 psi	1	250
			ESFR-pendent K = 16.8	QR/Ordinary	12 @ 35 psi	1	250
			ESFR-pendent K = 22.4	QR/Ordinary	12 @ 25 psi	1	250
			ESFR-pendent K = 25.2	QR/Ordinary	12 @ 25 psir	1	250
3	20	5	Spray K ≥ 8.0	SR/High	0.30 gpm/ft^2 over 2500 ft^2	2	500
		10	Large drop K = 11.6	SR/Ordinary	15 @ 75 psi	2	500
	25	15	ESFR-pendent K = 14.0	QR/Ordinary	12 @ 50 psi	1	250
			ESFR-pendent K = 16.8	QR/Ordinary	12 @ 35 psi	1	250
			ESFR-pendent K = 22.4	QR/Ordinary	12 @ 25 psi	1	250
			ESFR-pendent K = 25.2	QR/Ordinary	12 @ 25 psi	1	250
	30	5	Spray K ≥ 11.2	SR/High	0.60 gpm/ft^2 over 2500 ft^2	2	500
		15	ESFR-pendent K = 14.0	QR/Ordinary	12 @ 75 psi	1	250
			ESFR-pendent K = 16.8	QR/Ordinary	12 @ 52 psi	1	250
			ESFR-pendent K = 22.4	QR/Ordinary	12 @ 45 psi	1	250
			ESFR-pendent K = 25.2	QR/Ordinary	12 @ 25 psi	1	250

*QR = Quick Response; SR = Standard Response.

Source: NFPA 30B, *Code for the Manufacture and Storage of Aerosol Products,* Table 6.3.2.7(b).

has produced a substantial knowledge of appropriate sprinkler design and storage arrangements. It is very important that Level 2 and Level 3 aerosol products be arranged and protected according to the storage tables provided.

For the design and evaluation of sprinkler protection, Level 1 aerosol products are considered to be a Class III commodity, as defined by NFPA 13. Protective criteria for these commodities can be drawn from the standard appropriate for the storage configuration.

TABLE 6.16.4 Sprinkler Design for Rack Storage of Cartoned Level 2 Aerosol Products (SI Units)

		Ceiling Sprinkler Protection Criteria			In-Rack Sprinkler Protection Criteria					
						Sprinkler Type				
Maximum Roof Height (m)	*Maximum Storage Height (m)*	*Sprinkler Type/ Nominal Orifice ($L/min/bar^{0.5}$)*	*Response/ Nominal Temperature Rating**	*Design (Density/Area) (# Sprinklers @ Discharge Pressure)*	*Layout*	*Sprinkler Type/ Nominal Orifice ($L/min/bar^{0.5}$)*	*Response/ Nominal Temperature Rating*	*Discharge Flow (L/min)*	*Hose Stream Demand (L/min)*	*Water Supply Duration (hr)*
7.6	6.1	ESFR-pendent K = 202	QR/Ordinary	12 @ 3.4 bar	NA	NA	NA	NA	950	1
		ESFR-pendent K = 235	QR/Ordinary	12 @ 2.4 bar	NA	NA	NA	NA	950	1
		ESFR-pendent K = 314	QR/Ordinary	12 @ 1.7 bar	NA	NA	NA	NA	950	1
		ESFR-pendent K = 363	QR/Ordinary	12 @ 1.7 bar	NA	NA	NA	NA	950	1
9.1	4.6	ESFR-pendent K = 202	QR/Ordinary	12 @ 3.4 bar	NA	NA	NA	NA	950	1
		ESFR-pendent K = 235	QR/Ordinary	12 @ 2.4 bar	NA	NA	NA	NA	950	1
		ESFR-pendent K = 314	QR/Ordinary	12 @ 1.7 bar	NA	NA	NA	NA	950	1
		ESFR-pendent K = 363	QR/Ordinary	12 @ 1.7 bar	NA	NA	NA	NA	950	1
	6.1	Spray K ≥ 115	SR/High	12 mm/min over 232 m^2	Fig. 1 a–d	Spray K ≥ 81	QR/Ordinary	114	1900	2
	7.6	ESFR-pendent K = 202	QR/Ordinary	12 @ 3.4 bar	Fig. 1 a–d	Spray K ≥ 81	QR/Ordinary	114	950	1
		ESFR-pendent K = 235	QR/Ordinary	12 @ 2.4 bar	Fig. 1 a–d	Spray K ≥ 81	QR/Ordinary	114	950	1
		ESFR-pendent K = 314	QR/Ordinary	12 @ 1.7 bar	Fig. 1 a–d	Spray K ≥ 81	QR/Ordinary	114	950	1
		ESFR-pendent K = 363	QR/Ordinary	12 @ 1.7 bar	Fig. 1 a–d	Spray K ≥ 81	QR/Ordinary	114	950	1
		Spray K ≥ 161	SR/High	16 mm/min over 232 m^2	Fig. 1 a–d	Spray K ≥ 81	SR or QR/ Ordinary	114	1900	2
Unlimited	Unlimited	See Protection for Level 3 Aerosols with Unlimited Building and Storage Heights								

Note: See Section 6.3.2.9.1 of NFPA 30B for in-rack sprinkler design.
*QR = Quick Response; SR = Standard Response; NA = Not Applicable.
Source: NFPA 30B, *Code for the Manufacture and Storage of Aerosol Products,* Table 6.3.2.7(e).

TABLE 6.16.5 Sprinkler Design for Rack Storage of Cartoned Level 2 Aerosol Products (English Units)

		Ceiling Sprinkler Protection Criteria			In-Rack Sprinkler Protection Criteria					
						Sprinkler Type				
Maximum Roof Height (ft)	*Maximum Storage Height (ft)*	*Sprinkler Type/ Nominal Orifice (gpm/psi$^{0.5}$)*	*Response/ Nominal Temperature Rating**	*Design (Density/Area) (# Sprinklers @ Discharge Pressure)*	*Layout*	*Sprinkler Type/ Nominal Orifice (gpm/psi$^{0.5}$)*	*Response/ Nominal Temperature Rating*	*Discharge Flow (gpm)*	*Hose Stream Demand (gpm)*	*Water Supply Duration (hr)*
25	20	ESFR-pendent K = 14.0	QR/Ordinary	12 @ 50 psi	NA	NA	NA	NA	250	1
		ESFR-pendent K = 16.8	QR/Ordinary	12 @ 35 psi	NA	NA	NA	NA	250	1
		ESFR-pendent K = 22.4	QR/Ordinary	12 @ 25 psi	NA	NA	NA	NA	250	1
		ESFR-pendent K = 25.2	QR/Ordinary	12 @ 25 psi	NA	NA	NA	NA	250	1
30	15	ESFR-pendent K = 14.0	QR/Ordinary	12 @ 50 psi	NA	NA	NA	NA	250	1
		ESFR-pendent K = 16.8	QR/Ordinary	12 @ 35 psi	NA	NA	NA	NA	250	1
		ESFR-pendent K = 22.4	QR/Ordinary	15 @ 25 psi	NA	NA	NA	NA	250	1
		ESFR-pendent K = 25.2	QR/Ordinary	12 @ 25 psi	NA	NA	NA	NA	250	1
	20	Spray K ≥ 8.0	SR/High	0.3 gpm/ft^2 over 2500 ft^2	Fig. 1 a–d	Spray K ≥ 5.6	QR/Ordinary	30	500	2
	25	ESFR-pendent K = 14.0	QR/Ordinary	12 @ 50 psi	Fig. 1 a–d	Spray K ≥ 5.6	QR/Ordinary	30	250	1
		ESFR-pendent K = 16.8	QR/Ordinary	12 @ 35 psi	Fig. 1 a–d	Spray K ≥ 5.6	QR/Ordinary	30	250	1
		ESFR-pendent K = 22.4	QR/Ordinary	12 @ 25 psi	Fig. 1 a–d	Spray K ≥ 5.6	QR/Ordinary	30	250	1
		ESFR-pendent K = 25.2	QR/Ordinary	12 @ 25 psi	Fig. 1 a–d	Spray K > 5.6	QR/Ordinary	30	250	1
		Spray K ≥ 11.2	SR/High	0.4 gpm/ft^2 over 2500 ft^2	Fig. 1 a–d	Spray K ≥ 5.6	SR or QR/ Ordinary	30	500	2
Unlimited	Unlimited	See Protection for Level 3 Aerosols with Unlimited Building and Storage Heights								

Note: See Section 6.3.2.9.1 of NFPA 30B for in-rack sprinkler design.
*QR = Quick Response; SR = Standard Response; NA = Not Applicable.
Source: NFPA 30B, *Code for the Manufacture and Storage of Aerosol Products,* Table 6.3.2.7(f).

SUMMARY

The manufacture and storage of aerosol products involve fire hazards present throughout the process, including the usage of containers, propellants, base products, and the aerosol products themselves. Effective fire prevention includes proper handling and storage procedures, the installation of fire detectors such as gas detection systems, and the installation of audible and visual alarms. For fire protection purposes, aerosol products have been divided into three levels, based on the aggregate chemical heat of combustion. An appropriate fire suppression system depends on the level of aerosol product and the type of facility. For example, alcohol-based and petroleum solvent–based aerosol products in a warehouse setting are best protected by a quick-response sprinkler system.

As with other NFPA codes and standards, the experts on the technical committee are constantly working to update this code to the most up-to-date and safest practices known.

BIBLIOGRAPHY

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1. Best, R., "$100 Million Fire in Kmart Distribution Center," *Fire Journal,* Vol. 77, No. 2, 1983, pp. 36–42.
2. Isner, M. S., "$49 Million Loss in Sherwin-Williams Warehouse Fire," *Fire Journal,* Vol. 82, No. 2, 1988, pp. 65–73.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the manufacture and storage of aerosol products discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 30B, *Code for the Manufacture and Storage of Aerosol Products*
NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*

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Factory Mutual Research Corporation, "Aerosol Flammability Test," Technical Advisory Bulletin, filed with Loss Prevention Data Sheet 7-29S, Factory Mutual Research Corp., Norwood, MA.
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Sanders, P. A., *Handbook of Aerosol Technology,* 2nd ed., Van Nostrand Reinhold, New York, 1979.
UL 913, *Intrinsically Safe Apparatus and Associated Apparatus for Use in Class I, II, and III, Division I, Hazardous (Classified) Locations,* Underwriters Laboratories Inc., Northbrook, IL, 1988.

Chapter 17

Tables and Charts

Compiled by
Vytenis Babrauskas

Chapter Contents

Notes to Tables 6.17.1, 6.17.2, 6.17.3, 6.17.4, and 6.17.5
Notes to Table 6.17.7

NOTES TO TABLES 6.17.1, 6.17.2, 6.17.3, 6.17.4, AND 6.17.5

Heats of Combustion: The heat of combustion is, by definition, the enthalpy of reaction when fuel and oxidant at standard conditions are reacted and form products at standard conditions. A unique value for the heat of combustion is possible only if these conditions are fully specified.[1,2] In normal combustion work the standard conditions are taken as follows:

1. Fuel and oxidant enter at 1 atmosphere pressure and 25°C (298 K) temperature. An amount of heat, which is equal to the heat of combustion, is extracted, so that the products are also at 25°C and 1 atmosphere.
2. The oxidant is gaseous oxygen.
3. The main products consist of liquid H_2O, gaseous CO_2, and gaseous N_2. There is no CO formed.
4. For fuels containing sulfur, the standard products include liquid $H_2SO_4 \cdot 115H_2O$. For chlorine-containing fuels reference states consisting of either liquid HCl in water solution or gaseous Cl_2 have been used.
5. In the combustion of silicones, the silicon goes to amorphous silica, SiO_2.

The state of the fuel—gaseous, liquid, or solid—is not standardized and must be specified. The heat of combustion as defined above is termed the gross or upper value and is customarily determined in an oxygen bomb calorimeter.[3] For common materials the value is a negative number; however, customarily a minus sign is included in the definition to make heat of combustion a positive value.[4] Heat of combustion, enthalpy of combustion, calorific value, and heating value are synonyms, the latter two being used more commonly in the heating industry.

In many cases the products are not cooled down to 25°C. For modest temperature differences the change in the effective value could be taken as $C_p(T - 25°)$, where C_p is the constant pressure heat capacity of the products. For this relationship to hold, the enthalpy curve has to be smooth and cannot include condensation. Thus it often becomes convenient to define a lower, or net, heat of combustion where the products are as before except that H_2O stays in gaseous form (and sulfur, if any, goes into gaseous SO_2). The relationship between the values for simple fuels can be expressed as:

$$\Delta h_c^l = \Delta h_c^u - 0.2183\ [\%H]$$

where

Δh_c^l = lower heat of combustion (MJ/kg)

Δh_c^u = upper heat of combustion (MJ/kg)

[%H] = percent, by mass, of hydrogen in fuel

In practice, combustion is rarely complete. For example, some carbon often goes to CO instead of CO_2. Reactions with fuels containing sulfur, or chlorine or other halogens can go into

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TABLE 6.17.1 Heats of Combustion and Related Properties for Pure, Simple Substances

Material	*Composition*	*W Molecular Weight*	Δh_c^u *Gross (MJ/kg)*	Δh_c^l *Net (MJ/kg)*	$\Delta h_c^l/r_o$ *(MJ/kg O_2)*	r_o *Oxygen-Fuel Mass Ratio*	T_b *Boiling Temperature (°C)*	Δh_v *Latent Heat of Vaporization (kJ/kg)*	C_{pl} *Liquid Heat Capacity (kJ/kg-°C)*	C_{pv} *Vapor Heat Capacity (kJ/kg-°C)*
acetaldehyde	C_2H_4O	44.05	27.07	25.07	13.81	1.816	20.8	583	1.94	1.24
acetic acid	$C_2H_4O_2$	60.05	14.56	13.09	12.28	1.066	118.1	395	2.05	1.11
acetone	C_3H_6O	58.08	30.83	28.56	12.96	2.204	56.5	501	2.12	1.29
acetylene	C_2H_2	26.04	49.91	48.22	15.70	3.072	–84.0	—	—	1.69
acrolein	C_3H_4O	56.06	29.08	27.51	13.77	1.998	52.5	505	—	1.17
acrylonitrile	C_3H_3N	53.06	33.16	31.92	14.11	2.262	77.3	615	2.10	1.20
(allene) → propadiene										
ammonium perchlorate*	NH_4ClO_4	117.49	2.35	2.16	3.97	0.545	—	—	—	—
iso-amyl alcohol	$C_5H_{12}O$	88.15	37.48	34.49	12.67	2.723	132.0	501	2.90	1.50
aniline	C_6H_7N	93.12	36.44	34.79	13.06	2.663	184.4	478	2.08	1.16
benzaldehyde	C_7H_6O	106.12	33.25	32.01	13.27	2.412	179.2	385	1.61	0.97
benzene	C_6H_6	78.11	41.83	40.14	13.06	3.073	80.1	389	1.72	1.05
benzoic acid*	$C_7H_6O_2$	122.12	26.43	25.35	12.90	1.965	250.8	415	2.12	0.85
benzyl alcohol	C_7H_8O	108.13	34.56	32.93	13.09	2.515	205.7	467	2.00	1.19
bicyclohexyl	$C_{12}H_{22}$	166.30	45.35	42.44	12.61	3.367	236.0	263	1.70	—
1,2-butadiene	C_4H_6	54.09	47.95	45.51	13.99	3.254	10.8	—	2.27	1.48
1,3-butadiene	C_4H_6	54.09	46.99	44.55	13.69	3.254	–4.4	338	2.29	1.47
(1,3-butadiyne) → diacetylene										
n-butane	C_4H_{10}	58.12	49.50	45.72	12.77	3.579	–0.5	26	2.30	1.68
iso-butane	C_4H_{10}	58.12	48.95	45.17	12.62	3.579	–11.8	—	2.23	1.67
1-butene	C_4H_8	56.10	48.44	45.31	13.24	3.422	–6.2	—	2.22	1.53
n-butylamine	$C_4H_{11}N$	73.14	41.75	38.45	12.84	2.994	77.8	372	2.57	1.62
d-camphor*	$C_{10}H_{16}O$	152.23	38.75	36.44	12.84	2.838	203.4	—	—	0.82
carbon*	C	12.01	32.80	32.80	12.31	2.664	4200.0	—	—	0.71
carbon disulfide	CS_2	76.13	6.34	6.34	5.03	1.261	46.5	351	1.00	0.60
carbon monoxide	CO	28.01	10.10	10.10	17.69	0.571	–191.3	—	—	1.04
cellulose*	$C_6H_{10}O_5$	162.14	17.47	16.12	13.61	1.184	—	—	1.16	—
(chloroethylene) → vinyl chloride										
(chloroform) → trichloromethane										
chlorotrifluoroethylene	C_2F_3Cl	116.47	2.00	2.00	3.64	0.549	–28.3	188	1.34	0.72
m-cresol	C_7H_8O	108.13	34.26	32.64	12.98	2.515	202.2	399	2.00	1.13
cumene	C_9H_{12}	120.19	43.40	41.20	12.90	3.195	152.3	312	1.77	1.26
cyanogen	C_2N_2	52.04	21.06	21.06	17.12	1.230	–21.2	—	2.03	1.12
cyclobutane	C_4H_8	56.10	48.91	45.77	13.38	3.422	12.9	—	1.89	1.29
cyclohexane	C_6H_{12}	84.16	46.58	43.45	12.70	3.422	80.7	357	1.84	1.26
cyclohexene	C_6H_{10}	82.14	45.67	42.99	12.99	3.311	82.8	371	1.80	1.28
cyclohexylamine	$C_6H_{13}N$	99.18	41.05	38.17	12.79	2.984	134.5	—	—	—
cyclopentane	C_5H_{10}	70.13	46.93	43.80	12.80	3.422	49.3	389	2.23	1.18
cyclopropane	C_3H_6	42.08	49.70	46.57	13.61	3.422	–32.9	—	1.92	1.33
(decahydronaphthalene) → *cis*-decalin										
cis-decalin	$C_{10}H_{18}$	138.24	45.49	42.63	12.70	3.356	195.8	309	1.67	1.21
n-decane	$C_{10}H_{22}$	142.28	47.64	44.24	12.69	3.486	174.1	276	2.19	1.65
diacetylene	C_4H_2	50.06	46.60	45.72	15.89	2.877	10.3	—	—	1.47
(diamine) → hydrazine										
diborane	H_6B_2	27.69	79.80	79.80	23.02	3.467	–92.5	—	—	1.75
dichloromethane	CH_2Cl_2	84.94	6.54	6.02	10.65	0.565	39.7	330	1.18	0.60
diethyl cyclohexane	$C_{10}H_{20}$	140.26	46.30	43.17	12.58	3.422	174.0	—	1.87	—
diethyl ether	$C_4H_{10}O$	74.12	36.75	33.79	13.04	2.590	34.6	360	2.34	1.52
(2,4 diisocyanotoluene) → toluene diisocyanate										
(diisopropyl ether) → *iso*-propyl ether										
dimethylamine	C_2H_7N	45.08	38.66	35.25	13.24	2.662	6.9	577	3.03	1.60
(dimethyl aniline) → xylidene										
dimethyldecalin	$C_{12}H_{22}$	166.30	45.70	42.79	13.15	3.254	220.0	260	—	—

TABLE 6.17.1 Continued

Material	Composition	W Molecular Weight	Δh_c^u Gross (MJ/kg)	Δh_c^l Net (MJ/kg)	$\Delta h_c^l / r_o$ (MJ/kg O_2)	r_o Oxygen-Fuel Mass Ratio	T_b Boiling Temperature (°C)	Δh_v Latent Heat of Vaporization (kJ/kg)	C_{pl} Liquid Heat Capacity (kJ/kg-°C)	C_{pv} Vapor Heat Capacity (kJ/kg-°C)
(dimethyl ether) → methyl ether										
1,l-dimethylhydrazine (UDMH)	$C_2H_8N_2$	60.10	32.95	30.03	14.10	2.130	25.0	578	2.73	—
dimethyl sulfoxide	C_2H_6SO	78.13	29.88	28.19	15.30	1.843	189.0	677	1.89	1.14
1,3 dioxane	$C_4H_8O_2$	88.10	26.57	24.58	9.66	2.543	105.0	404	1.63	1.02
1,4 dioxane	$C_4H_8O_2$	88.10	26.83	24.84	9.77	2.543	101.1	406	1.74	1.07
ethane	C_2H_6	30.07	51.87	47.49	12.75	3.725	–88.6	—	—	1.75
ethanol	C_2H_6O	46.07	29.67	26.81	12.87	2.084	78.5	837	2.43	1.42
(ethene) → ethylene										
ethyl acetate	$C_4H_8O_2$	88.10	25.41	23.41	12.89	1.816	77.2	367	1.94	1.29
ethyl acrylate	$C_5H_8O_2$	100.12	27.44	25.69	13.39	1.918	100.0	290	—	1.14
ethylamine	C_2H_7N	45.08	38.63	35.22	13.23	2.662	16.5	—	2.89	1.61
ethyl benzene	C_8H_{10}	106.16	43.00	40.93	12.93	3.165	136.1	339	1.75	1.21
ethylene	C_2H_4	28.05	50.30	47.17	13.78	3.422	–103.9	—	2.38	1.56
ethylene glycol	$C_2H_6O_2$	62.07	19.17	17.05	13.22	1.289	197.5	800	2.43	1.56
ethylene oxide	C_2H_4O	44.05	29.65	27.65	15.23	1.816	10.7	978	1.97	1.10
(ethylene trichloride) → trichloroethylene										
(ethyl ether) → diethyl ether										
formaldehyde	CH_2O	30.03	18.76	17.30	16.23	1.066	–19.3	—	—	1.18
formic acid	CH_2O_2	46.03	5.53	4.58	13.15	0.348	100.5	476	2.15	0.98
furan	C_4H_4O	68.07	30.61	29.32	13.86	2.115	31.4	398	1.69	0.96
α-D-glucose*	$C_6H_{12}O_6$	180.16	15.55	14.08	13.21	1.066	—	—	—	—
(glycerine) → glycerol										
glycerol	$C_3H_8O_3$	92.10	17.95	16.04	13.19	1.216	290.0	800	2.42	1.25
(glycerol trinitrate) → nitroglycerin										
n-heptane	C_7H_{16}	100.20	48.07	44.56	12.68	3.513	98.4	316	2.20	1.66
n-heptene	C_7H_{14}	98.18	47.44	44.31	12.95	3.422	93.6	317	2.17	1.58
hexadecane	$C_{16}H_{34}$	226.43	47.25	43.95	12.70	3.462	286.7	226	2.22	1.64
hexamethyl-disiloxane	$C_6H_{18}Si_2O$	162.38	38.30	35.80	15.16	2.364	100.1	192	2.01	—
(hexamethylenetetramine) → methenamine										
n-hexane	C_6H_{14}	86.17	48.31	44.74	12.68	3.528	68.7	335	2.24	1.66
n-hexene	C_6H_{12}	84.16	47.57	44.44	12.99	3.422	63.5	333	2.18	1.57
hydrazine	H_4N_2	32.05	52.08	49.34	49.40	0.998	113.5	1180	3.08	1.65
hydrazoic acid	HN_3	43.02	15.28	14.77	79.40	0.186	35.7	690	—	1.02
hydrogen	H_2	2.00	141.79	130.80	16.35	8.000	–252.7	—	—	14.42
(hydrogen azide) → hydrazoic acid										
hydrogen cyanide	HCN	27.03	13.86	13.05	8.82	1.480	25.7	933	2.61	1.33
hydrogen sulfide	H_2S	34.08	48.54	47.25	16.77	2.817	–60.3	548	—	1.00
maleic anhydride*	$C_4H_2O_3$	74.04	18.77	18.17	14.01	1.297	202.0	—	0.91	1.22
melamine*	$C_3H_6N_6$	126.13	15.58	14.54	12.73	1.142	—	—	—	—
methane	CH_4	16.04	55.50	50.03	12.51	4.000	–161.5	—	—	2.23
methanol	CH_4O	32.04	22.68	19.94	13.29	1.500	64.8	1101	2.37	1.37
methenamine*	$C_6H_{12}N_4$	140.19	29.97	28.08	13.67	2.054	—	—	—	—
2-methoxyethanol	$C_3H_8O_2$	76.09	24.23	21.92	13.03	1.682	124.4	583	2.23	—
methylamine	CH_5N	31.06	34.16	30.62	13.21	2.318	–6.3	—	—	1.61
(2-methyl 1-butanol) → *iso*-amyl alcohol										
(methyl chloride) → dichloromethane										
methyl ether	C_2H_6O	46.07	31.70	28.84	13.84	2.084	–24.9	—	—	1.43
methyl ethyl ketone	C_4H_8O	72.10	33.90	31.46	12.89	2.441	79.6	434	2.30	1.43
1-methylnaphthalene	$C_{11}H_{10}$	142.19	40.88	39.33	12.95	3.038	244.7	323	1.58	1.12
methyl methacrylate	$C_5H_8O_2$	100.11	27.37	25.61	12.33	2.078	101.0	360	1.91	—
methyl nitrate	CH_3NO_3	77.04	8.67	7.81	75.10	0.104	64.6	409	2.04	0.99

(continued)

TABLE 6.17.1 Continued

Material	Composition	W Molecular Weight	Δh_c^u Gross (MJ/kg)	Δh_c^l Net (MJ/kg)	$\Delta h_c^l / r_o$ (MJ/kg O_2)	r_o Oxygen-Fuel Mass Ratio	T_b Boiling Temperature (°C)	Δh_v Latent Heat of Vaporization (kJ/kg)	C_{pl} Liquid Heat Capacity (kJ/kg-°C)	C_{pv} Vapor Heat Capacity (kJ/kg-°C)
(2-methyl propane) → *iso*-butane										
naphthalene*	$C_{10}H_8$	128.16	40.21	38.84	12.96	2.996	217.9	—	1.18	1.03
nitrobenzene	$C_6H_5NO_2$	123.11	25.11	24.22	14.90	1.625	210.7	330	1.52	—
nitroglycerin	$C_3H_5N_3O_9$	227.09	6.82	6.34	—	—	unstable	462	1.49	—
nitromethane	CH_3NO_2	61.04	11.62	10.54	15.08	0.699	101.1	567	1.74	0.94
n-nonane	C_9H_{20}	128.25	47.76	44.33	12.69	3.493	150.6	295	2.10	1.65
octamethyl-cyclotetrasiloxane	$C_8H_{24}Si_4O_4$	296.62	26.90	25.10	14.56	1.725	175.0	127	1.88	—
n-octane	C_8H_{18}	114.22	47.90	44.44	12.69	3.502	125.6	301	2.20	1.65
iso-octane	C_8H_{18}	114.22	47.77	44.31	12.65	3.502	117.7	272	2.15	1.65
1-octane	C_8H_{10}	112.21	47.33	44.20	12.92	3.422	121.3	301	2.19	1.59
(1-octylene) → 1-octene										
1,2-pentadiene	C_5H_8	68.11	47.31	44.71	13.60	3.288	44.9	405	2.21	1.55
n-pentane	C_5H_{12}	72.15	48.64	44.98	12.68	3.548	36.0	357	2.33	1.67
1-pentene	C_5H_{10}	70.13	47.77	44.64	13.04	3.422	30.0	359	2.16	1.56
phenol*	C_6H_6O	94.11	32.45	31.05	13.05	2.380	181.8	433	1.43	1.10
phosgene	$COCl_2$	98.92	1.74	1.74	10.74	0.162	8.3	247	1.02	0.58
propadiene	C_3H_4	40.06	48.54	46.35	14.51	3.195	–34.6	—	—	1.44
propane	C_3H_8	44.09	50.35	46.36	12.78	3.629	–42.2	343	2.23	1.67
n-propanol	C_3H_8O	60.09	33.61	30.68	12.81	2.396	97.2	686	2.50	1.45
iso-propanol	C_3H_8O	60.09	33.38	30.45	12.71	2.396	80.3	663	2.42	1.48
propene	C_3H_6	42.08	48.92	45.79	13.38	3.422	–47.7	—	2.42	1.52
(*iso*-propylbenzene) → cumene										
(propylene) → propene										
iso-propyl ether	$C_6H_{14}O$	102.17	39.26	36.25	12.86	2.819	67.8	286	2.14	1.55
propyne	C_3H_4	40.06	48.36	46.17	14.45	3.195	–23.3	—	—	1.51
styrene	C_8H_8	104.14	42.21	40.52	13.19	3.073	145.2	356	1.76	1.17
sucrose*	$C_{12}H_{22}O_{11}$	342.30	16.49	15.08	13.44	1.122	—	—	1.24	—
(1,2,3,4-tetrahydronaphthalene) → tetralin										
tetralin	$C_{10}H_{12}$	132.20	42.60	40.60	12.90	3.147	207.0	425	1.64	1.19
tetranitromethane	CN_4O_8	196.04	2.20	2.20	—	—	125.7	196	—	—
toluene	C_7H_8	92.13	42.43	40.52	12.97	3.126	110.4	360	1.67	1.12
toluene diisocyanate	$C_9H_6N_2O_2$	174.16	24.32	23.56	13.50	1.746	120.0	—	1.65	—
triethanolamine	$C_6H_{15}NO_3$	149.19	29.29	27.08	15.30	1.770	360.0	—	—	—
triethylamine	$C_6H_{15}N$	101.19	43.19	39.93	12.95	3.083	89.5	303	2.22	1.59
1,1,2-trichloroethane	$C_2H_3Cl_3$	133.42	7.77	7.28	11.02	0.660	114.0	260	1.11	0.67
trichloroethylene	C_2HCl_3	131.40	6.77	6.60	12.05	0.548	86.9	245	1.07	0.61
trichloromethane	$CHCl_3$	119.39	3.39	3.21	9.60	0.335	61.7	249	0.97	0.55
trinitromethane	CHN_3O_6	151.04	3.41	3.25	—	—	unstable	—	—	—
trinitrotoluene*	$C_7H_5N_3O_6$	227.13	15.12	14.64	19.80	0.740	240.0	322	1.40	—
trioxane	$C_3H_6O_3$	90.08	16.57	15.11	14.17	1.066	114.5	450	1.26	0.91
urea*	CH_4ON_2	60.06	10.52	9.06	11.34	0.799	—	—	—	1.55
vinyl acetate	$C_4H_6O_2$	86.09	24.18	22.65	13.54	1.673	72.5	167	2.00	1.05
vinyl acetylene	C_4H_4	52.07	47.05	45.36	14.76	3.073	5.1	—	—	1.41
vinyl bromide	C_2H_3Br	106.96	12.10	11.48	13.95	0.823	15.6	—	2.42	0.53
vinyl chloride	C_2H_3Cl	62.50	20.02	16.86	11.97	1.408	–13.8	—	1.43	0.86
(vinyl trichloride) → 1,1,2-trichlorolthane										
xylenes	C_8H_{10}	106.16	42.89	42.89	12.90	3.165	138–144	343	1.72	1.21
xylidine	$C_8H_{11}N$	121.22	38.28	36.29	12.79	2.838	192.7	366	1.77	—

*Denotes substance in crystalline solid form; otherwise, liquid if $T_b > 25°C$, gaseous if $T_b < 25°C$.

Sources: Domalski,[5] Gray,[1] Rossini,[6] Tinnermans,[7] Thermodynamics Research Center,[8] Stull et al.,[9] *Landolt-Bornstein Physikalisch-Chemische Tabellan,*[10] Reid et al.,[11] NACA,[12] Belenyessy et al.,[13] Rand Corp.,[14] Dreisback,[15] Cox and Pilcher,[16] Kharasch,[17] and Lipowitz.[18]

TABLE 6.17.2 Heats of Combustion and Related Properties for Plastics

Material	*Abbrev.*	*Recycling Symbol*	*CAS No.*	*Unit Composition*	*MW*	*Gross* Δh_c^u	*Net* Δh_c^l	$\Delta h_c^l/r$	r_o	Δh_m	C_{ps}	T_g (°C)	T_{soft} (°C)	T_m (°C)
(acetal) → polyoxymethylene														
(acrylic fibers) → polyacrylonitrile														
acrylic, rubber-modified				varies										137
acrylonitrile-butadiene styrene copolymer	ABS		9003-56-9	$C_{15}H_{17}N$	211.31	39.84	38.07	13.06	2.92		1.4–1.6	100	90	105–125
acrylonitrile-butadiene styrene copolymer, medium impact	ABS			varies								80		102–115
aniline-formaldehyde resin				C_8H_8N	118.16				2.71				>110	
aramid-arylester copolymer				$C_{14}H_{10}O_2N_2$	238.25	25.27	24.35	11.69	2.08					
arylether of hexafluorobisphenol-A and triphenylphosphine oxide				$C_{33}H_{21}O_3F_6P$	610.50	26.50	25.74							
benzyl cellulose				varies										150–180
bismaleimide	BMI		9006-49-9	$C_{21}H_{14}O_4N_2$	358.35	27.16	26.30	13.09	2.01			300		thermoset
bisphenol-A cyanate ester			1156-51-0	$C_{17}H_{14}O_2N_2$	278.31	29.92	28.81	12.85	2.24			150		263
bisphenol-E cyanate ester			47073-92-7	$C_{16}H_{12}O2N_2$	264.28	29.38	28.38	13.02	2.18					
bisphenol-M cyanate ester			127667-44-1	$C_{26}H_{24}O_2N_2$	396.49	34.39	33.06	13.21	2.50					
(butadiene/acrylonitrile copolymer) → nitrile rubber														
butadiene/styrene 8.58% copolymer			9003-55-8	$C_{4.18}H_{6.09}$	56.34	44.84	42.46	13.11	3.24		1.94			
butadiene/styrene 25.5% copolymer			9003-55-8	$C_{4.60}H_{6.29}$	61.59	44.19	41.94	13.08	3.21		1.82			
butyl rubber (copolymer of isobutylene and isoprene)	BR		9006-49-9	$C_{7.2}H_{13.5}$	100.09	45.10	42.13	12.46	3.38			–71		2
cellulose acetate	CA		9004-35-7	$C_{12}H_{16}O_8$	288.25	18.88	17.66	13.26	1.33		1.34	180	125–184	240–260
cellulose acetate butyrate	CAB		9004-36-8	$C_{12}H_{18}O_7$	274.27	23.70	22.26	14.67	1.52		1.70	140	125–175	180
cellulose acetate propionate			9004-39-1	$C_{13}H_{18}O_8$	302.28	20.01	18.70	13.08	1.43					190
cellulose nitrate	NC		9004-70-0	varies								53		decomp.
cellulose propionate	CP		9004-48-2	$C_{15}H_{22}O_8$	330.33	22.47	21.00	13.14	1.60			190		155
cellulose triacetate			9012-09-3	$C_{12}H_{16}O_8$	288.25				1.33				250	290–310
cellulose tripropionate														240
chlorinated PVC	CPVC		54242-36-3	$C_2H_2C_{l2}$	96.94	13.25	12.80	19.38	0.66			100		195–210
(chlorinated rubber) → polychloroprene														
chlorosulfonated polyethylene	CSPE		68037-39-8	$C_{282}H_{493}Cl_{71}SO_2$	6465.22	28.38	26.70	13.90	1.92			1		elastomer
diallyl phthalate	DAP		1-17-9	$C_7H_2O_2$	123.13	27.45	26.20	13.01	2.01			150		thermoset
dicyclopentadienyl bisphenol			1355-71-0	$C_{17}H_{17}ON$	251.33	33.64	32.15	12.17	2.64					
diglycidyl ether of bisphenol A	DGEBA		1675-54-3	$C_{21}H_{24}O_4$	340.42	30.80	29.25	12.45	2.35					

(continued)

TABLE 6.17.2 Heats of Combustion and Related Properties for Plastics

Material	*Abbrev.*	*Recycling Symbol*	*CAS No.*	*Unit Composition*	*MW*	*Gross* Δh_c^u	*Net* Δh_c^l	$\Delta h_c^l/r$	r_o	Δh_m	C_{ps}	T_g (°C)	T_{soft} (°C)	T_m (°C)
EPDM rubber (copolymer of polyethylene, polypropylene and a nonconjugated diene monomer)	EPDM		25038-36-2	C_5H_{10}	70.13	41.64	38.50	11.25	3.42					
epoxy, unhardened	EP		25928-94-3	$C_{31}H_{36}O_{5.5}$	496.62	32.92	31.33	13.05	2.40					
epoxy, hardened	EP		25928-94-3	$C_{39}H_{40}O_{8.5}$	644.74	30.27	28.90	13.01	2.22			120		thermoset
epoxy of bisphenol-A	EP		25068-38-6	$C_{11.85}H_{20.37}O_{2.83}N_{0.3}$	212.34	33.53	31.42	13.43	2.34					
epoxy of bisphenol-A, catalytic cure (Phenoxy-A)	EP			$C_{21}H_{24}O$	292.42	32.50	30.69	10.58	2.90			100		
epoxy, novolac, catalytic cure (Phenoxy-N)	EPN		28064-14-4	$C_{10}H_{11}O$	147.20	31.37	29.73	11.16	2.66			165		
ethyl cellulose			9004-57-3	varies								316	150	160–180
ethylene glycol ester of polyadipic acid														50–54
ethylene glycol ester of polyphthalic acid													60	
ethylene glycol ester of polysebacic acid														79
ethylene-propylene-diene rubber	EPDM		25038-36-2	C_5H_{10}	70.13				3.42		2.20	–49		elastomer
ethylene vinyl acetate	EVA		24937-78-8	C_5H_9O	85.13	35.63	33.30	13.12	2.54					105
fiberglass				varies										428–500
glycerol ester of polyphthalic acid														70
Halar (copolymer of polyethylene and polychlorotrifluoroethylene)	ECTFE		25101-45-5	$C_4H_4F_3Cl$	144.53	13.60	12.99	14.67	0.89					
hexafluorobisphenol-A cyanate ester			32728-27-1	$C_{17}H_8O_2N_2F_6$	386.26	18.71	18.25	13.35	1.37					
hexafluoropropylene/ polytetrafluoroethylene copolymer	Teflon FEP		25067-11-2	C_5F_{10}	250.06	7.70	7.70	24.07	0.32		1.09	58		275–290
Hypalon (chlorosulfonated polyethylene) rubber	CSM		68037-39-8	$C_{131}H_{231}O_2SCl_{31}$	2969.37	28.47	26.76	13.68	1.96					
Kalrez	FFKM		26425-79-6			6.55					0.95			elastomer
liquid crystal polymer	LCP			$C_{39}H_{22}O_{10}$	650.60	26.54	25.80	13.28	1.94					282–330
melamine formaldehyde	MF		9003-08-1	$C_6H_9N_6$	165.18	19.33	18.13	11.34	1.60		1.46			thermoset
modacrylic				$C_{21}H_{21}N_3Cl_4$	457.23								149	120–240
nitrile rubber (polybutadiene/ polyacrylonitrile copolymer); Buna-N	NBR		9003-18-3	varies		34.9–41.4						–30		elastomer
Noryl (polyphenylene oxide/polystyrene)						27.65								180
novolac cyanate ester			30944-92-4	$C_{24}H_{15}O_3N_3$	393.40	28.61	27.77	13.01	2.14					
nylon 6	PA6		25038-54-4	$C_6H_{11}ON$	113.16	30.94	28.80	12.30	2.33	26.00	1.52	40	170–185	207–225
nylon 6,6 (polyhexamethylene adiapamide)	PA66		32131-17-2	$C_{12}H_{22}O_2N_2$	226.32	30.90	28.76	12.33	2.33	57.80	1.47	47		250–265
nylon 6,10	PA610		9008-66-6	$C_{16}H_{30}O_2N_2$	282.43					71.70	1.56	30–50		210–222
nylon 6,12	PA612		24936-74-1	$C_{18}H_{24}O_2N_2$	300.40					80.10	1.60	46		207

nylon 11 (Rilsan)	PA11	25587-80-8	$C_{11}H_{21}ON$	183.29	36.99	34.47	12.54	2.75	44.70	1.66	46		177–202
nylon 12	PA12	24937-16-4	$C_{12}H_{23}ON$	197.32	39.26	36.70	13.12	2.80	48.40	1.64	37		170–185
phenol formaldehyde (Bakelite)	PF	9003-35-4	$C_{15}H_{12}O_2$	224.26	29.78	28.60	11.79	2.43		1.70	170		thermoset
polyacenaphthalene			$C_{12}H_8$	152.20	39.23	38.07	12.93	2.94			214		
polyacetaldehyde		9002-91-9	C_2H_4O	44.05				1.82			–32		165
polyacrylonitrile	PAN	25014-41-9	C_3H_3N	53.06	32.22	30.98	13.70	2.26		1.50	105	130–150	135
polyallylphthalate			$C_{14}H_{14}O$	198.26	27.74	26.19	9.54	2.74					
polyamideimide (Torlon)	PAI	42955-03-3	$C_{15}H_8O_3N_2$	264.24	24.97	24.30	12.95	1.88			275	278	
polyarylate	PAR		$C_{23}H_{18}O_4$	358.39	31.01	29.90	13.13	2.28			190	310	
polyaryletherketone	PAEK	55088-54-5	$C_{13}H_8O_2$	196.20	31.10	30.20	13.23	2.28			180		
polyarylsulfone		79293-56-4									282		303
polybenzimidazole	PBI	25928-81-8	$C_{20}H_{12}N_4$	316.31	22.22	21.39	10.07	2.12			425		
polybenzoxazine of bisphenol-A/aniline (b-a benzoxazine)			$C_{31}H_{30}O_2N_2$	462.59	34.89	33.46	12.90	2.59					
poly(benzoyl-1,4-phenylene), Poly-X	PX		$C_{13}H_8O$	180.21	38.35	37.37	14.51	2.57			160		
poly-1,4-butadiene	BDR	9003-17-2	C_4H_6	54.09	45.20	42.76	13.14	3.25	9.30	1.95	–58		148
poly-1-butene sulfone	P1BS		$C_4H_8O_2S$	120.17	21.55	20.09	11.60	1.73		1.20			
polybutyl acrylate	PBA		$C_7H_{12}O_2$	128.17						1.82	–55	–35	
poly-1-butylene (poly-1-butene)	PBUT	9003-27-4	C_4H_8	56.11	46.48	43.34	12.67	3.42		1.88	–24		124–138
poly(butylene terephthalate)	PBT	26062-94-2	$C_{12}H_{12}O_4$	220.22	27.90	26.70	14.14	1.89	32.00	1.61	40		224–237
polybutylmethacrylate	PBMA		$C_8H_{14}O_2$	142.20				2.36		1.85	20	33	
polycarbonate	PC	24936-68-3	$C_{16}H_{14}O_3$	254.28	31.53	30.32	13.38	2.27		1.26	145	150	220–265
polycarbonate/ABS blend	PC/ABS		$C_{45}H_{43}O_6N$	693.84	33.76	32.40	13.32	2.43			125		138–230
poly(carbon suboxide)			C_3O_2	68.03	13.78	13.78	14.65	0.94					
polychloral			C_2HOCl_3	76.48	5.29	5.00	7.97	0.63					
polychloroprene (Neoprene)	CR	9010-98-4	C_4H_5Cl	88.54	24.30	23.06	12.76	1.81			–40	120 (decomp.)	elastomer
polychlorotrifluoroethylene (Kel-F)	CTFE	9002-83-9	C_2F_3Cl	97.47	6.17	6.17	15.04	0.41	5.02	0.92	30–52		200–240
poly(diallyl phthalate)		25053-15-0										140	
poly(2,6-dimethyl-1,4-phenyleneoxide)		25134-01-4	C_8H_8O	120.15	34.21	32.75	12.94	2.53					
polydimethylsiloxane	PDMS	9006-65-9	C_2H_6OSi	74.16	19.53	17.75	10.31	1.72	2.75	1.59	–123		–39 to –29
polydimethylsiloxane (silicone rubber)	SIR		$C_{12}H_{10}O_3Si_2$	258.38	25.25	24.40					–127		elastomer
polydiphenylbutadiene			$C_{16}H_{10}$	202.26	39.30	38.21	13.06	2.93					
polyester, glycolized	PETG										80		
polyester, unsaturated	UPT		$C_{5.77}H_{6.25}O_{1.63}$	101.68	21.6–29.8	20.3–28.5	11.90	2.05		1.2–2.3	57		thermoset

(continued)

TABLE 6.17.2 Heats of Combustion and Related Properties for Plastics

Material	*Abbrev.*	*Recycling Symbol*	*CAS No.*	*Unit Composition*	*MW*	*Gross* Δh_c^u	*Net* Δh_c^l	$\Delta h_c^l/r$	r_o	Δh_m	C_{ps}	T_g (°C)	T_{soft} (°C)	T_m (°C)
polyester fabric				varies								80	229–254	238–292
polyester film				varies										250
polyester of hydroxybenzoic and hydroxynaphthoic acids			70679-92-4	$C_{39}H_{22}O_{10}$	650.60	26.54	25.80	13.28	1.94					
polyether, chlorinated				$C_5H_8OCl_2$	155.02	17.84	16.70	13.49	1.24					
polyetheretherketone	PEEK		29658-26-2	$C_{19}H_{12}O_3$	288.30	31.07	30.15	13.25	2.28			145–162		324–335
polyetherimide (Ultem)	PEI		61128-46-9	$C_{37}H_{24}O_6N_2$	592.61	29.59	28.70	13.29	2.16			215		337–425
polyetherketone	PEK		27380-27-4	$C_{13}H_8O_2$	196.20	31.07	30.17	13.21	2.28			161		367
polyetherketoneketone	PEKK		74970-25-5	$C_{20}H_{12}O_3$	300.31	31.15	30.27	13.21	2.29			157		305
polyethersulfone	PES		25667-42-9	$C_{12}H_8O_3S$	232.25	25.66	24.90	12.91	1.93		1.12	220–222	220	208–333
poly(ethyl acrylate)	PEA			$C_5H_{10}O_2$	102.13				2.04		1.75	–24	–5	
polyethylene	PE		9002-88-4	C_2H_4	28.05	47.74	44.60	13.03	3.42	4.11	1.83–2.3	–120		
polyethylene, LD (920 kg/m^3)	LDPE	4		C_2H_4	28.05			0.00	3.42			–125	95–110	105–115
polyethylene, MD (940 kg/m^3)	MDPE			C_2H_4	28.05			0.00	3.42			–125		120–135
polyethylene, HD (960 kg/m^3)	HDPE	2		C_2H_4	28.05			0.00	3.42			–125		120–137
polyethylene, chlorinated	CPE			C_2H_4	28.05			0.00	3.42			–12		elastomer
polyethylene, crosslinked	XLPE			C_2H_4	28.05			0.00	3.42		1.60	–78		135
polyethylene naphthalate	PEN			$C_{14}H_{10}O_4$	242.23	25.92	25.01	13.06	1.92					260
polyethylene oxide	PEO		25322-68-3	C_2H_4O	44.05	26.65	24.65	13.58	1.82			–67		35–69
polyethylene terephthalate	PET	1	25038-59-9	$C_{10}H_8O_4$	192.17	23.12	22.20	13.33	1.67	26.90	1.00	80		250–260
polyethylene-tetrafluoroethylene (Tefzel)	ETFE		25038-71-5	$C_8H_8F_8$	256.15	13.70					1.05	110		270
polyethylmethacrylate	PEMA		9003-42-3	$C_6H_{10}O_2$	114.14	29.53	27.60	13.13	2.10		1.45	65	81	
(polyformaldehyde) → polyoxymethylene														
(poly[hexamethylene adipamide]) → nylon 6,6														
poly-1-hexene sulfone				$C_6H_{12}O_2S$	148.22	29.78	28.00	13.65	2.05		1.30			
polyhydrocyanic acid				CHN	27.03	23.26	22.45	15.17	1.48					
polyimide, Kapton				$C_{22}H_{10}O_5N_2$	382.33				1.84		1.09	327–387		497
polyimide, thermoplastic	PI		26023-21-2	$C_{22}H_{10}O_5N_2$	382.33	26.03	25.45	13.82	1.84			250–365		340–388
polyimide, thermoset	PI											350		thermoset

polyisobutylene				C_4H_8	56.11	45.40	42.26	12.35	3.42	12.00	1.67	–73	–50	44
polyisobutylene (elastomer)												–59		elastomer
poly(isobutyl methacrylate)	PIBMA		9011-15-8	$C_8H_{14}O_2$	142.20	32.20	30.03	12.71	2.36		1.51	53	67	
polyisocyanurate	PIR			$C_6H_8O_2N$	126.13	25.70	24.30	13.69	1.78					thermoset
polyisocyanurate foam				varies		23.0–26.3	22.2–26.2							
polyisoprene (*cis*-1,4-polyisoprene; natural rubber)	NR		9006-04-6	C_5H_8	68.12	44.90	42.32	12.87	3.29		1.83	–70		40
polymethacrylate/butadiene/styrene	MBS			varies									100	100
polymethacrylic acid	PMAA		25087-26-7	$C_4H_7O_2$	87.10				1.75		1.11	228		
polymethylacrylate	PMA		9003-21-8	$C_4H_6O_2$	86.09				1.67		1.76	6	25	
poly-3-methyl-1-butene	PMB		25085-05-6	C_5H_{10}	70.13	46.55	43.41	12.69	3.42	4.35	1.86	60		300
(poly[methylene oxide]) → polyoxymethylene														
polymethylmethacrylate	PMMA		9011-14-7	$C_5H_8O_2$	100.12	26.86	25.10	13.09	1.92	9.60	1.44	114	105–120	160–200
poly-4-methyl-1-pentene	PMP		24979-98-4	C_6H_{12}	84.16	46.52	43.38	12.68	3.42	9.96	2.18	30	180	232–250
poly-α-methylstyrene	PAMS		25014-31-7	C_9H_{10}	118.18	42.31	40.45	12.99	3.11		1.30	168		176
polynitroethylene				$C_2H_3O_2N$	73.05	15.96	15.06	19.64	0.77					
polyoxymethylene	POM		9002-81-7	CH_2O	30.03	17.39	15.92	14.94	1.07	9.79	1.87	–69		160–185
polyoxyphenylene			25667-40-7	C_6H_4O	92.10	30.56	29.60	13.11	2.26			85		262
(polyoxypropylene) → polypropylene oxide														
polyoxytrimethylene	PO3M			C_3H_6O	58.08	31.52	29.25	13.27	2.20	9.44	2.01	–78		
poly-1-pentene	PPEN		25587-79-5	C_5H_{10}	70.13	45.58	42.44	12.40	3.42	6.30		–40		130
polyphenylacetylene				C_8H_6	102.14	40.00	38.71	13.00	2.98					
poly(*p*-phenylenebenzobisoxazole)	PBO		852-36-8	$C_{14}H_6O_2N_2$	234.21	29.18	28.62	14.44	1.98			>625		
polyphenylene ether	PPE			C_6H_4O	92.10	30.56	29.60	13.11	2.26			85		262
poly(*m*-phenylene isophthalamide)	Nomex		24938-60-1	$C_{14}H_{10}O_2N_2$	238.25	26.45	25.53	12.26	2.08		1.21	272		387–427
poly(*p*-phenylene isophthalamide)	Kevlar		26125-61-1	$C_{14}H_{10}O_2N_2$	238.25	26.92	26.00	12.49	2.08		1.30	307–347		500–600
poly(phenylene oxide) (2,6-dimethyl-1, 4-phenylene oxide)	PPO		25134-01-4	C_8H_8O	120.15	34.59	33.13	13.09	2.53		1.34	210	155	257–275
poly(phenylene sulfide)	PPS		9016-75-5	C_6H_4S	108.16	28.39	27.58	10.97	2.51			85–90		275–287
poly(*p*-phenylene terephthalamide)				$C_{14}H_{10}O_2N_2$	238.25	26.92	26.00	12.49	2.08					
poly(phenyl sulfone)	PPSU		25608-64-4	$C_{24}H_{16}O_4S$	400.45	28.08	27.20	12.38	2.20		1.17	219		360–390
polyphthalamide	PPA			$C_{14}H_{19}O_2N_2$	247.32	31.69	30.00	13.06	2.30			127		310
poly[2,2-propane bis(4-phenyl) carbonate]						31.10								
poly(propene sulfone)				$C_3H_6O_2S$	106.14	23.82	22.58	14.98	1.51					
poly-β-propiolactone	PPL			$C_3H_4O_2$	72.06	19.35	18.13	13.61	1.33	10.90	1.79	–24		93
polypropylene	PP	5	25085-53-4	C_3H_6	42.08	46.24	43.10	12.60	3.42	8.70		–13		160–176

(continued)

TABLE 6.17.2 Heats of Combustion and Related Properties for Plastics

Material	*Abbrev.*	*Recycling Symbol*	*CAS No.*	*Unit Composition*	*MW*	*Gross* Δh_c^u	*Net* Δh_c^l	$\Delta h_c^l/r$	r_o	Δh_m	C_{ps}	T_g (°C)	T_{soft} (°C)	T_m (°C)
poly(propylene oxide)	PPOX		25322-69-4	C_3H_6O	58.08	31.17	28.90	13.11	2.20	8.40	1.95	–75		66–82
poly(propylene sulfide)												–52 to –37		40–53
polystyrene	PS	6	9003-53-6	C_8H_8	104.15	42.20	40.51	13.18	3.07	10.00	1.21	100	70–115	110–115
polystyrene, foam				C_8H_8	104.15				3.07				74	82–93
polystyrene, high-impact	HIPS			$C_{14}H_{15}$	183.27	44.30	42.50	13.71	3.10			100		
poly(styrene-acrylonitrile)	SAN		9003-54-7	$C_{27}H_{27}N$	365.52				2.95			120		115–150
polystyrene/maleic anhydride				varies								115		
polystyrene/PMMA	PS/PMMA		25034-86-0	varies							1.42	102		177
polysulfone	PSU		25154-01-2	$C_4H_8O_2S$	120.17	24.04–26.47	22.25–25.01	14.79	1.73		1.30	190		190
polysulfone of bisphenol-A	PSF		25135-57-7	$C_{27}H_{22}O_4S$	442.53	30.28	29.19	12.61	2.31					
polysulfur				S	32.06	9.72	9.72	6.49	1.50					
polytetrafluoroethylene	Teflon PTFE		9002-84-0	C_2F_4	100.02	6.68	6.68			4.10	0.51	–73		325–332
polytetrafluoroethylene/perfluoro(propyl vinyl ether) copolymer	Teflon PFA		26425-79-6	C_5OF_{10}	266.05	5.00	5.00	20.79	0.24			–12		305–310
polytetrahydrofuran			24979-97-3	C_4H_8O	72.11	34.39	31.95	13.09	2.44			–84		
poly(tetramethylene oxide)	PTMO			C_4H_8O	72.11	34.34	31.90	13.07	2.44			–83		47
polytrifluoroethylene	P3FE			C_2HF_3	82.03	12.17	11.90	20.34	0.59	5.44	1.14	31		222
polyurea				$C_{15}H_{18}O_4N_4$	318.33	24.91	23.67	13.45	1.76					
polyurethane	PUR			$C_{80}H_{120}O_2N$	1127.83	28.64	26.30	8.50	3.09					
polyurethane, elastomer	PUR			varies								–50	175	elastomer
polyurethane, ester-based	PUR			$C_{6.3}H_{7.1}O_{2.1}N$	130.43	23.90	22.70	13.17	1.72					
polyurethane, flexible	PUR		9009-54-5	varies										62–97, 149
polyurethane, rigid	PUR			varies										120–160; 250
poly(vinyl acetal)	PVA			$C_6H_{10}O_2$	114.14				2.10				90–100	82–175
polyvinyl acetate	PVAc		9003-20-7	$C_4H_6O_2$	86.09	23.04	21.51	12.86	1.67		1.29	31	35–86	60–88
polyvinylalcohol	PVOH		9002-89-5	C_2H_4O	44.05	24.20	22.20	12.23	1.82	7.11	1.70	85		218–250
poly(vinyl benzoate)			24991-32-0	$C_9H_8O_2$	148.16						1.11	74		
poly(vinyl butyral)	PVB		63148-65-2	$C_8H_{14}O_2$	142.20	32.90	30.73	13.01	2.36			51	50–60	174

poly(*N*-vinylcarbazole)	PVK		25067-59-8	$C_{14}H_{11}N$	193.25	37.65	36.40	13.12	2.77		1.60	150	180–210	290
poly(vinyl chloride), flexible	PVC	3		$C_{26}H_{39}O_2Cl$	419.05	26.75	24.70	9.38	2.63			–25	75–115	150–185
poly(vinyl chloride), rigid	PVC	3	9002-86-2	C_2H_3Cl	62.50	17.95	16.89	13.20	1.28	11.00	0.90–1.20	81	90	210–230
poly(vinyl chloride)/poly(vinyl acetate)	PVC/PVA			varies										127
poly(vinyl fluoride)	PVF		24981-14-4	C_2H_3F	46.05	21.70	20.27	11.66	1.74	7.54	1.19	41–70	121	200–230
poly(vinyl formal)	PVFM		9003-33-2	$C_5H_8O_2$	100.12				1.92			103–113	140–170	210–220
poly(vinylidene chloride)	PVDC		9002-85-1	$C_2H_2Cl_2$	96.94	13.55	13.10	19.84	0.66		1.34	–18	116–140	156–200
poly(vinylidene fluoride)	PVDF		24937-79-9	$C_2H_2F_2$	64.04	14.39	13.70	13.71	1.00	6.70	1.38	–40		155–192
polyvinylidenefluoride/hexafluoropropylene copolymer (Viton A)	FKM		9011-17-0	$C_{10}H_7F_{13}$	374.17	12.71	12.30	16.92	0.73			–18		elastomer
poly(vinyl isobutyl ether)						35.80						–22	0	
poly(vinyl methyl ether)	PVM		9003-09-2	C_3H_6O	58.08	30.50	28.23	12.81	2.20			–13	55–70	144
styrene/acrylonitrile	SAN		9003-54-7	$C_{27}H_{27}N$	365.52	40.43	38.80	13.13	2.95					
styrene-butadiene rubber	SBR		9003-55-8	$C_{10}H_{13}$	133.21	44.15	42.00	13.20	3.18		1.83	–52		elastomer
polytetrafluoroethylene/polyethylene copolymer (Tefzel)	ETFE			$C_4H_4F_4$	128.08	16.88	16.19	16.20	1.00					271
tetramethylbisphenol-F cyanate ester				$C_{19}H_{18}O_2N_2$	306.36	31.23	29.94	12.74	2.35					
urea formaldehyde	UF			$C_3H_6O_2N_2$	102.09	15.90	14.61	13.31	1.10					thermoset
vinyl ester	VE			$C_{29}H_{36}O_8$	512.60	29.35	27.80	13.10	2.12			100		thermoset

Note: Nomenclature Description
- Abbrev.: abbreviation
- Recycling symbol
- CAS No.: unique identifier set by the American Chemical Society
- Unit composition
- MW: molecular weight
- Gross Δh_c^u: gross heat of combustion
- Net Δh_c^l: net heat of combustion
- $\Delta h_c^l/r$: oxygen consumption constant
- r_o: oxygen/fuel mass ratio
- Δh_m: enthalpy of melting (kJ/mol)
- C_{ps}: heat capacity (solid) (kJ/kg·°C)
- T_g: glass transition temperature
- T_{soft}: softening temperature
- T_m: melting temperature

Sources: Throne and Griskey,[19] Hognon,[20] NBS,[21] Roff and Scott,[22] Joshi,[23] Van Krevelen,[24] Berlin et al.,[25] Franz et al.,[26] Janssens,[27] Walters et al.,[28] Hshieh et al.,[29] "Safety Standard for Oxygen and Oxygen Systems,"[30] *Aldrich Handbook of Fine Chemicals*,[31] Ash and Ash,[32] ATHAS Thermal Analysis Data,[33] Braun,[34] Brydson,[35] Ellis,[36] Harwood,[37] Hatch,[38] Kourtides, Parker, and Hilado,[39] Krause, Lange, and Ezrin,[40] Lyon,[41] Stoliarov, Williams, Walters, Crowley, and Lyon,[42] and Van Krevelen.[43]

TABLE 6.17.3 Heat of Combustion of Miscellaneous Substances

Material	Δh_c^u Gross (MJ/kg)	Δh_c^l Net (MJ/kg)
(acetate) → cellulose acetate		
acrylic fiber	30.6–30.8	
blasting powder	2.1–2.4	
butter	38.5	
celluloid (cellulose nitrate and camphor)	17.5–20.6	16.4–19.2
cellulose acetate fiber, $C_6H_{12}O_6$	17.8–18.4	16.4–17.0
cellulose diacetate fiber, $C_{10}H_{14}O_7$	18.7	
cellulose nitrate, $C_6H_9N_1O_7/C_6H_8N_2O_9/C_6H_7N_3O_{11}$	9.11–13.48	
cellulose triacetate fiber, $C_{12}H_{16}O_8$	18.8	17.6
charcoal	33.7–34.7	33.2–34.2
coal-anthracite	30.9–34.6	30.5–34.2
-bituminous	24.7–36.3	23.6–35.2
coke	28.0–31.0	28.0–31.0
cork	26.1	
cotton	16.5–20.4	
corrugated cardboard boxes (made up with starch-based adhesive or silica-protein adhesive)	7.72	
diacetate	18.69	
dynamite	5.4	
epoxy, $C_{11.9}H_{20.4}O_{2.8}N_{0.3}C_{6.064}H_{7.550}O_{1.222}$	32.8–33.5	31.1–31.4
fat, animal	39.8	
flint powder	3.0–3.1	
fuel oil-No. 1	46.1	
-No. 6	42.5	
gasketing-chlorosulfonated polyethylene (Hypalon)	28.5	
-vinylidene fluoride/ hexafluoropropylene (Fluorel, Viton A)	14.0–15.1	
gasoline	46.8	43.7
jet fuel-JP1		43.0
-JP3		43.5
-JP4	46.6	43.5
-JP5	45.9	43.0
kerosene (jet fuel A)	46.4	43.3
lanolin (wool fat)	40.8	
lard	40.1	
leather	18.2–19.6	
lignin, $C_{2.6}H_3O$	24.7–26.4	23.4–25.1
lignite	22.4–33.3	
meat and bone meal	18.4	
modacrylic fiber	24.7	
naphtha	43.0–47.1	40.9–43.9
neoprene, C_5H_5Cl-gum	24.3	
-foam	9.7–26.8	
Nomex (polymethaphenylene isophthalamide) fiber, $C_{14}H_{10}O_2N_2$	27.0–28.7	
oats	13.3	
oil-castor	37.32	34.77
-coconut	37.45	34.94
-cottonseed	39.04	36.25
-linseed	39.37	37.03
-mineral	45.8–46.0	
-olive	39.6	
-rapeseed	39.71	37.29
-sesame	39.54	37.20
-solar	41.8	
-soybean	39.54	37.14
paper-brown	16.3–17.9	
-magazine	12.7	
-newsprint	19.7	
-wax	21.5	
paraffin wax	46.2	43.1
peat	16.7–21.6	
petroleum jelly ($C_{7.118}H_{12.957}O_{0.091}$)	45.9	
rayon fiber	13.6–19.5	
rubber-buna N	34.7–35.6	
-butyl	45.8	
-isoprene (natural) C_5H_8	44.9	42.3
-latex foam	33.9–40.6	
-GRS	44.2	
-tire, auto	32.6	
silicone rubber (SiC_2H_6O)	15.5–16.8	
-foam	14.0–19.5	
sisal	15.9	
spandex fiber	31.4	
starch	17.6	16.2
straw	15.6	
sulfur-rhombic		9.28
-monoclinic		9.29
tobacco	15.8	
triacetate	18.93	
wheat	16.3	
wood*-beech	20.0	18.7
-birch	20.0	18.7
-douglas fir	21.0	19.6
-maple	19.1	17.8
-red oak	20.2	18.7
-spruce	21.8	20.4
-white pine	19.2	17.8
-hardboard	19.9	
woodflour	19.8	
wool	20.7–26.6	

*The actual heat of combustion developed by wood during normal fires (in contrast to tests in the oxygen bomb) is 12.5 MJ/kg. For more information, see Heskestad, G., and Delichatsios, M. A., "Update: The Initial Convective Flow in Fire," *Fire Safety Journal,* Vol. 15, 1989, pp. 471–475.

Sources: *Landolt-Bornstein Physikalisch-Chemische Tabellan,*[10] NACA,[12] Throne and Griskey,[19] Moore,[44] Domalski et al.,[45] Bostic et al.,[46] Lobanov and Martynovskaya,[47] Ohe et al.,[48] Lowrie,[49] Koseki et al.,[50] Dean,[51] Wolański,[52] Ohe et al.,[53] Ng and Chee,[54] and Manchester.[55]

TABLE 6.17.4 Heats of Combustion of Selected Metals and Nonmetallic Elements

Element Symbol	*Element Name*	*Oxide Formed*	Δh_c *(MJ/kg)*
Al	Aluminum	Al_2O_3	31.06
B	Boron	B_2O_3	58.83
Ba	Barium	BaO	4.03
Be	Beryllium	BeO	67.48
Ca	Calcium	CaO	15.85
Cd	Cadmium	CdO	2.30
Ce	Cerium	CeO_2	7.77
Cr	Chromium	Cr_2O_3	10.78
Cu	Copper	CuO	2.48
Fe	Iron	FeO	4.87
Hf	Hafnium	HfO_2	6.42
Li	Lithium	Li_2O	43.08
Mg	Magnesium	MgO	24.73
Na	Sodium	Na_2O	9.00
Si	Silicon	SiO_2	32.44
Sr	Strontium	SrO	6.76
Th	Thorium	ThO_2	5.29
Ti	Titanium	TiO_2	19.6
U	Uranium	UO_2	4.56
W	Tungsten	WO_3	4.59
Zn	Zinc	ZnO	5.37
Zr	Zirconium	ZrO_2	12.03

Source: V. Babrauskas, *Ignition Handbook,* Fire Science Publishers/ Society of Fire Protection Engineers, Issaquah, WA, 2003.

a variety of products, depending on exact reaction conditions. Incomplete combustion acts to lower the heat of combustion. There are no simple general rules to aid in determining the degree of incomplete combustion. Also explosive and propellant materials rarely exhibit reactions where H_2O and CO_2 are the main products; thus, their heats of explosion or reaction will tend to be substantially different from the heat of combustion.

Even though the state of reactants is not described in the definition, most commonly it is taken as the natural state at ambient pressure and temperature. In some references, however, the gaseous state of fuels such as benzene or methanol is assumed, even though they would be normally considered as liquid fuels. The heat of combustion of fuels from the gaseous state is higher than from the liquid state by an amount equal to the fuel's heat of vaporization at 25°C. For combustion of plastic fuels, the most convenient reference state is the solid phase. In such cases, to compute the heat liberated in a given application, it is not necessary to subtract the heat of gasification from the heat of combustion.

Heats of combustion (per kg of fuel) are listed in Tables 6.17.1 through 6.17.4. Also listed in Tables 6.17.1 and 6.17.2 is r_o, the stoichiometric oxygen-fuel mass ratio. The heats can be seen to vary quite a bit for different fuels. Recently, however, increasing engineering use is made of the observation that the heat of combustion per kg of oxygen consumed is nearly constant for most organic fuels. It can be shown that a value of $\Delta h_c^l r_o$ = 13.1 MJ/kg O_2 is near-constant.[56] An assumption of constant heat of combustion per kg of oxygen is useful in heat release rate measurements and for air-limited combustion problems.

For certain fuels it is more convenient to express heats of combustion by use of equations or charts, rather than tables. Two such instances are woods and certain petroleum products. The gross heat of combustion for dry woods is typically in the vicinity of 18–21 MJ/kg. This value varies, however, according to the species and according to the part of the plant. Furthermore, when wood normally burns, pyrolysates are first released and burned, which are lower in calorific value, followed by burning of the remaining char, which has a higher value. The following empirical correlation can be derived, applicable to all species of dry woods, provided the percent carbon, by weight is known.[57]

$$\Delta h_c^u = 0.433\ [\%C] - 1.527$$

where Δh_c^u is the gross heat of combustion for dry wood (MJ/kg) and [C] is the percent of carbon, by weight. This correlation is equally applicable to charred wood and to wood pyrolysates, provided their ultimate analysis is known. For wet fuels, an additional correction should be made:

$$\Delta h_{c,eff}^u = \Delta h_c(1 - M/100) - 0.0257M$$

where M is the percent water in the fuel. Lower heats of combustion, if needed, can then be determined as noted above.

For petroleum products a series of empirical rules is available for estimating thermochemical properties, based on specific gravity or on API degrees[58] (see Table 6.17.10). A determination of the exact heat of combustion by calorimetry is usually not required for typical petroleum products, which include crude oils, fuel oils, kerosenes, and volatile products. These empirical rules are as follows:

Heat of combustion

$$\Delta h_c^u = 52.12 - 8.79d^2 - 0.14d\ \text{(MJ/kg)}$$

Percent hydrogen

$$[\%H] = 26 - 15d$$

Heat of vaporization, at 25°C

$$\Delta h_v = \frac{240}{d}\ \text{(kJ/kg)}$$

Specific heat at 25°C, liquid

$$C_{pl} = \frac{1770}{\sqrt{d}}\ \text{(J/kg°C)}$$

Specific heat at 25°C, vapor

$$C_{pv} = C_{pl} - \frac{380}{d}\ \text{(J/kg°C)}$$

In all the above relationships, d = specific gravity at 15.6°C (60°F). For conversion from degrees API, see Table 6.17.10. The relationship for [%H] can be used to obtain net heat of combustion, according to the general equation given earlier. A more detailed method, requiring additionally the determination

TABLE 6.17.5 Heats of Combustion of Selected Metal Alloys

Material	Δh_c *(MJ/kg)*
Copper alloys	
Bronze (88 Cu/10 Sb/2 Zn)	2.64
Red brass (85 Cu/15 Zn)	2.89
Cartridge brass (70 Cu/30 Zn)	3.33
Yellow brass (60 Cu/40 Zn)	3.62
Iron alloys	
Carbon steels	7.4–7.5
Stainless steels	7.7–8.4
Nickel alloys	
Incone 600	5.40
Monel 400	3.60

Sources: Hust and Clark,[59] Stull and Prophet,[60] and Brandes.[61]

of percent aromatics, volatility, and sulfur content, is available as an ASTM method.[65]

In some cases the combustion properties, including heat of combustion, are desired for burning metals. The specified combustion product in each case is a stable metal oxide in crystalline form. Tables 6.17.4 and 6.17.5 list the heats of combustion of selected metals, metal alloys, and nonmetallic elements. For further discussion consult the references.[59,62]

Also listed in the tables, where available, are T_b, the boiling point; the heat capacities C_{pl}, C_{pv}, and C_{ps}, of the liquid, vapor, and solid phases respectively, taken at constant pressure at T_b; and Δh_v, the latent heat of vaporization at T_b. For purposes where the total heat of vaporization (i.e., heat to bring a liquid at 25°C up to a gas at T_b) is desired, an estimate can be made by adding to Δh_v the quantity $C_{pl} \cdot (T_b - 25)$. More precise values can be obtained by using enthalpy tables.[8,60]

In some common applications, especially for building materials, a laboratory technique for assessing the possible effect

TABLE 6.17.6 Oxygen Index Values

Material	*Oxygen Index Value**	*Material*	*Oxygen Index Value**
methanol	11–12	nylon	20.1–26.0
benzene	13–16	birch wood	20.5
sulfur	13.6	polyester fibers	20.6
polyacetal	14.9	phenolic resin	21.0
polyoxymethylene	15.7	phenolic-paper laminate	21.7
acetone	16.0	polyvinyl alcohol	22.5
kitchen candle	16.0	polycarbonate	22.5–28.0
cotton	16.0–18.5	polyvinyl fluoride	22.6
mineral oil	16.1	red oak	23.0
polyurethane foam, typical	16.5	wool	23.8
cellulose acetate	16.8	neoprene rubber	26.3–40.0
styrene-butadiene-rubber foam	16.9	Nomex fibers	26.7–28.5
polybutadiene foam	17.1	modacrylic fibers	26.8
natural rubber foam	17.2	polyphenylene oxide	29.0
polymethylmethacrylate	17.3	silicone rubber	30.0
polyethylene	17.4	polysulfone	30–32
polypropylene	17.4	leather	34.8
polystyrene	17.6–18.3	carbon powder	35.0
polyacrylonitrile	18.0	phenol-formaldehyde resin	35.0
paper, cellulose filter	18.2	polyimide	36.5
polybutadiene	18.3	polyvinyl chloride	37.1–49
ABS	18.3–18.8	Kynol fibers	38.0
cellulose triacetate	18.4	polybenzimidazole	40.6–41.5
polyisoprene rubber	18.5	polyvinylidene fluoride	43.7
rayon	18.7–18.9	polyvinyl chloride, chlorinated	45–60
polymethylsiloxane (silicone fluid)	18.9	carbon black	56–63
cellulose	19.0	polyvinylidene chloride	60.0
cellulose acetate-butyrate	19.6	polychlorotrifluoroethylene	95.0
epoxy resin	19.8	polytetrafluoroethylene	95.0
polyethylene terephthalate	20.0		

*The values in the table above were determined using the ASTM Oxygen Test (D2863) and represent typical values for materials without added fire retardants. Adding fire retardants to polymers can increase substantially the measured oxygen index value.

Sources: Skinner,[62] Cullis and Hirschler,[63] and Factory Mutual Research Corp.[64]

TABLE 6.17.7 Miscellaneous Properties of Plastics and Other Combustibles

Material	*Density (kg/m^3)*	*Min. Radiant Flux for Ignition (kW/m^2)*	*Min. Mass Loss Rate for Ignition (g/m^2-sec)*	*Ignition Temperature (K)*	*Effective Heat of Gasification (MJ/kg)*	*Smoke Specific Extinction Area (m^2/kg)*	*Soot Yield (kg soot/kg specimen)*
ABS					3.2		
benzene, liquid						830–900	
cellulose					3.5	10–15	
Douglas fir					1.8		
fiberglass, FR	—	7	—	740	1.7–2.2	250–370	
nylon 6/6					2.3	410	0.14
paper, corrugated					2.2		
phenolic, foams, rigid	67	45	5.5	944	3.7		
polycarbonate					2.1		
polyethylene	920	19	2.5	761	1.5–2.7	290–510	
polyethylene, foams	36–143	19–22	2.5–2.6	761–807	1.5–2.7	360–810	
polyethylene, foam, chlorinated					2.1–3.1	1010–1360	
polyisocyanurate, foams, rigid	33–36	23	5.5–6.8	798	4.5		
polymethylmethacrylate	1170	18	4.4	751	1.6	110–260	0.012
polyoxymethylene	1400	17	4.5	740	2.4	0–10	
polypropylene	905	20	2.7	771	1.4–2.0	380–610	0.07–0.09
polystyrene	1050	29	4.0	846	1.7	730–1430	
polystyrene, foams, rigid	16–34	18–27	4.9–6.3	751–831	1.3–3.1	940–1300	
polytetrafluoroethylene		43		933			0.02
polyurethane, foams, flexible	29–47	16–30	5.3–7.2	729–852	1.2–2.7	100–500	
polyurethane, foams, rigid	36–321	20–28	6.9–8.4	771–838	2.0–4.5	100–1000	
polyvinyl chloride	1305	21	—	780	1.7–2.5	1100–1400	0.23
red oak	740	11	2.5	730	1.7–5.5	80–130	0.0002–0.018
styrene, liquid					0.64	780–920	

Sources: Tewarson;[66–68] Tewarson, Khan, and Steciak;[69] and Tewarson, Lee, and Pion.[70,71]

of incomplete combustion is desired. The potential heat test procedure used to be determined by NFPA 259, *Standard Test Method for Potential Heat of Building Materials.* The potential heat test is now rarely specified. Values of "effective heat of combustion" are more commonly determined using ASTM E1354, *Standard Test for Heat and Visible Smoke Release Rates for Materials and Production Using an Oxygen Consumption Calorimeter.*[72]

Conversion Units: To convert kcal/kg to megajoules/kg

multiply by 4.184×10^{-3}

to convert kcal/mol to MJ/kg multiply by $4.184/W$

where W = molecular weight (g/mol)

to convert kJ/mol to MJ/kg multiply by $1/W$

to convert Btu/lb to MJ/kg multiply by 2.322×10^{-3}

NOTES TO TABLE 6.17.7

In recent years measurement data have started to be tabulated on the engineering performance of plastics. These data are usually measured in heat release rate calorimeters on a bench scale (specimens typically 0.1 m dimension). A number of these data are summarized in Table 6.17.7. In many cases wide variations for a property are shown. These can be attributed to (a) specimen size differences, (b) specimen orientation differences, (c) air flow rate differences, (d) heating flux (irradiance) differences, and (e) specimen composition differences. The data for the plastics listed do not represent pure polymers, but rather engineering plastics, which vary in additives, degree of polymerization, and so on. When only a single number is indicated, this should be taken as reflecting a paucity of data, rather than a high precision of measurement.

The minimum flux needed for ignition has sometimes been considered to be a constant. Table 6.17.7 shows that it varies

TABLE 6.17.8 Specific Gravity Equivalents for Degrees Baumé (Liquids Lighter Than Water)

Baumé	*Specific Gravity*	*Pounds per Gallon**
10	1.0000	8.33
11	0.9929	8.27
12	0.9859	8.21
13	0.9790	8.16
14	0.9722	8.10
15	0.9655	8.04
16	0.9589	7.99
17	0.9524	7.93
18	0.9459	7.88
19	0.9396	7.83
20	0.9333	7.78
21	0.9272	7.72
22	0.9211	7.67
23	0.9150	7.62
24	0.9091	7.57
25	0.9032	7.53
26	0.8974	7.48
27	0.8917	7.43
28	0.8861	7.38
29	0.8805	7.34
30	0.8750	7.29
31	0.8696	7.24
32	0.8642	7.20
33	0.8589	7.15
34	0.8537	7.11
35	0.8485	7.07
36	0.8434	7.03
37	0.8383	6.98
38	0.8333	6.94
39	0.8284	6.90
40	0.8235	6.86
41	0.8187	6.82
42	0.8140	6.78
43	0.8092	6.74
44	0.8046	6.70
45	0.8000	6.66
46	0.7955	6.63
47	0.7910	6.59
48	0.7865	6.55
49	0.7821	6.52
50	0.7778	6.48
51	0.7735	6.44
52	0.7692	6.41
53	0.7650	6.37
54	0.7609	6.34
55	0.7568	6.30
56	0.7527	6.27
57	0.7487	6.24
58	0.7447	6.20
59	0.7407	6.17
60	0.7368	6.14
61	0.7330	6.11
62	0.7292	6.07
63	0.7254	6.04
64	0.7216	6.01
65	0.7179	5.98
66	0.7143	5.95
67	0.7107	5.92
68	0.7071	5.89
69	0.7035	5.86
70	0.7000	5.83
71	0.6965	5.80
72	0.6931	5.78
73	0.6897	5.75
74	0.6863	5.72
75	0.6829	5.69
76	0.6796	5.66
77	0.6763	5.63
78	0.6731	5.60
79	0.6699	5.58
80	0.6667	5.55
81	0.6635	5.52
82	0.6604	5.50
83	0.6573	5.48
84	0.6542	5.45
85	0.6512	5.42
86	0.6481	5.40
87	0.6452	5.38
88	0.6422	5.36
89	0.6393	5.33
90	0.6364	5.30
91	0.6335	5.28
92	0.6306	5.25
93	0.6278	5.23
94	0.6250	5.21
95	0.6222	5.18
96	0.6195	5.16
97	0.6167	5.14
98	0.6140	5.11
99	0.6114	5.09
100	0.6087	5.07
101	0.6061	5.05
102	0.6034	5.03
103	0.6009	5.00
104	0.5983	4.98
105	0.5957	4.96
106	0.5932	4.94
107	0.5907	4.92
108	0.5882	4.90
109	0.5858	4.88
110	0.5833	4.86

*One lb per gallon equals 119.8 kg/m^3.

TABLE 6.17.9 Specific Gravity Equivalents for Degrees Baumé (Liquids Heavier Than Water)

Baumé	*Specific Gravity*	*Pounds per Gallon**	*Baumé*	*Specific Gravity*	*Pounds per Gallon**
0	1.0000	8.33	40	1.3810	11.51
1	1.0069	8.38	41	1.3942	11.61
2	1.0140	8.46	42	1.4078	11.72
3	1.0211	8.51	43	1.4216	11.84
4	1.0284	8.56	44	1.4356	11.96
5	1.0357	8.63	45	1.4500	12.08
6	1.0432	8.69	46	1.4646	12.21
7	1.0507	8.75	47	1.4796	12.33
8	1.0584	8.81	48	1.4948	12.46
9	1.0662	8.88	49	1.5104	12.58
10	1.0741	8.94	50	1.5263	12.72
11	1.0821	9.01	51	1.5426	12.85
12	1.0902	9.09	52	1.5591	12.99
13	1.0985	9.15	53	1.5761	13.13
14	1.1069	9.21	54	1.5934	13.27
15	1.1154	9.29	55	1.6111	13.42
16	1.1240	9.36	56	1.6292	13.57
17	1.1328	9.43	57	1.6477	13.72
18	1.1417	9.51	58	1.6667	13.87
19	1.1508	9.59	59	1.6860	14.04
20	1.1600	9.67	60	1.7059	14.21
21	1.1694	9.74	61	1.7262	14.38
22	1.1789	9.81	62	1.7470	14.55
23	1.1885	9.90	63	1.7683	14.72
24	1.1983	9.99	64	1.7901	14.91
25	1.2083	10.07	65	1.8125	15.10
26	1.2185	10.16	66	1.8354	15.29
27	1.2288	10.24	67	1.8590	15.48
28	1.2393	10.32	68	1.8831	15.68
29	1.2500	10.41	69	1.9079	15.89
30	1.2609	10.51	70	1.9333	16.10
31	1.2719	10.59	71	1.9595	16.32
32	1.2832	10.69	72	1.9864	16.55
33	1.2946	10.78	73	2.0139	16.78
34	1.3063	10.84	74	2.0423	17.01
35	1.3182	10.98	75	2.0714	17.25
36	1.3303	11.09			
37	1.3426	11.18			
38	1.3551	11.29			
39	1.3679	11.39			

This table has been adopted by the U.S. National Bureau of Standards from the formula:

Liquids heavier than water, degrees Baumé $= 145 - \frac{145}{R}$

Liquids lighter than water, degrees Baumé $= \frac{140}{R} - 130$

where R is the ratio of the density of a liquid to that of distilled water, both densities being taken at 60°F (15.5°C).

Note: Degrees API, used to measure the density of petroleum oils, differ slightly from the Baumé scale for liquids lighter than water. API specific gravity is determined by a similar formula, using the figures 141.5 and 131.5 instead of 140 and 130.

*One lb per gallon equals 119.8 kg/m^3.

TABLE 6.17.10 Specific Gravity Equivalents, Degrees API[a]

Degrees API	*Specific Gravity at 60/60°F*	*Pounds per Gallon[b] at 60°F*	*Degrees API*	*Specific Gravity at 60/60°F*	*Pounds per Gallon[b] at 60°F*	*Degrees API*	*Specific Gravity at 60/60°F*	*Pounds per Gallon[b] at 60°F*
0	1.076	8.962	35	0.8498	7.076	70	0.7022	5.845
1	1.066	8.895	36	0.8448	7.034	71	0.6988	5.817
2	1.060	8.828	37	0.8398	6.993	72	0.6953	5.788
3	1.052	8.762	38	0.8348	6.951	73	0.6919	5.759
4	1.044	8.698	39	0.8299	6.910	74	0.6886	5.731
5	1.037	8.634	40	0.8251	6.870	75	0.6852	5.703
6	1.029	8.571	41	0.8203	6.830	76	0.6819	5.676
7	1.022	8.509	42	0.8155	6.790	77	0.6787	5.649
8	1.014	8.448	43	0.8109	6.752	78	0.6754	5.622
9	1.007	8.388	44	0.8063	6.713	79	0.6722	5.595
10	1.0000	8.328	45	0.8017	6.675	80	0.6690	5.568
11	0.9930	8.270	46	0.7972	6.637	81	0.6659	5.542
12	0.9861	8.212	47	0.7927	6.600	82	0.6628	5.516
13	0.9792	8.155	48	0.7883	6.563	83	0.6597	5.491
14	0.9725	8.099	49	0.7839	6.526	84	0.6566	5.465
15	0.9659	8.044	50	0.7796	6.490	85	0.6536	5.440
16	0.9593	7.989	51	0.7753	6.455	86	0.6506	5.415
17	0.9529	7.935	52	0.7711	6.420	87	0.6476	5.390
18	0.9465	7.882	53	0.7669	6.385	88	0.6446	5.365
19	0.9402	7.830	54	0.7628	6.350	89	0.6417	5.341
20	0.9340	7.778	55	0.7587	6.316	90	0.6388	5.316
21	0.9279	7.727	56	0.7547	6.283	91	0.6360	5.293
22	0.9218	7.676	57	0.7507	6.249	92	0.6331	5.269
23	0.9159	7.627	58	0.7467	6.216	93	0.6303	5.246
24	0.9100	7.578	59	0.7428	6.184	94	0.6275	5.222
25	0.9042	7.529	60	0.7389	6.151	95	0.6247	5.199
26	0.8984	7.481	61	0.7351	6.119	96	0.6220	5.176
27	0.8927	7.434	62	0.7313	6.067	97	0.6193	5.154
28	0.8871	7.387	63	0.7275	6.056	98	0.6166	5.131
29	0.8816	7.341	64	0.7238	6.025	99	0.6139	5.109
30	0.8762	7.296	65	0.7201	5.994	100	0.6112	5.086
31	0.8708	7.251	66	0.7165	5.964			
32	0.8654	7.206	67	0.7128	5.934			
33	0.8602	7.163	68	0.7093	5.904			
34	0.8550	7.119	69	0.7057	5.874			

[a]The specific gravity of gasoline and other petroleum products is commonly given in Degrees API (American Petroleum Institute). The API degree is based on the following formula:

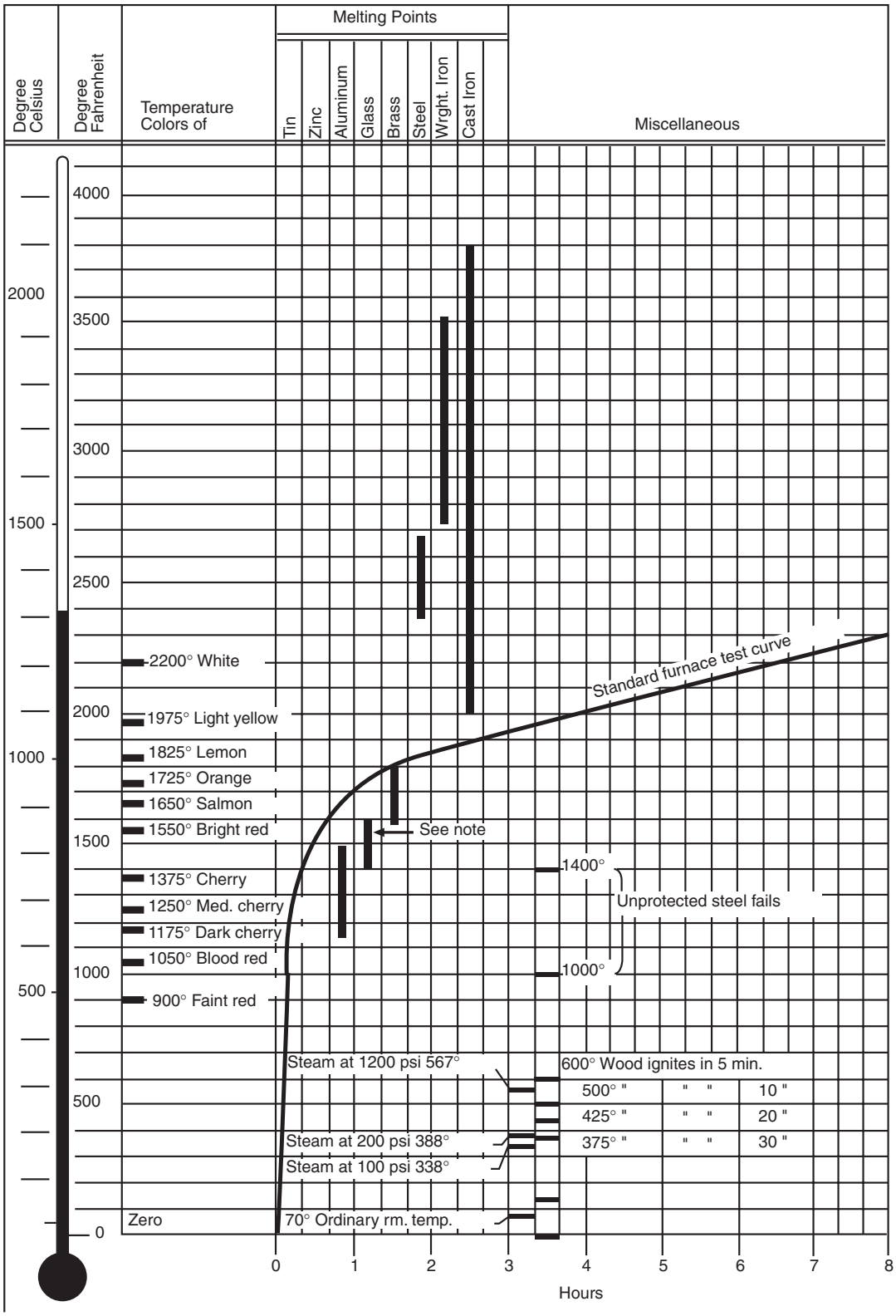
$$\text{Degrees API} = \frac{141.5}{\text{Specific gravity}} - 131.5$$

The standard method of test for gravity of petroleum and petroleum products by means of a hydrometer specifies 60°F as the test temperature, and the formula is based on the specific gravity of the liquid tested at 60°F as compared with water at 60°F.

[b]"Apparent weight," or weight when weighed in air. True weight corrected for weight of air, differs by less than 1 /10 of 1 percent. One lb per gallon equals 119.8 kg/m^3. 60°F equals 15.55°C.

among materials, but only over a range of about 2:1. Ignition temperatures are seen to vary little for common plastics. The total absorbed energy (kJ/m^2) required for ignition has more recently been considered a measure of ignitability.

The effective heat of gasification is a parameter intended to represent the ease of achieving a given heat release rate. The tabulated values, however, do not show the wide range of heat release rate behaviors seen with commercial products. This is



NOTE: Glass has no definite melting point but softens between 1400 and 1600°F (750 and 850°C)

FIGURE 6.17.1 Temperature Colors, Melting Points of Various Substances, and Data on the Behavior of Some Materials at Elevated Temperatures and Pressures

TABLE 6.17.11 Materials Subject to Spontaneous Heating

Name	*Tendency to Spontaneous Heating*	*Usual Shipping Container or Storage Method*	*Precautions Against Spontaneous Heating*	*Remarks*
Alfalfa meal	High	Bags, bulk	Avoid moisture extremes. Tight cars for transportation are essential.	Many fires attributed to spontaneous heating probably caused by sparks, burning embers, or particles of hot metal picked up by the meal during processing. Test fires caused in this manner have smoldered for 72 hours before becoming noticeable.
Burlap bags "used"	Possible	Bales	Keep cool and dry.	Tendency to heat dependent on previous use of bags. If oily would be dangerous.
Castor oil	Very slight	Metal barrels, metal cans in wooden boxes	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Possible heating of saturated fabrics in badly ventilated piles.
Charcoal	High	Bulk, bags	Keep dry. Supply ventilation.	Hardwood charcoal must be carefully prepared and aged. Avoid wetting and subsequent drying.
Coal, bituminous	Moderate	Bulk	Store in small piles. Avoid high temperatures.	Tendency to heat depends upon origin and nature of coals. High volatile coals are particularly liable to heat.
Cocoa bean shell tankage	Moderate	Burlap bags, bulk	Observe extreme caution to maintain safe moisture limits.	This material is very hygroscopic and is liable to heating if moisture content is excessive. Precaution should be observed to maintain dry storage, etc.
Coconut oil	Very slight	Drums, cans, glass	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Only dangerous if fabrics, etc. are impregnated.
Cod liver oil	High	Drums, cans, glass	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated organic materials are extremely dangerous.
Colors in oil	High	Drums, cans, glass	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	May be very dangerous if fabrics, etc. are impregnated.
Copra	Slight	Bulk	Keep cool and dry.	Heating possible if wet and hot.
Corn-meal feeds	High	Burlap bags, paper bags, bulk	Process material carefully to maintain safe moisture content and to cure before storage.	Usually contains an appreciable quantity of oil which has rather severe tendency to heat.
Corn oil	Moderate	Barrels, tank cars	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Dangerous heating of meals, etc. unlikely unless stored in large piles while hot.
Cottonseed	Low	Bags, bulk	Keep cool and dry.	Heating possible if piled wet and hot.
Cottonseed oil	Moderate	Barrels, tank cars	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	May cause heating of saturated material in badly ventilated piles.
Distillers' dried grains with oil content (brewers' grains)	Moderate	Bulk	Maintain moisture 7 percent to 10 percent. Cool below 100°F (38°C) before storage.	Very dangerous if moisture content is 5 percent or lower.
No oil content	Moderate	Bulk	Maintain moisture 7 percent to 10 percent. Cool below 100°F (38°C) before storage.	Very dangerous if moisture content is 5 percent or lower.

TABLE 6.17.11 Continued

Name	*Tendency to Spontaneous Heating*	*Usual Shipping Container or Storage Method*	*Precautions Against Spontaneous Heating*	*Remarks*
Feeds, various	Moderate	Bulk, bags	Avoid extremely low or high moisture content.	Ground feeds must be carefully processed. Avoid loading or storing unless cooled.
Fertilizers				
Organic, inorganic, combination of both mixed	Moderate	Bulk, bags	Avoid extremely low or high moisture content.	Organic fertilizers containing nitrates must be carefully prepared to avoid combinations that might initiate heating.
Synthetic, containing nitrates and organic matter	Moderate	Bulk, bags	Avoid free acid in preparation.	Insure ventilation in curing process by small piles or artificial drafts. If stored or loaded in bags, provide ventilation space between bags.
Fish meal	High	Bags, bulk	Keep moisture 6 percent to 12 percent. Avoid exposure to heat.	Dangerous if overdried or packaged over 100°F (38°C).
Fish oil	High	Barrels, drums, tank cars	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated porous or fibrous materials are extremely dangerous. Tendency of various fish oils to heat varies with origin.
Fish scrap	High	Bulk, bags	Avoid moisture extremes.	Scrap loaded or stored before cooling is extremely liable to heat.
Foam rubber in consumer products	Moderate		Where possible remove foam rubber pads, etc. from garments to be dried in dryers or over heaters. If garments containing foam rubber parts have been artificially dried, they should be thoroughly cooled before being piled, bundled, or put away. Keep heating pads, hair dryers, other heat sources from contact with foam rubber pillows, etc.	Foam rubber may continue to heat spontaneously after being subjected to forced drying as in home or commercial dryers, and after contact with heating pads and other heat sources. Natural drying does not cause spontaneous heating.
Grain (various kinds)	Very slight	Bulk, bags	Avoid moisture extremes.	Ground grains may heat if wet and warm.
Hay	Moderate	Bulk, bales	Keep dry and cool.	Wet or improperly cured hay is almost certain to heat in hot weather. Baled hay seldom heats dangerously.
Hides	Very slight	Bales	Keep dry and cool.	Bacteria in untreated hides may initiate heating.
Iron pyrites	Moderate	Bulk	Avoid large piles. Keep dry and cool.	Moisture accelerates oxidation of finely divided pyrites.
Istle	Very slight	Bulk, bales	Keep cool and dry.	Heating possible in wet material. Unlikely under ordinary conditions. Partially burned or charred fiber is dangerous.
Jute	Very slight	Bulk	Keep cool and dry.	Avoid storing or loading in hot wet piles. Partially burned or charred material is dangerous.
Lamp black	Very slight	Wooden cases	Keep cool and dry.	Fires most likely to result from sparks or included embers, etc., rather than spontaneous heating.
Lanolin	Negligible	Glass, cans, metal drums, barrels	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Heating possible on contaminated fibrous matter.

(continued)

TABLE 6.17.11 Continued

Name	*Tendency to Spontaneous Heating*	*Usual Shipping Container or Storage Method*	*Precautions Against Spontaneous Heating*	*Remarks*
Lard oil	Slight	Wooden barrels	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Dangerous on fibrous combustible substances.
Lime, unslaked (calcium oxide, pebble lime, quicklime)	Moderate	Paper bags, wooden barrels, bulk	Keep dry. Avoid hot loading.	Wetted lime may heat sufficiently to ignite wood containers, etc.
Linseed	Very slight	Bulk	Keep cool and dry.	Tendency to heat dependent on moisture and oil content.
Linseed oil	High	Tank cars, drums, cans, glass	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Rags or fabrics impregnated with this oil are extremely dangerous. Avoid piles, etc. Store in closed containers, preferably metal.
Manure	Moderate	Bulk	Avoid extremes of low or high moisture contents. Ventilate the piles.	Avoid storing or loading uncooled manures.
Menhaden oil	Moderate to high	Barrels, drums, tank cars	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Dangerous on fibrous product.
Metal powders*	Moderate	Drums, etc.	Keep in closed containers.	Moisture accelerates oxidation of most metal powders.
Metal turnings*	Practically none	Bulk	Not likely to heat spontaneously.	Avoid exposure to sparks.
Mineral wool	None	Pasteboard boxes, paper bags	Noncombustible. If loaded hot may ignite containers and other combustible surroundings.	This material is mentioned in this table only because of general impression that it heats spontaneously.
Mustard oil, black	Low	Barrels	Avoid contact of leakage with rags, cotton, or other fibrous combustible materials.	Avoid contamination of fibrous combustible materials.
Oiled clothing	High	Fiber boxes	Dry thoroughly before packaging.	Dangerous if wet material is stored in piles without ventilation.
Oiled fabrics	High	Rolls	Keep ventilated. Dry thoroughly before packing.	Improperly dried fabrics extremely dangerous. Tight rolls are comparatively safe.
Oiled rags	High	Bales	Avoid storing in bulk in open.	Dangerous if wet with drying oil.
Oiled silk	High	Fiber boxes, rolls	Supply sufficient ventilation.	Improperly dried material is dangerous in form of piece goods. Rolls relatively safe.
Oleic acid	Very slight	Glass bottles, wooden barrels	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated.
Oleo oil	Very slight	Wooden barrels	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	May heat on impregnated fibrous combustible matter.
Olive oil	Moderate to low	Tank cars, drums, cans, glass	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.

TABLE 6.17.11 Continued

Name	*Tendency to Spontaneous Heating*	*Usual Shipping Container or Storage Method*	*Precautions Against Spontaneous Heating*	*Remarks*
Paint containing drying oil	Moderate	Drums, cans, glass	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Fabrics, rags, etc. impregnated with paints that contain drying oils and driers are extremely dangerous. Store in closed containers, preferably metal.
Paint scrapings	Moderate	Barrels, drums	Avoid large unventilated piles.	Tendency to heat depends on state of dryness of the scrapings.
Palm oil	Low	Wooden barrels	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Peanut oil	Low	Wooden barrels, tin cans	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Peanuts, "red skin"	High	Paper bags, cans, fiber board boxes, burlap bags	Avoid badly ventilated storage.	This is the part of peanut between outer shell and peanut itself. Provide well ventilated storage.
Peanuts, shelled	Very slight or negligible	Paper bags, cans, fiber board boxes, burlap bags	Keep cool and dry.	Avoid contamination of rags, etc. with oil.
Perilla oil	Moderate to high	Tin cans, barrels	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Pine oil	Moderate	Glass, drums	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Powdered eggs	Very slight	Wooden barrels	Avoid conditions that promote bacterial growth. Inhibit against decay. Keep cool.	Possible heating of decaying powder in storage.
Powdered milk	Very slight	Wooden and fiber boxes, metal cans	Avoid conditions that promote bacterial growth. Inhibit against decay. Keep cool.	Possible heating by decay or fermentation.
Rags	Variable	Bales	Avoid contamination with drying oils. Avoid charring. Keep cool and dry.	Tendency depends on previous use of rags. Partially burned or charred rags are dangerous.
Red oil	Moderate	Glass bottles, wooden barrels	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated porous or fibrous materials are extremely dangerous. Tendency varies with origin of oil.
Roofing felts and papers	Moderate	Rolls, bales, crates	Avoid over-drying the material. Supply ventilation.	Felts, etc. should have controlled moisture content. Packaging or rolling uncooled felts is dangerous.
Sawdust	Possible	Bulk	Avoid contact with drying oils. Avoid hot, humid storage.	Partially burned or charred sawdust may be dangerous.
Scrap film (nitrate)	Very slight	Drums and lined boxes	Film must be properly stabilized against decomposition.	Nitrocellulose film ignites at low temperature. External ignition more likely than spontaneous heating. Avoid exposure to sparks, etc.
Scrap leather	Very slight	Bales, bulk	Avoid contamination with drying oils.	Oil-treated leather scraps may heat.

(continued)

TABLE 6.17.11 Continued

Name	*Tendency to Spontaneous Heating*	*Usual Shipping Container or Storage Method*	*Precautions Against Spontaneous Heating*	*Remarks*
Scrap rubber or buffings	Moderate	Bulk, drums	Buffings of high rubber content should be shipped and stored in tight containers.	Sheets, slabs, etc. are comparatively safe unless loaded or stored before cooling thoroughly.
Sisal	Very slight	Bulk, bales	Keep cool and dry.	Partially burned or charred material is particularly liable to ignite spontaneously.
Soybean oil	Moderate	Tin cans, barrels, tank cars	Avoid contact with rags, cotton, or fibrous materials.	Impregnated fibrous materials may heat unless well ventilated.
Sperm oil—see whale oil				
Tankage	Variable	Bulk	Avoid extremes of moisture contents. Avoid loading or storing while hot.	Very dry or moist tankages often heat. Tendency more pronounced if loaded or stored before cooling.
Tung nut meals	High	Paper bags, bulk	Material must be very carefully processed and cooled thoroughly before storage.	These meals contain residual oil which has high tendency to heat. Material also susceptible to heating if over-dried.
Tung oil	Moderate	Tin cans, barrels, tank cars	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Turpentine	Low	Tin, glass, barrels	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Has some tendency to heat but less so than the drying oils. Chemically active with chlorine compounds and may cause fire.
Varnished fabrics	High	Boxes	Process carefully. Keep cool and ventilated.	Thoroughly dried varnished fabrics are comparatively safe.
Wallboard	Slight	Wrapped bundles, pasteboard boxes	Maintain safe moisture content. Cool thoroughly before storage.	This material is entirely safe from spontaneous heating if properly processed.
Waste paper	Moderate	Bales	Keep dry and ventilated.	Wet paper occasionally heats in storage in warm locations.
Whale oil	Moderate	Barrels and tank cars	Avoid contact of leakage from containers with rags, cotton, or other fibrous combustible materials.	Impregnated fibrous materials may heat unless ventilated. Tendency varies with origin of oil.
Wool wastes	Moderate	Bulk, bales, etc.	Keep cool and ventilated or store in closed containers. Avoid high moisture.	Most wool wastes contain oil, etc. from the weaving and spinning and are liable to heat in storage. Wet wool wastes are very liable to spontaneous heating and possible ignition.

Note: Originally prepared by the NFPA Committee on Spontaneous Heating and Ignition, which has been discontinued. Omission of any material does not necessarily indicate that it is not subject to spontaneous heating. Newer information is available in Babrauskas, V., *Ignition Handbook,* Fire Science Publishers/Society of Fire Protection Engineers, Issaquah, WA, 2003.

*Refers to iron, steel, brass, aluminum, and other common metals.

partly because for most materials the heat release progress is highly transient, whereas the definition of the effective heat of gasification (average energy required to gasify a unit mass of material) requires assuming steady-state conditions.

Smoke properties can be measured in two ways: (1) Optically, by determining the obscuration along a light beam. This can be expressed as smoke specific extinction area per unit specimen mass (m^2/kg). The unit system implied here is natural-log (Base-e). (2) Gravimetrically, by determining the soot mass evolved, per unit specimen mass.

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SECTION 7

Storage and Handling of Materials

L. Jeffrey Mattern

7.1 Storage and Handling of Solid Fuels
7.2 Storage of Flammable and Combustible Liquids
7.3 Storage of Gases
7.4 Storage and Handling of Chemicals
7.5 Hazardous Waste Control

The proper methods for storage and handling of materials, along with the control of ignition sources, are the keys to minimizing the potential for fires in occupancies where such materials are found. Proper separation of volatile materials limits the possibility of a fire spreading from areas where these materials are stored and handled to their adjacent areas. The type of materials discussed in the chapters within this section are often easily ignited and lead to rapid fire growth. Thus, it is essential that such materials be properly stored and handled, and that ignition sources be properly controlled. As a last resort, adequate fire protection concepts are important to mitigate the effects of a fire, should one occur.

The purpose of this section is threefold: (1) to discuss the common arrangements of storage found for the specific materials, (2) to identify the fire hazards associated with the specific materials, and (3) to provide methods by which the fire hazard of the specific materials is reduced and mitigated.

Chapter 1, "Storage and Handling of Solid Fuels," discusses the bulk storage of materials such as coal used in the utility industry, or large manufacturing plants that have power generation such as pulp and paper mills, and storage of wood products in the form of logs, chips, sawdust, and related by-products. The proper storage arrangements, fire prevention concepts, and fire control methods are introduced.

Chapter 2, "Storage of Flammable and Combustible Liquids," thoroughly discusses the storage of combustible and flammable materials in their extensive array of storage arrangements, from large holding tanks to small containers. The chapter discusses the fundamentals of the design and construction of large tanks, their proper venting, emergency containment, and fire suppression concepts. The chapter also discusses the use of small container storage and provides a brief discussion on transportation of these materials.

Chapter 3, "Storage of Gases," provides background on the construction of gas cylinders and tanks, as well as their associated safeguards and control of ignition sources. Chapter 4, "Storage and Handling of Chemicals," provides a tutorial on the hazards of various commonly used chemicals, along with their fire control methods. Lastly, Chapter 5, "Hazardous Waste Control," explains the control of hazardous waste, including its source, characteristics, collection, handling, storage, recovery, and disposal.

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Chapter 1

Storage and Handling of Solid Fuels

Kenneth W. Dungan

Chapter Contents

Coal as a Fuel
Storage Practices for Coal
Gas Generation and Explosions with Coal
Coal Handling and Coal Dust Explosions
Wood as a Fuel
Hazards of Wood Fuels
Storage Practices for Wood Fuels
Handling Wood Fuels
Fire Prevention for Wood Fuels
Fire Protection for Wood Fuels
Solid Waste as Fuel

Key Terms

coal fuel, dust, explosion, solid fuel, spontaneous heating, wood, wood-derived materials

Solid fuels are used commercially for the generation of heat for steam, electrical power, or process needs. This chapter addresses the major solid fuel sources of coal, wood, and wood by-products. The hazards and safe practices in the storage and handling of these fuels are discussed.

The actual combustion of these fuels in boilers and furnaces is covered in Section 10, Chapter 6, "Boiler Furnaces"; on the hazards of dust, see Section 6, Chapter 8, "Dusts." Incinerators are addressed in Section 11, Chapter 1, "Waste Handling and Control."

COAL AS A FUEL

Coal is an abundant fuel source in many parts of the world. It is the predominant fuel for boilers that generate hot water and steam for process use, heating, and the generation of electricity. As of the year 2000, 57 percent of the electricity in the United States was supplied by coal-burning power plants.[1] Coal is also a key ingredient in the making of steel. Since coal, by and large, fueled the industrial revolution, its properties and uses have been studied for more than a century.

The hazards of the storage and handling of coal include fires, flash fires, and dust explosions. An important cause of coal fires in storage piles, bins, hoppers, and other containers is spontaneous heating. Coal, when heated, can release gases, some from entrained volatile hydrocarbons and some from oxidation (e.g., carbon monoxide). This chapter covers the hazards of the storage and handling of coal and outlines methods of reducing the likelihood and consequences of fire and explosions in this operation.

Ranking of Coals

ASTM D388, *Standard Classification of Coals by Rank,* is used to rank coals. The ranking provides useful data on the behavior of the coal and the equipment necessary to handle and burn it. Table 7.1.1 lists the rankings by class and group of coals. Through most of the twentieth century, Class II or bituminous coal was the staple of coal-fired boilers. These coals, mined in places like Tennessee, Kentucky, Ohio, West Virginia, and Illinois, offer high heat values, usually above 15,000 Btu/lb (34.9 MJ/kg), but are soft enough to grind or pulverize for combustion. Unfortunately, these coals also contain sulfur in the form of pyrites, which cause SO_2 emissions, a prime cause of acid rain. To meet SO_2 emission restrictions without costly scrubbers, more power boilers started burning Class III or subbituminous coal, which typically contains significantly less sulfur but also has lower heat values. These are often referred to as western coals, because they are mined in places like Montana and Wyoming. One of the more common sources of these coals is the Powder River Basin deposits, or PRB as it is sometimes called. The ranking of the coal can give some indication of its propensity for spontaneous heating and also its dust explosion hazards.

Spontaneous Heating of Coals

One major hazard of the storage and handling of coal is spontaneous heating. Spontaneous heating occurs from a slow oxidation reaction within the coal pile causing heat to build up to the point

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TABLE 7.1.1 Classification of Coals by Rank (ASTM D388)

Class	*Group*
I. Anthracitic	1. Meta-anthracite 2. Anthracite 3. Semianthracite
II. Bituminous	1. Low volatile bituminous coal 2. Medium volatile bituminous coal 3. High volatile *A* bituminous coal 4. High volatile *B* bituminous coal 5. High volatile *C* bituminous coal
III. Subbituminous	1. Subbituminous *A* coal 2. Subbituminous *B* coal 3. Subbituminous *C* coal
IV. Lignitic	1. Lignite A 2. Lignite B

of igniting the coal. This phenomenon is a problem displayed by bituminous and lignite coals. For this oxidation to reach an ignition potential, heat of oxidation must build up faster than it dissipates. The chemical and physical makeup of the coal greatly affects the potential for spontaneous heating. Principal conditions affecting coal's susceptibility to spontaneous heating include the following:

1. Susceptibility of the coal to breakage (friability) and the fineness of the particles produced
2. Ability of the coal particles to absorb oxygen, as well as the percentage of actual oxygen content
3. Amount of moisture trapped and confined in the coal (moisture assists oxidation)
4. Chemical composition of the coal, especially of impurities (generally, the lower the grade of coal, the greater the possibility of spontaneous heating)
5. Extent of air trapped in the voids of the coal pile
6. Presence of sulfur in the form of pyrites or marcasites (in general, an increase of sulfur content results in increased friability of coal; the brittle coal breaks more easily, thus exposing more surface area for oxidation)
7. Free gases trapped in the coal pile
8. Amount of foreign substances in the pile such as wood, sticks, timber, leaves, and grass
9. Method and depth of the coal pile
10. Temperature of the surrounding area (the oxidation reaction increases with temperature)
11. Type and amount of ventilation allowed in the coal pile

STORAGE PRACTICES FOR COAL

The methods used to build outside storage piles and to fill silos, bins, and bunkers have a significant effect on the oxidation hazard of coal. The spontaneous heating problem is controlled either by compacting to reduce the air movement or by minimizing the coal storage time by keeping it moving to the boiler. Coal is usually stored either in an uncompacted (50 to 55 lb/ft^3 [801 to 881 kg/m^3]) or compacted (70 to 75 lb/ft^3 [1121 to 1201 kg/m^3]) form. When coal is not compacted, air occupies approximately 35 percent of the volume of the pile, so it is relatively easy for air to move through the pile. Coal is at this density when it is handled on conveyors or placed in trucks, railroad cars, bunkers, silos, or in any form of "live" pile. Coal is uncompacted whenever it is moved and falls on itself. Table 7.1.2 shows the range of densities of coal.

Compacted Coal Storage

Generally, when coal is compacted, it is placed in relatively thin layers from 6 to 12 in. (150 to 300 mm) thick. Each layer is then rolled over with a device that has a relatively high loading in lb/ft^2 (kg/m^2) of surface area (1 lb/ft^2 equals 4.9 kg/m^2). Rubber-tired carryalls are normally used for this purpose, since they compact the coal while they convey the coal to the desired location.

A coal pile should be compacted on all sides to eliminate any low-density areas. When coal is compacted, it has a density of about 70 to 75 lb/ft^3 (1100 to 1200 kg/m^3) and air occupies only 12 percent of the pile. This makes it far less likely that there would be appreciable air movement through the pile. Virtually all types of coal have been stored successfully in this manner, including piles exceeding 1 million tons (1 ton equals 1016 kg) and at depths approaching 100 ft (30 m).

Large users of coal (e.g., utilities and large industries) will generally have compacted permanent storage piles and uncompacted "live" storage piles, whereas the smaller users (e.g., small industry, commercial, and residential) normally have uncompacted storage. All coal users have some form of uncom-

TABLE 7.1.2 General Ranges of Densities of Coal

Physical Description of Coal	*Range of Density lb/ft^3 (kg/m^3)*	*Approximate Percentage of Coal Pile Occupied by Air*
Coal in the seam before mining	80–85 (12.8–13.6)	0%
Coal size 2" × 0 normal shipping size as loaded in RR car, truck, etc., no compaction	50–55 (8–8.8)	36%
Coal size 2" × 0 compacted with track-mounted dozers	60–65 (9.6–10.4)	24%
Coal size 2" × 0 compacted with rubber-tired carryall or sheepsfoot roller	70–75 (11.2–12)	12%

pacted storage and this form of storage might require special fire protection considerations.

Uncompacted Coal Storage

Ideally, all uncompacted coal is stored in properly designed bunkers, silos, bins, and even outside piles so all of the coal moves through the storage system with no dead or unmoving portion of the coal pile. Although the coal is still subject to slow oxidation, it will move through the system before any appreciable heating can occur. Many new bunkers, silos, and bins are designed for mass flow of coal and heating problems have been minimized. Coal piles can be worked in such a manner that the piles are rotated and the first coal in is the first coal out. This achieves the same results as the mass flow conditions in bins where none of the coal remains for prolonged periods of time.

When bunkers, silos, or bins have not been, or cannot be, designed to achieve mass flow, heating of the coal might occur and create problems. As much as practical, sealing off the bottom of the storage system can minimize the airflow through the coal; however, space above the coal in the storage system should not be sealed. This will prevent the accumulation of gases that can become liberated from freshly mined or crushed coal. In these cases, the area above the coal should be ventilated to carry off any accumulation of gases. Some storage systems, particularly ones where pulverized coal is stored, are designed to prevent the formation of a hazardous mixture of gases and coal dust with air.

It might be necessary to routinely draw down the storage system and clean the static deposits of coal from the bunker to minimize problems. Because cleaning bunkers, silos, or bins can be hazardous, special safety precautions should be taken.

If heating occurs in a bunker, silo, or bin, it is generally in an area where static deposits of coal have remained for a period of time. Once spontaneous heating develops to the fire stage, it becomes very difficult to extinguish the fire, short of emptying the bin, bunker, or silo. Therefore, provisions for emptying the bunker should be provided. Fire fighting in coal silos is a difficult, long-duration activity, and can take several days to completely extinguish the fire. NFPA 850, *Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations,* provides excellent guidance on how to combat these types of fires.

Carbon dioxide vapor has proved to be an effective fire-suppression agent when forced through the coal by pressure injection in the upper and lower parts of the silo. The rate of application should be sufficient to compensate for absorption by the coal. Inerting can normally be accomplished within an 8 hour shift, if an adequate supply of carbon dioxide is available.

Since carbon dioxide is stored as a liquid, it must be vaporized before injection into the silo. This is accomplished using an external, in-line vaporizer sized such that the anticipated application rate can be increased if the maximum anticipated leakage rate is exceeded.

Normal inerting procedure involves starting the carbon dioxide flow at a preset volume from the flow-control valve. Initially, the carbon dioxide vapor should be injected into the top of the silo, into the space above the coal, to mitigate the potential of developing an explosive atmosphere. Once this inerting is established, the flow can be reduced and the primary flow directed into the bottom (while continuing trickle injection into the top) of the silo. Silo geometry creates a chimney effect, which will prevent the carbon dioxide from settling throughout the silo. Therefore, it is necessary to add injection points near the bottom. In addition, high-expansion foam can be added to the top.

Carbon dioxide inerting is generally considered successful when the carbon dioxide concentration reaches 65 percent. However, the logistics of injecting carbon dioxide might result in almost 100 percent saturation throughout most of the silo in order to achieve at least 65 percent concentration in all portions of the silo. Since leakage in the silo is inevitable, it will be necessary to anticipate using a large quantity of carbon dioxide. It is advisable to order a quantity of carbon dioxide equivalent to about three times the gross volume of the silo when using a low-pressure system.

When carbon dioxide is used, there is a risk of oxygen depletion in the area above, around, or below a silo, bin, or bunker. Areas where gas could collect and deplete oxygen should be identified with appropriate barriers and warning signs.

Nitrogen has been used successfully to inert silo fires. It is applied in a manner very similar to carbon dioxide. A notable difference is that nitrogen has about the same density as air (whereas carbon dioxide is significantly more dense). Therefore, it must be applied at numerous injection points around the silo to ensure that it displaces available oxygen. This results in the need for more injection equipment and a larger quantity of agent.

Another method is the use of Class A foams and penetrants. These agents have found some success, but it is difficult to predict the resources required for successful fire control. The agents generally require mixing with water prior to application, usually in the range of 1 percent by volume. The typical application of Class A foam is 1 percent to fight wetland fires. However, coal plants have reported success with using Class A foams at 0.1 percent. This causes the agent to act as a surfacant. Higher percentages have caused excessive bubble accumulation, which impedes penetration into the coal.

Water and steam are not recommended, because the potential for explosion exists when water reaches the hot spot and the expansion of the steam is trapped by the water. The introduction of steam can actually increase spontaneous heating because of the introduction of additional heat and moisture.

Suppression activities can be enhanced by using portable infrared heat detectors to search for hot spots, either on the sides or top of the silo, to facilitate injection of the agent as close as possible to the fire area. The infrared imagery can be used to evaluate performance and monitor progress of the attack. The agent solution must penetrate to the seat of combustion to be effective. This can be affected by the degree of compaction, voids, rate of application, evaporation rate, and so on. Runoff must be drained through feeder pipes and will require collection, cleanup, and disposal.

Detection and location of hot spots can be achieved by using CO gas monitors, portable infrared heat detection, or thermography. A long thermocouple (10 ft [3.1 m]) connected

to a portable instantaneous readout monitor can be employed. Pushing the thermocouple into the coal storage can detect developing hot areas or strata at different depths. Periodic monitoring of temperature change in these areas will help predict spontaneous combustion development and aid in response preplanning.

Regardless of the type of suppression approach selected, prefire planning is an important element of successful fire control and extinguishment. If all necessary fire-fighting resources are not stockpiled on site, suppliers should be contacted in advance to ensure that equipment and supplies are available on relatively short notice.

Personnel requirements for this fire-fighting activity should be identified in advance. Personnel should be trained and qualified for fire fighting in the hot, smoky environment that might accompany a silo fire. This includes the use of self-contained breathing apparatus (SCBA) and personal protective equipment. Personnel engaged in this activity should be minimally trained and equipped to the structural fire brigade level, as defined in NFPA 600, *Standard on Industrial Fire Brigades.* See also NFPA 1081, *Standard for Industrial Fire Brigade Member Professional Qualifications.*

Selecting an Outside Storage Site

Many plants have uncompacted storage piles on the ground and some precautions must be taken in selecting and preparing a storage site. First, it should be determined that the proposed site is not over open sewers or other devices that might bring air into the base of the pile. Neither should the site contain any steam lines or systems that could raise the temperature of a portion of the pile beyond normal ambient temperatures.

Once selected, the site should be cleaned of all vegetation and foreign materials, particularly materials that could have heating tendencies. Then it should be graded smoothly and contoured so that water will not drain into the base of the pile. The periphery of a pile should be given special attention in the grading process to make sure that all of the water draining from the pile will be carried away.

Recognizing that uncompacted piles tend to heat, a good practice is to size and/or shape a pile for easy access to areas that have heat so that they can then be handled appropriately. It is also good practice to limit the height of an uncompacted pile to approximately 15 ft (4.6 m) if the coal is known to have high heating tendencies. Greater pile heights can be tolerated if the coal has low heating characteristics and if the pile can be rotated with ease.

Weatherproofing of Coal Piles

In very special cases (e.g., when coal piles are to be retained for long periods or coking properties are of special importance) the exclusion of air can be further improved by covering the completed pile with road tar in the same manner as dressing is applied to roads. Road tar is an efficient and economical method and, in addition, can be used on heated heaps that, in the complete absence of air, would then stop oxidizing and cool off. The sealing of a coal pile has some added advantages, such as protection against wind loss and reduction of channeling due to heavy rain. A secondary effect, therefore, is reduction of atmospheric and river pollution.

Special Storage Precautions

It is beneficial to handle coal going to storage in a manner that prevents segregation of coarse coal from the fines. Segregation occurs when coal is placed in a conical pile; the coarse coal runs to the edge and outside of the pile, and the fines collect in the center. The air can then move readily through the coarse coal to the fines containing the large surface area, greatly encouraging heating of the pile.

Placing coal in storage near a vertical wall presents special problems, because coal tends to be less compacted when it is placed near these vertical surfaces unless special precautions are taken. Preferably, coal should not be stored around supporting beams or similar members. Less dense coal provides a natural flue for air ventilation. When vertical walls or surfaces of any kind cannot be avoided, the coal should be stored along the wall or parallel to the wall, as opposed to pushing the coal up to the vertical surface.

Selecting Storage Method for Coal

Commercial and domestic users select the size of coal best suited for their burning equipment, and, in most cases, it is usually a double-screened coal with a 1¼ in. (32 mm) top size, a ¼ in. (6 mm) bottom size, and a relatively small percentage of fines. This size coal, if handled reasonably well, will not segregate and a pile can be considered fully ventilated. There will be a minimum tendency of heating because of fewer fines and because any heat generated will be readily removed from the pile.

Industries and utilities normally use a coal with a larger percentage of fines, and it is advantageous to use a coal that can be handled and stored with ease. Normally, a good shipping size is 2 in. (50 mm) top size or less, but if a larger size is used, extra care should be exercised to minimize segregation and oxidation in storage.

GAS GENERATION AND EXPLOSIONS WITH COAL

Methane and other gases can be liberated from freshly mined and freshly crushed coal. An accumulation of a dangerous proportion of gas from this source is rare, but when explosions do occur, severe and fatal losses can result. Spontaneous heating can cause the generation of carbon monoxide, which is both a health and explosion hazard.

Dangerous accumulations of gas can occur over the tops of bins, silos, and bunkers and in underground coal reclaiming facilities. Adequate ventilation is the best solution to prevent dangerous accumulation. The ventilation system should sweep airflow across the tops of bins, silos, and bunkers and through the conveyor gallery of underground reclaiming systems. Care should be taken in the design and operation of the storage system to minimize any airflow through the stored coal, thus preventing spontaneous heating. In addition, any airflow through

the pile should be in a direction that will minimize any dangerous accumulations of gas.

If there is any suspicion of gas accumulations, gas monitors can be permanently installed, and portable detectors can be used by personnel working in these areas. The areas should be monitored both for CO and for methane.

COAL HANDLING AND COAL DUST EXPLOSIONS

Coal handling facilities include receiving operation, crushers, and conveyors. A major hazard common to all these facilities is the potential for coal dust explosions. (General information on the hazards of dust is discussed in Section 6, Chapter 8, "Dusts.") Finely divided particles of coal can produce violent explosions under conditions favorable for such explosions. The minimum explosive concentration for coal dust in air required for an explosion has been determined to be 0.035–0.050 oz/ft^3 (35–50 g/m^3). The explosion pressures developed by a coal dust explosion may vary from 5 to 100 psi (34.5 to 690 kPa). The principal factors influencing the violence of a dust explosion are the specific chemical structure of the coal dust, concentration of material, particle size, source of ignition, oxygen concentration, enclosure type and size, turbulence of mixture, and effectiveness of vent closure. The effect of moisture on coal dust explosibility is negligible below about 10 percent.

The principal dust-producing mechanisms in coal handling processes include transfer points, screens, pneumatic cleaning equipment, crushers, and conveyors. Each of these items of equipment can create and/or distribute combustible dust-air mixtures that might be explosive. These mechanisms can also provide the means of ignition unless properly designed, constructed, and maintained. Crushing or pulverizing equipment and frictional sparks or sparks from tramp metal are major causes for fire risk and dust explosion losses.

Dust Collection Systems

Because of coal dust explosibility, minimizing the production and emission of coal dust is essential in the design of any coal handling facility. Where coal dust production is unavoidable, dust collection systems might be required. Care should be taken to size the dust collection equipment appropriately to ensure that the coal dust will be controlled as rapidly as it is formed. All dust collection systems should be located outdoors. Fans for dust collectors should, if possible, be installed downstream of collectors so that they handle only clean air. Under special circumstances, where located inside buildings, explosion-relieving panels should be vented to the outside. Explosion protection should be provided for all dust collection systems in the form of explosion-relief vents. The vents should be sized in accordance with NFPA 68, *Standard on Explosion Protection by Deflagration Venting.* Residual coal dust contributes to the risk of dust explosion propagation. Often, in dust explosions, the initial "puff" creates a secondary explosion caused by disturbing the built-up layer of dust. Good housekeeping to minimize residual dust is paramount to controlling the hazard. Vacuum cleaning is the best way to clean up the dust without creating a potential cloud.

Vacuum cleaner tools should be made of nonsparking, electrically conductive materials. The piping and suction hose should be permanently grounded to prevent static sparks.

Coal Conveyors

Coal conveyors provide a vital link between receiving, storage, and processing equipment. In addition to the dust explosion hazard discussed earlier, the combustibility of coal creates another major fire hazard for conveying systems. Burning coal could be transported throughout the plant causing widespread damage. Belt material itself might also be combustible. Belts constructed of fabric-reinforced rubber or synthetics can burn with an intensity that produces high heat release rates and dense smoke. Materials meeting fire resistance standards of the Mine Safety and Health Administration are more difficult to ignite than noncompliant, typically older materials. Selection of the proper belt materials can reduce the probability of conveyor fires. This selection does not obviate the need for adequate protection. Even the best belts can get coated with lubricants or coal residues after use and can present increased fire hazards.

The most common ignition source in conveyor fires is friction between belts and rollers. This can be caused by either a driver or a stuck idler. Misalignment or misadjustment of belts can cause a heat buildup capable of igniting belts or coal. One successful control of friction ignition sources from drivers is "zero speed" or slippage switches. These devices shut down the power to the drivers if the belt speed drops to below a safe threshold. Poor preventive maintenance can result in rollers sticking, which can also cause friction between belts and rollers. These hot idler–caused fires usually show up after the shutdown of a transfer operation, when the still belt stays in contact with the hot idler.

The selection of fixed fire protection for use on coal conveyors depends largely on the construction of the conveyor housing. Open, uncovered conveyors that can be reached with hose streams can be adequately protected with manual fire suppression. More common are the light noncombustible construction enclosures protecting coal conveyors from the weather. These types of conveyors as well as underground conveyors make manual fire suppression extremely difficult.

Since manual fire fighting is both difficult and slow, detection systems and automatic suppression systems might be desirable. Two basic approaches have been effectively applied successfully for the suppression of coal conveyor fires. If conveyors are not shut down upon the detection of a fire, an open-head deluge system operation of the length of the belts must be applied to control and extinguish the possible moving fire on the belt. This might not be a very effective approach and could result in chasing a "moving" fire and operating many adjacent systems. The second method of suppressing coal conveyor fires is to use thermal detectors to shut down the conveyors combined with a typical closed-head automatic sprinkler, which will operate only in the zone affected by the fire. Because of freezing problems in cold climates, this closed-head system is frequently combined with a preaction valve, which will open on the same detection signal that shuts down the conveyor. Because of the concerns discussed earlier, the best approach, whether using

deluge or closed-head systems, is to stop the belts on a "fire" signal and to tie this to the interlocks referenced previously.

The design of automatic sprinkler and water spray systems will depend on the physical arrangement of the conveyors. Where multilevel conveyors are used and where potential for coal accumulation beneath belts exists, suppression system coverage should be extended to both above and below conveyor belts. Guidance on the protection of coal conveyors appears in NFPA 850.

WOOD AS A FUEL

Wood is becoming widely used because of the cost and because of improved technology for whole tree chipping on site. Maine, New Hampshire, Vermont, and other northern tier states that have reasonably abundant supplies of wood are continuing to research how wood can be converted into usable form to produce energy for heat and power generation. The U.S. Department of Energy reported an electricity-generating capacity of 5886 MW from wood and forest products as of 2002. The capacity curve has been relatively flat in the last decade.

The increasing use of wood as an energy source competes with the use of wood as raw material for pulp, paper, and building products. Consequently, much of the research into wood use today is concentrated on the less commercially useful wood species and on wood waste from the forest products industry. The emphasis is on total use of the tree, either in the production of the product or of the waste as fuel. Environmental regulations on the disposal of wood wastes have provided additional encouragement for their use as fuel.

HAZARDS OF WOOD FUELS

Given a source of ignition, wood in all its forms will burn. As the tree is cut and processed into its eventual use, the hazard of fire increases from two directions: (1) reduction of moisture content from air drying, and (2) reduction of the wood particle size from the standing tree to finished lumber, to chips for fuel and chemical pulp, and to waste wood particles the size of finely divided dust and flour. As the drying and reduction process proceeds from the relatively large particles down to the dust/flour stage, the hazard changes from that of a Class A combustible material subject to typical burning characteristics to one of such rapid combustion that it is termed an explosion. In considering the storage of wood as a fuel, the hazards encountered will range from those for solid wood to those for wood dust/flour.

Solid Wood

The hazard for solid wood is Class A combustible material not readily ignited but capable of generating a large amount of heat if allowed to burn unimpeded. The rapidity with which fire will spread depends on pile configuration, moisture of the wood and surrounding atmosphere, physical characteristics of the wood (i.e., size of individual pieces), whether wood is peeled or with bark, and species of wood. Pile size and configuration will determine the amount of radiant heat released.

Chips

This form of wood is being used on an ever-increasing scale as fuel for heat and power generation because it can be mechanized on the scale needed. The hazard is again one of a Class A combustible and, because of its small size (⅝ to 1¼ in. [16 to 32 mm]), fires in piles tend to be surface type with no more than about 50 mm or more (few inches) of fire penetration into the pile itself. Internal fires do occur from spontaneous heating as a result of excessive internal heat buildup. These fires are usually from fines that cause too much compaction or humus material within the pile, which is subject to more rapid oxidation than clean wood chips.

The chip fines can present a flash fire or explosion hazard if handled inside and dispersed in a manner that allows the wood dust to collect on structural members or to be suspended in air at concentrations above the minimum explosive concentration (MEC).

Sawdust and Shavings

Sawdust and shavings, by-products of lumber mills and wood processing plants, are generally used as a fuel on site. If strategically located, the usable material, along with other waste wood, might be shipped to other locations for use in manufacturing pulp, particleboard, or pellet fuel. The hazards are Class A combustible material and possible explosion in storage and handling from wood dust buildup.

Other Wood Waste

Wood scrap and edgings are another waste by-product, particularly of lumber mills and furniture manufacturing plants. This material is generally put through a hog to reduce the size for conveying or blowing to storage bins and boiler rooms for fuel. If the larger pieces of scrap are recoverable for use as chips in pulp manufacturing, they are conveyed to a chipper and pneumatically blown to a loading station for transfer into rail cars or tractor trailers for shipment. The hazards are similar to those for chips and sawdust. The larger wood particles are readily ignited, whereas the fines generated by the sawing, planing, and chipping processes can contain particles small enough to be an explosion hazard.

Pellets

The process uses pulverized wood waste from the forest products industry, which is formed under high temperature and pressure into pellets approximately ¼ in. by ¾ in. (6 mm by 19 mm). The finished pellets are stored in bulk form inside to keep them dry; the raw stock of wood waste is stored outside. The finished pellet storage presents little dust hazard but will burn as a Class A combustible material.

Bark

Bark is generated at pulp mills, sawmills, and chip plants as a waste material and used to a limited extent as a soil conditioner and as fuel for limited-size boilers (when mixed with other wood

scrap from the process), or it is simply disposed of by burning in teepee-type bark burners. Until recent years, bark was basically a disposal problem. Some pulp mills, however, generated too much bark over the years to be disposed of by the preceding means and it was simply piled at a detached site convenient to the plant. Over many years of operation, these piles have grown into miniature mountains. The sheer height and bulk of the piles have created a fire hazard from internal heating leading to spontaneous ignition and from external sparks from heavy equipment used to build the pile, particularly during dry periods.

A method has been outlined for eliminating fires in wood bark piles by controlling the flow of air (oxygen) horizontally into the pile. Oxygen control is achieved by sloping the pile at a 30 to 40 degree angle from the horizontal. In Figure 7.1.1 dimension A is the depth at which pressure and moisture allow the chemical reaction to generate enough heat and volatile material to provide two sides of the fire triangle (i.e., heat and fuel). Dimension B is the distance air (oxygen) must travel to complete the fire triangle and is approximately three times greater, with a 30 degree slope than with a 60 degree slope. The upward flow of heated gases within the pile prevents oxygen from reaching the point of combustion except from the nearly horizontal direction, which means the resistance to oxygen flow increases as dimension B increases. Where increasing the slope is not practical, sealing the slope to air penetration is an alternative.

What was formerly a waste disposal problem has become a valuable commodity as the price of fuel oil has gone up and the technology for burning bark on a large scale has improved. For those with such piles, they can be reclaimed as fuel for relatively large bark boilers. The reclaimed bark is mixed with the bark generated daily in the pulp manufacturing process.

STORAGE PRACTICES FOR WOOD FUELS

Logs that are to be brought to the site of use for industrial and commercial conversion to chips for fuel should be stored in ranked piles (i.e., piled in parallel form), because such piles are lower in height with less volume and less radiant heat exposure than stacked piles (i.e., large, circular, "matchstick" piles). The use of long logs, which is likely, will dictate the ranking method of storage. The piles should be 100 ft (30 m), but preferably more, from the nearest important building. The length and width of piles and pile height should be kept as small as practical to make fire fighting easier and to limit the amount of wood subject to a fire. The storage area should be clean and on solid ground with good access for fire-fighting purposes.

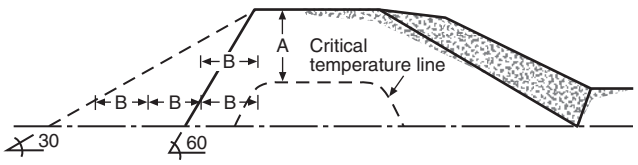

FIGURE 7.1.1 Method for Eliminating Fires in Wood Bark Piles by Controlling the Flow of Oxygen Horizontally into the Pile

Residential use of cordwood and long logs is generally in the 5- to 15-cord range and presents a relatively light hazard. Common sense dictates maintaining as much clear space as possible between the rough storage and dwelling. After cutting and splitting for use, the wood often is moved into the basement or garage for seasoning where there can be a fire potential from heating appliances, electrical wiring, and smoking. Care should be taken to store the wood away from the furnace in which it is to be burned, electrical switchboxes, and wiring. A better method is to store the wood in a pile detached from the residence and bring in a week's supply as needed.

The use of wood chips for a residential fuel is still in the developmental stage. Furnaces and the means of automatically stoking them with the chips as well as chip storage are being developed and marketed. Wood chips for fuel, often mixed with other biomass, have forged ahead in industrial and independent energy projects as illustrated by the numerous wood-to-energy projects proposed in the state of Maine.

Where chips for fuel are used on a large scale, it likely will be in a relatively isolated area close to the source of the wood and, unfortunately, away from municipal fire protection facilities and water supplies. Only the larger operations under these conditions can economically justify an independent water supply distribution system and it will be doubly important to limit outdoor chip pile size and height to dimensions less than those recommended in NFPA 1, *Uniform Fire Code*™. The plant should be located, if possible, near a pond or stream so water is available for hose streams. Any outside storage should be well isolated from processing buildings and surrounding forests.

Storage of chips, sawdust, shavings, and sander wood waste in silos, bins, and buildings can present fire and explosion hazards. Therefore, storage should be arranged to minimize these hazards by proper location, preferably outside the buildings, and by physical construction of the bin or silo and associated ducts with explosion-relief venting and explosion-isolating chokes.

Large-scale bark-burning boilers require a continuous supply of fuel to avoid fluctuations in steam output or the need to fire oil burners to take up the slack. Consequently, it is common practice to provide an enclosed surge storage area capable of providing a one- or two-day supply of fuel. One design used for such a storage building is the "A" frame style with storage capacities up to 2000 tons (1800 metric tons) at 50 to 60 percent moisture. These storage buildings should be designed to minimize the possibility of wood dust buildup on structural building members by minimizing surface areas on which the wood dust can collect. If possible, the walls should be sloped at angles approaching 60 degrees. Structural members that cannot be sloped should be covered with sheet metal designed to eliminate flat surfaces on which the dust can settle.

HANDLING WOOD FUELS

Logs, either tree length or cordwood, are loaded and piled using mechanical equipment mounted either on the log truck or on a separate vehicle. Logs present minimal fire hazard exposure to the wood-handling operation.

Wood chips and wood waste material are generally transferred either pneumatically or by belt conveyor from one place to another. The fans, ducts, cyclones, and collectors associated with air movement of wood fuel constitute a fire and explosion hazard to the process of which they are a part; therefore, they should be located so as to minimize this exposure, preferably outside the buildings whenever possible.

Magnetic separators should be provided to reduce the possibility of a spark igniting the dust. The fans should be downstream of the collectors, if possible, to prevent passage of the wood fuel through the fan.

Belt conveyors present a fire hazard from the belt material as well as from the wood material being conveyed. Sources of ignition are frictional heat from belt slippage, cutting and welding, smoking, and overheated bearings. Belt conveyor fires are sometimes complicated by the need to run the belts overhead, particularly in large bark-burning boilers. Overhead conveyors present an access problem for hose stream use.

Screw conveyors and rotary air locks should be utilized to provide chokes for fire and explosion isolation where the wood material being handled is fine enough to present an explosion hazard. It is necessary to remove a revolution (helix) of the screw in order to provide the choke. Backdraft dampers can also be used in high-velocity systems (Figure 7.1.2).

FIRE PREVENTION FOR WOOD FUELS

Where there is outside bulk storage of wood for fuel in any form, the first line of defense should be to limit the pile size to the absolute minimum required for economical operation. The homeowner and small commercial stick wood consumer will likely limit inventory to one or possibly two years' supply, whereas the larger commercial and industrial users who consume wood fuel to generate heat and power will likely restrict inventory to one day or even hours because, in many cases, they are consuming the wood waste as it is generated in the process.

Logs should be ranked rather than stacked. If large chip piles are necessary, they should be arranged as outlined in NFPA 1. Two or more smaller piles are better than one large pile.

There is indication that foreign material in piles of chips or bark accelerates the buildup of heat, possibly from chemical reaction or simply the increased porosity that allows freer movement of air through the pile. Keeping the piles free of contamination is effective fire prevention.

Pile site selection, whether for chips or bark, should take into consideration the topography of the ground, which should be clean and free of combustibles. Clearance from surrounding forest, brush, or grass should be adequate to prevent an exposure fire from reaching the storage pile. Piles should be detached from buildings and located sufficiently apart from each other to allow fire-fighting efforts to control an exposing fire.

Bark piles stored outside, whether rough or hogged bark, create heat that can lead to spontaneous ignition under certain conditions. The piles should be limited in height and contoured to restrict the flow of air (oxygen) through the pile. Heat that is generated within the pile rises to the surface and is dissipated to the surrounding air, which tends to keep the internal temperature below the spontaneous ignition point. However, in northern climates, a blanket of ice and snow can impede heat release to the extent that combustion does occur. Thus, restricting the pile height to limit heat from pressure and restricting airflow through the side of the pile become doubly important under these conditions (see Figure 7.1.1).

Storage bins, silos, and vaults for waste wood fine enough to be an explosion hazard should be outside plant buildings, if possible, or, if inside, should be arranged to vent explosions to the outside. For further details, see NFPA 664, *Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities.*

The need to control moisture content of wood waste fuel for more efficient combustion might require use of lightly constructed metal buildings on a concrete slab to protect the fuel from the weather. Such buildings should be designed to minimize dust buildup on structural members. Lighting, if required, should conform to applicable provisions of NFPA 70, *National Electrical Code®*.

If the wood waste being stored contains a considerable amount of fines in the dust/flour range (such as sander fines), it might be necessary to incorporate explosion relief in the building design. A partially open structure may be a feasible design.

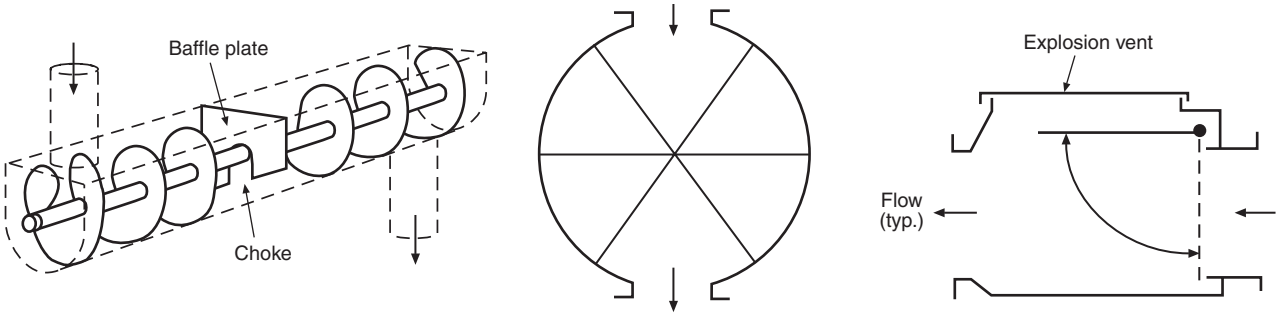

FIGURE 7.1.2 Types of Chokes Used to Isolate Fire and Explosion When Wood Material Is Fine Enough to Explode

FIRE PROTECTION FOR WOOD FUELS

The bins, silos, or vaults in which chips and other wood waste are collected should be constructed of metal and located outside the boiler building, if possible. Collector and storage units handling fines that present an explosion hazard should be constructed with explosion-relief venting arranged to operate well below the design strength of the equipment. If bulk storage must be in or adjacent to the boiler building, it should be cut off with a fire-rated masonry wall.

Ranked log piles, arranged as previously described, should be protected with a yard hydrant system suitable for the storage arrangement and size, as defined in NFPA 1. If the plant location and size preclude having an adequate water supply and a plant fire brigade, smaller, more segregated piles will be necessary with greater clear space between the wood storage and plant.

Chip and bark piles also require large amounts of water to control and extinguish fires. Although it is likely that storage piles of chips and bark to be used as fuel would not be the same size as piles of these materials at pulp mills, conscious effort should be made to keep the piles limited in size in order to reduce the volume of water and the fire-fighting effort needed to combat a fire. (See NFPA 1 for details of yard fire protection.)

Automatic sprinkler or water spray protection should be provided in the collecting, conveying, and storage areas. Where fuel storage buildings are utilized in the system, they should be provided with automatic sprinkler protection in accordance with NFPA 13, *Standard for the Installation of Sprinkler Systems;* NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection;* and NFPA 850.

Where bark or chips are transported from the outside storage pile or silo to an inside bin for feeding to the boiler by enclosed conveyors, the structure should be noncombustible and arranged to meet applicable safety codes. Regardless of the system type used, the conveyor should be interlocked to shut down on actuation of the sprinkler or detection system. As a result of the increased interest in resource recovery and the expansion of independent, nonutility power generation, the use of nontraditional (alternative) solid fuels has become common.

SOLID WASTE AS FUEL

Each year in the United States more than 200 million tons of solid waste are generated in municipal waste facilities. Approximately one-third of these wastes are used productively to generate electricity or through recycling. The rest are destined for landfills. As landfill space and waste transportation become more limited, incineration of these wastes will increase. Incinerators are addressed in Section 11, Chapter 1, "Waste Handling and Control." However, larger facilities where waste is transported to centralized facilities are discussed here.

According to USDOE statistics, more that 3300 MW of electric-generating capacity exists in the United States as of 2002. Solid waste or refuse is also used for steam and hot water production. The processing of municipal solid waste (MSW) varies according to the furnaces used to combust the waste.

Storage of Waste

MSW is usually delivered to the plant by truck and dumped on the tripper floor or into waste pits. Facilities that dump MSW on tripper floors use this area as a first sorting site to remove noncombustibles, recyclables, and other undesirables from the waste stream. In facilities where this sorting is done in pits or prior to delivery to the site, the tripper floor should be relatively free of residual combustibles. Housekeeping is important in this area because of the potential ignition sources from delivery trucks. MSW should not be allowed to accumulate. MSW stored in pits should be monitored by cameras or plant personnel to ensure that fires and unsafe conditions are detected. If the tripper floor is enclosed (walls and roof), it should be provided with automatic sprinkler protection or the structure should be built of fire-resistive construction. Building codes would limit the area for Type V construction (i.e., unprotected structural steel) to no more than 8500 ft^2 (Figure 7.1.3).

Processing of MSW

Some facilities burn the MSW with a minimum of processing. These are often referred to as mass burn plants. More frequently,

FIGURE 7.1.3 Fire Fighters Spraying Water on Full Engulfed Fire at Nashville Thermal Plant (Source: *The Tennessean*)

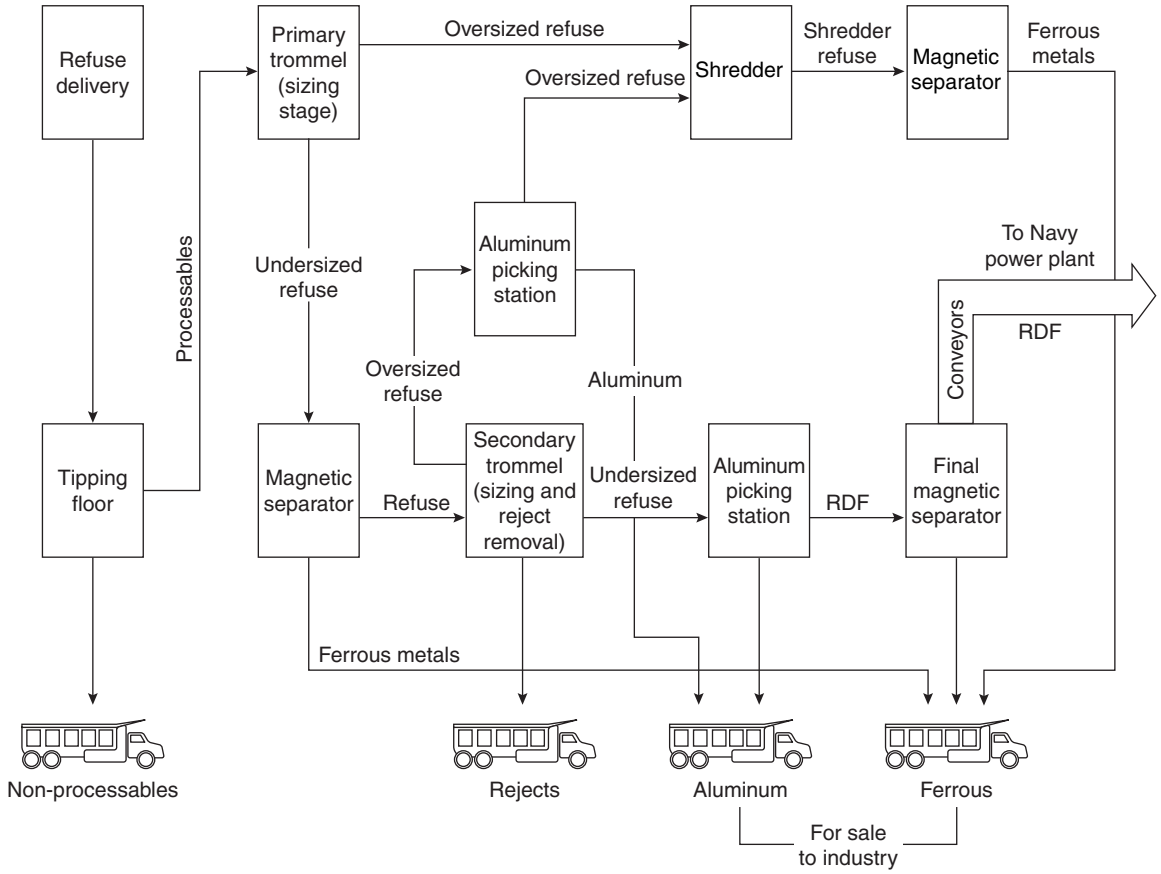

FIGURE 7.1.4 MSW Processing That Converts Waste into Fuel (Source: Courtesy of Southeastern Public Service Authority)

to improve combustion efficiency, the MSW is processed. These processes include size reduction and drying. The subsequent treated fuel is referred to as refuse derived fuel (RDF). Figure 7.1.4 shows one such processing plant, which sizes and separates as the first step, followed by shredding. In this plant the shredded fuel is conveyed to the boiler.

Shredders introduce the risk of explosions, usually from dusts generated by the shredding. The most common ignition source is "tramp" metal that fails to get separated. Magnetic separators are provided to reduce the likelihood of ferrous metals being carried into the shredder. To reduce the damage to plant and personnel in the event of an explosion, venting in combination with resistant construction should be provided.

Some RDF facilities further process the MSW by drying and by pelletizing. The resulting fuel can be consumed at the site or can be shipped to other facilities to fuel boilers. Figure 7.1.5 shows an example of a pellet extrusion process. The pellets can be stored in bins or silos at the power plant. The fuel is transferred to the boiler by either belt conveyors, chain conveyors, or screw conveyors. The pellets can also be a source of dust. Housekeeping and dust collection systems are necessary to prevent the accumulation of dust to dangerous levels.

Chapter 9 of NFPA 850 provides fire protection recommendations for these and other alternative solid fuels.

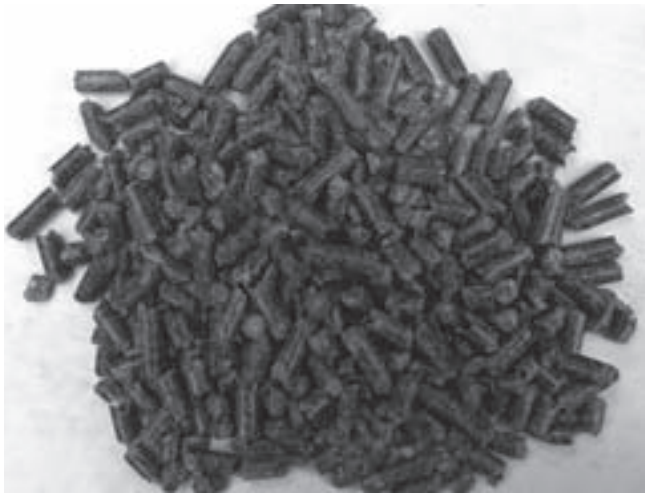

FIGURE 7.1.5 Wood Waste Pellets (Source: Photo courtesy of USDA-NRCS Missouri)

SUMMARY

Safe practices are required for the storage and handling of solid fuels, which are used to generate heat for steam, electrical power, or process needs. Major sources of solid fuel are coal, wood, wood by-products, and solid waste, which need to be stored and handled properly in order to minimize hazards. Coal is susceptible to such hazards as fire, flash fire, and dust explosion, and wood in all its forms burns if ignited. Storage and handling factors that need to be properly implemented and maintained include storage facilities and practices, housekeeping, conveyance materials, fire suppression methods, and prefire planning.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the storage and handling of solid fuels discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 664, *Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities*
NFPA 850, *Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations*

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Chapter 2

Storage of Flammable and Combustible Liquids

Anthony M. Ordile

Chapter Contents

Tank Storage
Other Storage of Flammable Liquids
Handling of Flammable and Combustible Liquids
Transportation of Flammable and Combustible Liquids

Key Terms

combustible liquid, container storage, flame arrester, flammable liquid, hazardous materials storage locker, lower explosive limit (LEL), lower flammable limit (LFL), pressure relief valve, pressure vessel, safety can, storage tank (aboveground), storage tank (underground), tank, tank vehicle, vent valve

The first requirement for the storage of flammable and combustible liquids is properly designed containers that are liquid-tight and from which release of vapors, if required, is carefully controlled. The containers range from large, vertical, outdoor storage tanks of thousands of gallons capacity (264,200 gal = 1000 m^3) down through drums to small containers that hold a few ounces of liquid.

This chapter discusses the various types of containers used in the storage and transportation of flammable and combustible liquids and the precautions that should be observed in handling the liquids as they are loaded, unloaded, or dispensed.

Additional information relevant to the storage of flammable and combustible liquids can be found in Section 2, Chapter 8, "Explosions"; Section 6, Chapter 1, "Fire Hazards of Materials"; Section 11, Chapter 5, "Control of Electrostatic Ignition Sources"; Section 14, Chapter 8, "Gas and Vapor Detection Systems and Monitors"; Section 15, "Water Supplies for Fixed Fire Suppression"; Section 16, "Water-Based Fire Suppression Equipment"; and Section 17, "Fire Suppression Systems and Portable Extinguishers."

TANK STORAGE

Tanks can be installed aboveground, underground, or, under certain conditions, inside buildings. Openings and connections to tanks, for venting, gauging, filling, and withdrawing, can present hazards if they are not properly safeguarded.

Given substantially constructed, properly installed, and well-maintained tanks, storage of flammable and combustible liquids should be less dangerous than transferring these liquids because storage does not involve any active steps where human error can lead to spills and where distance from ignition sources may be less consistently achieveable. The severity of the storage hazard might seem to depend on the quantity stored. As a practical matter, however, the size of the tank or the number of tanks is less important than such factors as the characteristics of the liquid stored, the design of the tank and its foundation and supports, the size and location of vents, and the piping and its connections.

Flammable liquids expand when heated. Gasolines expand about 0.07 percent in volume for each 10°F (6°C) increase in temperature within ordinary atmospheric temperature ranges. The effect of temperature increase on the volume of acetone, ethyl ether, and certain other flammable liquids with higher coefficients of expansion is greater than in the case of gasolines. To avoid danger of overflow, tanks should not be filled completely, particularly where cool liquid is placed in a tank in a warm atmosphere—for example, when filling a gasoline can from an underground tank at a service station on a warm day.

Several methods are used to prevent storage evaporation loss and loss of vapors as the tank is filled. Underground tanks reduce evaporation losses because there is less fluctuation of temperature. Aboveground tanks often are painted with aluminum or white paint to reflect heat, thus decreasing the temperature rise of liquid contents and slowing evaporation of tank contents. Floating roof tanks

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minimize vapor loss and tend to reduce the fire hazard. Storage in pressurized tanks reduces the loss of vapor. In some cases, vapors are conserved by the use of lifter roof or vapor dome tanks, or the vents from several cone roofed tanks might be connected through manifolds to a vapor dome or pressure-type tank.

The vapor space in tanks storing flammable liquids with vapor pressures above an absolute pressure of 28 kPa (4 psia), such as gasoline, is normally too rich to burn. The ratio of vapor to air is above the upper flammable (explosive) limit (UFL). However, if the temperature of the liquid gasoline is in the range of –10 to –50°F (–23 to –46°C), the vapor space might be within the flammable range. When a tank is being off-loaded or when there is a sudden cooling rainstorm on a hot day, a portion of the tank vapor spaceway might be within flammable limits, resulting from introduction of air. This condition might remain for several hours or even days, due to stratification of the vapors.

The vapor space in tanks storing low vapor pressure liquids (below approximately 2 psia or 14 kPa), such as kerosene, is normally too lean to burn. The ratio of vapor to air is below the lower flammable (explosive) limit (LFL). However, if the entire body of liquid is heated to its flashpoint, as can happen during refining processes or by exposure to fire, the vapor space might enter the flammable range. It should be noted that it is the temperature of the liquid and not the temperature of the vapor space that determines the presence of a flammable vapor–air mixture. The vapors driven off by the heated air in the vapor space are condensed back to liquid by the cooler body of liquid in the tank. Therefore, the vapors are only flammable for a very short distance above the liquid surface despite the fact that the air within the tank might be considerably above the flashpoint temperature.

Tank storage of ethyl and methyl alcohol, JP-4 or Jet B turbine fuel, and other liquids of similar vapor pressure (approximately 2 to 4 psia at 100°F or 14 to 28 kPa at 38°C) presents an unusual hazard, since the vapors are normally in the flammable range. Storage in floating roof or similar tanks or the addition of inert gas in the vapor space is desirable to reduce the possibility of an explosion in the vapor-air mixture in the tank. Floating roof tanks, cone roof tanks with internal floating roofs, lifter roof tanks, and vapor dome tanks are also used for vapor conservation purposes for Class I liquids.

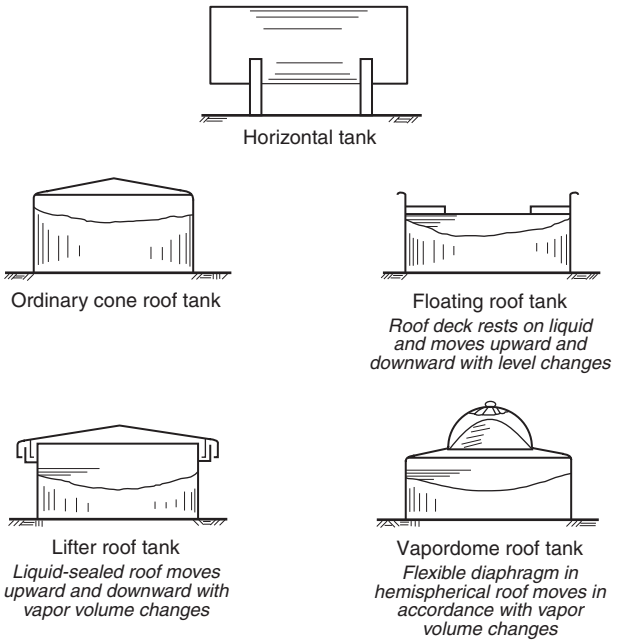

FIGURE 7.2.1 Common Types of Atmospheric Storage Tanks

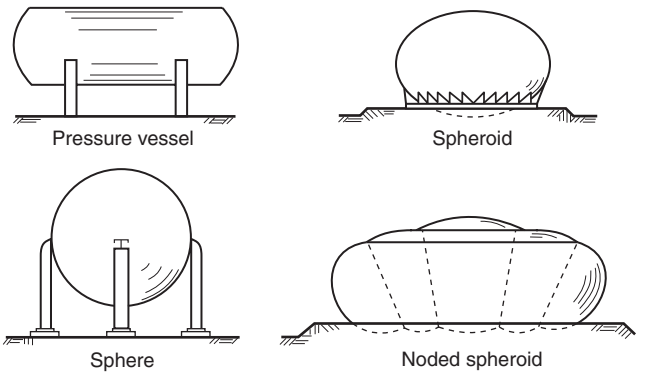

FIGURE 7.2.2 Common Types of Low-Pressure Tanks or Pressure Vessels

Aboveground Storage Tanks

Storage tanks come in a variety of design and construction types. They are divided into three general categories of pressure design: (1) atmospheric tanks, for pressures of 0 to 1.0 psig (0 to 6.9 kPa); (2) low-pressure storage tanks, for pressures from 1.0 to 15 psig (6.9 to 103 kPa); and (3) pressure vessels, for pressures above 15 psig (103 kPa). Some of the more common types of aboveground storage tanks are shown in Figures 7.2.1 and 7.2.2. Pressure tanks and pressure vessels normally are used for vapor conservation purposes, particularly for liquids with high vapor pressures.

In recent years, aboveground secondary containment-type tanks have become increasingly more popular for atmospheric storage of flammable and combustible liquids. The popularity of these tanks has been aided by federal regulations now imposed on underground tanks. Various types of aboveground secondary containment tanks are manufactured and approved for use. Figures 7.2.3 and 7.2.4 show typical aboveground secondary containment tanks. These tanks incorporate a primary steel tank that is either completely encased by another steel or fiberglass tank or a geomembrane shell so that any leakage from the primary tank is contained by the outer tank or shell. For protection against exposure fires and vandalism, many aboveground secondary containment tanks are encased with 6 in. (152 mm) of reinforced concrete, thus also providing fire resistance. Requirements covering size limitations, pipe connections, and overfill protection are contained in NFPA 30, *Flammable and Combustible Liquids Code*. Figure 7.2.5 shows the various construction and protection requirements provided on secondary containment tanks listed by Underwriters Laboratories Inc. (UL).

FIGURE 7.2.3 Common Type of Rectangular Aboveground Secondary Containment Tank (Source: Courtesy of Highland Tank & Manufacturing Company, Inc.)

Construction. All aboveground storage tanks should be built of steel or concrete, unless the character of the liquid necessitates the use of other materials. Both steel and concrete tanks resist heat from exposure fires. Tanks built of materials less resistant to heat (e.g., low melting point materials) might result in tank failure and fire spread.

The thickness of the metal used in tank construction is based not only on the strength required to hold the weight of the liquid but also on an added allowance for corrosion. When intended for storing corrosive liquids, the specifications for the thickness of the tank shell are increased to provide additional metal and allow for the expected service life of the tank. In some cases, special tank linings are used to reduce corrosion. Periodic inspection should be made to ascertain metal thickness of the tank, establish safe operating limits, and avoid overstressing the tank. The inspection of tanks for corrosion can be through the use of visual, magnetic particle, ultrasonic, and radiographic methods, or by experience gained from the storage of similar materials. Ultrasonic devices operate on a principle of the length of time it takes for sound waves to reflect from a surface. Any difference in metal thickness is quickly disclosed by these instruments, which are particularly effective when large areas with many potential corrosion spots are involved.

For atmospheric, vertical, cylindrical, and aboveground welded tanks, API Standard 650, *Welded Steel Tanks for Oil Storage,*[1] may be used in calculating the minimum thickness of shell plates. The required nominal thickness of shell plates must be the greater of the design shell thickness, including any corrosion allowance, or the hydrostatic test shell thickness, but in no case less than the values given in Table 7.2.1.

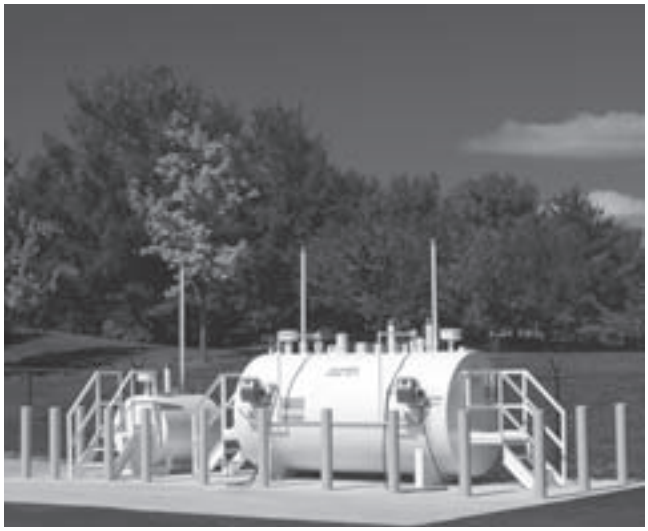

FIGURE 7.2.4 Common Type of Cylindrical Aboveground Secondary Containment Tank (Source: Courtesy of Highland Tank & Manufacturing Company, Inc.)

TABLE 7.2.1 Shell Plate Thickness

Nominal Tank Diameter (ft)	*Nominal Thickness (in.)*
Smaller than 50	3/16
50 to, but not including, 120	1/4
120 to 200, inclusive	5/16
Over 200	3/8

For SI units: 1 ft = 0.304 m; 1 in. = 25.4 mm.

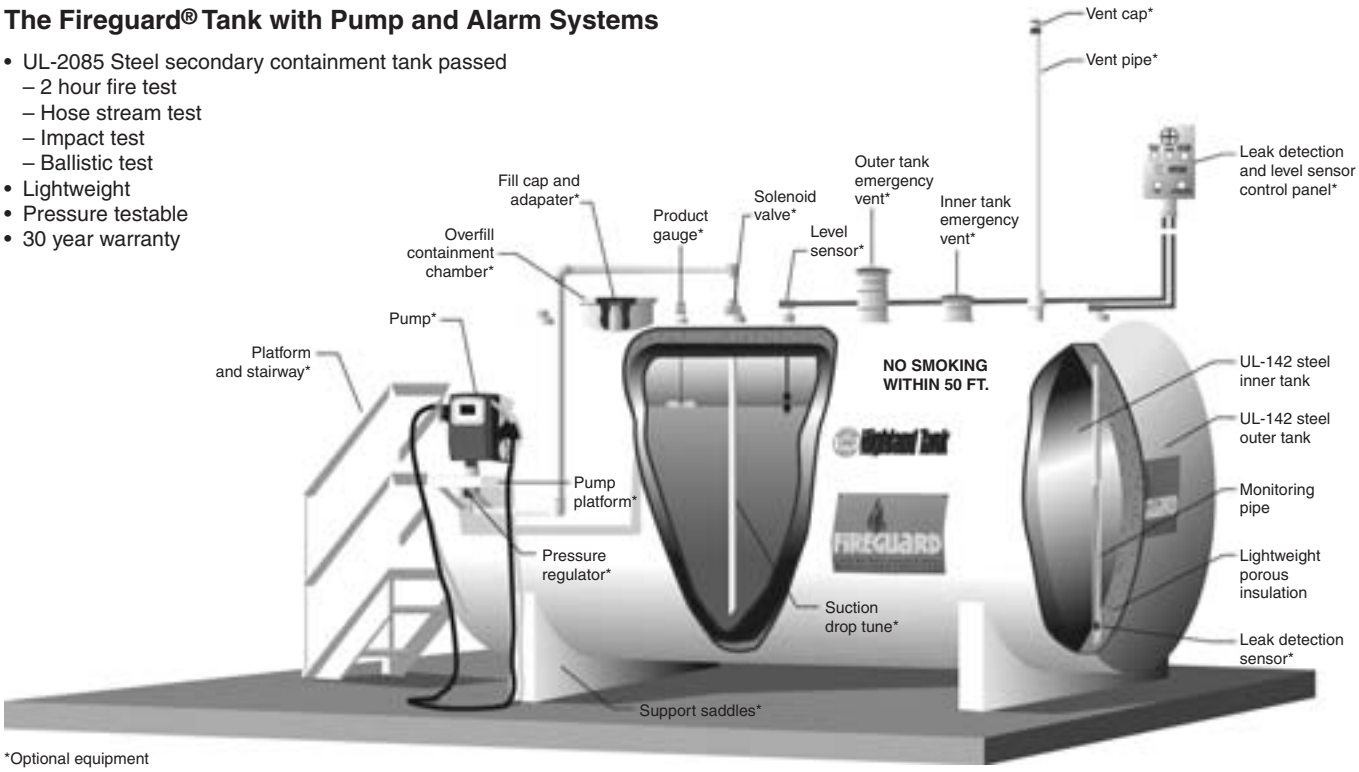

FIGURE 7.2.5 Typical Construction and Protection Features Required of Aboveground Secondary Containment Tanks (Source: Courtesy of Highland Tank & Manufacturing Company, Inc.)

Those tanks listed by UL and other testing organizations or built in accordance with American Petroleum Institute (API) standards meet the required construction specifications.

Concrete tanks require special engineering. Unlined concrete tanks should be used only for the storage of liquids with a specific gravity of 40 degrees API or heavier. Concrete tanks with special linings are permitted for other services, provided the design is in accordance with appropriate engineering practices. Tanks built of material other than steel should be designed to specifications embodying equivalent steel safety factors.

Installation. Aboveground tanks should be installed in accordance with NFPA 30, which specifies distances from tanks to property lines that can be built on and to public ways or important buildings. These distances will vary depending on whether the pressures in the tanks, including those attained during fire exposure, can be under or over 2.5 psig (17 kPa), as well as whether the contents are stable or unstable liquids, or liquids having boil-over characteristics. Other factors affecting distances are the size and design of the tank, protection for exposures, fire-extinguishing or control systems provided, and other protection features. The spacing between tanks is also specified in NFPA 30.

When a tank is located in an area that is subject to flooding, applicable provisions in NFPA 30 should be followed.

Venting and Flame Arresters. An appropriate vent must be provided for normal operation of any tank to permit filling and emptying and for the maximum expansion or contraction of the tank contents with changes in temperature. API Standard 2000, *Venting Atmospheric and Low-Pressure Storage Tanks,*[2] provides the design bases for sizing vents for product movement and breathing. Alternatively, the normal vent should be at least as large as the largest filling or withdrawal connection, but in no case should it be less than 1.25 in. (32 mm) nominal inside diameter. Clogged or inadequately sized vents can result in the rupture of tanks from internal pressure or collapse due to internal vacuum. During the filling operation, the vents discharge flammable vapors. If the mixture is sufficiently rich or if the vent location is such that the released vapor is a hazard, the vapors should be piped to a safe outside location at least 12 ft (3.7 m) above grade. The vapor release should not occur under eaves or close to doors, windows, or possible sources of ignition.

Some venting devices are normally closed when the tank is not under pressure or vacuum and this is required by NFPA 30 for Class IA liquids (flashpoint below 73°F [28°C]; boiling point below 100°F [38°C]). Devices installed on vent pipes can be approved pressure-vacuum conservation (breather) vent valves or flame arresters to prevent flashback into tanks (Figures 7.2.6 and 7.2.7). These devices are required when a flammable mixture is present and for the storage of all Class I liquids. Arresters constructed of banks of parallel metal plates or tubes having a large surface of metal to dissipate heat are more effective than screens for larger openings and are less subject to clogging and

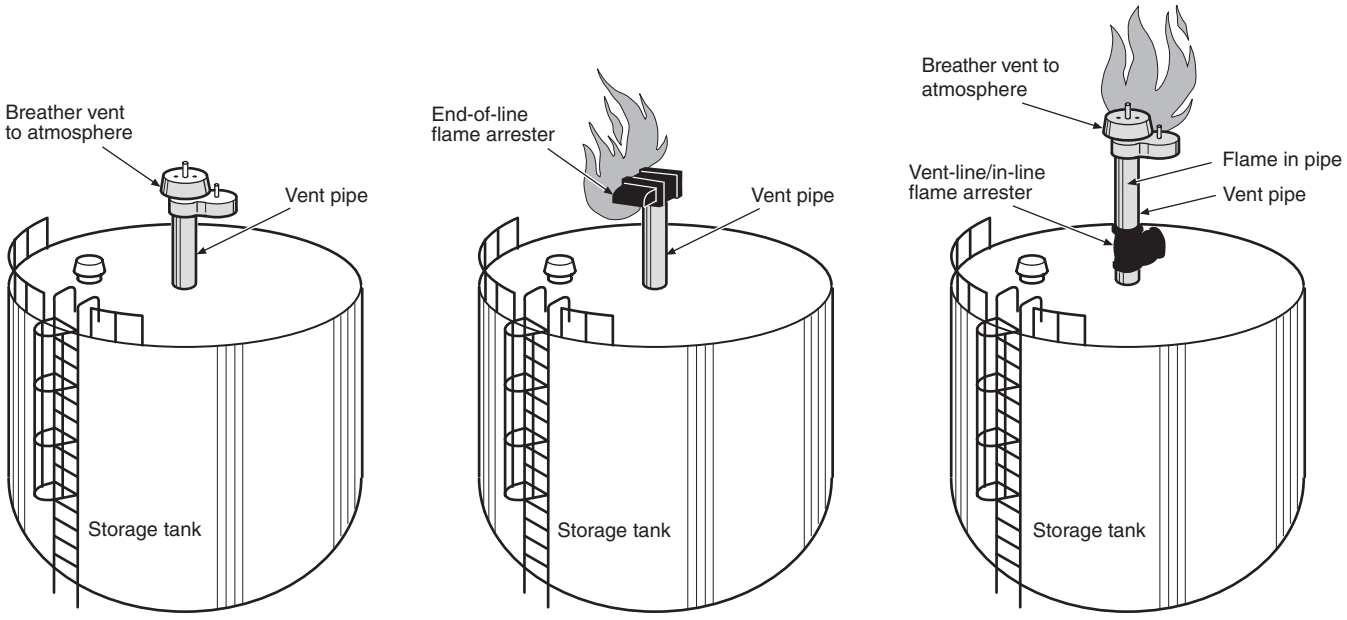

FIGURE 7.2.6 Typical Arrangement of Pressure-Vacuum Conservation (Breather) Vent Valves and Flame Arresters

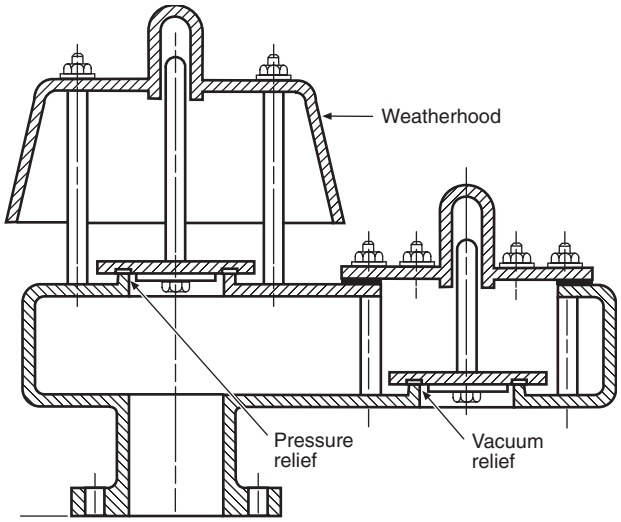

FIGURE 7.2.7 Typical Pressure-Vacuum Conservation (Breather) Vent

corrosion. Heat from exterior flames is absorbed by the plates or tubes, thus quenching the flames and preventing ignition of vapors inside the tank. However, if the flame arrester is exposed to long burning periods, the metal plates can become sufficiently hot on the bottom side to ignite any flammable vapor-air mixtures in the tank. Approved flame arresters are cellular arresters that include perforated-plate arresters, parallel-plate arresters, crimped-metal-ribbon arresters, and sintered metal arresters. The two critical parameters that govern the effectiveness of cellular arresters are (1) diameter or width and (2) length of the flame passages.

Vent design should be suitable for venting tank vapor space in accordance with API 2000[2] and NFPA 30 and should not restrict vapor relief under design conditions.

Where the liquids stored have flashpoints in the range of normal summer temperatures, the vapor space above the liquid in the tank will normally contain vapors in the flammable range. Flame arresters have their most important application on such tanks. However, condensation and crystallization of certain liquids and freezing of moisture in winter might make conservation vents and flame arresters impractical. Steam tracing (steam heating) is provided in some cases to prevent freezing or crystallization of contents.

Although a wire screen of 40 mesh* ordinarily will prevent the passage of flame through small openings, it cannot be relied on as an effective flame arrester because of possible physical damage to the wires or clogging of the mesh by dirt or other residues.

Pressure-Relief Devices. Appropriate venting of aboveground tanks and pressure vessels can also be achieved by the use of pressure-relief devices. These devices are actuated by inlet static pressure and are designed to open during an emergency or abnormal conditions to prevent a rise of internal pressure in excess of a specified value within the tank or vessel.

*A woven wire fabric in which there are 40 wires per in. (25.4 mm) in each direction and 1600 interstices per in.^{2} (645 mm^2). The size of the openings depends on the diameter of the wires and on the mesh of the screens, but the size of wire is approximately uniform for any given mesh, and specifying a screen in terms of its mesh determines the size of the openings with sufficient accuracy for practical purposes. The individual opening in a 40-mesh screen has an area of about 0.00022 in.^{2} (0.14 mm^2).

Pressure-relief valves are frequently of the spring-loaded type, which are designed to automatically reclose after actuation and prevent the further release of gas, vapor, or liquid (Figure 7.2.8).[3]

Other types of pressure-relief devices are (1) pilot-operated pressure-relief valves that include a pressure-relief valve combined with and controlled by an auxiliary pressure-relief valve and (2) rupture disk devices that are nonreclosing differential pressure-relief devices actuated by inlet pressure and designed to function by bursting the rupture disk (Figure 7.2.9).[3]

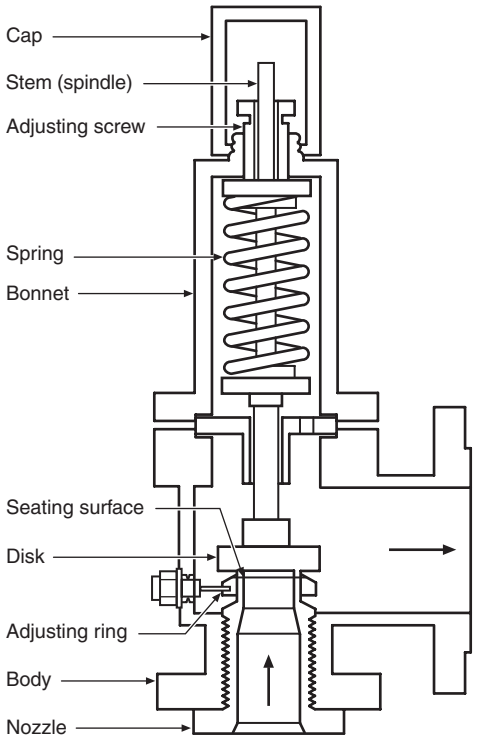

FIGURE 7.2.8 Typical Pressure-Relief Valve Device of the Spring-Loaded Type

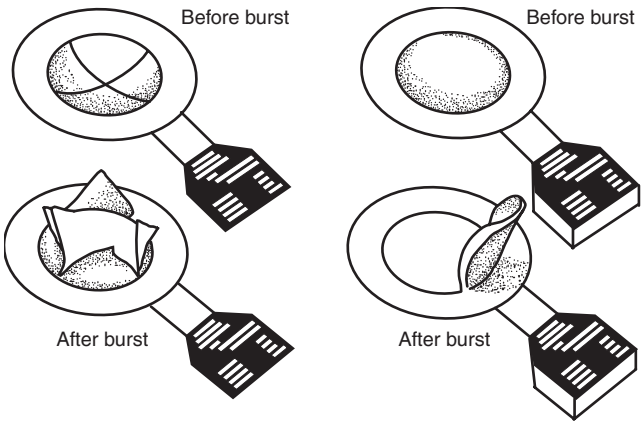

FIGURE 7.2.9 Types of Rupture Disk Devices

Emergency Venting. In addition to the normal operating vents, emergency relief of internal pressure is required for most aboveground tanks in the event a fire occurs under or around the tank. In the absence of a proper provision for such relief, high pressures can be generated when the tank is exposed to external fire, sometimes leading to explosions. Such explosions are infrequent, but when they do occur, the results can be disastrous to life and property. They can be prevented by providing adequate pressure relief, which permits the vapors to escape and burn at the vents and prevents the tank from rupturing. Emergency relief venting can take the form of loose manhole covers that lift under pressure, weak roof-to-shell seams, rupture disks, remotely actuated vapor depressuring, or commonly used pressure-relief devices designed for the purpose. The provision of floating roofs negates the need for emergency relief venting.

Unless they are adequately vented, horizontal cylindrical tanks under excessive internal pressure commonly fail, and failure typically occurs at the ends. For vertical cone-roofed tanks designed with weakened seams at the roof-to-shell joint, the lifting of the roof or top of the roof-to-shell seam affords adequate emergency pressure relief.

The danger of tank failure from internal pressure when exposed to fire depends to a considerable extent on the characteristics of the liquid, the size and type of the tank, and the intensity and duration of the fire. The smaller the tank or the smaller the volume of the liquid in the tank, the shorter the time under fire exposure before an explosion might occur.

On small cone-roofed tanks, under 20 ft (6 m) in diameter, supplemental venting might be needed to prevent preferential failure of the shell-to-bottom seam.

Dome-roofed tank designs should meet the requirements of API 650[1] for construction and venting. Dome-roofed designs should not be mistaken for cone-roofed designs.

Table 7.2.2 is based on the required discharge from both normal and emergency vents. It is derived from a consideration of the probable maximum rate of heat transfer per unit area; the size of tank and the percentage of total area likely to be exposed; the time required to bring tank contents to boil; the time required to heat unwet portions of the tank shell or roof to a temperature where the metal will lose strength; and the effect of drainage, insulation, and the application of water in reducing fire exposure and heat transfer. Due to the wide variance in flow characteristics of manufactured vents, each vent design under 8 in. (200 mm) should be flow tested rather than relying on vent size. The flow capacity of larger vents may be flow tested or calculated in accordance with the formula in NFPA 30.

The wetted area referred to in Table 7.2.2 is the internal portion of the tank in contact with the liquid (assuming a full tank) that is expected to be exposed to the flame from an external ground fire. The requirements for emergency venting are based on the heating of the liquid in the tank. Therefore, the wetted area (exposed to an external ground fire, such as a spill) varies with different tank designs: 55 percent of the total exposed area of a sphere or spheroid, 75 percent of the total exposed area of a horizontal tank, and the first 30 ft (9 m) abovegrade of the exposed shell area of a vertical tank.

For tanks and storage vessels designed for pressures over 1 psig (6.9 kPa), the total rate of venting can be obtained from

TABLE 7.2.2 Wetted Area Versus Amount of Free Air per Hour Required for Relief Venting for Aboveground Tanks. For purposes of calculating the capacity of venting devices, "free air" is defined as air at 14.7 psia and 60°F or 101 kPa and 15.5°C.

ft^2	m^2	ft^3/hr	m^3/hr
20	1.86	21,100	597
30	2.78	31,600	895
40	3.71	42,100	1,192
50	4.64	52,700	1,492
60	5.57	63,200	1,790
70	6.50	73,700	2,037
80	7.43	84,200	2,384
90	8.36	94,800	2,675
100	9.29	105,000	2,973
120	11.15	126,000	3,568
140	13.00	147,000	4,163
160	14.86	168,000	4,757
180	16.72	190,000	5,380
200	18.58	211,000	5,975
250	23.23	239,000	6,768
300	27.87	265,000	7,504
350	32.51	288,000	8,155
400	37.16	312,000	8,834
500	46.45	354,000	10,024
600	55.74	392,000	11,100
700	65.03	428,000	12,120
800	74.32	462,000	13,082
900	83.61	493,000	13,960
1,000	92.90	524,000	14,838
1,200	111.48	557,000	15,772
1,400	130.06	587,000	16,622
1,600	148.64	614,000	17,387
1,800	167.22	639,000	18,095
2,000	185.80	662,000	18,746
2,400	222.96	704,000	19,935
2,800	260.12	742,000	21,011

Note: Interpolate for intermediate values.

Table 7.2.2, except when the exposed wetted area or the surface is greater than 2800 ft^2 (260 m^2), the total rate of venting can be obtained from Table 7.2.3, or it can be calculated by the following formula:

$$CFH = 1107A^{0.82}$$

where

CFH = Venting requirement, in ft^3 of free air per hour

A = Exposed wetted surface, in ft^2

For SI units:

$$m^3/hr = 220A^{0.82}$$

where A is in m^2. The foregoing formulae are based on $Q = 21{,}000A^{0.82}$ where Q is heat absorption in Btu/hr.

The total emergency relief venting capacity for any specific stable liquid can be determined by the following formula:

TABLE 7.2.3 Rate of Venting for Tanks with an Exposed Wetted Area Larger than 2800 Ft^2 (260 m^2)

ft^2	m^2	ft^3/hr	m^3/hr
2,800	260	742,000	21,011
3,000	279	786,000	22,257
3,500	325	892,000	25,258
4,000	372	995,000	28,175
4,500	418	1,100,000	31,149
5,000	464	1,250,000	35,396
6,000	557	1,390,000	39,360
7,000	650	1,570,000	44,457
8,000	743	1,760,000	49,838
9,000	836	1,930,000	54,652
10,000	929	2,110,000	59,749
15,000	1,393	2,940,000	83,252
20,000	1,858	3,720,000	105,339
25,000	2,322	4,470,000	126,577
30,000	2,787	5,190,000	146,965
35,000	3,251	5,900,000	167,070
40,000	3,716	6,570,000	186,043

$$Ft^3 \text{ of free air per hour} = V\frac{1{,}337}{L\sqrt{M}}$$

For SI units:

$$m^3/hr = V\frac{3107}{L\sqrt{M}}$$

where

V = ft^3 or m^3 of free air per hr from Table 7.2.2

L = Latent heat of vaporization of specific liquid in Btu per lb or kJ/kg

M = Molecular weight of the specific liquid

The required rate of venting is permitted by NFPA 30 to be multiplied by a reduction factor listed in the following schedule when protection is provided as indicated (only one factor may be used for any one tank):

- A reduction factor of 0.5 for approved drainage for tanks over 200 ft^2 (18.6 m^2) of wetted area
- A reduction factor of 0.3 for approved water spray and drainage
- A reduction factor of 0.3 for approved automatic water spray
- A reduction factor of 0.3 for approved insulation
- A reduction factor of 0.15 for approved water spray with approved insulation

With some restrictions, the above factors may be reduced by 50 percent for liquids with heats of combustion and rates of burning equal to or less than those of ethyl alcohol (ethanol), but in no case can the factors be reduced to less than 0.15. See NFPA 30.

When pressure tanks or vessels are exposed to fire, a violent BLEVE (boiling liquid expanding vapor explosion) can

result if the steel in the vapor space is softened by heat. Localized overheating of the tank shell has been caused by vent fires impinging on tank surfaces. The outlets of all vents and vent drains on aboveground tanks designed for 2.5 psi (17 kPa) or greater should be arranged to prevent localized overheating of any part of the tank from a vent fire.

Foundations and Supports. Tanks should be set on firm foundations. They should be adequately supported to minimize the possibility of uneven settling and to minimize the corrosion in any part of the tank resting on the foundation. Vertical tanks are normally set on a slightly elevated concrete pad to provide a sound base and normally above the adjacent ground level to protect the bottom of the tank from any water in the area. Exposed pilings or steel supports under any flammable liquid tank should be protected by fire-resistive materials with a fire resistance rating of not less than 2 hours.

In certain situations, the use of water spray protection on tank supports may be approved for use, in lieu of providing fire-resistive materials.

Drainage and Dikes. Where important facilities, waterways, or adjoining properties would be endangered by release of liquids stored in tanks, it is necessary to provide a means to control any spillage. The most desirable method is to locate the tanks on sloping ground. Directional dikes or drainage ditches could then divert spillage away from all tanks and into an impounding basin where the liquid could burn safely without exposing other tanks, property, or waterways. Where impounding basins cannot be used, dikes built around the tanks can prevent the spread of liquid. Dikes may be constructed of earth, concrete, solid masonry, or steel built to withstand the lateral pressure of a full liquid head. When several large tanks are in a single diked enclosure, it may be desirable to place drainage channels or intermediate dikes between tanks. Intermediate dikes, which should be at least 18 in. (457 mm) in height, are effective in preventing small spills from exposing other tanks in the diked enclosure. Such spills typically result from a leaking valve or connection or from overfilling the tank.

Diked enclosures should be designed to contain the greatest amount of liquid that can be released from the largest tank within the enclosure, assuming a full tank. When calculating the volumetric capacity of the diked enclosure, the volume of other tanks within the diked area to the height of the dikes must be considered as unavailable for retaining liquid.

Where needed, diked areas are provided with trapped drains to remove rainwater or water used for fire fighting. The best practice is to keep drain valves normally closed and open them at intervals as needed, since permanently open drains would discharge liquids in case of leakage from the tank. The drain valves should also be accessible under fire conditions (i.e., they should be located outside the dike). Oil separators are effective in skimming off oil flowing on the surface of water, but separators normally will not control oil discharge when the entire flow through the drain is oil.

Dikes higher than 6 ft (1.8 m) are not desirable without additional safety measures. Where circumstances require high, close dike walls, means should be provided for access to tanks, valves, and other equipment and for safe egress from the diked enclosure. Where the average height of a dike containing Class I liquids is over 12 ft (3.6 m) high or where the distance between a tank and the inside edge of the dike wall is less than the height of the dike wall, provisions should be made for normal operation of valves and for access to tank roofs without entering below the top of the dike. These provisions reflect a concern for the accumulation of Class I liquid vapors reaching harmful levels when confined in the narrow space between the high dike wall and the tank.

Aboveground secondary containment-type tanks meeting the requirements of NFPA 30 are not required to meet the provisions for drainage or diking, as long as their capacity does not exceed the capacities allowed by NFPA 30.

Fire Hazards of Aboveground Tanks. A commonly encountered type of aboveground tank installation includes tanks on unprotected steel supports. Tank truck loading can be accomplished by gravity when done immediately adjacent to these tanks. The common fire at such installations originates at the tank vehicle and, in short order, the unprotected steel supports fail and drop the tanks to the ground. The tanks might break the piping or rupture on hitting the ground, releasing their entire contents. To prevent tank collapse, steel supports should be protected by 2 hour fire-resistive coverings. The loading rack should be at least 25 ft (7.6 m) from the tanks if Class I flammable liquids are handled, and 15 ft (4.6 m) with Class II and Class III liquids.

Improper and inadequate emergency venting can be a factor in tank failures during exposure to fire. Because these tank failures can lead to severe explosions, deaths, and injuries to fire fighters and others, it is of vital importance that the requirements on venting be followed. In fighting tank fires, it is essential to cool the shell above the liquid level to keep the steel from overheating. Failure to do so could cause the tank to bulge and rupture, regardless of the adequacy of the venting.

Also, a factor in fires involving storage tanks has been the failure of piping and valves. Such failures have resulted in the addition of their contents to the ground fire. Pipe systems may be located either aboveground or underground. Piping from aboveground tanks is normally placed aboveground to avoid corrosion problems and to aid in detecting pipe leaks. If piping is in open trenches, suitable fire barriers should be placed at certain intervals to prevent the flow of liquid from one section of the facility to another. Underground piping is not subject to fire exposure. All piping must be protected against physical damage and excessive stresses that arise from expansion, contraction, vibration, and settlement. Materials that are subject to failure due to thermal shock, such as cast iron, and low melting point materials such as aluminum, copper, and brass, should not be used. Steel or nodular (malleable) iron pipe and valves should be used for external tank connections through which liquid would normally flow, unless the chemical characteristics of the liquid stored are incompatible with steel. Welded pipe connections or flanged joints are preferred for aboveground piping, particularly for large-size pipe. Screwed pipe connections larger than 3 in. (76 mm) are subject to disengagement in a long-exposure fire unless the connections are back-welded. Pipe joints dependent

on the friction characteristics of combustible materials for mechanical continuity of piping are subject to failure under fire exposure conditions.

Storage tank fires may originate with an internal explosion or by a spill fire exposing the tanks. In a prolonged tank fire, the shell of a large vertical tank is likely to fold into the tank above the burning liquid level, without splitting the tank shell.

Internal explosions of storage tanks can occur when the vapor space above the liquid reaches the flammable range. Liquids with flashpoints near the stored temperature are most susceptible to ignition. Liquids with low flashpoints will have a flammable vapor-air mixture in the vapor space if the temperature is markedly reduced and high-flashpoint liquids will form a flammable vapor-air mixture when heated. During fire exposures, internal explosions have occurred in tanks containing liquids with flashpoints above the stored liquid temperature. Such explosions occur because the liquid is heated by the exposure fire and the vapor passes into the flammable range when a part of the tank shell in the vapor space is hot enough to ignite the vapors.

Floating roof tanks provide greater fire safety for aboveground installations and, as a result, are permitted to be located closer to a property line than are other types of tanks. Explosions might occur when floating roof tanks are virtually empty of liquid and the roof has been allowed to rest on the low-level supports, thus creating a flammable vapor space beneath. When fires occur in floating roof tanks, they are normally restricted to the seal space between the roof and the shell and can be extinguished by portable extinguishers or handheld foam lines. Full-surface fires can result from the roof sinking. Roof sinking can occur as a result of the roof hanging up due to overfill or tank obstructions, excessive snow loading or rainwater, and excessive water or foam from fire-fighting activities. A good tank roof and seal maintenance program, along with proper tank operating procedures, is the best way to prevent problems resulting in fires (Figure 7.2.10).

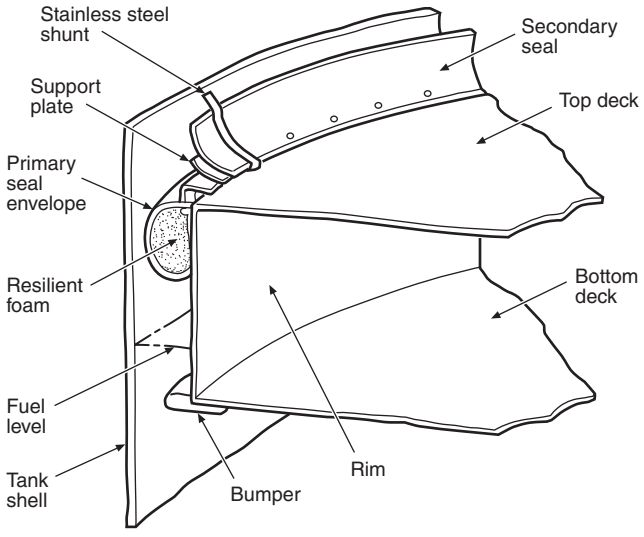

FIGURE 7.2.10 Double-Seal System for Floating Roof Tanks

Fire protection equipment should be installed on tanks where needed. (See NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam.*)

Underground Storage Tanks

Underground tanks are generally considered the safest form of storage. However, concern about groundwater contamination has increased concern about use of underground storage tanks. Environmental safety regulations should be reviewed when planning installation of underground storage tanks.

Underground tanks must be designed to withstand safely the service to which they are subjected, including the pressure of the earth, concrete, or possible aboveground vehicle traffic. Typical sizes for underground tanks are shown in Table 7.2.4.

Construction. Underground tanks are constructed of coated steel, fiberglass-reinforced plastic, and plastic-clad steel and come in both single-wall and double-wall varieties. Almost all are listed by UL and other testing agencies and most are designed according to industry standards. Underground tanks also can be of unlined concrete for the storage of liquids having a specific gravity of 40 degrees API or heavier. Lined concrete tanks may be used for liquids having a lighter specific gravity, provided the lining is suitable for the liquid being stored and has satisfactory adherence to the concrete.

Installation. Underground tanks may be buried outside or under buildings. Tanks that are buried underneath buildings

TABLE 7.2.4 Typical Sizes of Underground Flammable Liquid Tanks

Capacity		Diameter			Length		
gal	*L*	*ft*	*in.*	*m*	*ft*	*in.*	*m*
300	1,136	3	0	0.91	6	0	1.83
560	2,120	4	0	1.22	6	0	1.83
1,000	3,785	4	0	1.22	11	0	3.35
1,000	3,785	5	4	1.62	6	0	1.83
1,000	3,785	4	0	1.22	11	0	3.35
1,000	3,875	5	4	1.62	6	0	1.83
1,500	5,678	5	4	1.62	9	0	2.74
2,000	7,571	5	4	1.62	12	0	3.66
2,500	9,463	5	4	1.62	15	0	4.57
3,000	11,356	5	4	1.62	18	0	5.49
3,000	11,356	6	0	1.83	14	0	4.27
4,000	15,142	5	4	1.62	24	0	7.32
4,000	15,142	6	0	1.83	19	0	5.79
5,000	18,927	6	0	1.83	24	0	7.32
6,000	22,712	6	0	1.83	29	0	8.84
6,000	22,712	8	0	2.44	16	0	4.88
7,500	28,390	8	0	2.44	20	0	6.10
10,000	37,854	8	0	2.44	27	0	8.23
10,000	37,854	9	0	2.74	21	0	6.40
10,000	37,854	10	0	3.05	17	0	5.18
10,000	37,854	10	6	3.20	15	7	4.75

should have fill and vent connections outside the building walls. Tanks should be set on firm foundations and surrounded with sand or gravel that is well tamped into place.

Excavation for underground storage tanks should be made with due care to avoid undermining the foundations of existing structures.

Underground tanks must be protected against damaging loads imposed by the cover over the tanks and such factors as building foundations and vehicular traffic. Normally, no special protection is needed if the tanks are well supported underneath and buried sufficiently deep. However, if tanks are located in areas where higher-than-normal loads might be imposed, concrete, paving, or additional earth coverage might be necessary. Piping subject to possibly damaging loads or vibrations is frequently protected by sleeves, casings, or flexible connectors to ensure the integrity of the line.

Poor workmanship is one of the largest causes of failure and leaks in underground tanks. Generally, poorly installed piping systems connected to underground tanks might show evidence of leakage in the first year. The normal life expectancy of a properly installed underground steel tank with either a fiberglass outer wall or cathodic protection is 25 to 30 years.

Environmental regulations or a hazard analysis might require the use of a double-walled tank design and/or the use of groundwater monitoring for tank and piping leaks. The soil in which the tank is buried is very important, because some soils, such as red clay, can be highly corrosive because of their chemical composition or moisture content. This is also true if construction debris, cinders, shale, or other foreign matter is mixed, even in very small quantities, with otherwise "clean" backfill. The use of homogeneous, clean backfill and protective coatings prolongs the life of steel tanks and piping. Cathodic protection of buried tanks and piping is often necessary. NFPA 30 requires that tanks and their piping be protected either by using corrosion-resistant materials of construction, such as special alloys and fiberglass, or by using a properly engineered, installed, and maintained cathodic protection system in accordance with recognized standards of design.

Electrolytic corrosion in an electrically conductive tank and piping system might occur at points where metals having different electromotive qualities, such as steel and brass, are connected. Connections of two dissimilar metals should be avoided to prevent galvanic corrosion.

Stray electrical currents can initiate corrosive action, but their presence might be difficult to determine until after the action has progressed to the point where damage has been done to the tank or piping. Cathodic protection or insulation is sometimes used to protect underground tanks from stray currents.

Fiberglass-reinforced plastic (FRP) tanks for underground installation eliminate the corrosion problem encountered with steel tanks. However, it is vitally important that the manufacturer's instructions for proper installation of these tanks be followed closely. Improper installation can result in major failure of the tank. Care should be taken in the use of FRP tanks to ensure that liquids stored in the tanks are not destructive to the plastic tank construction.

Tanks should be anchored or weighted to prevent floating in locations where the groundwater level is high or might rise in case of flood. Details of installation and protection are covered in NFPA 30.

The proximity of underground tanks to a building foundation is not a direct measure of the potential danger to the building if a leak should develop in the tanks. Leaking contents from underground tanks can travel substantial distances underground or can penetrate 24 in. (610 mm) of waterproofed concrete before appearing in a building. Tanks suspected of leaking should be tested hydrostatically with the same liquid stored in the tank (Figure 7.2.11). Air tests or testing with liquids other than that stored in the tank can be dangerous and inconclusive for detecting suspected leaks in underground tanks. Additional details about the causes of corrosion, locating leaking tanks, and removal of liquids in the ground are covered in NFPA 329, *Recommended Practice for Handling Releases of Flammable and Combustible Liquids and Gases.*

Tanks Inside Buildings and Storage Tank Buildings

Tank installations storing Class I, II, and IIIA flammable and combustible liquids are permitted inside buildings when meeting the requirements of NFPA 30 for storage tank buildings. NFPA 30 imposes no requirements on noncombustible constructed tanks in buildings storing Class IIIB (flashpoints at or above 200°F [93°C]). A tank installation that has a canopy or roof that does not limit the dissipation of heat or dispersion of vapors and does not restrict fire-fighting access and control is considered by NFPA 30 as an outside aboveground tank installation and not a storage tank building.

Design. Tanks designed for installation within buildings have the same shell thickness and design features as required for outside aboveground storage tanks. In certain specialized pro-

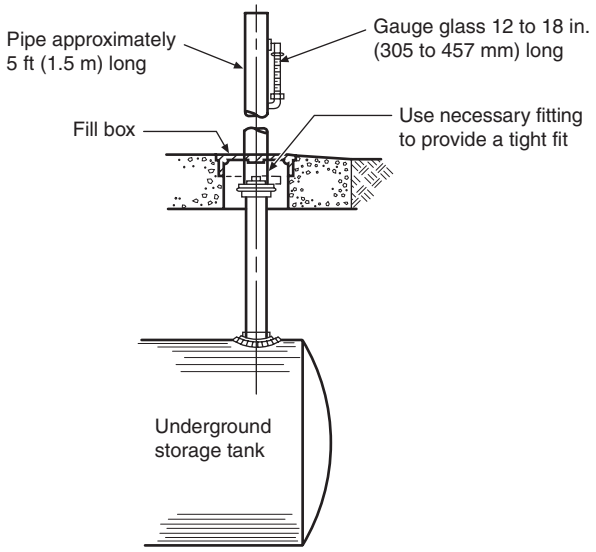

FIGURE 7.2.11 Simple Leak Test Equipment in a Typical Underground Tank Installation

cessing operations, large tanks are required and are designed as low-pressure storage tanks or pressure vessels.

For the storage of flammable and combustible liquids in accordance with NFPA 30, the capacity of any individual storage tank within a building is limited to a nominal capacity of 100,000 gal (380,000 L) unless the authority having jurisdiction permits the use of larger tanks. Storage tank buildings should be constructed so as to maintain their structural integrity for 2 hours under fire exposure conditions and to provide adequate access and egress for unobstructed movement of all personnel and fire protection equipment.

For the storage of fuel oil in accordance with NFPA 31, *Standard for the Installation of Oil-Burning Equipment,* unenclosed supply tanks in buildings are permitted to be connected to oil-burning appliances. Tanks and tank systems with a maximum individual capacity of 1320 gal (5000 L) are permitted; if tanks are located on higher floors, the maximum individual capacity of the tank is limited to 660 gal (2500 L). Where a tank or tank system is not located in a dedicated room or enclosure, the maximum capacity in the building should not exceed 1320 gal (5000 L) for a nonengineered system and should not exceed 1375 gal (5200 L) for an engineered system. Where a tank or tank system is located in a dedicated room or enclosure that is separated from the rest of the building by construction having a fire resistance rating of at least 3 hours, the maximum total capacity in the room is permitted to exceed 1320 gal (5000 L) for a nonengineered system and 1375 gal (5200 L) for an engineered system.

Installation. Tanks and any associated equipment within a storage tank building should be located so that a fire in the area should not constitute an exposure hazard to adjoining buildings or tanks for a period of time consistent with the response and suppression capabilities of the fire-fighting operations available to the location.

For specific requirements covering the installation of storage tank buildings, with respect to exposed property lines, public ways, and important buildings, see NFPA 30.

Storage tank buildings storing Class I liquids or Class II or Class IIIA liquids at temperatures above their flashpoints are required to be ventilated at a rate sufficient to maintain the concentration of vapors within the building at or below 25 percent of the lower flammable limit. The tank vents should be arranged to ensure that flammable vapors are not released inside the building. Also, electrical equipment and wiring should be specified and installed in accordance with NFPA 70, *National Electrical Code®*, to prevent a source of ignition for any flammable vapors that might be present under normal operations or during a spill.

Drainage systems should be provided in storage tank buildings to minimize fire exposure to other tanks and to prevent the discharge of flammable or combustible liquids to public waterways, public sewers, and adjacent properties.

Storage tank buildings should also have fire prevention control systems and methods for (1) life safety, (2) minimizing property loss, and (3) reducing fire exposure to adjoining operations and property. Such systems and methods include emergency alarm systems; automatic sprinkler, foam-water, water spray, or deluge systems; and thermally or remotely actuated valves at liquid transfer connections, along with programs to control ignition sources and static electricity.

Vaults for Aboveground Tanks

Aboveground tanks are permitted to be installed in vaults that meet the construction and protection requirements of NFPA 30. Vaults are permitted to be either above or below grade. For the storage of liquid petroleum products in accordance with NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages,* tanks enclosed in vaults are permitted outside and inside buildings where it is impractical because of property or building limitations to install the tanks aboveground or underground in accordance with NFPA 30.

Design. The walls and floor of the vault should be constructed of reinforced concrete at least 6 in. (150 mm) thick. The top of above-grade vaults should be constructed of noncombustible material and should be designed to vent any explosion occurring inside the vault. The top of an at-grade or below-grade vault should be designed to relieve or contain the force of an explosion occurring inside the vault. The vault should be liquid-tight.

Requirements also exist for vaults containing Class I liquids to be ventilated either continuously or upon activation of vapor and liquid detection systems. Tanks in vaults are required to have vent pipes for normal tank venting, emergency vents, and overfill protection in accordance with the requirements of NFPA 30.

Installation. Each tank should be in its own vault and should be completely enclosed by the vault. Sufficient clearance between the tank and the vault must be provided to allow for visual inspection and maintenance of the tank and its appurtenances. No separation distance is required between vaults and property lines, public ways, and important buildings.

Gauging Tanks

Tank openings for gauging or measuring the quantity of liquid can permit the escape of vapors during the gauging operation. Such openings are particularly undesirable in tanks located in buildings or buried under basements and are prohibited by NFPA standards unless protected by a spring-loaded check valve or other approved device. Substitutes for manual gauging include heavy-duty flat-gauge glasses; magnetic, hydraulic, or hydrostatic remote reading devices; and sealed float gauges. These devices, however, must be maintained in reliable operating condition. Ordinary gauge glasses should not be used, since their breakage may permit the escape of liquid.

Cleaning Tanks

Cleaning tanks for the purpose of making repairs requires great care. Precautions must be taken to avoid igniting flammable vapors and to protect personnel against toxic vapors.[4,5]

Work on empty tanks must be performed only under the supervision of persons well versed in fire and explosion hazards and in the procedures required to properly safeguard the

operation. Unless the work can be done with the tank and all connected piping and fittings completely filled with water, all vapors should be removed by cleaning with steam or chemical solutions or by displacement with water, air, or inert gas. In some instances, the tank vapor space can be filled with inert gas by specially qualified personnel to provide a safe atmosphere. The selection of the method of rendering a tank safe will depend on several factors, such as the character of the liquid, the size of the tank, the flammability and reactivity of residues, and the type of work to be performed. With many reactive materials, it will be necessary to obtain information from the manufacturer regarding recommended practices for safe cleaning.

Removal of Flammable Vapors by Displacement. This is sometimes referred to as "purging" and can be accomplished by one of several methods:

1. *Displacement with water.* Where the flammable liquid previously contained is known to be readily displaced by or soluble in water, it can be removed completely by using water to alternately fill and drain the tank. The operation should be repeated several times until tests with a combustible gas indicator show that the vapors are no longer present. Acetone and ethyl alcohol are examples of water-soluble liquids.
2. *Displacement with air.* Frequently, flammable vapors can be removed by purging with air through the use of venturi-type air movers or low-pressure blowers, with a safe atmosphere sustained by continuous ventilation. Air movers should be restricted to those operated by steam, by air, or by electric motors approved for use in the atmosphere involved. When steam operates the air mover, the air mover should be bonded or in electrical contact with the tank. When small tank openings cannot accommodate an air mover, the contents can sometimes be purged with compressed air connected to a metallic pipe bonded to the tank. Care should be exercised to prevent overpressuring a small tank if compressed air is used. Irregularly shaped tanks might not be thoroughly purged by this method because the tank can contain pockets that cannot be reached effectively by the air stream. In air purging, the concentration of flammable vapors in air in the tank might go through the flammable range before safe atmospheres are obtained. Therefore, all precautions must be taken to minimize the hazards of ignition by static electricity. Air movers should be clamped or bolted, and thereby inherently bonded, to the vessel being ventilated. Compressed air or steam is admitted to the bell of the air remover and enters the horn through the annular orifice around the base. As the steam or compressed air passes through the horn, its expansion induces a rapid flow of air, equal to approximately 10 times the volume of the steam or compressed air (Figure 7.2.12).
3. *Displacement with inert gas.* When nitrogen in cylinders or carbon dioxide in low-pressure containers or in solid form (dry ice) is available in sufficient quantity, it may be used to purge the flammable vapors from tanks without the hazards of having the vapor-air mixture in the tank vapor space pass through the flammable range. This procedure should be followed by air ventilation of the tank. High-pressure carbon dioxide, such as that from a fire extinguisher, should not be used because static electricity is generated.

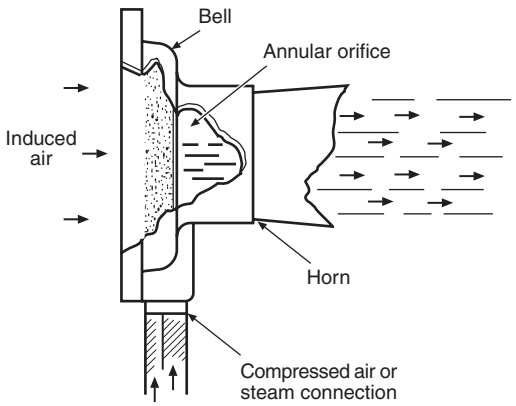

FIGURE 7.2.12 Schematic Drawing of the Operation of an Air Remover

Inerting the Vapor Space. Inerting is a means of safeguarding a tank so that work can be performed on it. Inerting a tank can be accomplished by reducing the oxygen content to the point where combustion cannot take place in the vapor space.

Inerting gases include carbon dioxide and nitrogen. Both may be obtained in pressurized cylinders, and carbon dioxide may also be obtained in solid form. Individuals in direct charge of the work must be thoroughly familiar with the limitations and characteristics of the inert gas being used. Attempting such work without proper knowledge or equipment can be hazardous because a false sense of security is engendered. The oxygen content should be maintained at substantially zero during the entire period work is in progress.

Removal of Residues. The removal of liquid and solid residues is necessary, as they may release flammable vapors during repair operations involving hot work. The removal of residues can be accomplished by steam or chemical cleaning or by other recognized methods. In steam cleaning, the rate of steam supply should be sufficient to exceed the rate of condensation and the steam nozzle should be electrically bonded to the container shell. During the steam cleaning process, the entire container is, of course, heated close to the boiling point of water (212°F [100°C]). Chemical cleaning might be necessary to remove some residues, but this could present personnel health hazards that should be guarded against.

Although a tank's atmosphere is safe for entry, the removal of residues can cause the release of additional hazardous or flammable vapors. During such work conditions, continuous ventilation can maintain the vapor concentration at a safe limit. Tanks can be continuously ventilated by air movers at the roof manholes. Continuous monitoring of the tank's atmosphere will provide notification of potentially hazardous vapor levels.

Special care must be taken to eliminate any source of ignition in the vicinity of the tank or in the path of vapors being displaced. Bonding, either with special bond wires or by metal-

to-metal contact with clamped or bolted connections providing inherent bonding, must be used where static-producing devices are used. All electrical equipment, such as inspection lights and motors, used in connection with the cleaning operations must be designed for such use.

Tests for the presence of flammable vapors constitute the most important phase of the cleaning or safeguarding procedure and must be made before commencing any alterations or repairs; immediately after starting any welding, cutting, or heating operations; and frequently during the course of such work. The tests made with a combustible-gas analyzer in good working order will normally produce reliable readings. Considerable care should be exercised to ensure that the analyzer is calibrated for the vapors involved, correctly scaled, and properly used and read and that the readings are interpreted and applied properly. Where an inert gas is used, the oxygen content of the tank is measured to determine whether a hazardous condition exists. This can be determined directly by the use of an oxygen analyzer or indirectly by the use of an analyzer showing the concentration of the inert gas being used. All testing must be conducted by persons experienced in the operation and in the limitations of the analyzers used.

When hot work is to be done on small tanks or containers that cannot be entered, the combustible-gas analyzer should show no appreciable indication of the presence of flammable vapors. Extra precautions are necessary if the container last contained a high-flashpoint liquid, because no vapor reading will show on the analyzer. If welding or cutting is done, the heat might vaporize some of the liquid, create a flammable vapor-air mixture in the drum, and explode it. Such containers require special precautions.

Hot work can be performed safely, under qualified supervision, in tank cars, tank trucks, and tanks that can be entered when the flammable vapors are under 10 percent of the lower flammable limit. Additional precautions, such as protective clothing and self-contained breathing apparatus, are necessary to protect the health of persons entering tanks that have contained leaded gasoline or other highly toxic residues.

Where toxic materials have been stored in a tank, additional tests might be required to determine if the atmosphere is safe from the standpoint of health. For example, leaded gasoline tanks need to be lead-free before they can be entered without breathing equipment and specialized protective clothing.

More complete instructions for cleaning tanks or containers are covered in NFPA 326, *Standard for the Safeguarding of Tanks and Containers for Entry, Cleaning, or Repair;* NFPA 306, *Standard for the Control of Gas Hazards on Vessels;* API 2013, *Cleaning Mobile Tanks in Flammable or Combustible Liquid Service;*[4] and API 2015, *Cleaning Petroleum Storage Tanks.*[5]

OTHER STORAGE OF FLAMMABLE LIQUIDS

Flammable and combustible liquids are packaged, shipped, and stored in bottles, drums, and other containers ranging in size up to 60 gal (225 L). Additionally, liquids are shipped and stored in intermediate bulk containers up to 793 gal (3000 L) and in portable intermodal tanks up to 5500 gal (20,818 L). Storage requirements for these containers are covered in the NFPA 30 chapter entitled "Container and Portable Tank Storage," with the exception of those portable tanks larger than 793 gal (3000 L) that are required to meet the applicable requirements covered in the NFPA 30 chapter entitled "Tank Storage."

Examples of container types used for the storage of liquids include glass, metal, polyethylene (plastic), and fiberboard. The maximum allowable size for the different types of containers is governed by the class of flammable or combustible liquid to be stored in it (Table 7.2.5).

The principal hazard of closed container storage is the possibility of overpressure failure of the container when exposed to fire. This results in a release of liquid that adds to the intensity of the fire and can cause the rupture of additional containers, resulting in a rapidly spreading fire. Fire tests have shown that automatic sprinkler systems with ordinary sprinkler densities and even newer technology sprinkler systems involving early suppression fast-response sprinklers can be inadequate in preventing overpressure failure and rupture of containers of flammable and combustible liquids, when they are stored in high-piled arrangements. Additionally, the ability to drain away spilled liquid in a fire is critical in controlling a flammable and combustible liquids fire, especially when sprinkler protection consists of water-only sprinkler systems.

Container Storage in Buildings

Container storage of flammable and combustible liquids can be found in mercantile and industrial occupancies and in general-purpose and flammable liquid warehouses. Any liquid-storage building or room or any portion of a building or room where containers are stored should be designed to protect the containers from exposure fires and contain or drain any spilled liquids. This might require the installation of fire walls or partitions or separating the containers from other storage arrangements or processes.

The life hazard to the occupants of buildings, exposure to other buildings, building construction, and the degree of fire protection provided are factors to be considered when evaluating the amount of container storage in buildings. Details and limitations on closed container storage are given in NFPA 30.

Inside Liquid Storage Areas. A room or building used for the storage of flammable and combustible liquids can be considered an inside room or liquid warehouse.

Inside rooms are totally enclosed within a building with none of the walls being part of the building's exterior walls. A liquid warehouse can be either a separate, detached building or an attached building used for warehousing operations. Design and construction requirements vary for each type of inside liquid storage area. These requirements are addressed in NFPA 30.

Inside rooms are limited in the quantities of liquids that are permitted to be stored within the room, whereas the total quantity of liquids stored in a liquid warehouse is not restricted. For all inside liquid storage areas, the permitted storage arrangements, such as quantities and storage heights, are based on the level of fire protection systems provided.

TABLE 7.2.5 Maximum Allowable Size—Containers, Intermediate Bulk Containers, and Portable Tanks

	Flammable Liquids			Combustible Liquids	
Type	*Class IA*	*Class IB*	*Class IC*	*Class II*	*Class IIIA*
Glass	0.5 L (1.05 pt)	1 L (1.05 qt)	5 L (1.3 gal)	5 L (1.3 gal)	20 L (5.3 gal)
Metal (other than drums) or approved plastic	5 L (1.3 gal)	20 L (5.3 gal)	20 L (5.3 gal)	20 L (5.3 gal)	20 L (5.3 gal)
Safety cans	10 L (2.6 gal)	20 L (5.3 gal)	20 L (5.3 gal)	20 L (5.3 gal)	20 L (5.3 gal)
Metal drum (e.g., UN 1A1 or 1A2)	450 L (119 gal)	450 L (119 gal)	450 L (119 gal)	450 L (119 gal)	450 L (119 gal)
Approved metal portable tanks and IBCs	3000 L (793 gal)	3000 L (793 gal)	3000 L (793 gal)	3000 L (793 gal)	3000 L (793 gal)
Rigid plastic IBCs (UN 31H1 or 31H2) and composite IBCs with rigid inner receptacle (UN31HZ1)	NP	NP	NP	3000 L (793 gal)	3000 L (793 gal)
Composite IBCs with flexible inner receptacle (UN31HZ2) and flexible IBCs (UN13H, UN13L, and UN13M)	NP	NP	NP	NP	NP
Bag-in-Box Nonbulk	NP	NP	NP	NP	NP
Polyethylene UN 1H1, or as authorized by DOT exemption	5 L (1.3 gal)	20 L (5.3 gal)*	20 L (5.3 gal)*	450 L (119 gal)	450 L (119 gal)
Fiber drum NMFC or UFC Type 2A; Types 3A, 3B-H, or 3B-L; or Type 4A	NP	NP	NP	450 L (119 gal)	450 L (119 gal)

*For Class IB and IC water-miscible liquids, the maximum allowable size of plastic container is 230 L (60 gal), if stored and protected in accordance with Table 6.8.2(g) of NFPA 30.
NP = Not permitted.
Source: NFPA 30, *Flammable and Combustible Liquids Code,* 2003 ed., Table 6.2.3.

Beginning with the 1996 edition of NFPA 30, credible mandatory fire protection criteria have been included in NFPA 30 for various storage arrangements and protection systems utilized in inside liquid storage areas. These protection criteria include design requirements for water-only and foam-water sprinkler systems. Also, the type of sprinkler systems installed and the type of liquids being protected determine if drainage is required in the storage area. The criteria are based on the results of large-scale fire tests conducted at nationally recognized testing laboratories. Inside liquid storage areas that meet these protection criteria are considered as protected within the scope of NFPA 30. Storage areas not meeting these criteria are considered as unprotected, even though some areas might contain automatic sprinklers.

Flammable Liquid Storage Cabinets. Specially designed storage cabinets are available for storing not more than 120 gal (454 L) of Class I, Class II, and Class IIIA liquids. These cabinets are typically constructed of No. 18 gauge sheet steel consisting of a double wall with 1½ in. (38 mm) air space, although wood cabinets constructed in accordance with the requirements of NFPA 30 are permitted. The door should have a three-point latch, with a sill raised to at least 2 in. (51 mm) above the bottom of the cabinet to retain spilled liquid within the cabinet. The cabinet should be marked in conspicuous lettering: "FLAMMABLE—KEEP FIRE AWAY" (Figure 7.2.13).

Hazardous Material Storage Lockers

Hazardous material storage lockers have become very popular in recent years, as they meet the environmental concerns dictated by the special handling of hazardous chemicals, some of which are flammable and combustible liquids. These lockers are movable, modular, prefabricated storage buildings that provide a safe and cost-effective means of storing hazardous materials. The lockers are equipped with spill containment features and can be provided with electricity, mechanical ventilation, and fire suppression systems. Generally, the lockers are located outside, but NFPA 30 permits the lockers to be utilized as inside liquid storage rooms, as long as the lockers are constructed with the fire-resistive ratings and applicable requirements listed in NFPA 30. NFPA 30 limits the gross floor area of the lockers to 1500 ft^2 (140 m^2) (Figure 7.2.14).

Container Storage Outdoors

Outdoor container storage should be located in such a manner as to reduce the spread of fire to other materials in storage, adjacent buildings, or neighboring properties (Table 7.2.6). The storage area should be graded in a manner to divert possible spills away from buildings or other exposures, or curbing should be used to contain spills. Areas used for container storage should be kept free of ignition sources, such as open flames, and com-

FIGURE 7.2.13 Typical Metal Flammable Liquid Storage Cabinet (Source: Courtesy Justrite Manufacturing Company, Des Plaines, IL)

FIGURE 7.2.14 Hazardous Materials Storage Lockers (Source: Courtesy Justrite Manufacturing Company, Des Plaines, IL)

bustibles, such as weeds and debris. The area should also be protected against tampering or trespassers, and smoking should be prohibited in the area.

HANDLING OF FLAMMABLE AND COMBUSTIBLE LIQUIDS

Loading and Unloading

Spills can occur at loading and unloading stations for tank cars and tank vehicles, which if ignited could endanger neighboring tanks and buildings. Tank vehicle and tank car loading and unloading stations for Class I liquids should be located a minimum of 25 ft (8 m) from storage tanks, other plant buildings, and the nearest line of property that can be developed. For Class II and Class III liquids, the separation distance is 15 ft (4.6 m). Level ground is desirable, and drains, diversionary curbs, or natural ground slope can be utilized to prevent spills from spreading to other parts of the plant or to other property.

Many liquids, including gasoline, jet fuels, toluene, and light fuel oil, can build up dangerous static electrical charges on the surface of the liquid. If a flammable vapor-air mixture is present at the surface of the liquid when high static electrical discharges occur, an explosion or fire can result. Excessive turbulence, pumping two dissimilar materials, the free fall of liquid through the vapor space, and the use of filters capable of removing micron-sized particles are among the most possible causes of explosions or fires originating from static electricity in aboveground tanks, tank vehicles, tank barges, and tank ships.

TABLE 7.2.6 Outdoor Liquid Storage in Containers and Portable Tanks

	Containers Maximum per Pile		Rigid Plastic and Composite IBCs Maximum per Pile[a]		Portable Tanks and Metal IBCs Maximum per Pile[b] (gal)		Distance Between Piles or Racks	Distance to Property Line That Is or Can Be Built Upon	Distance to Street, Alley, or a Public Way
Class	*(gal)*[b,c,d]	*Height (ft)*	*(gal)*	*Height (ft)*	*(gal)*[b,d]	*Height (ft)*	*(ft)*	*(ft)*[c,e]	*(ft)*[c]
IA	1,100	10	—	—	2,200	7	5	50	10
IB	2,200	12	—	—	4,400	14	5	50	10
IC	4,400	12	—	—	8,800	14	5	50	10
II	8,800	12	8,800	12	17,600	14	5	25	5
III	22,000	18	22,000	18	44,000	14	5	10	5

[a]Storage of Class I liquids in rigid plastic and composite IBCs not permitted.
[b]See 6.7.1.1 of NFPA 30 regarding mixed-class storage.
[c]See 6.7.1.4 of NFPA 30 for smaller pile sizes.
[d]For storage in racks, the quantity limits per pile do not apply, but the rack arrangements shall be limited to a maximum of 50 ft (15 m) in length and two rows or 9 ft (2.7 m) in depth.
[e]See 6.7.1.3 of NFPA 30 regarding protection for exposures.
For SI units, 1 ft = 0.3 m; 1 gal = 3.8 L.
Source: NFPA 30, *Flammable and Combustible Liquids Code,* 2003 ed., Table 6.7.1.

Where flammable vapors may exist, and to reduce static-caused ignitions, it is recommended that the delivery rate be slowed until the fill pipe is covered. A minimum 30 second relaxation time should be provided downstream of a filter.

Bonding provisions for protection against static sparks must be provided at all stations when Class I liquids are loaded or unloaded. The bonding must be provided between the fill pipe or piping and the tank vehicle. Bonding connections should be made before the dome covers are opened and should remain in place until filling or unloading is complete and all dome covers have been closed and secured. Closed metal piping systems (eliminating exposure to air) for loading and unloading can eliminate the need for special bonding provisions, since the piping system is inherently bonded to the vehicle. Bonding provisions are not required when Class II and Class III liquids are being transferred at ambient temperatures and when vehicles are loaded or unloaded with products not having a static-accumulating tendency, such as asphalts, crude oils, and water-soluble liquids.

Stray electrical current protection is necessary for ship and tank car loading and unloading in those areas where stray currents may be present. To protect against stray currents at tank car stations, the fill pipe can be permanently bonded to at least one rail and to the rack structure. In addition, all pipes entering the rack area should be provided with insulating sections to electrically isolate the rack piping from the pipelines.

For further details on control of static, refer to NFPA 77, *Recommended Practice on Static Electricity,* and API Standard 2003, *Protection Against Ignitions Arising Out of Static, Lightning, and Stray Currents.*

Tank ships and barges are loaded and unloaded at wharves (piers) that might or might not be used exclusively for this purpose. The location and arrangement of the piers is governed by direction and velocity of the waterway, the range of tides, and the direction and frequency of prevailing high-velocity winds. Hazards related to the loading and unloading of vessels are comparable to those for tank vehicles and tank cars, except the quantities of liquid involved are generally larger. NFPA 30 contains a number of requirements involving bulk liquid transfer at wharves.

Piping and Valves

Piping systems protected against physical damage are preferable to portable containers for conveying quantities of liquids within buildings. All piping systems should be designed so that, in case of pipe breaks, liquid will not continue to flow by gravity or by siphoning. Valves should be provided at accessible points to control or stop the flow. Emergency remote controls are frequently provided for valves or pumps, particularly at dispensing locations. Other remotely controlled valves installed for normal operating procedures can frequently be used during fire emergency procedures to control or stop the flow of liquids. Valves are available that close automatically if subjected to fire conditions. Dispensing outlets for systems under gas pressure or gravity head should be equipped with self-closing valves.

Pipe materials should be used that (1) are resistant to the corrosive properties of the liquid handled; (2) have adequate design strength to withstand the maximum service pressure (including shock and surge pressures that are expected) and temperature; and (3) when possible, are resistant to physical damage and thermal shock. Where low melting point materials, such as aluminum and brass; materials that soften on fire exposure, such as plastics; or nonductile material, such as cast iron, are necessary, special consideration should be given to their behavior on exposure to fire. After installation, piping systems should be tested at 150 percent of the maximum anticipated pressure of the system, or pneumatically tested to 110 percent of the maximum anticipated pressure of the system, but not less than 5 psig (35 kPa) at the highest point of the system. The test should be maintained for a sufficient time to complete visual inspection of all joints and connections, but not for less than 10 minutes.

Since some valves are used infrequently, it is necessary to make periodic maintenance inspections to ensure that the valves will operate during emergency conditions. All aboveground piping and connections should be inspected periodically to detect and prevent leakage. Internal corrosion in pipes is a particular problem when liquids are corrosive or where piping is used for the continuous flow of liquid under high-pressure operations common at refineries or chemical plants. Maintenance inspections of the thickness of pipe walls can be performed in several ways similar to the inspection of tanks. Underground piping is also subject to external corrosion and should be protected against such corrosion by suitable coatings and cathodic protection. Tests for possible leaks in underground piping can be performed hydrostatically, using the liquid normally handled in the piping system.

Dispensing and Handling Methods

Large quantities of flammable or combustible liquids are best transferred through piping by pumps. Gravity flow is not desirable, except as required in process equipment. If positive displacement pumps are used, they should be provided with a pressure relief that discharges back to the tank or to the pump suction. Only inert gas should be used to transfer Class I liquids. The use of air pressure to transfer Class II and Class III liquids is acceptable, unless the liquids are heated above their flashpoint, in which case inert gas should be used. Whenever air or inert gas pressure systems are used for transfer, the vessels, containers, tanks, and piping systems should be capable of withstanding the operating pressures. In addition, safety and operating controls, such as pressure-relief devices, should be provided to prevent overpressuring any part of the system.

One of the safest methods for handling flammable or combustible liquids is to pump the liquid from underground storage tanks, through an adequately designed piping system protected from physical damage, to the dispensing equipment located outdoors or in specially designed inside dispensing rooms. Such rooms should have at least one exterior wall for explosion relief and accessibility for fire fighting, interior walls with appropriate fire resistance ratings, adequate ventilation and drainage, and free of sources of ignition.

Where solvents are pumped from storage tanks to the point of use in an industrial building, emergency switches should be

located in the dispensing area, at the normal exit door or at other safe locations outside the fire area, and at the pumps to shut down all pumps in case of fire.

Where dispensing is by gravity flow, such as in the filling of containers in an industrial operation, a shutoff valve should be installed as close as practical to the vessel being unloaded. A control valve should be located near the end of the discharge pipe. Additionally, in some filling operations, a heat-actuated valve is desirable to shut off the flow of liquid.

The preferred method of dispensing flammable and combustible liquids from a drum is by use of an approved hand-operated pump drawing through the top. An approved self-closing drum faucet can also be used for dispensing from a drum. However, hand-operated pumps are safer than faucets, because the hazard of leakage is reduced.

For handling small quantities of flammable and combustible liquids, safety cans are preferred. Safety cans are substantially constructed to avoid the danger of leakage and are designed to minimize the likelihood of spillage or vapor release and of container rupture under fire conditions. Typical safety cans have pouring outlets with tight-fitting caps or valves normally closed by springs, except when held open by hand, so that contents will not be spilled if a can is tipped over. The caps also provide an emergency vent when the cans are exposed to fire (Figure 7.2.15).

Liquids can also be dispensed from the original shipping containers. Open pails or open buckets should never be used for storage or the transfer of liquids.

Flammable liquids should always be handled and dispensed in a well-ventilated area free of sources of ignition, and bonding should be provided between the dispensing equipment and the container being filled (Figure 7.2.16).

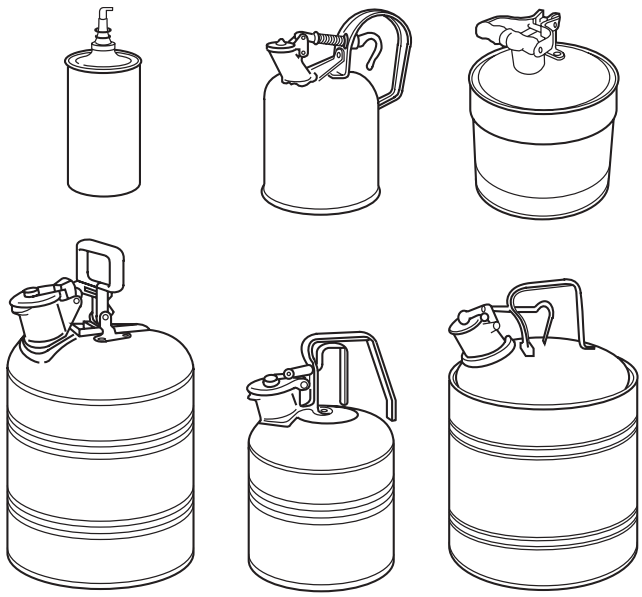

FIGURE 7.2.15 Typical Safety Cans

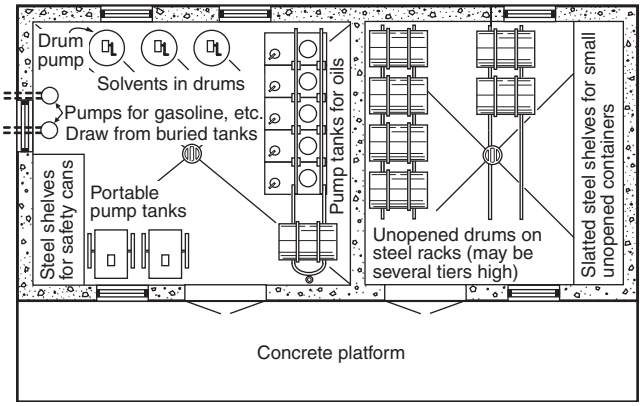

FIGURE 7.2.16 Layout of a Storage and Dispensing House

TRANSPORTATION OF FLAMMABLE AND COMBUSTIBLE LIQUIDS

Tank Vehicles

NFPA 385, *Standard for Tank Vehicles for Flammable and Combustible Liquids,* and rules of the U.S. Department of Transportation provide for substantially constructed vehicles and tanks that present relatively little danger of fire when involved in minor traffic accidents. Under these recommendations, tanks are constructed to withstand all but the most violent impact without rupturing and releasing liquid. Vents are provided so that, if a tank is subjected to fire, vapor will burn at the vent, avoiding the danger of rupture from excessive internal pressure.

For all but viscous liquids, a shutoff valve located inside the shell of the cargo tank is required. It is kept closed, except during loading or unloading operations. A shear section is provided in the piping connected to the internal valve. Therefore, in an accident that could damage the piping, the piping breaks at the shear section, leaving the internal valve undamaged and closed (Figure 7.2.17).

The operating mechanism for the valve is also required to have a secondary control, remotely located, that can be used to shut off the valve in case of fire or severe spillage during unloading. In addition, a fusible element (to operate at not more than 250°F [121°C]) is required in the control mechanism for the valve, to permit the valve to close automatically in case of fire (Figure 7.2.18). Other important fire protection features are detailed in NFPA 385.

Tank-truck traffic through congested districts of cities should be avoided as much as possible, because any fire is likely to have more serious consequences in congested districts than in sparsely settled areas. Bypass routes, such as those commonly specified for all kinds of through truck traffic, are the obvious solution to this particular problem.

Parking of loaded tank vehicles is another activity that can be appropriately regulated by municipalities. Such parking can be prohibited on city streets. Similarly, tank vehicles should not be parked in public garages. Permissible parking locations for tank vehicles may be specified, if necessary. Any property

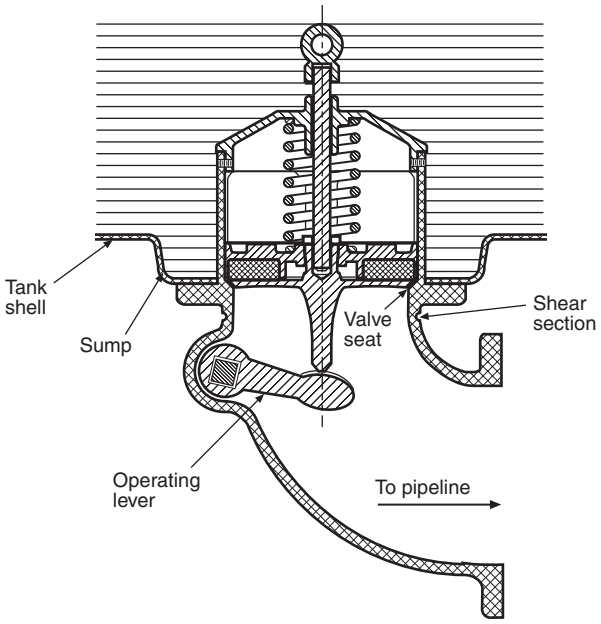

FIGURE 7.2.17 Shutoff Valve Located Inside Tank Shell, with Shear Section to Leave Valve Seat Closed if Discharge Faucet Breaks

zoned for aboveground oil storage (e.g., the ordinary bulk oil plant), should be a location where tank vehicles can be parked without any undue increase in hazard to the public.

To prevent the hazards associated with "switch loading," no tank vehicle compartment that has been utilized for transporting Class I liquids should be loaded with Class II or Class III liquids until the compartment and all piping, meters, and hoses have been completely drained. If Class II or Class III liquids are loaded into a tank vehicle that previously contained a Class I liquid that was not adequately drained out, there exists the potential for the generation of a static spark to occur in a mixture that is within the flammable range, resulting in an explosion.

Transportation of flammable liquids in tank vehicles in interstate commerce is governed by regulations of the U.S. Department of Transportation (DOT), as contained in the Code of Federal Regulations, Title 49, "Transportation."[6] There are comprehensive specifications and labeling requirements for shipping containers for various types of products. (Absence of a label does not necessarily mean that the material is nonhazardous, however.)

Rail, Ship, and Pipeline

The transportation of flammable liquids by railroad tank cars is under the jurisdiction of DOT in the United States.[6] The design of tank cars is rigidly controlled and is governed by the nature of the contents being carried. Emergency venting requirements are included in DOT regulations.

The transportation of flammable and combustible liquids in bulk on board vessels in the United States is under the jurisdiction of the Commandant of the U.S. Coast Guard. These transportation requirements include the design of the vessel, whether a tank ship or tank barge, as well as requirements for extinguishing systems or portable extinguishers. Further requirements include limitations on container storage of drums or portable tanks, restrictions for passenger-carrying vessels, and many other requirements for the safe transportation of flammable and combustible liquids by water. Details of these requirements can be secured at the nearest U.S. Coast Guard Merchant Marine Inspection Office.

Standards for pipelines transporting liquids are published by the American Society of Mechanical Engineers (ASME). These standards include piping requirements and installation recommendations.

SUMMARY

The safe storage of flammable and combustible liquids requires properly designed liquid-tight containers and tanks from which vapor release, if needed, is carefully controlled. Tanks can be installed aboveground, underground, or, under certain conditions, inside buildings. Containers such as bottles and drums can be stored inside flammable liquid storage cabinets, inside liquid stor-

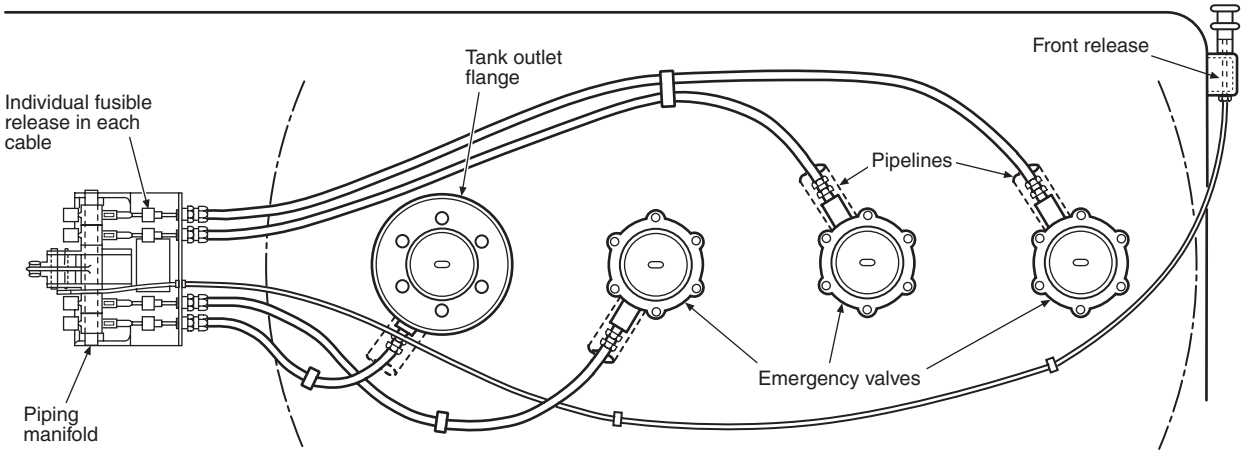

FIGURE 7.2.18 Bottom View of Tank Vehicle Showing Typical Installation of Emergency Valves and Controls

age rooms and warehouses, and outside in yard areas or hazard material storage lockers. Special precautions must be taken when flammable and combustible liquids are handled and transported. Transportation methods include tank vehicles, railroad tank cars, tank ships or barges, and pipelines.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on storage of flammable and combustible liquids discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*
NFPA 31, *Standard for the Installation of Oil-Burning Equipment*
NFPA 70, *National Electrical Code®*
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 306, *Standard for the Control of Gas Hazards on Vessels*
NFPA 326, *Standard for the Safeguarding of Tanks and Containers for Entry, Cleaning, or Repair*
NFPA 329, *Recommended Practice for Handling Releases of Flammable and Combustible Liquids and Gases*
NFPA 385, *Standard for Tank Vehicles for Flammable and Combustible Liquids*

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Chapter 3

Storage of Gases

Theodore C. Lemoff ■ Carl H. Rivkin

Chapter Contents

Gas Containers
Storage Safety Considerations

Key Terms

boiling liquid expanding vapor explosion (BLEVE), cabinet heaters, container, cylinder, Interstate Commerce Commission (ICC), overpressure, pipeline

This chapter describes essential fire safety characteristics of containers in which gases are stored, as well as some fundamental precepts for storage arrangements.

A gas must be stored in a container that is gastight for (1) the range of temperature and pressure conditions present at the storage location and (2) the conditions represented by the transportation environment prior to arrival at a storage site. The storage container should contain the source of energy needed to remove the gas from storage and convey it to the point of use. This energy is the pressure of the gas in the container.

In the case of containers in which the gas is entirely in the gaseous phase (compressed gases), the pressure is applied at the charging plant or, in the case of pipelines, by compressors spaced along the pipeline. In the case of containers of gas in which the gas is partly in the gaseous phase and partly in the liquid phase (i.e., liquefied gases, including cryogenic liquefied gases), the pressure is obtained as a result of heat stored in the liquid, which is directly related to how much the temperature of the liquid is above its normal boiling point.

Therefore, gas containers, whether shaped as tanks or as pipelines, are closed pressure vessels containing considerable energy per unit of volume, and they require careful design, fabrication, and maintenance. Furthermore, because the containers are closed and excessive pressures can develop when they are exposed to rather nominal heat sources and fire (or by overfilling, in the case of liquefied gas containers), overpressure protection is usually needed.

For additional material on storage safety considerations, see Section 6, Chapter 10, "Gases."

GAS CONTAINERS

Most countries have similar regulations for the design, fabrication, and maintenance of gas containers. This chapter concentrates on North American practices.

In North America, there are two types of gas containers: (1) cylinders and (2) tanks. Originally, the distinction between cylinders and tanks was based on size. Cylinders, being the smaller, were considered portable; the tanks, being the larger, were essentially used in stationary service. There was also a distinction that reflected the pressures in the containers. Cylinders were thought of as being used for high pressures and tanks for low or moderate pressures. Over the years, these distinctions have lessened so that, today, the only real distinction lies in the regulations or codes under which the container is built.

Practically all gases must be transported from the manufacturer to the user, making the safety of the container in transportation a matter of primary concern. As a result, criteria for many gas containers reflect transportation safety conditions. Because it could be hazardous as well as uneconomical to require gases to be transferred from a shipping container to a separate container for other use, every effort has been made to utilize the same container whenever feasible. This procedure is generally used for the smaller containers.

Gas Cylinders

Gas cylinders are fabricated in accordance with regulations and specifications of the U.S. Department of Transportation (DOT) in the United States and Transport Canada (TC) in Canada.

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FIGURE 7.3.1 Two-Piece Composite Cylinder (Courtesy of Lite Cylinder Co.)

FIGURE 7.3.2 One-Piece Composite Cylinder (Courtesy of Ragasco)

The requirements are the same in both countries. Prior to April 1, 1967, DOT regulations were promulgated by the Interstate Commerce Commission (ICC). Some cylinders are still in service with ICC markings. Cylinders are limited to a maximum water capacity (i.e., the capacity when completely filled with water) of 1000 lb (454 kg), approximately 120 gal (450 L) of water.

The regulations cover the service pressure for which the cylinder must be designed, the gas or group of gases that it can contain, safety devices, and requirements for in-service (transportation) testing and requalification. The specifications cover such criteria as metal composition and physical testing, wall thickness, joining methods, nature of openings in the container, heat treatments, proof testing, and marking.

Cylinders have historically been constructed of metals; a new type of cylinder made of a composite fiberglass construction, however, has been approved by the Department of Transportation for use in the United States. At this time, these composite cylinders are available in sizes used with gas grills and propane-powered industrial trucks (forklift trucks). Figures 7.3.1 and 7.3.2 show two types of composite cylinders. The cylinder valve is metal, and a metal boss is added to the completed cylinder after the cylinder shell is formed. These composite cylinders have been in use in propane service in the Scandinavian countries since the early 1990s. Composite cylinders have several unique features that make them attractive: they are lighter in weight than steel cylinders and they are translucent so the liquid level can be seen. However, they are currently more costly than steel cylinders.

The use of composite cylinders has been proposed and is being considered by the NFPA Technical Committee on Liquefied Petroleum Gases for use in conjunction with portable space heaters called *cabinet heaters.* Fire tests were conducted at a major fire test facility in fires that simulated room fires. The composite cylinders did not explode or BLEVE (boiling liquid expanding vapor explosion), but released their contents over a period of about 15 minutes when exposed to fire for several minutes. Some observers of the tests stated that the fire was typical of a living room fire. The subject is controversial, and the reader is encouraged to review NFPA 58, *Liquefied Petroleum Gas Code,* on this subject.

Gas Tanks

Gas tanks are fabricated in accordance with Section VIII, "Unfired Pressure Vessels," of the *Boiler and Pressure Vessel Code,* published by the American Society of Mechanical Engineers (ASME), or tank fabrication standards of the American Petroleum Institute (API). ASME tanks are usually smaller tanks under moderate pressure, and API tanks are usually very large tanks under low pressure.

Cylinders or tanks that are part of transportation units, such as cargo vehicles or railcars, are subject to additional criteria in

the regulations, primarily to reflect the fact that the containers are on wheels. Tanks for cargo vehicles are basically ASME code tanks, whereas tanks for railcars are covered by specific DOT and TC specifications.

In the late 1960s and early 1970s, a series of serious railcar derailments occurred in the United States, reflecting the deterioration of tracks and track beds due to inadequate maintenance. For example, an LP-gas distribution plant fire occurred in Kingman, Arizona, in 1973.[1] These incidents were characterized by both impact and fire-caused BLEVEs of tank cars containing liquefied flammable gases. As a result, DOT regulations were revised in 1977 to require that these tank cars be protected thermally and equipped with a type of coupler that prevents vertical disengagement. Unless the insulation is contained in a steel outer jacket, the car also must be equipped with heavy steel-plate head shields for impact protection. Existing cars were required to be retrofitted by the end of 1980. In the few derailments involving tank cars outfitted in this fashion, these safeguards have proved effective—a BLEVE either has not occurred at all or has been delayed for several hours.

Some containers are exempted by the regulations. These containers include certain very small containers and containers with nonflammable cryogenic gases, including oxygen, where the pressure in the container as shipped is below 40 psia (an absolute pressure of 276 kPa).

There is usually a lag in time between the need to ship a gas that is new to commerce and the promulgation of specifications for a transportation container. In such cases, DOT or TC exemptions, which spell out safety criteria agreed on by the authorities, are issued.

The DOT and TC regulations apply then only to cylinders and tanks in transportation in interstate or interprovincial commerce. However, many consensus codes and standards extend these regulations to transportation in intrastate commerce and also extend applicable criteria to use and storage at consumer sites.

The requirements for "in-service" reinspection and requalification of DOT specification containers are also extended to use and storage at consumer sites by the consensus standards and codes. However, the ASME *Boiler and Pressure Vessel Code*[2] and API standards do not contain such provisions. If not covered by consensus standards and codes, in-service inspection and requalification become a matter of owner judgment, applicable state or local regulations, or conditions set forth in an insurance contract.

Regardless of the degree of structural integrity incorporated into gas containers, abuse of the container must be avoided. This is especially true of portable cylinders, which are subject to mishandling. General safety precautions for gas cylinders are contained in the Compressed Gas Association's P-1 "Safe Handling of Compressed Gases in Containers."

Pipelines

Gases used in large volumes are often transported by pipelines. Natural gas is customarily transported by pipeline, as is much LP-gas and some industrial gases, such as anhydrous ammonia, oxygen, hydrogen, and ethylene.

Since 1968, most of the transmission and distribution of flammable gases by pipeline has been regulated in the United States by the DOT Office of Pipeline Safety and is covered by federal regulations. These regulations cover such items as pipe materials; design for pressure and other stresses (which, among other criteria, require stronger piping as population density increases); piping components, including valves (emergency flow control valve spacing in the pipeline system is also affected by population density); joining methods; installation of meters, service regulators, and service lines; corrosion control; test requirements; certain operating requirements; and maintenance, including leakage surveys.

Normally, DOT regulations do not apply to piping on consumer premises. Such piping for the more common gases is covered by consensus codes and standards, notably NFPA 54 (ANSI Z223.1), *National Fuel Gas Code,* and ANSI/ASME B31.1, Power Piping, and B31.3, Process Piping.[3] Note that the expertise of the ASME Boiler and Pressure Vessel Code Committees is in the area of design and construction of pressure vessels, not the use of pressure vessels.

STORAGE SAFETY CONSIDERATIONS*

Fire protection safeguards for gas storage reflect (1) the hazards of the container/gas combination and (2) the hazards of the gas when it escapes from the container. Discussions of the basic hazards of gases, gas emergency control, and specific gases are especially pertinent to the safe storage of gases.

During at least some period, any fire incident can manifest both of these hazards at the same time. However, the container/gas combination hazard always exists. The fire hazard of escaping gas, on the other hand, might be negligible if the gas is nonflammable.

The newer composite cylinders, which are being used initially for propane, have a different failure mode compared to steel and aluminum cylinders when exposed to fire, which is relevant to the indoor storage of propane cylinders in occupancies where allowed, such as industrial occupancies. Refer to the section on Gas Cylinders in this chapter for more information on the subject.

Container/Gas Hazard Safeguards

The major container/gas hazard is the BLEVE. The BLEVE hazard is restricted to containers of liquefied gases and the major cause of such BLEVEs in storage is fire exposure. BLEVEs resulting from corrosion of a container are far less frequent and impact-caused BLEVEs even more so for containers in storage.

Container Insulation. The BLEVE hazard is greatly affected by container features that restrict the opportunity for the container metal to be overheated. Especially notable in this respect is the presence of insulation between an exposing fire and the portion of the container subject to internal pressure. All cryogenic liquefied gas containers are insulated as a matter of functional

*The philosophy of this analytical approach is developed in Section 6, Chapter 10, "Gases"; it would be worthwhile to review that chapter before proceeding further in this chapter.

necessity. The BLEVE hazard can be reduced by the installation of an insulation system. North American standards for storage containers allow insulation of containers. For example, insulation for flammable cryogenic gas containers is required to be noncombustible, and (if in a form such that loss of an enclosing jacket could cause a serious loss in insulating capacity, e.g., powder or granules) the container jacket is required to be steel or concrete rather than aluminum.

Containers of noncryogenic gases are not required to be insulated for operational reasons and are seldom insulated for fire safety reasons. However, insulation of larger liquefied flammable gas tanks is becoming more frequent in specific installations where other BLEVE prevention measures (e.g., water cooling) are deficient.

A basic BLEVE safeguard is to reduce the chances of fire exposure to the container. This safeguard is also applicable to containers of nonliquefied gases (compressed gases) because, although by definition they are not subject to a BLEVE, they can still fail explosively from fire exposure.

Indoor Storage. NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks,* sets maximum allowable quantities (MAQs) of gases that can be stored per control area. A control area is a space within a building or an entire building that is separated by a fire barrier from exposures. If these MAQs, which are shown in Table 7.3.1, are exceeded, additional fire protection control requirements must be implemented.

Limiting Combustibles in the Area. Essential to reducing the chance of fire exposure is limiting the quantity of combustibles in the vicinity of gas containers. This concern applies whether the storage is indoors or outdoors. Except where small quantities of gas are involved (e.g., one or two cylinders of compressed gas), it is highly desirable that storage rooms or docks be of noncombustible or limited combustible construction. (See NFPA 220, *Standard on Types of Building Construction,* for these definitions.) If the building that houses the storage room presents a substantial fire load, the storage room walls should have a suitable fire resistance rating.

Containers of flammable gases should not be stored with nonflammable oxidizing gases. Oxidizing gases, such as oxygen and nitrous oxide, increase the speed of burning of all flammable gases, resulting in higher flame temperatures. Explosions of flammable gas–oxidizing gas mixtures are also possible. NFPA 55 requires separation of flammable, oxidizing, corrosive, toxic, or highly toxic pyrophoric and unstable reactive class 2, 3, or 4 gases. Gases classified as other gas require no separation. This is illustrated in Figure 7.3.3.

The use of barriers around larger containers of flammable gases is not recommended unless the barriers permit application of cooling water, prevent pocketing of escaping gas, and allow unrestricted egress of personnel from the area in an emergency.

When oxidizing gases are stored near combustibles, the degree of combustibility (i.e., flammable or combustible liquid, fast-burning or slow-burning solid) is not the primary consideration. The flammability of the combustible in an enriched oxygen environment is the primary consideration. An example of the

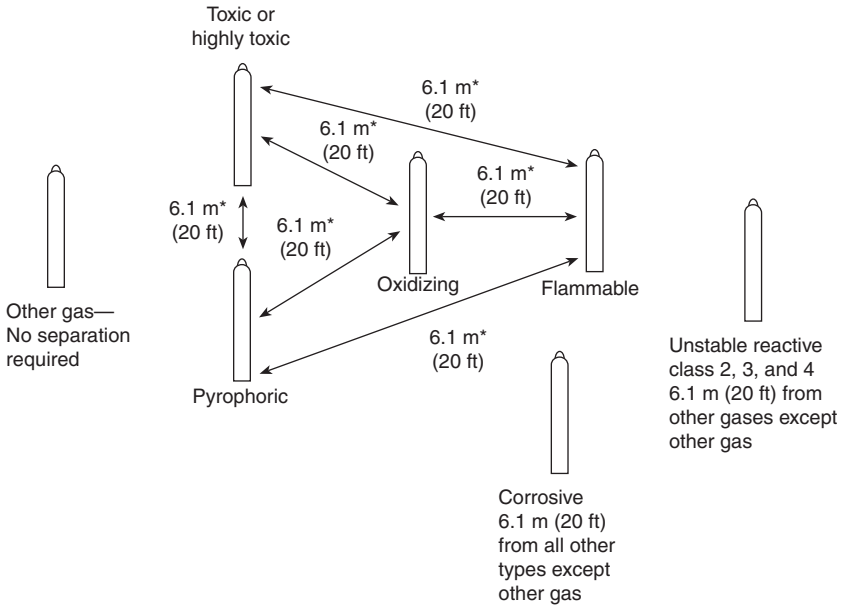

FIGURE 7.3.3 Separation of Gas Cylinders by Hazard. *The 20 ft (6.1 m) distance can be reduced without limit when separated by a barrier of noncombustible materials at least 5 ft (1.5 m) high that has a fire resistance rating of at least one-half hour. (Source: NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks*)

TABLE 7.3.1 Maximum Allowable Quantity of Gases per Control Area (Quantity Thresholds for Gases Requiring Special Provisions

	Unsprinklered Areas		Sprinklered Areas	
Material	*No Gas Cabinet, Gas Room, or Exhausted Enclosure*	*Gas Cabinet, Gas Room, or Exhausted Enclosure*	*No Gas Cabinet, Gas Room, or Exhausted Enclosure*	*Gas Cabinet, Gas Room, or Exhausted Enclosure*
Corrosive Gas				
Liquefied	68 kg (150 lb)	136 kg (300 lb)	136 kg (300 lb)	272 kg (600 lb)
Nonliquefied	23 m^3 (810 ft^3)	46 m^3 (1620 ft^3)	46 m^3 (1620 ft^3)	92 m^3 (3240 ft^3)
Cryogenic Fluid				
Flammable	0 L (0 gal)	170 L (45 gal)	170 L (45 gal)	170 L (45 gal)*
Oxidizing	170 L (45 gal)	340 L (90 gal)	340 L (90 gal)	681 L (180 gal)
Flammable Gas				
Liquefied	114 L (30 gal)	227 L (60 gal)	227 L (60 gal)	454 L (120 gal)
Nonliquefied	28 m^3 (1000 ft^3)	28 m^3 (2000 ft^3)	28 m^3 (2000 ft^3)	56 m^3 (4000 ft^3)
Highly Toxic Gas				
Liquefied	0 kg (0 lb)	2.3 kg (5 lb)	0 kg (0 lb)	4.5 kg (10 lb)
Nonliquefied	0 m^3 (0 ft^3)	0.6 m^3 (20 ft^3)	0 m^3 (0 ft^3)	1.1 m^3 (40 ft^3)
Nonflammable Gas				
Liquefied	No limit	No limit	No limit	No limit
Nonliquefied	No limit	No limit	No limit	No limit
Oxidizing Gas				
Liquefied	57 L (15 gal)	114 L (30 gal)	114 L (30 gal)	227 L (60 gal)
Nonliquefied	43 m^3 (1500 ft^3)	85 m^3 (3000 ft^3)	85 m^3 (3000 ft^3)	170 m^3 (6000 ft^3)
Pyrophoric Gas				
Liquefied	0 kg (0 lb)	0 kg (0 lb)	1.8 kg (4 lb)	3.6 kg (8 lb)
Nonliquefied	0 m^3 (0 ft^3)	0 m^3 (0 ft^3)	1.4 m^3 (50 ft^3)	2.8 m^3 (100 ft^3)
Toxic Gas				
Liquefied	68 kg (150 lb)	136 kg (300 lb)	136 kg (300 lb)	272 kg (600 lb)
Nonliquefied	23 m^3 (810 ft^3)	46 m^3 (1620 ft^3)	46 m^3 (1620 ft^3)	92 m^3 (3240 ft^3)
Unstable Reactive (Detonable) Gas, Class 3 or Class 4				
Liquefied	0 kg (0 lb)	0 kg (0 lb)	0.5 kg (1 lb)	1 kg (2 lb)
Nonliquefied	0 m^3 (0 ft^3)	0 m^3 (0 ft^3)	0.3 m^3 (10 ft^3)	0.6 m^3 (20 ft^3)
Unstable Reactive (Nondetonable) Gas, Class 3				
Liquefied	1 kg (2 lb)	2 kg (4 lb)	2 kg (4 lb)	4 kg (8 lb)
Nonliquefied	1.4 m^3 (50 ft^3)	3 m^3 (100 ft^3)	3 m^3 (100 ft^3)	6 m^3 (200 ft^3)
Unstable Reactive Gas, Class 2				
Liquefied	114 L (30 gal)	227 L (60 gal)	227 L (60 gal)	454 L (120 gal)
Nonliquefied	21 m^3 (750 ft^3)	43 m^3 (1500 ft^3)	43 m^3 (1500 ft^3)	85 m^3 (3000 ft^3)
Unstable Reactive Gas, Class 1				
Liquefied	No limit	No limit	No limit	No limit
Nonliquefied	No limit	No limit	No limit	No limit

Note: The maximum quantity indicated is the aggregate quantity of materials in storage and use combined.
*A gas cabinet or exhausted enclosure is required. Pressure relief devices or stationary or portable containers shall be vented directly outdoors or to an exhaust hood.

Source: NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks,* 2005 edition, Table 6.3.1. For LP-gas storage, see NFPA 58.

importance of an enriched oxygen environment is the concern for any organic material in contact with liquid oxygen. Organic materials in the presence of liquid oxygen can detonate, and the detonation can be initiated by a shock. The unloading areas for liquid oxygen bulk trucks must be paved with concrete for this reason, because asphalt in contact with liquid oxygen spillage from a delivery hose can explode if the truck tire runs over it.

Application of Water. During a fire exposure, the application of water is a basic safeguard to prevent a compressed gas container failure via BLEVE or other overpressure. Outdoor storage areas are usually not provided with sprinkler protection. Indoor storage areas do not require sprinklers for storage of a small number of cylinders (up to 2500 SCF [71 standard m^3]). Storage of larger quantities of flammable gases requires separation of additional groups of cylinders or sprinkler protection. Refer to NFPA 55 for more information on sprinkler protection requirements for flammable gas cylinder storage areas.

A water spray fixed system of similar capacity is also effective and can be installed outdoors. For the protection of larger containers of liquefied flammable gases (chemically not self-reactive), a density in excess of 0.25 gpm of water per ft^2 (10 [L/min]/m^2) of container surface is required by NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection,* to prevent failure.

Water application might not always be appropriate for tanks containing cryogenic liquids. Most cryogenic liquid storage tanks are pressure vessels, but their design pressure is not high enough to retain the internal pressure if the liquid is heated to atmospheric temperature. The liquid is kept at or slightly above its atmospheric boiling point; thus, a BLEVE is not likely. Application of water could result in water entering the pressure relief device and freezing, rendering it inoperative and resulting in pressure vessel failure. Also, water is at a temperature well above the temperature of the liquid and is a heat source that could promote vaporization of the liquid.

Overpressure Limiting Devices. The satisfactory operation of container overpressure limiting devices is vital to controlling the BLEVE or compressed gas container failure hazard. Even though these devices cannot by themselves always prevent container failure, they do extend the prefailure time in all cases and can prevent failure under many fire exposure conditions. It is essential that the device not be blocked closed by corrosion, paint deposits, and so on, and not be damaged mechanically. Portable containers should be checked for this every time they are taken into the facility and whenever they are connected to consuming equipment or are filled.

Spring-loaded pressure relief valves on the larger stationary storage containers should be tested at five- to ten-year intervals (more often if in corrosive or reactive gas service).

Relief devices on liquefied gas containers should always directly contact and monitor the vapor space, because their relieving capacity is determined under vapor discharge conditions and is severely restricted if liquid is discharged. With the exception of some LP-gas containers used in mobile engine fuel systems and 1 ton (907 kg) chlorine containers, portable liquefied gas containers should be stored in an upright position to attain this effect.

Care in Handling. Also reflecting the container/gas hazard, it is important that the containers not be subjected to physical abuse. Although quite sturdy as a result of their design as pressure vessels, any dent or gouge in the container can reduce safety factors and, at the least, shorten failure times from fire exposure or lead to impact failures on subsequent movement. If the valve is broken off on some smaller portable compressed gas containers, the nozzle reaction from escaping gas can be sufficient to propel the cylinder violently. Where the container is designed for a valve-protecting cap or collar, these always should be in place during storage or movement.

DOT Requalification. DOT containers must be requalified at intervals specified in the federal regulations. These intervals vary with the kind of gas and type of container. In most cases, this interval is five years but can be as long as twelve years, depending on the retest method used. A requalified DOT container must be marked with the date of requalification. If such a marking is not present on a compressed gas DOT specification container and the manufacture date marking is more than five years old, it should be brought to the attention of whoever last charged the container.

The container owner is responsible for requalification. In many instances, the user/storer of portable gas containers is not the owner. In others, however, the user/storer is the owner, such as for LP-gas containers used in industrial truck service and filled on site. Those responsible for such containers should be aware of this and of the fact that the requalification procedures are rigorous and require considerable technical expertise.

Safeguards for Escaping Gas

The major escaping gas hazard is combustion of flammable gas and is, in turn, manifest as either a fire or a combustion explosion. Fire can also lead to explosive container failures. See Section 6, Chapter 10, "Gases," for a discussion of the elements of this hazard.

Gases in storage do not leak beyond those already discussed under container/gas hazard safeguards. The container, its valves, and overpressure protection devices are the only sources of escaping gas, provided that the gas is not being transferred into and out of storage.

Inspection for Leakage. All storage containers should be inspected periodically for leakage from container appurtenances or from the container itself. Portable containers should not be placed into storage if they are leaking. To prevent this, incoming shipments should always be inspected on arrival.

The senses of sight, sound, and smell are invaluable leak detectors. Although most gases are invisible, some do have color (e.g., chlorine). Liquefied gases escaping as liquids can lead to the formation of a visible cloud of condensed water vapor. Because gases are stored under pressure, a leak can be accompanied by a hissing sound. Although many gases are odorless, some do possess strong odors (e.g., chlorine and anhydrous ammonia). Natural gas and LP-gas usually have an odorant added to them. Many gas detection instruments are manufactured. Leak detection solutions are available that, when applied to small leaks, show bubbles.

One source of gas leaks in storage locations is the operation of overpressure protection devices. Because the pressure in a gas container is directly related to the gas temperature and the gas temperature in uninsulated containers reflects the temperature of the surroundings, room temperature and solar radiation will affect the pressure. In general, the container pressure will result in the operation of overpressure devices on fully charged containers if the temperature reaches 130 to 140°F (54 to 60°C). Therefore, storage areas should not be allowed to reach such temperatures and reflective paint should be maintained on outdoor containers subject to solar radiation.

Leakage from containers is less common and develops slowly, so leaks can be detected prior to the development of a hazardous situation. Leakage from the inner container of an insulated container for a cryogenic gas is indicated by the formation of water condensate or frost on the outside container due to contact with air on the cold surface. Although this often indicates only a void in the insulation rather than leakage, this appearance should be investigated.

Overpressure Protection. Overfilled liquefied gas containers can lead to overpressure device operation at much lower temperatures. (See discussion of Charles' Law in Section 6, Chapter 10, "Gases.") Portable liquefied gas containers should be checked for proper quantities before being placed into storage. Many such containers can be checked by weighing them. The weight of the empty container (tare weight) must be marked on the container in accordance with DOT regulations. The weight of gas must be determined by the use of data that include the specific gravity of the gas at the fill temperature. In other cases, the quantity is checked by the use of a gauge that measures the liquid level. The most accurate gauge requires that a small amount of gas be released. This release should be done outside under carefully controlled conditions. These gauges are known as fixed-tube gauges or try-cocks. They will release gas only if the level is safe and will release liquid if there is too much in the container.

Ventilation of Spaces. Indoor storage areas should be ventilated, regardless of the chemical hazard of the gas. In areas used solely for storage (no filling of containers), the amount of ventilation need not be great. Storage areas can be ventilated in different ways. Enclosed storage areas that have 25 percent of the available wall area open are considered the same as outdoor storage. Indoor storage areas are required by NFPA 55 to have natural or mechanical ventilation that provides a minimum of 1 cfm/ft^2 (0.3 m^3/min m^2) of floor area. Ventilation systems must discharge a minimum of 50 ft (15 m) from intakes of air handling systems, air-conditioning equipment, and air compressors. However, even inert gases, because they are often odorless, tasteless, and colorless, can present asphyxiation hazards in unventilated areas.

Controlling Ignition Sources. Ignition sources should be controlled in flammable gas storage areas. The vapor density of the gas, in part, determines the extent of the area in which ignition sources should be eliminated or controlled. Many gases are heavier than air at all times. Others will be temporarily heavier than air when they are released in liquid form and vaporize. In general, flammable gas storage areas with no container filling are classified as Division 2 locations for purposes of installing electrical equipment because of the ventilation provided and the nominal leakage potential.

Electrical equipment installed in storage areas used for flammable gases must be selected based on the properties of the gases to be stored. Gases are assigned to a group by testing that determines the gap through which burning gas will propagate. It determines the design, construction, and testing of electrical equipment enclosures for use in classified areas. Most flammable gases are Group C or Group D materials, which allow the largest gaps. Acetylene is a Group A material and hydrogen is a Group B material. Because of the limited availability of electrical equipment for use with Groups A and B materials, electrical equipment for use where Group A or B materials are used might have to be purged and pressurized. For further information on this subject refer to NFPA 70, *National Electrical Code®*, or NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment.*

Fire protection and control of gas fires are discussed in Section 6, Chapter 10, "Gases." Sprinkler and water spray protection are also discussed in that chapter. An essential aspect is that the extinguishment of gas fires by the application of extinguishing agents should be restricted to small leaks where the consequences of reignition can be tolerated.

SUMMARY

Gases must be stored in containers that are gastight for both the range of temperature and pressure conditions present at the storage site as well as the conditions of the transportation environment prior to arrival there. The design, fabrication, and maintenance of gas containers, which in North America are either of the cylinder or tank type, are regulated by the U.S. Department of Transportation in the United States and by Transport Canada in Canada. Gases used in large volumes are often transported by pipelines.

Fire protection safeguards for gas storage revolve around the hazards of the container/gas combination and the hazards of escaping gas. Container/gas hazard safeguards include container insulation to restrict overheating of the container metal, the limitation of combustibles in the area, the application of water during fire exposure, the presence of overpressure limiting devices, care in handling of the containers, and the DOT requalification of containers. Safeguards for escaping gas include periodic inspection for leaks, provision of overpressure protection, the ventilation of storage areas, and the control of ignition sources.

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3. ANSI/ASME B31, *Code for Pressure Piping,* American National Standards Institute, New York.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on storage of gases discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 50, *Standard for Bulk Oxygen Systems at Consumer Sites*
NFPA 50B, *Standard for Liquefied Hydrogen Systems at Consumer Sites*
NFPA 51, *Standard for the Design and Installation of Oxygen–Fuel Gas Systems for Welding, Cutting, and Allied Processes*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 54, *National Fuel Gas Code*
NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 59, *Utility LP-Gas Plant Code*
NFPA 59A, *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*
NFPA 70, *National Electrical Code®*
NFPA 99, *Standard for Health Care Facilities*
NFPA 220, *Standard on Types of Building Construction*
NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment*

Chapter 4

Storage and Handling of Chemicals

John A. Davenport

Chapter Contents

Sources of Information
Principles of Good Storage
Toxicity of Chemicals
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Combustible Chemicals
Unstable Chemicals
Water- and Air-Reactive Chemicals
Corrosive Chemicals
Radioactive Material
Material Subject to Self-Heating
Mixture, Transportation, and Disposal of Chemicals

Key Terms

hazardous chemical, hazardous material (chemical), NFPA "diamond," oxidizer, spontaneous heating, Texas City (Texas) explosion

Chemicals are a valuable part of our modern society. They give us better lives by providing sanitation, more and healthier food, warmer clothing, medicines and cosmetics, control of pests, and tires for our vehicles—to name just a few benefits. Many chemicals are building blocks for making other chemicals and products. When safely used, safely transported, and safely stored, chemicals are not a hazard to our health or to the environment. However, when containers are breached or are involved in a fire, some chemicals can pose a serious threat, especially to emergency responders.

The quantity, size, and nature of the container, as well as its storage arrangement, affect the safety of storage. In addition to knowledge of the hazard potential, it is also necessary for safe handling to have details on the process in which the chemical is to be used. The temperature, pressure, and concentration of all chemicals involved in the process must be known. Other factors to be considered include potentially hazardous by-products resulting from normal operating conditions and by-products that could be formed by contamination or operation outside the normal parameters. Only with complete information can safe storage and handling of chemicals be achieved.

Knowledge of the properties of a chemical is the most important factor in deciding how to handle, transport, and store the material. Knowledge of the properties is also important in deciding how to handle a chemical under emergency conditions.

For a discussion of the hazards and properties of cellulose nitrate, see Section 6, Chapter 13, "Polymeric Materials"; and for a discussion of sodium, see Section 6, Chapter 9, "Metals."

SOURCES OF INFORMATION

There are numerous sources of information on chemicals for both designers of chemical handling and storage facilities and for emergency responders. Most of the information originates from chemical manufacturers and is available in various forms and formats.

All manufacturers are required by law to prepare and distribute material safety data sheets (MSDS) for all products they make. The MSDS gives information on toxicity, flammability, reactivity, and stability, as well as safe handling and storage practices. These are available from operators of facilities handling and storing the chemicals in question.

The NFPA publishes the *Fire Protection Guide to Hazardous Materials.* This book contains the previous NFPA 49, *Hazardous Chemicals Data,* NFPA 325, *Fire Hazard Properties of Flammable Liquids, Gases and Volatile Solids,* and NFPA 491, *Guide to Hazardous Chemical Reactions.* These documents give valuable information on properties, emergency response procedures, fire properties, reactivity hazards, and storage recommendations.

The U.S. Coast Guard offers Chemical and Hazardous Response Information System (COMDTINST 16465.12C). This CD-ROM-based system contains physical data and emergency procedures in a searchable format. In addition to the information contained on the CD-ROM, the system contains a search engine to access the USCG website for the most current information.

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The U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), and the U.S. Environmental Protection Agency have developed a Chemical Reactivity Worksheet. This electronic tool gives the hazardous properties of chemicals and also gives the hazards involved with mixing a number of chemicals as specified by the user. This worksheet is available for download from the NOAA website.

PRINCIPLES OF GOOD STORAGE

Segregation

The first principle of good storage practice for chemicals is segregation, including separation from other materials in storage, from processing and handling operations, and from incompatible materials. Segregation can take the form of isolation in a separate detached structure or isolation in the same building (by means of fire walls and drainage or other liquids control). Segregation can also be achieved by separating chemicals within the same building by an intervening empty area or by intervening storage of inert or nonhazardous materials. The extent of segregation depends on the quantity of materials being stored, the physical state of the chemicals, and their degree of incompatibility. In addition, the known behavior of materials under fire conditions will affect the extent and type of segregation needed. Rupture of vessels and possible mixing of incompatible materials under fire conditions must be considered.

Protection Against Physical Damage

Containers for chemicals are designed to be compatible with the materials they contain. However, when containers are subjected to physical abuse, containers can be damaged and the chemicals released, which can considerably increase fire and explosion hazards. For this reason, protection of the containers against physical damage in shipment, transfer, and storage is very important. In addition, the container might represent a potential hazard under fire conditions. For example, storage of oxidizers in fiber packs or even plastic containers might be safe under normal conditions, but if a fire occurs, the oxidizers and the combustible packages can magnify fire intensity.

Hazard Identification

All storage areas should conspicuously display signs to identify the material stored and handled in the area. The hazard identification system described in NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response,* should be used. See especially the tables on the degrees of health, flammability, and instability hazards in NFPA 704. When materials having different hazard identifications are stored in the same area, the area should be marked to indicate the most severe health, flammability, and reactivity hazard present. Hazard identifications for many materials can be found in NFPA 49 and NFPA 325, found in the NFPA *Fire Protection Guide to Hazardous Materials* (Figure 7.4.1).

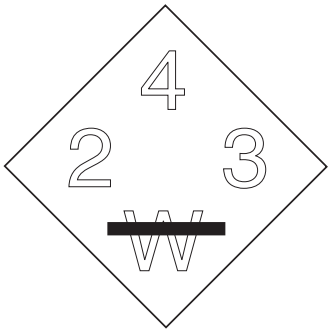

FIGURE 7.4.1 Sample NFPA Marking (Source: NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response,* 2001 ed., Figure 9.1(a)(c))

Fire Control

The selection of extinguishing agents is determined by the reactivity of the chemical, the physical state of the chemical (i.e., solid, liquid, or gas), the toxicity of the chemical, and its expected products of combustion or decomposition. Water is normally used as the extinguishing agent, except on chemicals that are dangerously water-reactive. However, the toxicity of the material in water must be considered as an additional factor. The contamination of potable water supplies and environmentally sensitive areas by toxic runoff from fire fighting could create a major health and environmental hazard.

Automatic sprinkler protection for storage should be employed wherever possible. The protection must be specifically designed based on the extent of fire hazard, the arrangement of material, and the maximum quantity that can be stored.

Manual fire fighting to supplement the automatic protection might be severely limited by the toxicity of the material, obscuration due to smoke, the nature of the products of combustion, or the possibility that fires might lead to explosions in storage areas for reactive chemicals. Fire fighters should wear self-contained breathing apparatus (SCBA) and other appropriate personal protective equipment (PPE) to avoid the hazard of toxic materials. Where explosion is a possibility, manual fire fighting should be conducted from a remote location. In some cases, the hazard will be sufficiently high so that fire fighters should not approach the area to attempt any type of manual fire fighting.

TOXICITY OF CHEMICALS

The toxicity of chemicals is particularly important from the point of view of fire protection, regardless of the toxic material's fire hazard. A fire or explosion can subject fire fighters to a severe life safety hazard if the toxic material is accidentally released while they are present. In situations where fire officers are aware of a real or potential toxicity hazard, the decision might be made to forgo manual fire fighting. Fire fighters should be aware that products of combustion may present very different

hazards. These products may be more or less hazardous than the uncombusted chemical.

Before using a chemical, one should obtain and evaluate information about its toxicity. When the toxicity problem appears to be severe, an effort should be made to find a suitable less toxic substitute. If there is no practical way to eliminate the toxic material, protection should be provided for those subject to daily exposure and for fire department personnel. Those who might be exposed during a fire or other emergency should be informed of the potential hazard and advised of the proper protective clothing and breathing apparatus to wear. Automatic fire protection should always be provided when a fire hazard is present in conjunction with a toxicity hazard.

In addition to the information sources discussed at the beginning of this chapter, information on the toxicity of chemicals can be obtained from Patty's *Industrial Hygiene and Toxicology* and other references.

There are two ways to protect against the toxic effects of chemicals during handling. First, use the most practical of the available methods for controlling and confining the chemical so that the toxic material cannot be contacted, swallowed, or inhaled in dangerous quantities during normal operations. Second, in areas where toxic chemicals are handled, educate all persons about the hazards, precautionary procedures, danger signals, and emergency procedures to be followed.

Of the methods used to control and confine toxic chemicals, handling them in a closed system is absolutely necessary. However, a leak in the system is always possible and could subject persons to a severe health hazard. If a gas is not an irritant, personnel must be warned of the exposure by automatically operated toxic gas indicators or other alarm devices. In some installations, it might be possible to maintain a slight negative pressure on the closed system to prevent the escape of toxic materials in case of a minor leak. Generally, such systems are ducted to a scrubber where the toxic gas can be neutralized. Wherever possible, processes should be installed outdoors where natural air movement will dilute and dissipate toxic gases or vapors.

OXIDIZING CHEMICALS

In considering storage facilities for oxidizing chemicals, remember that oxidizing chemicals usually are not themselves combustible, but can provide oxygen to accelerate the burning of combustible materials. Combustible materials and flammable liquids, therefore, should not be stored in the same storage areas with oxidizing chemicals. Storage buildings should be of noncombustible or fire-resistive construction. Combustible packaging and wood or plastic pallets represent a severe hazard and should be eliminated. Because certain oxidizing materials undergo dangerous reactions with specific noncombustible materials, the possibility of dangerous reactions should be considered when deciding on acceptable storage facilities. Chlorates, for example, should not be stored with acids or combustible materials. Inorganic peroxides also react with acids, yielding hydrogen peroxide. A suitable storage facility for inorganic peroxides would be a dry, fire-resistive storage room in which there are no combustible contents or acids. When classifying chemicals for storage purposes, one should keep in mind that the label on the container required for interstate shipment classifies the chemical by hazard for transportation purposes only; a thorough knowledge of the fire, health, and reactivity hazards of the chemical should be the guide when arranging storage.

Because of the probability that spilled material will become mixed with combustible refuse, it is important to clean up all spills immediately and thoroughly. Combustible linings of barrels should be removed from the storage area and destroyed as soon as the barrels are empty.

NFPA 430, *Code for the Storage of Liquid and Solid Oxidizers,* addresses storage of oxidizing chemicals.

Nitrates

Awareness of the fire hazard properties of inorganic nitrates is important because these materials are widely used in fertilizers, salt baths, and other industrial applications. Under fire conditions, inorganic nitrates can melt and release oxygen, causing the fire to intensify. Molten nitrates react with organic materials with considerable violence, usually releasing toxic oxides of nitrogen. When solid streams of water are used for fire fighting, they can produce steam explosions on contact with molten material.

Nitrates are soluble in water and some are hygroscopic. Water solubility can be indirectly responsible for serious fires. Paper, burlap, or cloth bags of nitrates that become moist during shipment or storage retain an impregnation of nitrate after drying and are thus highly combustible. For this reason, nitrates should be transferred from bags or wood barrels to noncombustible bins for storage. The bags or barrels should be thoroughly washed. For the same reason, storage of bulk nitrates on wood floors or against wood walls or posts is hazardous.

Common nitrates are discussed in this section. Other nitrates have somewhat similar properties.

Sodium Nitrate. Noncombustible sodium nitrate promotes combustion of other materials. It evolves oxygen when heated to about 700°F (370°C), thereby increasing the intensity of any fire in its vicinity. An intimate mixture of sodium nitrate and organic material can be exploded by a flame.

Potassium Nitrate. The properties and hazards of potassium nitrate are similar to those of sodium nitrate; however, potassium nitrate is less moisture absorbent.

Ammonium Nitrate. Like other inorganic nitrates, ammonium nitrate is an oxidizing agent and will increase the intensity of a fire. The oxidizing gas it gives off is nitrous oxide, rather than oxygen. Chemical- and fertilizer-grade ammonium nitrate must not be confused with certain ammonium nitrate combustible material mixtures used as explosives. All grades of ammonium nitrate can be detonated if they are in the proper crystalline form, if the initiating source is sufficiently large, or if heated under sufficient confinement (the purest material needing the greatest confinement).

As is evident from the shipboard explosions at Texas City, Texas, and Brest, France (both in 1947), and in the Red Sea in 1953; the explosion following a freight train wreck at Traskwood, Arkansas, in December 1960; and explosions in bulk warehouses near Pryor, Oklahoma, in January 1973, and in Toulouse, France, in September 2001, certain conditions other than initiation by explosives can cause ammonium nitrate to detonate. An extensive series of tests to determine the explosion hazards of fertilizer-grade ammonium nitrate under fire exposure was conducted by the U.S. Bureau of Mines,[1] and from that study it would appear that the following conclusions can be reached:

1. Although detonation initiation in ammonium nitrate as a result of fire exposure cannot be ruled out completely, a direct burning-to-detonation transition in commercial fertilizer-grade ammonium nitrate (AN) appears to be possible only in a pile of extremely large dimensions, with ignition at the bottom or center of the pile. (The ammonium nitrate involved in the Texas City, Brest, and Red Sea explosions was organic coated, with substantially different burning characteristics from those of the AN manufactured today.)
2. Projectiles derived from nearby explosions can initiate reactions leading to detonations, particularly in hot AN. Ordinary sporting arms bullets are incapable of initiating detonations of AN under normal storage conditions.
3. When AN is intimately mixed with fuel oil, ground polyethylene, or ground paper, transition from burning to detonation is possible, although quite unlikely, in pile sizes that are typical of those found in storage and transportation. Such mixtures are properly classified as blasting agents and should be stored according to the requirements in NFPA 495, *Explosive Materials Code.*
4. Gas detonations are incapable of initiating detonation of AN.
5. Hot AN can be detonated by projectile impact. (Initiation of detonation of AN in the Traskwood freight train wreck and fire could have been by projectiles derived from a gasoline-nitric acid detonation, because tank cars of gasoline and of nitric acid were also in the wreck. Nitric acid could have become mixed with the burning gasoline.)

Tests conducted many years ago indicate that mixtures of ammonium nitrate and ammonium sulfate containing not more than 40 percent by weight of ammonium nitrate and mixtures of ammonium nitrate and calcium carbonate (calcium ammonium nitrate) containing not more than 61 percent ammonium nitrate are not explosive under conditions met in practice. When exposed to fire, calcium ammonium nitrate forms calcium nitrate and ammonium carbonate, which absorbs heat while decomposing to ammonia, carbon dioxide, and water. However, the contamination problem has not been thoroughly investigated.

Ammonium nitrate in water solution is not hazardous unless spilled into combustible material and permitted to dry. Research, however, has shown that solutions containing up to 8 percent water can be detonated.[2]

Cellulose Nitrate. For hazards and properties of cellulose nitrate, see Section 6, Chapter 13, "Polymeric Materials."

Nitric Acid

(See section entitled "Corrosive Chemicals" in this chapter.)

Nitrites

Nitrites should not be confused with nitrates. Nitrites contain one less oxygen atom than nitrates but are more active oxidizing agents since they melt and release oxygen at lower temperatures. Because nitrites in mixtures with combustible substances are hazardous, such mixtures should not be subjected to heat or flame. Certain nitrites, notably ammonium nitrite, are by themselves explosive. Nitrites should be treated like nitrates with respect to storage, handling, and fire fighting.

Inorganic Peroxides

Sodium, Potassium, and Strontium Peroxide. Although these chemicals are themselves noncombustible, they react vigorously with water and release oxygen as well as large amounts of heat. Large quantities of sodium and potassium peroxides can react explosively with water, and heat from reaction with just a little water might cause the contents of an entire container to decompose. If organic or other oxidizable material is present when this reaction takes place, fire is likely to occur.

Barium Peroxide. Heat releases oxygen from barium peroxide. Intimate mixtures of barium peroxide and combustible or readily oxidizable materials are explosive and easily ignited by friction or by contact with a small amount of water.

Hydrogen Peroxide. In contrast to the four abovementioned peroxides, which are white powders, hydrogen peroxide is a syrupy liquid. In pure form, it is relatively stable. When heated to and kept at a temperature of 212°F (100°C), 99.2 percent hydrogen peroxide decomposes at the rate of 4 percent per year and 50 to 90 percent hydrogen peroxide at a rate of something less than 2 percent a day. An increase in temperature increases the decomposition rate of hydrogen peroxide about 1½ times for each 18°F (–8°C). Near the boiling point, the rate of decomposition is very rapid and, if adequate venting is not provided, the pressure in the container might cause it to rupture. In general, the dilute material is less stable than the concentrated.

The hazards of hydrogen peroxide/water solutions are highly dependent on the concentration. Solutions at concentrations of between 86 and 90.7 percent hydrogen peroxide have been demonstrated to be detonatable.[3] At a concentration above about 92 percent, the liquid can be exploded by shock. Concentrated hydrogen peroxide vapors can be exploded by a spark. At atmospheric pressure, the boiling material must be 74 percent hydrogen peroxide or higher to produce explosive vapors.

Decomposition of hydrogen peroxide produces water, oxygen, and heat. At concentrations above 35 percent, the heat is sufficient to turn all the water into steam, assuming that the decomposition begins at room temperature (72°F [22°C]). This means that a steam explosion is possible with the sudden decomposition of concentrated material. Decomposition can be caused by contamination with iron, copper, chromium, and many other metals (except aluminum) or their salts. Decompo-

sition can also be caused by combustible dust or by contact with a rough surface, such as ground glass.

Hydrogen peroxide is a strong oxidizing agent and can cause ignition of combustible material with which it remains in contact. This possibility, however, is remote unless the concentration is greater than 35 percent.

Chlorates

An adequate understanding of the fire hazard properties of the chlorates can be gained from the best-known member of the group, potassium chlorate.

Potassium Chlorate. This white crystalline substance is water soluble, noncombustible, and a strong oxidizing agent. When heated, it gives up oxygen even more readily than do nitrates. Mixing with combustible materials, for example, floor sweepings, should be prevented because, under such conditions, potassium chlorate might ignite or explode spontaneously. Drums containing chlorates might explode when heated. Sodium chlorate has properties similar to potassium chlorate.

Chlorites

Sodium Chlorite. This is a powerful oxidizing agent that forms explosive mixtures with combustible materials. In contact with strong acids, it releases explosive chlorine dioxide gas. At 347°F (175°C), sodium chlorite decomposes with the evolution of heat.

Dichromates

Among the dichromates, all of which are noncombustible, ammonium dichromate is most readily decomposed. It begins to decompose at 356°F (180°C); above 437°F (225°C) the decomposition becomes self-sustaining and is accompanied by swelling and the release of heat and nitrogen gas. Closed containers rupture at the decomposition temperature.

The other dichromates, such as potassium dichromate, react with readily oxidizable materials which, in some cases, can cause them to ignite. They release oxygen when heated.

Hypochlorites

Calcium hypochlorite at a concentration above 50 percent by weight can cause combustible or organic materials to ignite on contact. When heated, it gives off oxygen. With acids or moisture, it freely evolves chlorine, chlorine monoxide, and some oxygen at ordinary temperatures. It is sold as bleaching powder or, when concentrated, as a swimming pool disinfectant.

Calcium hypochlorite is one of the most widely used oxidizers. As a swimming pool disinfectant, it can be found in many retail establishments, lawn and garden warehouses, and in home utility rooms. It is often packaged in plastic bottles, drums, or bags. If contaminated or exposed to a fire, the material, in conjunction with the plastic container, will decompose rapidly, giving off a large amount of heat. This heat can open a large number of automatic sprinklers and ignite surrounding combustible materials. Depending on the sprinkler system design and the strength of the water supply, the sprinkler protection might be overtaxed, leading to destruction of the building. NFPA 430 discusses the storage and protection of oxidizers in retail occupancies. The protection scheme outlined could also be used for calcium hypochlorite storage in warehouses.

Perchlorates

Perchlorates contain one more oxygen atom than chlorates. They have roughly similar properties, but are more stable than chlorates. They are explosive under some conditions, such as when in contact with concentrated sulfuric acid.

Ammonium Perchlorate. This chemical has great explosive sensitivity when contaminated with such impurities as sulfur, powdered metals, carbonaceous materials, and reducing agents. The pure material in finely divided form can detonate if involved in a fire. A mixture with a chlorate can form spontaneously explosive ammonium chlorate.

Potassium Perchlorate, Sodium Perchlorate, and Magnesium Perchlorate. Each of these chemicals forms explosive mixtures with combustible, organic, or other easily oxidizable materials. Magnesium perchlorate is sometimes used in laboratories in place of calcium chloride as a dessicant. Such use requires vigilance to avoid dangerous contamination.

Permanganates

Mixtures of inorganic permanganates and combustible material are subject to ignition by friction or can ignite spontaneously if an inorganic acid is present. Explosions can occur whether the permanganate is in solution or is dry.

Potassium Permanganate. This chemical reacts violently with finely divided oxidizable substances. On contact with sulfuric acid or hydrogen peroxide, potassium permanganate is explosive.

Persulfates

Persulfates, for example, potassium persulfates, are strong oxidizing agents that can cause explosions during a fire. Oxygen released by the heat of a fire can cause an explosive rupture of the container, or the explosion might follow an accidental mixture of the persulfate with combustible material.

Fire Control Methods

With one or two exceptions, water appears to be the only suitable extinguishing agent for fires involving inorganic oxidizing agents. Water in large quantities should be used to control fires involving nitrates, nitrites, and chlorates. Carbon dioxide and other smothering agents are of little or no extinguishing value for fires involving nitrates, nitrites, and chlorates because the oxidizing material furnishes its own oxygen for combustion. Although inorganic peroxides decompose when moist and liberate oxygen, water should still be used on fires in combustible materials that are located in the vicinity of the peroxide.

It might be possible to extinguish a fire involving a peroxide spill with a dry chemical extinguisher or by smothering with dry sand or soda ash. If these methods fail, the area should be flooded with water from hose streams.

Self-contained breathing apparatuses should be worn by fire fighters. During a fire involving nitrates, one of many dangers is inhalation of oxides of nitrogen. As much ventilation as possible should be provided to permit rapid dissipation of the products of combustion and heat. When water in solid streams strikes molten nitrate, steam explosions can cause a violent eruption of the molten material.

COMBUSTIBLE CHEMICALS

Essentially, all organic chemicals are combustible. Storage practices for such chemicals closely follow those for the more common solid combustible materials discussed in other chapters.

Carbon Black

Carbon black is used in the manufacture of rubber and plastic products, such as tires. Carbon black is manufactured by the decomposition of acetylene, by incomplete combustion of natural gas or a mixture of natural gas and a liquid hydrocarbon, or by cracking hydrocarbon vapor in the absence of air. It is most hazardous immediately following manufacture when bags of the finished product might contain red-hot carbon particles. While carbon black adsorbs oxygen, slow smoldering can develop. To prevent this hazard, carbon black is stored in an observation warehouse before shipment or final storage. It is well established that carbon black will not heat spontaneously after thorough cooling and airing, although it might generate heat in the presence of oxidizable oils.

Tests show that a dust explosion hazard does not exist. Red-hot metal, electric sparks, and burning magnesium ribbon will not cause carbon black dust clouds to ignite explosively, but ignition has been obtained by using 1 oz (28 g) of gunpowder.

Carbon black comprises 98 percent of the world's production of powdered carbon.

Lamp Black

Lamp black is formed by burning low-grade heavy oils or similar carbonaceous materials with insufficient air. It adsorbs gases to a marked degree and often ignites spontaneously when freshly bagged. It has great affinity for liquids and heats in contact with drying oils. The possibility of lamp black dust explosions is increased by the presence of unconsumed oil that adheres to the carbon. U.S. Bureau of Mines' tests indicate that a dust explosion hazard exists if the oil content exceeds 13 percent. Lamp black should be thoroughly cooled before it is bagged and then stored in a cool, dry area away from oxidizing materials.

Lead Sulfocyanate

Lead sulfocyanate burns slowly. It decomposes when heated, yielding decomposition products which include highly toxic and flammable carbon disulfide and highly toxic but nonflammable sulfur dioxide.

Nitroaniline

This combustible solid melts at 295°F (146°C), and its flashpoint is 390°F (199°C). In the presence of moisture, it nitrates organic materials, which could result in their spontaneous ignition.

Nitrochlorobenzene

Nitrochlorobenzene is a solid material at ordinary temperatures and gives off flammable vapors when heated.

Sulfides

Antimony Pentasulfide. This is readily ignited and hazardous in contact with oxidizing materials. On contact with strong acids, antimony pentasulfide yields hydrogen sulfide, a very toxic gas.

Phosphorus Pentasulfide. This ignites readily, and in the presence of moisture may heat spontaneously to its ignition temperature (287°F [142°C]). The products of combustion include highly toxic sulfur dioxide and phosphorus pentoxide. Reaction of phosphorus pentasulfide with water yields hydrogen sulfide, a very toxic gas.

Phosphorus Sesquisulfide. With an ignition temperature of only 212°F (100°C), this chemical is easily ignited and is considered highly flammable. Toxic sulfur dioxide is a product of combustion.

Potassium Sulfide and Sodium Sulfide. These are moderately flammable solids that form toxic sulfur dioxide when burning, and toxic hydrogen sulfide on contact with acids.

Sulfur

Sulfur at ordinary temperatures is a yellow solid or powder consisting of rhombic crystals that melt in the vicinity of 234°F (112°C), depending on their purity. Sulfur boils at about 832°F (444°C). Except in small quantities, it is shipped and stored as a liquid at a temperature below 300°F (149°C). It is combustible, and its vapor forms explosive mixtures with air. (Its flashpoint is 405°F [207°C].) Finely divided sulfur dust likewise possesses an explosion hazard that requires control during storage and handling. Ignition temperatures of dust clouds vary upward from 374°F (190°C).

Sulfur contains varying amounts of hydrocarbons, depending on the source. These hydrocarbons gradually react with the molten material to form combustible and highly toxic hydrogen sulfide. Storage tanks and pits for molten sulfur must be ventilated to prevent accumulation of this gas. Except in the presence of lamp black, carbon black, charcoal, and a few less common substances, spontaneous ignition of sulfur is practically nonexistent. It melts and flows when burning and evolves large quantities of toxic, irritating, and suffocating sulfur dioxide. This gas attacks the eyes and throat, and complicates fire fighting. Sulfur also forms highly explosive and easily detonated mixtures with chlorates and perchlorates and forms gunpowder when mixed with potassium nitrate and charcoal.

Water should be used for fighting sulfur and sulfide fires. For fighting fires of sulfur dust, water spray is recommended, principally to avoid stirring up dust clouds and causing a dust explosion. Fires in closed spaces, for example, tanks of molten sulfur, can best be fought by closing the container and allowing the heavy sulfur dioxide produced by combustion to smother the fire.

Naphthalene

Naphthalene is combustible both in solid and in liquid form. Naphthalene vapors and dusts form explosive mixtures with air.

UNSTABLE CHEMICALS

Special precautions must be taken for storage of chemicals that are subject to spontaneous decomposition or other dangerous reactions. The precautions should be planned to minimize the possibility of a dangerous reaction and to prevent injuries and extensive property damage if one should occur. Steps to be taken to protect against the hazard will depend on the conditions that affect the stability of the chemical being stored. Points peculiar to unstable chemicals to be considered are: (1) the catalytic effect of containers, (2) materials in the same storage area that could initiate a dangerous reaction, (3) the presence of inhibitors, and (4) the effect of direct sunlight or temperature changes. There is a need for pressure-relief vents for containers and explosion venting for the storage area in addition to the usual considerations, such as automatic sprinkler or water spray protection, and elimination of all combustible material from the storage area. Whenever possible, unstable chemicals should be stored in a detached outside location.

Fire fighters should be thoroughly briefed on the proper procedures to be followed if called on to fight a fire involving or exposing a storage area containing unstable chemicals.

Acetaldehyde

Acetaldehyde is a highly reactive compound. Under suitable conditions, the oxygen or any hydrogen can be replaced. Acetaldehyde undergoes numerous condensation, addition, and polymerization reactions, which can take place with explosive violence.

Ethyl Acrylate, Methyl Acrylate, Methyl Methacrylate, and Vinylidene Chloride

These are flammable liquids that can polymerize at elevated temperatures, as in fire conditions. If the polymerization takes place in a closed container, the container can rupture violently. These liquids usually contain an inhibitor to prevent polymerization.

Ethylene Oxide

Ethylene oxide can polymerize violently when catalyzed by anhydrous chlorides of iron, tin, or aluminum; oxides of iron (i.e., iron rust) and aluminum; and alkali metal hydroxides. Violent polymerization of ethylene oxide can be initiated by heat or shock. Ethylene oxide reacts with alcohols, organic and inorganic acids, ammonia, and many other compounds. The heat liberated by these exothermic reactions can cause polymerization of the unreacted ethylene oxide. Ethylene oxide vapors can detonate if some initiating heat source is present. Ethylene oxide vapors in a tank exposed by fire can be rapidly heated to their ignition temperature unless the tank is kept wet with water spray. The flammable range of ethylene oxide in air is 3 to 80 percent. Although the upper limit is frequently reported to be 100 percent, explosions of mixtures containing greater than 80 percent ethylene oxide are the result of chemical decomposition.

Hydrogen Cyanide

Hydrogen cyanide is flammable and poisonous. In either liquid or vapor states, it has a tendency to polymerize. The reaction is catalyzed by alkaline materials and, since one of the products of the polymerization reaction is alkaline (ammonia), an explosive reaction will eventually take place. By adding sulfuric, phosphoric, or some other acid to neutralize the ammonia, the rate of polymerization in the liquid can be held down to a safe rate. Potassium cyanide and sodium cyanide on contact with acids release poisonous and flammable hydrogen cyanide vapor.

Nitromethane

Nitromethane is a combustible liquid. At 599°F (315°C) and 915 psig (6308 kPa), it decomposes explosively. Noteworthy detonations of nitromethane in railroad tank cars occurred at Niagara Falls, New York, and at Mt. Pulaski, Illinois, in 1958. Although undiluted nitromethane can detonate under certain conditions of heat, pressure, shock, and contamination, the causes of these two tank car explosions were not definitely determined. A possible explanation is contamination of the nitromethane by some material previously carried in the tanks. For a discussion of the hazards of nitromethane and other nitroparaffins, see AIA Research Report No. 12.[4]

Organic Peroxides

Organic peroxides are an important group of chemicals widely used in the plastics industry as polymerization reaction initiators, in the milling industry as flour bleaches, and in the chemical and drug industries as catalysts. All organic peroxides are combustible and, as in the case of inorganic peroxides, increase the intensity of a fire. Many organic peroxides can be decomposed by heat, shock, or friction. The rate of decomposition depends on the particular peroxide formulation and the temperature. Some, such as methyl ethyl ketone peroxide, are detonatable. Organic peroxides can be liquid (e.g., *t*-butyl perbenzoate) or solid (e.g., benzoyl peroxide) and are often dissolved in flammable or combustible solvents. The peroxides are often found wet with water or diluted with stable liquids. With solutions, sensitive crystals can be formed by freezing.

This widely used group of unstable chemicals deserves special attention. Many organic peroxides are diluted to the point where hazardous reactions are impossible; others require special precautions. Organic peroxides are shipped in specific containers that are designed not to confine the peroxide under

fire conditions. Care should be taken if the peroxide is transferred to another container. The manufacturer of the peroxide should be consulted for specific recommendations.

NFPA 432, *Code for the Storage of Organic Peroxide Formulations,* gives quantity and arrangement specifications for various formulations.

Benzoyl Peroxide. In undiluted form, benzoyl peroxide ignites very readily and burns with great rapidity, similar to burning an equal amount of black powder. Decomposition by heat is rapid, and, if the benzoyl peroxide is confined when heated, explosive decomposition will occur. Decomposition can also be initiated by heavy shock or frictional heat. Most benzoyl peroxide is shipped diluted or water-wet to reduce the fire hazard.

Ether Peroxides. During storage, practically all ethers form ether peroxides. When the ether peroxide mixture is heated or concentrated, the peroxide can detonate. With some ethers, the quantities of peroxide formed are too small to be of significance. Peroxide formation is a hazardous property of diethyl ether, ethyl tertiary butyl ether, ethyl tertiary amyl ether, and the isopropyl ethers. Isopropyl ether is said to be considerably more susceptible to peroxide formation than other ethers. When pure, dry ether is stored under laboratory conditions in a clear and colorless bottle, it will develop detectable amounts of peroxides in one month. Light seems to be a more important factor than heat, although peroxides have been known to form in amber bottles. Ether sealed in copper-plated cans or in otherwise inhibited cans is not likely to form peroxides. Although there is apparently no means yet available to completely eliminate peroxide formation, using any one of numerous patented inhibitors or copper or iron along with storage in metal or opaque amber glass containers provides sufficient stability for all practical purposes. Ether should not be dry-distilled unless peroxides have been proved absent.

Styrene

Styrene polymerizes slowly at ordinary temperatures, and the rate increases as the temperature increases. Since the polymerization reaction is exothermic, the reaction will eventually become violent as it is accelerated by its own heat. Inhibitors are added to styrene to prevent dangerous polymerization.

Vinyl Chloride

Vinyl chloride is a toxic and flammable gas that can polymerize at elevated temperatures, as in fire conditions, and cause violent rupture of the container. Vinyl chloride usually contains an inhibitor to prevent polymerization.

Fire Control Methods

Water is the recommended extinguishing agent for fires involving unstable chemicals, including organic peroxides. Automatic sprinklers are the best protection because fires involving such materials can lead to explosions. Manual fire fighting must be conducted from a distance where the fire fighters will be protected from an explosion.

WATER- AND AIR-REACTIVE CHEMICALS

Water-reactive and air-reactive chemicals present significant fire hazards. Significant quantities of heat are liberated during the reactions. If the chemical is combustible, it is capable of self-ignition; if noncombustible, the heat of reaction might be sufficient to ignite nearby combustible materials.

Water-Reactive Chemicals

Anhydrides, carbides, hydrides, alkali metals (lithium, sodium, potassium), and similar chemicals should be stored in dry areas in waterproof and airtight containers that are kept off the floor on skids. The storage area should not contain combustible material and/or incompatible chemicals.

Air-Reactive Chemicals

Aluminum hydride, aluminum alkyls, yellow phosphorous, and similar chemicals must be stored to avoid contact with air. Yellow phosphorous, for example, is stored under water. Other materials, such as aluminum alkyls, which react with both water and air, must be stored under inert liquids or inert gas. Storage areas should contain no incompatible materials.

Alkalies (Caustics)

Caustic soda (sodium hydroxide or lye) and caustic potash (potassium hydroxide) are the most common alkalies. Although caustics are noncombustible, they generate heat when mixed with water. In contact with water, dry solid caustics will react. The heat generated (heat of solution) can be sufficient to ignite combustible material. Caustic solutions can generate hydrogen on contact with zinc, galvanized metals, or aluminum.

Aluminum Trialkyls

Most of these organic metal compounds are pyrophoric, that is, they ignite spontaneously on exposure to air, and react violently with water and certain other chemicals. Triethylaluminum, the most common member of this group, ignites spontaneously in air and on contact with water. When it is mixed with strong oxidizing agents or with halogenated hydrocarbons, violent reactions or detonations can occur.

Anhydrides

Acid anhydrides are compounds of acids from which water has been removed. They react with water, usually violently, to regenerate acids. Organic acid anhydrides are combustible and usually are more hazardous than their corresponding acids, because their flashpoints are lower. Acetic anhydride has a flashpoint of 129°F (54°C); propionic anhydride, 165°F (74°C), open cup; butyric anhydride, 190°F (88°C), open cup; and maleic anhydride, 218°F (103°C). Inorganic acid anhydrides, for example, chromium anhydride and phosphorus anhydride, are not combustible.

Carbides

The carbides of some metals, such as sodium and potassium, can react explosively on contact with water. Many, such as calcium

carbide, lithium carbide, potassium carbide, and barium carbide, decompose in water to form acetylene. In addition to the hazard of the formation of flammable gas, another fire hazard of certain carbides is the generation of heat in contact with water. When one-third its weight of water is added to a water-reactive carbide, the temperature can be raised sufficiently to ignite the gas generated. Sodium carbide becomes heated to incandescence when placed in chlorine, carbon dioxide, or sulfur dioxide. The carbides of silicon and tungsten are very stable.

Charcoal

Under certain conditions, charcoal reacts with air at a sufficient rate to cause the charcoal to heat spontaneously and ignite. Charcoal made from hard wood by the retort method appears to be particularly susceptible. Spontaneous heating occurs more readily in fresh charcoal than in old material; the more finely divided it is, the greater the hazard. Among the conditions that can lead to spontaneous heating of charcoal are (1) lack of sufficient cooling and airing before shipment; (2) charcoal becoming wet; (3) friction in grinding of finer sizes, particularly of material insufficiently aired before grinding; and (4) carbonizing of wood at too low a temperature, leaving the charcoal in a chemically unstable condition.

Coal

Under some conditions, virtually all grades of coal (except high-grade anthracite) are subject to spontaneous heating and ignition. Although the basic causes for the spontaneous heating of coal are not well defined, it is believed that adsorption of oxygen or oxidation of finely divided particles is the main cause.

Among the conditions believed to affect the susceptibility of coal to spontaneous heating are (1) the fineness of the particles, (2) the oxygen adsorptive abilities of the particles, (3) the trapped and confined moisture content of the coal, (4) air trapped in voids in coal piles, (5) the presence of sulfur in the form of pyrites or marcasites, (6) free gases in the pile, (7) foreign substances in the pile, (8) the method and depth of piling, (9) the temperature of the containing walls and floor or of surrounding or surrounded surfaces, and (10) the type and amount of ventilation.

Hydrides

Most hydrides are compounds of hydrogen and metals. Metal hydrides react with water to form hydrogen gas.

Sodium Hydride. A gray-white crystalline, free-flowing powder, sodium hydride will ignite with explosive violence on contact with water. When exposed to air, absorption of moisture may cause ignition.

Lithium Hydride. When this combustible solid reacts vigorously with water, hydrogen gas and heat are evolved. Lithium hydride dust is likely to explode in humid air. Static electricity can cause the dust to explode in dry air.

Lithium Aluminum Hydride. Like lithium hydride, this chemical is a combustible solid that reacts rapidly with water to form hydrogen gas and heat. The heat will probably cause the hydrogen to ignite. When lithium aluminum hydride is in a solution with ether, a fire involving the solution is essentially an ether fire. Small amounts of water cause the burning to intensify. Combustible materials on which the solution has spilled may ignite spontaneously or be ignited by light friction.

Oxides

Oxides of some metals and nonmetals react with water to form alkalies and acids, respectively. This reaction takes place violently with the infrequently used sodium oxide. Calcium oxide, more commonly known as quicklime or unslaked lime, also reacts vigorously with water (slaking) with the evolution of enough heat to ignite paper, wood, or other combustible material under some conditions.

Phosphorus

Two forms of phosphorus, that is, white and red, are in common use.

White (or Yellow) Phosphorus. This type is the more dangerous because of its ready oxidation and spontaneous ignition in air. It is common practice to ship and store white phosphorus under water, usually with the mixture in a hermetically sealed metal container. Periodic checks should be made to ensure that containers do not leak. White phosphorus is very toxic and should not be permitted to come in contact with the skin. On ignition, dense white clouds of toxic fumes are evolved which attack the lungs.

Red Phosphorus. This type is less hazardous than white, does not oxidize and burn spontaneously at ordinary temperatures, and can be shipped and stored without the protection of water, although it should be kept in closed containers away from oxidizing agents. It is formed by heating white phosphorus. The solid form is not toxic but, once vaporized, it takes on all the fire hazards of white phosphorus to which it reverts on condensation. Care should be taken in opening containers of red phosphorus because spontaneous ignition can take place with exposure to air.

Sodium

(See Section 6, Chapter 9, “Metals.”)

Sodium Hydrosulfite

Sodium hydrosulfite burns slowly and produces sulfur dioxide as a combustion product. On contact with moisture and air, sodium hydrosulfite heats spontaneously and can ignite nearby combustible materials.

Fire Control Methods

The value of automatic sprinklers depends on the type of chemical reaction that will occur when the chemical comes in contact with water. Fires involving hydrides, for example, can be smothered with a special graphite-base powder or with inert material,

such as dry, finely divided calcium magnesium carbonate (dolomite). Hydride fires in an enclosed space should not be put out because the continued evolution of hydrogen after extinguishment will create an explosion hazard. For the fires involving air-reactive white (or yellow) phosphorus, water will solidify the phosphorus melted by the heat of the fire, after which it can be covered with dry sand or dirt. All of the chemical must be disposed of before it can dry out and reignite.

Several of these chemicals are both air- and water-reactive and the water reaction can be particularly violent, for example, aluminum alkyls. Fires of such materials can be contained by dry chemical while the material burns out under control. Metallic sodium, which is both water- and air-reactive, can be extinguished by the use of dry chemical. The residual sodium should then be submerged in oil.

CORROSIVE CHEMICALS

The term *corrosive* refers to those chemicals that have a destructive effect on living tissues. Although some corrosive chemicals are strong oxidizing agents, they are separately classified to emphasize their injurious effect on contact or inhalation. It should not be inferred, however, that a chemical is not injurious because it is otherwise classified. For example, caustics, classified as water- and air-reactive chemicals, are also corrosive.

Inorganic Acids

Concentrated aqueous solutions of the inorganic acids are not in themselves combustible. Their chief hazard lies in the danger of leakage and possible mixture with other chemicals or combustible material stored in the vicinity, since fire or explosions could occur from mixing of the chemicals.

Hydrochloric Acid. In concentrated solution, hydrochloric acid is hazardous because its reaction with certain metals (including tin, iron, zinc, aluminum, and magnesium) forms hydrogen gas. Strong oxidizing agents mixed with hydrochloric acid cause the release of chlorine gas. A mixture of nitric and hydrochloric acids generates chlorine and nitrous oxide.

Hydrofluoric Acid. Either anhydrous or aqueous hydrofluoric acid is noncombustible and does not cause ignition of combustible materials with which it comes in contact. However, it is highly toxic, irritating to the eyes, and inflicts severe skin burns. When it comes in contact with metals, hydrogen is generated.

Nitric Acid. Under certain conditions, nitric acid nitrates cellulose material. Thus, wood that comes in contact with the acid or its vapor can ignite much more easily. Spontaneous heating follows if strong solutions of the acid mix with organic material. In general, concentrated nitric acid nitrates organic materials; dilute acid oxidizes them, giving off oxides of nitrogen during the process. These oxide fumes (colorless to brown) are usually present in fires in buildings where nitric acid is used. A concentration of this gas (actually a mixture of several gases) so small that it is not objectionable at the time of inhalation can result in serious illness or death to the victim, although no effects might be felt for some time. If white fuming nitric acid (more than 97.5 percent nitric acid) is spilled into burning gasoline, it will detonate.[1]

Perchloric Acid. When misused or used in concentrations greater than 72 percent, perchloric acid can be extremely dangerous. At the normal commercial strength (72 percent), it is a strong oxidizing and dehydrating agent when heated, but a strong nonoxidizing acid at room temperature. Because of this and other advantageous properties, it is widely used in analytical laboratories. The rate of burning of organic substances is greatly increased by contact with perchloric acid. Explosions have occurred at wood and plastic laboratory hoods after long exposure of the hoods to perchloric acid vapors. Strong dehydrating agents, such as concentrated sulfuric acid or phosphorus pentoxide, convert perchloric acid solution to anhydrous perchloric acid, which decomposes even at room temperature and explodes with terrific violence. It also explodes on contact with many organic substances. For these reasons, dehydrating agents should never be mixed with perchloric acid.

Sulfuric Acid. This chemical has the added hazardous property of absorbing water from organic material with which it might come in contact. Charring takes place and sufficient heat can be evolved to cause ignition. Particular care must be taken to avoid painful skin burns inflicted by bodily contact. Dilute sulfuric acid will dissolve metals with the evolution of hydrogen.

The Halogens

The members of the halogen (salt-producing) group are all chemically active and have similar chemical properties. The individual elements, that is, fluorine, chlorine, bromine, and iodine, differ from each other in decreased chemical activity in the order named. Bromine and iodine have the least fire hazard. They are noncombustible, but will support combustion of certain substances. Turpentine, phosphorus, and finely divided metals ignite spontaneously in the presence of the halogens. The vapors are poisonous, as well as corrosive and irritating to the eyes and throat.

Bromine. This is a dark reddish-brown corrosive liquid which can cause fire when in contact with combustible materials.

Chlorine. This is a heavy, greenish-yellow, highly toxic gas given off in some manufacturing processes and by bleaching powder (chloride of lime), especially in the presence of strong acids. It is not flammable itself, but can cause fires or explosions, especially if it comes in contact with acetylene, ammonia, turpentine, hydrocarbons, or finely powdered metals. At 484°F (251°C), mild steel ignites and burns in chlorine. Adequate ventilation should be provided in any process where this gas is generated.

Fluorine. A greenish-yellow gas, fluorine is one of the most reactive elements known. It combines, in most cases spontaneously, with practically all known elements and compounds under suitable conditions. Fluorine reacts violently with hydro-

gen and many organic materials. It explodes on contact with metallic powders, attacks glass and most metals, and reacts explosively on contact with water vapor. It can be safely handled in nickel or Monel™ cylinders. Fluorine reacts with these two metals, but forms a protective nickel fluoride layer that prevents further action. However, moisture or other impurities within the cylinder can cause such violent reaction that the metal will melt and ignite in the fluorine. The tank will then burst and scatter molten metal.

Iodine. This chemical is usually in the form of purplish-black volatile crystals that are corrosive. Reports indicate that iodine is explosive when diffused with ammonia (it forms explosive nitrogen triiodide) and when mixed with turpentine or lead triethyl.

Fire Control Methods

Water in spray form is recommended for fighting fires in acid and alkali storage areas. Water from straight streams mixing with concentrated acid or a caustic agent will heat and spatter the corrosive chemicals. A fire involving perchloric acid can cause an explosion if the acid becomes mixed with organic material. Ample precautions should be taken to protect fire fighters from possible explosions. Fire fighters should avoid contact with spilled acids and inhalation of their toxic fumes by the use of self-contained breathing apparatuses.

Chlorine and fluorine do not represent fire hazards, but the release of dangerous toxic gases should be expected if cylinders are present in a fire. It is mandatory that a self-contained breathing apparatus be used when fighting a fire where chlorine or fluorine cylinders are located.

RADIOACTIVE MATERIAL

Radioactive elements and compounds have fire and explosion hazards identical to those of the same material when not radioactive. An additional hazard is introduced by the various types of radiation emitted, all of which are capable of causing damage to living tissue. Under fire conditions, vapors and dusts (smoke) can be formed that could contaminate not only the building of origin, but also neighboring buildings and outdoor areas. The fire protection engineer's main concern with radioactive materials is to prevent the release or loss of control of these materials by fire during fire extinguishment.

Fire Protection for Radioactive Materials

The life safety hazard introduced by an escape of radioactive dusts and vapors during a fire makes it vitally important to take all practical steps to prevent a fire from involving these materials. Radioactivity is not detectable by any of the human senses. Special instruments and measuring techniques are required to identify and evaluate it. The hazard is affected by the form of the material—whether solid, liquid, or gas—and by the container in which it is kept or handled.

Radioactivity can cause loss of life, injuries, and damage to and extended loss of materials used, as well as damage to equipment and buildings. Manual fire fighting might be limited by the danger to fire fighters from exposure to radioactivity. Salvage work and resumption of normal operations at a property can be delayed where a fire or explosion causes loss of control over radioactive substances. The need to decontaminate buildings, equipment, and materials presents a serious and complicated problem.

Smoke and products of combustion from fires in places where there are radioactive materials must be controlled. The runoff of water used in fighting fires must also be controlled. Fire fighters require protective clothing and respiratory protection equipment. Fire control must be thoroughly preplanned. With radiation hazards, automatic sprinklers are preferable to measures requiring manual fire fighting. This lessens the amount of radioactive smoke or products of combustion and water runoff to be dealt with manually.

Handling Radioactive Materials

The possibility of accidental release of radioactive material because of a fire or explosion, with the resultant health hazard to fire fighters and others, is a strong argument for careful attention to methods of fire prevention and control in laboratories and other occupancies handling radioactive materials.

More information can be obtained from NFPA 801, *Standard for Fire Protection for Facilities Handling Radioactive Materials.* This publication calls attention to basic information concerning radiation protection methods and provides some guidance on fire protection practices to those who design and operate such facilities. Most radioactive materials introduce little or no fire or explosion hazard, so the fire hazard of facilities handling radiation usually can be determined by a knowledge of the combustibility of the building and its furnishings and of the fire and explosion hazards of the nonradioactive chemicals.

The fire and explosion hazard can be substantially reduced by use of a fire-resistive building, noncombustible interior finish and furnishings, wherever possible, and enforcement of strict controls to minimize the hazards of flammable liquids and other chemicals that are necessary for laboratory work or for other occupancies. In any facility handling radioactive materials, one feature that can cause trouble, unless the building has been properly designed, is the duct system usually required for the safe disposal of contaminated vapors, gases, and dusts. Unless this system is properly arranged, it can spread radioactive contaminants to noninvolved parts of a facility during a fire.

Fire Control Methods

Due to the need to immediately control any fire that might eventually release radioactive materials and the potential health hazard to those who could be exposed to radiation during manual fire control, there can be no question as to the desirability of automatic sprinkler protection for radiation laboratories and other areas where radioactive materials are handled. Special precautions to be followed by fire-fighting personnel are described in *Hazardous Materials Response Handbook.*[5] The procedures stress steps that should be taken to protect fire fighters at all

times, including the use of radiation monitoring devices, self-contained breathing apparatuses, and regular fire department protective clothing.

MATERIAL SUBJECT TO SELF-HEATING

Charcoal

Spontaneous heating hazards with charcoal can be controlled by thorough cooling and ventilation before bagging and storage. It is important to keep the charcoal dry, to prevent contamination with foreign combustibles, and to avoid contact with heat sources. Small quantities of charcoal are normally stored in heavy paper bags. The spontaneous heating hazard of individual small bags, as might be found in a dwelling, is not serious.

When fire occurs in charcoal, water should be used, but directed only on the fire, without wetting nonburning material. The damaged and wet materials should be removed from the storage building at once, because wet charcoal is even more susceptible to self-heating than when dry.

Agricultural Products

Spontaneous heating in agricultural products can be prevented by control of moisture. Proper curing (as for hay) and adequate aeration will prevent heat buildup. Where the moisture content cannot be controlled, or where any suspicion of spontaneous heating exists, thermocouples can be used in stacks or bales. Pointed, hollow metal rods or pipes with holes drilled in the lower ends often are used to permit insertion of temperature-recording instruments into the subsurface areas of the stored material. Regular checks can then be made for the development of any hazardous temperature conditions. Where evidence of dangerous spontaneous heating is noted, the material should be removed quickly from storage.

When spontaneous heating occurs in agricultural products, it is important to have ample fire-fighting facilities available. Water hoses are needed to combat a fire that might occur spontaneously on exposure of the hot spots to air. Hay, in and around hot spots, should be wetted thoroughly before complete uncovering or attempted removal.

MIXTURE, TRANSPORTATION, AND DISPOSAL OF CHEMICALS

Mixtures of Chemicals

This chapter has presented several examples of dangerous reactions that can occur when certain chemicals are mixed. Examples have been given of chemicals that can increase the ease of ignition or the intensity of burning of the combustible materials with which they are mixed. In order to recognize the innumerable combinations of so-called incompatible chemicals, it is necessary to have a knowledge of the potentially dangerous reactions of individual chemicals. NFPA 491 contains more than 3400 dangerous reactions that have been reported in chemical literature and elsewhere. NFPA 491 can be found in NFPA *Fire Protection Guide to Hazardous Materials.*

Transportation of Chemicals

The safe transportation of chemicals depends on a knowledge of the hazardous properties of the chemicals, the normal and abnormal conditions to which the chemicals might be exposed during shipment, and the conditions of packing and shipping that will minimize the possibility of accidental release or reaction of chemicals.

In the United States, shipments of hazardous chemicals in interstate or foreign commerce by land, water, or air must comply with U.S. Department of Transportation's (DOT) Hazardous Materials Regulations (HMR). Among the subjects covered by the HMR are (1) responsibilities of shippers; (2) construction of and performance standards for containers; (3) a marking code for hazardous materials packaging, which includes information on package type, material of construction, and maximum allowable gross mass; (4) marking and labeling of packaging; (5) loading, placarding, and movement of railroad cars; and (6) regulations for carriage by rail, by aircraft, by vessel, and by public highway. In addition, the HMR contains a Table of Hazardous Materials, which identifies the Proper Shipping Name, United Nations (UN) Number, Hazard Class, Packing Group, and allowable packaging types for the transport of hazardous materials. State regulations for intrastate transportation usually agree with DOT interstate commerce regulations.

In Canada, Transport Canada (TC) regulates shipment of explosives and other dangerous chemicals. Chemicals shipped in accordance with Canadian regulations are allowed to be shipped to a destination in the United States or through the United States en route to or from a point in Canada. International transport of hazardous materials by sea is regulated by the International Maritime Organization (IMO) through the International Maritime Dangerous Goods Code (IMDG), and transport by air is regulated by the International Civil Aviation Organization (ICAO) through its Technical Instructions (TI). The International Air Transport Association (IATA) also issues Dangerous Goods Regulations (DGR), which are similar to ICAO's TI. In general, hazardous materials packaged in compliance with the IMDG or the TI may be shipped by other modes within the United States before or after they are shipped by sea or air, even if they are not in full compliance with the HMR.

Principles governing the safe transportation of chemicals include the following:

1. Constructing the container of material that will not react with or be decomposed by the chemical
2. Excluding chemicals that can react dangerously with each other from the same outside container
3. Packaging toxic and radioactive chemicals so they will not present a health hazard during normal transportation conditions and will not be released in an accident or under other abnormal conditions
4. Providing sufficient outage for maximum expansion of liquids under conditions to be expected during transportation
5. Limiting the amount of chemical that can be released through container breakage or leakage by limiting maximum size of individual containers; this principle must be balanced against the efficiencies inherent in the use of larger containers

6. Cushioning containers to minimize the possibility of breakage

Waste Chemical Disposal

The safe disposal of hazardous chemical waste is controlled by a 1976 federal law—the Resource Conservation and Recovery Act (RCRA PL 94-590, Subtitle C, Hazardous Waste Management). This act provides for cradle-to-grave regulation of potentially dangerous by-products spawned by industrial technology. Specifically, the law covers any solid, liquid, or gaseous waste that exceeds federal criteria established for the following characteristics: (1) toxicity, (2) persistence and degradability in nature, (3) potential for accumulation in tissue (bioaccumulation), (4) reactivity, (5) flammability, (6) corrosivity, and (7) radioactivity.

Standards have been published that regulate generators of hazardous waste in several different areas, that is, recordkeeping practices, labeling and containerization, disclosure of waste composition to haulers and disposers, use of a manifest to monitor the life cycle of a waste stream, and reporting requirements to applicable local, state, and federal agencies. Additionally, standards have been developed to control the storage, transportation, and final disposition to ensure that these compounds are handled in properly designed facilities. For example, secured chemical landfills must have a sufficiently impervious base to prevent contaminated leachate from entering adjacent groundwater, and incinerators must achieve a 99.9 percent destruction efficiency. Significant legal liabilities can accrue to violators of these standards.

Recognizing the hazards involved, it is advisable to verify the capabilities of any firm utilized for disposal of hazardous wastes. At the very minimum, operating permits should be reviewed to confirm that a particular waste can be legally processed by any company under consideration for this service.

SUMMARY

Safe storage and handling of chemicals requires knowledge of all of the hazardous properties of the chemical, which can be obtained from the manufacturer's material safety data sheet. Safe storage also depends on the quantity, size, and nature of the containers and their storage arrangement. Principles of good storage include segregating the chemical from other materials in storage, from processing and handling operations, and from incompatible materials; protecting containers from physical damage; using a hazard identification system; and providing fire protection based specifically on the nature of the hazard.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on storage and handling of chemicals discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 430, *Code for the Storage of Liquid and Solid Oxidizers*
NFPA 432, *Code for the Storage of Organic Peroxide Formulations*
NFPA 490, *Code for the Storage of Ammonium Nitrate*
NFPA 495, *Explosive Materials Code*
NFPA 655, *Standard for Prevention of Sulfur Fires and Explosions*
NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*
NFPA 801, *Standard for Fire Protection for Facilities Handling Radioactive Material*

Chapter 5

Hazardous Waste Control

Revised by
Paul R. Severson

Chapter Contents

Regulation of Hazardous Waste
Sources of Waste
Characterization of Waste
Collection, Handling, and Disposal of Waste
Hazard Prevention and Control
Specific Wastes

Key Terms

Environmental Protection Agency (EPA), gaseous waste, hazardous materials incident, hazardous waste, Hazardous Waste Operations and Emergency Response (HAZWOPER) standard, liquid waste, solid waste, waste handling systems and equipment, waste recovery

Waste is a by-product of many human activities. Increased technological development can lead to activities that may involve more waste, more hazardous waste, or at least different hazards in waste. With the proper emphasis it can also lead to waste that is less hazardous and less in volume. The Environmental Protection Agency (EPA) estimated that, in 2005, municipal solid waste alone totaled 245 million tons.[1] This is but a small fraction of the total solid waste produced by commercial, mining, construction, agricultural, manufacturing, and other industrial activities. During the course of a year, roughly over 3.5 billion tons (3.3 billion metric tons) of solid waste is produced—100 lb (45 kg) per day for every man, woman, and child.[2]

In addition to solid waste, many gaseous products, such as those produced in combustion processes (e.g., CO_2, NO_x, SO_2, soot, and hydrocarbons), and to a lesser extent chlorofluorocarbons (CFCs), are generated as waste and released into the atmosphere as gases. The pollution of air with such gaseous waste products not only is detrimental to human health but also reduces visibility and contributes to corrosion and deterioration of clothing, art treasures, historical structures, metals, rubber, and paint. Acid rain, the product of further atmospheric oxidation and dissolution of NO_x and SO_x in rain water, adversely affects the growth of forests and agricultural products and the survival of aquatic life in streams, ponds, and lakes. The accumulation of CO_2 in the atmosphere may be causing warming of the planet with dire climatological, agricultural, and ocean-level implications. CFCs destroy the ozone layer in the stratosphere; ozone protects us against harmful ultraviolet radiation from the sun. The depletion of this layer increases the risk of skin cancer.

Domestic, commercial, and industrial liquid wastes, if not treated properly, may find their way to bodies of water and add to the problem of the dwindling potable water supply by causing pollution of existing supplies. Industrial liquid waste might contain metallic salts that have immediate or long-term effects on humans. High concentrations of these salts can also build up in fishes, crustaceans, and plants, with similar effects on people who consume them. Some organic wastes from commercial, household, and industrial sources reduce the concentration of dissolved oxygen in water supplies. This can lead to the loss of aquatic life and the growth of disease-carrying bacteria and parasites. Other wastes might contain known or suspected carcinogens, such as chlorinated hydrocarbon solvents, benzene, and polychlorinated biphenyls (PCBs).

Although all waste is a nuisance to society, not all waste is necessarily hazardous. Hazardous waste can be defined as that which poses a threat to human health, the environment, or public property if handled or disposed of improperly. The hazard is created by virtue of the toxicity, flammability, explosivity, reactivity, radioactivity, corrosivity, or etiologic (disease-causing) potential of the waste.

Under Section 313 of the Emergency Planning and Community Right-to-Know Act of 1986, which was expanded under the Pollution Prevention Act of 1990, EPA collects annual data on the emission rates of over 570 listed toxic chemicals and 30 chemical categories from over 23,000 qualifying companies. These companies employ 10 or more full-time employees and process or manufacture more than 25,000 lb (11,340 kg) or use more than 10,000 lb (4536 kg) of the listed

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chemicals. These data[3] show that, in 2003, the reporting facilities released 5.0 billion lb (2.3 billion kg) of the listed chemicals in on-site and off-site releases to the environment. The preferred hierarchy in dealing with waste is (1) reduction or reuse at the source, (2) recycling the waste, and (3) treatment or disposal (Figure 7.5.1).

This chapter (1) discusses the regulation of hazardous waste and the sources and characteristics of waste materials with particular emphasis on hazardous waste, (2) summarizes waste handling, disposal, and recovery procedures, and (3) examines the various approaches to fire prevention and protection in cases involving hazardous waste.

See also Section 11, Chapter 1, "Waste Handling and Control."

REGULATION OF HAZARDOUS WASTE

Many federal, state, and local laws and regulations have been enacted to protect the public and the environment against exposure to hazardous waste. The federal laws attempt to specify and control the quantities, concentrations, and types of chemicals released and how they are packaged, stored, transported, and disposed of.

Table 7.5.1 is a summary of relevant federal laws and related terms used in this chapter. In addition to the federal acts listed in the table, parts of other laws and amendments to existing laws regulate specific waste-disposal and handling operations. For example, the Marine Protection, Research, and Sanctuaries Act regulates ocean dumping and incineration on the high seas; the Hazardous Materials Transportation Act regulates the packaging and containerization of hazardous materials, including hazardous wastes; the Hazardous and Solid Waste Amendments to RCRA (Subtitle I) provide for the development and implementation of a comprehensive regulatory program for underground storage tanks; and the Safe Drinking Water Act establishes maximum contaminant levels for drinking water and regulates underground injection of hazardous wastes.

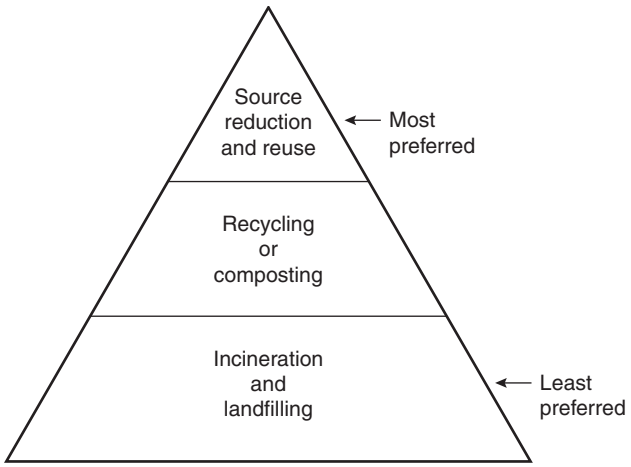

FIGURE 7.5.1 Solid Waste Management Hierarchy (Source: http://www.denvergov.org/recycle/rr.asp)

SOURCES OF WASTE

There are many sources of waste materials in present-day society. To a great extent, the source determines the waste composition, density, quantity, and the type and degree of hazard that it might present. These factors, together with regulatory requirements, determine how the waste should be collected, processed, or disposed of in a practical and safe manner.

Domestic, Commercial, and Industrial Sources

Figure 7.5.2 shows typical breakdowns of the contents of collected solid waste from domestic, commercial, and industrial sources.

The nature of an industry determines the content of the waste generated. A typical furniture plant, for example, produces scrap wood, sawdust and shavings, oily rags, stain, varnish, lacquer, glue, paper, metal, and other commercial items. The waste products of chemical processing plants vary considerably depending on the raw materials used and the end products made. These plants might discard substantial amounts of off-grade or reject products, by-products, tars, spent catalyst, precipitates, and so on. Nuclear power plants produce radioactive waste.

In addition to waste materials produced during machine maintenance, some materials may be spilled in storage and handling. Cleanup operations from filling equipment, fabrication operations, and general plant maintenance will generate some waste. Rejected and aged products, damaged packages, off-specification materials, and overruns will also be discarded.

Transportation Sources

Broken packages, leaking drums, and overheated or frozen cargo can occur during transit. Washing tank cars or tank trucks

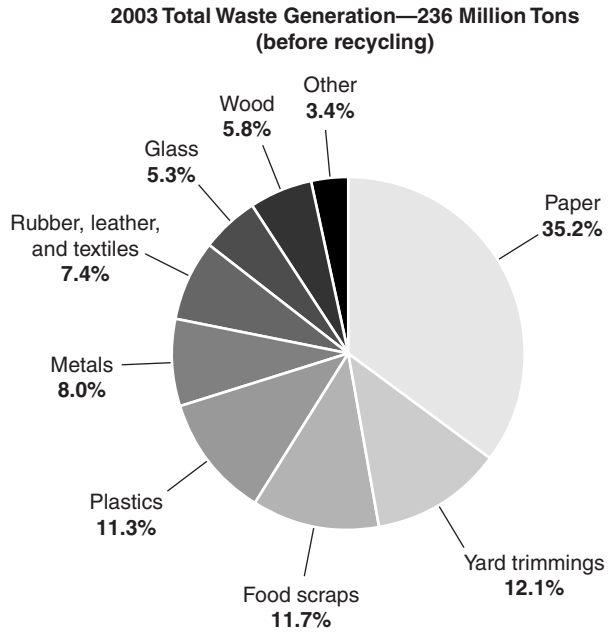

FIGURE 7.5.2 Typical Contents of Solid Waste (Percent by Weight) (Source: http://www.epa.gov/msw/facts.htm)

TABLE 7.5.1 Summary of Pertinent Federal Laws and Terminology

CAA	Clean Air Act (1966, 1970, 1977, 1990)—a federal law that mandates and enforces toxic emissions standards for stationary sources and motor vehicles. The CAA amendments of 1990 added restrictions on air toxics, ozone-depleting chemicals, stationary and mobile emission sources, and emissions implicated in acid rain and global warming. They also required industries that handle threshold quantities of listed hazardous chemicals to prepare a risk management plan.
CERCLA	Comprehensive Environmental Responsibility, Compensation and Liability Act (1980, 1986), sometimes referred to as Superfund—a federal law that authorizes the identification and remediation of abandoned hazardous waste sites.
CWA	Clean Water Act (1972, 1987)—a federal law that regulates the discharge of pollutants into surface waters and to publicly owned and municipal water treatment facilities.
EPA	Environmental Protection Agency—established under the Reorganizational Plan 3 of 1970 as an independent federal agency to ensure the protection of the environment by abating and controlling pollution. It coordinates all governmental action; conducts research; and monitors, sets, and enforces environmental standards.
FEMA	Federal Emergency Management Agency—a federal agency that is accountable for all federal emergency preparedness, mitigation, and response activities for all natural, man-made, or nuclear emergencies; also responsible for administering certain training funds under SARA.
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act (1972, 1988)—a federal law that mandates toxicity testing and registration of pesticides and establishes tolerance levels for residues of these agents in food.
OSHA	Occupational Safety and Health Act (1970)—a federal law that called for the establishment of the Occupational Safety and Health Administration, which oversees and regulates workplace health and safety. OSHA standards require facilities that process specified quantities of listed toxic and flammable chemicals to comply with 29 CFR 1910.119, "Process Safety Management." It also requires employers to inform and train employees in the hazards of the chemicals they handle, under 29 CFR 1910.1200, "Hazard Communication."
RCRA	Resource Conservation and Recovery Act (1976, 1984)—enacted as an amendment to the Solid Waste Disposal Act, RCRA protects human health and the environment and encourages the conservation of valuable material and energy sources. It provides assistance to state and local governments for prohibiting open dumping; regulating the management of hazardous wastes; and encouraging recycling, reuse, and treatment of hazardous wastes. RCRA provides for "cradle-to-grave" tracking of hazardous waste, from generator to transporter to treatment, storage, or disposal.
SARA	Superfund Amendments and Reauthorization Act (1986)—a federal law that reauthorizes and expands the jurisdiction of CERCLA and designates requirements mandated in Title III of SARA for public disclosure of chemical information and the development of emergency response plans.
TSCA	Toxic Substances Control Act (1976)—a federal law that authorizes EPA to gather information on new and existing chemical risks to human health and the environment.
UST	Underground Storage Tanks—regulated by RCRA, Subtitle I, these are tanks with 10 or more percent of their volume underground, used to store CERCLA-regulated hazardous chemicals or petroleum products.
DOT	The United States Department of Transportation (DOT)—established by an act of Congress in 1966. Among other responsibilities, DOT is responsible for oversight of transportation of hazardous and other materials.

can produce substantial amounts of waste material that may be emulsified or dissolved in water. A spill of a hazardous liquid or solid chemical cargo, as a result of a railway, truck, ship, or pipeline accident, may contaminate soil and/or nearby bodies of water and create a public hazard and another waste disposal problem. This is particularly true of incidents occurring in remote areas where trained personnel may not be readily available to assess the potential hazard to the public and the environment and provide guidance in controlling the hazard.

Storage Sources

Warehouse inventory control sometimes necessitates that unmarketable or undesirable materials be occasionally discarded. Tanks must be cleaned as storage needs change. The washing of transfer lines and tanks results in a waste product.

Materials may inadvertently be released in plants, such as when packages are damaged by forklifts, requiring cleanup and disposal. Water, fire, or explosion damage can also result in substantial amounts of waste material.

Other Sources

Several other human activities produce waste. Harvesting of agricultural products, mining operations, and demolition of structures are examples of operations that generate large quantities of waste products with various characteristics.

CHARACTERIZATION OF WASTE

Safe handling, collection, and disposal of hazardous waste can be accomplished only if the physical, chemical, and hazardous

properties of its components are known and that information is properly applied. Often the composition is not known because the waste is a mixture of many components with differing properties. This section discusses the physical, chemical, and hazardous properties that might influence the selection of response procedures to accidental releases and the appropriate disposal techniques for wastes.

Physical State

The ease of handling and disposal of waste is highly dependent on its physical state.

Solid Waste. Solid waste includes most domestic, commercial, and industrial trash, metal, wood, plastic scrap, chemicals, and food (see Figure 7.5.2). It also includes agricultural waste products, demolition waste, spent ore from mining operations, combustible metal waste (e.g., magnesium shavings), and semisolids, such as waxes, soaps, and elastomers.

Liquid Waste. Liquid waste includes aqueous and nonaqueous solutions and suspensions generally produced as a result of cleaning operations. Nonaqueous solvents might be flammable (e.g., toluene and xylene) or noncombustible (e.g., trichlorethylene). Viscous liquids, such as pastes and tars, and suspensions, such as acid sludges, require special handling procedures and equipment.

Gaseous Waste. Most gaseous waste is generated from industrial operations and is disposed of by venting into the atmosphere. Hazardous gaseous-waste products may be regulated by the EPA. They are controlled by heating, flitering, scrubbing, recovery, or destruction of the hazardous components by other means. Of particular concern to fire-fighting and other response personnel are unidentifiable gas cylinders with walls that might have become weakened due to age and corrosion. Discarded small butane and LP-gas cylinders in household trash can also pose an explosion hazard to trash collectors and compactors, and to operators of shredding equipment.

Properties of Hazardous Waste

Few discarded materials are so compatible with the environment or so inert as to have no short-term or long-term impact. Hazards that appear minor can have unexpected impacts long after disposal. When two or more hazards pertain to a material, the lesser might not receive the necessary consideration. Mixing two discarded substances can result in a chemical reaction with severe and unexpected consequences.

Since waste is generally a mixture of many components, its physical and chemical properties usually cannot be defined with any degree of accuracy. Whenever possible, the approximate composition of a hazardous waste should be obtained from the originating source or from the manifest accompanying the waste being transported. Generally, when one component predominates, the physical and chemical properties of the waste mixture are nearly those of the major component. This is not true for the hazardous properties of waste mixtures consisting of a relatively harmless major component and small amounts of highly toxic, radioactive, or etiologically active components. The hazard, in this case, is determined by the smaller components.

Hazardous Solid Waste

The EPA defines hazardous solid waste as that which might "(i) cause, or significantly contribute to, an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or (ii) pose a substantial present or potential hazard to human health or the environment when it is improperly treated, stored, transported, disposed of, or otherwise managed." The determining characteristic of a hazardous solid waste must be "measurable by an available standardized test method . . . or reasonably detectable by generators of solid waste through their knowledge of their waste."[4]

Basically, EPA standards require that a solid waste be treated as hazardous if it is a listed waste and/or if it meets the ignitability, corrosivity, reactivity, and/or toxicity characteristics prescribed by the standard. Highlights of the standard are given below.[5]

Ignitability. A solid waste exhibits this characteristic if a representative sample of the waste has any of the following properties:

1. It is a liquid and has a closed-cup flashpoint less than 140°F (60°C) (Class I and Class II liquids, excluding wine and latex paint, as defined in NFPA 30, *Flammable and Combustible Liquids Code*), as determined by an approved test method.
2. It is not a liquid and is capable under standard temperature and pressure of causing fire through friction, absorption of moisture, or spontaneous chemical changes and, when ignited, burns so vigorously and persistently that it creates a hazard.
3. It is a flammable compressed gas as defined by another federal standard.[6] A flammable compressed gas is defined as one that forms flammable mixtures with air at concentrations less than 13 percent (by volume) or has a flammability range with air which is wider than 12 percent regardless of the lower flammable limit (LFL). The standard specifies additional criteria for defining flammable vapors and aerosols.
4. It is an oxidizer, such as a chlorate, permanganate, inorganic peroxide, or a nitrate, that yields oxygen readily to stimulate the combustion of organic matter.[7]

Corrosivity. A solid waste exhibits this characteristic if a representative sample of the waste has either of the following properties:

1. It is aqueous and has a pH of less than or equal to 2 (i.e., highly acidic) or greater than or equal to 12.5 (i.e., highly alkaline, or basic).
2. It is a liquid and corrodes steel at a rate greater than ¼ in. (6.35 mm) per year at a test temperature of 130°F (55°C).

Reactivity. A solid waste exhibits this characteristic if it behaves in any of the following ways:

1. It is normally unstable and readily undergoes violent change without detonating.
2. It reacts violently with water.
3. It forms potentially explosive mixtures with water.
4. When mixed with water, it generates toxic gases, vapors, or fumes in a quantity sufficient to present a danger to human health or the environment.
5. It is a cyanide-bearing or sulfide-bearing waste that, when exposed to pH conditions between 2 and 12.5, can generate toxic gases, vapors, or fumes in a quantity sufficient to present a danger to human health and the environment.
6. It is capable of detonation or explosive reaction if it is subjected to a strong initiating source or if heated under confinement.
7. It is readily capable of detonation or explosive decomposition or reaction at standard temperature and pressure.
8. It is a known forbidden or a Class A or B explosive.

Toxicity. The EPA defines toxic wastes as those that have been found to be fatal to humans in low doses or, in the absence of data on human toxicity, it has been shown in studies to have an oral LD_{50} toxicity (rat) of less than 50 mg/kg, an inhalation LC_{50} toxicity (rat) of less than 2 mg/L, or a dermal LD_{50} toxicity (rabbit) of less than 200 mg/kg or is otherwise capable of causing or significantly contributing to an increase in serious irreversible, or incapacitating reversible, illness. A toxic waste is also one that contains or degrades into a listed toxic material in large enough concentrations to pose a potential hazard to the public and/or the environment. The standard for toxicity provides descriptions of laboratory tests for extracting and analyzing the potentially toxic components of wastes.

Hazardous Medical Waste

During the summer of 1988, a number of incidents were reported where medical waste, such as blood vials and bags, syringes, pill bottles, and bandages, washed ashore at various public Atlantic coast beaches. The publicity associated with these incidents and others involving the disposal of medical waste in dumpsters hastened the promulgation of the Medical Waste Tracking Act of 1988. The law required EPA to develop a two-year demonstration "cradle-to-grave" tracking system for four participating states. This law has since expired. Individual states have developed their own environmental standards in which they define what constitutes hazardous medical waste and identify acceptable disposal methods. Further, the Occupational Safety and Health Administration (OSHA) has promulgated a standard[8] for the protection of employees against exposure to bloodborne pathogens. The Department of Transportation (DOT) has also developed standards for the proper packaging and shipment of hazardous medical waste.[9]

Medical waste is generated during the diagnosis, treatment, or immunization of human beings or animals; in medical research; and in the production or testing of regulated biologicals. It is generated at facilities such as hospitals, health care centers, nursing homes, funeral homes, blood banks, veterinary clinics, and medical-research laboratories.

Medical waste is a likely source of pathogens (infectious agents). Some of the diseases that can be transmitted through improper disposal and handling of infectious medical waste are acquired immune deficiency syndrome (AIDS), typhoid, cholera, dysentery, anthrax, salmonellosis, tuberculosis, and burcellosis. Development and implementation of a well-thought-out medical-waste management plan can reduce the risk of infection to staff, patients, and the general public.

Medical waste can be categorized as follows:

1. *Cultures and stocks.* Cultures and stocks of infectious agents and associated biologicals, including cultures from medical and pathological laboratories; cultures and stocks of infectious agents from research and industrial laboratories; wastes from the production of biologicals; discarded live and attenuated vaccines; and culture dishes and devices used to transfer, inoculate, and mix cultures.

2. *Pathological wastes.* Human pathological wastes, including tissues, organs, and body parts and body fluids that are removed during surgery, autopsy, or other medical procedures, and specimens of body fluids, and their containers.

3. *Human blood and blood products.* Liquid-waste human blood; products of blood; items saturated and/or dripping with human blood; items that were saturated and/or dripping with human blood that are now caked with dried human blood, including serum, plasma, and other blood components, and their containers, which were used or intended for use in either patient care, testing, and laboratory analysis, or the development of pharmaceuticals. Intravenous bags are included in this category.

4. *Sharps.* These are objects that have been used in animal or human patient care or treatment, or in medical, research, or industrial laboratories. They include hypodermic needles, syringes (with or without the attached needle), pasteur pipettes, scalpel blades, blood vials, needles with attached tubing, and culture dishes (regardless of presence of infectious agents). Also included are broken and unbroken glassware that came into contact with infectious agents, such as used slides and cover slips.

5. *Animal waste.* Contaminated animal carcasses, body parts, and bedding of animals that were known to have been exposed to infectious agents during research (including research in veterinary hospitals), production of biologicals, or testing of pharmaceuticals.

6. *Isolation waste.* Biological waste and discarded materials contaminated with blood, excretion, exudates, or secretions from humans who are isolated to protect others from certain highly communicable diseases, or isolated animals known to be infected with highly communicable diseases.

7. *Unused sharps.* Unused, discarded sharps, for example, hypodermic needles, suture needles, syringes, and scalpel blades.

COLLECTION, HANDLING, AND DISPOSAL OF WASTE

The safe disposal of hazardous waste introduces challenges for the facility generating the waste, the waste-transporter, the

disposal facility, and fire fighters and other response forces who might be called on to clean up an unintentional release. These issues arise because the contents of waste may usually not be well defined—perhaps even known. Waste is often a mixture of many components with differing hazardous properties. One component, for example, might be a flammable solvent and another a highly toxic pesticide. Disposing of the solvent by incineration might release the pesticide (or its toxic combustion products) to the atmosphere. Additional problems can arise during handling and storing waste products. Self-heating and ignition, corrosion of pipe and tank-wall materials, and reaction with other noncompatible wastes can cause major catastrophic events. Fire fighters can also be inadvertently exposed to a hazardous-waste material released as a result of an unrelated fire or an explosion to which they have responded.

Refuse recycling and the recovery of energy from waste streams have become economically more attractive as the costs of energy and raw materials increase. Otherwise, the disposal of waste can be achieved through a variety of techniques and processes, depending on the physical, chemical, and hazardous properties of the waste. These techniques range from improvements in operations that reduce the quantity of waste produced, reduce the concentration of hazardous components to acceptable levels, or eliminate the hazardous component entirely.

Treatment of Gaseous Waste

Industrial gaseous waste can be released in the atmosphere, provided that the concentrations of the contaminants meet allowable levels set by EPA and state agencies, the Clean Air Act, and applicable permits. Table 7.5.2 summarizes the primary ambient air quality standards set by EPA for typical contaminants. Also shown are contaminant background levels in nature.

Gaseous waste streams can be purified by removing undesirable components or by reducing their concentrations to acceptable levels. This can be achieved by chemical conversion, absorption, adsorption, particulate removal, or thermal destruction.[10]

TABLE 7.5.2 Ambient Air Quality Standards[11,12]

Contaminant	*Background Level*	*EPA Primary Level*	*Allowable Exposure*
SO_2	<0.002 ppm	0.03 ppm	AAM
		0.14 ppm	Max. 24-hr conc., N
CO	0.03 ppm	9 ppm	8-hr AC, N
		35 ppm	1-hr AC, N
O_3	0.01–0.05 ppm	0.12 ppm	1-hr AC, N
NO_2	4 ppb	53 ppb	AAM
Particulates (PM_{10})	10–60 μg/m^3	150 μg/m^3	24-hr AC
		50 μg/m^3	AAM

Note: AAM = annual arithmetic mean, AC = average concentration, hr = hour, and N = not to exceed once per calendar year.

Chemical Conversion. An undesirable component can be allowed to react chemically with other compounds to form a harmless component or one that is removed easily. Sulfur dioxide, for example, is removed by reaction with lime or magnesia. Catalytic converters and other thermal oxidizers are used to convert nitrogen oxides and hydrocarbons into nitrogen, CO_2, and H_2O.

Absorption. Several gaseous pollutants can be removed by absorption. Ammonia and hydrogen chloride, for example, can be removed by water scrubbing. Sulfur dioxide can be absorbed in an alkaline solution.

Adsorption. Certain solids with a large pore-surface area selectively adsorb small concentrations of specific gases. Activated carbon, silica or alumina gel, fuller's earth and other clays are typical adsorbents. The operator is left with the problem of disposing of the contaminated adsorbent or the concentrated stream of undesirable gas released on adsorbent regeneration.

Particulate Removal. Many industrial gaseous streams contain undesirable dusts, mist, or smoke. These suspensions can be removed by filtration, sedimentation, centrifugal separation, electrostatic precipitation, and wet scrubbing.

Thermal Destruction. Many gaseous components can be destroyed or converted to less hazardous components, using the proper combination of elevated temperature and residence time.

Liquid Waste Treatment

In many cases volume and strength of industrial aqueous waste can be reduced by various process modifications. Although the hazard is not completely eliminated, a smaller volume of contaminated water or a stream with a lower concentration of a hazardous component is usually easier to handle and dispose of. Neutralization of acidic or alkaline waste can be achieved by chemical reaction with the appropriate compounds. Inorganic salts can be removed by precipitation, ion exchange, and adsorption by carbon beds. Holding ponds may be used to retain industrial waste so that it can be disposed of with domestic waste at a constant rate rather than overloading the sewage disposal system at any one time of the day.

Suspended solids can be separated by such processes as sedimentation (allowing heavy particles to sink to the bottom), flotation (skimming floating materials off the surface), drying followed by incineration, centrifuging, and filtration. Colloidal solids are more difficult to remove because their particle size range falls between that of suspended and dissolved solids. Colloidal solids will not settle unless chemicals are added that help coagulate the solid into larger masses that will sink. Many toxic pesticides, insecticides, and herbicides can be removed by adsorption in certain clays and carbons.

Many food-processing operations, as well as textile making and papermaking processes, produce waste that is high in organic matter. Biological degradation is generally achieved by

lagooning, treatment with biologically activated sludge, using trickling filters, wet combustion, deep-well injection, and other methods.

Wastewater from tanneries, slaughterhouses, and canneries might contain etiologic agents. These waters must be sterilized by processes such as chlorination, ozonization, or ultraviolet radiation before they are discharged into public water supplies.

Organic liquid waste components can be recovered by fractional distillation. The remaining components may be disposed of by incineration or burial in environmentally acceptable locations.

Disposal and Recovery of Solid Waste

Figiure 7.5.2 shows that a large fraction of domestic, commercial, and industrial solid waste is combustible. Burning scrap and refuse under controlled conditions is a common method of disposal. Municipal incinerators operated primarily for domestic and commercial trash will usually accept industrial refuse as long as it does not introduce additional hazards or operating problems.

Recovery of glass and metal from these wastes and the use of the recovered energy from the combustible component has become economically attractive. The basic steps involved in these recovery operations are waste collection, transportation to the disposal site, storage, shredding, separation and recovery of glass and metal, burning of the combustible component, and ash removal (Figure 7.5.3).

Air-pollution-control equipment is commonly needed on industrial incinerators. The choice of environmental control devices depends on the composition of the stack effluent. Such devices include the following:

- Afterburners to ignite combustible particles
- Cyclones to remove larger particles
- Low-energy scrubbers to remove larger particulates
- High-energy venturi scrubbers to remove fine particulates and/or water-soluble acid gases
- Electrostatic precipitators to remove fine particulates and mists
- Fabric filters (bag houses) to remove fine particulates

Principal hazards of operating an incinerator are the following:

- Overheating due to feeding a large amount of volatiles
- Overheating due to an increase in the heat of combustion
- Structural failure due to overheating and/or corrosion
- Corrosion of scrubber due to acid
- Failure of scrubber system

Compacted trash on transportation vehicles can cause fires. Ignition sources might be smoldering ashes from fireplaces or unextinguished cigarettes. Shredding operations can also have occasional explosions and fires, sometimes as a result of discarded explosive materials. Small butane and LP-gas cylinders and gasoline containers with some fuel remaining in them can be the source of the flammable vapor. The ignition sources are frictional sparks between the grinding or shredding teeth, the walls of the shredder, and other solid components of the refuse.

Another approach for recovering the heating content of combustible waste is by pyrolysis. When polymers and organic materials are heated, they yield oils and other recoverable compounds. Although pyrolysis has not yet been widely adopted, it has promise as a conservation measure. A retort is charged with selected scrap and then heated to cause decomposition and distillation of the volatiles and oils. The process is somewhat similar to a coke oven, and similar operating hazards should be expected (Figure 7.5.4).

Much of the nonhazardous domestic, commercial, and industrial waste today is disposed of in sanitary landfills. In a landfill operation, discarded material is mixed with earth and then compacted in a wide trench or other depression. Layer upon layer of mixture is added and then a layer of earth is spread and compacted on top. This process helps control odors, rodents, and scavenger birds.

Successful decomposition of landfilled materials depends heavily on biological activity within the fill material. There is a tendency for methane gas to be generated during biological activity. There can be fires and explosions in buildings constructed over old landfills due to the buildup of biologically generated methane into the building and its eventual ignition. The recovery and use as fuel of natural gas from waste landfills occurs in parts of the United States.

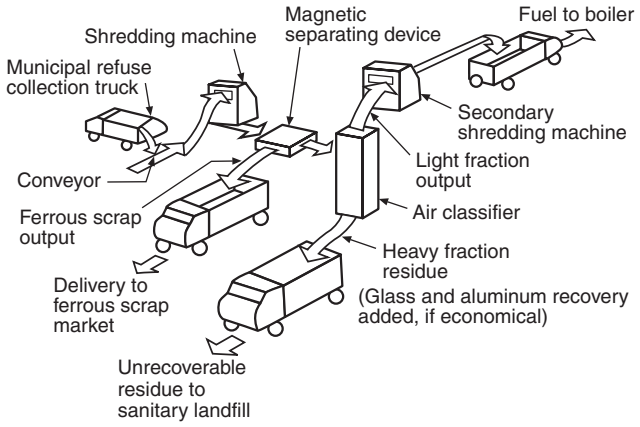

FIGURE 7.5.3 Typical Refuse Recovery Process

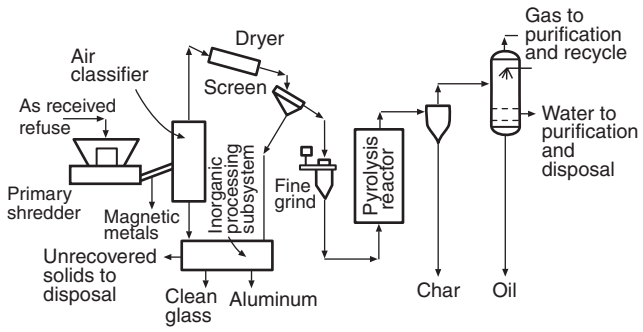

FIGURE 7.5.4 Pyrolysis Recovery System

Hazardous wastes must not be disposed of in a sanitary landfill. They must be either chemically treated or incinerated in properly designed furnaces that ensure the complete degradation of the hazardous components of the waste. Otherwise, they may be disposed of in secure landfills. These are properly designed and engineered containment facilities that ensure that no waste seeps into the underground water system to pollute natural bodies of water or the public water supply system. Transporting the hazardous waste from the source to the disposal site requires special permits. Waste must be packaged or containerized in approved containers. A manifest describing the contents, and their hazards must accompany the shipment. The operator of the secure landfill generally requires a chemical analysis of the hazardous waste so that it may be handled and sited properly.

Treatment of Hazardous Medical Waste

State standards differ governing the packaging, segregation, and identification of hazardous medical waste. These standards generally require reporting, recordkeeping, and tracking of medical waste. The standards apply to waste generators, transporters, on-site incineration facilities, and off-site treatment, destruction, and disposal facilities.

Noninfectious medical waste generated at any medical facility typically constitutes most of the total medical waste. To reduce disposal costs, the noninfectious waste is commonly segregated from infectious medical waste at the source. This reduces the potential for cross-contamination and allows disposal at sanitary waste-disposal sites without further treatment. Segregation at the source also reduces the volume of medical waste that needs to be treated before disposal.

A standard operating procedure (SOP) should be developed by all facilities that store, handle, transport, or dispose of infectious waste.[13] Unsightly pathological waste should be placed in opaque plastic bags. All containers and bags should be red and labeled with the word "infectious" and/or with the international biohazard symbol (Figure 7.5.5). Wastes that are to be transported should be double-bagged and placed in a semirigid container to prevent leakage. Wastes should be loaded and unloaded manually and never compacted, to prevent compromising the integrity of the packaging. These wastes should be arranged chronologically to meet state regulations for storage periods. All storage facilities should have limited access with the entrances marked by the international biohazard symbol and the word "infectious."

FIGURE 7.5.5 International Biohazard Symbol

Infectious medical waste must be treated and rendered harmless prior to disposal at a sanitary waste disposal site. Several treatment methods are available, including the following methods:

- Steam sterilization
- Incineration
- Thermal inactivation (dry heat sterilization)
- Gas/vapor sterilization
- Sterilization by irradiation
- Chemical disinfection

Steam sterilization is the most commonly used method for destroying pathogens in medical waste. It is preferred for contaminated solid surfaces such as sharps and low-density waste, which are easily penetrated by steam. Incineration is the preferred method for treating AIDS-contaminated and combustible infectious waste. Proper incineration of waste reduces the volume that needs to be disposed of by up to 95 percent and renders the waste harmless. Like steam sterilization, thermal inactivation is used for the sterilization of contaminated surgical instruments and equipment. Dry heat has the advantage of not corroding instruments, thereby increasing their life.

Although the remaining three methods can be used to treat medical waste, they tend to be more costly and require special precautions to protect the operator. Gas/vapor sterilization, for example, requires the use of ethylene oxide or formaldehyde, both of which are highly flammable and hazardous to human health. Irradiation with ultraviolet (UV) and gamma radiation is a more recently developed technology that is used for presterilization of medical products and can be used to treat waste water. Chemical disinfection is carried out by applying hydrogen peroxide, acids, or alcohols to exposed surfaces, utensils, and medical supplies.

To ensure the effectiveness of any treatment, it is important that an SOP be established for each waste stream to be treated. Each SOP should address the type of waste, variations in the waste stream, and the limitations of the treatment apparatus. The SOP must also specify procedures for biologically monitoring and testing of the treated waste to ensure that it is no longer hazardous.

Protection of Hazardous Waste Operators

OSHA standard "29 CFR 1910.120: Hazardous Waste Operations and Emergency Response" protects workers involved in hazardous-waste operations, and in responding to accidental releases of hazardous materials and wastes. This regulation[14] requires the following:

1. The development and implementation of a written safety and health program for employees (and subcontractors' employees) who are involved in hazardous-waste operations. The program must be designed to identify, evaluate, and control safety and health hazards, and provide for emergency response for hazardous-waste operations.
2. Hazardous-waste-site characterization, analysis, and control in order to identify specific site hazards, determine appropriate safety and health control procedures, and implement these procedures to control employee exposure to the identified hazards

3. Extensive training and retraining of employees before they are permitted to engage in hazardous-waste operations and informational programs to ensure that employees and subcontractors are aware of the degree and nature of safety and health hazards specific to the work site
4. Medical surveillance of employees exposed to (or potentially exposed to) hazardous substances or health hazards and of employees who wear respirators
5. Implementation of engineering controls, work practices, and personal protective equipment and the continuous monitoring of the work area to ensure that employees are not exposed to levels that exceed permissible exposure limits for hazardous substances at the site
6. Development of a written emergency-response plan to handle anticipated emergencies prior to beginning of hazardous-waste operations
7. Additional requirements for the development and implementation of decontamination and materials-handling procedures and ensuring the presence of adequate illumination and sanitation facilities at the work site and that proper excavation procedures are followed

HAZARD PREVENTION AND CONTROL

Prevention Measures

The probability of exposure to hazardous waste can be reduced through preventive actions achieved through pre-incident planning, proper waste-handling, and storage-handling procedures. Preventive measures include the following:

1. Segregating chemically incompatible wastes, for example, by ensuring that combustible waste is separated from self-heating or oxidizing materials
2. Disposing of hazardous waste promptly so that large quantities are not allowed to accumulate at any one time
3. Storing combustible waste piles away from buildings, roadways, and ignition sources
4. Maintaining flammable and corrosive liquid wastes in approved metal containers
5. Inspecting hazardous-waste containers regularly to ensure their integrity
6. Properly identifying and marking waste containers. The hazards associated with each waste should be shown clearly on the exterior of each container, storage tank, transport vehicle, or building
7. Training personnel in proper waste-handling procedures, use of personal protective equipment, and emergency response measures to an accidental release of hazardous waste. Training should include drills simulating a variety of credible release scenarios

Emergency Response Planning

A fire department should coordinate and preplan its approach to the handling of hazardous-waste emergencies with all waste-generating industries or disposal facilities within its jurisdiction. The fire department should be aware of the types, quantities, and hazards of raw materials, products, and wastes stored at each plant site and those that are transported to and from the plant. The fire department should ensure the availability to its personnel of any necessary specialized handling equipment and materials, detection devices, and personal protective equipment.

In preparing fire-response plans, fire fighters should recognize that water used to control or extinguish fires at chemical plants or warehouses where hazardous materials are stored will itself likely become contaminated with these materials and may become a hazardous waste. If the contaminated water is allowed to reach natural bodies of water, such as through the rain-water drainage system, the hazard will spread outside the plant and may endanger the public and the environment. A good example of such an event is the fire that occurred in November 1986 at a warehouse for agricultural chemicals located along the Rhine River in Basel, Switzerland. The contaminated water resulted in a massive fish kill and a water-pollution problem that spread all the way to Germany and Holland.

It is very important that the fire department, together with plant personnel, predetermine the locations of storm-water drains and sewers and the general layout and slope of the land on which the plant is built. Plant personnel should invite fire department representatives for regular facility tours. Precautions must then be built into the emergency-response plan to ensure that fire-fighting water will not pollute natural water bodies or drinking-water supplies.

Response Procedures

The potential severity of an incident involving the release of a hazardous waste can be reduced through response measures developed and tested under realistic drill conditions. In the absence of emergency plans, or when the waste components are unknown, it should be assumed that an industrial waste could present any hazard and to treat it as an extreme hazard until more reliable information becomes available. In general, response procedures include the following:

1. Wearing full protective clothing and breathing apparatus
2. Using the appropriate detection devices to check for the flammability, toxicity, or radioactivity of the released waste or its products of combustion
3. Stemming the flow of the waste at the source
4. Diking the area around a liquid spill to limit its spread to sewage lines and drains and to reduce the vapor release rate
5. Staying upwind when vapors or fumes are being generated
6. Controlling ignition sources
7. Evacuating people who are downwind

The decision to extinguish burning waste should be made only after a full assessment of the consequences. Questions to be considered include the following:

1. Is the extinguishing agent to be used compatible with the waste?
2. Are sealed drums or containers of flammable liquids or compressed gases in danger of exposure to the fire?
3. Are there radioactive, explosive, or oxidizing materials in the burning waste or near the fire?

4. Will extinguishment exacerbate the problem by allowing flammable or toxic vapors to be released once the fire is extinguished?
5. Will the use of water result in a severe pollution problem?

SPECIFIC WASTES

Combustible Refuse

Highly combustible refuse, such as dry waste paper, excelsior, and so on, should be collected in metal containers and not allowed to accumulate in large quantities. Quantity storage of these materials should be separated from buildings, roadways, and ignition sources by a distance of 50 ft (15 m) or more. Transport to an incinerator, recycler, or landfill on a frequent schedule will minimize the fire hazard.

Drying Oils

Rags or paper that have absorbed drying-type oils, such as linseed oil or turpentine, are subject to spontaneous heating. To prevent fires they should be kept in well-covered metal cans and thoroughly dried before collection or transport.

Flammable Liquids and Waste Solvents

Waste solvents have variable flashpoints, depending on composition. Some contain solids, tars, waxes, and other materials that impede flow. Chlorinated solvents and water might also be present.

Common methods of disposal for these wastes are (1) incineration, (2) recycling, and (3) fuel blending. If a contractor is used, the approximate composition of the waste must be provided. Some contractors are able to recover reusable materials through distillation or other processes. Reuse of these materials reduces the demand for virgin materials and can help to protect the environment.

Locations having substantial amounts of waste solvent may choose to install their own solvent-recovery system or incinerator. For an incinerator, an auxiliary gas or oil burner is needed to maintain adequate destruction temperature. Usually a scrubber section is used to remove acid gases and other pollutants. See NFPA 82, *Standard on Incinerators and Waste and Linen Handling Systems and Equipment,* for further information on industrial incinerator installations.

Polychlorinated Biphenyls (PCBs)

PCBs were manufactured and used in a variety of electrical and mechanical applications from the early 1930s until regulated by the Toxic Substances Control Act in 1976. They had been extensively used as a dielectric fluid in capacitors and transformers and as a lubricant in compressors and other machinery. They continue to be used today, but only in enclosed systems.

PCBs can cause temporary skin irritations and nervous-system abnormalities in humans and are suspected carcinogens. Improper combustion of PCB-containing material can produce highly toxic and carcinogenic products.

Extreme care must be taken in handling PCBs and fires involving PCBs. Waste PCBs from old electrical equipment must be disposed of by incineration at an approved site, buried in an approved secure landfill, or other approved method.

Liquid and Solid Oxidizing Materials

Spilled oxidizing materials and leaking or broken containers should be immediately removed to a safe area to await disposal in conformance with applicable regulations and manufacturers' instructions (see NFPA 430, *Code for the Storage of Liquid and Solid Oxidizers*). Most, if not all, oxidizers can be rendered harmless by dilution with water.

Combustible and Reactive Metals

Small scraps of sodium from laboratory use can be dissolved in ethyl alcohol (not isopropyl alcohol) and the resulting alkoxide neutralized with acid. Large quantities may be offered to a vendor for purification and recycling. Oil-contaminated dispersions or other moderate quantities can be burned in dry pans if provision is made to control the oxide fumes, which are highly alkaline. Disposal of sodium by throwing it directly into water is spectacular but extremely hazardous and will contaminate the water with sodium hydroxide. Equipment contaminated with small amounts of sodium may be cleaned by a remotely controlled introduction of water or steam. Potassium, sodium-potassium alloy (NaK), and lithium are handled in the same manner as sodium. Lithium reacts somewhat less violently with water.

It is usually feasible to reclaim magnesium fines and scrap in the form of defective castings, clippings, and coarse chips. If this is to be done, either locally or through a smelting firm, the scrap should be thoroughly dried before remelting. Scrap in the form of fine chips and dust-collector sludge can be disposed of in a specially constructed incinerator or by burning in a safely located outdoor area paved with fire-brick or hard-burned paving brick. By spreading the scrap or sludge in a layer about 4 in. (102 mm) thick, on which ordinary combustible material is placed and ignited, the combustion of magnesium can be safely conducted. Another method of deactivating magnesium sludge is to treat it with a 0.5 percent solution of ferrous chloride. Since hydrogen is generated by this reaction, this method of disposal is conducted in an open container in an outdoor location where the hydrogen can safely dissipate. (See NFPA 484, *Standard for Combustible Metals.*)

Spontaneous combustion of titanium has occurred in fines, chips, and swarf that were coated with water-soluble oil. Disposal containers should be tightly closed and segregated so that if spontaneous burning occurs it will not involve other materials. Incineration in the open, as for magnesium scrap, might be feasible (see NFPA 484).

Whereas small amounts of zirconium fines can be mixed with sand or other inert material and buried, incineration of this combustible metal is generally preferred for larger quantities. Because of the spontaneous ignition potential, personnel carrying scrap should wear flame-protective clothing and equipment and carry the scrap in buckets on a yoke between them. A layer can be ignited with excelsior (see NFPA 484).

Lithium hydride and lithium aluminum hydride can ignite on contact with water or moist air. Alkaline oxides resulting from incineration can be collected and neutralized.

Radioactive Waste

Radioactive waste is generated at nuclear power plants in the form of spent fuel and contaminated instruments, equipment, piping, and other objects such as clothing, gloves, and cleaning rags. Other sources include nuclear physics research laboratories and tailings from uranium mines.

Recent advances in the use of radioactive materials in medical diagnostics and therapy has led to an increase in the sources of radioactive medical waste. Radioactive isotopes of iodine, cesium, iridium, phosphorus, and gallium are widely used in hospitals and laboratories for diagnostics and patient treatments. Contaminated vials, containers, and capsules are growing in quantity. All radioactively contaminated materials must be properly disposed of.

The packaging of all radioactive waste, including radioactive medical waste, is regulated by the Nuclear Regulatory Commission (NRC) and DOT regulates transportation of all radioactive waste. The EPA has developed standards for protecting the public against exposure to nuclear-reactor wastes in general and for the proper storage and disposal of such waste. The specific requirements vary greatly and depend on the type of radioactive waste that is generated.

For most installations, a contractor licensed to dispose of radioactive materials can be employed. (See NFPA 801, *Standard for Fire Protection for Facilities Handling Radioactive Materials.*) Radioactive materials that are flammable or combustible must be handled with particular care. Combustible radioactive wastes should not be allowed to accumulate. Storage of such wastes near an air intake is particularly undesirable. If the products of combustion of waste materials containing long-lived radioactive materials are dispersed through air-conditioning or compressed-air systems, extensive decontamination might become necessary.

Liquid radioactive waste can be concentrated and retained until the radioactivity has decayed to a safe level. Combustible radioactive waste, such as absorbent paper used to wipe contaminated surfaces, should be placed in approved containers for disposal.

The treatment of radioactive medical wastes is less extensive than that for other medical wastes. For radioactive medical waste with a half-life of less than 65 days, the waste may be stored in a secure area for a minimum period of 10 half-lives and discarded as sanitary wastes. Most "spent" or used nuclear fuel is currently being stored in specially designed deep pools of water at nuclear reactor sites.[15] Some radioactive military waste is being stored at federal reservations aboveground in heavy, thick-walled metal or concrete structures. All of these storage facilities are temporary. In 1982 the Office of Civilian Radioactive Waste Management was charged by Congress to develop a mined geologic repository for the disposal of these wastes. Although there is movement to prepare the Yucca Mountain, Nevada, site to receive and store spent nuclear reactor fuel, as of 2006, no permanent site had been established.

Oil Spills on Water

Using booms is effective in containing spills of oil and other floating liquids on relatively calm and current-free waters. Makeshift designs of booms are relatively ineffective, but commercially available booms designed for the hydrodynamics and aerodynamics involved in the confinement of spills on water can be quite effective. Because of ecological considerations, this has become an important means of containing an oil spill and more effective equipment continues to be developed.

Following the confinement of spills on water, various ways of removing the confined liquid are used, including skimming devices or absorbents. Absorbents, such as straw, plastics, sawdust, peat moss, and commercially available products have been spread on the surface of the spill and then collected and disposed of on shore. Skimming devices operate on several principles, including pumps and separators. Power boats with skimmers on the bow can scoop up oil and water, sending it through an oil separator and rollers to which oil adheres. The oil is then removed by scraping or compression.

Sinking agents to which oil adheres and sinks to the bottom have been used in the past. Several proprietary sinking agents have been developed, but such products as carbonized sand, brick dust, crushed clinkers, and cement also have been used. However, sinking agents are objectionable because they contribute to water pollution and should not be used, except possibly in the ocean far from land.

Regardless of whether a spill occurs on land or on water, pre-incident planning is imperative. Planning should include prompt notification of all appropriate local, state, or federal agencies dealing with water pollution.

Underground Storage Tanks

Before implementing more restrictive requirements EPA estimated there were more than two million underground-storage-tank (UST) systems in the United States located at more than 700,000 operating facilities nationwide.[16] Today EPA estimates that number has been greatly reduced by removal of existing tanks. In addition, there are numerous retired-in-place tanks. Although most of these tanks are (or were) used for the storage of motor and other fuels, many are (or were) used for the storage of other hazardous chemicals.

Liquid leaks from underground tanks can readily find their way to groundwater. Leaking petroleum products also contaminate the soil and the air. Their vapors can accumulate in confined spaces, such as septic tanks, sewers, and building basements. The vapors are hazardous to human health. If ignited, they can result in a fire or an explosion.

To protect the public and the environment against leaks from USTs, the federal government extended and strengthened the provisions of the Solid Waste Disposal Act as amended by RCRA. Subtitle I of RCRA regulates USTs containing "regulated substances" and releases of these substances to the environment.

Subtitle I defined a UST as a tank system, including its piping, that has at least 10 percent of its volume underground. Regulated substances include those defined as hazardous under CERCLA as well as petroleum products. This standard requires USTs installed after 1988 to be built to certain specifications, certified, equipped with overfill protection and detection systems, and, if made of steel, protected against corrosion. By 1998, all existing USTs had to have corrosion protection for steel tanks and piping, and devices to prevent overfilling.

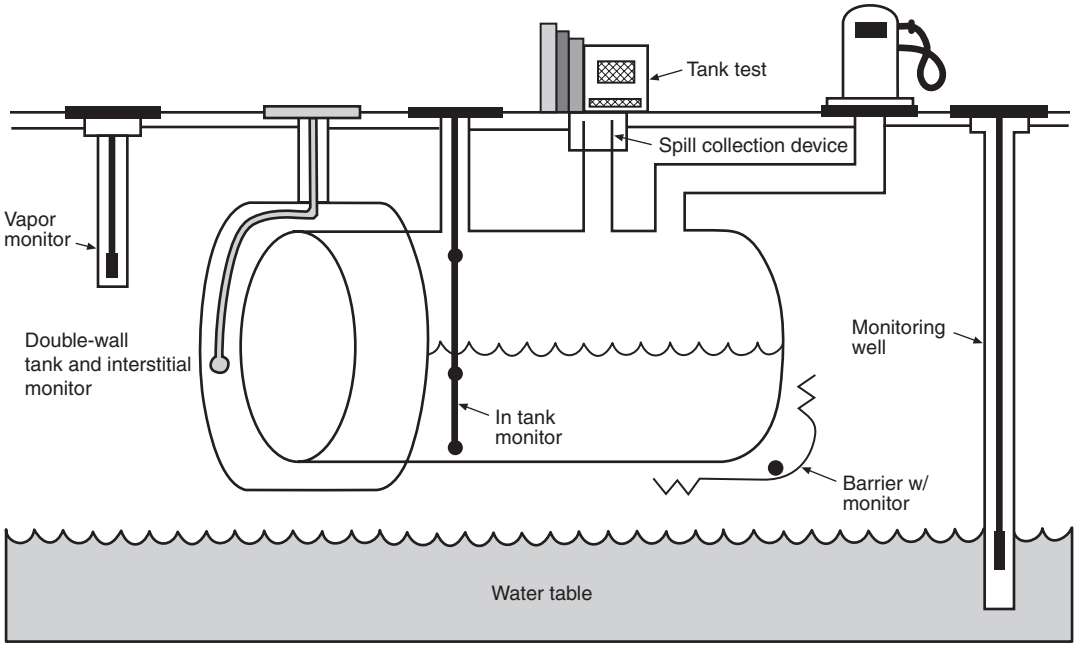

FIGURE 7.5.6 UST Leak Detection Alternatives

Existing tanks must also be tested for leaks in accordance with a schedule determined by their age[17] (Figure 7.5.6).

USTs must have at least one (or a combination) of the following leak monitoring methods:[18]

- Automatic tank gauging
- Monitoring for vapor in the soil
- Interstitial monitoring between the inner and outer walls of the tank (double wall)
- Monitoring for the presence of contaminants in groundwater

SUMMARY

Waste is a by-product of many human activities. The source of the waste—whether domestic, commercial, industrial, transportation, or storage—determines its composition, its degree of hazard, and how it should be safely handled and disposed of. An emphasis today is placed on reducing the amount of waste generated, as well as reusing or recycling the waste material. These options should be attempted before deciding to dispose of the waste.

A large fraction of solid waste, including most domestic, commercial, and industrial trash, is combustible, with an ever increasing amount being recovered. Most nonhazardous solid waste is discarded in sanitary landfills, although a substantial amount is burned for fuel. Hazardous solid waste, however, must be chemically treated, incinerated in properly designed furnaces, or disposed of in secure landfills. Liquid waste, which includes aqueous and nonaqueous solutions and suspensions, can sometimes be reduced by various process modifications (e.g., neutralization, sedimentation, adsorption, distillation, reformulation), depending on the nature of the material. Gaseous waste can be purified through chemical conversion, absorption, adsorption, particulate removal, or incineration.

Standards regarding hazardous medical waste generally require the reporting, record keeping, and tracking of this special category of waste. Prevention and control of hazardous waste include taking preventive measures such as following proper waste- and storage-handling procedures and having a rehearsed written emergency response plan and proper equipment in place, should a release occur.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on hazardous waste control discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 40, *Standard for the Storage and Handling of Cellulose Nitrate Film*
NFPA 55, *Standard for the Storage, Use, and Handling of Compressed and Liquefied Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks*
NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities*
NFPA 82, *Standard on Incinerators and Waste and Linen Handling Systems and Equipment*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 329, *Recommended Practice for Handling Releases of Flammable and Combustible Liquids and Gases*
NFPA 430, *Code for the Storage of Liquid and Solid Oxidizers*
NFPA 434, *Code for the Storage of Pesticides*
NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents*
NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents*
NFPA 484, *Standard for Combustible Metals*
NFPA 490, *Code for the Storage of Ammonium Nitrate*
NFPA 495, *Explosive Materials Code*
NFPA 498, *Standard for Safe Havens and Interchange Lots for Vehicles Transporting Explosives*
NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*
NFPA 655, *Standard for Prevention of Sulfur Fires and Explosions*
NFPA 664, *Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities*
NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*
NFPA 801, *Standard for Fire Protection for Facilities Handling Radioactive Materials*

SECTION

8

Special Equipment

L. Jeffrey Mattern

8.1 Air-Moving Equipment
8.2 Chemical Processing Equipment
8.3 Materials-Handling Equipment
8.4 Automated Equipment
8.5 Lasers
8.6 Protection of Electronic Equipment
8.7 Heat Transfer Systems and Fluids
8.8 Industrial and Commercial Heat Utilization Equipment
8.9 Oil Quenching and Molten Salt Baths
8.10 Stationary Combustion Engines and Fuel Cells
8.11 Fluid Power Systems
8.12 Refrigeration Systems
8.13 Electrical Systems and Appliances

Continuity of business operations are extremely important in a competitive environment. Unnecessary fires negatively affect a corporate business plan. This section reviews the hazards, prevention, and suppression concepts for equipment commonly associated with industrial operations, with additional, but more limited, coverage of other occupancy classifications. Many fires in industry occur due to inadequate fire prevention and control for specialized equipment. This section strives to identify basic design, fire prevention, and fire control concepts which will help prevent and mitigate fires. Approximately half of the section concentrates on a particular manufacturing or commercial process, and half focuses on the hazards of a specific manufacturing operation.

Chapter 1, "Air-Moving Equipment"; Chapter 3, "Materials-Handling Equipment"; Chapter 7, "Heat Transfer Systems and Fluids"; Chapter 10, "Stationary Combustion Engines and Fuel Cells"; Chapter 11, "Fluid Power Systems"; Chapter 12, "Refrigeration Systems"; and Chapter 13, "Electrical Systems and Appliances," are all chapters covering equipment or operations that support manufacturing or commercial processes. Each chapter details the nature of the operation and the associated hazards along with the fundamental fire prevention and fire control concepts.

Additional chapters in this section, including Chapter 2, "Chemical Processing Equipment"; Chapter 4, "Automated Equipment"; Chapter 5, "Lasers"; Chapter 6, "Protection of Electronic Equipment"; Chapter 8, "Industrial and Commercial Heat Utilization Equipment"; and Chapter 9, "Oil Quenching and Molten Salt Baths," deal with specific manufacturing operations. These chapters emphasize the hazards associated with these processes and how to prevent or mitigate a significant fire.

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Chapter 1

Air-Moving Equipment

Jane I. Lataille

Chapter Contents

Components of Air-Moving Systems
Hazards of Specific Uses
Fire Protection

Key Terms

air-moving device (AMD), collecting equipment, duct, duct system, dust collection system, exhaust system, gas, mist, particulate, restaurant-type cooking equipment, separating equipment, smoke control, smoke management, vapor, vapor (corrosive), vapor (flammable), ventilation, venting

Many industrial and commercial operations require the removal of airborne materials that are generated by normal processes. These materials could include vapors, gases, and particulate solids. Some facilities also require emergency smoke control or smoke management systems. Properly designed air-moving equipment can serve either of these purposes. These air-moving systems are in addition to the normal building systems for heating, ventilating, and air conditioning. NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems,* covers those systems. Also see Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems," and Table 8.1.1.

Air-moving equipment for use during normal operations is addressed in NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids,* and NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids.* NFPA 91 covers air-moving equipment for vapors, gases, mists, and noncombustible particulate solids and includes the following:

- Specifies that concentration of combustible vapors not exceed 25 percent LEL
- Contains requirements for duct construction and clearance
- Identifies where fire dampers must be provided
- Describes protection by special extinguishing systems with provision of adequate drainage for system discharge
- Requires inspection, testing, and maintenance of the air-moving system and its protective features

NFPA 654 covers air-moving equipment for combustible particulate solids. It contains applicable material from NFPA 650, which has been withdrawn, and includes guidance on preventing fires and explosions in this equipment.

Other codes and standards also apply to air-moving equipment for specific materials or operations (Table 8.1.2).

NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences,* covers smoke control systems; NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces,* covers smoke management systems for large spaces; and NFPA 204, *Standard for Smoke and Heat Venting,* covers heat and smoke venting.

Air-moving systems play an important role in fire protection. If the materials they remove were allowed to accumulate, the result could be an explosion from vapor-air mixtures, a flash fire due to accumulations of lint or other combustibles, and generally poor housekeeping conditions conducive to fires in general.

Additional information about hazards of air-moving equipment can be found in Section 6, Chapter 1, "Fire Hazards of Materials"; Section 8, Chapter 2, "Chemical Processing Equipment"; Section 8, Chapter 8, "Industrial and Commercial Heat Utilization Equipment"; Section 9, Chapter 1, "Woodworking Facilities and Processes"; Section 9, Chapter 5, "Metalworking Processes"; Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems"; Section 10, Chapter 5, "Ventilation of Commercial Cooking Operations"; and Section 11, Chapter 5, "Control of Electrostatic Ignition Sources."

Jane I. Lataille, P.E., ARM, has over 30 years experience working in fire protection and loss prevention.

TABLE 8.1.1 General Air-Moving Systems and Relevant NFPA Code or Standard

System	*NFPA Code or Standard*
Combustible particulate solids	NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*
Heat and smoke venting	NFPA 204, *Standard for Smoke and Heat Venting*
Normal building HVAC	NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
Smoke control	NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
Smoke management in large spaces	NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*
Vapors, gases, mists	NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*

TABLE 8.1.2 Materials/Operations and Relevant NFPA Code or Standard

Material or Operation	*NFPA Code or Standard*
Agricultural dusts	NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Products Facilities*
Combustible metals	NFPA 484, *Standard for Combustible Metals*
Cooking appliances	NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations*
Health care	NFPA 99, *Standard for Health Care Facilities*
Laboratories	NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals*
Ovens	NFPA 86, *Standard for Ovens and Furnaces*
Semiconductors	NFPA 318, *Standard for the Protection of Semiconductor Fabrication Facilities*
Spraying/dipping operations	NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials* NFPA 34, *Standard for Dipping and Coating Processes Using Flammable or Combustible Liquids*
Woodworking	NFPA 664, *Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities*

COMPONENTS OF AIR-MOVING SYSTEMS

Air-moving equipment includes all mechanical-draft duct systems, of both the pressure and exhaust types, for removal of dusts, vapors, and waste material, and for the conveying of materials. The hazards of such systems lie in the possibility of igniting flammable materials or vapors by sources such as sparks generated by fans or foreign material, for example, tramp metal, or by overheated fan bearings. Also, such systems could inadvertently spread fires through the building. Tables 8.1.3 through 8.1.10 describe patterns of fires originating in ducts, separating homes from other structures. Note that many fires originate not in materials being conveyed into or through ducts, but rather in elements that are installed in or near ducts, such as insulation, wiring or cables, and structural members. Note also the role of torch operations in starting fires in ducts.

Air-moving systems usually contain axial flow fans or centrifugal blowers; several different designs of each kind are available (Figure 8.1.1). A straight-blade centrifugal fan is suitable for exhausting materials containing large particles, because it resists clogging and the blades can withstand considerable abra-

TABLE 8.1.3 Structure Fires Other Than Homes Originating in Duct as Area of Origin, by Item First Ignited, 1999–2003 Annual Average

Item First Ignited	*Fires*	*Percentage*
Dust, fiber, or lint	280	25
Electrical wire or cable insulation	140	13
Unclassified item first ignited	140	13
Cooking materials	70	6
Rubbish, trash, or waste	60	6
Insulation within structural area	60	5
Flammable or combustible liquid or gas	30	3
Structural member or framing	30	3
Pipe, duct, conduit, or hose	20	2
Agricultural crop, including fruits and vegetables	20	2
Conveyor belt, drive belt, or V-belt	20	2
Multiple items first ignited	20	2
Filter, including evaporative cooler pads	20	2
Exterior roof covering	20	2
Interior ceiling covering	20	2
Unclassified structural component or finish	20	2
Other known item first ignited	160	14
Total	1130	100

Notes: These are national estimates of fires reported to U.S. municipal fire departments, excluding fires reported as confined fires, and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Fires are estimated to the nearest ten and reflect a proportional share of fires with unknown or unreported area of origin and duct fires with equipment involved in ignition unknown or unreported.

Source: NFIRS and NFPA survey.

TABLE 8.1.4 Home Structure Fires Originating in Duct as Area of Origin, by Item First Ignited, 1999–2003 Annual Average

Item First Ignited	*Fires*	*Percentage*
Electrical wire or cable insulation	170	20
Structural member or framing	120	14
Dust, fiber, or lint	110	13
Unclassified item first ignited	70	8
Insulation within structural area	60	7
Exterior wall covering or finish	30	3
Appliance housing or casing	30	3
Rubbish, trash, or waste	20	3
Flammable or combustible liquid or gas	20	3
Unclassified structural component or finish	20	3
Interior wall covering excluding drapes	20	3
Pipe, duct, conduit, or hose	20	2
Other known item first ignited	170	20
Total	860	100

Notes: These are national estimates of fires reported to U.S. municipal fire departments, excluding fires reported as confined fires, and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Fires are estimated to the nearest ten and reflect a proportional share of fires with unknown or unreported area of origin and duct fires with item first ignited unknown or unreported.

Source: NFIRS and NFPA survey.

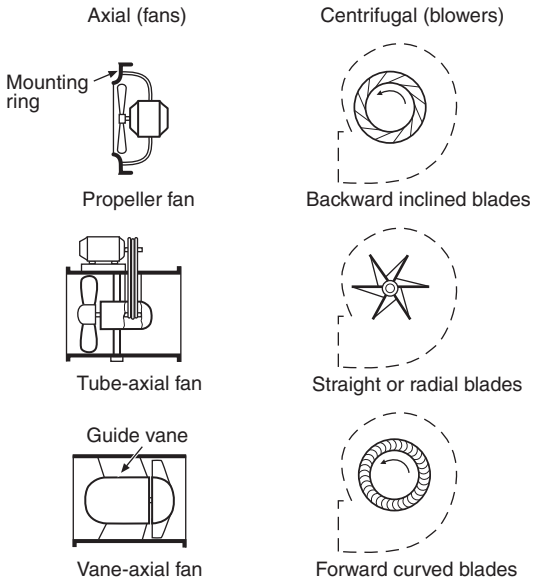


FIGURE 8.1.1 Fan and Blower Designs Suitable for Use in Exhaust Systems

sion. Propeller fans will move large volumes of air, but only against small resistance. Because these fans could not operate efficiently against the friction a duct would introduce, they are not suitable for ducts of any appreciable length.

TABLE 8.1.5 Structure Fires Other Than Homes Originating in Duct as Area of Origin, Excluding Fires Where Item First Ignited Is Organic or General Material, by Type of Material First Ignited, 1999–2003 Annual Average

Type of Material First Ignited	*Fires*	*Percentage*
Unclassified type of material	80	18
Plastic	50	10
Sawn wood	40	9
Cotton, wool, or rayon fabric or fiber	40	9
Unclassified wood or paper	20	5
Paper	20	4
Cooking oil or transformer or lubricating oil	20	4
Fiberboard, particleboard, or hardboard	20	4
Multiple types of material	20	4
Plywood	10	3
Wood chips, sawdust, or shavings	10	3
Fat, grease, butter, margarine, or lard	10	2
Unclassified fabric, textile, or fur	10	2
Natural gas	10	2
Other known type of material	100	22
Total	470	100

Notes: These are national estimates of fires reported to U.S. municipal fire departments, excluding fires reported as confined fires, and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Fires are estimated to the nearest ten and reflect a proportional share of fires with unknown or unreported area of origin and duct fires with the indicated items first ignited that have type of material first ignited unknown or unreported. Beginning in 1999, type of material first ignited is not required when item first ignited is organic material (e.g., cooking materials) or general material (e.g., electrical wire or cable insulation; papers; dust, fiber or lint; rubbish, trash or waste); these items first ignited are excluded from the calculations.

Source: NFIRS and NFPA survey.

To reduce the hazard of fire, fans should be (1) of noncombustible construction, (2) able to be shut down by remote control in case of fire, (3) accessible for maintenance, and (4) structurally sound enough to resist wear and overcome distortion and misalignment caused by structural weakness or overloading. Fans used for heat and smoke venting should be able to withstand temperatures of 932°F (500°C) for 4 hours. Construction materials for all fans must be appropriate for the intended use. A spark caused by a blade hitting the housing, due to distortion or misalignment, could result in ignition when the exhaust contains flammable solids or vapors. This possibility of friction sparks is minimized if the fan and fan housing are of nonsparking material. Aluminum and magnesium alloys are not compatible with ferrous alloys, which can rust.

Components of smoke control and smoke management systems have additional requirements, including the following:

- Reliability of power source(s) under fire conditions
- Arrangement of power feeds to remain in service when facility power is shut down
- Integrity of controls and wiring under fire conditions

TABLE 8.1.6 Home Structure Fires Originating in Duct as Area of Origin, Excluding Fires Where Item First Ignited Is Organic or General Material, by Type of Material First Ignited, 1999–2003 Annual Average

Type of Material First Ignited	*Fires*	*Percentage*
Sawn wood	140	28
Unclassified type of material	70	14
Plastic	50	11
Cotton, wool, or rayon fabric or fiber	40	7
Unclassified wood or paper	30	6
Plywood	30	5
Multiple types of material	20	5
Fiberboard, particleboard, or hardboard	20	4
Natural gas	20	3
Kerosene or No. 1 or 2 fuel oil	10	2
Paper	10	2
Other known type of material	60	12
Total	490	100

Notes: These are national estimates of fires reported to U.S. municipal fire departments, excluding fires reported as confined fires, and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Fires are estimated to the nearest ten and reflect a proportional share of fires with unknown or unreported area of origin and duct fires with the indicated items first ignited that have type of material first ignited unknown or unreported. Beginning in 1999, type of material first ignited is not required when item first ignited is organic material (e.g., cooking materials) or general material (e.g., electrical wire or cable insulation; papers; dust, fiber or lint; rubbish, trash or waste); these items first ignited are excluded from the calculations.

Source: NFIRS and NFPA survey.

TABLE 8.1.7 Structure Fires Other Than Homes Originating in Duct as Area of Origin, by Equipment Involved in Ignition, 1999–2003 Annual Average

Equipment Involved in Ignition	*Fires*	*Percentage*
No equipment involved	220	19
Torch, burner, or soldering equipment	110	9
Unclassified or unknown-type heating, ventilating, or air conditioning	90	8
Air conditioner	90	8
Shop or industrial equipment	90	8
Central heating unit furnace	80	7
Clothes dryer	50	5
Grease hood or duct exhaust fan	50	4
Industrial furnace or kiln	30	3
Steamline, heat pipe, or hot air duct	30	2
Extractor or waste recovery machine	30	2
Unclassified equipment involved in ignition	30	2
Fixed space heater	20	2
Fan	20	2
Separate motor	20	2
Other known equipment involved in ignition	180	16
Total	1130	100

Notes: These are national estimates of fires reported to U.S. municipal fire departments, excluding fires reported as confined fires, and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Fires are estimated to the nearest ten and reflect a proportional share of fires with unknown or unreported area of origin and duct fires with equipment involved in ignition unknown or unreported.

Source: NFIRS and NFPA survey.

- Equipment materials and construction that will withstand fire conditions
- Supervision of condition/status of system
- Ability to handle expected pressure differentials

Design of smoke control and smoke management systems depends on the occupancy and layout of the facility, whether air pressure or airflow is used to control smoke movement, and whether the system is dedicated or nondedicated.

HAZARDS OF SPECIFIC USES

Ventilation of Flammable Vapors

Because flammable vapors ignite easily, precautions must be taken to eliminate ignition sources in ducts that carry them. Using a single system to exhaust flammable vapors and particles from spark-producing processes is obviously dangerous. Similarly, drawing different vapors that individually may not be flammable, but that may be hazardous as a mixture in a single exhaust system, is extremely poor practice. For example, perchloric acid acts as an oxidizing agent at elevated temperatures. If perchloric acid vapors were drawn into a system exhausting organic materials, the combination could cause a fire or explosion.

It is important that vapors be withdrawn from the rooms or equipment in which they are generated and taken directly to the outside of the building or to suitably protected pollution-control equipment. Processes generating flammable vapors are best located along an outside wall of the building to facilitate efficient vapor removal.

When flammable vapors cannot readily be picked up at a specific source, general ventilation through a system of suction ducts with inlets to the room or area may be used. Because suction inlets have minimal directional effect beyond a few inches (1 in. equals 25.4 mm) from the face of the inlet, they should be located so that they produce a sweeping or purging effect that will eliminate pockets in which vapors may accumulate. A makeup air supply, properly located in relation to the point where vapors are generated, and openings for exhaust ducts will aid in the dilution and removal of vapors. The ventilation system should provide sufficient air movement to maintain the vapor concentration below 25 percent of the lower flammable limit (LFL) in the area where vapors are being liberated. If vapors are toxic, it may be necessary to maintain concentrations well below those required for flammability.

NFPA 86, *Standard for Ovens and Furnaces,* gives procedures for calculating the volume of air per minute necessary to dilute flammable vapors below their LFL.

TABLE 8.1.8 Home Structure Fires Originating in Duct as Area of Origin, by Equipment Involved in Ignition, 1999–2003 Annual Average

Equipment Involved in Ignition	*Fires*	*Percentage*
No equipment involved	230	26
Central heating unit furnace	180	21
Unclassified or unknown-type heating, ventilating, or air conditioning	80	10
Air conditioner	80	9
Clothes dryer	50	6
Fixed space heater	50	6
Fireplace	30	4
Fan	20	2
Unclassified electrical wiring	10	2
Chimney	10	1
Steamline, heat pipe, or hot air duct	10	1
Water heater	10	1
Grease hood or duct exhaust fan	10	1
Other known equipment involved in ignition	80	9
Total	860	100

Notes: These are national estimates of fires reported to U.S. municipal fire departments, excluding fires reported as confined fires, and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Fires are estimated to the nearest ten and reflect a proportional share of fires with unknown or unreported area of origin and duct fires with equipment involved in ignition unknown or unreported.

Source: NFIRS and NFPA survey.

TABLE 8.1.9 Structure Fires Other Than Homes Originating in Duct as Area of Origin, by Heat Source, 1999–2003 Annual Average

Heat Source	*Fires*	*Percentage*
Radiated or conducted heat from operating equipment	300	27
Spark, ember, or flame from operating equipment	180	16
Unclassified heat from powered equipment	180	16
Arcing	120	11
Heat or spark from friction	70	6
Unclassified hot or smoldering object	60	5
Unclassified heat source	40	4
Unclassified heat from other open flame or smoking materials	40	3
Hot ember or ash	30	2
Lighted tobacco product	30	2
Molten or hot material	20	2
Other known heat source	60	5
Total	1130	100

Notes: These are national estimates of fires reported to U.S. municipal fire departments, excluding fires reported as confined fires, and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Fires are estimated to the nearest ten and reflect a proportional share of fires with unknown or unreported area of origin and duct fires with heat source unknown or unreported.

Source: NFIRS and NFPA survey.

Where heavier-than-air vapors or mixtures are handled, exhaust openings located near the floor line are generally the most effective. Conversely, for vapors or mixtures lighter than air, exhaust openings located near the top of the room, hood, or enclosure are the most effective. Adjusting the vapor density is necessary for unusual temperatures and pressures.

Fans. All fans should be suitable for moving vapors and air. If the vapor contains a material that could condense and build up on the fan blades, this possibility should be minimized by selecting a fan with backward curved blades. Both the fan and the fan housing should be of nonferrous construction. The construction material chosen should not be adversely affected by the vapors handled.

Ducts. Ducts for systems handling flammable vapors need to be structurally capable of withstanding some fire exposure. Where vapors can condense, continuously welded joints in the ducts will prevent leakage.

Because flash fires or explosions can occur in ducts, ductwork should be installed away from combustibles, but where it will be readily accessible. Ducts should never be concealed in a wall or ceiling. Duct systems that exhaust flammable materials should terminate outside in an area where the vapors cannot be ignited and where they will not form deposits, such as overspray residue, on the building or other structures. An enclosure is sometimes used around the discharge end of a duct to prevent deposits on exposed property. These enclosures should be sprinklered.

Frequent cleaning of ducts, filters, and any enclosures will minimize both the intensity of a fire in a duct system and any spontaneous heating of deposits subject to this phenomenon.

Electrical Equipment. All equipment that may be exposed to flammable vapors should comply with NFPA 70, *National Electrical Code*®, for such hazardous locations.

Ventilation of Corrosive Vapors and Fumes

The degree of expected corrosion is the governing factor in the construction of ducts exhausting corrosive vapors. In some cases, a heavier-gauge metal is used, and in others, protective coatings may be sufficient. Occasionally, however, the corrosiveness is so extreme that a special lining is required. Stainless steel has been used very successfully in some cases.

Plastic duct systems are also used, but only if the corrosive vapors are nonflammable and the plastic has a flame-spread rating of 25 or less and a smoke-developed rating of 50 or less, when tested in accordance with NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials.*

TABLE 8.1.10 Home Structure Fires Originating in Duct as Area of Origin, by Heat Source, 1999–2003 Annual Average

Heat Source	*Fires*	*Percentage*
Radiated or conducted heat from operating equipment	240	28
Unclassified heat from powered equipment	160	18
Arcing	140	16
Spark, ember, or flame from operating equipment	90	11
Unclassified hot or smoldering object	50	6
Hot ember or ash	40	5
Unclassified heat source	40	4
Lightning	20	3
Unclassified heat from open flame or smoking materials	20	2
Match or lighter	10	1
Heat or spark from friction	10	1
Lighted tobacco product	10	1
Molten or hot material	10	1
Other known heat source	20	3
Total	860	100

Notes: These are national estimates of fires reported to U.S. municipal fire departments, excluding fires reported as confined fires, and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Fires are estimated to the nearest ten and reflect a proportional share of fires with unknown or unreported area of origin and duct fires with heat source unknown or unreported.

Source: NFIRS and NFPA survey.

Automatic fire protection is necessary in the ducts and also at the hood, canopy, or intake to plastic duct systems. Figures 8.1.2 and 8.1.3 show typical exhaust systems.

Ventilation of Restaurant-Type Cooking Equipment

Exhaust systems for restaurant equipment require careful design, because grease condenses in the interior of the ducts. Grease accumulations may be ignited by sparks from the cooking appliance or by a small fire on the cooking appliance caused by overheated cooking oil or fat in a deep-fat fryer or on a grill. If the duct did not have a grease accumulation, cooking appliance fires could often be extinguished before causing appreciable damage. Fire risk is especially high in frying because cooking oils and fats are heated nearly to their flashpoints. Thus, fats and oils can reach their self-ignition temperatures by being inadvertently overheated or by being ignited when spilled on a cooking appliance. Details of a typical kitchen range exhaust system are shown in Figure 8.1.4. The duct riser shown in Figure 8.1.4 should either be outside or be enclosed in an approved fireproof material.

Fans. Fans should be selected according to their ability to exhaust the required quantity of air against all calculated friction losses.

Ducts. The following should be considered when designing a duct system for commercial cooking equipment:

- The system should be designed to minimize grease accumulations, with a minimum air velocity of 1500 ft/min (458 m/min) through any duct.
- Ducts should be arranged with ample clearance from combustible materials to minimize the danger of ignition, in case of fire in the duct.
- Ducts of substantial construction (not lighter than No. 16 Manufacturers Standard Gauge steel or No. 18 Manufacturers Standard Gauge stainless steel) should be used with all seams and joints having a liquid-tight, continuous weld.
- Systems should be separated to ensure there is no connection with any other ventilating or exhaust system.
- Ducts should be led directly outside the building, without dips or traps, unless automatic grease removers are employed at the dips and traps.
- Openings should be provided for inspection and cleaning. Dampers should not be installed in any duct system, unless required as part of a grease extractor or extinguishing system.

Grease-Removal Devices. All kitchen exhaust systems require a means for removing grease. These may be grease extractors, grease filters, or other grease-removal devices, such as water-wash systems and special fans designed to remove grease vapors effectively and provide a fire barrier. Grease filters should be listed for use in commercial cooking operations. Mesh filters should not be used.

Electrical Equipment. Manual control of the fan motor should be provided near the motor and also near the hood. In addition, it is desirable to have automatic shutdown of the motor by a heat-sensitive device in the hood close to the outlet.

All electrical equipment that may be exposed to vapors, grease, or heat should be installed in accordance with NFPA 70 requirements for those conditions. Fixtures should not be installed in ducts or hoods used for removal of cooking smoke or grease-laden vapors or located in the path of travel of such exhaust products, unless they are specifically designed and tested for such use. Electrical equipment may be placed outside the path of vapor travel by locating it on the outside of the hood with illumination through tight-fitting glass panels in the hood.

Dust Collecting and Stock and Refuse Conveying Systems

These systems consist of suction ducts and inlets, air-moving equipment, feeders, discharge ducts and outlets, collecting equipment, vaults, and other receptacles designed to collect powdered, ground, or finely divided material.

Collecting and conveying systems are often a very important part of the operations of a plant. When the material they handle is a combustible dust, there is danger of a fire or explosion.

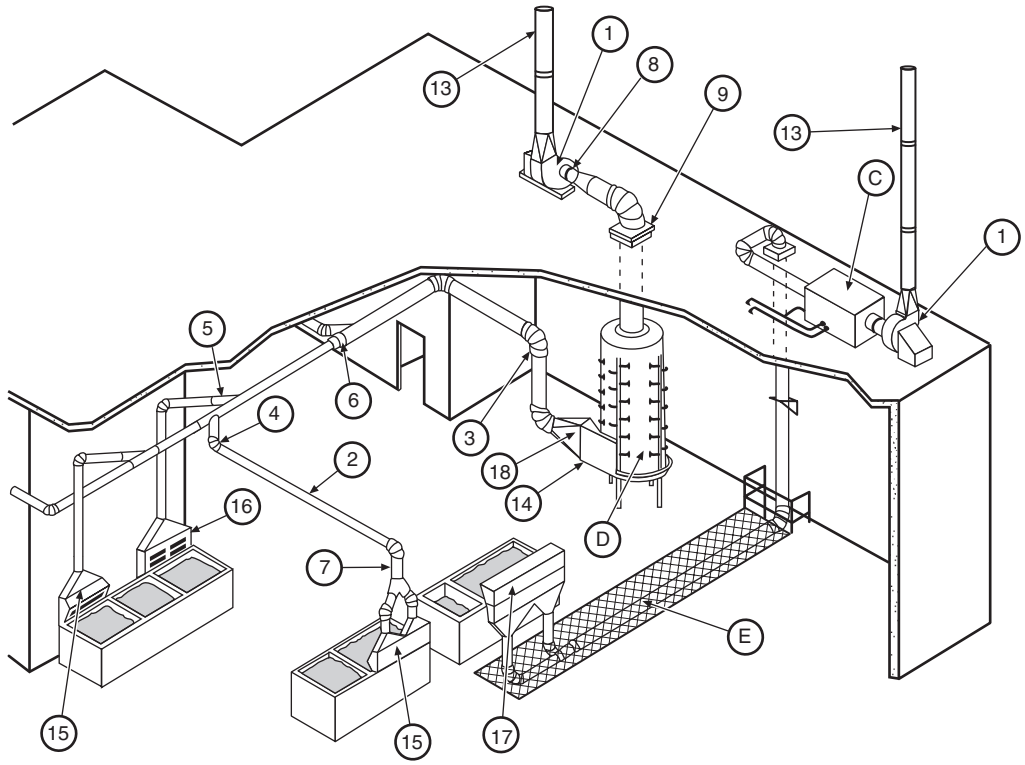
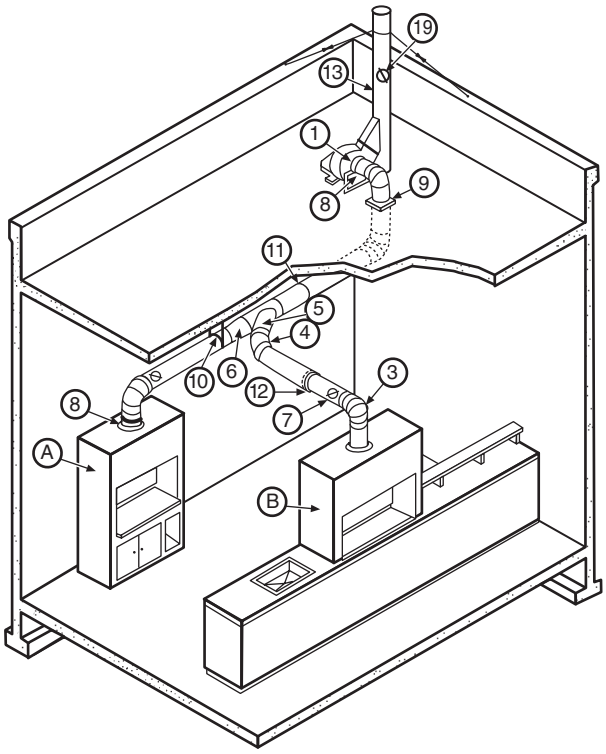


FIGURE 8.1.2 Industrial Exhaust System for Fume Hoods with Vertical Fume Scrubber and Service Trench



Nomenclature for Figures 8.1.2 and 8.1.3:

I. Equipment
- A. Cabinet-type fume hood
- B. Bench-type fume hood
- C. Horizontal-type fume scrubber
- D. Vertical-type fume scrubber
- E. Service pit or trench

II. System components
1. Air-moving equipment (centrifugal-type exhaust fan)
2. Horizontal duct section
3. 90-degree elbow
4. Elbow (less than 90 degrees)
5. Lateral entry
6. Transition
7. Manual balancing damper
8. Flexible connection
9. Counterflashing
10. Duct hanger
11. Circumferential girth joint (butt welded)
12. Bell end duct seam
13. Fan discharge stack
14. Flanged duct connection
15. Open-face tank exhaust hood (updraft)
16. Slotted-face tank exhaust hood (updraft)
17. Open-face tank exhaust hood (downdraft)
18. Round to rectangular (or square) transitional fitting
19. Gravity-operated backdraft damper

FIGURE 8.1.3 Laboratory Exhaust System for Cabinet-Type Fume Hoods and Bench-Type Fume Hoods

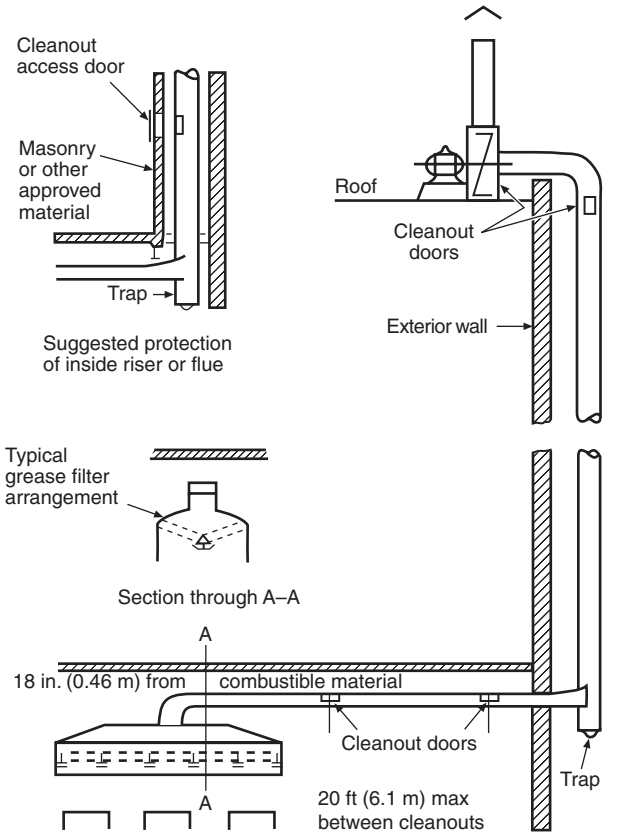


FIGURE 8.1.4 Typical Commercial Cooking Exhaust System for Building with Two Stories or More

These factors make it a prime necessity that the design, construction, and operation of the systems conform to recognized standards. The general recommendations given in the first part of this chapter should be observed, as should the following more specific ones.

Fans. Systems conveying combustible dust should be arranged so that the fan is on the clean air side of the collector, so that the system operates under suction, and dust collecting equipment removes the dust before the air stream reaches the fan. This arrangement prevents combustible dust from passing through the fan where it may be ignited. If such an arrangement is not possible and the fan must be located between the dust-producing equipment and the collector, the blades and spider of the fan and the fan housing should be made of nonsparking material, with ample clearance between the blades and the housing. Fan bearings and motors should be outside of casings unless the fan and motor assembly are designed and tested for use in the dust atmosphere present.

Ducts. For conveying dusts or stock, ducts should be constructed of metal. Changes in direction in the duct system should be made with long bends or elbows. This minimizes accumulations of solid particles at the turns.

Following are some general design techniques recommended for ducts conveying dusts and other solid materials:

- Every duct should be kept open and unobstructed throughout its length.
- Not more than two branches should connect to any section of the main suction duct.
- Branch ducts should be connected to the top or side of the main duct at an angle not exceeding 45 degrees, inclined in the direction of airflow.
- Main suction and discharge ducts should be as short as possible.
- Flexible duct sections should not restrict airflow and should be as short as possible.
- Systems handling combustible dusts should, as far as possible, be located outside of the building. Branch ducts from each floor should pass through the wall and discharge into the main duct outside.
- Additional branch ducts should not be added without redesigning the system. Disconnected or unused portions of the system should not be blanked off without providing orifice plates to maintain required airflow.

System design must incorporate adequate pickup and carrying velocities for the materials being conveyed. These velocities are achieved through appropriate fan and duct sizing and duct routing. Design information is contained in *ASHRAE Handbook—HVAC Applications* and in *ASHRAE Committee on Industrial Ventilation—Industrial Ventilation.*

Separating and Collecting Equipment

Separating equipment includes cyclones, condensers, wet-type collectors, cloth screen and stocking arresters, centrifugal collectors, and other devices used for the purpose of separating solid material from the airstream in which it is carried. Then the material is collected in hoppers, bins, silos, and vaults. See Figures 8.1.5 through 8.1.8 for typical examples of some of this equipment and how sprinklers may be used in some types.

Separating and collecting equipment is designed to withstand anticipated explosion pressures, allowance being made for deflagration relief vents. This equipment should be constructed of steel or enclosed in steel and located outside the building. To prevent the equipment from collapsing (which could result in an explosible dust cloud), equipment should be well supported on steel, masonry, or concrete. Equipment and discharge ducts should be well separated from combustible construction and unprotected openings into buildings.

Collectors that must be located indoors, and that cannot be constructed of sufficient strength to withstand anticipated explosion pressures, can be located in rooms near outside walls to facilitate deflagration venting.

Gravity feed through tightly fitted ducts is the best arrangement for delivering stock from separators, cyclones, or other collection equipment to storage receptacles. Delivery ducts from collection equipment should not convey refuse directly into the fireboxes of boilers, furnaces, refuse burners, or incinerators.

Where processes produce very fine dusts or where combustible metal dusts are handled, wet collectors provide efficient dust control. Dust is removed by passing the flow of air through a water curtain and is collected as a sludge sub-

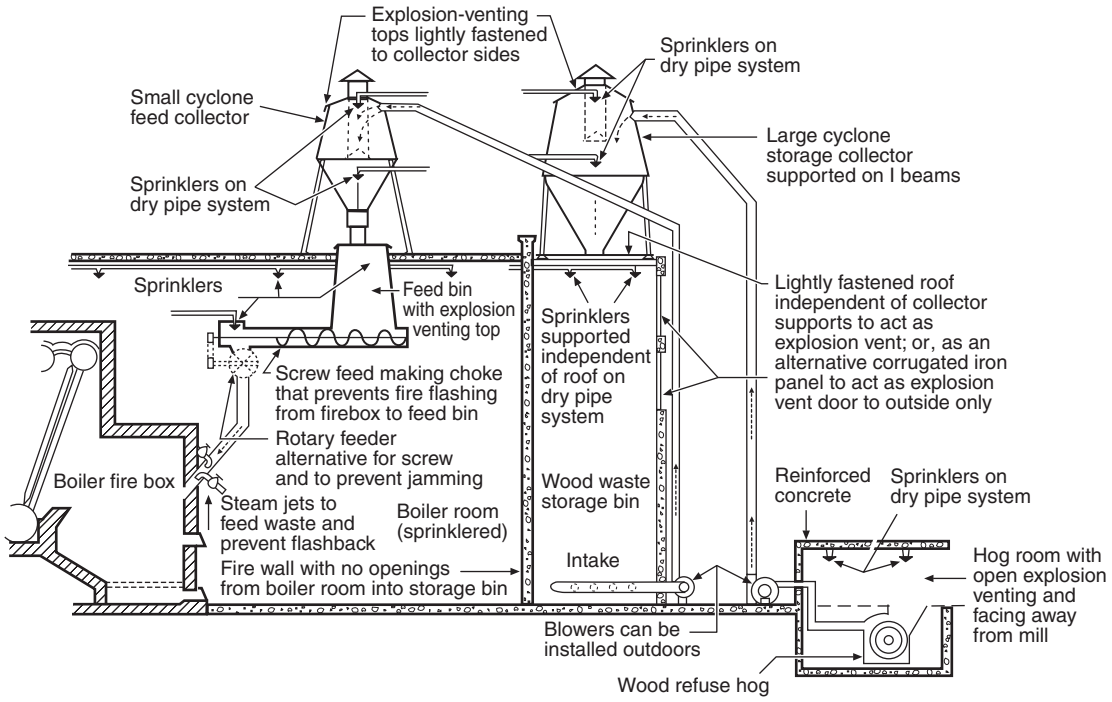


FIGURE 8.1.5 Suggested Arrangement for Wood Waste Firing of Boiler to Minimize Explosion and Fire Hazard

merged in water. Except where combustible metal dusts are collected, these wet collectors generally have no fire or explosion hazards.

Where refuse is to be used as fuel, the discharge system from the storage receptacle or intermediate feed bin to the furnace should be designed to prevent a flashback from the furnace. This may be accomplished by means of a choke feeder or choke conveyor so that a positive cutoff is provided. The installation of a steam spray in the duct to the furnace that blows steam in the direction of the fuel flow is recommended because it provides an added safety factor in preventing a flashback. See Figure 8.1.5 for a typical installation of this type.

The installation of screw conveyors or rotary feeds at appropriate points in stock or dust conveying systems has been used to good advantage in many plants by providing a "choke," which helps stop the spread of a flash fire. The installation of a deflagration vent also relieves the pressure of an explosion and prohibits its progress. This combination can prevent small fires or explosions from becoming large and disastrous.

High-Efficiency Air Filter Units. Particulate air filter units are used to remove very fine particulate matter, that is, to remove not less than 99.97 percent of 0.3-micron-diameter particles, from the air of industrial and laboratory exhaust systems.

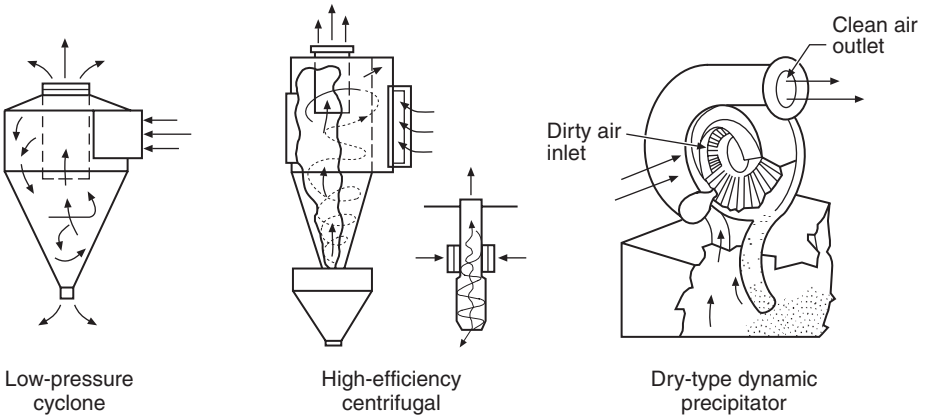


FIGURE 8.1.6 Typical Types of Dust Collecting Equipment

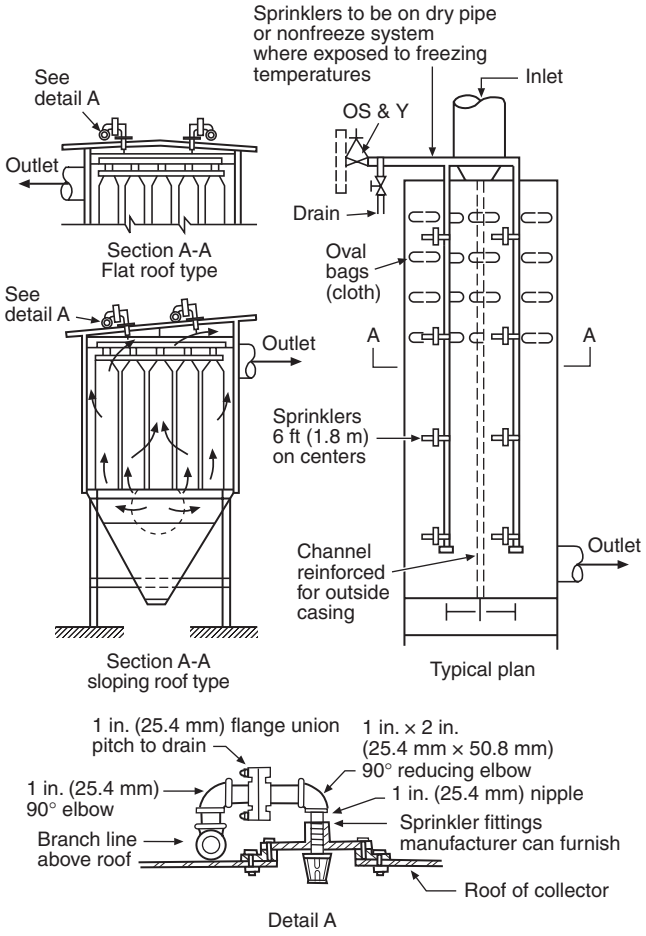


FIGURE 8.1.7 Typical Sprinkler Protection for a Bag-Type Dust Collector

These filters are commonly used in cleanrooms to keep air in the cleanroom pure. They are also used in equipment, such as glove boxes, to keep the air exhausting from the glove boxes pure (nonpolluting).

Glove Boxes. Glove boxes are used to perform operations involving hazardous materials, such as biological, toxic, and radioactive materials. The Nuclear Regulatory Commission (NRC) requires high-efficiency filters for filtering air exhausted from spaces where radioactive materials are handled. The filter units used are made of a filter medium of glass fiber, or equivalent inorganic material. Although the adhesive used is combustible, it contains a self-extinguishing additive. Fire of sufficient temperature and duration to melt glass fibers can damage the filter at points of contact, but will not stop the exhaust of filtered air through the undamaged area. The NRC regulations generally require large banks of these filters, limit the number of filters in a fire area, and require automatic sprinkler protection. DOE Standard 1066 and DOE Order 420.1A contain guidance for designing and protecting these glove boxes.

Battery Rooms

Battery banks often supply backup power for critical systems. Keeping these batteries charged can generate hydrogen gas. To keep hydrogen buildup from reaching dangerous levels, specially designed ventilation is provided for battery rooms. NFPA 111, *Standard on Stored Electrical Energy Emergency and Standby Power Systems,* provides guidance for these power backup systems.

FIRE PROTECTION

Fire Extinguishing Systems

Because of the combustibility either of the ducts themselves or of the material being transferred through them, the installation of automatic extinguishing systems is justified. The systems may be automatically or manually controlled and may use any of several appropriate extinguishing agents.

For example, if the material being transported is a flammable vapor or an easily ignited combustible dust, a deluge system actuated by heat-sensitive devices may be most appropriate. If the problem is the combustibility of the duct itself, an automatic sprinkler system may be adequate. In still other systems, a special extinguishing agent may be required or deemed more suitable. Sprinklers and discharge nozzles may have to be coated or covered to protect them from the environment inside the duct; they may have to be inspected on a regular basis and cleaned periodically to avoid serious buildup of deposits. Similarly, heat detectors or other types of detectors used to activate the extinguishing system may have to be periodically cleaned of deposits that might hamper their proper operation.

One important problem frequently overlooked is the obstruction of automatic sprinklers or other discharge nozzles by the ductwork. Care should be taken that ductwork does not seriously interfere with the discharge pattern. In many cases, additional sprinklers or nozzles will have to be extended down below the ductwork to provide satisfactory coverage. NFPA 13, *Standard for the Installation of Sprinkler Systems,* contains guidance for locating sprinkler heads near ducts so their water distribution pattern will not be obstructed.

Separating and Collecting Equipment. Cloth screen or bag-type dust collectors used for the collection of fine dusts present a special problem because of the use of a combustible fabric even where the dust is noncombustible. Automatic sprinkler protection may be needed where cloth dust collectors are important for continuity of production or where they provide exposure to other property. Figures 8.1.7 and 8.1.8 show typical layouts of sprinkler protection for cloth dust collectors.

Equipment of large volume, such as bins, or dust collectors in which pulverized stock is stored or may accumulate, should be protected by automatic sprinklers. Automatic carbon dioxide, dry chemical, or water spray extinguishing systems can be used effectively in dust collecting systems. Inert gas, such as nitrogen, may be effectively used to create safe atmospheres in conveying systems.

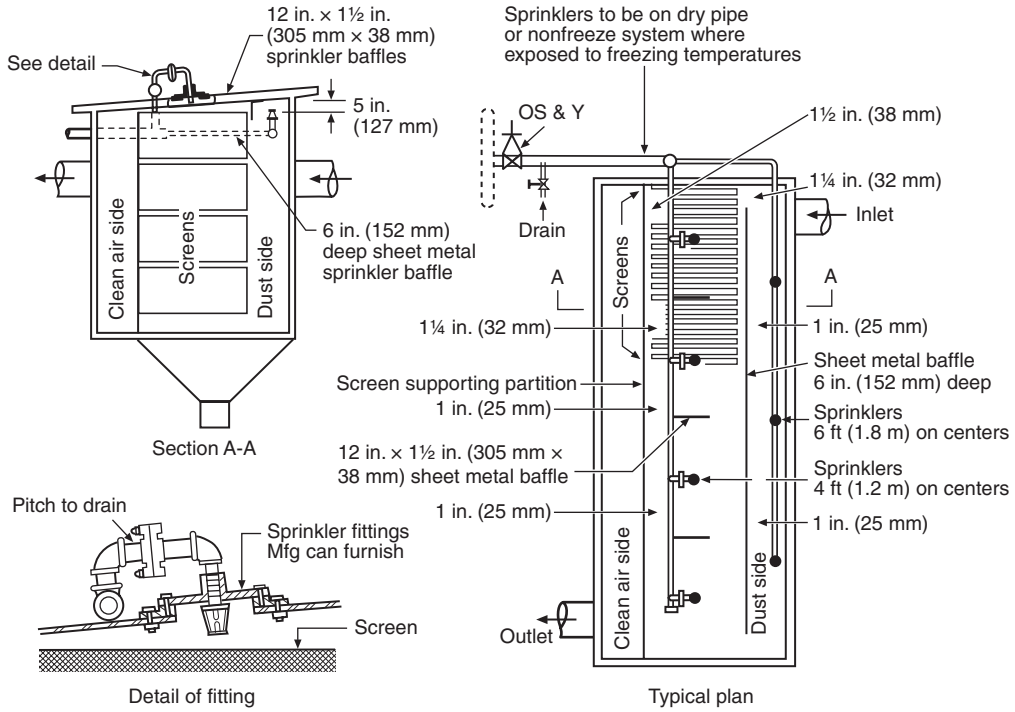


FIGURE 8.1.8 Typical Sprinkler Protection for a Screen-Type Dust Collector

Ventilation of Flammable Vapors. Fixed fire suppression systems suitable for the flammable material involved, as well as portable fire extinguishers, should be provided. The extinguishing agent should be water, foam, dry chemical, or CO_2 as appropriate for the hazard.

Ventilation of Kitchen Cooking Equipment. For cooking installations, this equipment may consist of fixed-pipe carbon dioxide, dry chemical, wet chemical, foam-water sprinkler, water spray, or sprinkler systems, supplemented by portable alkaline (sodium bicarbonate or potassium bicarbonate) dry-chemical extinguishers.

Acidic base extinguishing agents, such as ammonium-phosphate-based multipurpose types (ABC rated), impede saponification. Therefore, if the cooking equipment being protected involves exposed liquefied fat or oil in depth, such as deep-fat fryers, extinguishers employing these extinguishing agents are not recommended, as they may interfere with alkaline-based fixed systems.

Where fixed extinguishing systems are installed, they should (1) be located so that they easily can be manually activated from the path of egress; (2) be arranged for simultaneous automatic operation of all systems in a single hazard area, upon operation of any one system; and (3) automatically shut off all sources of fuel and heat to all equipment protected, upon operation of the system.

Portable Extinguishing Equipment

Portable fire extinguishers of appropriate type and small hose with spray nozzles are helpful where fires may occur in ducts. This is true even where fixed extinguishing systems have been provided. Judicious placement of extinguishers and hose lines with respect to location of access panels will make them more effective.

Magnetic Separators

As with flammable-vapor conveying systems, combustible-dust collecting systems should not be used with processes that may produce sparks. If there is a possibility of particles of ferrous materials ("tramp metal") entering the collecting systems, permanent magnetic separators should be installed at points where ferrous particles may enter. After collection, the dust passes into rooms or bins. These places of collection should be made of noncombustible construction and provided with deflagration vents terminating outside of the building.

Explosion Prevention and Deflagration Venting

When ignition sources are difficult to control, inerting may be used to create a safe atmosphere within the system, or an explosion suppression system or spark extinguishing system may be used. There are limits to these systems—inerting is generally practical for essentially closed systems, while explosion suppression is limited to those materials and enclosures that can be successfully protected. Efforts to suppress explosions in some materials, for example, metal dusts, have not been successful. Spark extinguishing systems are suitable for fibers and flyings.

Refer to NFPA 69, *Standard on Explosion Prevention Systems,* for additional information.

Deflagration relief vents prevent or minimize damage to duct systems that carry explosible mixtures. The vents should lead by the most direct practical route to the outside of the building. NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* gives information on designing deflagration vents. The use of suppression and inerting systems is limited by the configuration of the equipment and the physical and chemical properties of the material being conveyed.

Control of Static Electricity

When flammable vapors, dusts, or other materials pass through a duct, static charges on the duct are generated. If a charge is allowed to accumulate on an electrically insulated portion of a duct system, it could discharge to an adjoining duct section, at a joint for example, and ignite the material being conveyed. For this reason, exhaust systems carrying flammable vapors, dusts, gases, or other materials should be electrically bonded and grounded. Methods of eliminating dangerous static charges are treated in detail in NFPA 77, *Recommended Practice on Static Electricity.*

Dampers

Whenever ducts penetrate rated walls, floors, or partitions, dampers with equivalent fire resistance ratings should be provided to preserve the integrity of the fire area. Dampers should also be used to prevent backdrafts in manifolded duct systems to keep undesirable vapors, dusts, or impurities from being sucked upstream of their collection point and being spread. Firestopping spool pieces are available for plastic ductwork. These pieces collapse when warm and block the duct, preventing fire spread.

Cleaning

Although clean ducts are essential in preventing fire spread, cleaning them may be neglected because it is difficult and unpleasant, and can be dangerous if flammable solvents are used. Satisfactory cleaning results have been obtained with a powder compound consisting of one part calcium hydroxide and two parts calcium carbonate. This compound saponifies the grease or oily sludge, thus making it easier to remove and clean. Proper ventilation must be provided and safety precautions taken if cleaning is done inside the duct or fan housings.

Spraying the duct interiors with hydrated lime after cleaning is a fire prevention method in commercial use. Though this tends to saponify the grease and may facilitate subsequent cleaning, it does not provide any permanent fire protection or flame resistance, for grease eventually coats the compound.

Filters

High-efficiency particulate air filter units (HEPA filters) should be UL 900 listed. Filters so listed will not contribute to any fire in a duct system. They will also reduce the chance of spreading contamination, such as toxic or radioactive contamination, to the environment.

SUMMARY

Air-moving equipment includes all mechanical draft systems for removing gases, vapors, and solid particulates from processes, and for conveying materials. The primary hazard associated with air-moving equipment is ignition of combustible or flammable materials in the equipment by sparks, overheated bearings, or outside heat sources.

Despite the hazards associated with air-moving equipment, this equipment is essential for removing combustible, flammable, and other hazardous materials from processes and buildings. As with providing sprinklers, providing fire protection features for air-moving equipment protects people, property, and the environment.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on air-moving equipment discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*
NFPA 34, *Standard for Dipping and Coating Processes Using Flammable or Combustible Liquids*
NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals*
NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*
NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations*
NFPA 99, *Standard for Health Care Facilities*
NFPA 111, *Standard on Stored Electrical Energy Emergency and Standby Power Systems*
NFPA 204, *Standard for Smoke and Heat Venting*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 318, *Standard for the Protection of Semiconductor Fabrication Facilities*
NFPA 484, *Standard for Combustible Metals*
NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*
NFPA 664, *Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities*

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Chapter 2

Chemical Processing Equipment

Richard F. Schwab

Chapter Contents

Plant Siting
Exposure Protection
Ignition Sources
Control of Spills
Heat Transfer Hazards
Stability and Shock Sensitivity
Chemical Plant Operations and Equipment

Key Terms

Bhopal (India), chemical processing, chemical release, endothermic reaction, exothermic reaction, explosion, flammable liquid, hazardous material, heat transfer fluid, hot work, nucleate boiling, separation, vapor cloud

This chapter discusses chemical reactions, the means of controlling them, and the equipment used to produce chemicals and synthetic materials, such as fibers, plastics, and drugs. Operations that chemically change the properties of materials, as in chemical pulping of wood and the tanning of leather, are also covered. However, in discussing fire and explosion prevention and loss control, the hazards of each system must be considered as a whole when appropriate separation and other means of minimizing damage are examined.

For information on related topics see Section 2, Chapter 8, "Explosions"; Section 6, Chapter 8, "Dusts"; Section 8, Chapter 7, "Heat Transfer Systems and Fluids"; Section 17, Chapter 8, "Explosion Prevention and Protection."

PLANT SITING

Loss Prevention in the Process Industries[1] notes that safety is a prime consideration in plant siting. The most important feature is distance between the site and areas of high population density. Distance tends to reduce casualties—that is, if a toxic release occurs, the effect of distance reduces the concentration of gas and allows time for evacuation. The disaster at Bhopal, India, in December 1984 was undoubtedly exacerbated by the very high population density immediately adjacent to the plant. If the hazard is fire or explosion, distance will reduce the intensity of heat or blast overpressures as well as damage done by missiles. The density of population adjacent to the liquefied petroleum gas storage tanks involved in a fire and explosion in Mexico City, Mexico, in September 1984, led to a very high loss of life.[2] These two incidents resulted in 15,000 and 500 fatalities, respectively, and rank among the worst industrial accidents in history.[3]

Population Control

A consideration associated with plant siting is the function of government control of population around industrial plants. The effect of this is frequently overlooked. There have been numerous cases where industrial plants are initially located in remote areas, which are then subsequently populated with homes and other businesses unrelated to the operation of a chemical processing plant. To avoid this situation, a company must acquire sufficient land area around the operation and maintain it population free. This might become an economic problem for the operating company because of the imposition of taxes on the land acquired for this purpose. It also requires action on the part of the government to maintain the area population free by zoning restrictions

A plant with the potential for the release of toxic gases or the potential for a major fire or explosion must be designed to high standards of safety and loss prevention. Distance and siting alone cannot be relied on to prevent such disasters, but they must be considered as key features in limiting the potential magnitude of the incident.[4]

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Separation Distances

Block Approach. Single or allied processes are usually located on individual blocks of land surrounded by access roads. The theory behind the block approach is that fires or unignited spills of flammable material can then be attacked from all directions. This approach provides maximum latitude to take advantage of both wind direction and the shelter afforded by peripheral structures in the block. If the right of way for these roads is 50 ft (15 m) wide a minimum distance of 50 ft (15 m) between structures on adjacent blocks is ensured. This distance has proved adequate to prevent the spread of fires through highly protected properties.

Chemical manufacturing plants pose a special danger of explosion, especially in a large-loss incident. During the years 1971 to 2005, for example, there were 36 chemical manufacturing plant large-loss fires reported to NFPA, each involving at least $5 million in direct property damage in the year of occurrence (Table 8.2.1). Collectively, these 36 incidents caused

TABLE 8.2.1 Large-Loss U.S. Fires in Chemical Manufacturing Plants, Involving at Least 5 Million in Direct Property Damage in Year of Occurrence, 1971–2005

				Direct Property Damage (in Millions of Dollars)		
Year	*State*	*Did Explosion Occur?*	*Deaths*	*In Year of Occurrence*	*In 2005*	*CPI for Year*
1987	Texas	Yes, initiated incident	1	215.3	369.3	0.880
1988	Nevada	Yes, caused by fire	1	103.0	169.9	0.846
1991	Louisiana	Yes, caused by fire	1	105.0	150.2	0.734
1991	Texas	Yes, initiated incident	0	80.0	114.5	0.734
1974	Texas	Yes, initiated incident	2	16.1	63.5	2.029
1989	Illinois	No	0	40.0	62.9	0.807
2000	Texas	Yes, initiated incident	1	50.0	56.6	0.581
1976	Texas	Yes	1	16.2	55.4	1.757
1982	Pennsylvania	Yes, caused by fire	5	25.0	50.4	1.035
1992	Texas	Undetermined	0	32.3	44.9	0.713
1980	Texas	No	7	18.6	44.1	1.215
1994	Ohio	Yes, initiated incident	1	33.0	43.4	0.675
1974	Virginia	Yes, initiated incident	0	10.1	39.9	2.029
1983	Texas	Yes, caused by fire	5	20.0	39.1	1.003
1999	Texas	Yes, caused by fire	1	25.0	29.2	0.600
1985	Iowa	Yes, initiated incident	0	13.0	23.5	0.928
1986	Ohio	Yes	1	11.9	21.1	0.913
1984	Utah	Undetermined	0	11.0	20.6	0.961
1986	Mississippi	Yes	0	10.0	17.8	0.913
1992	Louisiana	Yes, initiated incident	0	12.5	17.4	0.713
1991	South Carolina	Yes, initiated incident	1	10.0	14.3	0.734
1982	Texas	Yes, initiated incident	0	6.8	13.6	1.035
2001	Nevada	Yes, initiated incident	1	12.0	13.2	0.565
1990	Alaska	Yes, caused by fire	8	8.5	12.7	0.766
1985	North Carolina	Undetermined	1	7.0	12.7	0.928
1982	Minnesota	Yes, initiated incident	5	6.0	12.1	1.035
1998	Maryland	Yes	1	10.0	12.0	0.614
1986	California	Yes, initiated incident	5	6.0	10.7	0.913
1990	Georgia	No	1	7.0	10.5	0.766
1988	Illinois	Yes, initiated incident	1	5.0	8.2	0.846
1995	Texas	No	1	6.0	7.7	0.656
1995	Texas	Yes, initiated incident	1	6.0	7.7	0.656
1990	Ohio	Yes, initiated incident	1	5.0	7.5	0.766
1991	Georgia	No	1	5.0	7.2	0.734
2000	California	No	0	6.0	6.8	0.581
1999	Pennsylvania	Yes, initiated incident	5	5.0	5.8	0.600
Total			60	959.3	1596.4	2.466

Note: Does not include some fires in chemical, plastic, or petroleum plants of unknown specific type. The 15 highest ranking fires on this list are the 15 costliest chemical manufacturing plant fires in 1971–2005. Other fires on this list have inflation-adjusted losses that could be less than the inflation-adjusted losses for other, earlier fires whose losses in the year of occurrence were less than 5 million. A 5.0 million loss in 1971 would be 24.0 million in 2005.

Source: NFPA Fire Incident Data Organization, NFPA analysis of reports to determine whether explosion occurred.

$959.1 million in direct property damage without adjustment for inflation (or $1,596.3 million in 2005 dollars) and also caused 60 deaths. Of the 36 incidents, 27 involved explosions (17 as the cause of the fire, 6 only as a result of the fire, and 4 of undetermined type), 6 did not, and 3 were undetermined.

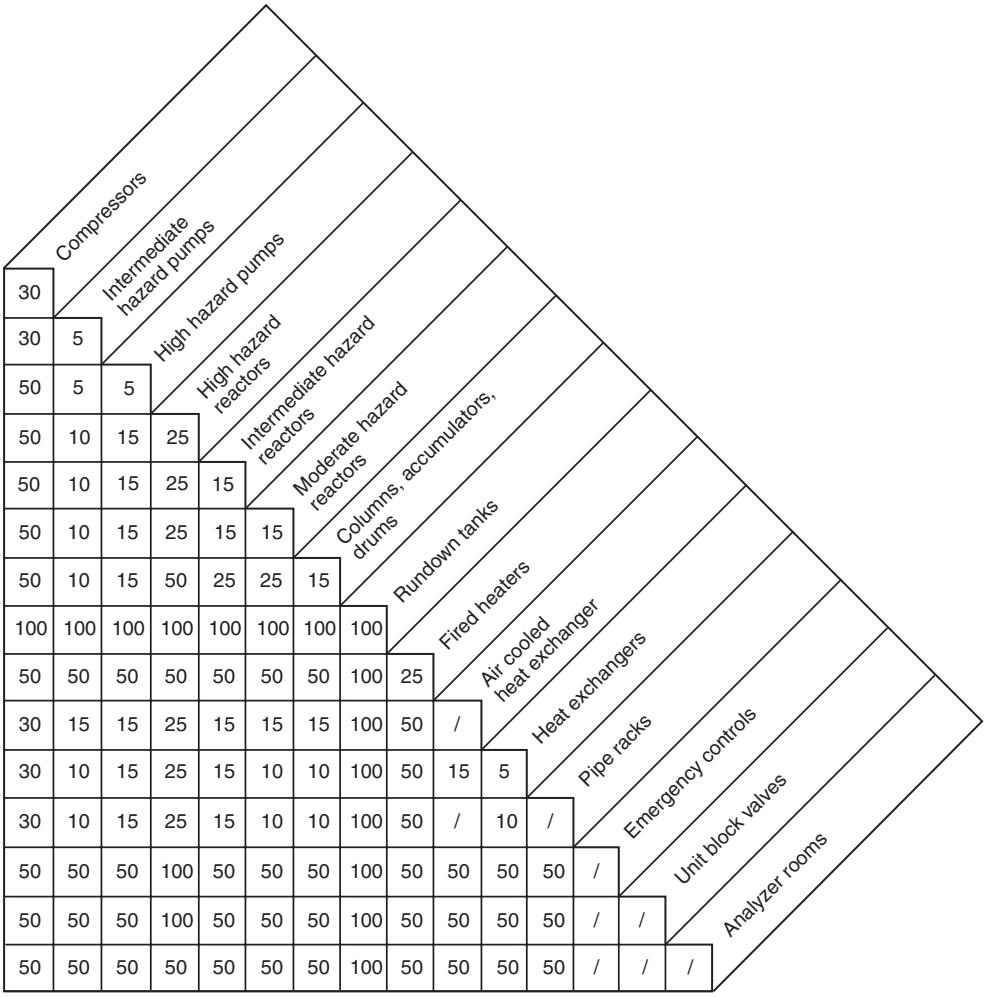
Where an explosion is possible, the 50 ft (15 m) distance does not provide sufficient protection. One solution has been to place any unit involving an explosion hazard away from the perimeter of the block. This gives a minimum distance (in the adjacent blocks) of 100 ft (30.5 m) between explosion hazards. In the case of equipment explosions resulting from an increase in internal pressure, the shock wave would be adequately attenuated by that distance. This is true whether the explosion is of the thermal type, represented by an ordinary runaway reaction and the failure of the reaction vessel, or of the shock type, where the pressure release is caused by a reaction at supersonic speed. In the latter case, the rapid pressure increase could produce shrapnel, so a containment barricade might be needed. If the material that might cause the explosion is a true explosive, whether formed intentionally or accidentally and whether inside or outside of the equipment, spacing should be in accordance with the American Table of Distances for Storage of Explosives. (See also NFPA 495, *Explosive Materials Code.*)

Conservative views on spacing are taken by the American Oil Company (now BP). Its *Engineering for Safe Operations* states: "Generally a distance of 250 ft (76.2 m) between units or between tankage has been used as a desirable spacing."[5] Figures 8.2.1, 8.2.2, and 8.2.3 show recommendations developed by GE Global Asset Protection Services (GE GAP), formerly Industrial Risk Insurers (IRI), with respect to process units and storage tanks in petrochemical plants. This reference also suggests

Service buildings	Motor control centers and electrical substations	Utilities areas	Cooling towers	Control rooms	Compressor buildings	Large pump houses	Process units moderate hazard	Process units intermediate hazard	Process units high hazard	Atmospheric storage tanks	Pressure storage tanks	Refrigerated storage tanks dome roof	Flares	Unloading and loading racks	Fire water pumps	Fire stations
/																
/	/															
50	50	/														
50	50	100	50													
/	/	100	100	/												
100	100	100	100	100	30											
100	100	100	100	100	30	30										
100	100	100	100	100	30	30	50									
200	100	100	100	200	50	50	100	100								
400	200	200	200	300	100	100	200	200	200							
250	250	250	250	250	250	250	250	300	350							
350	350	350	350	350	350	350	350	350	350							
350	350	350	350	350	350	250	250	350	350							
300	300	300	300	300	300	300	300	300	300	300	400	400	/			
200	200	200	200	200	200	200	200	200	300	250	250	350	500	50		
50	50	50	50	50	200	200	200	300	300	350	350	350	300	200	/	
50	50	50	50	50	200	200	200	300	300	350	350	350	300	200	/	/

1 ft = 0.305 m.
/ = no spacing requirements.

FIGURE 8.2.1 Interunit Spacing Requirements for Oil and Chemical Plants



1 ft = 0.305 m.
/ = no spacing requirements.

FIGURE 8.2.2 Intraunit Spacing Requirements for Oil and Chemical Plants

distances for separation of units in refineries, gasoline plants, terminals, oil pump stations, and offshore property.[6]

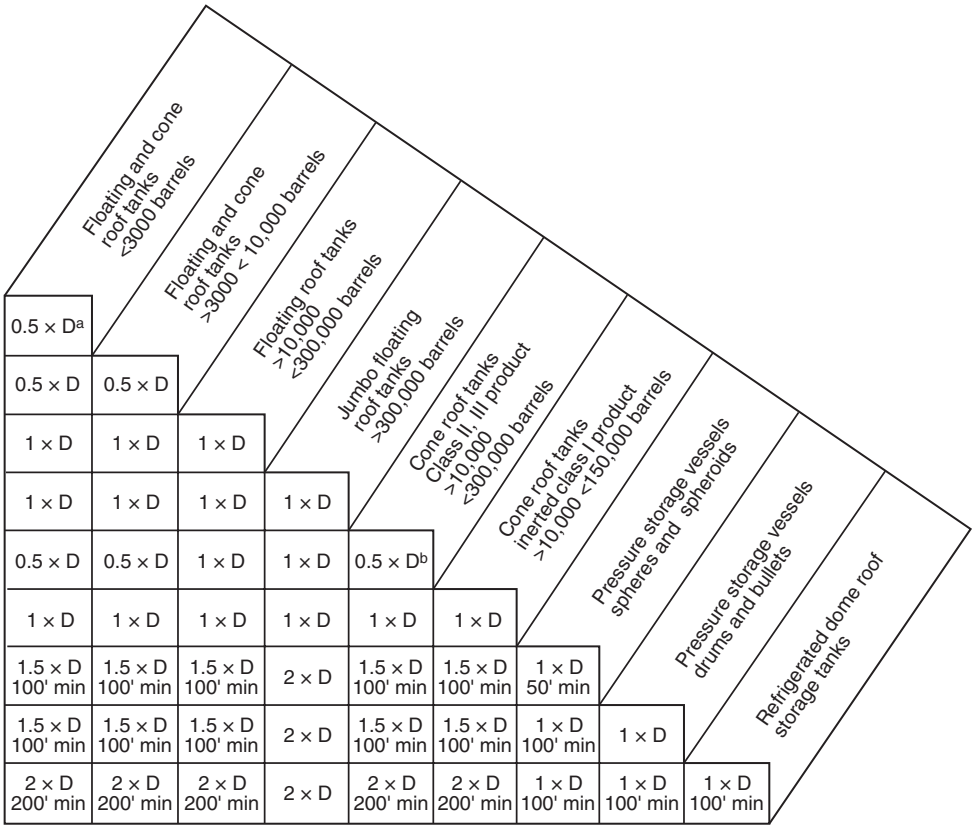
The greater distance suggested by BP and GE Global Asset Protection Services are justified by the large amounts of flammable liquids usually present in equipment and piping in oil refineries and petrochemical plants. They are probably adequate for controlling even large flammable liquids fires.

Hazard Ranking Approach. Another method for plant spacing is the MOND Fire, Explosion and Toxicity Index.[7] This index was developed as a result of the official inquiry into the Flixborough disaster in 1974. It requires a ranking of hazards of various process units at an early stage of design. The rankings are used to lay out the plant to minimize potential losses.

For another type of explosion hazard, no spacing standards exist. This is the type of explosion hazard that results when a flammable gas or superheated flammable liquid is released into the atmosphere and mixes with air to form a vapor cloud with a volume in the flammable range. Such a vapor cloud can release 2 to 10 percent of its heat of combustion in the form of explosive energy. In estimating potential losses from vapor clouds, GE GAP uses the 2 percent figure. This decision was reached after studying the results of 79 cases of vapor cloud formation.[2,8] In 70 cases there was no ignition; in 17 there was ignition but no pressure was generated. If a hydrocarbon material releases 20,000 Btu/lb (47 MJ/kg) when burned and 2 percent of that, or 400 Btu/lb (0.93 MJ/kg) were released explosively by igniting its mixture with air, then 5 lb (2.3 kg) of hydrocarbon would release about 2000 Btu (4.7 MJ) explosively—the same as about 1 lb (0.5 kg) of TNT. Where such releases are possible, spacing is not a reliable defense against damage, because no one can predict where the cloud will drift before it is ignited.

Procedures used to estimate the damage from explosion pressure resulting from ignition of a flammable vapor cloud are as follows:[9,10]

1. Estimating the volume of the vapor produced by the release



D = Largest tank diameter.
1 barrel = 42 gallons (159 L).
°C = (°F – 32) × 0.555.
1 ft = 0.305 m.

[a]For Class II, III products, 5 ft spacing is acceptable.
[b]Or Class II or III operating at temperatures > 200°F.

FIGURE 8.2.3 Storage Tank Spacing Requirements for Oil and Chemical Plants

2. Assuming that a percentage of the heat of combustion of this volume will be released as explosion energy
3. Equating this energy to an equivalent amount of TNT
4. Estimating the damage, based on the explosion of that amount of TNT

These procedures are discussed briefly by Davenport.[8,11] More extensive comments, with a table of pressure ranges at which different units of equipment can be expected to fail, have been made by Nelson.[12]

Van Wingerden et al.[9] extensively discuss the problems of evaluating vapor cloud explosions. Experimental work has been performed to develop an improved method to predict the blast effect from vapor clouds.[13] The method recognizes the importance of partial confinement with regard to the strength of vapor cloud explosions. The experiments were made to quantify the influence of obstacles and partial confinement.[9]

Other Means of Loss Control

As chemical plants process larger quantities of materials, it becomes impractical to provide ever increasing separation of process units. Where toxic, flammable, reactive, or otherwise hazardous materials might be spilled, the logical approach is to do the following:

1. Minimize the possibility of uncontrolled spills
2. Minimize the size of a possible spill (if spills do occur, the design features should keep them small)
3. Minimize the spread of a possible spill (if spills are large in volume, design features should keep them confined)
4. Prepare alarm and evacuation plans if toxic releases can occur
5. Control sources of ignition
6. Provide protection for exposed property if ignition does occur

A number of means are available to control spills. One is the obvious technique of providing diking or curbing to restrict the spread of a liquid spill. Another is the use of foam to cover the liquid spill so as to inhibit vaporization of the liquid, carefully considering the physical and chemical properties of the liquid to make sure that the foam is compatible.

Another is the use of water spray, using either a fixed sprinkler or water spray system with monitor nozzles (in some cases remotely controlled) to wash the vapor from the atmosphere. This method is appropriate for vapors that are water soluble and also for liquids that can be expected to be released as a mist. It also requires a large water supply at high pressure to be immediately available to respond to the emergency. In many cases,

fire water systems have been tapped, because they are usually available at the required pressure and amount.

Steam fogging systems have also been used to help dissipate vapor releases in plants where a large steam supply is always immediately available for this purpose. Generally speaking it would be unusual to have a large available steam supply available for an emergency in a modern plant where the requirements of steam demand and steam supply are closely balanced, mostly for economic reasons. In all cases, drainage systems are required and must be designed to accommodate the expected water or foam discharge along with the expected spill.[14]

EXPOSURE PROTECTION

Automatic fire control and extinguishing systems are the first line of defense against fire and explosion emergencies. However, if an explosion hazard exists, system design would require barricades for the protection of important components, such as deluge valves and dry pipe valves.[15] If they might be exposed to explosion pressure, however improbably, process control houses, including areas where people congregate (e.g. change houses), should be of explosion-resistant design.[16–20] The procedure cited in "Design of Control Houses to Withstand Explosive Forces"[16] is based on resistance to static overpressure. In Chemical Manufacturers Association (CMA, now known as the American Chemistry Council) Safety Guide SG-22,[17] it is based on elastic response—dynamic response to a pressure impulse (see Lawrence and Johnson[19]).

Reliably available water at pressure and volume sufficient to supply maximum foreseeable fire-fighting and exposure protection demand for a minimum of 4 hours is desirable. Of course, built-in or added fire resistance can give excellent exposure protection.

Protection for a chemical plant generally requires a specialized fire department where each fire fighter is equipped with full protective clothing, including self-contained breathing apparatus (SCBA), as well as acid-resistant hose and special extinguishing equipment where available. Appropriate symbols from NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response,* posted at locations on the property where chemicals are present, can give helpful guidance on inherent hazards of materials present and on planning effective fire-fighting operations.

IGNITION SOURCES

As recommended in Figure 8.2.2 open flames should be kept at least 100 ft (30.5 m) from any hazardous area. This recommendation refers to fixed equipment; however, it could also apply to maintenance work. A better approach is to prohibit open flames or other hot work in all but predetermined specified areas, except where hot work is to be done under a permit that limits scope and duration. It must be remembered that piping for high-pressure steam, heat transfer media, and hot-process streams might need insulation to keep from being a source of ignition. When piping operating at high temperatures is insulated, it might be necessary to leave flanges uninsulated. If the bolts joining flanges get too hot, their thermal expansion will relax the compression on the joints, and that could lead to leakage.

CONTROL OF SPILLS

Confinement

Large flammable liquid spills should be confined where they occur. Although diking is often used, it might not prevent liquid around a source of the spill from igniting and burning. Equipment can be damaged further or the spill aggravated unless efficient, prompt, and preferably automatic fire control measures are taken. A better approach is to provide drainage to an impounding basin located where a burning liquid can burn out harmlessly or a nonburning toxic material can be appropriately neutralized. A spill can be ignited some time during the drainage process, so care must be taken to avoid damage during drainage. If the facility's sewer system is underground and is not provided with liquid seals at all entrance points, explosions in the system can result. Fire in open drainage systems could damage anything without adequate protection that is located alongside the ditches or that crosses them, such as utility or piping systems. Problems associated with such drainage can be avoided by using the trench system described in NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection.*

Total confinement of a large flammable gas or vapor spill is not possible, due to the gaseous nature of the spill. Hose lines or monitors with spray nozzles can be used, because of the air entrained by the spray, to dilute the gas cloud and to move it in a desired direction until it dissipates. Fixed water spray nozzles can be used to set up water curtains, which will prevent a cloud from drifting to a furnace or other ignition source. Units that have been effective in experiments with small, low-level vapor releases were discussed in a number of articles in *Loss Prevention.*[18,21]

The use of steam nozzles to dilute and direct vapors upward at an installation have been reported.[22] There are problems with this approach. Large steam capacity must always be available, and there is need for meticulous grounding of all metallic material that could be charged by steam passing over it or condensing on it in order to avoid static electric sparks that might ignite the material being dispersed.

Keeping Spills Small

Hazardous spills can be kept small by keeping the amount of hazardous material used in a process small. Where this is impractical, valves to isolate all large quantities of material should be provided. These valves should be installed at each outlet of any large container through which material might escape (except at relief devices). They can also be used to subdivide long runs of large diameter pipe. The valves should be fire safe; that is, they should not leak appreciably when exposed to fire after being closed, and they should be arranged to operate both remotely and at the valve.

If operated by electric motor, both the power wiring to the motor and the signal wiring to the starting switch should be arranged to remain functional during any fire or other emer-

gency requiring valve operation, for at least as long as it might take to discover the emergency, transmit the alarm, and operate the valve. A minimum of 15 minutes for this fire protection sequence is suggested. If valves are held open by instrument air pressure and closed by spring or gravity when air pressure is lost, plastic tubing can be used in the air line, at least near the valve. The plastic should melt quickly in a fire and the valve will then close before it is damaged. Because it is necessary to detect spills before ignition, flammable vapor detectors of the diffusion head type can be used for that purpose.[23]

The distinction between a small spill and a large one must be fixed individually for each plant. A small spill is one that can be easily handled by means of exposure protection and confinement. All others are large spills. In case of jets of liquefied flammable gas[24,25] or hot flammable liquid,[26] where spacing is not a reliable defense against explosion damage, various quantities have been proposed as limits that must not be exceeded. One organization suggests 10,000 lb (4500 kg) of gas or vapor as a maximum permissible leakage rate that would permit formation of no more than 1000 lb/min (450 kg/min) of flammable gas or vapor.

Preventing Spills

Because many chemicals cause unusual corrosion or abrasion problems or their processing requires unusually high or low temperature, chemical plants should be constructed of appropriate materials and should follow good maintenance practices. Assuming that there are no problems in these areas, the reaction systems themselves might cause trouble.

In general, reactions are used to produce desired commodities that differ chemically from the raw materials from which they are made. The differences are produced by controlled chemical changes. Uncontrolled changes tend to produce unwanted materials and violent system failures that result in spills. The common denominator in these failures is overheating—that is, the overheating of a container, so that it softens and fails, or the overheating of the content, so that the container bursts from overpressure.

Accidents of these types result from a failure to move adequately from a heat source to a heat-absorbing system or to a coolant from a heat-releasing system. Heat is usually produced when materials dissolve, crystallize, condense, or are adsorbed. Heat is also produced mechanically, by crushing, grinding, milling, compressing, and pumping, and by exothermic chemical reactions. Heat transfer is also required when heat is needed for evaporation, melting, decreasing viscosity, initiating exothermic chemical reactions, and driving endothermic reactions. In any case, loss prevention requires an understanding of heat transfer.

HEAT TRANSFER HAZARDS

Heat Transfer Process

When a hot fluid, gas, or liquid transfers heat to a cooler fluid with a barrier such as the metal wall of a vessel, the resistance to heat flow, as shown by a temperature drop, is mainly by a thin film of fluid on the metal surfaces rather than the thermal conductivity of the metal (Figure 8.2.4). Flow in the heating and heated fluids is usually turbulent, with invisible swirls and eddies, but in the films, it is laminar with thin layers of molecules sliding slowly over each other.

The film layer nearest the metal moves slowest and its temperature is nearest to that of the metal. This is important because temperature causes decomposition of most organic and some inorganic fluids. Although a large temperature differential between the fluids moves heat faster than a small one, the hottest of the heated film must be kept cool enough so that it does not decompose and form a solid film. When such a solid film forms, the temperature of the metal on the heated side will increase, so that the metal is damaged (softened or chemically altered) and a "burnout" occurs.

Precautions consist of methods to detect fluid breakdown, such as checking the fluid for tar, solids, or significant change in viscosity or volatility. Where the heater is a single tube design, an internal buildup will cause an easily observable increased pressure drop as the fluid flows through the tube. For this reason single-pass tube heaters are preferred over those of multiple fluid path designs.

When the breakdown of the fluid is intentional, as in the case of cracking a petroleum fraction, the internal deposits are removed on a scheduled basis before they reach a dangerous thickness. This is usually done by burning them out with air or mixture of air and steam.[27] Requirements for safety involve the following:

- Purging the unit of flammables, usually with steam, before introducing the oxidizing atmosphere
- Purging after burning out the deposits
- Safely disposing of the materials purged
- Having a system of valves, usually involving double valves with a purged or vented space between, to ensure against mixing air and combustibles

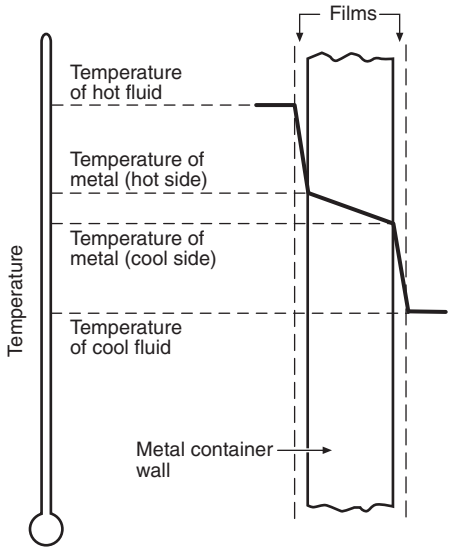


FIGURE 8.2.4 Effect of Fluid Films on Temperatures at the Surfaces of the Metal Wall of a Vessel

If the heated fluid is a liquid and starts to boil, heat transfer improves as the film is thinned by the action of the bubbles on the metal, growing and breaking away. The formation of bubbles on the heated surface is called "nucleate boiling." If the temperature of the heat source is then raised in an attempt to increase the rate of boiling, the temperature might become too high. Vapor bubbles then coalesce into vapor film instead of breaking away individually. This is called "film boiling." Vapor films offer more resistance to heat flow, so again "burnout" could occur.

Endothermic Reactions

Endothermic reactions are most commonly supplied with heat by combustion processes. This energy might be obtained by partial oxidation of the reaction stream, for example, cracking natural gas to acetylene by burning part of it with oxygen and then quenching the partially oxidized stream suddenly; or concentrating liquid by submerged combustion (burning a premixed gaseous fuel beneath the surface of a liquid); or roasting ore or cementitious material in a kiln. The energy might also be supplied through the walls of a container via a heat transfer media or by hot gases from a combustion process or another hot stream.

The same general hazards exist whether the material being heated is a reacting system or one being decomposed or heated. All cases require consideration of the metallurgical and construction characteristics of the equipment. These problems are accentuated in the case of direct-fired equipment. The heater must resist corrosion, pitting, and scaling from the materials being heated as well of the stream supplying the heat.

Construction must be such that heated and cooled portions can expand and contract freely. This is particularly important if the alloys used enter or pass through a brittle phase at any stage of heating or cooling.

Two more important but sometimes overlooked points are the following:

1. The metal of the heater and the heat transfer system and the fluids with which they are in contact must be compatible. A common molten heat transfer medium, a mixture of sodium nitrate and sodium nitrite used in indirect fired heaters, will support the combustion of steel if the temperature is high enough and ignition occurs.[28] Steel and copper in thin sections, as in the fins of heat transfer tubes, can ignite easily in hot chlorine.
2. The heat transfer medium should not create a hazard if it leaks into the material being heated or vice versa. Where leakage one way but not in another can be temporarily tolerated (e.g., sulfuric acid into water as opposed to water into sulfuric acid), pressures of the coolant and the cooled material must be suitably different. Alternatively, annular tubes with the annulus separating the two fluids can be used, with means to detect leakage into the annulus from either direction. To promote heat transfer, the annulus can be filled with a conducting liquid inert to both fluids or, as in "still" tubes, intermittently bridged with heat-conducting metal wires or perforated discs. The preceding discussion applies equally well when the heat transfer is from an exothermic reaction to a fluid used for cooling.

It is impossible to be all inclusive about the hazards of heat transfer. Two examples, however, indicate the scope of the problem. In the first example, electric inductive heat was being used on a cast-iron vessel with thermostatic controls. Cast-iron growth caused intercrystalline cracking. The cracks interrupted the flow of the induced electric currents throughout the vessel, the thermostats called for more heat, and the vessel eventually failed from localized overheating. In another instance, sodium silicate was condensed on a stainless steel pipe where it acted as a flux to remove the alloying elements so that the pipe lost its corrosion resistance and failed.

Exothermic Reactions

Proper application of heat transfer principles is essential to the control of exothermic reactions. Such use requires knowledge of the reaction system. First it is necessary to know the thermal stability and shock sensitivity of the system and its components, raw materials, intermediates, products, and by-products. Second, the reaction kinetics, that is, the total amount of heat released and how fast it is released, must be known.

For process design, it is necessary to have all of this data under conditions that would exist if the reactants were supplied in grossly incorrect proportions, in the wrong order, without mixing (both with and without a subsequent late start in the mixing system), at the wrong temperatures, if power failed, if the coolant line broke, or any other upset condition imaginable should occur. These matters need to be reviewed and documented during a hazard operations review (hazop).[29,30]

STABILITY AND SHOCK SENSITIVITY

Most chemicals are reasonably stable and insensitive. Where this is not true, data are available from the supplier or in the literature. NFPA 704 and *The Handbook of Reactive Chemical Hazards*[31] are excellent references in this field and provide an extensive bibliography.

When data are not available, thermodynamic calculations and laboratory-scale stability testing should be used.[32–37] Many test procedures have been developed by ASTM International Committee E27 on Hazard Potential of Chemicals and are published by the ASTM.

Hazard Reduction

Where explosive materials are involved, the hazard can be reduced to an acceptable level by diluting the explosive material in an inert chemical or by providing barricades. If the instability hazard is less than explosive, there are various ways to reduce it. Chemical reactions progress faster as the temperature rises, so the methods used involve keeping the material from being heated to an unsafe level. For example, the boiling point of a liquid is lowered by vacuum. Vacuum or freeze drying can help avoid overheating. A high boiling material (containing water) that becomes unstable at or near its boiling point can have steam

bubbled through it at a temperature below its (normal) boiling point. Vapor from the material goes along with the steam and separation can be made after condensing the steam-vapor mixture. Viscous materials can be concentrated by running them down the heated interior walls of a wiped film evaporator. Mechanically operated blades keep wiping the interior surface and the film cannot thicken, so the film layer nearest to the hot wall cannot overheat (see Figure 8.2.4). Liquid nitrogen or dry ice (solid CO_2) can be added to the grinder. This not only takes care of the heat produced mechanically but also tends to inert the atmosphere and reduce chances of a dust explosion.

In some cases, pressure can affect stability. Liquids such as propargyl bromide and nitromethane will simply boil away when heated at atmospheric pressure. If heated under pressure however, the boiling point might be raised to a point where the liquid decomposes violently with resulting explosion of the container. Pure gases, such as acetylene, ethylene, and nitrous oxide, will decompose violently under pressure. The testing described earlier should be thorough enough to detect such a possibility. Also, when considering systems, one should keep in mind that pressures might cause a phase change. For example, chlorine gas liquefies fairly easily, and a system easy to control when using a gas could be difficult to control if chlorine liquid is formed.

Reactors

Reaction systems are of two types: (1) continuous and (2) batch. A continuous reacting system can be thought of as a pipe, although it contains pumps, compressors, elongated vessels, and so on, with the raw materials and possibly inert carrier flowing in at one end or at appropriate intervals along the pipe and products and by-products flowing out the other end. In a batch process, the chemicals are added to a single process unit all at once or at appropriate feed rates; then the reaction takes place, the unit is emptied, and the process is repeated. Batch process systems have more flexibility in that, generally speaking, the equipment can be used to make several different products. Continuous process equipment is generally limited to the production of one product.

Continuous Reactors

It is common to have one reactant, pure or diluted, circulating continuously throughout the reactor with another being added, reacting, and its products removed by condensation, washing, filtering, or similar appropriate means. In normal operation, the major safety control is automatically cutting off the appropriate feed stream if the heat transfer system fails. Arrangements are often made for alternative means of supplying heat transfer fluids. Reliability of the shutoff system can be enhanced by using two valves in series with a vent between (known as a double block and bleed system). Depending on the complexity of the system, this same shutoff can be actuated by changes in the process conditions. An example of process change might be too low a temperature, which would indicate that the reaction was not proceeding properly. This signals that the concentrations of unreacted materials could be building up to the point where they could react with violence and overpower the means for heat removal or could react in a part of the system designed to recover product rather than control the reaction. Also when starting up or shutting down, the continuous reactor could go through situations that are more hazardous than its normal operation.

Batch Reactors

The essential parts of a batch reactor are as follows:

- A vessel to contain the reaction at its maximum pressure
- A heat transfer system to control the temperature of the reacting material
- A stirrer or agitator to keep the temperature and composition of the reacting mixture uniform
- A relief system to protect the vessel against overpressure

Vessel. The process vessel can range from an open wood or rubber-lined steel tank in which bauxite ore reacts with sulfuric acid to produce a solution of alum to a glass-lined or stainless steel pressure vessel. Regardless of the size of the configuration, the vessel used as a batch reactor will probable have to be entered for cleaning and inspection, whereas the continuous reactor can be cleaned automatically with a cleaning fluid. Cleaning or entering vessels will require special precautions if flammable cleaning agents are used or if vapors or residues make entry hazardous.

Heat Transfer Methods. Common methods of heat transfer use jackets or coils on the exterior of the vessel or coils in the interior. Others circulate the reacting mixture from the vessel through an external heat exchanger and back into the vessel. A third method allows the reacting mixture to boil. The heat of vaporization is then removed by condensing the vapor externally, which allows the condensed liquid to run back and thus continue the cycle. This last method does not provide means to heat the material in the vessel, which might be needed to start the reaction, even though cooling is needed as the reaction progresses. These methods can be used in combination.

Mixing. Mixing is usually performed with an agitator mounted on a shaft driven by an external motor. If an external heat exchanger is used, the mixture leaving it can be recirculated back into the vessel to accomplish the needed mixing. Where heat-sensitive materials are involved and it is necessary to avoid frictional heating by moving parts, mixing can be accomplished by "sparging" (bubbling) an inert gas, or possibly air, through the reactants.

Pressure Relief of Batch Reactors. Batch reactors in which a flammable atmosphere might sometimes exist are usually designed to contain the pressure that might result from ignition or they are purged or inerted to eliminate the hazard. If vessels are constructed according to the *Pressure Vessel Code* of the American Society of Mechanical Engineers (ASME), they are required to have a relief device adequate to keep the vessel from being overpressured because of heating from an external source, including an exposure fire, normal heating, or the introduction of fluids at pressures higher than those for which the vessel is designed. The code gives no guidance for the relief of pressure

caused by the heat of reaction or, as it is more commonly known, a runaway reaction.

Most chemical reactions double in speed with each rise in temperature of 18°F (–8°C). This means that a heat removal system would have to remove twice as much heat at 140°F (60°C) as at 122°F (50°C), four times as much at 158°F (70°C) and so on. For this reason, it is unsafe to run a batch reaction more than 30°F (16 to 18°C) above that of the cooling medium.[38] If the cooling system is overpowered, the reaction keeps increasing in speed, the retained heat builds up pressure, and the pressure must be relieved or the vessel will rupture. Austin gives a good explanation of this problem.[39] The Dow Chemical Company's *Guidelines for Process Scale-Up* asks the following questions about runaway reactions.[40]

Can you prevent runaway reactions?	*Yes*	*No*
By adequate heat transfer	—	—
By quenching the reaction	—	—
By stopping feed streams	—	—
By dilution of the reactor contents	—	—

Score: Two or more methods—You're in good shape. Only one method—Better find a second line of defense. None of the above—You'd better stop right now and reconsider your design for safety.

However, since even multiple safeguards can fail, emergency venting is supplied as a last ditch protection for the vessel. For example, loss of mixing could make all the suggested preventive measures inoperative or dangerously inefficient. Materials that have leaked into the hollow shaft of the agitator have created pressure and spewed materials into the main reaction system, which speeds up the main reaction so that it overpowers the cooling system. Other problems were discussed earlier in this chapter in the subsection "Endothermic Reactions." The problem of adequate sizing of emergency venting was recognized by the AIChE and a committee was organized to study the problem. This became known as the Design Institute for Emergency Relief Systems (DIERS).[30] Twenty-nine companies sponsored the work and spent $1.6 million on research. The project was successively completed in 1985. The key contributions developed to provide the chemical process industry with tools necessary to evaluate emergency vent requirements are as follows:

1. Emphasizing the importance of proper determination of the source term (i.e., energy release rate and gas generation rate for vapor and gassy systems, respectively) under upset conditions and the development of a new bench-scale apparatus in which such determination can be obtained and extrapolated directly to a full-scale application
2. Emphasizing the importance of two-phase flow in the emergency relief discharge process and development of vent sizing techniques that are valid for multiphase behavior

The DIERS methodology can be complex and time-consuming and is sometimes beyond the capability of many small plants. As a result, some inexpensive and easily employed techniques have been developed. These commercially available tools should make it possible for all facilities to design adequate emergency venting for process vessels and equipment. A number of articles have appeared in AIChE publications, *Chemical Engineering Progress* and *Process Safety Progress* (also its predecessor *Plant/Operations Progress*) concerning the DIERS program and the ways to use it.[41–50] The theoretical advances allowing a rational design procedure to be used for handling potentially runaway reaction conditions are best summarized in reference by Fisher et al.[51] Symposia on this subject primarily sponsored by DIERS and AIChE are held periodically.[52]

Safety Instrumentation

Safety instrumentation will vary from process to process and from plant to plant. There are, however, a few general rules:[53]

1. Measure, as directly as possible, the variables of interest. If an agitator is driven by an electric motor, a relay can be used to show that the switch to the motor is closed. An ammeter would be better because that would show that the current is flowing; a wattmeter would be best because it would show that work is being done and that the impellor had not fallen off the agitator shaft.

2. Ensure that reliability and maintenance are of high quality—for example, if an external fire could upset the reaction, the warning instrument should not be disabled by the fire. Since safety instruments will not have to operate often, frequent checks must be made to ensure they are in operating condition.

3. Provide redundancy or diversity in the system. If temperature is critical, provision of two thermocouples could lead to two different readings. It is best to provide three and trust the majority of the readings. Since a temperature increase is usually accompanied by a pressure increase, one pressure sensor and one thermocouple could be used, with credence given to the more pessimistic report.

CHEMICAL PLANT OPERATIONS AND EQUIPMENT

The generally accepted unit physical operations require equipment to carry out the following functions:

- Heat transfer
- Fluid flow
- Crushing and grinding
- Mixing
- Mechanical separation
- Distillation
- Evaporation
- Crystallization
- Filtration
- Absorption
- Adsorption
- Drying

Descriptions of individual pieces of equipment can be found in most chemical engineering handbooks.[54–56]

Heaters and Coolers (Heat Transfer)

Heaters and coolers (heat transfer) are either (1) direct (flue gas, kilns, spray cooling, vaporization) or (2) indirect (coils and

jackets). Heat transfer media usually work by boiling to absorb heat or condensing to give it up, but can work just by becoming hotter or cooler without phase change. Hazards of heat transfer have been discussed previously in this chapter.

Fluid Flow

Fluid flow is accomplished by (1) fans and compressors, (2) pumps, or (3) vacuum jets. Fans, compressors, and pumps heat the material they move because of mechanical work. Compressors require good aftercoolers. The liquid in pumps can boil and the pump bearings can fail from overheating if the pump operates against a closed discharge valve. If the suction head of a centrifugal pump is inadequate, cavitation might cause the pump rotor to fail. Failure of vacuum devices could permit unwanted air to enter the equipment and cause the temperature in the equipment to rise.

Crushing and Grinding

Equipment for crushing and grinding operations includes (1) mills (impact, ball, hammer, roller, disk) and (2) crushers (cone, gyratory, jaw). All of these devices produce heat and can produce fine material capable of a dust explosion. Ball mills can become overpressured as liquid in their contents are heated. If gaskets fail and the fluids are flammable, a dangerous situation will result.

Mixing

Devices used in the mixing process include (1) tumblers; (2) venture mixers; (3) kneaders, rolls, and mullers; and (4) propellers, blades, and turbines. These devices also produce heat to varying degrees. When it is necessary to produce a hazardous mixture, for example, a blend of starch and an oxidizer for use as a flour aging material, the mixer should be vented to prevent explosions. Any dust collector should be of the water-wash type.

Mechanical Separation

Equipment for mechanical separation include (1) cyclones, (2) bag filters (shake or blowback), (3) ore tables, (4) screens, (5) electrostatic precipitators, (6) flotation separators, and (7) centrifuges. The first five are usually dry type and the latter two wet type, although there are liquid cyclones and wet screening processes. Devices used in dry service for combustible dusts should have explosion (deflagration) venting or an explosion suppression system.

If collectors have internal combustible bags, an internal sprinkler system is desirable. It might not save the bags, but it will save the housing and the mechanical devices. When materials wet with flammable liquids are centrifuged, the operation should be conducted under inert gas or with an explosion suppression system.

Distillation

The types of stills are (1) batch, (2) continuous, (3) pressure, (4) vacuum, and (5) steam. All distillations involve heat transfer. The major hazard of this operation is that flammable vapor can be released to the atmosphere.[57]

Evaporation

The three types of evaporators are (1) multiple-effect, (2) vacuum, and (3) wiped film. All three use heat transfer. The multiple-effect system condenses vapor from the first unit to heat the second, and so on. The initial heat transfer medium is used in the first. Vacuums and wiped film evaporators have been discussed previously in this chapter.

Crystallization

Crystallization is the formation of solid particles within a homogeneous phase. It can occur as the formation of solid particles in a vapor (snow), as solidification from a liquid melt, or as crystallization from a liquid solution. Dissolved or molten substances are recoverable in solid form by precipitation on cooling or on removal of the solvent or by the addition of precipitating agents. Crystallization requires an understanding of phase equilibrium with respect to temperature and pressure. The equipment to accomplish this is extensively described in Perry and Green and other sources.[54,55]

Filtration and Agglomeration

Filtration and agglomeration involve (1) plate and frame filters, (2) Nutsche vacuum filters, (3) drum-type filters, (4) rotary-cell-type filters, (5) agglomerating tables, and (6) pelletizers. No unusual hazards are involved other than possible exposure of flammable liquids to the air.

Adsorption

The two types of adsorbers are (1) activated carbon and (2) zeolites (molecular sieves). Adsorption can result in heat just as absorption does. However, when the material being adsorbed is a flammable vapor or gas, the heat is retained on the surface of the adsorbent. Heat can build up enough to cause a fire (or "hot spot") in the activated carbon. In some cases it can initiate polymerization of adsorbed reactive materials, such as ethylene.

Drying

The six general types of dryers are (1) spray, (2) fluidized bed, (3) vacuum, (4) tray, (5) belt, and (6) drum. All involve the transfer of heat. In many of these dryers, when a flammable liquid or vapor is removed from the solid material, which may be in the form of a powder, it enhances the danger of igniting a dust explosion. (See Section 6, Chapter 8, "Dusts.")

SUMMARY

The following summarizes the necessary knowledge those dealing with chemical processing equipment should have and the procedures they should follow to ensure safe chemical processing:[58]

1. Know the total reaction energy in the system
2. Know the rate of energy release
3. Evaluate thermal and shock sensitivity data

4. Design the process to control the rate of energy release; ensure the process addresses the following concerns:
   a. Detection of trace compounds or catalytic impurities that could accelerate reaction rates
   b. Prevention of buildup or concentration of high-energy materials in the system
   c. Calculation of a material balance
   d. Designed mechanism within the process to safely accommodate inadvertent releases

Before beginning operations, a hazard analysis of the proposed or modified process is generally required.[59,60]

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59. Hendershot, D., et al., *Guidelines for Hazard Evaluation Procedures,* 2nd ed., AIChE-CCPS, New York, 1992.
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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for chemical processing equipment discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 306, *Standard for the Control of Gas Hazards on Vessels*
NFPA 495, *Explosive Materials Code*
NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*

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Annual Book of Standards, American Society of Testing and Materials, Philadelphia, PA (updated annually).
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Chapter 3

Materials-Handling Equipment

Revised by
John K. Bouchard

Chapter Contents

Powered Industrial Trucks
Mechanical Conveyors and Elevators
Pneumatic Conveyors
Cranes

Key Terms

automatic guided vehicle (AGV), bucket elevator, crane, hot work, mechanical conveyor, pneumatic conveyor, powered industrial truck

Materials-handling equipment, particularly powered industrial trucks and automatic guided vehicles (AGVs), mechanical and pneumatic stock conveying systems, and cranes, provides essential services to industry and commerce. This chapter describes the basic types of equipment and systems for handling of materials, describes inherent fire and explosion hazards, and outlines protection methods. Materials-handling equipment has accounted for a large number of vehicle fires as reported to U.S. local fire departments, including large loss property damage, injuries, and even deaths.

Readers interested in or concerned with materials-handling equipment should also consult Section 6, Chapter 8, "Dusts"; Section 6, Chapter 9, "Metals"; Section 8, Chapter 1, "Air-Moving Equipment"; Section 8, Chapter 13, "Electrical Systems and Appliances"; Section 9, Chapter 6, "Welding, Cutting, and Other Hot Work"; Section 9, Chapter 7, "Storage and Handling of Grain Mill Products"; Section 11, Chapter 5, "Control of Electrostatic Ignition Sources"; Section 16, Chapter 9, "Water Spray Protection"; and Section 17, Chapter 8, "Explosion Prevention and Protection."

POWERED INDUSTRIAL TRUCKS

Industrial trucks, which include lift trucks and AGVs, are among the most common types of materials-handling equipment. Lift trucks are available in many special designs to suit the many different uses and types of loads to be handled, with the fork and squeeze/clamp types being most common. They may be propelled electrically or by diesel, gasoline, liquefied petroleum (LP) gas, or compressed natural (CN) gas engines. AGVs are usually propelled electrically. Unless these vehicles are of a type listed by a recognized testing laboratory and properly maintained and operated, they may introduce serious hazards such as fires, explosions, container damage, spills, and leaks. All vehicles should be selected, outfitted, maintained, and operated in accordance with the hazards of the specific environment in which they are operated.

Type Designations and Areas of Use

NFPA 505, *Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operations,* lists 18 different type designations of powered industrial trucks or tractors. These designations are divided by power types: CN (compressed natural gas), D (diesel), E (electric), G (gasoline), and LP (liquified petroleum gas). The designation letter reflects the power type. In addition, dual-fuel trucks are available. The power types are additionally subtyped to indicate the level of safeguards inherent in the particular truck, as determined by testing and evaluation by a recognized testing laboratory. For example, a Type ES truck

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is an electrically (battery) powered unit that meets the minimal requirements for Type E units and has additional safeguards for the electrical system to prevent emission of hazardous sparks and to limit surface temperatures.

To review and understand the "minimal" and "additional" safeguards included in these "type" designations, refer to NFPA 505 and the appropriate UL Classification test standards (UL 558, *Standard for Safety Industrial Trucks, Internal Combustion Engine-Powered,* and UL 583, *Standard for Safety Electric-Battery-Powered Industrial Trucks*). The level of safeguarding determines the acceptability of a particular truck in a specific environment within an occupancy. Various types of industrial trucks are limited to the locations specified in Table 8.3.1. Fires and/or explosions can result if less than minimum type trucks are operated in hazardous locations.

A potential fire source for gasoline-, diesel-, and LP- and CN-gas–powered trucks is fuel leaks that are ignited by the hot engine, hot muffler, ignition system, other electrical equipment, or other sparks. Additionally, the potential of ignition of hydraulic oils should also be recognized. The danger of ignition is somewhat lower for diesel-fueled trucks and hydraulic oils because of the higher flashpoint of these liquids.

A special hazard in LP-gas trucks is that the vapors are difficult to disperse and tend to gravitate toward lower spots or pits. Care must be exercised with LP- and CN-gas trucks to avoid high temperatures near ovens, furnaces, and similar heat sources. Special safeguards in the design of some types of gasoline, diesel, and LP- and CN-gas trucks help to reduce these fire hazards, but the hazards cannot be completely avoided and areas of use should be strictly controlled (Table 8.3.1).

To facilitate identification of truck types and their areas of use, a uniform system of marking has been developed and is described in NFPA 505 and included here (Figures 8.3.1 and 8.3.2). Using these trucks and building markers allows easy and quick recognition of vehicles approved for the location.

Conversion of Powered Industrial Trucks

Certain powered industrial trucks can be converted to another type designation. Trucks designated as Type G, LP, or G/LP can

TABLE 8.3.1 Recommended Types of Trucks for Various Occupancies

Location	*Typical Occupancies*	*Types of Trucks*[b,c] *Approved and Listed*
Indoor or outdoor locations containing materials of ordinary fire hazard	Grocery warehouse Cloth storage Paper manufacturing and working Textile processes except opening, blending, bale storage, and other Class III locations Bakery Leather tanning Foundries and forge shops Sheet-metal working Machine-tool occupancies	Electrical—Type E Gasoline—Type G Diesel—Type D LP-gas—Type LP Compressed natural gas—Type CN Dual fuel—Type G-LP —Type G-CN
Class I, Division 1.[a] Locations where explosive concentrations of flammable gases or vapors may exist under normal operating conditions or where accidental release of hazardous concentrations of such materials may occur simultaneously with electrical equipment failure	Few areas in this division in which trucks would be used	Electrical—Type EX[f] Gasoline, diesel, LP- and CN-gas—not recommended for this service
Class I, Division 2.[a] Locations where flammable liquids or gases are handled in closed systems or containers from which they can escape only by accident or locations where positive mechanical ventilation normally prevents hazardous concentrations	Paint mixing, spraying, or dipping Storage of flammable gases in cylinders Storage of flammable liquids in drums or cans Solvent recovery Chemical processes using flammable liquids Paper and cloth coating using flammable solvents in closed equipment Rubber-cement mixing	Electrical—Types EE, EX[g] Diesel—Type DY[g] Gasoline, diesel Types D & DS, LP- and CN-gas—not recommended for this service
Class II, Division 1.[a] Locations where explosive mixtures of combustible dusts may be present in the air under normal operating conditions or where mechanical failure of equipment might produce such mixtures simultaneously with arcs or sparks from electrical equipment or where electrically conductive dusts may be present	Grain processing Starch processing Starch molding (candy plants) Wood-flour processing	Electrical—Type EX[d] Diesel—Type DY Gasoline, diesel Types D & DS, LP- and CN-gas—not recommended for this service

TABLE 8.3.1 Continued

Location	*Typical Occupancies*	*Types of Trucks*[b,c] *Approved and Listed*
Class II, Division 2.[a] Locations where explosive mixtures of combustible dusts are not normally present or likely to be thrown into suspension through the normal operation of equipment but where deposits of such dust may interfere with the dissipation of heat from electrical equipment or where such deposits may be ignited by arcs or sparks from electrical equipment	Storage and handling of grain, starch, or wood flour in bags or other closed containers Grinding of plastic molding compounds in tight systems Feed mills with tightly enclosed equipment	Electrical—Types EE, EX, ES[e] Gasoline—Type GS[e] Diesel—Type DY, DS[e] LP-gas—Type LPS[e] Compressed natural gas—Type CNS[e]
Class III, Division 1.[a] Locations where easily ignitable fibers or materials producing combustible flyings are handled, manufactured, or used	Opening, blending, or carding of cotton or cotton mixtures Cotton gins Sawing, shaping, or sanding areas in woodworking plants Preliminary processes in cordage plants	Electrical—Types EE, EX Diesel—Type DY Gasoline, diesel Types D & DS, LP- and CN-gas—not recommended for this service
Class III, Division 2.[a] Locations where easily ignitable fibers are stored or handled (except in process of manufacture)	Storage of textile and cordage fibers Storage of excelsior, Kapok, or Spanish moss	Electrical—Types EE, ES, EX, preferred; E[e] Gasoline—Type GS Diesel—Type DS, DY LP-gas—Type LPS Compressed natural gas—Type CNS

[a]Hazardous location as classified in NFPA 70, *National Electrical Code®*.
[b]Type G (gasoline), Type D (diesel), Type LP (LP-gas), and Type CN (compressed natural gas) trucks are considered to have comparable fire hazard.
[c]Type GS (gasoline), Type DS (diesel), Type LPS (LP-gas), and Type CNS (compressed natural gas) trucks are considered to have comparable fire hazard.
[d]Acceptable for Groups G and F, but subject to special investigation.
[e]Acceptable but subject to special investigation.
[f]Class I, Division 1, Group D, only; no truck should be used in Groups A, B, and C.
[g]Class I, Division 2, Group D, only; may be used in Groups A, B, and C areas subject to local authority.
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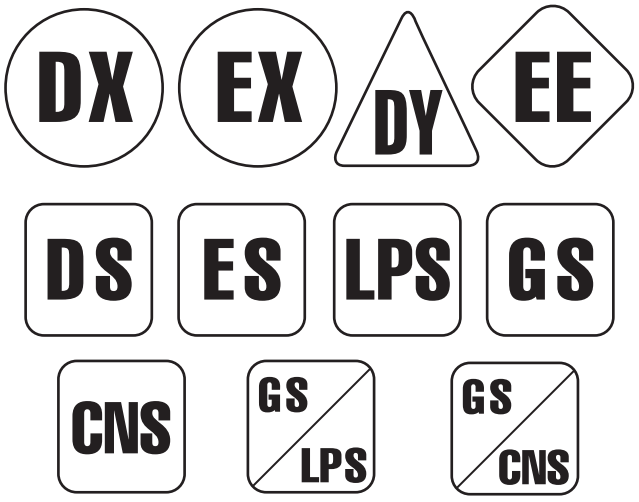


FIGURE 8.3.1 Markers Used to Identify Types of Industrial Trucks

be converted to another of those designations, and the converted unit must conform to the requirements of the new designation in accordance with the test standard (UL 558). Kits available for these conversions must conform to the requirements of the new type designation in accordance with the test standard (UL 558). These kits must be approved by a recognized testing laboratory.

A conversion kit must include certain items, including all parts necessary to complete the installation, instructions, and a new plate to indicate the converted type designation for mounting on the truck next to the manufacturer's (original) nameplate. Also, specific elements of a kit that apply to specific types of trucks are required.

The responsibility for the acceptance of an industrial truck that has been converted rests entirely with the inspection authority having jurisdiction. The responsibility for determining whether a truck has been properly converted is that of the authority having jurisdiction because it is impractical to ship each converted truck back to the testing laboratory to be reexamined or retested, and it is also impractical for the laboratory to send a representative into the field to examine or test every converted truck.

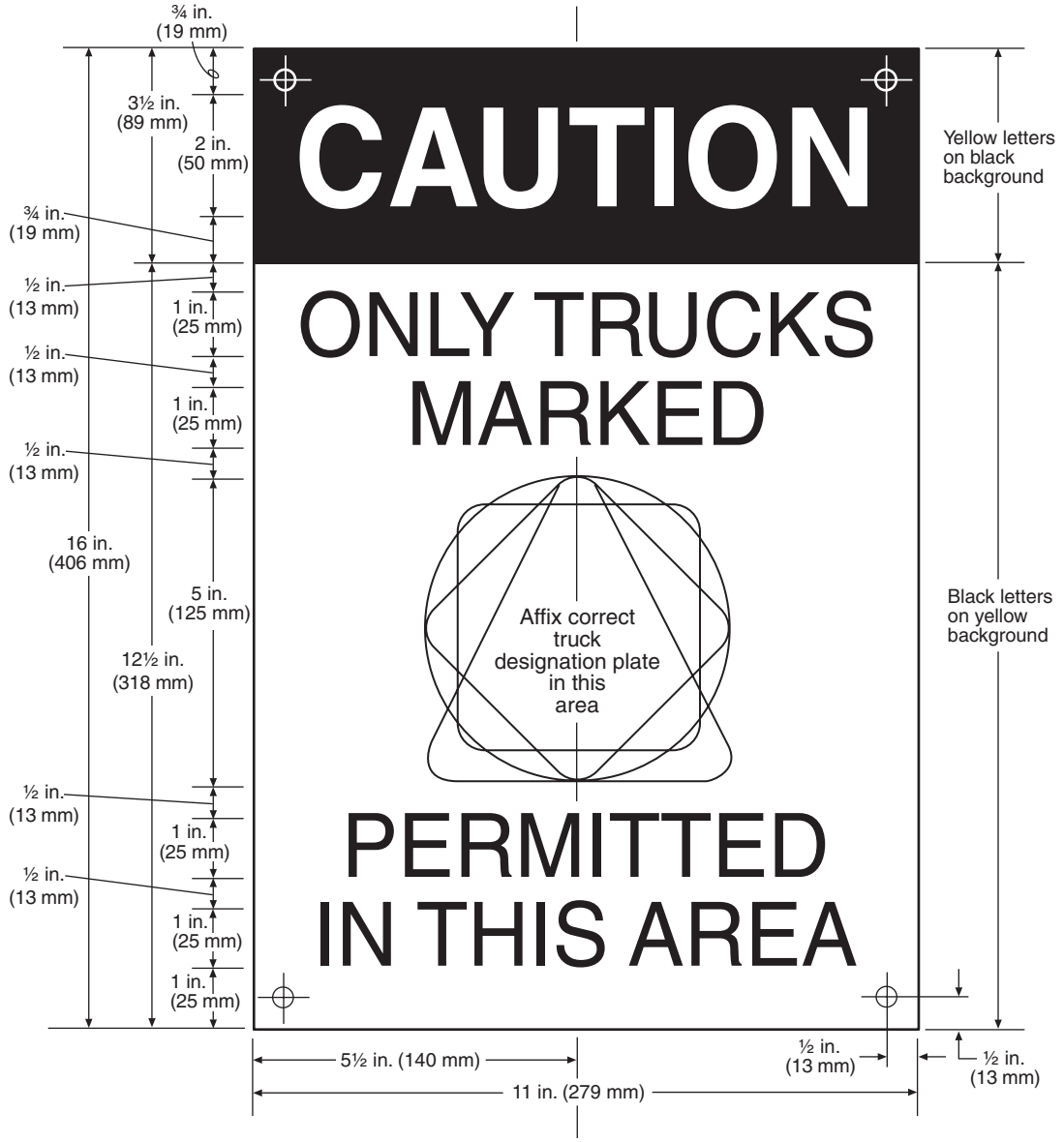


FIGURE 8.3.2 Building Signs for Posting at Entrances to Hazardous Areas

Fire Hazards and Prevention

Industrial trucks can contribute to property loss through careless operation or operation by inadequately or improperly trained operators. Collision with sprinkler piping, fire doors, and other fire protection equipment; excessively high stacking of storage; and careless handling of loads, such as containers of flammable liquids, can contribute directly to fires and make fire fighting more difficult. This aspect of the danger of powered industrial trucks has long been recognized, and guidelines for these vehicles are included in OSHA standards.

A comprehensive instruction course for truck operators can reduce the risk of such accidents. Adequate, clear passageways for truck travel and clear warnings of overhead and exposed piping also reduces the number of incidents. Good sources for safe operating rules are ANSI B56.1, *American National Safety Standard for Low Lift and High Lift Trucks,* and the Code of Federal Regulations 29, Part 1910 (*Occupational and Health Standards*), Section 178, *Powered Industrial Trucks*.

Fires involving industrial trucks can be caused by equipment failure due to inadequate or improper maintenance. Regularly scheduled maintenance should be based on engine-hour or motor-hour experience to reduce the risk of these fires. Because many trucks operate on a nearly continuous basis, maintenance programs must be carefully followed. OSHA standards require an inspection of each truck before each day/shift of operation. Especially important is detecting faulty or damaged fuel connections on gasoline, diesel, and LP- and CN-gas trucks and removing accumulated grease, lint, and dirt. Portable extinguishers suitable for the hazards presented by the truck and the envi-

ronment are recommended. If provided, such fire extinguishers should be subjected to inspection and maintenance requirements per NFPA 10, *Standard for Portable Fire Extinguishers.*

LP-gas fuel containers require special care to prevent fires. They must not be overfilled; a calibrated scale is recommended to verify "full" weight. A soap solution should be used to check for leaks, never a match or an open flame.

Means should be provided in the LP-gas fuel system to minimize the escaping fuel when exchanging removable LP-gas containers, for example, closing the valve on the LP-gas container and using an approved automatic quick-closing coupling in the fuel line. Removable LP-gas containers must be securely mounted to keep them from jarring loose, slipping, or rotating. The powered industrial truck must not be operated without all clamps, couplings, and mounting devices fully closed/engaged. The pressure relief device inlet should always be in contact with the vapor space at the top of the container. An indexing pin is provided to assure that the LP-gas container is positioned correctly. It is good practice to examine all LP-gas containers for defects or damage before refilling.

Fires involving battery-powered trucks can occur due to electrical short circuits, hot resistors, arcing and fused contacts, lint accumulation, or exploding batteries.

Two types of batteries commonly used are lead and nickel-iron. They contain corrosive chemical solutions, either acid or alkali, and therefore present a chemical hazard. When charging, they generate hydrogen and oxygen, which, when combined in certain concentrations, can explode.

Battery-charging installations should be located in areas specifically set aside for that purpose. The facilities should include means for flushing and neutralizing spilled electrolyte; barriers for protecting charging apparatus from damage by trucks; adequate ventilation for dispersal of fumes from gassing batteries; and adequate fire protection. A carboy filler or siphon is needed for dispensing acid from carboys. Open flames, smoking, sparks, or electric arcs in battery-charging areas should be avoided when charging batteries. Also, the vent caps should be kept in place to avoid electrolyte spray, and ensure that vent caps are functioning. The battery or compartment cover(s) should remain open during charging to dissipate heat and gas.

Recharging and Refueling

Refueling and battery-charging operations should be performed by trained and designated personnel, and only in specified, well-ventilated areas away from manufacturing and service areas; outdoor refueling is recommended where practicable. Smoking should be prohibited in these areas. Scales for weighing LP-gas containers should be calibrated periodically to ensure accurate filling.

Many hazards present in filling operations can be avoided by utilizing a local supplier in an exchange program. The vendor will deliver full tanks while retrieving empty tanks (to be filled off-site at the vendor's facilities). On site, tanks should be stored in a secure, exterior, well-ventilated location, with a noncombustible weather cover.

Trucks using liquid fuels, such as gasoline and diesel fuel, should be refueled only from approved dispensing pumps in safe locations away from heat and ignition sources. Care must be taken not to spill fuel or overfill the vehicle fuel tank, as many fires involving trucks using liquid fuels result from spillage during refueling.

Maintenance and Repair

Trucks should never be repaired in Class I, II, and III hazardous locations. Repairs to the fuel and ignition systems of industrial trucks that involve fire hazards should be conducted in locations designated for such repairs. Repairs to the electrical system of battery-powered industrial trucks should be performed only after the battery has been disconnected. All parts of any industrial truck that need to be replaced should be replaced only with parts providing the same degree of fire safety as those used in the original design. Water mufflers should be filled daily or as frequently as needed to maintain the water supply at 75 percent of filled capacity or above. Vehicles with clogged mufflers, screens, or other parts should not be operated. Any vehicle that emits hazardous sparks or flames from its exhaust system should be immediately removed from service and not returned to service until the cause of sparks and flames has been eliminated. When the temperature of any part of any truck exceeds normal operating temperature, a hazardous condition is created, and the vehicle must be removed from service until the cause of overheating has been eliminated.

When hot work (welding, soldering, cutting, grinding, etc.) is necessary for the repair, a formal hot work permit program should be followed. For this reason it is preferred that such repair work be carried out outside of the facility in an open area. (See Section 9, Chapter 6, "Welding, Cutting, and Other Hot Work.")

It is good practice to keep industrial trucks clean and free of lint, excess oil, and grease. The conditions under which the truck operates and frequent inspections should govern the frequency of cleaning. Noncombustible agents should be used for cleaning trucks; low-flashpoint (below 100°F [38°C]) solvents must not be used. Precautions regarding toxicity, ventilation, and fire hazard should be appropriate for the agent or solvent used. When the cooling system requires antifreeze, a glycol-based material should be used.

MECHANICAL CONVEYORS AND ELEVATORS

Commonly used equipment in materials-handling operations are mechanical conveyors and elevators that efficiently transport bulk and packaged materials. There are many classes and designs of mechanical conveyors. The primary selection considerations are the distance and inclination over which material is to be conveyed; the types of atmosphere and location through which material is to be conveyed; and the lump size, density, fluidity, abrasiveness, toxicity, corrosiveness, and other properties of the materials to be conveyed. Dust materials, dust atmospheres, or both require equipment that can be enclosed adequately. The lump size screw and en masse conveyors can handle high temperatures that often rule out belt conveyors; long distances usually require belt conveyors. Bucket elevators best handle substantial vertical lifts.

Important fire protection considerations around conveyors and elevators include location, housekeeping, temperature, dust, and the material being conveyed. For belt conveyors both the belt's combustibility and the material being conveyed must be considered; both can contribute to fire and its spread. When conveyors are designed and installed, protecting openings and controlling static charges must be given careful attention.

Temperature

Screw, vibrating, and certain pan conveyors are normally the best choices for handling very hot materials or for use in very hot atmospheres. Although the upper limit for most belt conveyors is 200°F (93°C), their use is normally restricted to atmospheres of less than 150°F (65°C). The highest rate of flame propagation occurs with rubber belts but the ignition characteristics of neoprene, rubber, and polyvinyl chloride differ little. Thus, most belt conveyors are not suitable for moving hot or molten materials and are not used in high-temperature atmospheres. Less combustible, fire-retardant belt materials are available for some applications.

Fire Protection

Often the criticality of a belt conveyor may warrant the use of fire-retardant, or less combustible, belts. Automatic sprinkler or water spray protection is generally needed for important belt conveyors, particularly if they are enclosed. Controls should be provided to shut down the conveyor when sprinklers operate. Hose stream protection to reach all portions of the conveyor is also needed. This protection can be provided by 1½ in. (38 mm) hose connections to sprinkler piping or from hydrants.

Another important factor to consider is the location of the conveyor. Exposures to critical conveyors, particularly exterior conveyors, must be carefully considered. Structures, buildings (including temporary buildings and/or trailers), or operations can create severe exposure to overhead conveyors. The route and height of conveyors should be carefully reviewed early in the design stage to avoid exposures. In addition, the height of the conveyor may make it difficult for manual fire fighting, which may warrant the installation of automatic sprinkler or water-spray protection.

Dust Control

Factors in fires involving mechanical conveyors can include dusty material, a dust atmosphere, and dust usually created by the materials-handling process. Dust is produced in most materials-handling systems, especially at inlet and discharge points and at long chutes for free-falling materials.

Dusty material should be fed to belt conveyors through a choke feed to prevent dust clouds. Where dusty conditions prevail, adequate aspiration should be provided to remove dust to collectors in safe locations. If dust clouds cannot be avoided, it is better to use spiral or enclosed conveyors where the escape of dust can be more readily prevented. When combustible or explosive dusts are handled, conveyor piping should be strong enough to withstand the maximum pressure produced in explosions of the dust involved; adequate static grounding is essential. Sharp changes in direction should be avoided wherever possible, and vent pipes to outdoors should be provided at any necessary changes in direction and at the ends of lines. (This should not be construed as prohibiting the use of explosion-relief vents.)

Screw conveyors should be fully enclosed in tight, noncombustible housings with free-lifting covers at the discharge end and over each shaft coupling. En masse or drag-type conveyors should be of substantial metal construction designed to prevent the escape of dust. Covers on cleanout, inspection, and other openings should be securely fastened. Conveyors should be designed and constructed to withstand anticipated explosion pressures, considering the pressure release that explosion-relief vents afford. A choke or seal of proper design or a suppression system should be installed in a conveyor (other than pneumatic) to prevent an explosion from propagating from one building to another, or from one portion of a building to another portion separated by a fire wall, division wall, or other fire-resistive barrier.

Dust collectors should be located outdoors or in detached rooms with adequate explosion vents for the collectors and the rooms. Where it is necessary to use bag-type collectors, they should be enclosed in a metal housing. A single dust collector should not serve several separate processes. Individual collectors for progressive stages should be used in any one process. Water spray collectors may be located within buildings, but they are not recommended for certain types of dust.

Housekeeping and maintenance are very important when dusty material is transported by conveyors. Dust can collect on rollers and bearings, creating friction, which can accelerate degradation or cause excessive temperatures and result in ignition of the material or belt. Rollers or bearings could seize, creating friction with the moving belt, which could generate adequate heat for ignition or generate a static charge. See the Friction and Overheating section for more detail.

Static Protection

All machinery and conveyor parts should be thoroughly bonded and grounded to minimize static discharge. The chances of generating static electricity increase when heated or dry materials are pneumatically conveyed or a conveyor belt is operated in a heated or dry atmosphere. Static electricity can be controlled by using belts made of conductive material, by applying conductive dressing to the belt surface, or by installing a grounded static collector nearly in contact with the belt just beyond the point where the belt leaves the pulley. Pulleys, guards, and other metal bodies should also be grounded. Caution is necessary when handling or disposing of sludge from water wet-type collectors, as certain metal-dust and water combinations are hazardous. See NFPA 484, *Standard for Combustible Metals.*

Protection of Conveyor Openings

Water Spray Method. Protecting wall and floor openings through which conveyors pass presents difficulties in installing ordinary forms of closures due to the objects carried through the opening. Where fire doors or shutters are impractical for conveyor openings, a method of protection incorporating the pressure effect and the cooling action of water spray from directed spray nozzles is available for both horizontal and vertical

openings (Figure 8.3.3). With proper nozzle design and water pressure to provide suitable water velocity and droplet size, the pressure effect from the nozzles will overcome draft due to the temperature difference between one side of the wall and the other, and the height of the opening above floor level, unless adverse air currents are prevalent.

Since the spray's cooling effect is directly proportional to the time of exposure of hot gases in the draft to the spray, the effectiveness of the heat absorption may be increased by adding an enclosure to the opening (Figure 8.3.4). Although seldom used, this method may also protect conveyor openings through floors (Figure 8.3.5).

Fire Doors. That conveyorized openings cannot be protected by fire doors is a misconception. Where possible, conveyor penetration of a fire wall should be avoided by rerouting. If alterations to a labeled fire door are contemplated, a cutout of a labeled fire door done in the field to allow closure around a conveyor track or other components voids its label. This practice should be avoided, if possible. Where notching is distinctly advantageous and inspection finds the notched door in compliance with the laboratory standards in all other aspects, a certificate may be furnished by the testing laboratory affixing the label.

Figures 8.3.6, 8.3.7, and 8.3.8 illustrate some conveyor designs and/or programming devices that minimize or eliminate the threat of obstruction to complete fire door closure by the conveyor or conveyed stock. For details and more figures, see NFPA 80, *Standard for Fire Doors and Other Opening Protectives*.

The illustrations can show only basic concepts. Proper performance depends equally on conservative design, good workmanship in installation, operating inspection, and

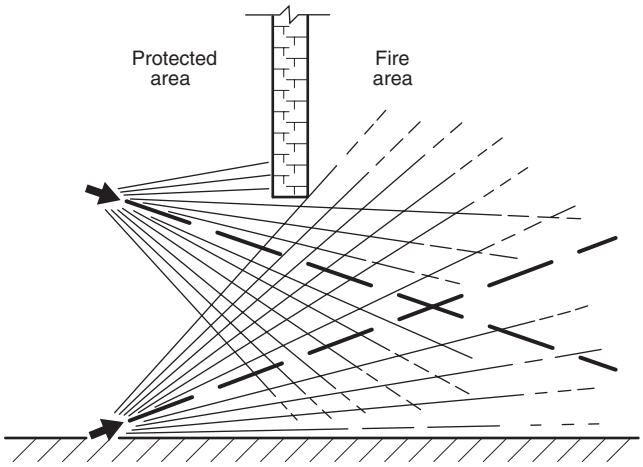


FIGURE 8.3.3 Spray Nozzles Protecting a Conveyor Opening in a Fire Wall

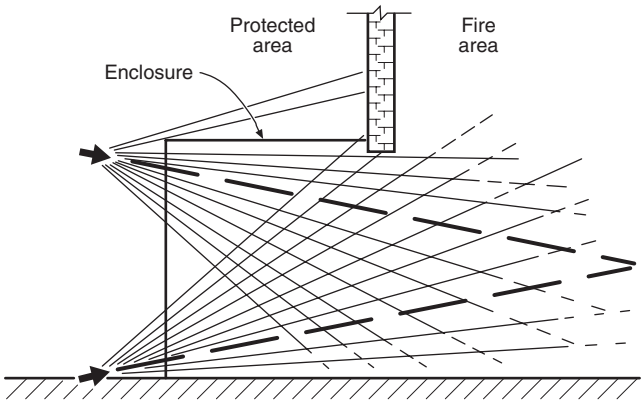


FIGURE 8.3.4 Greater Heat Absorption by Enclosing the Opening for a Conveyor

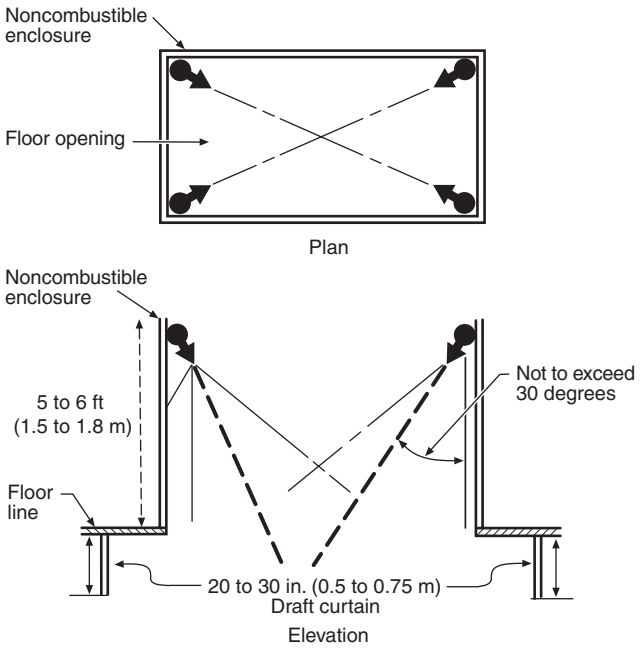
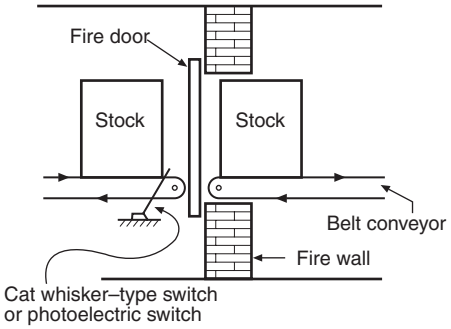


FIGURE 8.3.5 Spray Nozzle Protection for Floor Opening



Electromagnetic fire door release interlock with switch that stops conveyor with proper spacing of stock to prevent obstruction to door closer.

FIGURE 8.3.6 Protecting Openings When a Belt Conveyor Can Be Interrupted

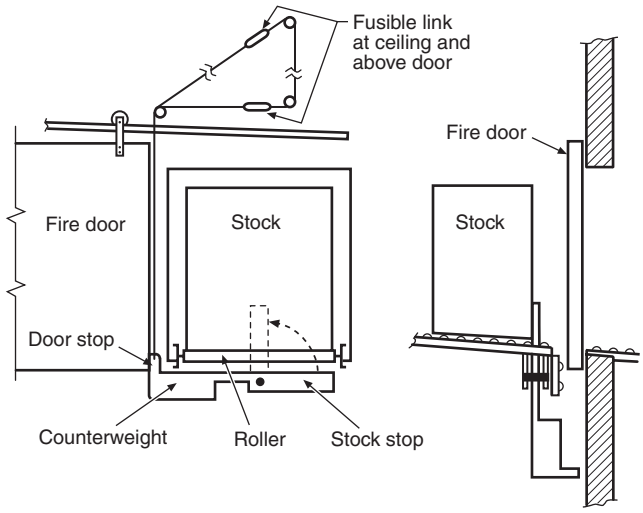


FIGURE 8.3.7 Method of Stopping Stock on a Gravity Roller Conveyor

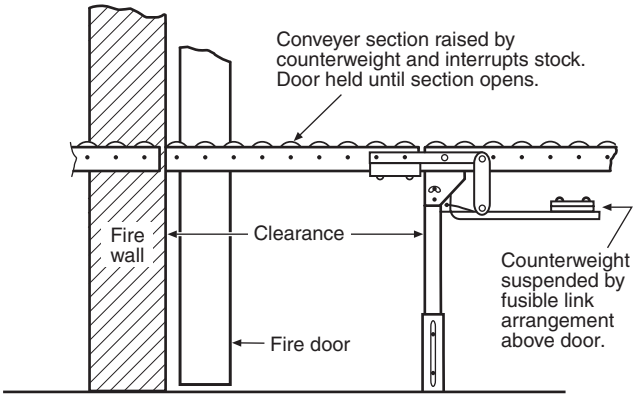


FIGURE 8.3.8 Counterweighted, Hinged Section of a Roller Conveyor

maintenance. Guidelines for design and installation include the following:

- Select a design that acts as simply and directly as possible. Emphasis should be on "fail-safe" operation.
- Program the sequence of operating steps and interlocks so that obstruction (conveyor or conveyorized material) to the door closure is positively and permanently—until manually reset—removed from the door's path before the door is released to close.
- Design structural and mechanical components, linkages, clearances, and so on conservatively. Counterweights, springs, and other operating forces that are uninterruptable by initial fire stages must have enough reserve strength to handle overload introduced by reasonably anticipated minor changes in configuration and weight of conveyorized material, normal wear, and friction. Major changes necessitate complete reengineering to ascertain design adequacy.
- Incorporate self-releasing features in conveyor component design, such as trolley track, chain, and supports.
- Maintain ⅜ in. (9.5 mm) clearance between the door and the sill.
- If advisable, provide another fire door on the opposite side of the opening to increase the reliability of the protection of the wall opening in the event of a fire. Similarly, when the property is sprinklered, consider reinforcing the protection of the opening by a water curtain from automatic sprinklers. Take care that sprinkler discharge does not impede the operation of fusible links on the fire door assembly. Water shields attached at the top of sprinklers below any ceiling sprinklers may be advisable.
- Following installation, conduct operating tests that reflect the range of varied adverse conditions anticipated to ascertain that all components operate smoothly, in proper sequence, within a specified time interval, and with adequate clearances and tolerances. Revisions to the installation may be necessary to correct deficiencies revealed by these tests.
- Close all fire doors during inoperative periods.
- Note that routine closure that simulates emergency operation can indicate the continued adequacy and reliability of the protection of the opening.

Friction and Overheating

The heat of friction can cause fires involving conveyors, such as those used for materials like raw cotton, grains, powders, and coal. This situation results from accumulated grease and dirt and overheating of defective or unlubricated parts, especially rollers and bearings. This common fire hazard is easily reduced and controlled by patrolling belts, by frequent equipment inspection, and by the removal of dirt and grease buildups on a frequency basis that is determined by routine inspections or patrols. Maintenance, including early replacement of old and worn parts, is also important. Maintenance and housekeeping should be included in any plant preventive maintenance program.

Bucket Elevators

Bucket elevators are used in bulk processing plants to convey loads vertically and are susceptible to the same fire hazards as mechanical conveyors. The same precautions need to be taken for temperature, dust control, protection of openings, and elimination of friction and overheating via maintenance and housekeeping. Elevators should be enclosed in substantial dust-tight casings of noncombustible construction; extend without reduction in size through the roof; and be fitted with light, weatherproof covers designed to lift readily and relieve explosion pressure.

Elevators should be installed close to an outside wall of the building and provided with short direct vents through the wall at 20 ft (6 m) intervals on tall elevator legs. Doors should be installed to provide access to head and boot pulleys and to facilitate housekeeping. All doors in elevator leg casings should be dust-tight. Ample clearance around elevator boots should be provided for cleaning and oiling. Safeguard elevators against overheating or choking by automatic releases actuated by overloading or a reduction in operating speed.

PNEUMATIC CONVEYORS

Pneumatic conveying is a common method of transferring powders and small solid particles from place to place in a building or from one building to another. This process presents an explosion hazard due to the ease and rapidity by which explosive proportions of dust can be introduced into the air.

Description of Systems

Pneumatic conveying systems consist of an enclosed piping system that normally transports material by an airstream with a velocity sufficient to keep the conveyed material suspended in motion. Noncombustible gases may be used in place of, or mixed with, air. (See Inert Atmospheres section.) These systems are of two principal types—pressure or suction—or a combination of the two types.

Pressure Systems. Pressure systems transport material using air at greater than atmospheric pressure. These systems basically consist of a blower that draws air through a filter, an airlock feeder that introduces materials into the system, piping or ducts, and a suitable air-material separator.

Suction Systems. Suction systems transport material using air at less than atmospheric pressure. These systems basically consist of a material and air intake, piping or ducts, a suitable air-material separator, and a suction fan or blower.

Conveyor Ducts

Conveyor ducts are fabricated of nonferrous, minimum-sparking metal or of nonmagnetic, minimum-sparking stainless steel. They are electrically bonded and grounded. Plastic or other nonconductive liners are not desirable but may be necessary, depending on the characteristics of the conveyed material. Where duct construction or liners are composed of combustible materials, automatic sprinkler protection within the ducts is often strongly recommended.

Inert Atmospheres

Inert gas is recommended in conveying systems wherever the concentration of powder or dust may come within the explosive range. The inert gas, such as nitrogen, argon, or helium, with a limited oxygen concentration based on the explosive characteristics of the particles in the system, is essential for preventing fires and explosions. Basically, it contains insufficient oxygen to permit combustion and no carbon monoxide, and it has a dew point such that no free moisture can condense or accumulate at any point in the system. The type of material being conveyed and the character of the inert gas dictate further limitations. For example, the inert gas for magnesium dust systems should not contain carbon dioxide. Oxygen limits of 3 to 5 percent should be maintained in aluminum powder systems using a controlled type of flue gas. Other limits are applicable where other inert gases and dusts are present. A continuous monitor is needed to sound an alarm if the oxygen content of the inert gas is not within the established safe range.

Various mechanical means of particle size degradation produce light metal and light metal alloy powders. These processes, as well as certain finishing and transporting operations, tend to expose a continuously increasing area of new metal surface. Most metals immediately experience a surface reaction with available atmospheric oxygen, which forms a protective oxide coating that then serves as an impervious layer to inhibit further oxidation. This reaction is exothermic, producing sensible heat. If a fine or thin lightweight particle having a large area of new surface is suddenly exposed to the atmosphere, enough heat will be generated to raise its temperature to the ignition point.

A completely inert gas will not promote operational safety and is not used for transport of light metal powder in a pneumatic or fluidized transfer device. This practice would be very unsafe because somewhere in the process of manufacture, packaging, or ultimate use, the powder is eventually exposed to the atmosphere where the unreacted surfaces react suddenly with available oxygen to produce sufficient heat to cause either a fire or an explosion. To provide maximum safety, a means for controlling oxidation of newly exposed surfaces is provided—as soon as they are exposed—by regulating the oxygen content of the inert gas. An inert gas containing a limited and controlled amount of oxygen is effective for this purpose. This mixture controls the oxidation rate, thus providing an environment that materially reduces the fire and explosion hazard.

Air Conveying

If the conveying gas is air, as it often is in atomizing, the dust-air ratio throughout the conveying system is held below the minimum explosive concentration of the metal dust. Although the metal-dust-air suspension may be held below the explosive concentration in the conveying system, the suspension necessarily passes through the explosive range in the collector at the end of the conveying system unless the dust is collected in a liquid, such as in a spray tower. Such wet collection is not always possible or desirable. Any liquid used must be nonflammable, nonreactive with metal dust, or reactive at a controlled minimum rate under favorably controlled conditions. The liquid remaining in or on the product must be compatible with subsequent processing requirements.

In an air conveying system, any dry collector must be considered an explosion hazard containing a dust-air mixture in the explosive range. It is, therefore, located in a safe place and provided with requisite barricades or other design means of protecting personnel. Construction should be of nonferrous, nonsparking metal or of nonmagnetic, nonsparking stainless steel. The entire system, particularly the collector, should be thoroughly and completely bonded and grounded. When checked with an ohmmeter, the ground system should show less than 5 ohms resistance to ground.

Where the conveying duct is exposed to weather or moisture, it should be moisture tight, because any moisture entering the system can react with the dust, generating heat and serving as a potential ignition source. A minimum conveying velocity is employed throughout the conveying system to prevent the accumulation of dust at any point and to pick up any powder that might drop out during an unscheduled system stoppage. If the

conveying gas is inducted into the system in a relatively warm environment and the ductwork and collectors are relatively cold, the gas temperature may drop below the dew point, causing condensation. To avoid this, the ducts and collectors should be insulated or provided with a heating means.

Relief Vents for Conveyor Ducts

Vents of sufficient area connected to ducts or openings protected with antiflashback swing valves and extending to the outside of the building can provide explosion relief. Care should be taken to limit the inertia of swing valves to the minimum required. Rupture diaphragms can be used in place of swing valves. Wherever damage may result from a ruptured duct, the duct is designed for a minimum internal working pressure of 100 psi (690 kPa) in case the relief vent fails to offer sufficient pressure relief. Where the duct is so located that no damage will result if it bursts, it may be of very light construction to intentionally fail as an auxiliary vent for the system.

Fan Construction and Arrangement

Fan blades and housings that are used to move air or inert gas in conveying ducts are constructed of conductive, nonsparking metal, such as bronze, nonsparking stainless steel, or aluminum. In no case should the design be such that it draws the dust through the fan before entering the final collector. Personnel should not be permitted within 50 ft (15 m) of the fan during operation. This means that the fan and associated equipment are shut down for oiling, inspection, or preventive maintenance. Appropriate lock out–tag out procedures (LOTO) should be followed. If the area must be approached during operation for a pressure test or other technical reasons, it must be done only under the direct supervision of competent technical personnel and with the knowledge and approval of the operating management. Ultimately, all fans in dust collector systems accumulate enough dust to be a potential hazard; for this reason, locating them outside of all manufacturing buildings is preferable.

It is good practice to equip fan bearings with suitable instruments for indicating the temperature or to monitor vibration. Such instruments are wired with an alarm device to warn of overtemperature or imbalance.

Sight Glasses

Avoid sight glasses in pneumatic systems whenever possible. If installed, they should be of noncombustible material that is not readily subject to physical damage. The ducting is supported above and below each sight glass so that the sight glass does not carry any of the system weight and is not, in itself, subject to resulting stresses or strains. The system's electrical bonding must be continuous around all sight glasses. The strength of the sight glass, its mounting mechanism, and its inside diameter are equal to the adjoining tube system. In pressure-type systems, connections between sight glass and tubing are butted squarely and fastened together with rigid, airtight couplings, connectors, or comparable devices. In suction systems, connections between the sight glass and tubing are butted squarely and sealed with approved sleeves extending a minimum of 3 in. (76 mm) above and below the sight glass and tubing connections. The sleeves are of a material with elastic properties that provide an airtight seal.

Air-Material Separators

Air-material separators should preferably be located outside the building and provided with lightning protection. Material discharge outlets are provided with positive choke devices. The separator should be electrically conductive and bonded. Exhaust air should be always discharged to the outside, except where provision is made to recirculate transport air directly back into the pneumatic conveying system. The air-material separators should be constructed of noncombustible materials and the cloth filters of low-hazard materials. Where using combustible filter media is necessary, flame-retardant treatment is desirable. In addition, the cloth filters should be housed in grounded metal enclosures, with provision for cleaning the filters. The construction of separators should eliminate ledges or other areas where dust may accumulate. (For additional information, see Section 8, Chapter 1, "Air-Moving Equipment.")

CRANES

Cranes are an essential and necessary part of many industrial or manufacturing operations where heavy materials must be lifted or moved. Many cranes, such as overhead traveling, gantry, tower, and bridge-type cranes, move along rails. Overhead traveling can be used effectively indoors or out, whereas gantry, tower, and bridge cranes are used mainly outdoors. Mounting other cranes on wheels makes them mobile. Cranes can be powered by electricity or by internal combustion engine drive. Normal safeguards and maintenance must be observed with these power systems.

Outdoor cranes are susceptible to damage by high winds, unless a positive means of anchorage is provided, in addition to the operating or service brakes. Large cranes that move along rails are generally provided with automatic or manual rail clamps. Other means of anchorage are crane traps, wedges, and cables. Anchorage and support are particularly necessary and advisable when a crane is not in use and unattended.

Crane operators should be thoroughly trained in the equipment's proper operation, including emergency action that may be necessary in a fire or other hazardous incident. The crane operator's cab should be of noncombustible construction and provided with an emergency means of egress. It should be kept free of oily waste, rubbish, and other combustibles. All electrical equipment should be in conformance with NFPA 70, *National Electrical Code®*, and securely mounted and maintained.

Portable fire extinguishers may be desirable in some operators' cabs. For large equipment, automatic fixed-piping extinguishing systems may be advisable.

SUMMARY

Materials-handling operations are found in nearly all industries. Although they can be considered critical to some occupancies, they are often incidental operations and do not always receive

the careful attention required for preventing fires. However, even an incidental operation can prove to be a major bottleneck, and if the materials-handling operation is shut down, it may have serious and/or lengthy impact on the overall production scheme, causing a large business interruption loss. Improper equipment selection, operation, and maintenance can result in ignition. Also, normally present hot surfaces, liquid and gaseous fuel handling, and high-amperage electrical equipment provide ignition and injury potential.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on materials-handling equipment discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 70, *National Electrical Code®*
NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 484, *Standard for Combustible Metals*
NFPA 505, *Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operations*

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Chapter 4

Automated Equipment

Revised by
L. Jeffrey Mattern

Chapter Contents

Overview
Automated Equipment Analyzed
Analysis of the Process
Design Solutions
Standards Related to Automated Equipment

Key Terms

automated equipment, automated shelving (carousel), automated systems, central processing unit (CPU), controller, electrical equipment, power network

Like many other facets of industry, automation has benefited greatly from the technological developments of the last few decades. Thirty-five years ago, automation was accomplished by use of large relay control panels. In 1969, programmable controllers (PCs) began to replace relays in the automotive industry. By 1971, other industries were using PCs. In 1977, microprocessor-based PCs were controlling automated processes. Today, automation has become very complex and sophisticated. A great deal of care is needed to design safe automated systems.

Programmable controllers have introduced new fire protection problems into the processes that they automate. This is because the PC has been given control over such things as flammable liquids flow, the position of combustible materials, the initiation of sparks and flames, the motion of friction-causing parts, and other potential sources of fuel and ignition. As a result, any kind of failure in the PC can cause a fire or explosion. This chapter addresses how to analyze and deal with the increased potential for fire or explosion with automated equipment. The chapter does not cover the hazards and protection of individual pieces of equipment that are included in other chapters of this handbook. Many of the issues raised are also germane to independently operated machines.

For related topics see Section 8, Chapter 1, "Air-Moving Equipment"; Chapter 2, "Chemical Processing Equipment"; Chapter 3, "Materials-Handling Equipment"; Chapter 8, "Industrial and Commercial Heat Utilization Equipment"; and Chapter 11, "Fluid Power Systems." See also Section 16, Chapter 5, "Sprinkler Systems for Storage Facilities."

OVERVIEW

Automated Equipment Defined

Modern automated machinery usually consists of many pieces of equipment acting in a coordinated manner without operating personnel control. These systems are commonly referred to as manufacturing cells or flexible manufacturing systems. Common examples include numerically controlled machine tools (NC), computerized numerically controlled machine tools (CNC), industrial robots, work-handling machines or systems, material/workpiece transfer equipment, and associated control and information-handling equipment. Automated systems also control many other types of processes.

Automated equipment is found in many different business and industrial applications. Although most often thought of in the robotic manufacturing frame of reference, it is also found in other areas of the industrial community. Other areas include material transportation and handling, weighing and filling operations, as well as packaging. The use of these types of operations is expanding dramatically.

Carousels

In some unique operations, incoming materials and subassembly parts are received, sorted, and stored in automated shelving systems referred to as carousels. These automated storage systems

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can be open grid shelf systems, typically between 8 and 12 ft (2.4 and 3.7 m) in height and 50 to 60 ft (15.2 to 18.3 m) deep or even deeper, which are referred to as horizontal carousels (Figure 8.4.1). A carousel can also, for example, be a "metal box" with rotating moveable shelves within it, with dimensions of 8 ft (2.4 m) wide, 6 ft (1.8 m) deep, by 12 ft (3.7 m) high. These carousels are referred to as vertical carousels (Figure 8.4.2).

Carousels often have plastic trays or bins on the shelves. Even when containing metal products or parts, the plastic containers create a formidable fire hazard in themselves. Additionally, the typical open-top containers, whether combustible or noncombustible, can collect water from automatic sprinklers and prevent the water from reaching the seat of the fire. Both of these conditions require special fire protection consideration in order to afford adequate protection.

Transportation and Handling

Another aspect of automated equipment is that associated with transportation and handling. This includes the packaging, palletizing, and storage of finished product. In this case, finished product is transported via a conveyor and loaded robotically into its shipping container, dispatched on a second conveyor to an automated palletizer, where shipping containers (for example, cartons) are loaded on pallets and then conveyed to a storage area. A conveyor then transfers the entire pallet into an automatic storage and retrieval system of high racks, often 80 to 100 ft (24.4 to 30.5 m) in height.

Hazards

A key hazard of this type of operation is the accumulation of pallets at the automatic palletizer. In addition to the design of adequate automatic sprinkler protection for the product storage racks, the storage of idle pallets at the palletizer requires a high-density automatic sprinkler system design to adequately control a fire involving this type of storage. See Section 16, Chapter 5, "Sprinkler Systems for Storage Facilities," for more information regarding fire protection of rack storage configurations.

FIGURE 8.4.1 Schematic of Horizontal Carousel (Source: Courtesy of SJF Material Handling, Inc.)

FIGURE 8.4.2 Schematic of Vertical Carousel (Source: Courtesy of SJF Material Handling, Inc.)

Another hazard is associated with conveyor systems that penetrate fire walls. The operational design of these conveyors must include arrangements to allow specially designed fire doors to close in the event of a fire.

The pharmaceutical, food processing, and various agricultural-type industries are among the largest users of automated equipment. Raw materials are blended into a specific formulation. The product then flows to a hopper, which feeds an automatic filling machine, which in turn places the exact amount of the product, likely by use of a load-cell, into the container, seals it, labels it, and then sends it on to the automatic cartoning unit (Figure 8.4.3).

Each application of automation must be reviewed for any hazardous situations it might introduce. This is done by reviewing both the PC as well as all aspects of the process being controlled.

Operation of Automated Systems

Automated systems consist of two or more machines grouped together to perform a series of operations on materials or parts.

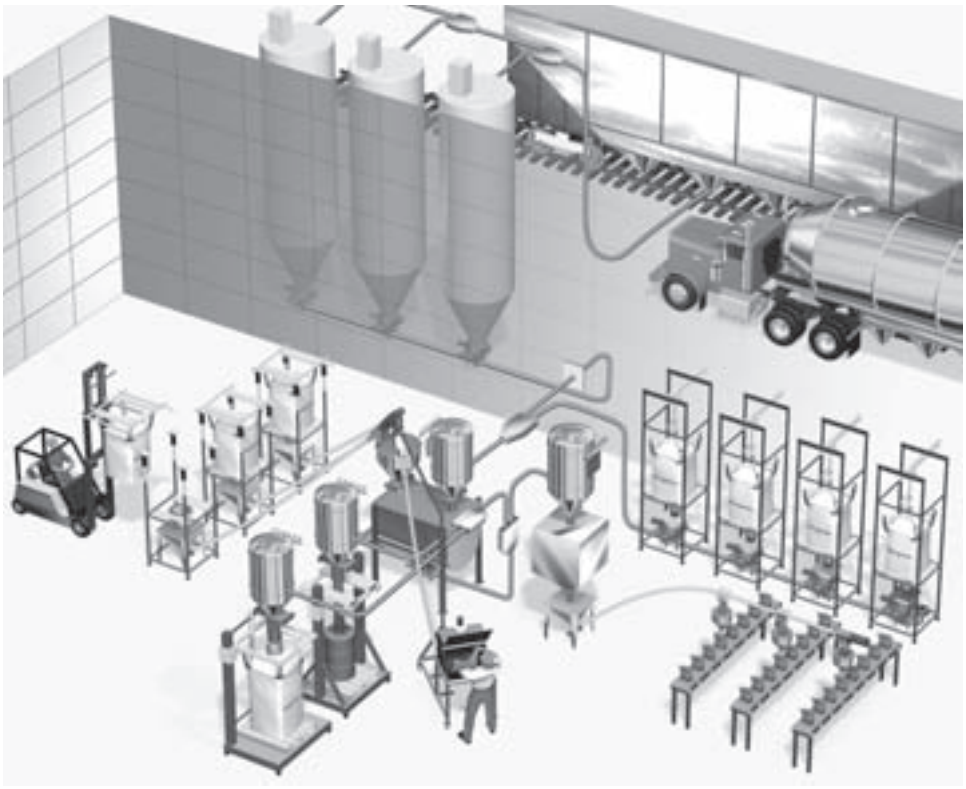

FIGURE 8.4.3 Conveying, Loading, Unloading, Weighing, Feeding, and Processing Bulk Solid Materials (Source: Courtesy of Flexicon Corp., http://www.flexicon.com)

Typically, these machines run automatically without an operator, or sometimes one person runs more than one machine. A supervisory controller (usually a computer) directs the interrelations between these machines, transmits information to the individual machine controllers, and monitors the process. The individual machine units (machine and controller) may be supplied by different vendors, thus requiring compatibility between the individual units and the supervisory controller. The issue of compatibility places additional responsibility on the manufacturer for proper installation, maintenance, and training of the end user. In addition, the machine controllers and the supervisory controllers utilize sophisticated computer equipment, operating in a real-time mode, that transmits large amounts of information at low levels and high speeds—conditions that require greater attention to the design, installation, operation, and maintenance of these systems.

AUTOMATED EQUIPMENT ANALYZED

Analysis of the Controller

Microprocessor-based PCs introduce failures never before dealt with in relay-controlled automation. The most common of these failures are described in Table 8.4.1.

Problems of personnel safety, power networks and distribution, grounding, electrical noise interference, software application and maintenance, and fail-safe requirements are more

TABLE 8.4.1 Programmable Computer Failures

CPU STALL	Processor ceases to execute the program.
INPUT/OUTPUT SCAN FAILURE	Processor fails to scan input/output signals for change in status.
INPUT FAILURE	Input module locks in "on" position and does not respond to further input changes.
ADDRESSING FAILURE	Processor fails to correctly consult input/output intelligence.
OUTPUT FAILURE	Output module locks in "on" position and does not respond to the controller.
MEMORY FAILURE	Incorrect bit in memory causes an improper instruction to be given.
WATCHDOG TIMER FAILURE	Timer controlling execution of instructions fails.
PROGRAM CARD FAILURE	Any problem with the program card occurs.
MOMENTARY POWER OUTAGE	Temporary loss of power to controller occurs.

evident in these integrated manufacturing systems. The introduction of PCs can also introduce fire or explosion potential by providing a new heat source into an area with easily ignited fuel. An example would be using a PC as an alternative to a relay control panel that didn't fit the space available, in an area subject to flammable vapors in the atmosphere. When this is done, the controller should be intrinsically safe as described in UL 913, *Standard for Safety for Intrinsically Safe Apparatus and Associated Apparatus for Use in Class I, II, and III, Division 1 Hazardous (Classified) Locations.*

Safety

The operation of integrated manufacturing systems is more automated than individual machines, in terms of starting motions and the transferring of material or parts, without operator intervention. Integrated systems can also cover more complex operations on larger areas of a factory floor or warehouse areas. It is, therefore, necessary to provide additional safety measures beyond those for conventional single-machine workstations. Typical measures include barriers and gates, presence-sensing devices, and visual or audible warning devices to announce pending machine operation and/or material movement.

Movement of a machine or workpiece and/or a material-handling device that occurs at unannounced times could catch personnel in a "pinch point" and result in a serious injury. Thus, the primary safety consideration is to keep personnel out of the work area while the system is operating. Enclosing the system in a cage or fence is one possible solution to the problem, but it is not always practical, since many systems require personnel in the work area during operation. Often it is not possible to determine if anyone is in the work area when the equipment is operating. One alternate solution in particularly hazardous work areas is to provide physical barriers and/or guards, interlocked with the individual controllers or the supervisory controller. All hazardous motions should be automatically stopped if the interlock is interrupted.

Another alternative is to provide presence-sensing devices, such as pressure-sensitive floormats or light-beam curtains, that will either stop all dangerous motions immediately or stop the automatic cycle once the motions in progress have been completed. Visual or audible annunciators that warn of pending axis motions or the cycling of auxiliary equipment also can be used if personnel must be in the work area during automatic operation.

Fail-safe travel limits, such as mechanical stops or hard-wired travel switches, should always be used in systems in which software controllers for individual machines or system monitoring are utilized. The fail-safe travel limits ensure that, if the controller should fail or a runaway condition should exist in either an axis motion or an auxiliary cycle, the motion would be physically restrained or the power would be removed from that motion. One added consideration involves the order in which the automated equipment is shut down. A sequential shut-down order may be necessary to ensure that a bad situation does not become worse.

ANALYSIS OF THE PROCESS

For some processes, failure of a PC will merely result in inconvenience. It is not unusual, however, for more serious problems to be introduced. For example, PC-controlled robot welders can destroy parts if the arc is not turned off at the right time. They could also ignite combustible materials that mistakenly end up in the area.

PCs controlling hazardous processes, such as spray painting, solvent drying, and fuel firing, also present many potential fire and explosion hazards. A PC failure could create hazardous conditions by not stopping paint guns, solvent introduction, or fuel flow.

Another complication of automated processing is the potential for interruption of production. In automated processes that cannot be run manually, PC failures will stop production. The length of time needed to repair or replace controllers must be considered. Off-the-shelf controllers are easier to replace than custom-made ones. Since off-the-shelf controllers would require reprogramming, software backup should be maintained in a safe location.

Power Networks and Distribution

Careful consideration must be given to the design of the automatic factory power network when large systems are installed. Busbars, which supply electrical power to machines and equipment that are highly inductive or utilize power converters, should be isolated from those that supply power to sensitive electronic equipment. Electrical noise on common power distribution lines or loss of phase can cause malfunctions or permanent damage to electronic equipment. Separate power buses, isolation transformers, and filtering devices are some of the techniques used to minimize the problems associated with power distribution. In some cases, it is necessary to monitor bus loading and automatically schedule the sequencing of particularly heavy electrical loads on the network.

Grounding

The grounding of electrical equipment has always been a consideration for the safety of personnel to guard them from electrical shock. In systems using sensitive electronic equipment, grounding is a primary concern to protect the controller and its input/output connections from the effects of electrical noise. The grounding of control equipment in industrial environments should be integrated by the equipment user into a coordinated ground system. When control equipment is grounded, it is interconnected into the system ground by building columns or ground rods.

In electrical/electronic controllers, there are usually subsystems that are tied to the ground system. It is essential that the noncurrent-carrying metallic enclosures be grounded, including all internal frames and equipment support structures. A specific ground point is provided within the enclosure for the equipment ground to make connection to the ground system. A separate tie point is provided to connect the control common (the zero potential reference point for the electrical and electronic

equipment) to the ground system. Having two separate ground reference points separates the two ground systems within the controller, eliminating ground loop problems. Providing two separate ground reference points within the enclosure allows the equipment ground to be connected to the building, whereas the control ground is connected to a separate ground rod independent of the building structure.

DESIGN SOLUTIONS

To ensure a high degree of reliability in programmable controller control functions, particularly those that are safety related, these functions should be either periodically checked for proper operation, continuously monitored, or be installed with either redundant or diversified circuits using independent circuitry. Input circuits, input/output addressing, and input/output scanning should be verified with a dynamic safety check, on the order of several times per second. Output devices, particularly those that control hazardous conditions, should be monitored and, in critical areas, designed using independent redundant circuits. The central processing unit (CPU) as well as output devices are monitored using a watchdog timer, which itself is provided with a dynamic safety check. Sum and parity checks are used on memories.

Above all else, the entire process control system must be designed to fail safely. The response to detection of PC abnormalities can be an alarm, the shutdown of chosen process functions, or both. However, if a PC failure can result in unsafe process conditions, the process should be safely shut down upon this failure. In other words, the system should be able to fail without serious consequences.

Process control devices that might fail in a shorted condition (e.g., rectifiers) can be arranged to be disabled manually. Critical controller functions can be independently hardwired to ensure the ability to operate properly in the event of failure.

Electrical Noise Interferences

Because entire books have been written on this complicated subject, only the most important considerations are covered here. The effects of coupling electrical noise into control equipment become more pronounced as the operating speed and equipment complexity increase, whereas the immunity to disturbances decreases. This is certainly the case with controllers applied to industrial automation equipment. The microelectronic circuits operate above 1 MHz, with harmonics in the range of 2100 MHz to 1 GHz. Signal levels are typically below 15 V. Noise coupling from disturbing sources, such as power inverters, motors, contactors, and relays, and associated wiring runs can be detrimental to the operating system unless proper techniques are used to reduce the disturbances or minimize coupling into the sensitive circuits. Commonly used methods of reducing the disturbing effects of electrical noise are (1) employing transformers or filters to isolate power wiring from signal and control wiring, and (2) shielding sensitive control and signal wiring by using shielded conductors or coaxial cable. Proper grounding of the shield (usually at only one end) is a must. For extremely sensitive circuits, the use of double shielding (one shield tied to the equipment ground and the other tied to the control common) may be required. Some circuits or subsystems may have to be entirely enclosed in a grounded shield.

Sensitive signal conductors should be separated to the greatest degree practical from noise sources. One example of this problem involves power leads that are run in the same cable or raceway as digital transmission or analog signal lines. Wherever possible, these lines should be in separate cables or raceways. When this is not possible, it is necessary to use shielding or additional conductors that are tied to the ground. Remember that all unused conductors should be grounded at one end to minimize coupling.

The effect of electrostatic discharge is another potentially serious problem that is often overlooked. Microelectronic devices (memory and logic chips) must be handled by personnel who are grounded by either a wrist strap or conductive plates located on the soles of their shoes. However, nonconductive materials (clothing, paper, etc.) in close proximity to the chips also carry an electrostatic charge that can be neutralized by ionized air. The precautions taken for handling microelectronic parts are typically discontinued once the chips are inserted into a printed circuit assembly. Although a completed printed circuit assembly will dissipate some of the charge, the chips are still subject to damage from electrostatic discharge. The grounding or discharging of personnel who are required to work with integrated circuits, including those who assemble, inspect, test, ship, or maintain the equipment, is important to ensure reliable operation of the electronic equipment. An electric charge of thousands of volts can be developed by simply getting up from a chair or paging through a set of schematic drawings. With the present technology, as little as 50 V of electric charge can permanently damage, degrade the performance of, or shorten the life of these components. In industrial systems employing thousands or tens of thousands of these devices, the potential for a malfunction or failure due to electrostatic discharge is very high and should be considered as serious a problem as shock hazard.

Software Application and Maintenance

The use of programmable electronic controllers and software programming has introduced a new series of problems that were not present with hardware systems. Failure modes and malfunctions are harder to detect and correct since the controllers must first verify the proper operation of the hardware and then test with application software. Since the software tends to be unique for each controller (one of the major advantages of programmable electronic controllers), elaborate testing and verification methods must be devised to ensure that the software functions properly under all dynamic conditions. This problem is compounded when the controllers must interact in a manufacturing system. Even if the software is properly certified before shipment to the end user, it is often modified in the field to correct for unexpected conditions of actual use. Many times, the corrected software is put into operation without a complete recertification, or, even worse, it is corrected at the job site without

being retested. In a large, complex system, the results of this "on-the-fly" modification method can be disastrous.

The typical failure mode being "failure to prevent a hazardous condition or situation" is another problem created by the introduction of electronic circuitry. Silicone-controlled rectifiers, triacs, and electronic switching devices usually fail in a shorted condition, resulting in such hazards as axis or auxiliary cycle runaway. Short of removing power to the portion of the system that has failed, the condition cannot be corrected. Typical methods of overcoming this problem are redundant circuits, hardwired contacts that can break the connection to the drives or motors that control motions or auxiliary cycles, or control circuits that monitor and automatically disable equipment that can create hazardous conditions.

The transmission of large amounts of digital information between system elements presents the potential of system malfunctions if the data are not properly received. Wrong axis commands, machine conditions, or even entirely incorrect part programs might be sent or received. Since there is no operator intervention before machine or controller action is initiated, injury can result to personnel or damage can occur to the machine or the work in progress. Redundant transmission or error checking and correction are means of reducing the effects of this problem. Proper shielding and protection of these transmission lines is mandatory if these problems are to be kept to a minimum.

STANDARDS RELATED TO AUTOMATED EQUIPMENT

A number of standards have been or are in the process of being developed that relate to factory automation and address subjects previously covered in this chapter. ANSI B11, *Construction, Care, and Use of Machine Tools,* correlated the hazards to persons created by various types of machine tools and the measures to be used to ensure minimum exposure to these hazards. A standard on safety issues related to manufacturing systems/cells (ANSI B11.20, *Safety Requirements for Construction, Care, and Use of Machine Tools, Manufacturing Systems/Cells*) has been developed. This standard deals with the hazards and their associated risks created from the interaction of a number of machines working in a coordinated manner to produce discrete parts or assemblies. There is also a safety standard for robots, developed by a committee sponsored by the Robotics Industries Association (RIA). In turn, these standards incorporate the electrical requirements found in NFPA 79, *Electrical Standard for Industrial Machinery.*

Internationally, safety standards have been developed to encompass industrial manufacturing systems and robots, as well as electrical equipment of industrial machines. International Organization for Standardization (ISO) Technical Committee 199 is responsible for basic safety standards related to machinery. International Electrotechnical Commission (IEC) Technical Committee 44, electrical standard IEC 60204-1, *Electrical Equipment of Industrial Machines—Part 1: General Requirements,* has been adopted as a European standard as part of a series of standards used to support the European Directive (law) 98/37/EC, on machinery safety. The Machinery Safety Directive has been in full effect since January 1, 1995, and affects all machinery manufacturers that are marketing their products in the European Union.

Within Europe itself, a number of standards related to general requirements for machines and machining systems have been or are in the process of being developed. These include requirements for machines, such as machine tools, rubber and plastic machines, and material-handling systems, as well as various types of devices, such as light screens, two-hand control, and interlocking devices. It is anticipated that much, if not all, of the research in Europe related to safety of machinery will be elevated into the international standards community (ISO and IEC) within the next few years, making it vital for the United States to participate in these activities, if U.S. industry does not wish to be severely affected in its ability to sell machinery and related products.

Standards related to programmable controllers have been developed by an IEC technical committee. These standards are divided into two series. The first covers such topics as operating conditions, input/output structures, and programming languages. The second is directed toward safety issues, including both hardware and software. There are no corresponding U.S. standards on programmable controllers, since all effort in this area has been focused on IEC activities.

There is also a new European directive on electromagnetic compatibility (89/336/EEC), which went into effect on January 1, 1996. This directive requires that all electrical equipment (with few exceptions) must not generate sufficient electrical fields to disturb other electrical equipment, and, at the same time, must not be susceptible to effects of electromagnetic interference (both electric fields and common mode) and electrostatic discharge in such a manner that a malfunction or failure of the equipment will result. Both European and IEC standards are being developed to provide guidance on the levels of emission and immunity, means for reducing the effects of electromagnetic interference, and testing methods.

The Institute of Electrical and Electronics Engineers (IEEE) has produced a standard on electrical interferences: IEEE 518, *Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources,* which covers various types of noise that can affect the operation of electrical equipment (e.g., common mode, electromagnetic, and electrostatic) and aims to reduce the effects of these interferences.

Considerable effort both in the United States and internationally has been expended on the encoding and transmission of digital information over industrial networks. The most prominent of these activities is the manufacturing automation protocol (MAP) specification, which is based on the international open system interconnection (OSI) model. Coupled with this work are the series of international standards on the manufacturing message specification (MMS). Adjunct to this work is standard IEC 61491 on the digital transmission of encoded serial information between machine controllers and drives.

Fire Protection Evaluation

As discussed throughout the chapter, there are many safety and fire protection considerations related to automated equipment. In addition to those already discussed, another concern is that

some of the industrial assembly operations contain hydraulic oil–operated equipment or central lubrication systems. In both cases, the oil, if not of the less-hazardous type, can present a severe fire exposure.

The oil tank and pumps ideally should be in some type of fire resistance rated enclosure so that the potential for a spray fire at the oil pump or a catastrophic spill at the tank is reduced. It is also important to consider that an oil spray fire may occur at the end point. These types of leaks can be detected by a low-level switch on the oil tank, but additional detection should be provided by the use of heat detection over the area where high-pressure oil piping is located. The heat detection is then interlocked to the hydraulic or oil lubrication pump and arranged for automatic shutdown when the heat detector is activated. (See Section 8, Chapter 11, "Fluid Power Systems.")

Fire protection for the area should also take into consideration the normal occupancy hazards present, such as in-process goods storage, rack storage in warehouses, and general work processing operations. The hazards outside the scope of those associated with the automated equipment may be greater than those of the automated equipment itself.

SUMMARY

Automated systems typically consist of two or more machines grouped together to perform a series of operations on materials or parts. In 1977, microprocessor-based programmable controllers (PCs) began controlling automated processes. Because PCs have been given control over potential sources of fuel and ignition, such as flammable liquids flow and position of combustible materials, they have introduced new fire protection problems into the processes they automate. This chapter has looked at how to analyze and deal with the increased potential for fire or explosion with automated equipment.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on automated equipment discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 70, *National Electrical Code®*
NFPA 79, *Electrical Standard for Industrial Machinery*
NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*

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Chapter 5

Lasers

Revised by
Fred P. Seeber

Chapter Contents

Laser Properties and Components
Laser Operation
Hazard Classification of Lasers
Hazards and Control Measures

Key Terms

electrical shock, flammable gas, hertz, laser, laser safety officer (LSO), maximum permissible exposure, monochromaticity, optical spectrum, reactive gas

Lasers have become a common part of life. To increase fire protection practitioners' understanding of lasers, this chapter examines how lasers work, their fire hazards, their safety classifications, and several hazard protection measures. Lasers have many applications, for example, in medicine, industry, and education. One of the most widely used applications of lasers is their use to scan product codes for identification and pricing. In the business world, lasers are used in printers and in CD-ROM drives in computers. In the entertainment industry, lasers are used to record music, movies, and special movie effects and to present public displays at theme parks. The medical field has taken advantage of lasers' properties for use in surgery. Additionally, veterinarians have also used lasers on their patients. In the construction industry, lasers are used for measuring distances and maintaining alignment for pipes, tunnels, ceilings, and floors. Manufacturers use lasers to cut, weld, and drill in items as diverse as metal, paper, and fabric. Lasers also have significant roles in research and military applications.

A primary benefit of lasers can also be a significant fire hazard. Lasers that are powerful enough to be used to cut, weld, and drill are an ignition hazard. Without proper attention and controls they can start fires. The laser itself also has potential fire concerns from the use of flammable liquids and gases, as well as high-voltage electrical components. Ideally, laser fire protection is achieved through physical controls. However, in certain fields, particularly the medical industry, administrative controls are the primary fire protection measure.

Further information on lasers can be found in Section 6, Chapter 11, "Medical Gases." The Bibliography references other applicable sources of information.

LASER PROPERTIES AND COMPONENTS

Laser Defined

The word *laser* is an acronym for "light amplification by stimulated emission of radiation." The radiation referred to in the acronym should not be confused with ionizing radiation associated with radioactive materials; rather, it refers to the broad spectrum of electromagnetic radiation that includes infrared light, visible light, and ultraviolet light.

Visible light is one form of electromagnetic radiation. Other forms of electromagnetic radiation—such as radio waves, ultraviolet light, and microwaves, which differ in frequency and wavelength—are not visible to the human eye.

All forms of electromagnetic radiation taken together produce the electromagnetic spectrum. Different portions of this spectrum describe the frequency and wavelength of the various electromagnetic wave forms (Figure 8.5.1).

Wavelength, which refers to the distance between peaks on a wave or the distance for the wave to complete one cycle, is measured in meters, micrometers, and nanometers. Frequency refers to

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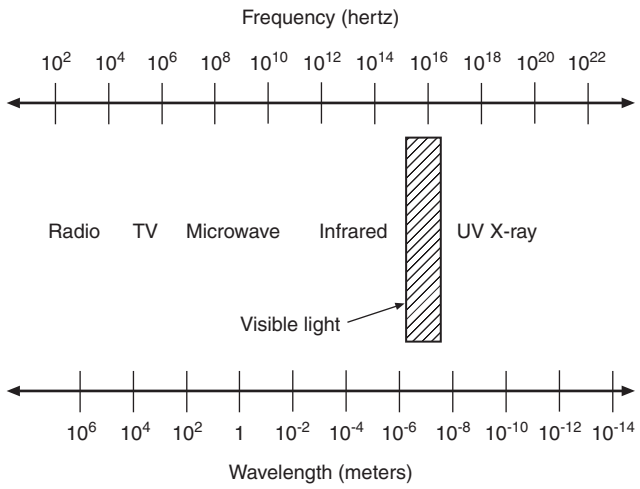

FIGURE 8.5.1 Electromagnetic Spectrum

the number of cycles the wave completes in one second. A *hertz* is one cycle per second and is the normal term of expression for frequency.

Figure 8.5.1 shows that low-frequency, long-wavelength radiation is found at the low end of the spectrum, whereas high-frequency, short-wavelength radiation is found at the high end of the spectrum. Examples of low-frequency, long-wavelength radiation are radio waves, television waves, and microwaves. Examples of high-frequency, short-wavelength radiation are ultraviolet light and x-rays. Radiation visible to the human eye in the form of light makes up a small portion of the entire spectrum. Figure 8.5.2 illustrates the visible light range within the electromagnetic spectrum.

The study of laser light is generally concentrated in the optical spectrum, or that portion of the electromagnetic spectrum from infrared to ultraviolet light, which includes visible light. Infrared radiation is radiation with wavelengths ranging between 10^{-4} and 10^{-6} m. The word *infrared* comes from the fact that the wavelengths are longer than the visible red end of the spectrum. Visible light has a wavelength between 400 and 700 nanometers (a nanometer is one billionth of a meter), as shown in Figure 8.5.2. The eye is most sensitive to green and yellow colors in the range of 555 nanometers and least sensitive to blue and red near their respective ends of the electromagnetic spectrum. Ultraviolet light is that portion of the electromagnetic spectrum with wavelengths between 10 and 400 nanometers, just beyond the visible portion of the electromagnetic spectrum at the violet end.

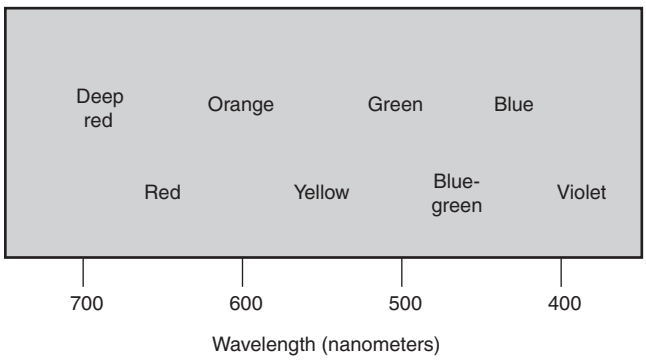

FIGURE 8.5.2 Visible Light Spectrum

Properties

Laser light has several unique properties. One of those properties, called monochromaticity, is that laser light consists of only a single color. In addition, the wavelengths of this single color are within a very narrow range. A second property is directionality. Normal light is radiated in all directions in random fashion. Laser light, however, is radiated in a narrow beam in a single direction. The third unique property of laser light is coherence. Laser light is radiated in an orderly pattern known as being "in phase." When all the separate waves are in phase, the resultant combination wave is much stronger because of constructive interference. Thus, laser light is a very intense light of a single color, being radiated in a single direction, with little divergence. It is these properties that give laser light its diverse applications and its hazards.

Components

A laser, then, must be constructed of components that can produce the necessary photons in sufficient quantities to produce a useful light beam. Lasers generally consist of three components: (1) a lasing medium, (2) an energy source (or pumping system), and (3) a feedback mechanism. Other accessories, such as lenses, mirrors, Q-switches, mode-lockers, and shutters, might be added to the system to produce special effects, but only the basic three are needed for lasing action.

Lasing Medium. The lasing medium is a collection of atoms that can be excited to a state to produce a stimulated emission of photons. The active medium may be a solid, liquid, or gas, or a semiconductor material. Some examples are ruby and Nd:YAG crystals; CO_2, Argon, and Excimer gases; and InGaAsP semiconductor materials.

Energy Source. The pumping system is a source of energy that can be used to raise the electrons in the lasing medium to their excited state. The pumping system can take one of several forms: (1) optical pumping systems use strong sources of light, such as xenon flashtubes or flashlamps, or a continuous arc lamp; (2) electron collision pumping is created when an electric current is passed through the laser material; or (3) chemical pumping is created by the making or breaking of chemical bonds. All of these forms of pumping are commonly in use. Other lasers are also used as an energy source.

Feedback Mechanism. The feedback mechanism is an apparatus that returns a portion of the laser light created in the lasing medium back to the lasing medium. This feedback creates a situation where the photons created in the lasing medium are passed back through the lasing medium, creating more photons. If suffi-

cient feedback is created, the creation of laser light can be made continuously and at high levels. The normal feedback mechanism is a pair of mirrors aligned to reflect the laser light back and forth. One of the mirrors is only partially reflective, permitting some light to leave the laser. The portion of the light that is not emitted continues to be reflected, creating more photons.

LASER OPERATION

Operation Steps

Laser operation can best be described in three steps:

1. Energy is supplied to the laser material by the pumping system. This energy is stored by the laser material in the form of electrons in their excited state. The pumping system must continue until a population inversion (i.e., more electrons in the excited state than in their normal state) takes place for laser light to be produced.

2. Once the population inversion is achieved, the decay of a few electrons to a lower energy level will start a chain reaction. Photons released will strike electrons, creating more photons of the same wavelength, phase, and direction.

3. When the photons reach one of the mirrors, they will be reflected back into the laser material, supporting continued chain reaction and the production of even more photons. Some photons will strike the partially reflective mirrors; when that occurs, some of them will be reflected back into the laser material and some will be emitted as laser light in the form of the beam.

Energy Delivery Rate

The modes of laser operation are differentiated by the rate at which energy is delivered. Some lasers produce a steady flow of light. These lasers are known as continuous wave lasers, or CW lasers. Pulsed lasers are operated to create repetitive laser pulses. A special type of pulsed laser is a Q-switched laser. In the Q-switched laser, a shutter-like device is placed between the mirrors of a laser to interrupt the lasing action. The shutter can act as a mirror in itself, allowing the continued reflection of photons and buildup of excited electrons, but not allowing any photons to escape through the partially reflective mirror. When the shutter opens, a very intense pulse is released.

HAZARD CLASSIFICATION OF LASERS

The American National Standards Institute (ANSI) has adopted a classification system for lasers, based on the ability of the primary laser beam or reflected primary laser beam to cause biological damage to the eye or skin during intended use. The hazard classification categories use maximum permissible exposure (MPE) to laser radiation as a threshold for determining potential hazard.

Old ANSI Laser Classification System

The old ANSI classification system found in the Z-136.1 (2000) follows:

Class 1. Low-powered laser devices that cannot, under normal circumstances, emit laser radiation that creates an optical hazard. These are sometimes called exempt lasers. (See note after Class 4 lasers.)

Class 2. Low-powered laser devices operating in the visible spectrum that cannot injure a person accidentally, but that might injure the eye when viewed directly for an extended period of time.

Class 3. Medium-powered laser devices that are capable of causing eye damage with short-duration exposures to the direct or specularly reflected beam. Occasionally, some upper level Class 3B lasers could be considered a fire hazard. These lasers would be in the half watt range of power.

Class 4. Lasers that can cause injury if viewed directly or if specular and diffuse reflections are viewed. These lasers can also cause severe skin damage and are considered a fire hazard. *Note:* Some Class 4 lasers are called "embedded lasers" and given a lower classification. They still have the same inherent fire risk due to the power of the beam. However, because of engineering controls, they do not have the same risk of laser radiation hazards as the normal Class 4 laser.

New ANSI Laser Classification System

The new ANSI laser classification found in the Z-136.1-2007 and the International Laser Safety Standard IEC 60825-1 follows.

Class 1. Class l lasers or laser systems may produce visible or invisible laser radiation. Under all normal conditions of operation, Class 1 lasers are considered to be incapable of causing injury when the beam is viewed directly.

Class 1M. Class lM lasers may produce visible or invisible laser radiation. A Class IM laser or laser system is considered to be incapable of producing hazardous exposure conditions during normal operation unless the beam is viewed with an optical instrument such as an eye loupe (diverging beam) or a telescope (collimated beam). Such viewing is prohibited by this standard.

Class 2. Class 2 lasers produce low-power visible laser radiation. The output power of a Class 2 laser does not exceed 1 mW and eye protection is normally afforded by the natural blink reflex time (0.25 sec), also called *natural aversion.* Direct viewing of Class 2 laser radiation is prohibited.

Class 2M. Class 2M lasers or laser systems emit visible laser radiation. Eye protection is normally afforded by the natural blink reflex time (0.25 sec); however, direct viewing of Class 2M laser radiation with certain optical aids is potentially hazardous and is prohibited.

Class 3R. Class 3R lasers produce moderate levels of visible or invisible laser radiation and require more stringent controls than

Class 2 lasers. The CW output power of a Class 3R visible laser is between 1 and 5 mW, and the normal aversion response is generally sufficient to prevent injury from inadvertently viewing the output with the unaided eye. However, the use of collecting optics, for example, binoculars, can produce retinal irradiances that are considered capable of causing injury. Optically aided eye exposure to Class 3R lasers that produce ultraviolet or infrared emissions may not be perceived by the eye at the end of injury. For such lasers, the Class 3R accessible emission limit does not rely on the normal aversion response, but rather on the fact that the eye does not fixate on the beam long enough to cause injury.

Class 3B. Class 3B lasers may produce visible or invisible emissions. The output power of CW visible and infrared Class 3B lasers range from 5 to 500 mW. They are considered medium-power lasers and are capable of producing eye injury when they are viewed directly or with optics, even if viewed momentarily. For visible Class 3B lasers, the normal aversion response (0.25 sec) does not prevent injury. Class 3B lasers do not usually produce a hazardous diffuse reflection or fire hazard. At the upper end of the Class 3B range, skin burns may be possible and also under some circumstances a fire hazard.

Class 4. Class 4 lasers are visible or invisible lasers emitting radiation capable of causing injury to the eye and skin as well as producing dangerous specular and diffuse reflections. They can also produce a fire hazard.

HAZARDS AND CONTROL MEASURES

In addition to the biological hazards classified by the ANSI system, lasers produce several other hazards—namely, electrical, ignition, flammable liquid, and flammable and reactive gas hazards—that must be considered.

Electrical Hazards

The most common hazard associated with lasers of all types is the electrical shock hazard. Almost all lasers contain high energy power supplies. These power supplies can produce both electrical shock hazards and, as in all electrical pieces of equipment, fire hazards. Using normal electrical safety devices—fuses, circuit breakers, insulation, grounding devices, and interlocks—and following standard maintenance guidelines can effectively control these hazards.

Many lasers use capacitors. Capacitors store electrical charges, with the intent to release high electrical charges in a very short period of time. Inadvertent discharge of capacitors is, therefore, extremely dangerous. Shorting or internal electrical faults can cause capacitor rupture, fires, or explosions. Because of these possible hazards, capacitors require certain safety precautions. Capacitors should be isolated within screens, shields, barriers, or uninhabited rooms designed to protect against shock, burns, and fire, and to contain fragments from an explosive capacitor failure. Covers or doors to capacitors should be interlocked to prevent charging (when open) by dumping and grounding the capacitors.

Ignition Hazards and Controls

The beam from Class 4 lasers and some Class 3B lasers is powerful enough to ignite combustible materials. The ignition hazard applies in all applications of use, including health care, industrial, manufacturing, commercial, research, and military. Some lasers are embedded lasers and are considered Class 1 lasers by the ANSI classification system. They are, in fact, a higher-class laser (generally a Class 4 laser), and the beam is a fire hazard.

Many different precautions can be taken to minimize the potential for fire from the laser beam ignition hazard. Some of them are engineering controls; however, the majority of the precautions are administrative, directed by a knowledgeable laser safety officer (LSO). Examples of these controls are instituting standard operating procedures (SOPs), providing warning signs, and mandating use of personal protective equipment. In addition, the beam intensity profile and alignment should be verified prior to use, appropriate beam stop materials should be in place, and attention needs to be given to the materials adjacent to the laser beam to ensure that they are not combustible.

Particular attention is required when using lasers in the health care field. The laser beam (which should be treated as though it were an open flame or other ignition source) is used in conjunction with many combustible materials.

The database established by the NFPA Technical Committee on Laser Fire Protection has recorded many case studies of laser fire incidents. With the exclusion of some metals, no material is "fire safe" around lasers. In the medical field, flammable anesthetic gases are still used in research in the United States and in some other countries.

CASE STUDY: Laser Ignites Bronchoscope and Endotracheal Tube During a Tracheal Stenosis Procedure. In 1997, during a tracheal stenosis procedure in a southwestern U.S. hospital, a nonfire-resistant endotracheal tube (ETT) was inserted into the patient's trachea, followed by a bronchoscope to view the area to be treated. A 0.6 mm laser fiber was then inserted through a biopsy port and positioned about 5 mm beyond the distal tip of the bronchoscope and then connected to a KTP/YAG laser. The oxygen concentration in the lasing area was about 100 percent. Combustible material included the ETT, the bronchoscope, and the outer coating of the fiber.

About midway through the procedure, the surgeon saw a flash of light related to a fire in the patient's throat and terminated the procedure. An investigation determined that the products of combustion had turned the inside of the ETT black and that the portions of the outer and inner coatings of the bronchoscope had melted. The laser functioned normally and the fiber was reusable, but it was not known how many times it had been used previously. The fiber was not stripped and cleaved prior to use. Investigators identified the ignition point as near the tip of the fiber and determined that ignition was most likely due to a fracture at the tip or a piece of the outer coating of the fiber lying slightly over the tip of the catheter.[1]

Flammable Liquid Hazards and Controls

Lasers can use flammable liquids as part of the process. In particular, dye lasers use a lasing medium of a complex fluorescent organic dye dissolved in an organic solvent as part of the process of exciting selected atoms. Often the organic solvent is a flammable liquid. Many of these lasers use only 1 qt (1 L) of solvent. Others use from 5 gal (20 L) to hundreds of gallons (liters) of solvent. In the event of a spill, there are ignition sources present, such as the laser beam itself and electrical components.

Many of the protective measures for handling flammable liquids are already well documented. It is important to incorporate into the design or installation a means of containing a spill. Pumps, motors, and other electrical components should be appropriately rated for the application or designed as intrinsically safe. Use of metal tubing instead of plastic tubing for the flammable liquids is suggested.

Compression-type fittings are recommended for flammable liquid lines instead of slip-on friction fittings without clamps. The integrity of tubing and connections should be checked periodically. Good housekeeping is necessary in these areas. Warning signs appropriate for the flammable liquids should be posted. Storage should follow accepted practice for flammable liquids. During cleanup and disposal, it needs to be recognized that the waste still has the properties of a flammable liquid. For larger-volume laser systems, the fire protection measures are similar to any industrial process using large quantities of flammable liquids. Methods to monitor the volume level, flow, and pressure of the systems should be installed. Consideration of the adequacy of the ventilation in the area is required. Remote shutdown capability should be incorporated into the system design.

Flammable and Reactive Gas Hazards and Controls

Occasionally, lasers use flammable or reactive gases. These gases should be checked to determine whether they are used in their pure form or mixed with an inert gas, for example, Excimer lasers. The smallest quantity and percentage of gas appropriate for the system should be used. Whenever possible, the gases should be stored outside the building or in a ventilated gas cabinet designed for that purpose. The ventilation in the area where the gases are used should be assessed to determine the consequences of a gas leak; that is, whether it is possible for the area to be within the flammable range for the particular gas. The integrity of the piping systems should be checked at regular intervals.

Consideration should be given to the installation of combustible gas detectors designed to activate at 25 percent of the lower flammable limit. Exhaust vents from gas piping should be located away from air intakes. The exhaust gases might need to be mixed with an inert gas, depending on the hazard. Care is required to ensure that the exhaust gases do not stagnate in the exhaust piping system. The regulator for the gas should not be used as a flow control valve; a supplemental valve should be installed. All piping should be labeled to identify specific contents. The general vicinity of the gases should have signs indicating the hazard. Emergency shutdown of the gases should be built into the system at the gas supplies and at another remote location.

Laser Safety Officer

It is recommended that any sites using lasers and laser systems and associated equipment have individuals who are trained and knowledgeable of laser safety hazards and fire safety practices. This individual is the laser safety officer (LSO). Only personnel trained by the LSO on the lasers should be permitted to use them. Other documents should establish training requirements for laser use. Maintenance should be performed only by knowledgeable personnel. A log of both the user and the maintenance activity should be kept. Manufacturers' recommendations and precautions should always be considered.

Emergency Response

Prior to using a laser that is considered a fire hazard, appropriate personnel should be familiar with emergency procedures. Issues to consider are the location of exits, emergency panic shutdown buttons, laser shutdown procedures, notification procedures, and location and use of fire extinguishers. Personnel in the vicinity of lasers generally have duties different from those involved in fire fighting; therefore, training about what to do in a fire is important. Responding fire fighters should be made aware of the hazards involving lasers.

SUMMARY

Lasers are a part of everyday life and are beneficial for humanity. However, adequate precautions must be taken to minimize their fire hazard. In particular, Class 4 lasers, embedded lasers (however they are classified), and some Class 3 lasers have significant fire safety concerns. The laser beam itself is an ignition hazard, and other products used in the process to generate the laser beam and laser procedures are fire hazards. It is important that those involved with using lasers are aware of the fire hazards and take appropriate control measures. With proper attention, lasers can be used in a fire-safe manner.

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NFPA Codes, Standards, and Recommended Practices

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NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 70, *National Electrical Code®*
NFPA 75, *Standard for the Protection of Information Technology Equipment*
NFPA 99, *Standard for Health Care Facilities*
NFPA 115, *Standard for Laser Fire Protection*

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Chapter 6

Protection of Electronic Equipment

Revised by
Brian P. Rawson

Chapter Contents

Information Technology (IT) Systems
Physical Facility, Location, and Construction
Equipment and Installation Features
Fire Protection
Automatic Sprinkler System
Special Extinguishing Systems
Smoke Alarms
Emergency Plans and Procedures

Key Terms

automatic sprinkler system, clean agent, electronic equipment room, information technology equipment, smoke alarm, uninterruptible power source

In 1953, the first commercial electronic computers made their debut and started to take on the tasks of their mechanical predecessors: punch card sorters and tabulating machines. The jobs that they performed at a much faster rate were the same, primarily related to the repetitive routines associated with accounting and inventory. Electronic data processing (EDP) was born and computer users often relabeled responsible departments as EDP. In the decades since, the electronics, computer hardware, and application programs have evolved at incredible rates. The data to be processed are actually all types of information from audio files and bank account numbers to travel reservations and real-time video. In recent years, the term *data processing* has again transformed to become information technology (IT). IT is a collective term that can be defined as applied electronic computer systems comprising both hardware and software, and often including wired and/or wireless networks and telecommunications, usually in the context of a business or other enterprise. This chapter examines the equipment, location, and construction features of IT systems and the factors and features involved in the protection of these systems from fire.

Other information relevant to protecting computers and electronic equipment from fire may be found in Section 9, Chapter 8, "Protection of Records"; Section 14, Chapter 1, "Fire Alarm Systems"; and Section 14, Chapter 2, "Automatic Fire Detectors."

INFORMATION TECHNOLOGY (IT) SYSTEMS

IT Centers and Equipment

The electronics hardware that comprises an information technology center is not just computers. The hardware includes an extensive selection of specialized devices that are connected together and configured to analyze, collect, distribute, manage, and store information. Some commonly recognized system hardware component types include, but are not limited to, blades or blade centers, computers, converters, local area networks (LAN), direct access storage devices (DASD), magnetic tape libraries, processors, routers, servers, storage area networks (SAN), and switches.

In addition to the actual information technology electronics, there is also a variety of support equipment required such as computer rated air-conditioning (CRAC) units, electrical power distribution units (PDU), and uninterruptible power system (UPS) units. Typically, all the equipment necessary to form a functional IT system would be installed in a special location referred to as an IT equipment room. In the context of building codes, this classification carries the responsibility of compliance with specific room design and construction. Figure 8.6.1 provides a graphical representation of some of the equipment that may be found in the makeup of an IT equipment room.

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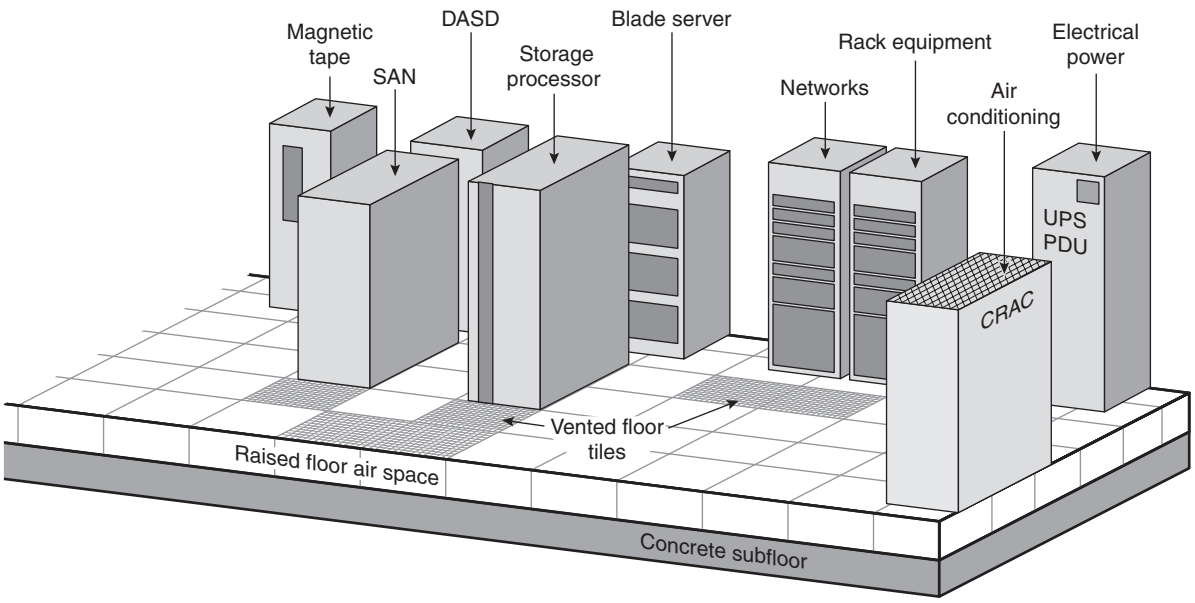

FIGURE 8.6.1 Equipment That May Be Found in an IT Equipment Room

Special Electronics

Besides IT equipment, there are also other sensitive electronics that people and business have come to depend on. Communications and control equipment play a vital role in our daily lives. Automation of one type or another permeates our world and is so commonplace that to many it has become invisible. Most large-scale manufacturing incorporates electronics and microprocessors to control assembly lines and robotics. Medical and scientific research also relies on highly specialized electronic equipment. Special electronic equipment is vital in the development, fabrication, and testing of semiconductors.

These special electronics are no longer relegated to business and government. The personal computer (PC), introduced in the early 1980s, has become a household necessity. Today there are over 800 million PCs in operation worldwide. Despite the growing numbers of PCs and the direct relationship between most of the business and home PCs and the larger, more complex, commercial computer systems through connectivity via business networks or the Internet, this chapter does not address the home computer. The focus is, instead, on the commercial and enterprise systems to which the business and home computers may communicate and with which they may transfer information. There is a strong and growing dependency for the commercial IT systems to be available to communicate with these remote PCs. Today, in the comfort of our own homes, we can do many tasks online. We have moved from fear and uncertainty to an almost total embrace of the online world.

Availability as an IT System Objective

Availability is an important objective of IT systems. Whether we learn, shop, or work from our PCs, we expect the IT systems to be available. This availability is key to the existence of many businesses. Business resilience practices examine the various potential interruptions and disruptions that could impact availability and service to clients. Among those is the threat of fire. Fire protection cannot be overemphasized. Because we have become so dependent on electronic systems, information technology centers can be attractive targets for arson and sabotage. Advances in technology allow for several backup and recovery strategies in the event of an interruption. The highest level of backup requires a fully redundant remote site, with mirror image application software and equipment hardware and real-time updates of information/data. This level of backup is not economically feasible for every IT system owner. There are less costly methods of providing backup and recovery, but each has a trade-off of time and/or lost information. IT system owners must evaluate their availability objectives along with a risk assessment and determine which strategies best fit their financial capabilities.

PHYSICAL FACILITY, LOCATION, AND CONSTRUCTION

State-of-the-art IT equipment hardware is designed with a very high level of reliability. Some electronics equipment has projected mean time before failure rates of over 100,000 hours, or 11.4 years, of operation, provided the intended operating environment is maintained. This reliability is well beyond anticipated need because electronics technology performance advances at a much faster rate of 1.5 to 2.0 years. Electronic equipment may be replaced or upgraded on a similar schedule with entire systems being replaced over a 5- or 6-year period.

Physical Facility and Location

Electronics and IT hardware are sensitive and are designed to be installed and operated in a specific environment that provides for optimum performance and reliability. Because the equip-

TABLE 8.6.1 Structure Fires Excluding Homes Originating in Electronic Equipment Rooms, by Year

				Direct Property Damage (in Millions of Dollars)	
Year	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*As Reported*	*2003 Dollars*
1980	1400	0	31	27	60
1981	1400	0	69	28	57
1982	1400	0	36	12	23
1983	1000	0	96	21	39
1984	1200	0	19	11	19
1985	1200	0	24	15	26
1986	1100	0	57	16	27
1987	1100	0	24	10	16
1988	1100	0	26	36	56
1989	900	0	42	24	36
1990	1000	0	35	30	42
1991	900	2	20	24	32
1992	900	0	65	18	24
1993	900	1	25	15	19
1994	900	0	10	41	51
1995	900	0	4	18	22
1996	1000	0	23	18	21
1997	900	0	16	36	41
1998	900	0	14	26	29
1999	900	0	0	12	13
2000	500	0	0	8	9
2001	300	0	0	5	5
2002	300	0	16	21	21
2003	300	0	2	11	11

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections, and these estimates include proportional allocation of fires with area of origin unknown or unreported. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries to the nearest one, and direct property damage to the nearest million dollars. Adjustment for inflation is done in the last column using the consumer price index. From 1999 on, the area of origin code is changed from *electronic equipment room* to the narrower *computer room or control center,* which may account for the decline in fires after 1998. From 1999 on, estimates are made using fires reported only in NFIRS Version 5.0, and confined and nonconfined fires are analyzed separately because incident details such as area of origin are not required for confined fires.

Source: NFIRS and NFPA survey.

ment and systems are complex and expensive, they should be installed in areas specifically designed for their purpose. Ideally, the IT room should be located in a separate, single-story fire-resistive or noncombustible building. IT areas need security, fire protection, and a controlled environment (Table 8.6.1). IT equipment installations may also be located in noncombustible and fire-resistive buildings where the IT rooms are adequately separated from other parts of the building. Local area networks (LANs) and wide area networks (WANs) commonly use host mainframes and servers that may be located 3000 miles (4828 km) away. Ancillary occupancies, such as programmer and maintenance offices, high-capacity printers, paper supplies, records, and data, should be separated from the IT room by rated partitions.

For ordinary hazard occupancies, the partitions should not have less than a 2-hour rating. Where IT equipment controls a process creating a higher hazard, the rating of the partition should be increased to a rating that is commensurate with the hazard. Listed fire doors and shutters of an equivalent rating should be provided to protect openings. Also, listed fire dampers should be provided to protect any necessary duct penetrations. The IT room should not be located above, below, or adjacent to areas housing hazardous processes, unless means for controlling that process and reliable protection and commensurate separation are provided (Table 8.6.2).

Construction

IT centers vary in size and complexity, depending on the size of the business, as well as the functions performed. An IT room may be as small as a typical single office, if it has only PC-based equipment installed. The more complex enterprise business on the other side of the spectrum, in contrast, may occupy 50,000 ft^2 (4645 m^2) or more. The larger IT room presents a greater opportunity for fire hazard and an equally greater challenge for fire detection and protection.

TABLE 8.6.2 Structure Fires Excluding Homes Originating in Electronic Equipment Rooms, by Equipment Involved in Ignition, 1994–1998 Annual Averages

Equipment Involved in Ignition	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
No equipment involved	133	0	1	5.14
Electronic equipment	120	0	4	8.92
Fuse, circuit breaker, or other overcurrent protection device	96	0	3	1.07
Fixed wiring	91	0	1	2.23
Unknown-type electrical distribution equipment	76	0	2	3.40
Transformer	71	0	0	0.41
Unclassified electrical distribution equipment	38	0	0	1.67
Meter or meter box	24	0	0	0.39
Separate motor or generator	21	0	0	0.08
Light fixture, lampholder, or sign	20	0	0	0.09
Switch, receptacle, or outlet	16	0	0	0.02
Office machine	16	0	0	0.14
Central air conditioning or refrigeration equipment	15	0	0	0.01
Cord or plug	15	0	0	0.23
Unclassified special equipment	13	0	0	0.23
Central heating unit	12	0	0	0.01
Television, radio, VCR, or phonograph	10	0	0	0.27
Room air conditioner	10	0	0	0.00
Torch	10	0	0	0.14
Unclassified appliance	10	0	0	0.80
Other known equipment involved in ignition	123	0	1	2.46
Total	944	0	13	27.71

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires and civilian deaths and injuries are estimated to the nearest one; and direct property damage is estimated to the nearest ten thousand dollars and has not been adjusted for inflation. Statistics include a proportional share of fires with unknown area of origin. Electronic equipment room fires with unknown equipment involved in ignition have been proportionally allocated. Sums may not equal totals because of rounding error.

Source: National estimates based on NFIRS and NFPA survey.

Auxiliary and support equipment are typically more extensive for the larger IT centers. Rather than a small uninterruptible power source (UPS), there may be separate battery rooms and diesel generators for backup power in case of an electric utility disruption. To facilitate redundancy and dual electrical power distribution, there may be large transformers and electrical switch gear in adjacent rooms. The heating, ventilation, and air-conditioning (HVAC) demand is also greater and more complex, as is overall security. Fire detection and suppression technologies have kept pace with electronics systems and offer a solution that can be engineered for every need.

Equipment Protection. Most fires damaging IT rooms do not originate in the IT equipment itself, but rather from ordinary equipment in or adjacent to the IT room. Only listed IT and IT support equipment should be allowed in the IT room. Control and operations offices or rooms strictly related to the IT system operation may also be allowed in or adjacent to the IT room. Combustibles and nonessential items should be kept out of the IT center or kept to minimum levels required for efficient operation. Personnel allowed access to the IT room should also be restricted to essential individuals for operations and maintenance.

Data and Record Protection. Important and vital records generated by the IT computer system should be protected according to their importance and difficulty to reproduce. In most cases, information stored is more valuable than the IT hardware itself. Keeping and protecting backup copies is extremely important. Most backup information is stored on magnetic tape or disks; however, other media may be used, including paper. All of these are subject to damage from fire, heat, combustion products, or water. Keeping backup copies of extremely critical information in a safe and/or remote location is very important. Backup systems should be tested on a regular basis to ensure that regenerated data are in a readily usable format.

Raised Floor as Protection Feature. Mainframe IT systems are generally installed on an access or raised floor. The raised floor facilitates equipment reconfigurations and room layout, provides a space for electrical wiring and connectivity, and allows for cooling air distribution to the electronic equipment. The floors, including structural supports, should be made of approved, noncombustible materials. Openings in the floor for cable access should be kept to a minimum to prevent debris and other combustibles from collecting beneath the floor. Edges of any cut openings should also be trimmed to prevent damage

to electrical cables. Where openings to another area under the raised floor are required, fire wall separations must be maintained with appropriate materials. Carpeting and the adhesive attaching it to the floor could increase damage to equipment involved in a fire. Carpeting should, therefore, be avoided on raised floor systems. Access panels in the raised floor shall be provided to allow for inspection and maintenance. Appropriate devices to remove these panels should also be provided in the room and be clearly marked.

When any equipment is removed from the IT room, the associated connection cables must also be removed. Abandoned or unused cables can add to potential fuel for a fire in the form of insulation and connectors. In addition to increased fuel load, the unused cables impede cooling airflow. A cable management program should be developed and implemented for the underfloor and cable spreading areas.

EQUIPMENT AND INSTALLATION FEATURES

Only equipment that meets the requirements of UL 478, *Standard for Electronic Data Processing Units and Systems,* or UL 1950, *Standard for Safety of Information Technology Equipment Including Electrical Business Equipment,* should be used. Where available, equipment should be listed in accordance with these standards. Equipment of combustible construction should be avoided. Some equipment such as automated information storage systems (AISS), or magnetic tape libraries, may be constructed to hold enough plastic tape modules to be considered a significant fuel source for a fire. Equipment of this type may be provided with internal detection and protection. Protection can be exempted only where the materials and their configuration in the equipment have undergone large-scale testing.

Power communications and signal cables as well as plugs and connectors should be listed and properly sized and applied in accordance with NFPA 70, *National Electrical Code®*. These should be suitable for installation under raised floors. Floor openings should be smooth to prevent damage to cables. Complex wiring of electronic equipment does not always allow power cables to be run in conduit. Where installations allow, the preferred arrangement of wiring power cables is within conduit. No splices or connections should be permitted in the power or wiring under the floor, except within listed junction boxes or approved receptacles or connectors. When used, the number of junction boxes should be minimal.

Cables should be arranged to avoid serious multiple failures because of fault or overheating in any one conduit. Very large computers and some other electronic data processing equipment produce a great deal of heat and require a large amount of air to pass through the equipment for cooling. Air-conditioning system design should be based on the requirements of NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems.* Each computer room should have its own air-conditioning system. Air intake should be located to minimize its exposure to flame, smoke, and undesirable fumes. All filters should be Class 1, in accordance with UL 900, *Standard for Air Filter Units.* Ductwork and its insulation should be noncombustible. The system should be capable of going to 100 percent makeup and exhaust automatically on detection of smoke. The air handling system should be capable of purging the room of combustion products. Shutting down minimizes recirculation contamination. As technology advances, IT systems become more dense and more powerful. As a result, they generate more heat. In plans for upgrading a computer system, cooling requirements may need modification for proper operation. The modern supercomputer may use coolant media other than air. Where liquid coolants are necessary, only noncombustible liquids or gases should be used for equipment cooling. An alarm for loss of fluid should be provided for any liquid coolant system.

Most large computer systems rely on an uninterruptable power source (UPS) for protection against power loss and voltage fluctuation. The UPS is commonly a large rechargeable battery system that is normally "on charge" while it provides power to the computer. The UPS has the capacity to maintain system operations during a power failure until power is restored or systematic shutdown can be accomplished. Electrical power supplies and other electrical equipment, such as transformers, motor generators, distribution controls, and circuit breakers, should have a disconnect switch and be located in a separate cutoff room. Larger battery banks should be kept in a separate, well-ventilated detached room. Diesel, natural gas, or gasoline generators for emergency power supplies should be in separate machinery rooms or outside the building. These units should be tested and maintained in accordance with NFPA 110, *Standard for Emergency and Standby Power Systems.* A minimum of a one-day fuel supply should be maintained.

FIRE PROTECTION

Computers and other IT equipment are particularly susceptible to fire damage and the accompanying heat, steam, and combustion products. Elevated temperatures may even damage equipment and data. There are many variations of electronic components and media and their failure points will differ somewhat. Tests have shown that above 120°F (49°C), permanent damage can begin. At 125°F (52°C), magnetic tapes, floppy disks, and similar materials start to lose information. A sustained ambient temperature of 150°F (66°C) damages hard disks. Equipment components begin to fail at 174°F (79°C), with major component failures occurring between 300 and 500°F (149 and 200°C). Microfilm damage begins at 225°F (107°C) in the presence of high humidity. Even paper products can be damaged at 350°F (176.5°C). Finally, between 650 and 750°F (310 and 399°C), polystyrene cases and reels degrade, producing flammable styrene monomer. Further evidence of this vulnerability may be seen in the high average loss per fire in electronic equipment room fires, even when they are confined to the object of origin (Table 8.6.3).

Computer rooms should be equipped with CO_2 or Class BC clean agent extinguishers in accordance with NFPA 10, *Standard for Portable Fire Extinguishers.* Dry chemical extinguishers should not be used. If paper or ordinary combustibles are present, a sufficient number of Class A pressurized water extinguishers should also be provided. Occupants need to be instructed on the proper use of extinguishers.

TABLE 8.6.3 Structure Fires Excluding Homes Originating in Electronic Equipment Rooms, by Extent of Flame Damage, 1994–1998 Annual Averages

Extent of Flame Damage	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*	*Average Loss per Thousand Fires (in Thousands of Dollars)*
Confined to object of origin	626	0	9	9.13	14.6
Confined to area of origin (part of room)	127	0	2	2.70	21.3
Confined to room of origin	79	0	1	2.85	36.1
Confined to fire-rated compartment of origin	4	0	0	0.11	30.3
Confined to floor of origin	11	0	0	1.03	89.4
Confined to building of origin	86	0	1	10.97	127.1
Beyond building of origin	11	0	0	0.92	87.0
Total	944	0	13	27.71	29.4

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires and civilian deaths and injuries are estimated to the nearest one; and direct property damage is estimated to the nearest ten thousand dollars and has not been adjusted for inflation. Statistics include a proportional share of fires with unknown area of origin. Electronic equipment room fires with unknown extent of flame damage have been allocated. Sums may not equal totals because of rounding error.

Source: National estimates based on NFIRS and NFPA survey.

AUTOMATIC SPRINKLER SYSTEM

Automatic sprinkler protection should be provided in accordance with NFPA 13, *Standard for the Installation of Sprinkler Systems.* The sprinkler protection should be installed on a hydraulic design basis arranged as a wet pipe or preaction system. With the increased delay time, a double interlock preaction system should not be used. Water distribution density should be evaluated for each installation. Few computer room installations meet the definition of light hazard occupancy, based on the amount of combustibles found in the room. Computer facilities with super printers that often handle a large amount of paper should be considered Group 2, ordinary hazard. Special media storage arrangements could affect sprinkler location and necessary discharge densities. Any areas exposing the IT area should be protected with automatic sprinkler protection that is commensurate with the hazard. In reported U.S. electronic equipment room fires in structures other than houses, automatic suppression equipment is more often absent than present, but when present, it reduces average loss per fire by three-fourths (Table 8.6.4).

SPECIAL EXTINGUISHING SYSTEMS

When the value of the equipment and risk of IT system interruption dictates, a fixed extinguishing system should be provided. The use of a gaseous agent is critical where there is a need to protect data in process, reduce damage to the equipment, or allow for rapid return to full operation. Where provided, gaseous agent systems should be designed in accordance with NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems,* or NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems.* Power should be disconnected on activation of extinguishing systems unless a risk assessment indicates there would be less severe damage if power were maintained. Air handling should

TABLE 8.6.4 Structure Fires Excluding Homes Originating in Electronic Equipment Rooms, by Performance of Automatic Suppression Equipment, 1994–1998 Annual Averages

Automatic Suppression Equipment Performance	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
Equipment present	379	0	7	3.89
Equipment operated	52	0	1	1.74
Equipment did not operate but fire not too small	14	0	0	0.20
Fire too small to activate equipment	313	0	5	1.95
No equipment present	551	0	6	23.66
Unclassified	14	0	1	0.16
Total	944	0	13	27.71

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires and civilian deaths and injuries are estimated to the nearest one; and direct property damage is estimated to the nearest ten thousand dollars and has not been adjusted for inflation. Statistics include a proportional share of fires with unknown area of origin. Electronic equipment room fires with unknown performance of automatic suppression equipment have been allocated. Sums may not equal totals because of rounding error.

Source: National estimates based on NFIRS and NFPA survey.

be interrupted wherever possible. Systems are typically designed for total flooding where the air handling is interrupted or for extended discharge where it must be left running. In the past, fixed total-flooding Halon 1301 systems were used. Serious environmental concern involving Halon 1301 and its effect on the ozone layer demands consideration of alternative means of protection. A few Halon 1301 extinguishing systems remain. These systems should be tested and maintained in accordance with NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems.* Replacement agents, also called clean agents, now in the market are capable of handling fires below raised floors. FM 200® and Inergen® have both been installed in extremely important computer rooms. Selection of substitute agents needs to include their long-term impact on the environment. Avoid replacements already scheduled for discontinuation.

SMOKE ALARMS

Smoke detection should be installed at ceiling level and under the raised floor system. Protection devices installed under floor areas should be listed specifically for this application. Airflow characteristics of underfloor plenums make many types of smoke alarms unsuitable. High-sensitivity sampling type and spot detectors should be listed for use under high-airflow conditions. Regardless of the smoke alarm used, the manufacturers' instructions for installation in high-flow areas should be consulted. Alarms and detection systems should be designed and installed in accordance with *NFPA 72®*, *National Fire Alarm Code®*. In reported U.S. electronic equipment room fires in structures other than houses, three of five fires show smoke alarm equipment present, with an associated two-thirds reduction in average loss per fire (Table 8.6.5).

TABLE 8.6.5 Structure Fires Excluding Homes Originating in Electronic Equipment Rooms, by Performance of Automatic Detection Equipment, 1994–1998 Annual Averages

Automatic Detection Equipment Performance	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
Detector present	589	0	6	9.00
Detector operated	372	0	3	6.79
Detector did not operate but fire not too small	121	0	2	1.96
Fire too small to activate detector	96	0	1	0.25
No detector present	335	0	6	15.24
Unclassified	19	0	2	3.46
Total	944	0	13	27.71

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires and civilian deaths and injuries are estimated to the nearest one; and direct property damage is estimated to the nearest ten thousand dollars and has not been adjusted for inflation. Statistics include a proportional share of fires with unknown area of origin. Electronic equipment room fires with unknown performance of automatic detection equipment have been allocated. Sums may not equal totals because of rounding error.

Source: National estimates based on NFIRS and NFPA survey.

EMERGENCY PLANS AND PROCEDURES

An emergency plan's primary purpose is to prepare key personnel to initiate actions during and after any emergency. Supervisory personnel should develop and regularly review plans and procedures. The plan should incorporate contingency factors for emergencies such as power failures, severe weather conditions, tornadoes, floods, earthquakes, and so on.

The plan should include actions to safeguard systems from damage and provisions to ensure that backup copies of program software and data are available in case damage occurs. There should be a contingency plan to relocate operations or to provide alternative means to complete critical functions if a computer center is temporarily out of service or permanently damaged.

Alternative equipment should be available, either within the organization or from an outside organization, if the operation is to continue during the restoration of damaged equipment. A prearranged plan should consider and test the compatibility of backup equipment.

The plan should include local emergency personnel such as security and/or local fire response organizations and outside fire departments. Local fire departments should be invited to visit the computer and electronic equipment rooms to familiarize them with the emergency plan. It is important that they be aware of any fixed automatic fire extinguishing systems and know how they operate and what procedures to follow, for example, where to enter the building if responding to a fire alarm.

Restoration companies can successfully restore much of the hardware involved in incidents. An effective preplan includes preliminary visits by a restoration company. This familiarity will allow the company to preplan for the chemicals, labor, and equipment needed for fast and effective restoration.

The second part of the plan is an emergency personnel evacuation procedure. The primary purpose of this plan is life safety for all persons in the IT area. The procedure should be posted and updated periodically—every six months—so that all employees and others entering the area know what to do when the alarm signal sounds. The alarm signal must be audible throughout the entire area, and when it is initiated, all occupants should immediately assemble at a predesignated location, for example, a safe, interior part of an adjacent building. Employees should remain in the assembly area until all are accounted for, and they are advised otherwise. Several persons should be assigned to check their areas to make certain all persons have exited. Laboratories, washrooms, storage rooms, and so on should be checked. The plan should include provisions for those who

may need physical assistance. Visible notification appliances should be provided for people who cannot hear the alarm, in accordance with *NFPA 72*.

Emergency lighting also should be provided for the entire interior of the building that houses the computers or electronic equipment and offices. Auxiliary battery lighting packs are permitted.

SUMMARY

Given our global dependence on information technology and other electronic equipment, protection from fire must be given a high priority. A fire protection system must take into account many factors, including security measures from arson and sabotage, physical characteristics of facilities and locations, hazardous arrangements, fire alarm and suppressions systems, and emergency procedures. Information technology equipment should be installed in specifically designed areas that provide security, fire protection, and controlled environment. Such installations may be located in computer rooms adequately separated from other parts of the building or even in separate structures. Combustible materials should be kept at a minimum and preferably located outside the computer room. Fire alarm and suppression systems include smoke alarms, automatic sprinkler systems, and portable fire extinguishers. The emergency plan should include actions to safeguard systems from damage and provisions to ensure that backup copies of data/information are available in case damage occurs, as well as provide for the evacuation of personnel. Local fire departments should be invited to visit the IT and electronic equipment rooms to become familiar with the emergency plan.

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Reference to the following NFPA codes, standards, and recommended practices will provide further information on protecting the electronic equipment discussed in this chapter. (See latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 70, *National Electrical Code®*
NFPA 72®, *National Fire Alarm Code®*
NFPA 75, *Standard for the Protection of Information Technology Equipment*
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*

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Chapter 7

Heat Transfer Systems and Fluids

John A. LeBlanc

Chapter Contents

Types of Heat Transfer Systems and Fluids
Heat Transfer System Components
Hazards of Organic Heat Transfer Fluids
Organic or Synthetic Heat Transfer Fluid System Safeguards

Key Terms

heat transfer fluid (organic), heat transfer fluid (synthetic), heat transfer oil, heater, molten salts, vaporizer

The term *heat transfer fluid* applies to a broad spectrum of liquid and vapor media used to transfer heat at a controlled rate from one place to another. There are many types of heat transfer fluids, ranging from the most common, water and steam, to molten salts. This chapter will discuss the use and hazards of organic and synthetic heat transfer fluids and the safeguards needed for them.

Heat transfer fluids have historically been associated with the chemical and petroleum industries but are now also used in industries ranging from food to plastics to paper manufacturing to commercial laundries. A clear understanding of the fire and explosion hazards that can be created by organic heat transfer liquids is needed to ensure that the plants and facilities using these liquids are adequately protected.

For additional information relevant to heat transfer systems, see Section 6, Chapter 12, "Flammable and Combustible Liquids"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 8, Chapter 2, "Chemical Processing Equipment"; and Section 8, Chapter 8, "Industrial and Commercial Heat Utilization Equipment."

TYPES OF HEAT TRANSFER SYSTEMS AND FLUIDS

There are two general types of heat transfer systems: liquid phase and vapor phase. Figure 8.7.1 illustrates a liquid-phase system. Figures 8.7.2 and 8.7.3 illustrate vapor-phase heat transfer systems. With liquid-phase systems, the temperature of the fluid changes as heat is transferred, resulting in nonuniform temperatures, even if circulation flow rates are high (see Figure 8.7.1). With vapor-phase systems, heat is transferred at the saturation temperature of the vapor, which affords controlled temperatures. Combinations of these systems can be used as well (see Figures 8.7.2 and 8.7.3). Types of transfer fluids include water, molten salts, and heat transfer oils and synthetic fluids.

Water

Water in either its liquid form or its vapor state is the most common heat transfer fluid. If the temperature required by the transfer process is above the freezing point of water and below about 350°F (177°C), the choice is usually between these two media. On the other hand, if the temperature needed is above or below this range, it is desirable, if not necessary, to consider other fluids. For temperatures below the freezing point of water, the most common heat transfer fluids are air; refrigerants, such as halogenated hydrocarbons or ammonia; brines; or solutions of ethylene glycol and water.

When temperatures increase above 350°F (177°C), the vapor pressure of water increases rapidly, requiring expensive high-pressure processing equipment. Therefore, a more practical and inexpensive means of heating or temperature control at higher temperatures is to use a fluid or

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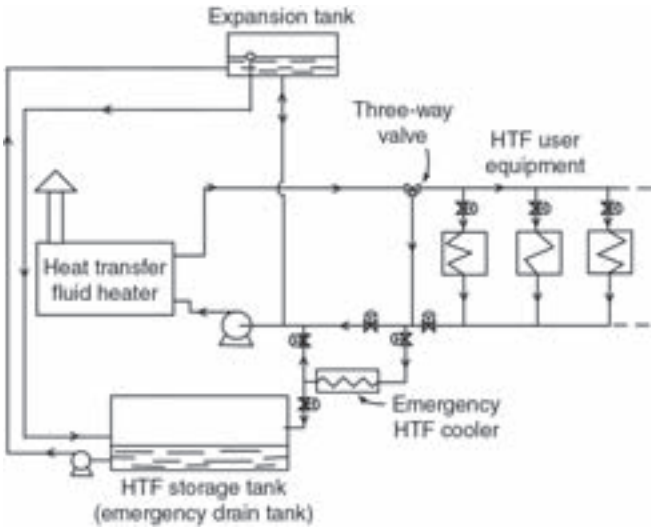

FIGURE 8.7.1 Liquid-Phase Heat Transfer System with Forced Circulation–Type Heater (Source: Reprinted with permission from FM Global)

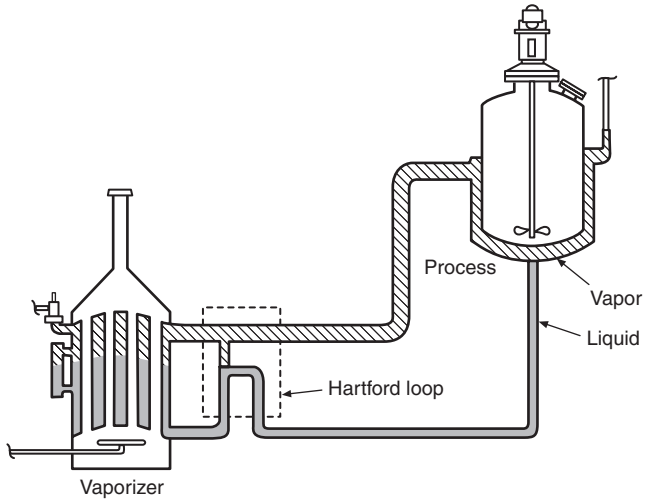

FIGURE 8.7.2 Vapor-Phase Gravity Condenser Return Heat Transfer System with a Vertical Fire-Tube-Type Vaporizer for Natural Circulation

vaporizing fluid with a high boiling temperature. Care should be taken to use high flashpoint, thermally stable, and noncorrosive fluids intended for this purpose. Liquids with a high boiling point that are commonly used can be generally categorized as molten salts, heat transfer oils, or specially formulated heat transfer media.

Molten Salts

Molten salts are generally used as heat absorbers or cooling media and thus serve to control exothermic reactions that occur in the manufacture of certain chemicals. The most frequently

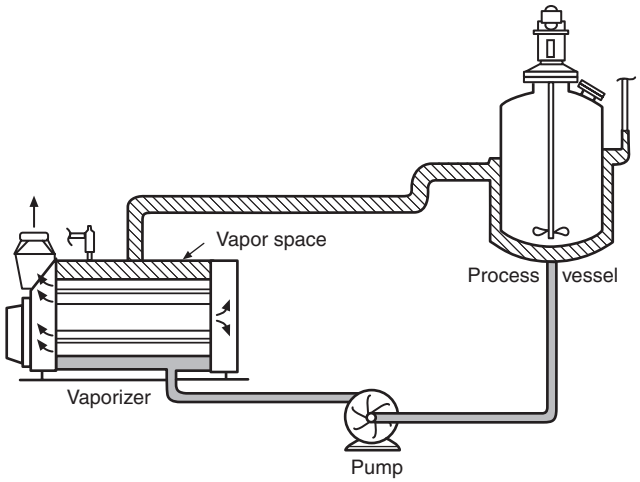

FIGURE 8.7.3 Vapor-Phase Heat Transfer System with Pumped Condensate Return and a Horizontal Fire-Tube-Type Vaporizer for Natural Circulation

used salt is a mixture of sodium and potassium salts having a relatively low melting point. Since these salts are solid at room temperature, care must be exercised to keep the temperature of the salt above its melting point to prevent solidification that can plug the system. Care also must be taken during start-up to control the heat input so the mixture will melt slowly. Many molten salts are strong oxidizers, and this factor should also be considered when the salts are used.

Heat Transfer Oils and Synthetic Fluids

Heat transfer oils and synthetic fluids are specially refined petroleum oils for use at temperatures up to approximately 600°F (315°C). At higher temperatures, the oils undergo excessive thermal cracking, which produces light hydrocarbons. Some amount of thermal cracking is common; however, certain liquids actually produce significant quantities of light hydrocarbons at normal operating temperatures. It is important to fully understand the properties of the fluids being used for heat transfer operations. The light hydrocarbons produced by this cracking process can collect in the system's expansion tank, and their presence must be considered when designing and arranging breather and emergency vents for the expansion tank. Petroleum oils are also subject to oxidation at temperatures above 392°F (200°C) and when in contact with air. These oils will provide a long service life and good heat transfer when the manufacturer's recommended guidelines are followed.

A variety of specially formulated synthetic fluids are used as heat transfer fluids. Synthetic fluids are subject to thermal cracking and oxidation as well; however, they are noncorrosive and generally thermally stable when used under the manufacturer's recommended guidelines. Table 8.7.1 gives the physical properties of some common heat transfer fluids and oils.

Some newer fluids have limited flammability and in some cases will not burn. These fluids are generally used in refrigeration processes but may have some application at elevated tem-

TABLE 8.7.1 Physical Properties Typical of Heat Transfer Fluids

	Freezing		Boiling Point		Flashpoint		Fire Point	
Compound	°F	°C	°F	°C	°F	°C	°F	°C
1,2,4-trichlorobenzene	63	17	417	213	210	99	[a]	[a]
Tetrachlorobenzene (isomer mixture)	170	77	480	249	None	—	[a]	[a]
Diphenyl ether—diphenyl eutectic	54	12	495	257	255	124	275	135
Biphenylyl phenyl ether (isomer mixture)	99	37	680	360	370	188	410	210
O-biphenylyl phenyl ether	122	50	670	354	370	188	410	210
Di- and triaryl ethers	<0	–17	572	300	305	152	315	157
Dimethyl-diphenyl ether (isomer mixture)	–40[b]	–40	554	290	—	—	—	—
Tetramethyl diphenyl ether (isomer mixture)	—	—	590	310	—	—	—	—
Di-*sec*-butyl diphenyl ether (isomer mixture)	—	—	705	374	380	193	400	204
Dicyclohexyldiphenyl ether (isomer mixture)	—	—	785	418	—	—	—	—
Dodecyldiphenyl ether (isomer mixture)	45[b]	7	>800	>42	410	210	440	227
Ethyldiphenyl (isomer mixture)	<–60[b]	<–51[b]	536	280	—	—	—	—
Partially hydrogenated terphenyl	–15[b]	–26[b]	690	366	335	168	375	191
Aliphatic oil	15	–9	720–950	382–510	425	218	475	246
Alkylaromatic oil	20	–7	~650	342	350	177	390	1997

[a]None to boiling point.
[b]Pour point.

peratures. Use of a fluid that does not burn and that does not have the limits of water would be ideal.

HEAT TRANSFER SYSTEM COMPONENTS

Heater or Vaporizer

Recirculating heat transfer systems consist of several common components. A heater or vaporizer provides the thermal energy that is carried by the heat transfer fluid to the process or piece of equipment where it will be used. When the fluid is used in the liquid state, the unit is referred to as a heater; when used in the vapor state, the unit is called a vaporizer. Two types of equipment are manufactured: (1) fuel-fired heaters, which are generally designed for heat duties in excess of about 1 million Btu/hr (290 kW), and (2) electric heaters, which are usually designed for smaller heat duties. Capacities of vaporizers and heaters range from less than a kilowatt to more than 175 million Btu/hr (50,000 kW). Figure 8.7.4 shows a typical heat transfer heater.

Piping System

The piping system allows the transport of the heat transfer fluid from the heater to the process or piece of equipment that is being heated or cooled. Piping can be arranged as a single primary loop between the heater and user equipment or it can be arranged to form primary and secondary loops. In either case, properly arranged control valves and emergency shutoff valves are necessary to ensure the proper operation of the system under normal conditions and to permit the isolation of the heat transfer fluid during a fire.

Expansion Tank

Expansion tanks are used in liquid-phase systems only. They accommodate the expansion and contraction of the heat transfer fluid as the system is heated or cooled. The expansion tank is typically located at the highest point in the system near the heater. It can be either inside or outside the building and is used to provide a constant hydraulic head on the system. In systems operating above the heat transfer fluid's boiling point, the expansion tank is normally pressurized with an inert gas blanket. Other systems operating below the fluid's boiling point may have the tank vented to atmosphere. The expansion tank is generally the point of lowest system pressure. Any light hydrocarbons

FIGURE 8.7.4 Typical Heat Transfer System Heater (Source: Courtesy of Heatec, Inc.)

produced by the degradation of the fluid will collect in the expansion tank.

Expansion tanks can be provided with a breather vent and/or an emergency overflow line. Breather vents must discharge to a safe location outside the building. Ideally, emergency overflow lines should be piped back to the system storage tank. If this procedure is not done, then this line must also discharge to a safe location outside the building.

HAZARDS OF ORGANIC HEAT TRANSFER FLUIDS

Fire and Explosion Hazards

The hazards associated with organic heat transfer fluids (hydrocarbon or synthetic) are not unexpected. These fluids are basically high-flashpoint liquids that are contained and circulated in a closed piping system while being heated above their flashpoints and sometimes above their boiling points. When these liquids are at room temperature, they are difficult to ignite. But, like any flammable or combustible liquid, when heated to or above their flashpoints, they will easily ignite and burn. Since most systems operate above the liquids' flashpoints, loss of containment can quickly produce a pool or spray fire. Containment can be compromised in the heater room (e.g., at pumps, valves, and other connection points), at the user equipment (e.g., at valves, rotary joints, and other connection points), and anywhere along the piping system if the system is exposed to potential physical damage.

If the liquids are released in the heater, they will create an uncontrolled fire within the unit, which can result in damage to the heater, excessive heating of the circulation fluid, or both. Within heaters and vaporizers precautions must also be taken to prevent the liquid level from falling below the tops of the tubes and impairing circulation. In direct-fired units, impingement of burner flames on empty tubes can produce excessive local temperatures, resulting in deposits and ultimate failure of the tubes.

The severity of the fire hazard depends on the amount of liquid in the system, the level of interlocks to shut down flow, and the surrounding occupancy. The chemical process plants where these systems originated are generally protected for large flammable liquid fires. Many of the occupancies where these systems are now found generally present a low fire hazard and are not protected against a flammable or combustible liquid pool fire.

In the case of organic heat transfer liquids that are heated above their boiling points, loss of containment can quickly produce large quantities of flammable vapor or mist that can produce a deflagration if ignited in an enclosed space. The explosion potential in the heater/vaporizer area and the use area needs to be examined closely. Depending on the amount of fluid released, the vapor/mist may spread well beyond the immediate release area.

Another problem associated with organic heat transfer fluids is the development of leaks in the piping system at points of connection. Heat transfer fluids generally have very low surface tensions and low viscosities, allowing them to escape through any small openings at pipe joints. Leaking oil can soak into common insulation materials used on piping. Oil-soaked pipe insulation can autoignite and allow fire spread along the piping system.

Loss History

For the period 1981 to 1990, loss experience from one industrial property insurance company shows 54 fire and explosion losses involving organic or synthetic heat transfer fluids. The gross total loss amount was $150,800,000. The average loss amount was $3 million, but the median loss amount was less than $300,000.[1]

Even an otherwise well-engineered and constructed system may be susceptible to leakage due to the high system temperatures and pressures and due to low fluid surface tension and viscosity. These smaller noncatastrophic leaks can result in fires, but a well-designed plant and heat transfer system will keep the loss in those fires well below a typical catastrophic or large-loss threshold.

These systems have the potential for great destruction as they involve the pumping of hot combustible liquids in conjunction with one or more unfavorable factors. Examples of unfavorable factors include the following:

- Heat transfer fluid virtually always well above its flashpoint
- Systems often having large liquid holdups and high flow rates
- Piping and user equipment located throughout the plant
- Piping and user equipment adjacent to other important equipment or nearby combustibles

Because of their inherent potential for severe fire, these systems require that all aspects of design, installation, maintenance, and operation adhere to the highest possible standards. One of the most common preventable causes of leakage and subsequent fire is the improper siting of the discharge outlet from a system breather vent or pressure relief valve. Improper siting of system discharge points, such as outlets from breather vents or pressure relief valves, has been implicated in numerous fire incidents due to the resulting discharge directly into plant areas. Any inspection or plan review of a heat transfer system should pay close attention to these easily identifiable potential danger points.

One manufacturer conducted a study of heat transfer fluids that also reveals some interesting facts. The 3-year study found 23 fire incidents among the users of its fluids and established the cause for 22 of the 23 fires. Operation/misoperation of the system was the primary cause for 5 of the fires (23 percent), system design was the primary cause for 5 of the fires (23 percent), and system maintenance was the primary cause for 12 of the fires (54 percent).[2]

The results of one loss[3] also clearly demonstrate the severe fire hazard created by heat transfer fluid systems. A 1995 fire in a sprinklered Georgia carpet mill resulted in a $400 million gross loss. The loss occurred when a rotary coupling failed, releasing the heat transfer fluid. The system was not shut down, and all heat transfer fluid pumped into fire.

ORGANIC OR SYNTHETIC HEAT TRANSFER FLUID SYSTEM SAFEGUARDS

The following recommendations for the safe design and operation of heat transfer fluid systems are based, in part, on Section 7.4, "Recirculating Heat Transfer Systems," of NFPA 30, *Flammable and Combustible Liquids Code.*

Location and Construction Considerations

Ideally the heater/vaporizer should be located at a distance from important buildings and facilities. If the heater/vaporizer needs to be located within an important building, it should be cut off from adjacent areas by a fire barrier wall having a fire resistance of at least 2 hours. If automatic sprinkler protection is provided, the fire barrier wall may have a fire resistance of 1 hour. Damage-limiting construction should be provided for rooms housing heater/vaporizers that use organic or synthetic heat transfer fluids with flashpoints below approximately 425°F (220°C), which are heated to or above their atmospheric boiling point.

Curbs, dikes, sloped floors, and drainage should be used to limit the spread of a fluid release within the heater/vaporizer room, around the expansion tank, and in utilization areas.

System Design Considerations

The following items should be considered when designing a heat transfer system:

- Providing an emergency drain line at the low points of the system and directing this drain line to a properly arranged storage tank to permit system drain down during an emergency and routine system maintenance
- Providing a low point drain line on elevated expansion tanks
- Avoiding use of organic/synthetic heat transfer fluids to provide direct building heat
- Terminating breather vent outlets from expansion tanks at a safe location so as not to expose buildings, equipment, or personnel to a potential liquid release
- Interlocking the heat transfer system to stop circulation of fluid throughout the system in the event of a fire
- Providing a well-marked manual emergency shutoff switch that is capable of safely shutting down the entire heat transfer system
- Providing a high liquid level switch on any expansion tank that can be automatically or manually filled directly from a storage tank, and arranging the switch to automatically shut down the fill pump

Fuel Burner Controls and Interlocks. Fuel burner controls and interlocks need to be considered when designing heat transfer systems. Specifically, oil- and gas-fired heaters/vaporizers should be arranged in accordance with NFPA 31, *Standard for the Installation of Oil-Burning Equipment;* NFPA 54, *National Fuel Gas Code;* or NFPA 85, *Boiler and Combustion Systems Hazards Code,* whichever is applicable. Instrumentation and interlocks also should be provided to sound an alarm and shut down the fuel supply to the heater/vaporizer when any one of the following conditions is detected:

- Low fluid flow through the heat exchanger tubes of the heater/vaporizer
- High fluid temperature or pressure at the heater/vaporizer outlet
- Low system pressure with bypass for start-up sequence
- Low fluid level in the expansion tank
- Low vaporizer liquid level
- Sprinkler system flow in any area containing heat transfer system equipment or piping

Piping. Piping, which should be run underground, outside, or in floor trenches wherever practical, should be insulated with closed-cell, nonabsorbent insulation. Welded pipe connections should be used throughout the piping system. For systems operating above 15 psig (1 bar ga), pipe materials and types should be in accordance with ANSI/ASME B31, *Code for Pressure Piping.* Copper, cast iron, or plastic pipe should be avoided.[4]

Fire Protection

Automatic sprinkler protection should be provided in building areas containing a heat transfer system heater or vaporizer. The sprinkler system should be designed in accordance with NFPA 13, *Standard for the Installation of Sprinkler Systems,* for an Extra Hazard Group 1 occupancy. It is also advisable to protect all building areas that contain heat transfer system equipment or piping with a properly designed automatic sprinkler system.

When a supply of steam or inert gas is available, a manually controlled steam or inert gas smothering system for the firebox is advisable. Throughout all areas containing heat transfer system equipment or piping, portable fire extinguishers should be provided.

Operational considerations include promptly correcting all system leaks and inspecting, calibrating, and testing all safety interlocks annually. In addition, operators of heat transfer systems should be trained in the proper operation of the system and the hazards of system misoperation and in how to recognize upset conditions that can lead to dangerous situations.

SUMMARY

Heat transfer oils and specially formulated synthetic fluids are now used as heat transfer fluids. A heat transfer system comprises such fluids, together with a heater or vaporizer, a piping system, and an expansion tank (for fluid-phase systems). NFPA 30 addresses the safe design and operation of recirculating heat transfer systems. Considerations for safe design and operation include location and construction, fuel burner controls and interlocks, and piping.

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4. ANSI/ASME B31, *Code for Pressure Piping,* American Society of Mechanical Engineers, NY, 1998.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on heat transfer systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 31, *Standard for the Installation of Oil-Burning Equipment*
NFPA 54, *National Fuel Gas Code*
NFPA 85, *Boiler and Combustion Systems Hazards Code*
NFPA 86, *Standard for Ovens and Furnaces*

Chapter 8

Industrial and Commercial Heat Utilization Equipment

Raymond Ostrowski

Chapter Contents

Industrial Heat Utilization Equipment
Ovens and Furnaces
Class A Ovens and Furnaces
Class B Industrial Furnaces
Class C Industrial Furnaces Using a Special Processing Atmosphere
Class D Vacuum Furnaces
Afterburner and Catalytic Combustion Systems
Heat Recovery
Lumber Kilns
Dehydrators and Dryers

Key Terms

furnace (class A), furnace (class B), furnace (class C), furnace (class D), heat exchanger, heat recovery, heat transfer fluid, heat utilization equipment, heating equipment, oven

Heat utilization equipment has potential hazards involving both heat generation and the process materials. Fuel-fired systems, electrically heated systems, and heat transfer systems all have their individual hazards. The hazards of exposure of adjacent materials and overheating are common to any type of heating system. The hazards and control methods are discussed in subsequent sections of this chapter.

The process hazards within the equipment can involve combustible materials, flammable liquids, or flammable gases; such hazards would occur in the curing of solvent-based coating materials, roasting or drying of combustible agricultural products, or heat treating in a flammable special atmosphere. The principal method of fire or explosion prevention is to prevent overheating or an accumulation of a gas or vapor-air mixture in the explosive range. Subsequent paragraphs in this chapter describe the various classes of ovens, furnaces, and dryers and present general process hazards. The prevention and protection methods that usually are applied to those processes and devices are also described.

Guidelines, rules, and methods applicable to the safe operation of such equipment are covered by NFPA standards and those of other organizations. These should be referred to for details that could not be included in this text.

Additional information is available in this handbook in the following chapters: Section 6, Chapter 10, "Gases," and Section 6, Chapter 12, "Flammable and Combustible Liquids." The grading of heat-producing appliances is discussed in these chapters: Section 8, Chapter 7, "Heat Transfer Systems and Fluids"; Section 10, Chapter 2, "Heating Systems and Appliances"; and Section 10, Chapter 6, "Boiler Furnaces."

Heat utilization equipment is so varied in size, complexity, location, and use that it has been difficult to develop rules that can apply to every type of oven, furnace, or dryer. Users and designers must use engineering and supervisory skills to bring together the proper combination of controls, protective devices, and operator training necessary for proper equipment operation.

Heat utilization equipment failures have resulted because someone either ignored safety procedures and designs or was unaware they existed, due to inadequate training of operators and maintenance technicians. Other reasons include faulty equipment design, complacency on the part of users, or improper selection of combustion safeguards.

This chapter is not a guide to solving all of these problems. However, if the guidelines and principles it presents are used, a number of problems will be either mitigated or solved.

INDUSTRIAL HEAT UTILIZATION EQUIPMENT

Types of Industrial Heat Utilization Equipment

Industrial heat utilization equipment includes a variety of forges, furnaces, kettles, kilns, ovens, and retorts that are heated by gas, oil, solid fuels, or electricity. They can be fired directly, with the products of combustion entering the process space, or indirectly, with radiant tubes or other heat

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exchanger methods. Heat transfer media, such as organic fluids, are also used where steam or hot water does not provide the temperature or thermal efficiencies desired for the equipment. Figures 8.8.1 and 8.8.2 illustrate typical industrial heat utilization equipment.

Industrial ovens and furnaces, special atmosphere furnaces, vacuum furnaces, afterburners and catalytic combustion systems, dehydrators, dryers, and lumber kilns are discussed in this chapter.

Fire and Explosion Problems

When heat utilization equipment is installed, the following factors need to be considered: (1) the proximity and combustibility of the contents of the building where the equipment is located; (2) construction of the building; (3) setting; (4) ventilation; (5) location within the building; (6) removal of waste heat, gas, and smoke; (7) maximum temperature required; and (8) handling of heated materials in connection with equipment. Fire in combustibles can be prevented by insulation or by separating them from the source of heat. Overheating can be prevented by temperature controls.

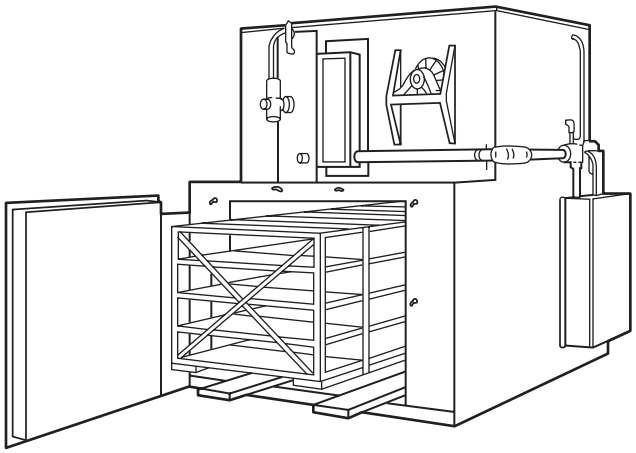

FIGURE 8.8.1 Typical Industrial Oven (Source: Fireye, Inc.)

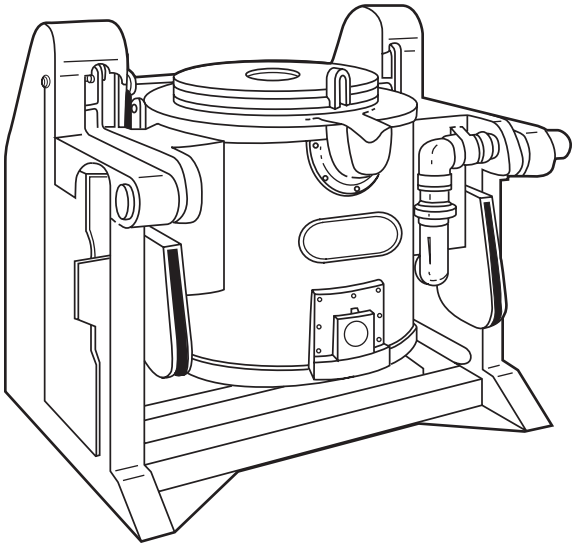

FIGURE 8.8.2 Fuel Fire Melting Furnace (Source: Fireye, Inc.)

Explosion hazards exist where there are flammable vapor-air mixtures from gas or oil fuel or from volatiles released from the material being dried. Explosions or fires can be prevented by ventilation and controls that keep the flammable vapor content below 25 percent of the lower flammable limit (LFL) of the vapor-air mixture.

Some special process ovens and furnaces contain hydrogen or other flammable gases for such purposes as annealing copper and heat treating other metal shapes. To operate these devices safely, it is necessary to prevent air from entering the processing enclosure under normal operating conditions. Both normal and unscheduled starts and stops of these devices require special safety procedures that depend heavily on a skilled operator and adequate control equipment.

OVENS AND FURNACES

This discussion covers the location, design, construction, operation, protection, and maintenance of the industrial heating enclosures known as ovens or furnaces. It does not cover small-cabinet or stove-type ovens for domestic use. The source of heat for industrial heating can be gas burners, oil burners, electric heaters, infrared lamps, induction heaters, or steam radiation systems. In practically all cases, there are fire or explosion hazards from either the fuel used, volatiles produced by material in the oven, or by a combination of both.

There is no clear distinction between an oven and a furnace. The dictionary definition of an *oven* is "a compartment or receptacle for heating, baking, or drying by means of heat"; a *furnace* is "an enclosed chamber or structure in which heat is produced for heating a building, reducing ores and metals, baking pottery, etc." It has been an industry rule of thumb to classify heating devices that do not "indicate color" (i.e., operate at temperatures of less than approximately 1000°F [540°C]) as ovens. This rule does not always apply. For example, coke ovens operate at temperatures in excess of 2000°F (1093°C), and some furnaces operate at temperatures below 1000°F (540°C).

NFPA Classification of Ovens and Furnaces

The classification system for heat processing equipment as set forth in NFPA 86, *Standard for Ovens and Furnaces,* is as follows:

> *Class A* ovens or furnaces are heat utilization equipment operating at approximately atmospheric pressure wherein a potential explosion and/or fire hazard may be occasioned by the presence of flammable volatiles or combustible material processed or heated in the oven.

Such flammable volatiles and/or combustible material may, for instance, originate from paints, powder, or finishing processes including dipped, coated, or sprayed-on impregnated materials; or wood, paper and plastic pallets; or spacers; or packaging materials. Polymerization or similar molecular rearrangements and resin curing are processes that may produce flammable residues and/or volatiles. Potentially flammable materials, such as quench oil, waterborne finishes, cooling oil, and so on, in sufficient quantities to present a hazard, are ventilated according to Class A standards. Ovens may also utilize a low-oxygen atmosphere to evaporate solvent.

Class B ovens or furnaces are heat utilization equipment operating at approximately atmospheric pressure wherein there are no flammable volatiles or combustible material being heated.

Class C furnaces are those in which there is a potential hazard due to a flammable or other special atmosphere being used for treatment of material in process. This type of furnace may use any type of heating system and includes the special atmosphere supply system(s). Also included in the Class C standards are integral quench and molten salt bath furnaces.

Class D furnaces are vacuum furnaces that operate at temperatures above ambient to over 5000°F (2760°C) and at pressures below atmospheric using any type of heating system. These furnaces may include the use of special processing atmospheres. During gas quenching, these furnaces may operate at pressures from below atmospheric to over 100 psig (7 bar).

Classification by Type of Handling System

Ovens and furnaces may be further classified according to the way a material is handled. The two principal types are (1) the batch oven or furnace, sometimes referred to as "in and out," "intermittent," or "periodic" type; and (2) the continuous oven or furnace.

Batch Oven or Furnace. In the batch oven or furnace the temperature is practically constant throughout the interior. The material to be heated is placed in a predetermined position and remains there until the process is complete. Material is then removed, generally through the opening by which it entered. Figures 8.8.3 and 8.8.4 are examples of a batch-type furnace and oven, respectively.

Continuous Oven or Furnace. In the continuous oven or furnace, the material moves through the furnace while being heated. The straight-line furnace is probably the most common of this type. The material passes through a continuous oven or furnace on a conveyor or on rollers. The oven or furnace might operate at a constant temperature throughout, or it might be divided into zones maintained at different temperatures. Figure 8.8.5 is an example of a continuous-type furnace.

A common variation of the continuous-type oven or furnace is one known as a rotating hearth or rotating table furnace. In it, the material is placed on the hearth and is removed after the hearth has completed one revolution. Another design feeds the material being processed through the revolving hearth furnace or tube by means of a stationary internal screw thread.

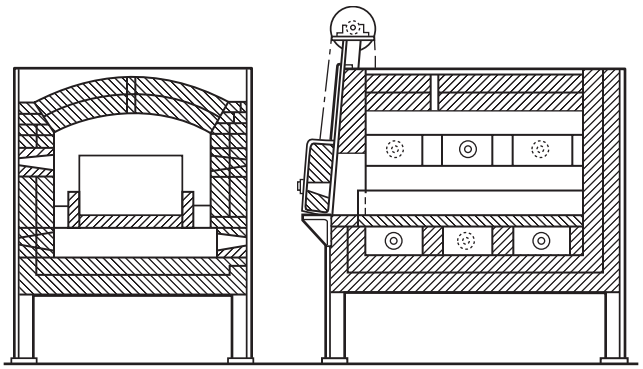

FIGURE 8.8.3 Large Batch-Type, Under- and Overfired, Semimuffle, Heat Treating Furnace

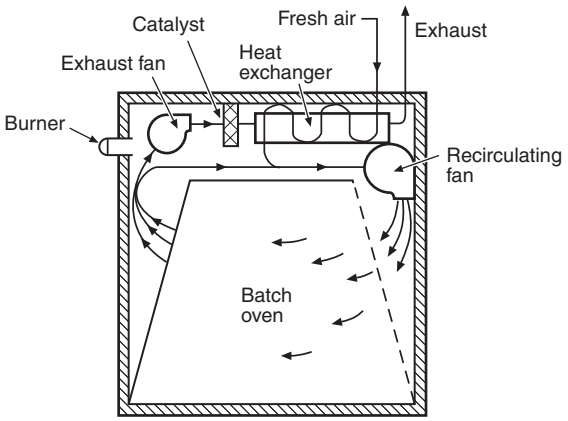

FIGURE 8.8.4 Batch Oven with a Catalytic Heater for Air Pollution Control

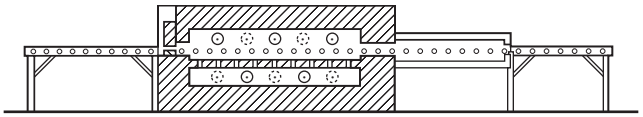

FIGURE 8.8.5 Continuous Roller Hearth Furnace

Location and Construction of Ovens and Furnaces

Ovens and furnaces should be located where they will present the least possible hazard to life and property. To prevent or minimize damage from a fire or explosion, they might need to be surrounded by walls or partitions and located either at or above grade, because basements below grade are difficult to ventilate and offer severe obstacles to proper explosion release.

The oven or furnace and the building that houses it need to be of noncombustible construction, and explosion-relief venting should be provided where required. Combustibles in the vicinity of the oven should be adequately separated or properly insulated and each oven or furnace should have its own venting facilities. When gas or oil fuel is used, the heater and the oven or furnace should have separate venting unless the products of combustion discharge directly into the oven. Except in special cases, separate mechanical means are needed to provide air for the combustion and ventilation; natural draft is usually inadequate.

Furnaces that exhaust directly outdoors are sometimes necessary, depending on the heating process, type of combustion, and the hazard to personnel. If a furnace exhausts directly into a room, the room must have a balanced mechanical ventilation system to bring in fresh air and carry the exhaust outdoors. The supply inlets and exhaust outlets should be arranged to provide a uniform flow of air throughout the area without any dead-air pockets. The system should also remove any toxic contaminants at their maximum anticipated rate of release and keep concentrations below the established maximum allowable concentration (MAC) values.

Some furnaces are made of metal with a brick or masonry covering; some are made of metal with metal supports but no covering; and others have an inner lining of ceramic fibers or fire clay products. Occasionally furnaces have air spaces or noncombustible fillers between the outer and inner walls.

Ovens and furnaces should be well separated from valuable stock, important power equipment, machinery, and automatic sprinkler risers, so there will be minimal interruption to production and protection if there are accidents to the oven or furnace. They should be readily accessible with adequate space above them for automatic sprinklers, the proper use of hose streams, the proper functioning of explosion vents, and routine inspection and maintenance. Roofs and floors of ovens should be insulated. The space above and below the ovens should be ventilated to keep temperatures at combustible ceilings and floors below 160°F (71°C).

Oven and Furnace Heating Systems

For the purpose of this chapter, the term "furnace heating system" includes the heating source, associated piping and wiring used to heat the furnace, auxiliary quenches, and the work therein. Please note the following:

1. For the protection of personnel and property, careful consideration should be given to the supervision and monitoring of conditions that could cause, or could lead to, a real or potential hazard on any installation
2. The presence of safety equipment on an installation cannot, in itself, ensure absolute safety of operation
3. There is no substitute for a diligent, capable, well-trained operator
4. Highly repetitive operational cycling of any safety device can reduce its life span

The three most common methods of transferring heat to materials in ovens or furnaces are (1) direct contact with the products of combustion, (2) convection and direct radiation from the hot gases, and (3) reradiation from the hot walls of the furnace. In muffle furnaces, the products of combustion are separated from the material being heated by a metal or refractory muffle, and heat transfer occurs by radiation (see Figure 8.8.3). In liquid bath furnaces (i.e., salt baths or molten metal used for tempering, hardening, galvanizing, tinning, etc.), a metal pot containing a liquid is heated and the heat is transferred through the liquid to the material placed in the pot.

Oven Heaters. The two general types of oven heaters are (1) direct fired and (2) indirect fired. In direct-fired heaters, the products of combustion enter the work chamber and contact the work in process; this is not the case in indirect-fired oven heaters. Instead, heating comes from radiation from tubes or from air passing over tubes and into the oven. Dangerous fuel-air mixtures cannot readily fill the work space of an indirect-fired oven. Nevertheless, explosions may still occur from vapors given off by a flammable liquid drying process.

There are several arrangements of these two types of oven heaters—direct-fired internal, direct-fired external, indirect-fired internal, and indirect-fired external heaters. Figure 8.8.6 shows three variations of direct-fired external heaters, two of indirect-fired internal heaters, and three of indirect-fired external heaters, with the advantages and disadvantages for each type. The exhaust ventilation arrangements in these designs provide for air movement through the oven with no recirculation through the exhaust fan. The direct-fired external-type oven can have a single burner or a relatively small number of burners that simplify the completing of automatic safety controls.

Furnace Heaters. Furnace heaters are usually arranged like ovens—direct-fired internal, indirect-fired external, and so on, though sometimes the terms are different. If products of combustion are under a hearth and then carried up and into the heating chamber, the furnace is said to be underfired. When the same thing occurs in a chamber at one side of the furnace and passes over a bridge wall into the heating chamber, the furnace is referred to as side-fired. A furnace in which the products of combustion are produced in a space above the heating chamber and pass through a perforated arch into the heating chamber is called an overfired furnace. If combustion occurs at some distance above the heating chamber and hearth, and the products of combustion are deflected onto the hearth by an arched roof, the furnace is called a reverberatory furnace. A radiant-tube-heated furnace is an arrangement for indirect firing (Figure 8.8.7).

Sources of Heat

Heat for an oven or furnace can be provided by gas-fired burners, oil-fired burners, electric heating systems, steam heating systems, or thermal heat transfer fluid systems. It is important that flames, heating surfaces, or other possible sources of ignition be located where drippings or dust cannot fall or accumulate on them.

Gas-Fired Burners. Gas fuel is any type of gas in common industrial use. It is important that the burner, its adjustment, and the means of combustion be suitable for the type of gas to

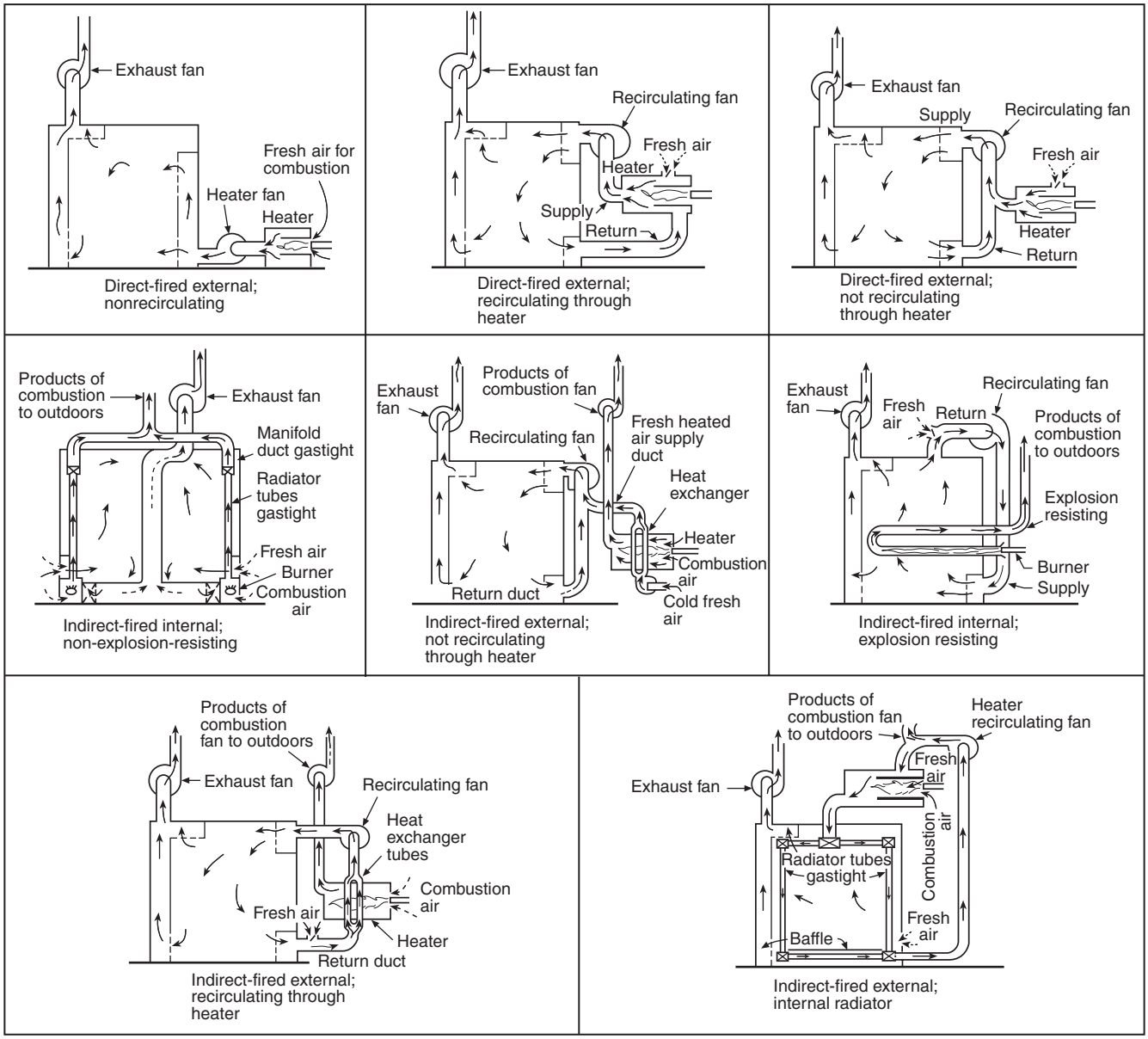

FIGURE 8.8.6 Types of Oven Heating Systems

be burned. The burner can have a single nozzle, with burners located singly or in groups, or it can have multiple nozzles in perforated-pipe, ribbon, or slot burners. Burners must light easily, have a stable flame at all ports, and not have the tendency to flash back or blow off over the entire range of turndown under all draft conditions in the oven. A supply of air adequate for complete combustion may be premixed with the gas, nozzle-mixed at the burner, or otherwise provided.

Oil-Fired Burners. Oven heating systems can be fired with fuel oil. Oil must be vaporized before it can be burned. Most oven and furnace burners atomize and then vaporize oil while mixing it with combustion air. Heat for vaporization is generated by the flame. Atomization can be effected by pressure, mechanical spraying into fine droplets, sonic vibration, low-pressure air, high-pressure air, or steam.

Combination gas- and fuel-oil fired systems use either separate gas and oil burners or configurations where an oil-atomizing nozzle is centered on a gas burner and arranged to use a common combustion air source.

Electric Heating Systems. There are five types of electric heating systems for ovens and furnaces: (1) resistance, (2) infrared, (3) induction, (4) arc, and (5) dielectric.

Resistance heat is produced by current flow through a resistive conductor. Resistance heaters can be "open," with bare

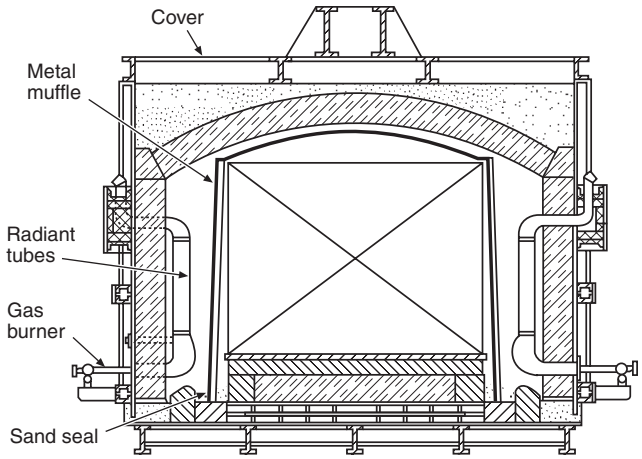

FIGURE 8.8.7 Annealing Muffle Furnace

heating conductors, or "insulated sheath," with heater conductors covered by a protective sheath that may be filled with electrical insulating material (Figure 8.8.8).

Infrared heat is transmitted as electromagnetic waves from incandescent lamps with filaments that operate at temperatures lower than the filament temperature of ordinary incandescent lamps, so that most of the radiation occurs in the infrared part of the spectrum. These waves pass through air and transparent substances but not opaque objects and release their heat energy to these objects.

Induction heat is developed by electric currents induced in the charge by an externally applied alternating magnetic field. Induction heaters have an electric coil surrounding the oven space, and heating is by electric currents induced in the work being processed.

Arc heat is caused by an electric current that passes between either a pair of electrodes or between electrodes and the work, causing an arc that releases energy in the form of heat.

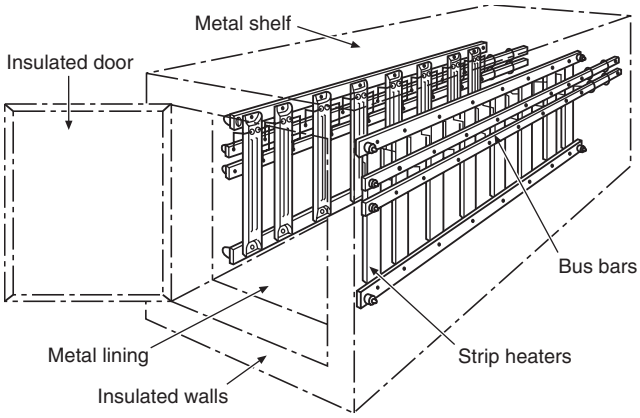

FIGURE 8.8.8 Strip Heaters Mounted in a Small Oven

Dielectric heat occurs when dielectric materials are exposed to an alternating electric field. The frequencies are generally 3 MHz or more—higher than those in induction heating. This type of heater is useful for heating materials that are commonly considered nonconductive.

Electric systems can be arranged so that processing does not require an oven enclosure. "Ovenless," that is, unenclosed heating systems, can employ lamps, resistance-type electric elements, or infrared heaters to vaporize flammable, toxic, or corrosive liquids and their residues. Enclosures around ovenless systems are advisable to prevent flammable, toxic, or corrosive vapors from escaping into the general area and to help provide better ventilation and safeguards for personnel. However, heating systems with energy input of under 100 kW may be excluded if adequate area ventilation is provided. (NFPA 70, *National Electrical Code®*, gives guidance for electrical installations in hazardous locations.)

All parts of heaters that operate at elevated temperatures within an oven or furnace and all other energized parts must be protected to prevent contact by persons and to prevent accidental contact with materials being processed and with drippage from the materials.

Steam Heating Systems. In steam heating systems, the steam pressure in heat exchanger coils must be regulated at the minimum required to provide the proper drying temperatures. This avoids unnecessarily high temperatures at coil surfaces. The coils must not be located on the floor of the oven or anywhere that paint drippings or other combustibles, such as recirculated lint, can accumulate on them.

Thermal Heat Transfer Fluid Systems. As with steam heating systems, the heat exchanger should be kept free of combustibles, such as lint. The heat exchanger may be located outside the work chamber and a recirculating heated air system may be used.

Fuel Hazards

Gas or vapors from unburned or incompletely burned fuel might, when mixed with air, be within the explosive range. These hazards develop during lighting off, firing, and shutting down the oven or furnace; therefore, it is necessary to treat each operation as a separate condition requiring certain specific operating procedures to avoid mishaps.

Lighting Off. Before torches, sparks, or other ignition sources are introduced, and until all burners are properly lighted, the operator must take every precaution, using all practical automatic safety controls, to avoid producing dangerous unburned fuel accumulations. The following precautions should be followed:

1. Purging possible accumulations of unburned fuel
2. Igniting burners promptly with substantial igniters
3. If another ignition attempt is necessary, purging before introducing the ignition source and fuel again

Firing. In the firing phase, safety requires continuous ignition and complete burning of the fuel before it passes beyond its

normal combustion zone. To maintain this, the mixer and burner assembly must proportion fuel and air properly throughout the combustion zone, and the mixture velocity in the combustion zone must be neither too high, causing extinguishment by blow-off, nor too low, causing the flame to flashback or "go out." Thus, good burner mixer design will be one of the main factors in safety during firing.

Air for combustion is obtained from the primary and secondary air supplied at the burner. Partial or total failure of the combustion air supply can cause an unstable flame, which in turn can lead to flame failure and the introduction of unburned fuel into the combustion chamber. When too little air is supplied, the result is an overrich mixture and incomplete combustion. Ignitable incomplete products of combustion that leave the burner at concentrations too high for prompt ignition can later, within the oven or ductwork, become diluted by air into the flammable range and ignite, causing an explosion. Overrich combustion can also produce rapid smothering and extinguishment of the burner flame. The flammable products of incomplete combustion followed by raw fuel likewise can become explosive when later diluted by air in another part of the system. Therefore, precautions must be taken to shut off the fuel and to require manual reset in the event that the air supply for combustion fails.

Liquid fuel, like fuel oil, must be atomized so that it will ignite easily and burn quickly. This can be accomplished by injecting the liquid fuel at high pressure, or by directing a steam or air jet into the oil stream. Improper oil temperature or high viscosity can prevent proper flow and can create partial obstructions in burner tips and loss of oil or atomizing medium pressures, causing improper atomization. Failure to atomize properly will usually result in an unstable flame, which in turn can lead to flame failure. Other conditions that cause flame failure are stoppage of fuel supply by an improperly closed fuel valve or other pipe obstruction and the presence of water in a fuel oil line.

Shutting Down. Following a shutdown, a dangerous accumulation of unburned fuel might occur in an oven and heating system if any manual fuel valves are left open or are leaking and/or safety shutoff valves are not tight-closing. If the leaking fuel subsequently is ignited by hot refractory material or by another ignition source when starting up, an explosion is possible.

Supervisory Controls for Ovens and Furnaces

It is essential that all ovens and furnaces processing flammable materials involving flammable vapors or heated with combustible fuels be provided with adequate supervisory devices that ensure sufficient preventilation, adequate ventilation during operation, and proper operating conditions that will not permit fires or explosions to develop. All safety devices must be listed for the service intended. Although it is true that a competent operator is essential, it is also true that assistance is needed because the operator cannot continually supervise everything. The operator is, however, responsible for the proper maintenance and testing of the oven's operating and control equipment.

The type of supervisory control equipment used with oven or furnace assemblies depends on the requirements of the particular operation. A list of the principal types of supervisory controls is given in Table 8.8.1. Figure 8.8.9 shows a typical arrangement of the devices for a gas-fired unit. Most of these units are tested by testing laboratories and listed according to the appropriateness of the devices for varying situations.

Equipment for Ovens and Furnaces

Full supervisory control of a gas- or oil-fired oven, especially one that is direct-fired, might require the following: (1) determining that all fuel valves are closed and not leaking, (2) establishing and maintaining required ventilation, (3) turning on and igniting the gas pilot only at the conclusion of a required preventilation period, and (4) opening the fuel valves (including the safety shutoff valve) that supply the burner only after the combustion safeguard shows that the pilot flame has been ignited and that fuel and air (or other atomizing agent) pressures are correct. If the burner flame is not promptly established, the safety shutoff valve will close and the entire cycle must be repeated, starting from the beginning. Once started, operation continues only as long as the supervisory controls indicate normal conditions; failure in any respect shuts down the entire system, and the full cycle must begin again.

NFPA 86 specifies in considerable detail the safeguards needed for different types of ovens and furnaces.

TABLE 8.8.1 Supervisory Control Equipment for Ovens and Furnaces

Ventilation controls
Airflow switches
Pressure switches
Fan shaft rotation detectors
Dampers
Position limit switches
Electrical interlocks
Preventilation time-delay relays

Fuel supervisory controls
Safety shutoff valves
Supervising cock (FM cock)
Flame detection units (combustion safeguards)
Flowmeters
Firechecks
Reliable ignition sources
Pressure switches
Program relays

Temperature controllers
Excess temperature limit controller
Continuous vapor concentration indicators and controls
Conveyor interlocks (with steam and electric-resistance heating equipment)
Electrical overload protection (with resistance and induction heating equipment)
Low oil-temperature limit controls (on oil-burner equipment using heavy residual fuel oil, such as No. 5 and No. 6, which require preheating)

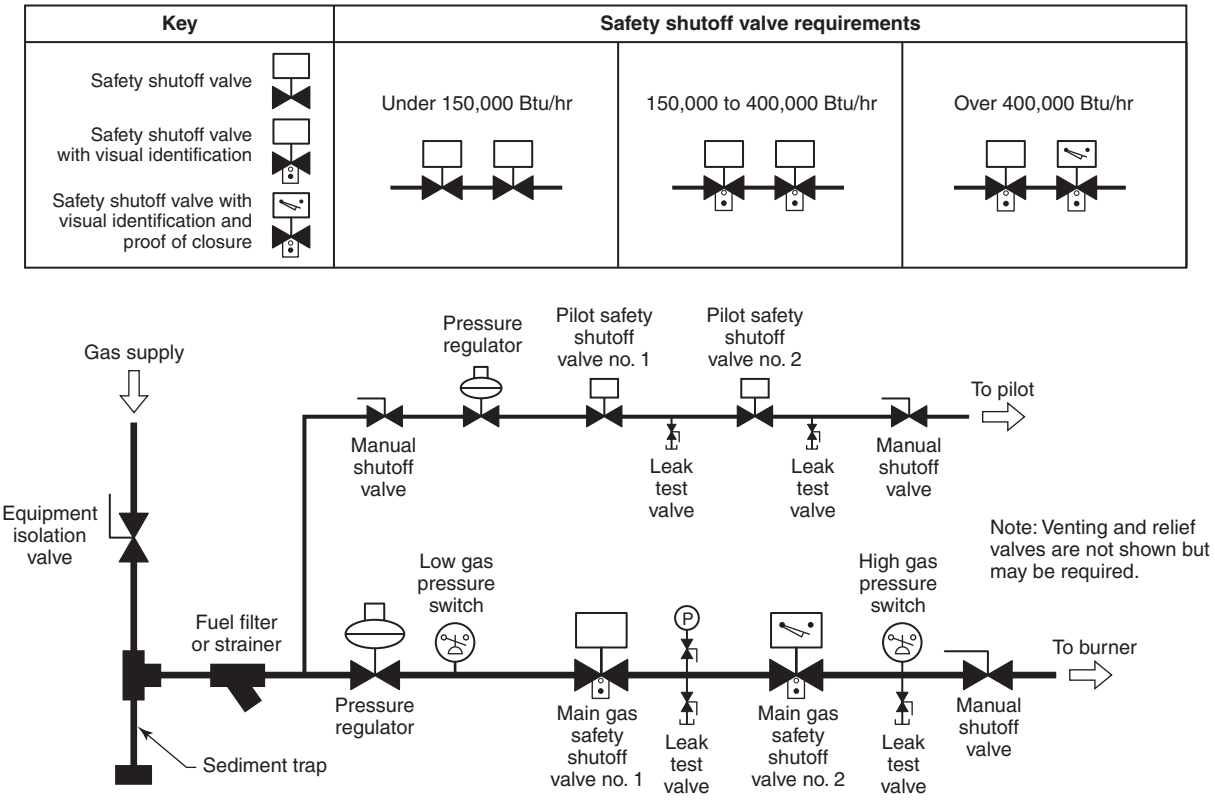

FIGURE 8.8.9 Typical Piping Arrangement Showing Fuel Gas Safety Shutoff Valves
(Source: NFPA 86, *Standard for Ovens and Furnaces,* 2003 ed., Figure A.7.7.2)

When installations contain a large number of burners, the usual supervisory controls for each pilot and each burner might not be considered practical; in such cases, special devices and arrangements might have to be employed. A special continuous line pilot for multiple burners is illustrated in Figure 8.8.10.

Controls for a large number of cup burners with flame propagation between individual burners can be provided as shown in Figure 8.8.11.

Multiburner combustion safeguards are now available, making it possible to install flame supervision for each burner,

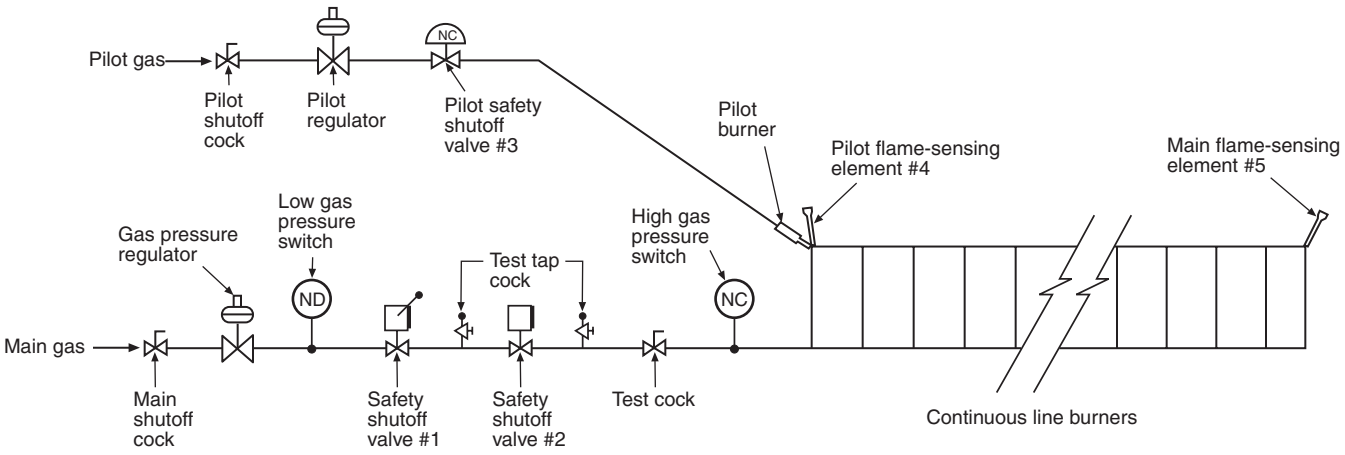

FIGURE 8.8.10 Approved Combustion Safeguard Supervising a Pilot for a Continuous Line Burner During Lighting-Off and the Main Flame Alone During Firing

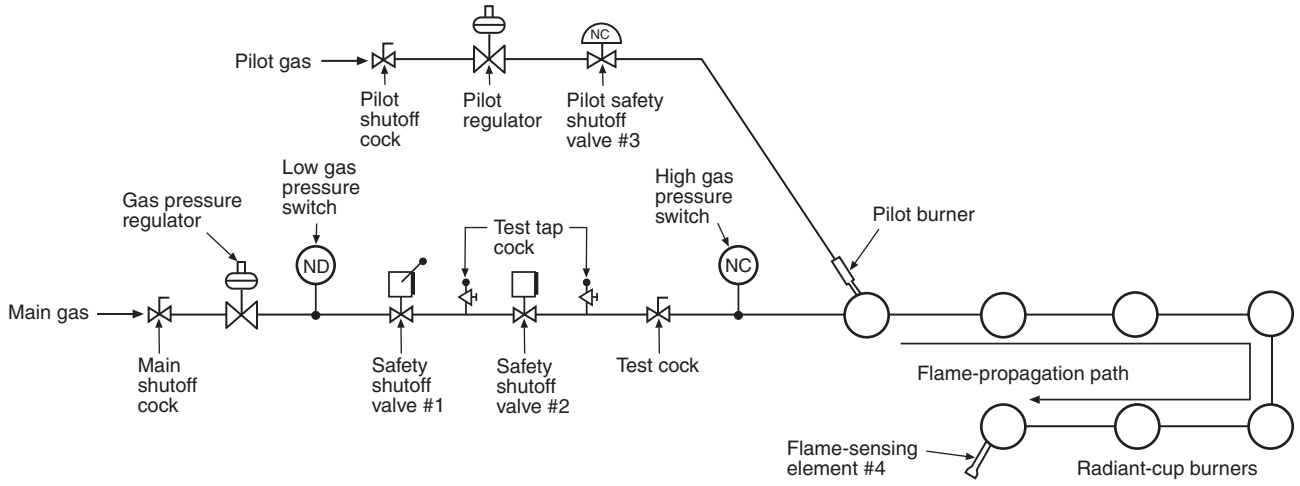

FIGURE 8.8.11 Approved Combustion Safeguard Supervising a Group of Radiant-Cup Burners Having Reliable Flame-Propagation Characteristics from One to the Other by Means of Flame-Propagation Devices

where previously the supervisory cock system was the only safeguard available.

When the capacity of a gas-fired burner system exceeds 400,000 Btu/hr (117 kW), two safety shutoff valves are required. A manually operated plug cock and test tap must be provided downstream of the safety valves. This arrangement ensures positive fuel shutoff when testing the valves for leakage.

Safety ventilation is not needed in an oven that never contains flammable or noxious vapors, and it is unnecessary to guard against flammable fuel-air mixtures in an electric or steam-heated oven.

Operator Training

Alert and competent operators are essential to safe operations. New operators should be thoroughly trained and tested in the use of the equipment. Regular operators should be retrained at intervals to maintain proficiency and effectiveness. Operators must have access to operating instructions at all times.

Operating instructions should be provided by the equipment manufacturer. These instructions should include schematic piping and wiring diagrams, as well as (1) light-up procedures, (2) shutdown procedures, (3) emergency procedures, and (4) maintenance procedures.

Operator training should include information on (1) combustion of air-fuel mixtures, (2) explosion hazards, (3) sources of ignition and ignition temperature, (4) atmosphere analysis, (5) handling of flammable atmosphere gases, (6) handling of toxic atmosphere gases, (7) functions of control and safety devices, and (8) purpose and basic principles of the gas atmosphere generators.

Testing and Maintenance for Ovens and Furnaces

The operating and supervisory control equipment of each oven should be checked and tested regularly, preferably once a week. At less frequent intervals, probably annually, a more comprehensive test and check must be performed by an expert. All deficiencies must be corrected promptly and a regular cleaning program followed to cover all portions of the oven and its attachments. Access openings for cleaning the oven enclosure and the connecting ducts must be provided.

A program for inspecting and maintaining oven safety controls is given in the appendices of NFPA 86.

CLASS A OVENS AND FURNACES

Adequate ventilation must be provided in the operation of Class A ovens and furnaces where there is an explosion potential because of the presence of flammable vapors or fuel-air mixtures. Such fires or explosions can generally be prevented by good ventilation and supervisory controls that keep the flammable vapor content well below the LFL.

Ventilation

Ventilation is required while an oven is in operation and flammable vapors are given off. Control devices ensure that the ventilating and preventilating systems are operating. Failure of the ventilating fan causes shutdown of the heating system and the conveyor that carries material into a continuous oven. The following discussion refers only to that ventilation required for safe operation and not that required for combustion and recirculation. It also does not apply to ovens operating in conjunction with solvent recovery systems, which sometimes use a low-oxygen atmosphere.

Proper ventilation includes a sufficient supply of fresh air, proper exhaust to outdoors, and properly distributed air circulation sufficient to ensure that the flammable vapor concentration throughout the oven is safely below the LFL at all times. The quantity of fresh air required for safe ventilation is determined by the amount of vapor released during the process.

In general, mechanical ventilation to outdoors is required on all ovens in which flammable or toxic vapors are liberated, as well as for ovens heated by direct-fired gas or oil heaters.

Ovens in which flammable or toxic vapors are never released do not require ventilation for safety, if heated by steam or electric energy or by gas- or oil-fired indirect heating equipment. On new ovens of every size, ventilation provided by a separate exhauster is advisable whenever appreciable amounts of flammable vapors are given off by the work.

Continuous Conveyor Ovens. The general rule for ventilating continuous conveyor–type ovens is to provide not less than 10,000 cfm (283 m^3/min) of fresh air at 70°F (21°C) for each 1 gal (3.79 L) of common solvent introduced into the oven. The basis for this rule is that 1 gal (3.79 L) of common solvent produces a quantity of flammable vapor that will diffuse in air to form roughly 2500 ft^3 (71 m^3) of the leanest explosive mixture. Because a considerable portion of the ventilating air might pass through the oven without completely traversing the zone in which vapors are given off, the ventilation air might be distributed unevenly. To provide a margin of safety, four times this amount of air, or 10,000 ft^3 (283 m^3) at 70°F (21°C) is required for each 1 gal (3.79 L) of solvent evaporated. In certain solvents, however, the volume of air rendered barely explosive exceeds 2500 ft^3 (71 m^3), and the safety factor decreases proportionately.

When a continuous-type oven is designed to operate with a particular solvent and the ventilating air can be accurately controlled, the required ventilation can be determined by calculation. (See NFPA 86 for information on how to calculate the volume of vapor produced by various solvents and the volume of air required to provide sufficient dilution to prevent an ignitable mixture.) As with the general rule for oven ventilation, the calculated rate of air change includes a factor of safety four times the volume of air required to prevent an ignitable mixture.

Batch Process (Box) Ovens. The nature of the work being processed is the basis for determining the ventilation rate in batch process ovens. Because of the wide variations in the materials, rate of evaporation, and coating thickness, it is preferable to make tests and calculations to figure the proper ventilation rate. However, years of testing and experience have shown that approximately 380 cfm (10.7 m^3/min) (at 70°F [21°C]) of ventilation for each 1 gal (3.79 L) of flammable volatiles released from a batch of sheet metal or metal parts being baked after dip coating is a reasonably safe rate of air change.

For other types of work, the figure of 380 cfm (10.7 m^3/min) (at 70°F [21°C]) is also used, unless the required ventilation rates can be calculated from reliable previous experience or the maximum evaporation rate is determined by tests run under actual operating conditions. In the latter case, a safety margin requires a rate of air change equaling four times the volume of air needed to produce an ignitable mixture. In any event, caution is needed when applying this estimating method to work of low mass (e.g., paper, textiles, etc.), which will heat quickly, or work coated with materials containing highly volatile solvents. Either condition can give too high a peak evaporation rate for the estimating method.

Temperature Correction. Temperature corrections must be made when using the preceding rules, since the volume of a gas varies in direct proportion to its absolute temperature (0°F is equivalent to approximately 460° abs, and 0°C is equivalent to approximately 273 K).

For example, to supply 10,000 ft^3 of fresh air at 70°F (530° abs) to an oven operating at 300°F (760° abs), it is necessary to exhaust:

$$\frac{760}{530} \times 10{,}000 = 14{,}320 \text{ ft}^3 \text{ of } 300°\text{F air}$$

To supply 283 m^3 of fresh air at 21°C (294 K) to an oven operating at 149°C (422 K), it is necessary to exhaust:

$$\frac{422}{294} \times 283 = 406 \text{ m}^3 \text{ of } 149°\text{C air}$$

In some cases, process requirements call for more ventilation than needed to maintain safe conditions in an oven. When this is true, an approximate method of figuring ventilation might be adequate for checking safety requirements. Except in these cases, all factors, including solvent characteristics, type of oven, material being processed, oven temperatures, and effect of temperature on the LFL, must be carefully considered so that an adequate safety factor is ensured.

Low-Oxygen Ovens. Low-oxygen ovens are used for evaporating solvent in an atmosphere where the oxygen concentration is below that required for combustion. For some solvents this operating value would be approximately 8 percent oxygen, which includes a safety factor of approximately 3 percent. There is a need for oxygen analysis to verify the low-oxygen concentrations. Inert gas is used to displace the oxygen (air) during startup and combustible gas or vapor during shutdown. These systems are used for solvent recovery from the coating cure process in the oven as shown in Figure 8.8.12. The treated product

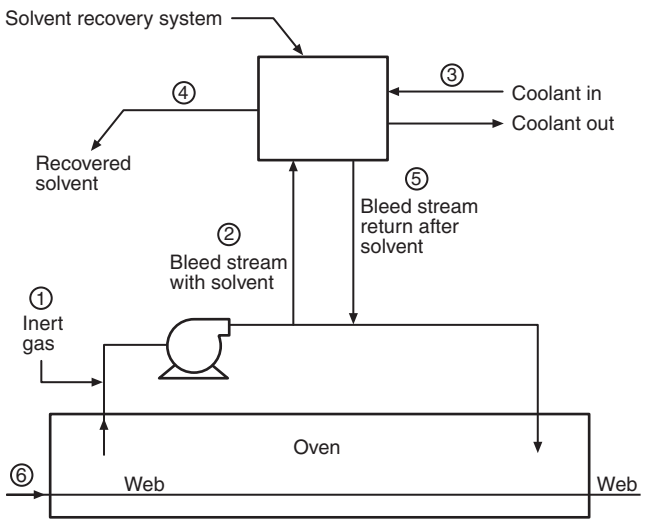

FIGURE 8.8.12 Low-Oxygen Oven with a Solvent Recovery System

passes into and out of the oven enclosure through the oven openings. The oven atmosphere consists of an inert carrier gas that is continuously recirculated through the oven enclosure (line 1). Solvents evolve from the treated product and build up to an equilibrium vapor level that is much higher than the allowable levels in an air atmosphere. A bleed stream (line 2), which is typically 1 percent of the recirculation flow, is processed by a solvent recovery system. A liquid (line 3), which provides cooling through vaporization, acts to condense the solvents that are pumped to storage (line 4). After solvents are stripped from the inert gas stream, it is returned directly to the oven enclosure (line 5) to resume its role as a solvent vapor carrier.

Fire and Explosion Protection

Automatic sprinklers and water spray systems should be considered for heat processing equipment that contains or processes sufficient combustible materials to sustain a fire. The amount of protection required depends on the construction and arrangement of the oven and the materials handled in it. If combustible material is processed, or if trucks or racks are combustible (or subject to loading with excess finishing material), fixed protection must extend as far as necessary into the enclosure and exhaust ducts. It also should be present where an appreciable amount of flammable drippings from finishing materials accumulates within the oven. If desired, supplementary carbon dioxide, foam, dry chemical, or halon protection can be permanently installed, but such protection is not a substitute for automatic sprinklers.

The use of steam for fire protection in ovens and dryers generally is not recommended. However, when there is no alternative, steam-smothering systems may be allowed when oven temperatures exceed 225°F (107°C) and large supplies of steam are available at all times. Complete standards have not been developed for the use of steam as an extinguishing agent. Steam is not as dependable as water, carbon dioxide, dry chemical, halon, or foam.

Portable extinguishers are needed near the oven, oven heater, and related equipment, including dip tanks or other finishing processes operated in conjunction with the oven. Small-hose stations with combination nozzles also should be provided so all parts of the oven structure can be reached.

Ovens that might contain flammable gas or vapor mixtures must be equipped with unobstructed relief vents to release internal explosion pressures. These vents, panels, or doors are secured with explosion-relieving hardware or gravity-retained panels that provide adequate insulation and possess the necessary structural strength. The weight of the panel should be minimal to permit movement at the lowest practical pressures. Explosion-relief panels must be proportioned according to the ratio of area to the explosion-containing volume of the oven, with due allowance made for openings or access doors equipped with approved explosion-relieving hardware. The preferred ratio is 1 ft^2 (0.09 m^2) of relief panel area to every 15 ft^3 (0.42 m^3) of oven volume.

CLASS B INDUSTRIAL FURNACES

In many ways, Class B furnaces are similar to Class A ovens and furnaces. However, because no flammable volatiles or residues are present, there is nothing combustible in the construction or contents of the Class B furnace.

In many Class B furnaces, little or no effective explosion-relief venting can be provided because of the weight and strength of the walls. Preventilation is important before a source of ignition is introduced into the furnace. In some cases, completely automatic purging might be practical; in others, purging might be partly manual. In either case, supervisory controls are needed to interlock the ventilation, fuel supply, combustion air, safety shutoff valve, and flame failure devices.

In multiburner installations, combustion safeguards with flame supervision should be applied. When furnaces have zones operating at different temperatures, the zones might have to be treated as separate units.

Changes in the usual safety requirements may be permitted in some ovens or furnaces, but if there is any possibility of explosion from unburned fuel, adequate safeguards should be provided. An audible alarm can be installed to indicate unsafe conditions.

CLASS C INDUSTRIAL FURNACES USING A SPECIAL PROCESSING ATMOSPHERE

Special atmosphere furnaces are used to improve the quality of metals and metal alloys by heating them in an atmosphere in which air has been replaced by other gases, some of which are combustible. In most cases, the gas is used to prevent oxidation of the metal during heating, but it can also prevent the removal or addition of carbon. Some processes that use atmospheric gases are bright annealing of copper and steel, scale-free hardening and annealing of castings, brazing, and sintering. Examples of protective gases used in these processes are hydrogen, charcoal gas, and dissociated ammonia. Also used are various hydrocarbon gases produced by equipment that processes the gas used for firing, generally in the presence of a catalyst. During the past few years, synthetic atmospheres that include methanol and other stored gas components have been used.

Some heat-treating furnaces contain an inert atmosphere (carbon dioxide, helium, argon, nitrogen) so they present no special fire hazard; however, these gases could present a health hazard. Other gases produce a flammable atmosphere (hydrogen, dissociated ammonia, incompletely burned hydrocarbon gas, carbon monoxide, and methane), which presents an explosion hazard; therefore, their use requires special safeguards. Atmosphere furnaces are not limited to flammable gases but also include acid gases, such as chlorine and anhydrous hydrochloric acid. When the latter are used in a special atmosphere, extreme care must be taken to keep air from entering the furnace. Regardless of the type of special atmosphere, Class C furnaces have fuel hazards similar to those of the Class A and B ovens and furnaces discussed earlier (although most Class C units are indirectly fired or electrically heated). The hazards in Class C furnaces exist chiefly at three times: (1) before the process starts and the flammable atmosphere is replacing air in the furnace; (2) when the process is finished and air is being readmitted; and (3) when, for some reason, the special atmosphere supply is interrupted and air is permitted to enter. If at each of these times sufficient inert gas can be introduced into the furnace to prevent

a combustible mixture, there is no danger of an explosion. Automatic introduction of inert gas on failure of the special atmosphere supply is desirable; at the least, an audible alarm should notify the oven operator of atmosphere supply failure or other upset conditions.

Inert Gas Purge Procedure

Begin by verifying the adequacy of the inert gas supply. After all doors (if any) are closed, make sure that the flammable atmosphere gas, flame curtain, and other valves are closed. The furnace may then be heated to operating temperature. If so, introduce the inert gas at a rate capable of maintaining a positive pressure in the furnace. Sample the furnace atmosphere until two consecutive readings indicate the oxygen content is below 1 percent. With at least one furnace zone above 1400°F (760°C), ignite the pilots at the outer doors and effluent vents. The flammable special atmosphere then may be introduced. When the flammable atmosphere is flowing, the inert gas should be turned off immediately. When flames appear at the vestibule effluent ports, the atmosphere introduction has been completed. The curtain burners then may be ignited.

To remove the flammable atmosphere with the furnace at operating temperature, the doors (if any) should remain closed, the inert gas purge actuated, and a positive furnace pressure maintained. Shut off the special atmosphere, flame curtain, and other valves, and sample the atmosphere until two consecutive analyses indicate the atmosphere is below 50 percent of its lower explosive limit (LEL). The furnace is then purged and the doors may be opened and the inert gas turned off.

The normal procedure for startup or shutdown of most Class C furnaces when the temperature is above 1400°F (760°C) is to burn out the air at the start of the process and the flammable atmosphere at the finish. In furnaces with an operating temperature above 1400°F (760°C), burning may be performed at the start by bringing the temperature up to 1400°F (760°C) before the special atmosphere is introduced. Automatic means are required to prevent the introduction of flammable fluids into a furnace before the furnace temperature has risen to 1400°F (760°C). At this temperature the flammable gas will burn in the oven until the oxygen is used up and the hazard removed, allowing the operation to be started. At the end of the process, the heating should be continued so the temperature stays above 1400°F (760°C); then the flammable gas supply is shut off and air gradually admitted. When burning stops, the flammable gas has been consumed. When an alarm indicates failure of the flammable gas supply or of the heating system, the oven operator must immediately initiate an inert gas purge or start the admission of air to burn the flammable gas in the furnace. This must be done before the furnace cools to below 1400°F (760°C). Where operators are not present and flammable gas flow is interrupted because of insufficient temperature inside the furnace, a flow control unit should automatically admit a flow of inert gas that will restore positive pressure without delay.

Special Atmosphere Generators

Special atmosphere generators are a source for the atmospheric gases used in some Class C furnaces. One type of generator (i.e., exothermic) produces the atmospheric gas by completely or partially burning fuel gas at a controlled ratio, usually at 60 to 100 percent aeration, whereas another type (i.e., endothermic) produces the atmosphere at a controlled ratio of less than 50 percent. Atmospheres from an exothermic generator are either inert or flammable, depending on the generator design and operating range, whereas those from endothermic generators are always flammable.

Another type of generator is an ammonia dissociator, which, by temperature reaction with a catalyst in an externally heated vessel, produces dissociated ammonia (25 percent nitrogen and 75 percent hydrogen) from ammonia.

The special atmosphere generator must be provided with adequate supervisory controls. These would normally include interlocking of raw gas, air (if needed), burners for heating or processing, feed and discharge pressures, and so on. Safety shutoff valves are usually provided in feed and discharge piping, and devices are also provided to indicate the pressure or rate of flow of processed gas to the furnace and its analysis. This can vary. The operator is thus assisted in his or her efforts to supply the furnace with the desired special atmosphere.

The best location for the generator and its auxiliary equipment, such as surge tank, compressor, aftercooler, storage tank, and so on, is in a separate, detached building of light, noncombustible construction.

CLASS D VACUUM FURNACES

Vacuum furnaces are used for heat treating metals; they are not, however, limited to this industry. In a vacuum furnace a vacuum pump is used to displace oxygen and, in most cases, to reduce the water vapor content or dew point as well.

Vacuum furnaces are usually batch furnaces. Batch furnaces are further classified into hot-wall and cold-wall furnaces; the latter are in greater use at the present time. Examples of hot-wall and cold-wall vacuum furnaces are shown in Figures 8.8.13 and 8.8.14, respectively. In the hot-wall furnace, the entire vacuum vessel is heated, though usually not above 1800°F (982°C) because of the reduction in the strength of materials at elevated temperatures. However, installation of a second vacuum vessel outside the vacuum retort (within which a roughing vacuum is maintained during the heating cycle) permits construction of larger hot-wall furnaces with higher operating temperatures.

Cold-wall furnaces consist of a water-cooled vacuum vessel. Usually the heating elements are inside the vacuum vessel. The walls can be maintained at near ambient temperature during high temperature operations; thus, large units operating at high temperatures (4000 to 5000°F [2204 to 2760°C]) can be constructed. The two most common methods of heating cold-wall furnaces are by resistance and induction, with the heating elements located within the vacuum vessel. The heating elements are usually water cooled, though occasionally they are air cooled. Insulation can be affected by radiation shields constructed of low-emissivity, oxidation-resistant metals with proper vapor pressure characteristics. Refractory insulation can be used in some instances, but this is difficult due to outgassing of entrapped air in the refractory.

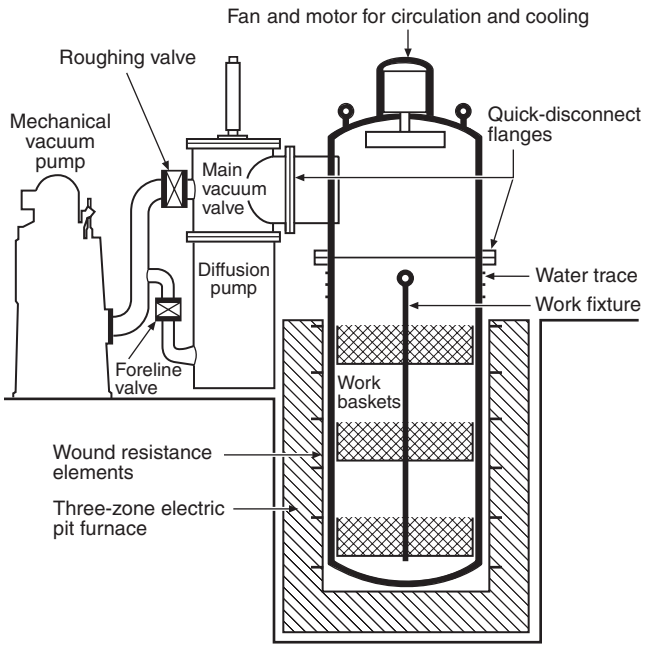

FIGURE 8.8.13 Hot-Wall, Single-Pump Retort Vacuum Furnace

Mechanical-type pumps may achieve vacuum pressures of 10^{-3} to 10^{-2} torr. (Torr is a unit of pressure equal to 1/760 of an atmosphere.) For greater vacuum, booster oil-diffusion pumps are used to achieve pressures in the range of 10^{-5} to 10^{-7} torr; they must be "backed" by a supplementary pump.

Fractionating oil-diffusion pumps also are used and should always be backed by a rotary pump, or rotary and mechanical booster combination. They produce pressures from below 10^{-3} torr down to about torr. The accidental admission of air into a heated diffusion pump has resulted in an explosion of the pump fluid. The explosion forces damaged both the pump and the furnace hot zone.

Vacuum furnaces have the same hazards as most Class C furnaces. Besides those hazards associated with the heat sources, the additional hazards of vacuum furnaces are the following:

1. Water leaks in either heating elements or vessel jackets can cause explosions; if water enters the furnace at operating temperatures, it will cause more than just a steam explosion
2. Collapse of the furnace wall if a relief valve on the water jacket fails
3. Collapse of the vacuum retort in a hot-wall furnace, if the vessel uses materials that have inadequate strength at high temperatures; if this occurs in a gas-fired unit, the flame can be pulled into the vacuum pump and ignite the oil in the pumps
4. Vacuum pumps that pull fluids (water or oil) from hydraulic seal pots
5. The condensed metallic vapors on electrical insulators, which can cause short circuiting, because this kind of furnace operates at pressures that can vaporize metals
6. Short circuiting, if improperly supported heat shields sag at high temperatures and contact heating elements
7. Hot spots on furnace walls that can weaken the furnace wall, if heat shields sag
8. Temperature control problems not present in other types of furnaces and ovens; optical pyrometers must have a line of sight to the work and their accuracy can be seriously impaired by gases, smoke, or discoloration of the sight glass
9. Heat transfer—unless the thermocouple is actually attached to the part being measured, the heat transfer is based

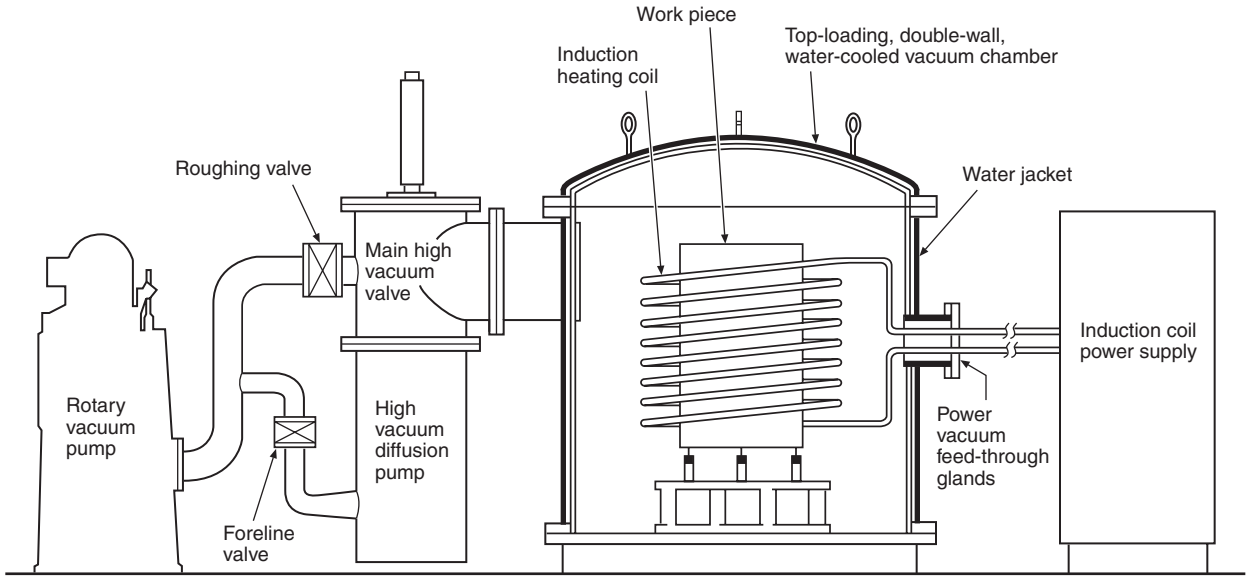

FIGURE 8.8.14 Cold-Wall, Induction-Heated Vacuum Furnace

wholly on radiation. In air, a thermocouple receives heat by conduction and convection; therefore, with no air (or gas) in the furnace, the thermocouple response is slower. A gap of as little as 0.001 in. (0.025 mm) between the thermocouple and part or surface being measured can change significantly the response time of the thermocouple. A thermocouple on the heating element could mean that the parts would not reach the desired temperatures because the heating elements would of necessity have a temperature higher than the part (center of furnace), at least until equilibrium has been reached.

10. Induction heating—keeping piping conduits, building columns, beams, and so on, out of the induction field, if the furnace is heated by induction. Any one of these items near an improperly shielded furnace can be heated by the induction coil inside the furnace. For instance, a steel bar placed so that it touches the furnace and a metal floor will be visibly hot in a matter of minutes. Of course, this also can happen on a Class B induction furnace.

AFTERBURNER AND CATALYTIC COMBUSTION SYSTEMS

Vapor incinerators are combustion oxidation chambers designed to destroy process exhaust vapors by heat. Both direct flame and catalytic oxidation are used to reduce odors, vapors, and gases to acceptable exhaust products, such as carbon dioxide and water vapor. Exhaust that contains something besides plain hydrocarbons and oxygenated species might require additional special treatment, scrubbing, and filtration to remove particulate matter as well as halogens, hydroxides, sulfur oxides, and nitrogen oxides.

The advantages of vapor incinerators can include reduced cleaning costs, reduced equipment downtime, reduced fire and explosion hazards, compliance with federal, state, and local pollution regulations, and savings in plant heating costs. Process fuel consumption can be reduced by the heat recovery of the burned exhaust fumes.

Installations have been damaged by fires in ducts between the process units and the incinerator, explosions of accumulated vapors in the ducts before or during startup, improper operation of gas-fired incinerators, and overheating of the catalytic element or combustion chambers. The causes of these fires have been inadequate duct cleaning; inadequate duct design; incomplete prepurging of the ducts, process unit, and incinerator; failure by the operator to follow proper operating procedures; and malfunction of burner and temperature controls.

Afterburner (Direct-Flame) Incineration

Direct-flame incinerators can be used for a wide range of organic solvent vapors, organic dusts, and combustible gases. In order to burn, the fumes must be heated to their autoignition temperatures with sufficient oxygen present to complete the chemical reaction. Quenching the burner flame might occur if the burner capacity is insufficient or the flame pattern and mixing are inadequate. The material being incinerated must reach the autoignition temperature and remain there long enough (dwell time) for the chemical reaction to occur (the dwell time is usually 0.4 to 0.8 sec). Ample oxygen, more than 16 percent, is necessary for complete combustion. The step sequence for successful incineration is shown in Figure 8.8.15.

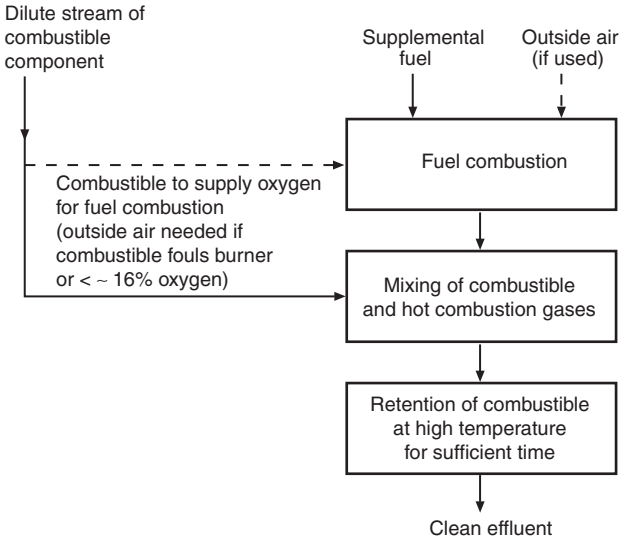

FIGURE 8.8.15 Steps Required for Successful Incineration of a Dilute Stream of Combustible Dust, Gas, or Vapor

Operating temperatures in the combustion chamber are usually designed for a range of 1200 to 1500°F (650 to 816°C). Tests on some units have reported approximately 92 percent conversion efficiency to CO_2 at 1300°F (704°C) and 96 percent conversion efficiency at 1450°F (788°C). These conversion percentages to CO_2 are frequently required by air pollution codes. In any case, complete combustion requires that the combustion component have sufficient air, proper mixing with the air, adequate dwell time, and adequate combustion chamber temperature.

Direct-flame combustion chambers are usually heavy refractory lined with external burners, such as tunnel burners, or light refractory with sectional line burners or line burners with mixing plates (Figure 8.8.16).

When metal construction is used, the design must take into account high thermal stresses and possible overheating of the metals. The combustion chambers, kiln, and boiler burner flames sometimes are used as fume incinerators.

Contaminated process waste streams might be inert gases with a low combustible hydrocarbon content. This mixture can be mixed with sufficient air to ensure combustion, then oxidized in a direct-flame or catalytic incinerator.

Special precautions must be taken where a concentrated combustible stream is exhausted from the process. For safety, the stream is usually diluted with air to below 50 percent LEL for transfer to the incinerator.

Concentrated combustibles above the LEL are normally burned in flare stacks or as fuel in various types of heating equipment. The latter requires special burner design and combustion control supervision.

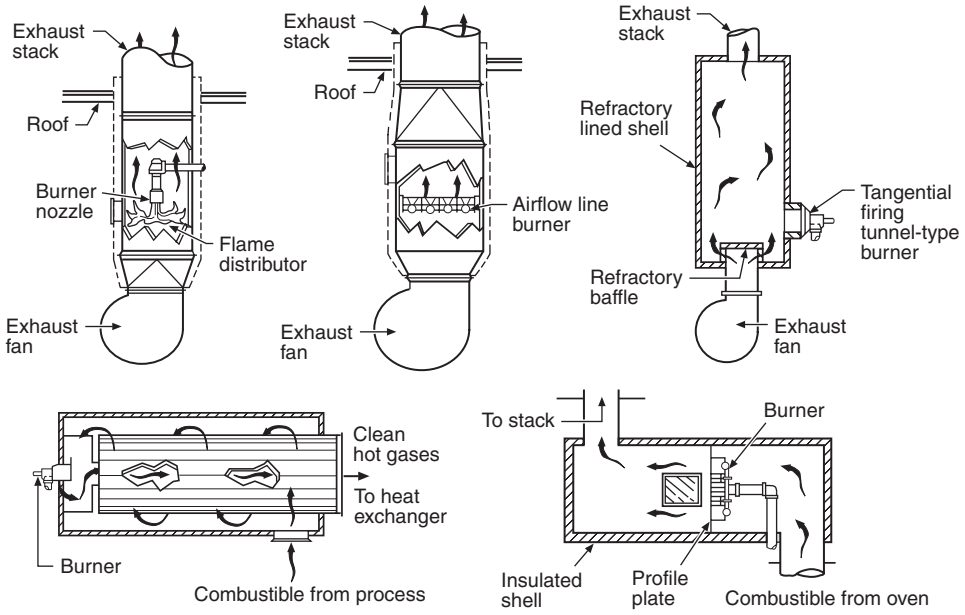

FIGURE 8.8.16 Typical Direct-Flame Dilute Stream of Combustible Component Incinerators (Source: Maxon Corp.)

Catalytic Combustion Systems

Air pollution from furnace exhaust often is removed or reduced by catalytic combustion systems. A catalytic heater employs catalysts to accelerate the oxidation or combustion of air-fuel mixtures, including waste streams, for eventual release of heat to an oven or other process. Catalytic heaters can be used to burn a fuel gas, with substantial portions of the energy released as radiation to the processing zone. Alternately, catalytic heaters can be installed in the oven exhaust stream to release heat from evaporated oven byproducts, with available energy returned by a heat exchanger for recirculation through the oven processing zone.

Three types of catalytic combustion elements are available. The first is an all-metal mat used either as a fuel-fired radiant heater or alternately to oxidize combustible materials in an exhaust stream. The second type is of ceramic or porcelain construction arranged in various configurations for gas fuel or vapor oxidation with catalyst media, including a variety of "rare earth" elements (e.g., platinum or metallic salts). Both types of these elements are classified as "fixed-bed" catalysts since they are normally held rigidly in place by clamps, cement, or other means. A third type of element consists of a bed, pellets, or granules supported or retained between screens in a fixed position but with the individual members free to migrate within the bed.

Heating systems that employ catalysts are widely used to conserve oven fuel and control air pollution emissions (Figures 8.8.17 and 8.8.18). Catalytic heaters cannot, however, oxidize or consume silicones, chlorine compounds, and metallic fumes as from tin, mercury, and zinc; these elements and various inorganic dusts can retard or paralyze the catalysts.

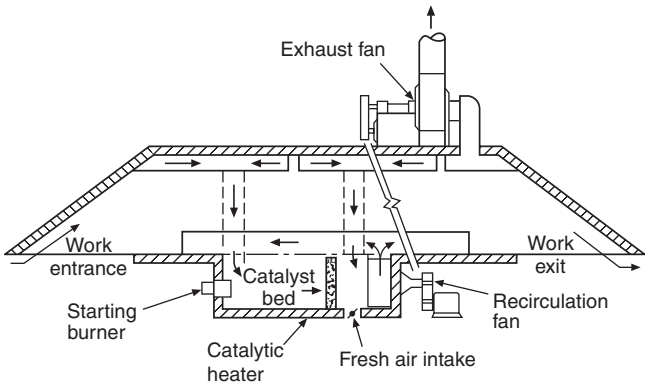

FIGURE 8.8.17 Direct-Type Catalytic Oven Heater for Partial Air Pollution Control

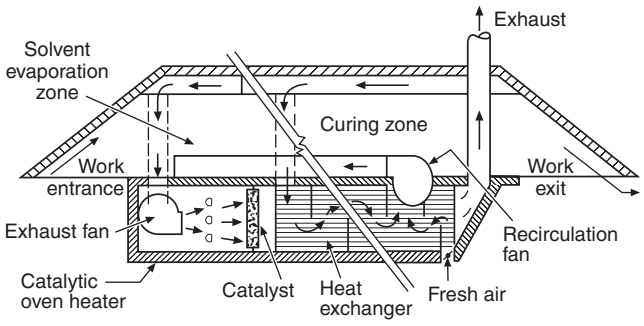

FIGURE 8.8.18 Indirect-Type Catalytic Oven Heater for Full Air Pollution Control

Installation

All components of the afterburners and catalytic combustion system, related process equipment, and interconnecting ducts must be provided with controls and safeguards to supervise conditions during startup, operation, and shutdown. In some installations, many different concentrations of the combustible stream develop. Collection and delivery of this stream to the incinerator is an important part of the system. A careful investigation must be made for the incinerator and the associated equipment, including the appropriateness of the design and operating procedures.

HEAT RECOVERY

Heat exchangers and direct recirculation methods of heat recovery are often used to make process and waste system incineration more economical. Some plants have calculated that if heat recovery methods are applied to heat generating processes, including incineration, the recovered heat can supply a substantial portion of the entire plant's heat or process demands (Figure 8.8.19).

Recovered heat can be used for (1) the process as either a sole or supplementary heat source, (2) the process for some zones in a multizone unit, (3) other nearby processes, (4) preheating the stream entering incinerator, (5) heating plant makeup air, and (6) a waste heat boiler serving multiple plant services. However, dirty stream deposits in the heat exchanger can make it inoperable. Combustible deposits and flammable liquids heated to high temperatures within the heat exchanger could cause a fire or explosion.

LUMBER KILNS

Drying lumber to a predetermined moisture content is accomplished in a variety of structures called kilns. Kilns make it possible to turn freshly cut, green wood into dry, accurately dimensioned lumber in a much shorter time than seasoning wood in open air. Because large quantities of combustible material are exposed to temperatures that can approximate ignition temperatures, kilns present a high degree of fire hazard.

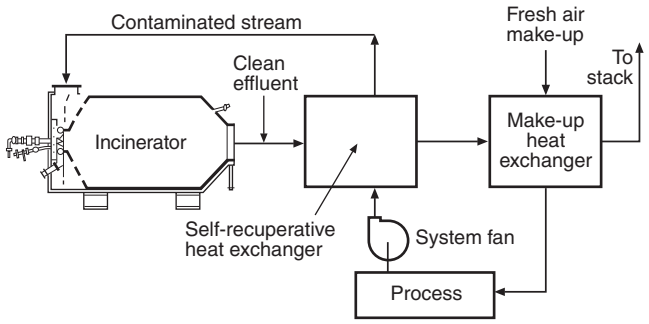

FIGURE 8.8.19 Typical Incineration System Incorporating Waste Heat Recovery with Fume and Process Air Preheating

Although called dry kilns, wood dryers usually employ moisture to maintain a uniform content within the wood during the drying, thus eliminating warping, checking, and splitting. The amount of moisture will vary with the species; significant variations are found within trees of the same species. The length of time required to bring the moisture content down to an optimum of about 2 percent depends on the species, its original moisture content, the dimensions of the pieces being seasoned, the type of kiln, and the volume of material.

Types of Kilns

A dry kiln is basically an oven with controlled heat and humidity. It can be either a batch dryer or a progressive dryer. The wood being dried in a batch or compartment kiln remains stationary throughout the process. Temperature and humidity in all parts of the kiln are maintained as uniformly as possible and are adjusted as the wood dries.

Progressive kilns permit green lumber to be introduced in one end while dried lumber is being removed from the other end. Such kilns are designed so that somewhat higher temperatures are maintained at the dry, or discharge, end rather than at the loading end.

In natural circulation kilns, heated air rises up through the stacked lumber by convection (Figure 8.8.20). Losing its heat, air travels down to the heating device and is reheated. During the first part of the drying cycle, the air flows up along the sides, over the stacked lumber, and down through air passages in the stack. When the moisture content has been reduced to somewhere between 20 and 10 percent, heated air is directed up through the center of the stack to equalize the drying. Vents in the walls or roof of the kiln exhaust the hot, moisture-laden air.

Forced circulation kilns move air through the stacked lumber by either internal or external blowers (Figure 8.8.21). Figure 8.8.22 shows an internal fan kiln with fans located beneath the

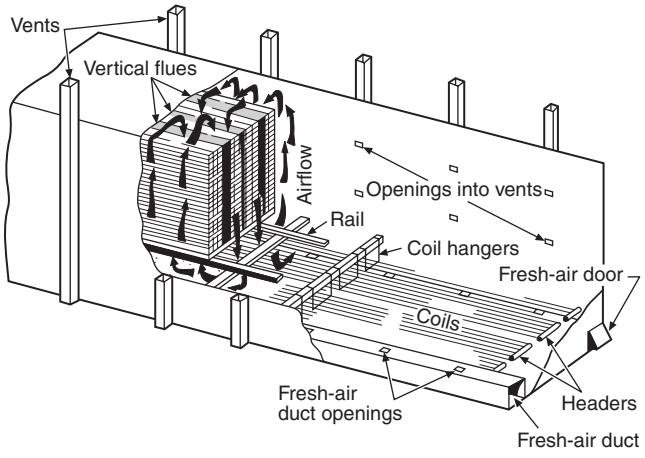

FIGURE 8.8.20 Natural Circulation, Steam-Heated Compartment Kiln. Arrows indicate air movement during the early stages of the drying cycle.

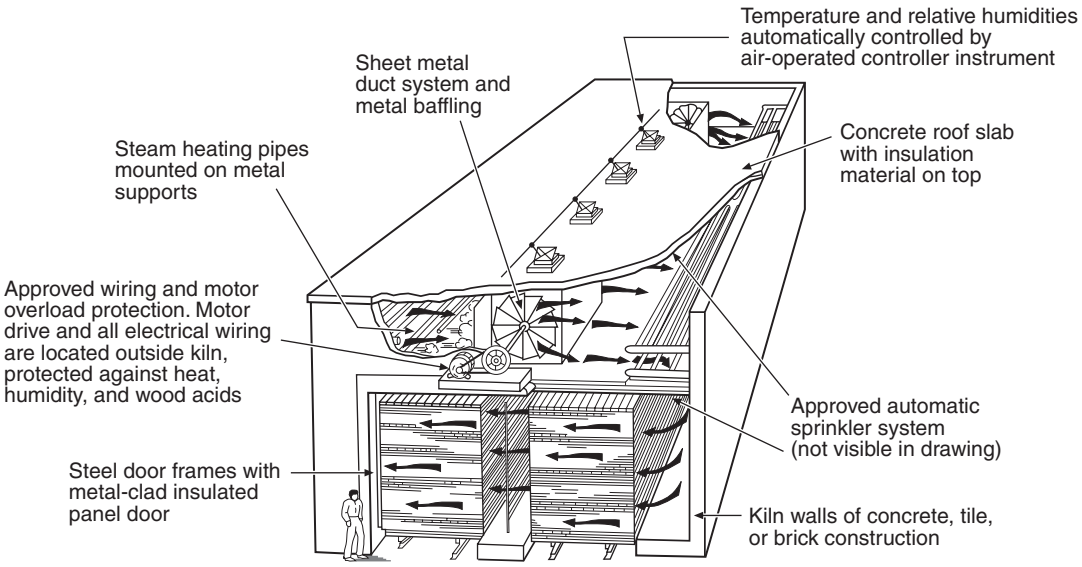

FIGURE 8.8.21 Forced Circulation Double-Track Compartment Kiln. Note that automatic sprinklers are installed above and below the platform between the kiln and the overhead fan room.

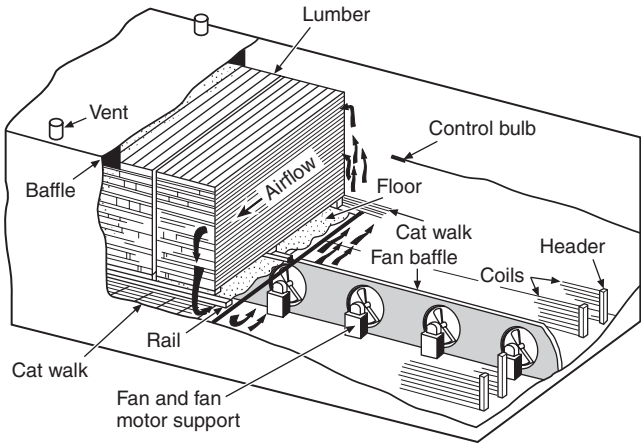

FIGURE 8.8.22 Compartment Kiln with Internal Fans and Steam Coils Located under Grating at Floor Level. Broken pieces of stickers and sawdust can fall through the grates and collect around the coils and fan motors to become a hazard, particularly if high-pressure steam coils are used.

floor. Internal fans are reversible, changing the airflow for optimum drying. Internal fan kilns normally require cloth or metal baffles to eliminate turbulence and keep the air flowing in the desired direction.

Much the same airflow systems are used in both batch and progressive kilns. There are some minor differences, however. In progressive kilns, the air flows through the length of the chamber and is discharged at the green end. Because the air has picked up moisture and is cooler by the time it reaches the loading end of the kiln, the drying rate there is much slower.

Kiln Construction

Unlike most other buildings, kilns are subjected to extreme variations in internal temperature and humidity. Such variations cause unusual expansion and contraction that reduce structural integrity of the kiln and increase heat loss. Untended structural defects can also lead to premature failure of the structure. To reduce the fire hazard, kilns should be of fire-resistant or heavy-timber construction.

Heat Sources

Dry kilns require a constant source of heat, provided either directly or indirectly, to vaporize the water content of the wood. Direct heating is accomplished by circulating hot gases (produced by burning gas, oil, sawdust, or other fuels) through the stacked lumber. It also can be done by heating large metal surfaces with an open gas or oil flame as in Figure 8.8.22. Air circulated by internal fans passes over the metal, which acts as a heat exchanger, then flows over the lumber, carrying off moisture vapor.

Steam is a common source of heat for indirectly heated kilns, but hot gases and electrical resistance heaters are also used. Steam is circulated through pipes and hot gases through ducts.

Fire Hazards

Lumber kilns present high fire hazards. This is especially true when direct-heat systems or high-pressure steam systems are used and in those instances where the structure itself is of combustible materials.

Direct-fired kilns present the greatest hazard because open ignition sources are close to the wood (Figure 8.8.23). The kilns should be considered analagous to Class A ovens in that they

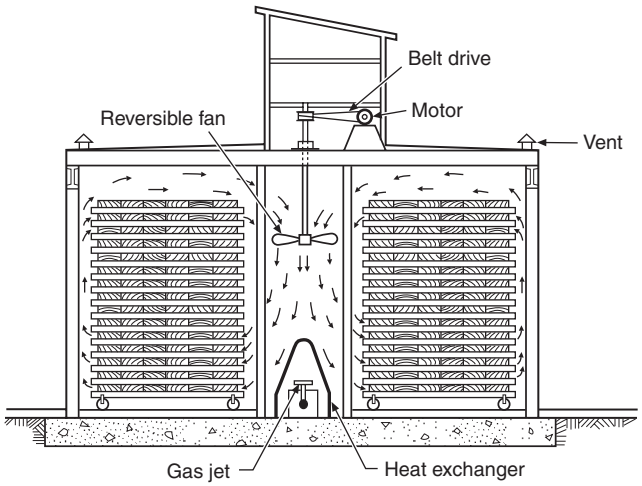

FIGURE 8.8.23 Double-Track, Internal Fan Compartment Kiln Heated Directly by a Gas Burner

should be equipped with all the combustion controls normally required for drying ovens where the heating fuel is introduced into the heating enclosure itself. Indirectly heated kilns utilizing steam coils as heat exchangers and having controlled humidity are usually considered to be of low hazard.

Safeguards

The important requirements for fire safety are automatic sprinkler protection, sound construction, good housekeeping, automatic humidity control, good air circulation, and proper ventilation. Kilns should be situated at safe distances from storage yards, sheds, and mill buildings. Ideally, they should be of fire-resistant construction and equipped with a complete automatic sprinkler system connected to an adequate water supply. The sprinkler protection should extend to fan houses and control rooms. Hydrants or hose connections should be located on the exterior for manual fire fighting.

DEHYDRATORS AND DRYERS

Dehydrators and dryers for agricultural products, commonly referred to as dryers, use heat to reduce the moisture content of products. The hazards of dryers are (1) the possibility of igniting combustible materials near them, (2) the use of fuel or electricity as a heat source, and (3) the ignition of stock being dried.

Types of Dehydrators and Dryers

The three types of agricultural product dryers are (1) continuous, (2) batch, and (3) bulk. They differ in the arrangement and operation of the drying chamber.

Continuous dryers include the following types:

1. Drum dryers for milk, puree, and sludges
2. Spray dryers for milk, eggs, and soup
3. Flash dryers for chopped forage crops
4. Gravity dryers (can also be batch type) for small grains, beans, and seeds (Figure 8.8.24)
5. Tunnel dryers (also batch type and can be further classified according to airflow and whether or not intermediate heat-

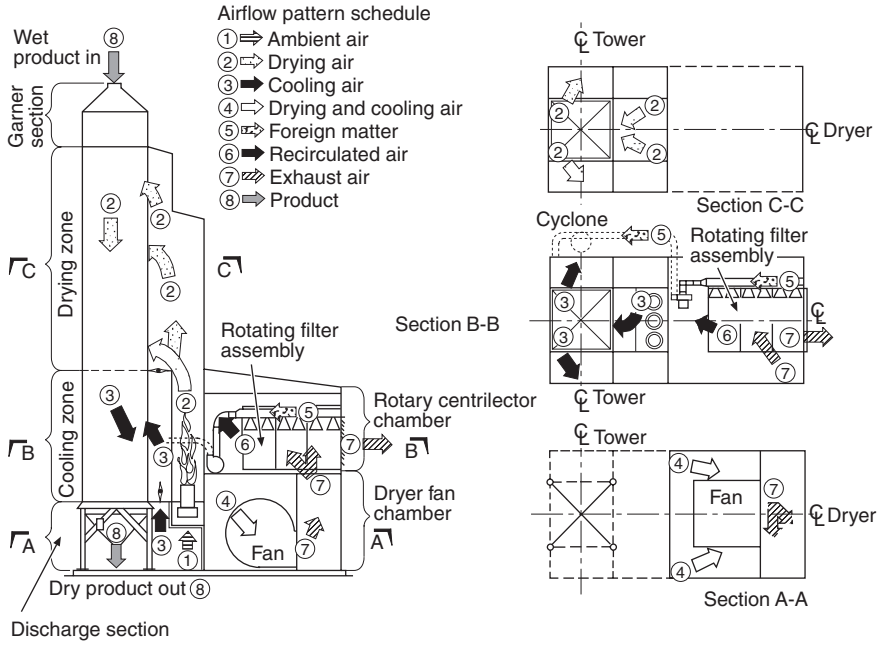

FIGURE 8.8.24 Tower-Type Gravity Dryer (Source: Aeroglide Corp., http://www.aeroglide.com)

ing is used) for fruits, vegetables, grains, seeds, nuts, fibers, and forage crops (Figure 8.8.25)
6. Rotary dryers for milk, puree, and sludges (Figure 8.8.26)

Batch dryers can be either fixed or portable and include pan dryers for sugar, puree, sludges, and other products (Figure 8.8.27).

Bulk dryers dry the product in a bin, crib, or compartment in which it is to be stored. They are used to dry seeds, grains, nuts, tobacco, hay, and forage (Figure 8.8.28).

Methods of Heating

Dryers for agricultural products can be direct-fired (where products of combustion contact the material being dried) or indirect-fired. The heaters can be oil-fired, gas-fired, solid-fuel-fired, electrical, or heated by a heat transfer medium, such as steam. In general, the requirements for burner installation and fuel storage are the same as those for other heat-producing devices.

If gas-fired infrared heaters or lamps are used, their focal length should be ample so the surface of the drying product does not reach unsafe temperatures. If electrical infrared lamps are used in dryers, the lamps should be located where they cannot collect combustible dust.

Solid-fuel furnaces (other than those burning coke and anthracite coal) should not be used where the products of combustion can enter the drying chamber. Indirect solid-fuel dryers need temperature-controlled heat relief openings to the outside.

Dryer Controls

Some suggested controls for dryers, except those on the heating equipment, include the following:

1. A method for automatically shutting down the dryer in the event of fire or excessive temperature
2. A thermostat in the exhaust air when the product is fed automatically from the dryer to a storage building; in the event of excessive temperature, the thermostat
   (a) shuts off heat to the dryer and stops airflow (except when the product being dried is in suspension)

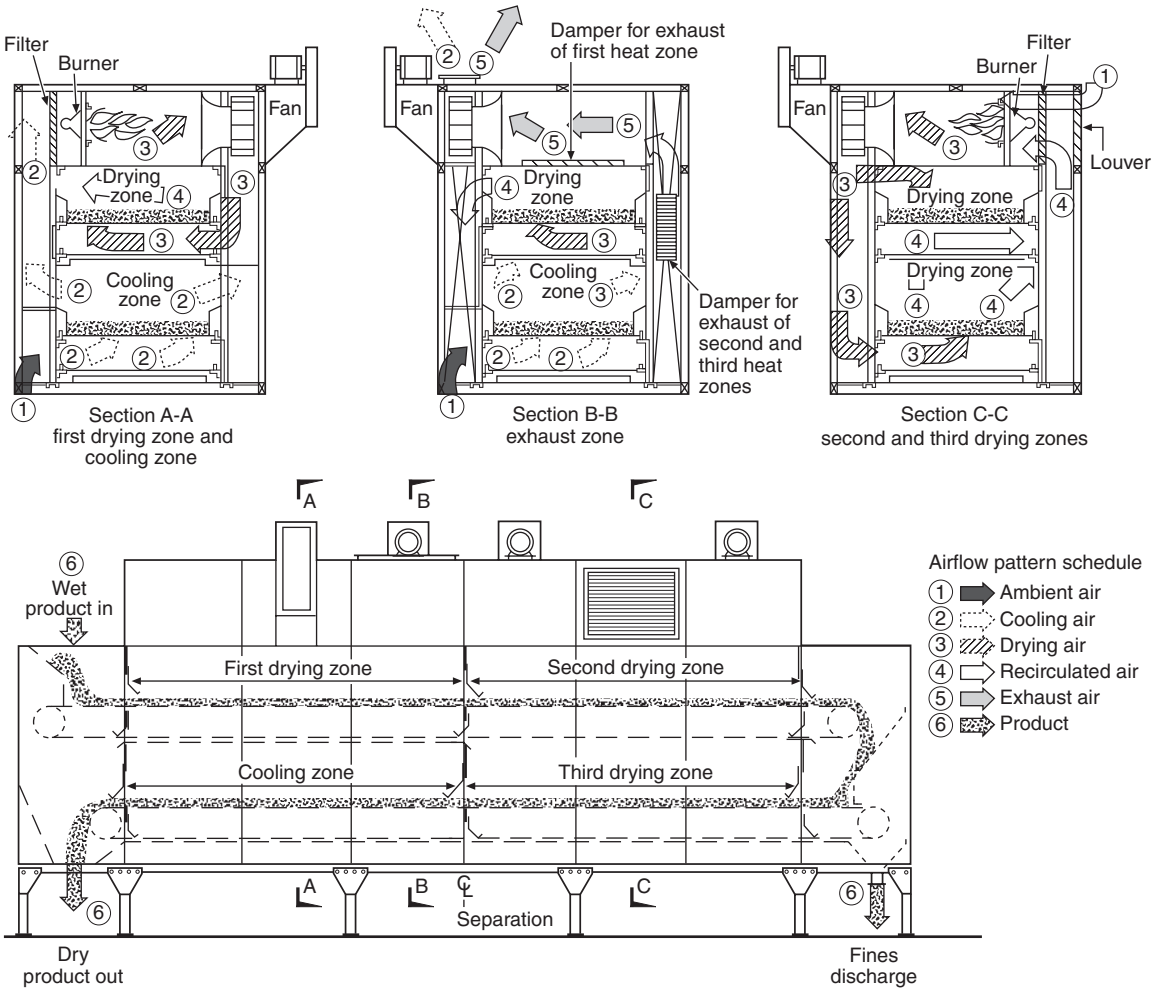

FIGURE 8.8.25 Tunnel Dryer (Source: Aeroglide Corp., http://www.aeroglide.com)

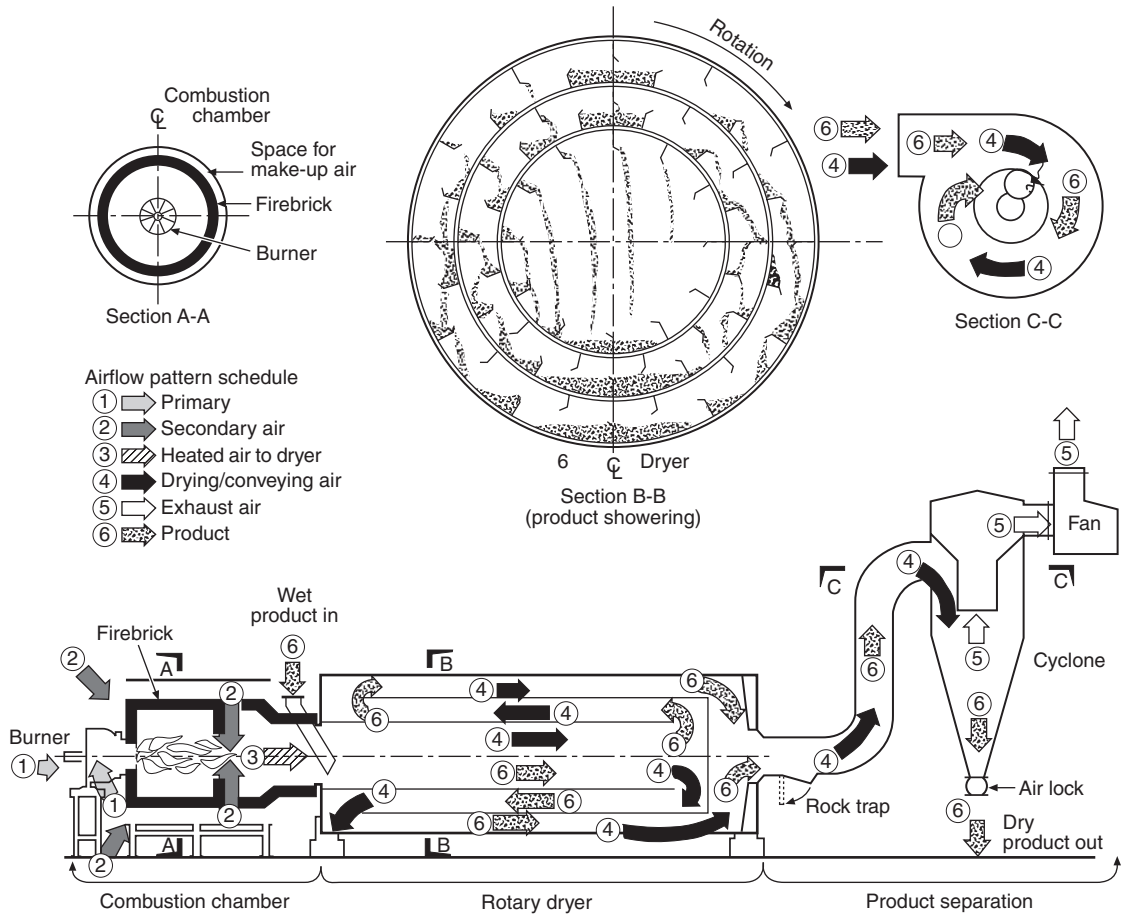

FIGURE 8.8.26 Rotary Dryer (Source: Aeroglide Corp., http://www.aeroglide.com)

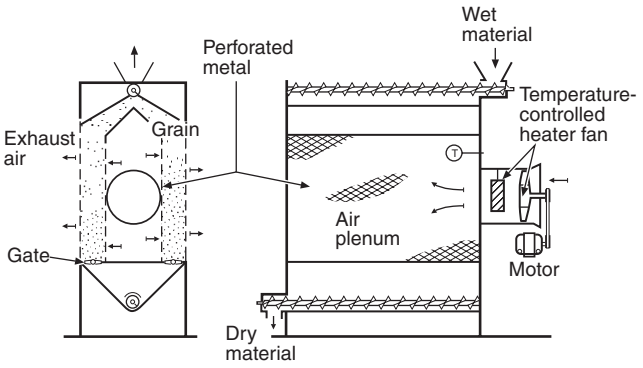

FIGURE 8.8.27 Batch-Type Grain Dryer

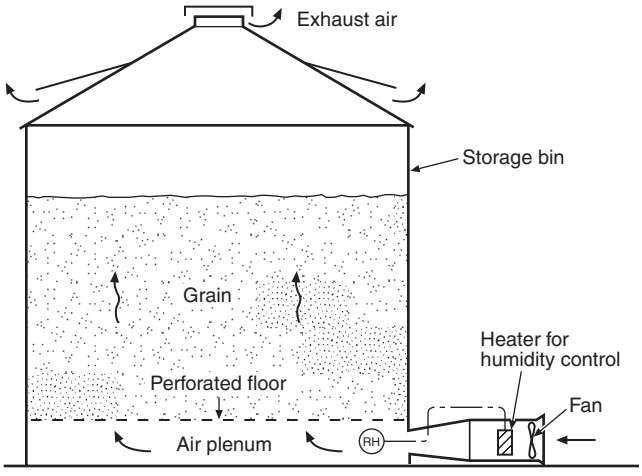

FIGURE 8.8.28 Bulk-Type Grain Dryer

(b) stops the flow of the product
(c) sounds an audible alarm

3. A thermostat in combustible dryers that, when the temperature of the combustible reaches 165°F (74°C), shuts off heat to the dryer but permits unheated air to pass through and activates an audible alarm
4. A device to shut off heat to the dryer if air movement through the dryer stops
5. A high-limit thermostat located between the heat-producing device and the dryer

Burner Controls

In general, the burner controls for dryers are the same as those for other automatically fired devices. A manual, quick-closing shutoff valve should be installed in the supply line of gas- and oil-fired burners and controls should be arranged so that, following automatic shutdown, manual restart will be necessary. Other control safeguards include flame failure protection and preventilation of the combustion chamber. All safety devices must be listed for the service intended.

Construction and Installation of Dryers

Because dryers operate at elevated temperatures, they should be made of fire-resistant or noncombustible materials. If combustible materials must be used, dryers must not be subjected to sustained temperatures in excess of approximately 165°F (74°C). Expansion joints should be provided to prevent damage from expansion and contraction.

Secondary air openings for direct-fired dryers are screened with ½-in. (12.7-mm) mesh screen so materials cannot enter the combustion chamber. Primary air openings require screens with mesh ¼ in. (6.4 mm) or smaller. An ample supply of easily opened access panels is necessary for inspection, cleaning, and fire fighting.

When stock is moved through the dryers in a way that generates static electricity, all conductive parts of the dryers should be electrically bonded and grounded.

Like any heat-producing device, a dryer must have adequate clearance from nearby combustibles to prevent overheating. If there is a combustible dust hazard in the same building as the dryer, the heating device and blowers are installed in a dust-free room or area separated from the rest of the building. Ducts to convey heated air to the dryer and exhaust air from the dryer to the outside should be noncombustible.

Extinguishing Equipment

The best way to protect a dryer enclosure is to install a water spray or automatic sprinkler system within the enclosure where possible. An exception to this is the direct-fired rotary dryer, which can be damaged by the internal application of water. A carbon dioxide system is satisfactory protection for this type of dryer.

Fire protection might be needed in the product and exhaust dust-collecting system, bins, chutes, ducts, cyclone collectors, and dust collectors. In addition to automatic sprinkler or deluge systems, high-speed infrared detectors with water spray might be needed to extinguish ignition sources, sparks, or embers in the ducts and to prevent propagation to the bins or dust collectors.

To extinguish small fires in and around most dryers, standpipe hoses are most useful, though water-type portable fire extinguishers also may be used.

Cooling of Dehydrated Products

A product being dried requires adequate cooling before it is packaged or stored. The amount of cooling required to prevent subsequent ignition will depend on the properties of each material and how it is to be packaged or stored.

SUMMARY

This chapter is meant to increase the awareness of designers, end users, and operators of industrial and commercial heat utilization equipment of the hazards involved with this type of equipment. The potential hazards involve both heat generation and the process materials.

Because heat utilization equipment is so varied in size, complexity, and location, developing rules that fit every type of oven, furnace, or dryer is difficult. Proper equipment operation depends on the right combination of controls, protective devices, and operator training. The best design and installation still require the competent and well-trained operator who is thoroughly familiar with the equipment, its hazard potential, and its maintenance requirements.

For additional requirements, the reader is directed to NFPA 86.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on industrial and commercial heat utilization equipment discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 31, *Standard for the Installation of Oil-Burning Equipment*
NFPA 54, *National Fuel Gas Code*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities*
NFPA 70, *National Electrical Code®*
NFPA 86, *Standard for Ovens and Furnaces*

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Chapter 9

Oil Quenching and Molten Salt Baths

Raymond Ostrowski

Chapter Contents

Oil and Polymer Quenching
Quench Tanks
Material Transfer
Oil Temperature Control
Central Oil System
Safety Considerations
Molten Salt Baths

Key Terms

controlled cooling, hardening processes, heat-treating operations, molten salt bath operations, oil (quenching), oil quenching operations, quenching (polymer), salt bath furnace, tempering processes

Oil-quenching operations are heat treatment processes that both harden and temper metals. Molten salt baths are used for heat treatment of metals, ceramics, or polymers to increase their hardness.

The first part of the chapter addresses the various elements of oil quenching, safeguards, and fire protection. The second part of the chapter describes salt bath types and applications, hazards, and safeguards.

Additional hazard and protection information relevant to oil quenching can be found in Section 8, Chapter 11, "Fluid Power Systems." Fire suppression information can be found in Section 15, "Water Supplies for Fixed Fire Protection"; and Section 17, "Fire Suppression Systems and Portable Fire Extinguishers."

Additional information on molten salt baths can be found in Section 7, Chapter 4, "Storage and Handling of Chemicals"; and Section 8, Chapter 8, "Industrial and Commercial Heat Utilization Equipment."

OIL AND POLYMER QUENCHING

One process in the heat treatment of metals is a controlled cooling or quenching of heated materials by immersion in a liquid-quenching medium. This process hardens and tempers the metal by imparting metallurgical changes to its surface. Due to the combustible nature of quench oils, the process presents serious fire hazard potentials.

Contributing to the hazards of oil quenching are the following:

1. Requirements for a special atmosphere (a flammable gas blanketing the surface of the oil)
2. Temperature requirements of the quench medium
3. Physical properties of the quench medium
4. Volume limitations of the quench medium
5. Size and configuration of process materials
6. Locations of furnaces and quench tanks
7. Mutual exposure between quenching and other processing or storage facilities

Whether the quenching is automatic and continuous, semiautomatic, or a batch operation, it will involve elevators, conveyors, hoists, and cranes, either individually or in combination, to immerse the work in, move it through, and remove it from the oil bath (Figure 8.9.1). Although all three steps are important to the process, the one that is critical to safety is the entrance of the work into the quench.

Quenching Oils

In most cases, mineral oils are used for quenching, but specific metallurgical requirements sometimes dictate the use of mixtures with animal or vegetable oils. In addition, wetting agents might

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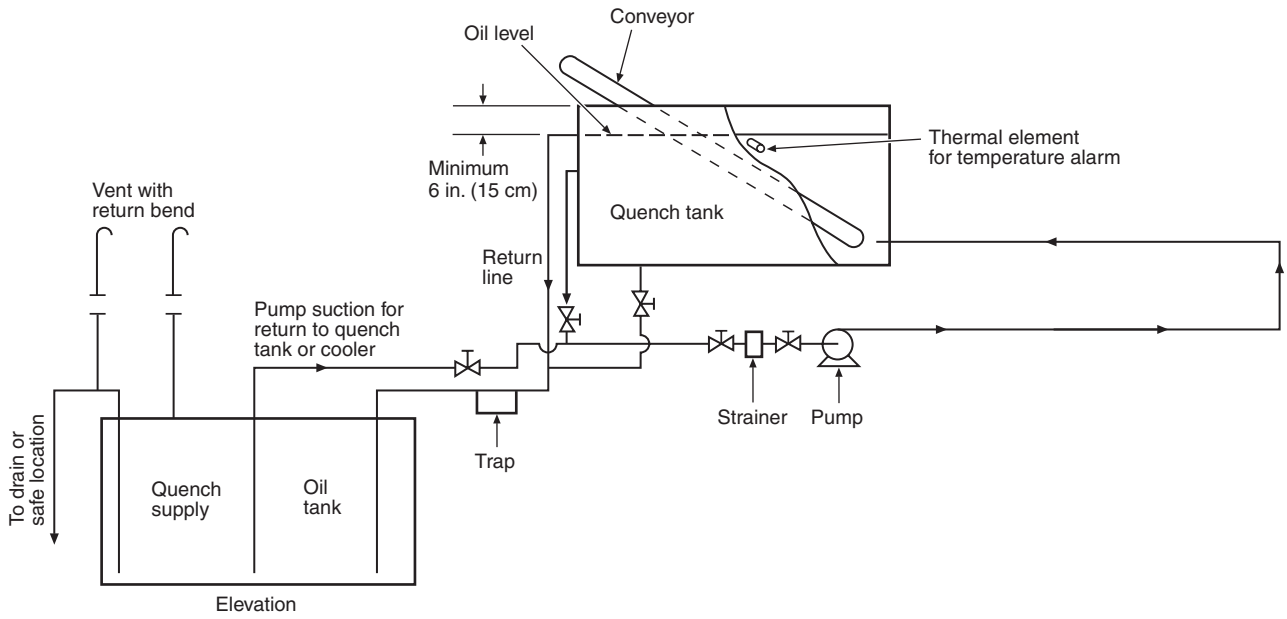

FIGURE 8.9.1 Typical Continuous-Type Oil Quench Tank

need to be blended with certain oils or oil mixtures. In any case, it is important to use a quenching oil with a low viscosity.

Essential quench oil properties include the ability to remain stable over periods of extended usage and to retain fluidity. For unheated quenching, operating temperatures between 100 and 200°F (38 and 93°C) are considered normal. Standard quench oils for use in this temperature range usually have flashpoints somewhat above 300°F (149°C). For heated quenching, operating temperatures between 200 and 400°F (93 and 204°C) are common. Quench oils used at these temperatures generally have a flashpoint above 500°F (260°C).

Polymer Quenching

A rather recent development is the use of polymer quenchant in integral quench furnaces. A furnace designed for oil is not designed for a quick change to polymer quenching. Caution should be observed and the original furnace manufacturer should be contacted prior to changing from oil to polymer quenchant.

QUENCH TANKS

A quench tank should allow proper quenching under normal conditions and provide for minor variations in equipment control functions and operator error. The designs of the tank freeboard, overflow drains, and liquid level control are all critical. A fire that is confined to the liquid surface within a tank is much more readily controlled and extinguished than a fire involving quench oil that has overflowed the tank.

The distance from the quench surface to the top of the tank, with the tank loaded to capacity, is known as the freeboard. Freeboard should take into account the splashing to be expected when the maximum workload is immersed with maximum speed. The distance between the liquid level with the workload submerged and any openings in the tank wall should be not less than 6 in. (152 mm) below the door or any opening into the furnace.

Adequately sized, fully trapped overflow drains are important safety features for all oil quench tanks. They should direct the overflow to a safe location outside of buildings or into special tanks. As a practical matter, small quench tanks frequently can be installed without overflow drains. However, quench tanks with a liquid capacity of 150 gal (570 L) or a liquid surface area of 10 ft^2 (0.93 m^2) or larger should be provided with overflow drains.

Although overflow drains should be specifically designed for each tank, certain minimum sizes have been established and accepted (Table 8.9.1). For large quench tanks, multiple overflow pipes are preferable to a single large pipe, provided the

TABLE 8.9.1 Quench Tank Overflow Drains, Minimum Pipe Sizes

Liquid Surface Area		Minimum Pipe Diameter (I.D.)	
ft^2	m^2	*in.*	*mm*
10–75	0.93–6.7	3	76
75–150	6.7–14	4	101
150–225	14–21	5	127
225–325	21–30.2	6	152
325+	30.2+	8	203

aggregate cross-sectional area is equivalent to that of a single pipe. Piping connections on drains and overflow lines must be designed to permit ready access for inspection and cleaning.

Emergency Drains

Under serious fire conditions, it might be necessary to empty a quench tank in order to reduce the amount of quench fluid available. This can be performed readily through adequately sized, fully trapped and valved bottom drains directed to safe locations. Where gravity drainage is not possible, special pumps can be provided for oil removal. Drains and pumps should be sized so that the quench oil can be removed within 5 minutes. Gravity drains should be sized according to the tank capacities and drain diameters given in Table 8.9.2.

Emergency drains must be used only under the guidance and control of well-trained and experienced personnel, as improper usage can result in greater hazards. Whenever a flammable gas processing atmosphere is maintained above the quench oil, removal of the oil can create a negative pressure that can result in explosion, an increase in fire severity, or both.

Tank Location

Heat-treating operations involving combustible quench oils should be housed in fire-resistive buildings and should be well separated from exit areas, combustible materials, valuable stock, power equipment, and important process equipment.

The safest location for quench tanks is at grade level. Boilover from tanks above grade can be expected to spread fire to floors below, thereby making fire control more difficult and significantly increasing the potential fire loss. Fires in below-grade locations will make manual fire fighting difficult and result in a significant increase in fire loss.

Hoods

Tanks should be provided with noncombustible hoods and vents or other equally effective means to facilitate removal of vapors from the process and to prevent condensate from forming on roof structures. All such vents and ducts should be treated as flues and should be kept well separated from combustible roofs or materials. Hoods and ducts should be protected with an approved automatic extinguishing system and should be located so as not to interfere with fire protection systems that protect the quench tank.

TABLE 8.9.2 Gravity Drain Pipe Diameters, I.D.

Tank Capacity		Pipe Diameter (I.D.)	
gal	m^3	*in.*	*mm*
500–750	1.9–2.8	3	76
750–1000	2.8–3.8	4	101
1000–2500	3.8–9.5	5	127
2500–4000	9.5–15	6	152
Over 4000	Over 15	8	203

MATERIAL TRANSFER

Rapid and complete immersion of the work in process is essential to safe and proper heat-treating metallurgical processes. The method of immersion must result in minimal splashing and no overflow of the quench oil outside of the tank. It is also essential that the possibilities for partial immersion be eliminated or minimized. Partial immersion of the work is the most common cause of quench oil fires.

Chutes

Many furnaces are designed so that the work in process drops off the end of a conveyor, through a chute, and into the quench oil. The chute design and construction must allow the work to fall freely under all normal furnace feed conditions. This will involve proper chute sizing to accommodate the work, proper pitch to ensure continued stock motion, and smooth surfaces to prevent the work from being stuck in the chute (Figure 8.9.2).

Elevators

When stock in process is handled on trays or in baskets, elevators are commonly used to immerse the work in the quench oil (Figures 8.9.3 and 8.9.4). Partial immersions are caused more

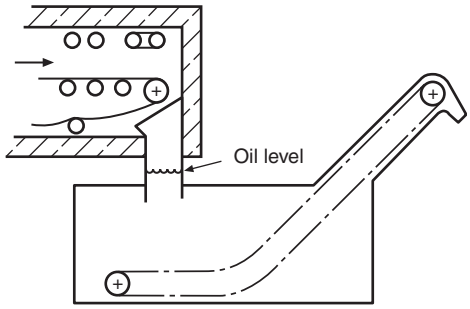

FIGURE 8.9.2 Bottom Chute-Type Quench

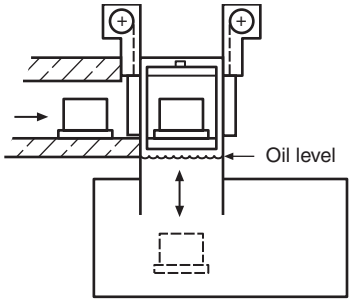

FIGURE 8.9.3 Dunk-Type Elevator Quench

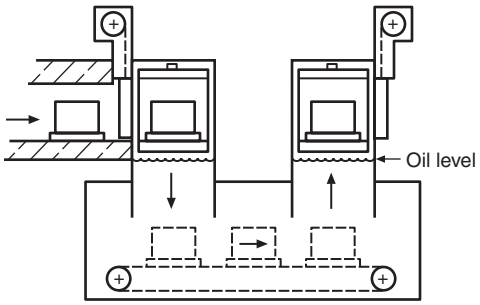

FIGURE 8.9.4 Transfer-Type Elevator Quench

by trays or baskets and elevators than by any other method. The following are three critical concerns:

1. The elevating mechanism must be adequately supported by structural members to prevent its falling unevenly.
2. Adequate guides must be provided to ensure uniform movement within the quench tank and to prevent an elevator from being wedged, as this could result in partial immersion.
3. Suitable guides and stops must be provided to prevent shifting of the workload, as this can cause elevator jamming and partial immersion.

Hoists and Cranes

A hoist or crane is usually required for moving large, specialized workloads into and out of the quench tank. Proper positioning of this equipment can be accomplished by stops and/or limit switches. Mechanical guides might be required to ensure that the work is properly positioned as it enters the quench tank.

Unless the oil drains off the work at the end of the quench period, an excessive amount of oil will be lost. Usually the work will still be warm at this time and some oil might vaporize. Any ignition source can produce a fire at this point in the process. Oil vapors will condense on cool surfaces above the drain area and, thus, contribute significantly to the potential fire loss.

OIL TEMPERATURE CONTROL

The control of quench oil temperature within specified design limits is essential to the heat-treating process as well as for safety. Failure of a cooling system can cause the oil to overheat. What is more hazardous, however, is a cooling system failure that allows water to enter the quenching oil. An excessive amount of water can produce a boilover when a hot workload is immersed in the quench. The exact critical water volume varies somewhat with the specific oil or oil mixtures being used, but if the water content reaches 0.50 percent by volume, the oil is no longer considered safe to use.

Cooling Methods

Quench oil can be cooled by water circulating through coils in the quench tank, by external heat exchangers, or by water jackets for the quench tank. Water jackets and internal water coils *must not* be used with combustible quenching oils. In these designs, any mechanical failure of the coil or the quench tank shell will result in water entering the quench medium. Such failures are not readily detectable; the first indication may be a boilover or a steam explosion when a hot workload is immersed in the quench.

If an external heat exchanger is used, quench oil must be circulated through the exchanger at a higher pressure than the exchange medium (water). If a leak should develop, oil will enter the water and be wasted. If the water pressure is higher than the oil pressure, such a leak would result in water entering the oil, creating a potential for boilover or steam explosion.

The continuous flow of cooling water is essential for temperature control. This can be properly supervised by observing the discharge from an open drain on the water side of the heat exchanger. Waterflow indicators are needed where a completely closed system must be used.

Safety Measures

An oil quench tank is built as an integral part of many special atmosphere furnaces. In these cases, the vestibule above the quench tank is water cooled, usually by water jackets. Many failures of the interior jacket walls have released cooling water into the quench tank below. As a result, safety considerations have dictated the use of special materials for vestibule jackets or the use of external coils. With special atmosphere furnaces, the use of a combustible gas for the atmosphere also will result in moisture development when the exit door is opened and the atmosphere is burned out.

If the oil level is too low and a large workload is immersed in the quench, the oil can overheat. Therefore, low-oil-level detectors should be used to sound an alarm and shut down quenching operations before overheating occurs.

Agitation is critical to maintaining safe quench oil temperature and uniformity of temperature throughout the bath. If the agitation mechanism fails, localized overheating will occur, which could cause a fire at the surface. Agitation failure and subsequent overheating can cause excessive vaporization, which could raise the pressure inside an enclosed special atmosphere furnace. Gas and oil vapor might then be forced out of the chamber around doors and through vents. Frequently, these escaping gases ignite, damaging the facilities. Agitation systems should be supervised automatically and their failure should result in the safe shutdown of operations.

Where the process requires that the quench be heated, fuel fired, electrically heated, or steam heated, immersion units are used as the heat source. All three methods of heating will create excessive temperatures at the interface of the heating unit and the quenching oil. A quench heating system should be prevented from operating if the oil level is too low, the agitation equipment is not functioning, or the oil temperature is too high. Where combustible oils are used, a separate excess high-limit temperature controller should be interlocked in the system to prevent quenching and to shut off the oil-heating system when the oil temperature exceeds a specified maximum limit.

CENTRAL OIL SYSTEM

Many heat-treating plants utilize a quenching oil that is common to several operations. Properly designed central oil systems can contribute to the maintenance of reasonably dependable and problem-free oil-quenching operations. A proper design includes filtering to remove particulate contamination, water removal for safety of operations and prevention of boilover, and cooling to deliver the quenching medium at an acceptable temperature.

Water separation can be accomplished by settling and the use of centrifuges. However, these systems are not dependable enough to eliminate the need for the oil in quench tanks to be tested periodically.

Since central systems involve a constant removal and replacement of oil from the quench tanks, it is essential for safety that oil flow be supervised. To avoid foaming and boilover, replenishment oil should not be added while the quench temperature is 212°F (100°C) or higher. Regardless of the oil being used, the temperature must never be permitted to rise to a value that is less than 50°F (10°C) below its flashpoint.

SAFETY CONSIDERATIONS

Safety Controls

All automatic shutdowns of quenching operations should result in the workload being completely immersed in, or removed from, the quench. Partial immersion always must be considered hazardous.

Whenever movement of the workload into, or out of, the quench has been stopped by a malfunction, qualified operating personnel must be permitted to override the safety interlocks so that manual attempts can be made to complete immersion or remove the workload. If exit doors must be opened, a fire condition should be anticipated. Extinguishing means adequate to protect the operator and prevent property damage should be available.

All safety controls and their interlocking functions should be tested on a regular schedule. The time interval between tests should not exceed six months. Refer to manufacturers' guidelines.

Hydraulic control systems add to the fire hazard in the vicinity of high-temperature equipment. Fire-resistant hydraulic fluids should be used. When combustible hydraulic oils must be used, proper maintenance of the hydraulic equipment is vital to safety. See NFPA 86, *Standard for Ovens and Furnaces.*

Fire Protection

Fire protection for combustible oil-quenching operations requires a detailed evaluation of the inherent fire potentials. One of the most effective forms of area protection is automatic water spray. Experience has shown that ceiling-mounted sprinkler systems will limit building and equipment damage from quench oil fires whether they are confined to the quench tank surface or spread over a large area by a quench oil boilover.

Specific protection for open quench tank surfaces and oil drainage areas is also important. Most oil fires can be extinguished by fixed carbon dioxide or dry chemical systems. In some operations, foam fire-fighting systems can also be effective. However, the suitability of foam will be determined by the quenching oil used and the temperatures involved. These systems are designed to operate automatically, well in advance of any potential sprinkler system discharge.

Those situations that require operating personnel to manually release jammed workloads and close furnace doors will dictate the provision of fire control and/or extinguishing facilities for the protection of the operator. In these instances, carbon dioxide or fixed water spray systems are the most effective. The most important fire protection features in every heat-treatment shop are the manual fire-extinguishing and control equipment and plant personnel properly trained in its use. In addition to an adequate supply of portable, hand-carried fire extinguishers, the larger, wheeled extinguishers should also be available.

Appropriately spaced hose connections with water fog or water spray nozzles should be considered an essential part of all heat-treating area fire protection. These can provide prolonged periods of fire control and life safety beyond the limited supplies of portable extinguishers.

MOLTEN SALT BATHS

Molten salt baths have become increasingly popular for the heat treatment of metals, ceramics (e.g., glass), or polymers (e.g., Teflon®) because they provide rapid and precise heat transfer and the required equipment is relatively inexpensive. A molten salt bath is defined as any heated container that holds a melt or fusion of one or more chemical salts in a fluid state. The work to be treated is immersed in the bath. There are many kinds of salt baths that use various salts and salt mixtures and that operate at various temperatures, depending on the results required.

As work is immersed fully into a salt bath, the salt serves as a protective environment. Heat is transferred more rapidly than by any other type of furnace heating. Moreover, because of the constant convection currents in the heated liquid medium, uniform temperature distribution is more easily attained.

Types of Salt Baths

The various types of salt baths available today can be classified by the heating method, application, or the particular salt mixture utilized.

Salt baths can be electrically heated or fuel fired. Electrically heated baths have electrodes introduced through the top surface of the molten salt or through the sides of the furnace below the salt surface (Figures 8.9.5 and 8.9.6). In some instances, ribbon-type resistance elements are used around a metal pot or container (Figure 8.9.7).

There are two types of fuel-fired salt baths. In one, the burners are fired directly outside a retort containing the salt. In some instances the burners are fired in metal tubes, known as radiant tubes, and the tubes are immersed in the molten salt (Figure 8.9.8).

Applications

Major uses of molten salt baths are descaling, liquid carburizing (case hardening), cyaniding and nitriding, neutral hardening,

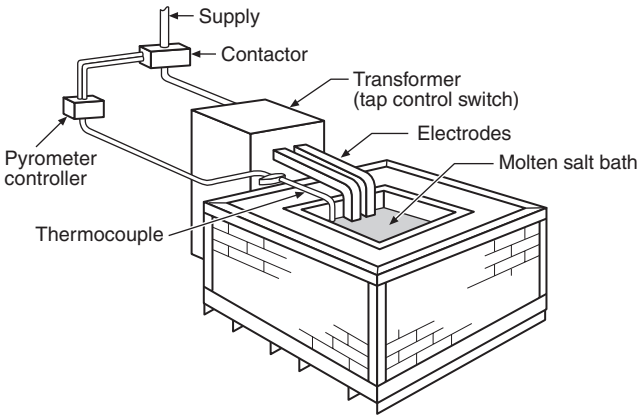

FIGURE 8.9.5 Typical Electrode Immersion–Type Electrical Heating Arrangement

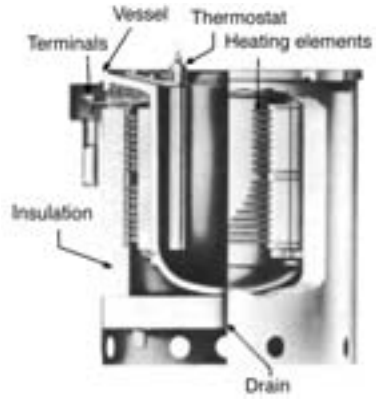

FIGURE 8.9.7 Resistance Heated Salt Bath with Pot (Source: SECO/WARWICK Corp.)

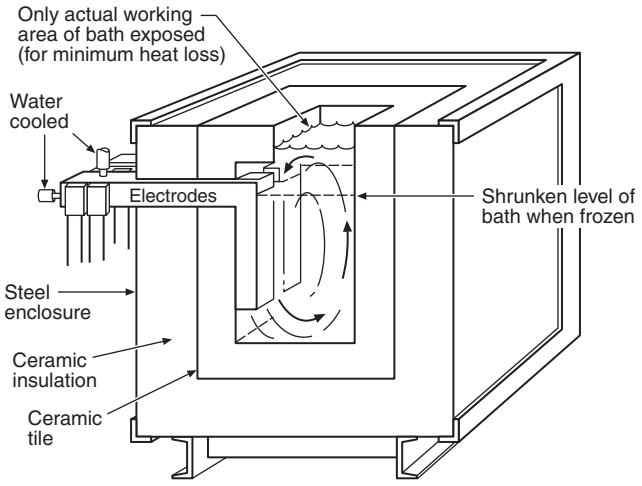

FIGURE 8.9.6 Submerged Electrode-Type Salt Bath

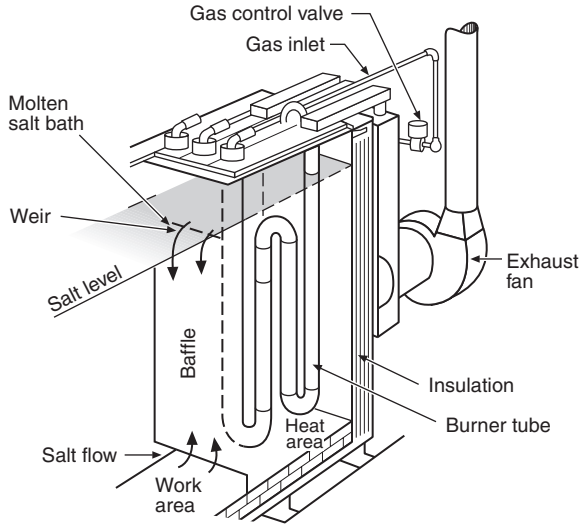

FIGURE 8.9.8 Gas-Fired Radiant Tube Salt Bath Heating Section

tool steel hardening, annealing, brazing tempering, and isothermal quenching. Each of these operations requires a different salt or salt mixture at different temperatures.

Descaling. For the removal of oxides that are difficult to remove by normal means (e.g., pickling, grit blasting, polishing, etc.), there are three different descaling processes. These processes are (1) the reducing sodium hydride process, (2) the oxidizing sodium hydroxide process, and (3) the electrolytic process. In the reducing sodium hydride process, a fused melt of sodium hydroxide and sodium hydride at temperatures between 650 and 780°F (343 and 415°C) is used. For oxidizing, a melt of sodium carbonate, sodium chloride, and sodium hydroxide is used at temperatures from 700 to 950°F (371 to 510°C). In the electrolytic process, a fused melt of sodium carbonate, sodium chloride, and sodium hydroxide is used at about 900°F (482°C). Electrolytic oxidation reduction is accomplished by passing direct current through the work. A reversing switch changes the polarity of the work from positive to negative, which effectively cleans the surfaces.

Liquid Carburizing. Case hardening is accomplished by diffusing carbon and small amounts of nitrogen into steel surfaces. The salts used are molten mixtures of sodium cyanide, sodium chloride, and barium chloride at temperatures between 1450 and 1750°F (788 and 955°C), depending on the depth of case required (Figure 8.9.9).

Cyaniding and Nitriding. These two operations are also performed with either sodium or potassium cyanides as the chief ingredient. Usually the operating temperatures are lower, typically 950 to 1050°F (510 to 566°C), for nitriding.

Neutral Hardening. The hardening of ferrous alloys without harmful surface effects is performed in mixtures of sodium,

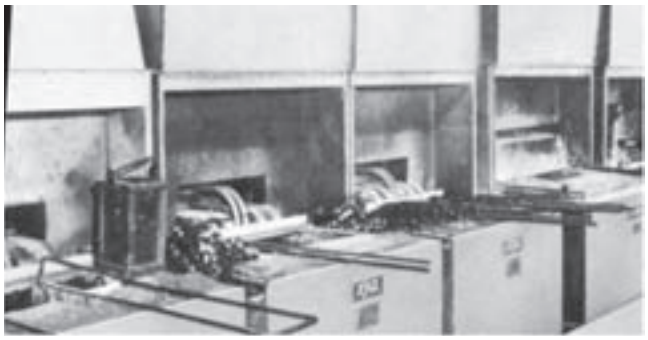

FIGURE 8.9.9 Liquid Carburizing and Isothermal Heat-Treating Line (Source: Ajax Electric Co.)

potassium, and barium chlorides. Operating temperatures may range from 1400 to 2350°F (760 to 1288°C).

Hardening of High-Speed Tool Steels. High-speed tool steels are hardened in a series of molten salt baths at various temperatures. A preheat bath at approximately 1400°F (760°C) might be followed by a high-heat bath at 2350°F (1288°C), which in turn is followed by a quench bath at 1100°F (593°C). All of these baths are mixtures of barium, sodium, and potassium chlorides (Figure 8.9.10).

Isothermal Quenching. To achieve various levels of physical properties in the heat treatment of steels, isothermal quenching rapidly cools metal parts in a molten salt bath. The three major types of isothermal quench are (1) austempering, (2) martempering, and (3) cyclic annealing. Each produces different hardness properties in metal alloys. Bath temperatures vary from 400 to 1300°F (205 to 704°C). The salts used are nitrate/nitrite salts for the lower temperatures and neutral chloride types for the higher temperatures.

FIGURE 8.9.10 Salt Bath for Hardening of High-Speed Tool Steel (Source: Ajax Electric Co.)

Annealing. Process annealing of carbon steels is usually carried out in carbonate and chloride salts at a temperature of 1250 to 1300°F (677 to 704°C). For stress relief of carbon steels, the melt is usually a nitrate salt at approximately 1000°F (538°C). Chloride salts are used to anneal stainless steel products as well as nickel-chrome alloys at temperatures of 1550 to 2150°F (843 to 1177°C).

Brazing. Salt bath brazing of ferrous and nonferrous alloys with silver and aluminum alloys, brass, and copper is another popular application for molten salt baths. Depending on the alloy and type of brazing, temperatures and salt mixtures vary considerably. For aluminum dip brazing, the salt is a mixture of chlorides with smaller percentages of sodium and/or aluminum fluorides, which act as fluxes. In copper brazing, barium chloride mixtures are used. Chlorides of sodium and potassium are used for silver alloy and brass brazing applications. Carburizing salts are used for a combination of brass brazing and carburizing.

Salt Bath Hazards

The hazards common to salt bath furnaces can be divided into the following three types:

1. Fire caused by contact of molten salt with combustibles
2. Explosion of the salt mixture due to physical or chemical reaction
3. The danger to operating personnel

Since salts are used at temperatures from 300 to 2400°F (149 to 1316°C), the ejection of salt by popping, spattering, or spilling will create a fire hazard if it comes in contact with anything combustible, including wood floors. Since molten salts have relatively little surface tension and low viscosities, any minor physical disturbance or chemical reaction can result in salt being ejected. When liquids (water, oil, etc.) or materials reactive to the particular salt utilized penetrate the surface of the salt bath, a violent ejection can result. Table 8.9.3 lists common salts and their melting points. Table 8.9.4 lists common salt mixtures and their melting points. Proprietary mixtures of these salts are formulated for specific applications and temperatures. Intermixing of certain salts is hazardous (e.g., nitrates and cyanide). Consult suppliers for recommendations.

Nitrates are particularly hazardous due to their ability to start and support combustion. When nitrates are overheated to temperatures in excess of 1100°F (593°C), rapid dissociation with the release of nitrous oxide fumes occurs. These fumes are injurious to operating personnel and are corrosive to the adjacent equipment. Explosions can occur if nitrate salt leaks from an externally heated container (pot) into a superheated combustion chamber. The overheating of nitrates can be caused by temperature controls that malfunction, an accumulation of sludge in the bath, or by operator errors.

If the operating temperature of a nitrate or nitrite bath exceeds the maximum limit, the following emergency action should be taken:

1. Shut off the heat supply.
2. Remove all work from the bath.
3. Move employees to a safe location.

TABLE 8.9.3 Melting Points of Common Chemical Salts

Salt	Melting Point °F	Melting Point °C
Barium chloride*	1764	963
Barium fluoride	2336	1280
Boric oxide (anhydride)	1071	578
Calcium chloride*	1422	773
Calcium fluoride	2480	1360
Calcium oxide	4662	2572
Lithium chloride*	1135	613
Lithium nitrate	491	255
Magnesium fluoride	2545	1396
Magnesium oxide	5072	2800
Potassium carbonate*	1636	891
Potassium chloride*	1429	776
Potassium cyanide*	1174	634
Potassium fluoride	1616	880
Potassium hydroxide*	716	380
Potassium nitrate*	631	333
Potassium nitrite*	567	297
Sodium carbonate*	1564	851
Sodium chloride*	1479	804
Sodium cyanide*	1047	564
Sodium fluoride*	1796	980
Sodium hydroxide*	605	318
Sodium metaborate	1771	966
Sodium nitrate*	586	308
Sodium nitrite*	520	271
Sodium tetraborate	1366	741
Strontium chloride	1603	873

*Most common salts.

Heated nitrate salts will react strongly with carbonaceous materials, such as oil, soot, tar, graphite, and cyanides—all of which might be utilized in some other metal-treating process. Accidental mixing of cyanides with molten nitrates can cause explosions of considerable magnitude.

The introduction of aluminum parts into a nitrate bath approaching or exceeding the melting points of these metals can cause fire and explosion. Magnesium alloys should never be immersed in a nitrate salt.

The storage of salts can cause serious problems. Chemicals, such as nitrates and cyanides, might mix and interact. Many salts are hydroscopic and, when stored in damp areas, will absorb moisture. When these salts are subsequently heated, moisture will be released below the surface and an explosion will ensue.

Intensive external reheating and remelting of a solidified salt bath might result in sufficiently rapid expansion to bulge or rupture the container. Such reheating can generate enough pressure to fracture the surface crust of the salt and scatter hot salts over a wide area.

When exposed to air having even a slight moisture content, the fumes from many salt baths become corrosive because chlorides, fluorides, and other salts will form acids by hydrolysis. These fumes are highly corrosive to adjacent building structures, wiring, and equipment and are, of course, detrimental to the bath operator.

Safety Control Equipment

A molten salt bath furnace must be equipped with control instrumentation and interlock systems that provide protection against the various and known types of potential equipment malfunctions.

Gas- and oil-fired salt bath furnaces must be provided with an approved flame safeguard device for each burner and must be interlocked to (1) shut off the fuel supply to the affected burner(s) and (2) activate an alarm.

An excess temperature control instrument must be provided that (1) has its own temperature-sensing element, (2) can be interlocked to shut off the heating system, and (3) activates an alarm when an excess temperature condition is detected.

When nitrate salts are used (regardless of the type of heating system), a "heat rate" controller should be installed to prevent a too-rapid heatup, thus preventing localized overheating and ignition of the salt.

The Safeguards

Although there appear to be many hazards connected with the operation of molten salt bath furnaces, fire, explosion, and injury can be prevented by the constant observance of ordinary precautions.

Clean dry sand can be used for diking purposes to confine and prevent the spread of the escaped melt. Carbon dioxide or dry chemical extinguishers can be used to extinguish burning carbonaceous material in the immediate vicinity of the salt bath.

The preferred location for a salt bath is a noncombustible area. The bath should be housed in a cement-lined pit or curbed area large enough to contain the contents in case of leakage or spill. It should be protected against leakage of liquids from other sources and be provided with baffles to prevent splashover from one tank to another. Salt bath furnaces provided with steel enclosures greatly reduce risks of leakage.

All salts should be shipped and stored in tightly covered containers designed to prevent the absorption of liquids or moisture. Nitrate salts should be stored in a fire-resistive, damp-free room and separated a reasonable distance from heat, liquids, and reactive chemicals. Nitrate and/or nitrite salts should never be stored in the vicinity of cyanide salts. Only the actual amount required to recharge the bath should be removed from the storage area and this amount should be melted immediately. Salts should be transported from the storage area to the furnace in suitable containers to prevent loss during transport.

The safety precautions that apply to the heating systems of salt baths are identical to those for the heating systems of other industrial furnaces. Some additional safety measures are necessary. Flame should be tangential to the wall of a salt pot or container when a gas- or oil-fired heating system is used. The products of combustion should be vented. Radiant tubes and electrodes should be of materials resistant to the corrosive action of the salts used.

TABLE 8.9.4 Melting Points of Common Salt Mixtures[a]

Mixture and Proportion	Melting Point *°F*	*°C*
Lithium nitrate 23.3, sodium nitrate 16.3, potassium nitrate 60.4	250	121
Potassium hydroxide 80, potassium nitrate 15, potassium carbonate 5	280	138
Potassium nitrate 53, sodium nitrate 7, sodium nitrite 40[b]	285	141
Potassium nitrate 56, nitrite 44	295	146
Potassium nitrate 51.3, sodium nitrate 48.7	426	219
Sodium nitrate 50, sodium nitrite 50[b]	430	221
Sodium hydroxide 90, sodium nitrate 8, sodium carbonate 2	560	293
Lithium chloride 45, potassium chloride 55	666	352
Barium chloride 31, calcium chloride 48, sodium chloride 21[b]	806	430
Calcium chloride 66.5, potassium chloride 5.2, sodium chloride 28.3[b]	939	504
Calcium chloride 67, sodium chloride 33	941	505
Potassium chloride 35, sodium chloride 35, lithium chloride 25, sodium fluoride 5[b]	960	516
Potassium chloride 40, sodium chloride 35, lithium chloride 20, sodium fluoride 5[b]	990	532
Barium chloride 48.1, potassium chloride 30.7, sodium chloride 21.2[b]	1026	552
Sodium chloride 27, strontium chloride 73	1049	565
Potassium chloride 50, sodium carbonate 50[b]	1086	586
Barium chloride 35.7, calcium chloride 50.7, strontium chloride 13.6	1110	599
Barium chloride 50.3, calcium chloride 49.7	1112	600
Potassium chloride 61, potassium fluoride 39	1121	605
Sodium carbonate 56.3, sodium chloride 43.7[b]	1177	636
Calcium chloride 81, potassium chloride 19	1184	640
Barium chloride 70.3, sodium chloride 29.7[b]	1209	654
Potassium chloride 56, sodium chloride 44[b]	1220	660
Sodium chloride 72.6, sodium fluoride 27.4	1247	675
Barium fluoride 70, calcium fluoride 15, magnesium fluoride 15	1454	790
Barium chloride 83, barium fluoride 17	1551	844
Calcium fluoride 48, magnesium fluoride 52	1738	948

[a]Lowest constant melting points given; proportions are percentages by weight.
[b]Most common salt mixtures.

The buildup of sludge in any type of salt bath should be avoided and the sludge periodically removed. Sludge is caused by the deterioration of salt, the introduction of foreign material into the bath, the dropping of small parts into the bath, or the freezing of salt due to a cold furnace bottom. Several methods of removing sludge and foreign objects are available. Some equipment has been designed to alleviate the buildup problem. Properly applied mechanical agitation greatly aids in the elimination and/or removal of the contaminants. Agitation prevents temperature stratification and freezing on the furnace bottom. Agitation also suspends and directs the contaminating particles into a settling pan or through a filter basket (Figures 8.9.11 and 8.9.12).

Two thermocouples properly located in the bath will provide safe control and protection from overheating. An overtemperature control should be arranged to automatically shut off the heat source and actuate visual and audible alarms in the event of a malfunction of the normal operating controls. All sensing couples must be protected from the corrosive effects of the particular salt used.

For the removal and control of any toxic, corrosive, or heated fumes, all salt bath furnaces should be equipped with hoods made of material that will not be affected by the corrosive nature of such fumes. In many cases, chemical scrubbers or suitable filters should be installed to remove the particulates (Figure 8.9.13). Removal or neutralization of fumes may require special equipment.

All fixtures used for dipping parts in baths, such as hooks, ladles, or baskets, should be of a solid, closed design without corners that could retain water. Parts, such as closed piping or other hollow metallic articles in which air or moisture can be trapped, should not be inserted into a molten bath without making provisions for venting the heated, expanded air or moisture. Immersion of hollow parts in salt baths should be very gradual. Any fixture used in one salt bath should be thoroughly cleaned and dried before it is immersed in another bath. When electrodes are water cooled, an instrument should be provided to detect failure of the water-cooling system.

If a salt bath is used as an internal quench in a furnace with a combustible atmosphere, measures should be provided

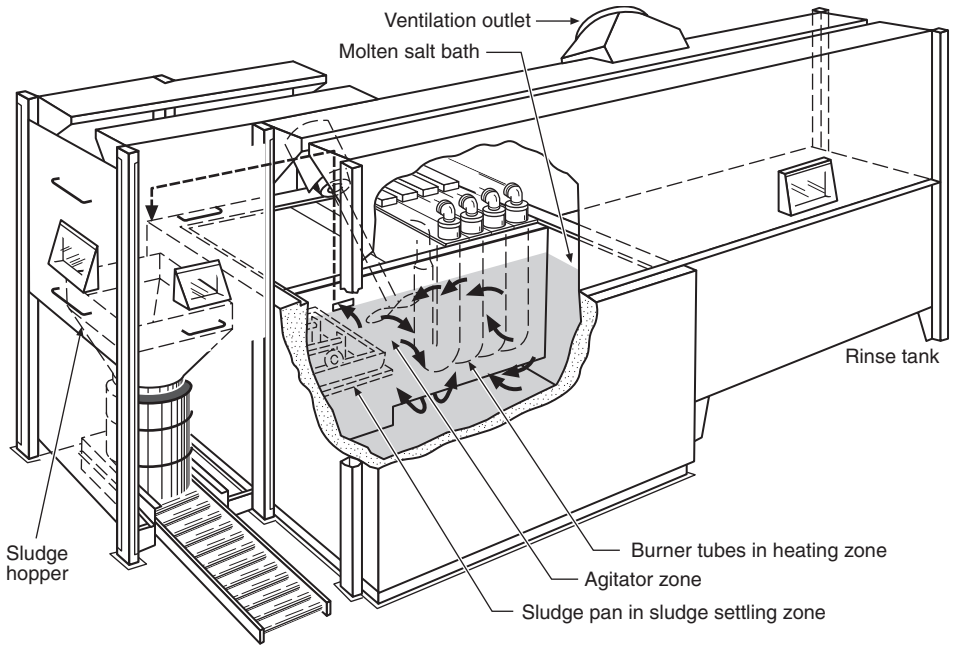

FIGURE 8.9.11 Descaling Salt Bath Showing Sludge Pan Construction (Source: Kolene® Corp.)

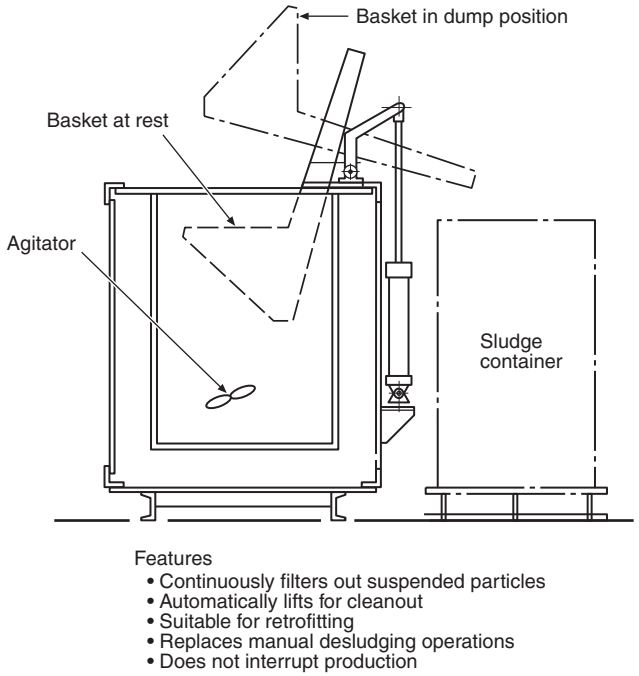

FIGURE 8.9.12 Automatic Basket Dumper

FIGURE 8.9.13 Typical Hooded Enclosure, Overhead Hoist, and Work Platform. These features greatly improve safety as well as productivity and ease of maintenance.

to prevent carbon precipitation onto the salt surface. In addition, adequate salt circulation should be provided to prevent localized hot spots whenever the salt is exposed to furnace temperatures.

A cold salt bath that has frozen over should be remelted or liquefied by applying initial heat as near to the top as possible. The application of heat to the external bottom surfaces will cause melting near the bottom and leave the top solidified. Expanding volume causes excessive pressure and failure of the container, with the subsequent ejection of hot salts. Breaking the surface crust will result in an explosive ejection of the salt. This hazard can be avoided by inserting a tapered solid bar in the molten salt

adjacent to the immersed electrodes. After the salt has frozen, the bar is removed. The cavity created by the removal of the bar will serve as a vent duct for the escape of the gases formed. Gas burners that heat the top layers and gradually heat downward can be used if they are used carefully. For the submerged type of electrodes, a resistance heating coil set in between electrodes is recommended. Pumps are available to remove salt while it is in the molten state. Considerable care should be exercised in removing any molten salt; it should be pumped directly into steel drums where it can freeze over immediately. Salt and drums can then be properly discarded. For all types of heating, a "soft start" with reduced power input is recommended until melting is established from top to bottom.

All operators and workers in the vicinity of molten salt baths should be provided with corrosion-resistant and heat-resistant shoes, gloves, aprons, hard hats, and face shields. Solutions for cleansing eyes and supplies for treating minor burns should be available at all times. Breathing apparatus should also be provided for emergency use against oxides of nitrogen or corrosive fumes, such as chlorides and fluorides.

Constant vigilance with safety in mind and good housekeeping by intelligent and well-trained personnel can keep a salt bath operation as safe as any other metallurgical process conducted in an industrial furnace.

SUMMARY

This chapter focused on two heat-treatment processes: oil-quenching operations, which harden and temper metals, and molten salt baths, which harden metals, ceramics, or polymers. In oil-quenching operations, the heated metal is cooled by immersion in a liquid-quenching material, which hardens and tempers the metal by imparting metallurgical changes to its surface. In molten salt bath operations, the metal, ceramic, or polymer work to be treated is immersed in a container that is either electrically heated or fuel fired and that holds a fusion of one or more chemical salts in a fluid state. Heat transfer is rapid and precise. Because quench oils are combustible, the oil-quenching process is inherently hazardous. Salt bath hazards include fire caused by contact of molten salt with combustibles, explosion of the salt mixture due to physical or chemical reaction, and danger to operating personnel, for example, from the fumes. After having described the two heat-treatment operations, the chapter discussed the hazards and the safeguards for both processes.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for oil quenching and molten salt baths discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
NFPA 34, *Standard for Dipping and Coating Processes Using Flammable or Combustible Liquids*
NFPA 70, *National Electrical Code®*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA *101®*, *Life Safety Code®*
NFPA 220, *Standard on Types of Building Construction*

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Chapter 10

Stationary Combustion Engines and Fuel Cells

James B. Biggins

Chapter Contents

Stationary Combustion Engines
Fuel Cells

Key Terms

flammable liquid, fuel cell, gas turbine engine, gaseous fuel, hydraulic oil, lubricating oil, reciprocating engine, stationary combustion engine

Stationary combustion engines are prime movers (e.g., as internal combustion engines, external combustion engines, gas turbine engines, rotary engines, and free piston engines) that are installed for use in a location as permanent equipment. Many codes and standards also treat portable engines that remain connected for use in the same location for a period of one week or more as stationary combustion engines.

Stationary engines are used for a number of applications in industry. The most common use is in tandem with a generator for the production of electricity in commercial and emergency situations. Larger engines are frequently used to drive large pumps and compressors, such as those used in the petrochemical and gas-pipeline transmission industries. Engine-driven pumps and compressors handle a variety of fluids, including flammable liquids and gases.

Fuel cells are an environmentally clean and highly efficient means for generating electricity. They differ from other power generation systems in that fuel cells are electromechanical devices that convert the energy of a chemical reaction directly into heat and energy without combustion as an intermediate step. Because the fuel is not burned, but electrochemically oxidized, fuel cells are not constrained by the same efficiency limitations that apply to engines.

Fuel cells are similar to batteries in that both convert energy that is stored in chemical form into direct current (DC) electricity. Also, like batteries, fuel cells can be combined into groups, called stacks, to obtain usable power outputs and voltages.

This chapter discusses the potential fire hazards associated with stationary engines and fuel cells and addresses the location, installation, and protection of both.

More in-depth discussions of the hazards that can be associated with the use and storage of fuels used in engines can be found in Section 6, Chapter 10, "Gases"; Section 6, Chapter 12, "Flammable and Combustible Liquids"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; and Section 7, Chapter 3, "Storage of Gases." Additional information on engines used to drive fire pumps is provided in Section 15, Chapter 7, "Fire Pump Controllers and Power Supply Arrangements for Motor-Driven Fire Pumps."

STATIONARY COMBUSTION ENGINES

Engine Types

The various types of engines noted above can be grouped into two primary types: (1) reciprocating engines and (2) gas turbine engines.

Reciprocating Engines. Reciprocating engines can range in size from small portable gasoline engines to very large diesel engines used for power generation. These engines are typically of two main types: (1) otto cycle engines, which use a spark plug to ignite a fuel-air mixture, and (2) diesel cycle engines, in which high-pressure compression raises the air temperature to the

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ignition temperature of the injected fuel oil. The characteristics of and hazards associated with all reciprocating engines are similar.

Gas Turbine Engines. The first patent for a gas turbine was granted in 1884, but it was not until about 1940 that the development and design of turbines reached the point where the machines were economically viable. The initial turbines were developed for aircraft applications, with the first commercial industrial unit placed in service in the late 1940s.

Gas turbine engines are typically larger engines, ranging in size from 100 to 100,000 hp (75 to 75,000 kW). Stationary gas turbine engines are used mainly for power generation and gas-pipeline transmission. Gas turbine engines are either open or closed cycle.

In an open cycle, the working fluid passes through the engine only once. In a closed cycle, the working fluid is continually recycled through the engine. The majority of gas turbine engines currently in use are of the open cycle design.

Potential Fire Hazards

The fire hazards associated with stationary combustion engines include (1) combustible liquids and flammable gases that are used as fuel, hydraulic fluids, lubricants, and in some cases, the material being pumped or compressed; (2) the temperature of exposed engine parts, particularly exhaust manifolds and pipes, which can be hot enough to ignite flammable or combustible materials; (3) the potential arcing of electrical components, such as starters, generators, distributors, and magnetos, which can ignite flammable vapors; (4) combustible materials stored within the engine room or used in the engine installation, such as air filters; and (5) engine disintegration.

Engine Installations

NFPA 37, *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines,* and local codes provide minimum requirements for the safe installation of engines, and include specifications for the engine installation, engine room compartmentation, fuel supply piping, room ventilation, and engine exhaust systems (Figure 8.10.1).

Engine Locations. Stationary combustion engines can be located outdoors, inside structures, or on the roofs of structures. The selection of an engine location should consider the distance from combustible walls and ceilings, exterior wall openings, and the availability of sufficient air for combustion and ventilation. Engine room compartmentation should comply with applicable standards and local codes, which might specify minimum fire resistance ratings.

Combustible materials should not be stored in rooms containing stationary engines or within the compartments of a gas turbine.

Engines should be isolated from locations where combustible dust or airborne flyings can be produced. Engine exhaust manifolds and piping can reach high temperatures, and combustible dusts and flyings deposited on these surfaces could ignite. For ignition to occur, conditions must be favorable for prolonged contact between the combustible material and the hot surface. A good maintenance and housekeeping program will lessen the chance of such an occurrence.

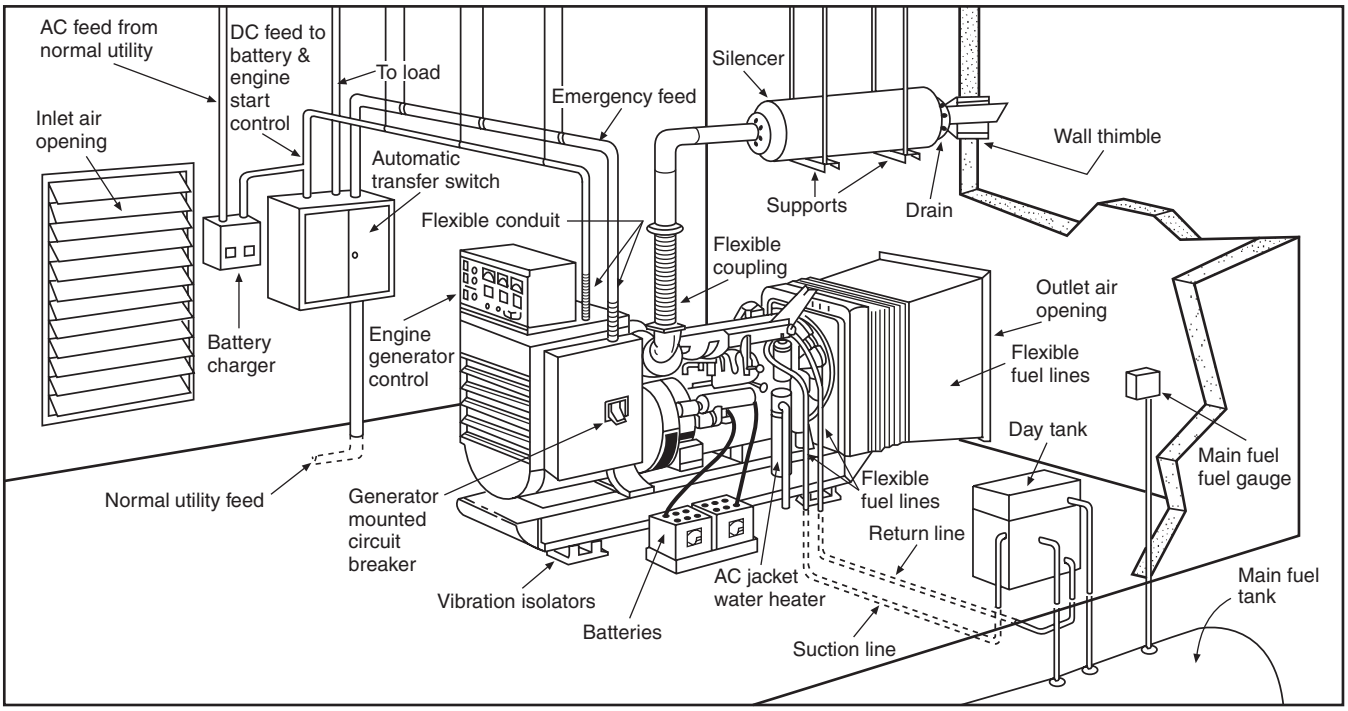

FIGURE 8.10.1 A Typical Generator Installation Used to Supply Emergency Power

Exhaust Systems. Fires can be caused by failure to allow sufficient clearance between exhaust piping and combustible walls, ceilings, or roofs. Engine exhaust systems (e.g., manifolds, mufflers, exhaust piping, etc.) can reach temperatures in excess of 1000°F (538°C), and special precautions are needed when these items penetrate combustible construction.

Engine exhaust systems should be designed based on the expected flue gas temperatures, which will typically vary with the size and type of engine. Exhaust pipes should be constructed of sufficient strength to withstand the pressures and temperatures developed by the exhaust system. Provisions are needed in the exhaust system to prevent damage from the ignition of unburned fuel. Low points, with suitable means to allow drainage of condensation, should also be incorporated into the system design.

It might be necessary to install a flexible connector from the engine to the exhaust pipe to minimize the potential for a break in the exhaust system due to engine vibration or heat expansion.

Exhaust systems should maintain a minimum clearance of 9 in. (229 mm) from combustible materials. Special precautions, such as a wall thimble, are required for cases where it is necessary to pass the exhaust system through walls or roofs of combustible construction. The exhaust system should terminate outside the structure at a point where the hot gases or sparks will be discharged harmlessly and not come in contact with combustible material.

Electrical Installations. The electrical installation for the engine should comply with NFPA 70, *National Electrical Code®*. Engine rooms or other locations are not to be classified as hazardous locations, as defined in the *NEC,* solely by reason of the engine fuel. Arcing electrical engine components should be safeguarded by flashover shielding, flame arresters, purging, or ventilation, if flammable liquids or gases are being pumped or compressed.

Fuel Supplies

Stationary combustion engines have been designed to operate with a number of different fuels. The two most common types are (1) flammable and combustible liquids, such as gasoline or diesel fuel, and (2) flammable gases, such as propane or natural gas.

Many engine applications require on-site fuel supplies of sufficient size for multiple hours of operation for reliability. The fuel supply can be stored either outdoors or within a building. Local codes and standards may restrict fuel tank size, construction, and location and should be consulted.

Liquid Fuels. Diesel fuel and gasoline are the two most widely used liquid fuels for stationary engines. Gasoline, due to its low flashpoint (–45°F [–43°C]), presents a greater fire hazard than other liquid fuels. Gasoline storage in buildings is limited to the capacity of the tank mounted on the engine, but NFPA 37 sets a limit on this amount at not more than 25 gal (95 L). When larger quantities of liquid fuel are required in buildings, a diesel-fueled engine generally is used.

Liquid fuel systems should be designed to minimize the potential for an accidental release of fuel into a structure. Alarms, float-controlled valves, gauges, and sight glasses should be installed to aid personnel in operating the fuel system. Diking, or some other method of spill containment, should be considered for fuel storage tanks installed either inside structures or aboveground outdoors.

Liquid fuels are supplied to engines by pumps. The exception is that gravity feed is permitted from an engine mounted tank. The fuel supply to tanks located above the lowest level of a building should be pumped to the tank in a manner acceptable to the authority having jurisdiction.

An overflow line, high-level alarm, and high-level automatic shutoff should be provided for all tanks that are filled by pumps. Care should be taken to avoid locating fuel lines, vents, and overflow lines near the engine combustion air intake.

Gaseous Fuels. Gas-fueled engines should be installed in accordance with applicable codes and standards, such as NFPA 54, *National Fuel Gas Code,* or NFPA 58, *Liquefied Petroleum Gas Code.*

Some gas fuels, such as propane, are heavier than air and will collect in low-lying areas. Special precautions need to be taken to ensure proper ventilation is provided, particularly with respect to the location of the supply and exhaust openings, when using these fuels. Gas pressure regulators located inside a structure should be provided with a vent to outdoors, discharging a minimum of 5 ft (1.5 m) from the structure. An alternative is to provide a listed vent limiting device.

Gas piping to engines should be provided with a shutoff valve located remote from the engine, preferably outside the structure for those engines located indoors. Each gas-fueled engine should be provided with a means to automatically shut off the flow of gas to the engine, in case the engine stops from any cause.

Lubrication and Hydraulic Systems

Engine lubrication and hydraulic systems for stationary combustion engines generally utilize a combustible oil. In some larger gas turbine units, the combustible oil may be replaced with a synthetic, fire-resistant fluid. This type of lubricating fluid has a higher flashpoint than lubricating oil. The use of a fluid with a higher flashpoint decreases the potential for ignition of a spill from a heat source, such as hot engine parts.

An oil mist is often present in the crankcases of large reciprocating engines, which, on ignition, can result in a combustion explosion within the crankcase. As a result, many such engines are equipped with crankcase explosion vents. In other cases, the crankcase is maintained under a nonflammable atmosphere.

Glass gauges and sight glasses should be protected against physical damage, if their breakage could permit the escape of oil.

Instrumentation and Control

Total mechanical failure or disintegration of a reciprocating engine occurs very infrequently. Gas turbines are at greater risk to this phenomenon than reciprocating engines, because of the turbine's very high rotational speeds.

This hazard is controlled by the provision of automatic engine speed governors. An overspeed shutdown device should be provided on large engines (greater than 100 hp [75 kW]) of both types. Furthermore, the design of gas turbines for stationary installations usually incorporates construction features to contain the compressor, turbine blades, and rotor parts in the event of mechanical failure.

Controls should be provided on all engines greater than 10 hp (7.5 kW) to shut down the engine for high jacket water temperature, high cylinder temperature, or low lubricating oil temperature. Additional shutdowns should be provided for high oil temperature on larger engines. Gas turbines should also be arranged to shut down on high exhaust temperatures.

The starting sequence for gas turbines should incorporate a purge cycle of adequate duration to ensure that a nonflammable atmosphere is present in the turbine and exhaust system prior to ignition.

Installation Safeguards

Larger engine installations should have provision for a remote emergency shutdown of the engine. Most installations also should have a remote means of shutting down fuel and lubricating oil pumps that are not directly driven by the engine.

Care should be taken in the selection of inlet air filters, particularly for larger gas turbine installations. Whenever possible, filters should be of materials that will not burn freely when exposed to fires.

Diesel engines installed in hazardous locations, as defined by the *NEC,* should be installed such that the engine is shut down by isolating both the fuel and combustion air supplies. This installation will prevent the diesel engine from "running on," utilizing the hazardous atmosphere as the fuel source.

Backfires through gas-air mixers and carburetor air intakes occur as a result of engine malfunction. These backfires can ignite grease and oil deposits on and around the engine. Flame arresting equipment should be provided at these points if flammable liquids or gases are being pumped or compressed.

Operating Instructions

Instructions for normal starting, stopping, operation, and routine maintenance procedures should be posted near the equipment.

Emergency procedures for the safe shutdown of the engine should be developed. These instructions typically include location and operation of remote shutdown stations, procedure for the shutdown of lubricating oil and hydraulic oil pumps, and closing of the fuel shutoff valve.

Fire Protection

Manual fire protection equipment, such as portable fire extinguishers, should be provided in accordance with applicable standards and codes. Larger installations, particularly those utilizing an appreciable amount of lubricating or hydraulic oils and those utilizing liquid fuel, should be protected by automatic fire suppression systems. Sprinkler systems are typically the protection provided for reciprocating engines installed within structures.

Gas turbine installations can be protected by a number of different system applications, dependent on the preference of the engine's manufacturer, operator, or both. Fire protection system options include preaction waterspray systems, carbon dioxide systems, clean agent systems, and water mist extinguishing systems. Dry chemical extinguishing systems are sometimes utilized to protect the exhaust compartments of these engines. The interlocking of fire protection system operation with the automatic closing of the fuel valves can be of assistance in limiting the size of a fire.

Emergency Planning

Emergency operating and shutdown procedures should be developed for each engine installation. Where fuel valves are not clearly identified, a diagram should be posted conspicuously near the engine, indicating the location of the fuel shutoff valves. Emergency procedures should be located where they are readily accessible to personnel operating or maintaining the engine. Individuals responsible for the operation and maintenance of the engine must be trained in operating and maintenance procedures, including emergency shutdown procedures.

FUEL CELLS

Characteristics

Fuel cells are similar to a battery, as two electrodes, an anode and a cathode, are separated by an electrolyte. However, in fuel cells, the fuel and oxidant are stored externally. This setup allows the fuel cell to continue operating as long as the fuel and oxidant are replenished. Direct current electricity is produced by a chemical reaction between a hydrogen-based fuel and an oxidant (usually oxygen) within the fuel cell, as shown in Figure 8.10.2. The hydrogen passes over the anode and is split into positively charged hydrogen ions and negatively charged electrons. The electrons then flow over an external circuit as electrical energy. Both the electrons and the protons, which pass through the electrolyte, eventually return to the cathode, where they combine with the oxidizer to produce water and heat.

The first fuel cell was built in 1839, but the first practical application was to provide electric power for NASA's Gemini and Apollo spacecraft. The industrial use of fuel cells has not been widespread, due to both the demanding technology associated with the design and operation of the fuel cells and the fact that other less expensive technologies have dominated the market. In recent years, the use of fuel cells for power generation is gaining favor due to the efficiency of the power production and the minimal impact on the environment.

The most efficient fuel cells use hydrogen and oxygen as the fuel and oxidizer. In conventional fuel cells, a carbon-rich fuel is reformed to produce hydrogen, which is then introduced into the fuel cell and electrochemically oxidized. In many cases, this reforming process is accomplished internally due to the very high temperatures (1382 to 1652°F [750 to 900°C]) encountered.

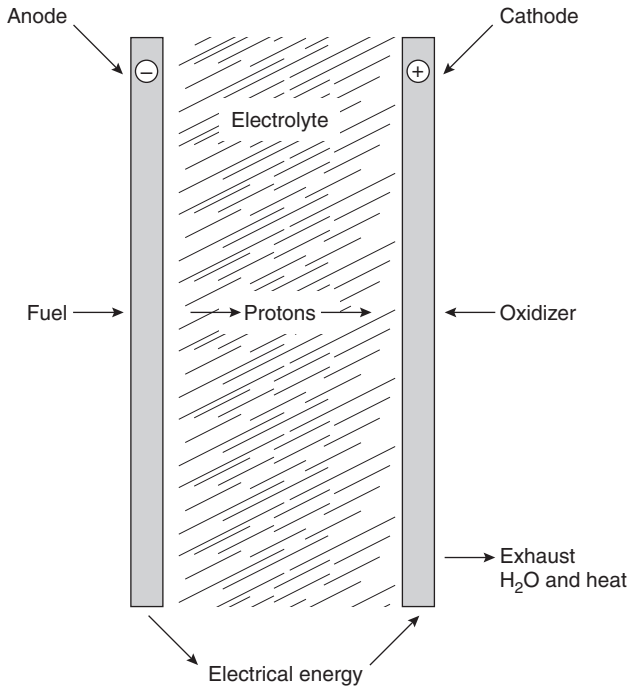

FIGURE 8.10.2 Typical Fuel Cell

Types

All fuel cells have an electrolyte that separates the two electrodes. Several different types of electrolytes are used in fuel cells, each having very different properties. The fuel cells are typically named after the electrolyte used and operate at different temperatures and supply varying amounts of heat. A brief discussion of some common fuel cell types follows.

Phosphoric Acid Fuel Cells. The phosphoric acid fuel cell is one of the oldest types of fuel cell and is the type that is most readily available commercially. Phosphoric acid fuel cells are presently used in a number of power generation projects. The fuel cell uses phosphoric acid as the electrolyte and is able to reform methane to a hydrogen-rich gas for fuel and also produces waste heat, which can be used for other purposes. This type of fuel cell operates at temperatures of 393°F (approximately 200°C).

Solid Oxide Fuel Cells. The electrolyte in this type of fuel cell is typically zirconia, which is sandwiched between the anode and cathode. Solid oxide fuel cells can operate on a number of different fuels ranging from hydrogen to methane to carbon monoxide. These fuel cells are being studied for their potential use as power generation units. Additionally, as the cells operate at extremely high temperatures of 1832°F (approximately 1000°C), the waste heat produced can be used in a cogeneration process.

Polymer Electrolyte Fuel Cells. These fuel cells use an electrolyte that is made up of a layer of solid polymer material, which allows protons to be transmitted from one face to the other. These fuel cells operate at lower temperatures of 309°F (around 154°C) and are primarily being used for mobile applications at this time.

Alkaline Fuel Cells. These are the best developed and most widely known type of fuel cell, due to their use in spacecraft. Alkaline fuel cells use a solution of either potassium hydroxide or lithium hydroxide as the electrolyte. The advantage of these fuel cells is that they operate at ambient temperatures.

Potential Fire Hazards

The fire hazards associated with fuel cells begin with the high temperatures at which several types of fuel cells operate, which in many cases can be sufficient to ignite nearby combustible materials. Additionally, the fuel used in the fuel cell is often a flammable gas or liquid, which presents fire protection concerns with respect to its handling and storage.

Fuel Cell Installations

Local building codes provide limited information on fuel cell installations, relying on the judgment of the local authorities having jurisdiction to address the installations as they arise. NFPA 853, *Standard for the Installation of Stationary Fuel Cell Power Systems,* was developed in 2000 and provides minimum requirements for the installation of fuel cell power plants with ratings of 50 kW or greater.

The selection of the fuel cell location should consider such items as the distance from combustible walls and ceilings and the distance to wall openings. Fuel cells and their related equipment can be located outdoors, inside structures, or on building roofs. Each of these installations has specific issues that need to be addressed for the installation. However, many common practices need to be considered for all fuel cell installations.

A fuel cell and its associated equipment, components, and controls should be placed on a firm foundation that is capable of supporting the equipment or components. The foundation and access to the fuel cell and its components should be located above the base flood elevation of the site. The fuel cell should also be anchored, located, and protected so that the plant and equipment will not be adversely affected by rain, snow, ice, freezing temperatures, wind, seismic events, or lightning.

The installation should be protected against access by unauthorized persons, commensurate with the location and installation environment. However, a means should be provided for fire department access. The fuel cell and related equipment installation should not affect required building exits during normal operations or fire emergencies.

Care should be taken to locate fuel cells outside of potentially hazardous atmospheres, as defined by the *NEC* and NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment,* unless listed and approved for the specific installation. The installations should also be located away from combustible materials, hazardous chemicals, high-piled stock, and other fire hazards.

Additionally, the vent or exhaust terminations should be separated from doors, windows, outdoor air intakes, and other openings into a building. Noncombustible materials should be used where vent pipes pass through roofs, walls, or other building features.

It is also suggested that the fuel cell installations be located in a manner that will readily permit service, maintenance, and emergency access to the fuel cell and associated equipment.

Outdoor. When an outdoor location is chosen, the fuel cell and its related components need to be specifically designed and constructed for outdoor installation. Security barriers, fences, landscaping, and other enclosures must not affect the required airflow into or exhaust out of the fuel cell or its components.

Fuel cell installations should not be located in areas that are used or are likely to be used for combustible, flammable, or hazardous materials storage. Air intakes to a fuel cell installation should be located so that the intake is not adversely affected by other exhausts, gases, or contaminants. The vent or exhaust terminations should not be directed onto walkways or other paths of travel for pedestrians.

Indoor. A fuel cell installation and its associated components not located in areas designed for industrial uses should be located in a room that is separated from the remainder of the building by floor, wall, and ceiling construction that meets the approval of a local authority having jurisdiction.

Rooftop. Where fuel cells are installed on roofs, in addition to addressing the issues associated with the outdoor installation of the fuel cell, the roofing material directly below and within a 1 ft (0.3048 m) horizontal distance should either be noncombustible or have a Class A rating.

Fuel Supplies

Fuel cells can be designed to use both gaseous and liquid fuels. Fuel cells typically require on-site fuel storage for reliability of the installation. These fuel supplies can be stored either outdoors or within a building. Local codes and standards might place restrictions on the fuel storage arrangement.

Gaseous Fuels. Fuel cells have been designed to utilize many types of gaseous fuels, including natural gas, compressed natural gas (CNG), liquefied petroleum gas (LP-gas), biogas, and hydrogen. Piping, valves, and fittings from the outlet of the supplier's piping to the outlet of the fuel cell power plant's shutoff valve should be in accordance with applicable codes and standards, such as NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks;* NFPA 52, *Vehicular Fuel Systems Code;* NFPA 54, *National Fuel Gas Code;* and NFPA 58, *Liquefied Petroleum Gas Code.*

The use of hydrogen as a fuel presents special concerns, as hydrogen is a colorless, odorless, highly flammable gas or liquid. The flammable range in air at atmospheric pressure is 4 to 75 percent by volume and it has a vapor density of 0.1. When hydrogen is used as a fuel, the installation of vapor detection devices is recommended.

Some of the gas fuels such as propane are heavier than air and will collect in low-lying areas. Special precautions need to be taken to ensure that proper ventilation is provided when using these fuels.

Liquid Fuels. Diesel fuel, JP-4, JP-5, ethanol, methanol, and naphtha are some of the liquid fuels that are used in fuel cell installations. The design of liquid fuel piping systems and the location and storage of liquid fuels should be in accordance with NFPA 30, *Flammable and Combustible Liquids Code.*

Liquid fuel systems should be designed to minimize the potential for the accidental release of fuel. Devices such as level alarms and float devices should be installed to aid personnel in operating the fuel system. Additionally, diking or some other means of spill containment should be considered for fuel storage installed either indoors, on roofs, or outdoors in aboveground tanks.

Fuel storage tanks should be provided with level alarms. Those tanks that are filled by pumps should also be provided with a high-level automatic shutoff.

Ventilation

The ventilation and exhaust system for fuel cells installed within a structure should be designed to provide a negative or neutral pressure in the room. A separate mechanical ventilation system should be provided for the area inside a structure where a fuel cell power plant is located, unless it can be verified that natural ventilation can provide all required ventilation and makeup air. The inlet air vent should be designed to prevent foreign matter from entering.

Pressure tanks and piping intended to be purged, pressure regulators, relief valves, and other potential sources of combustible gas should be vented to a safe location outside the building. The vent should be designed to prevent entry of water or foreign objects.

Exhaust Systems

The exhaust system for a fuel cell should be designed such that all emissions are exhausted to a safe location. An effective rate from a room inside a structure is typically considered to be a minimum of 1 cfm/ft^2 (0.3 m^3/min m^2) of floor area and not less than 150 cfm (45 m^3/min) for the total floor area.

If a mechanical exhaust is provided, the system design should incorporate the use of a control interlock to shut down the unit on loss of exhaust ventilation. The exhaust outlet shall be located away from the HVAC air intakes for the building.

Fire Protection

A combustible gas detection system should be provided in the enclosure, in the exhaust system, or in the room that encloses indoor or enclosed fuel cell installations. The combustible gas detection system should be arranged to alarm at 25 percent of the lower flammable limit (LEL) and be interlocked to shut down the fuel supply at 60 percent of the LEL. The LEL used should be the lowest of the gas or gas mixtures used. Additionally, a

combustible gas detector should be provided for all indoor or separately enclosed gas compressors.

Fuel cell enclosures should be provided with an automatic fire detection system that transmits the alarm to a constantly attended location. The room in which the fuel cell and its associated components are located should be provided with an automatic fire suppression system that is in accordance with applicable NFPA standards.

Indoor liquid fuel pumping should be protected by an automatic wet pipe sprinkler system. It is recommended that the sprinkler system be designed in accordance with the applicable requirements of NFPA 13, *Standard for the Installation of Sprinkler Systems*. An automatic safety shutoff valve is normally provided and interconnected to shut off the fuel supply when the sprinkler system is activated.

Emergency Planning

A written emergency plan should be developed for each fuel cell installation. The depth and details of the plan will vary, based on the size and location of the fuel cell installation. The plan should include the following:

- Information on emergency alarms, including responses to alarms and notification of personnel
- Evacuation of employees and visitors not directly involved in fire-fighting activities for the fire area
- Coordination with security forces or other designated personnel to admit public fire department and control traffic and personnel
- Fire extinguishment activities and identification of fire water application concerns on operating equipment
- Operator activities during fire emergencies
- Listing of frequency and requirements for periodic inspection, testing, and maintenance of the fuel cell power system emergency systems
- Posting of the location of the operating instructions and the location of the emergency controls

The plan should also include provisions for periodic training and drills to verify viability of the plan.

SUMMARY

Stationary combustion engines and fuel cells are two means of generating energy. In the case of stationary combustion engines, combustion generates energy; fuel cells generate energy electrochemically (i.e., without combustion). Stationary combustion engines are typically used in industrial settings, whereas the use of fuel cells, once limited to aerospace, is being extended to industry.

This chapter has described the characteristics, potential fire hazards, installation considerations, fuel supplies, and emergency planning for stationary combustion engines and fuel cells.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for stationary combustion engines and fuel cells discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 37, *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines*
NFPA 52, *Vehicular Fuel Systems Code*
NFPA 54, *National Fuel Gas Code*
NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 70, *National Electrical Code®*
NFPA 99, *Standard for Health Care Facilities*
NFPA *101®*, *Life Safety Code®*
NFPA 211, *Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances*
NFPA 220, *Standard on Types of Building Construction*
NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment*
NFPA 850, *Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations*
NFPA 853, *Standard for the Installation of Stationary Fuel Cell Power Systems*

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Chapter 11

Fluid Power Systems

Paul K. Schacht

Chapter Contents

Fluids Under Pressure and Fluid Leakage
Fire Characteristics
Less Hazardous Hydraulic Fluids (Fire-Resistant Fluids)
Environmentally Acceptable Fluids
International Fluid Designations

Key Terms

biodegradable fluid, hydraulic fluid, oil (pressurized), synthesized hydrocarbon fluids (SHF)

Fluid power systems are used for transmitting power or motion to various parts of equipment and machines. The function of the fluid is power multiplication as in a hydraulic press, actuation of automatic equipment as in die casting, or remote actuation or pressure control of machines or instruments. Hydraulic fluids are generally petroleum based and present fire hazards.

For additional information on allied topics, consult the following chapters: Section 6, Chapter 12, "Flammable and Combustible Liquids"; and Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids."

Early fluid power systems used water as the hydraulic medium. Because of its corrosive effect on the metal parts of the machine and lack of lubricity, it was replaced by petroleum oil. Except for its fire hazard, oil is an ideal hydraulic fluid. It is noncorrosive, compatible with a wide variety of materials of construction, readily available, relatively inexpensive, and can be recycled. Flashpoints range from 300 to 600°F (148 to 316°C), and autoignition temperatures range from 500 to 750°F (260 to 399°C).

Although petroleum oils are by far the most commonly used hydraulic fluids, synthetic lubricants are being used more frequently in industrial and mobile applications. There are several classes of synthetic lubricants. The most common are synthesized hydrocarbon fluids (SHF), such as polyalphaolefins (PAO) and dialkyl benzenes. Flashpoints of these fluids range from about 225 to 500°F (106 to 260°C).

Seals and hoses made from nitrile or fluorocarbon polymers are commonly used with petroleum oils, synthetic hydrocarbons, polyol esters, biodegradable fluids, and water-containing fluids such as water-glycols and water-in-oil emulsions. Phosphate esters require the use of fluorocarbons. The use of nitrile with phosphate esters will cause seals and hoses to soften and swell, resulting in failure and loss of fluid.

FLUIDS UNDER PRESURE AND FLUID LEAKAGE

Pressurized petroleum-based lubricants or synthesized hydrocarbons present a considerable fire hazard, particularly when ignition sources are constantly present, such as in die casting, plastic molding, automatic welding, heat treating of metals, molten glass, hot forgings, steel production, and the engines of mobile equipment (Figure 8.11.1). Other sources of fire are oil-impregnated floors, oil-saturated insulation in sound barriers, and external system leakage being ignited by cutting torches, sparks from a welder, and other human carelessness.

Fires in coal mines continue to be a common problem, particularly in some parts of the world. This is primarily the result of extremely hard usage of the hydraulically actuated equipment, without proper maintenance. Despite the known hazards of using oil as the hydraulic medium, because of increased fluid costs and fluid maintenance costs, many systems have not been converted to safer fluids.

High-pressure pipe with welded and threaded joints, steel tubing, and metal reinforced rubber hose is used to conduct oil at pressures ranging up to 10,000 psi (68,950 kPa). Failure of piping, particularly at threaded sections; failure of system components, gaskets, or fittings; tubing pulling out

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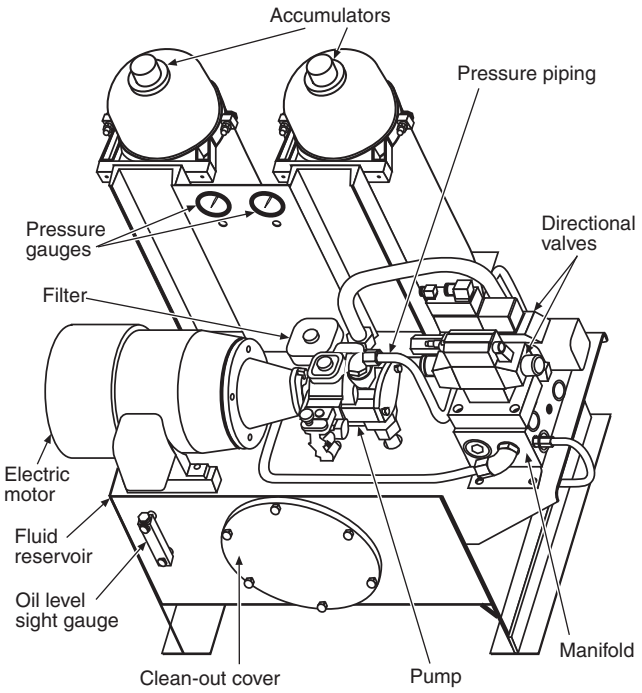

FIGURE 8.11.1 A Nonspecific Power Unit That Might Be Used to Run Any of a Variety of Machines

of fittings; and rupture of flexible hose are considered principal causes of oil being released from a fluid power system. Lack of adequate supports or anchorage to prevent vibration or movement of piping has also been a factor in these failures. Repeated flexing and abrasion of rubber hose against other hoses or parts of a machine can create weak spots that eventually fail. Tubing under pressure can fail due to being accidentally cut by torches, hit by a fork lift truck, or stepped on during maintenance procedures.

Even though a system is shut down, high-pressure fluid may be contained in accumulators and released for some of the previously mentioned reasons covering the loss of fluid. Guidelines to be followed when selecting tubing and burst pressure ratings of components can be found in the National Fluid Power Association and Society of Automotive Engineers (SAE) standards listed in the bibliography.

FIRE CHARACTERISTICS

When oils, synthesized hydrocarbons, or biodegradable fluids under pressure are released by failure of equipment, the usual result is an atomized spray of mist or oil droplets, which, depending on pressure, may encompass large areas. The oil spray is readily ignited and the resulting fire is usually torchlike with a very high rate of heat release.

If systems contain oil, the following recommendations should be met in addition to those recommended for less hazardous fluids:

1. Automatic sprinklers should be provided over areas where an oil-containing hydraulic system is located. Due to the type of fire associated with a high pressure (atomized oil) fire, the sprinkler system design area is often 5000 to 7500 ft^2 (465 to 697 m^2).

2. Automatic or remote manual switches should be provided to shut off the hydraulic pumps in the event of fire if over 100 gal (378 L) of fluid are involved. Automatic shutoff of hydraulic systems can be accomplished in several ways. Most commonly, heat detectors are placed over the areas where hydraulic fluids are present. This would include the hydraulic system reservoir, pump, and the associated piping to the equipment where the pressurized fluid is used. The heat detectors are interlocked to the hydraulic oil pump and arranged to shut it off when a heat detector is activated.

Another method of automatic shutoff of the hydraulic oil system is by the use of fusible links attached to cables at ceiling level, laced over the hydraulic fluid reservoir, pump, and other components, such as cylinders, fluid motors, and the associated piping. The cable under tension is secured to a building component at one end and to a microswitch at the oil pump controller at the other end. The microswitch, when activated by the fusible link, trips the switch on the controller to the off position, thus shutting off the flow of pressurized oil.

A third way to arrange for automatic shutoff is to provide a low level indicator in the fluid reservoir that, when activated, shuts off the pump. This method is less likely to stop the flow of pressurized oil as quickly as other methods discussed but can be acceptable under some conditions, such as in outdoor locations and in buildings of fire-resistive construction.

3. Fire extinguishers should be provided that are suitable for a Class B fire.

4. Threaded piping should be avoided. Where present, the fittings should be seal welded.

5. Machines should be isolated from positive ignition sources such as metal castings and open flames.

6. When rubber or synthetic hose is used, it should be of the armored type or enclosed in a metallic tube to contain escaping fluids.

7. Hydraulic oil systems should be inspected regularly for impending failures.

LESS HAZARDOUS HYDRAULIC FLUIDS (FIRE-RESISTANT FLUIDS)

Test Methods

For many years several different types of test methods have been used to evaluate the degree of fire resistance of less hazardous hydraulic fluids. Typical procedures were linear flame propagation, autoignition temperature, high-pressure spray flammability, flashpoint, and the Factory Mutual hot channel ignition test. Unfortunately, none of these tests individually, or sometimes collectively, reflect the degree of fire resistance achieved under various conditions encountered in industrial and mobile applications. Inability to agree on a standardized test procedure was of concern to industry, insurance underwriters, and the fluid suppliers.

Spray Flammability Parameter (SFP)

Perhaps the most respected certification of fire resistance is by Factory Mutual Approvals, which is a business unit within FM Global, one of the world's largest property insurers and risk management organizations. Factory Mutual Approvals certification is required by many industrial facilities. Additionally, in order to obtain insurance, some property insurance underwriters require that the fire-resistant fluid being used has received Factory Mutual Approvals certification.

Through Factory Mutual Approvals continual testing and research efforts, a revised standard, CN 6930, was introduced early in 2002. This standard defines the test that is commonly known as the spray flammability parameter (SFP). The SFP value is determined by measuring various parameters during fluid ignition testing. These data are used in an equation that calculates the SFP value. Fluids are classified by the SFP number, which is an indication of their degree of fire resistance. The SFP number is an important criterion when selecting the hydraulic medium, because some fluids offer a much greater margin of safety than others. The Factory Mutual Approvals test has been used quite extensively, although there are still some unresolved issues pertaining to the test, which is prompting revisions to CN 6930.

It is perhaps a bit unrealistic, at this point, to believe that in the near future there will be a single test method to determine fluid fire resistance that will be universally accepted throughout the world. Some fluids that pass the Factory Mutual Approvals test will, with use, lose their fire resistance due to fluid degradation. It is also not uncommon for oil, solvents, or process fluids to enter the system or to be added to the system accidentally or through carelessness or improperly marked storage containers. A very common problem is poorly maintained fluids, primarily the loss of water in water-containing fluids. A decrease in water level through evaporation will seriously affect level of fire resistance of the fluids.

Water-Glycol Fluids

Water-glycol fluids normally consist of 35 to 50 percent water, and ethylene or propylene-glycol, thickeners, and additives. Recommended temperature limits are 0 to 150°F (–18 to 66°C), with normal operating temperatures of 120 to 130°F (49 to 54°C). At higher temperatures, the rate of water evaporation is such that addition of makeup water is frequently required. As the water evaporates, the viscosity increases and the fire resistance decreases.

Water-glycol fluids are compatible with most types of seals, gaskets, and hoses made from nitrile, fluorocarbon, butyl, or ethylene-propylene but are incompatible with certain types of leather, cork, and paper. These fluids generally have a solvent action on most petroleum-compatible paints and coatings.

Synthetic Fluids

Synthetic fluids are non-water-containing man-made materials, such as phosphate esters, blends of phosphate esters with petroleum oil, and polyol esters. Recommended temperature limits are 20 to 150°F (–7 to 66°C), with normal operating temperatures of 120 to 130°F (49 to 54°C).

Phosphate esters and phosphate ester blends are not compatible with seals, gaskets, or hoses made from nitrile, neoprene, or natural rubber, and these elements must be replaced with fluorocarbon or other compatible materials.

Polyol esters are compatible with seals, gaskets, or hoses made from nitrile or fluorocarbon.

All synthetics typically attack paints, coatings, and electrical insulation.

Water-in-Oil Emulsions

Water-in-oil emulsions consist of 35 to 40 percent water, petroleum oil, emulsifiers, and additives. The water is dispersed in fine droplets in the oil phase. Recommended temperature limits for the emulsion are 50 to 150°F (10 to 66°C), with normal operating temperatures of 120 to 130°F (49 to 54°C). At higher temperatures, frequent addition of water is required. Loss of water tends to reduce viscosity and increase flammability. Water-in-oil emulsions are compatible with most seals and gaskets and with hoses made from nitrile, fluorocarbon, or neoprene. Seals or gaskets made from cork, paper, leather, or butyl are unacceptable. These fluids generally have a solvent action on most petroleum-compatible paints and coatings.

ENVIRONMENTALLY ACCEPTABLE FLUIDS

Currently there are four major classes of environmentally acceptable fluids. They are vegetable-based oils, polyglycols, synthetic esters, and synthetic hydrocarbons. Although these fluids are typically used in equipment such as turf maintenance and tree harvesting equipment, man lifts, as well as in off-road construction equipment, they are on occasion used in hydraulically actuated elevators, presses, cranes, winches, and other machinery that may cause ground contamination. In general, these fluids have flashpoints ranging from 410 to 480°F (210 to 249°C).

INTERNATIONAL FLUID DESIGNATIONS

Fluids experts from other countries who represent ISO (International Standards Organization) often attend meetings of the Fluid Power Association's Fluid Standards Committee. Through the input of these experts, the committee prepares standards that can be applied internationally. Some types of hydraulic fluids, such as phosphate esters, are not used extensively throughout the world because of degradability and disposability problems.

All categories of hydraulic fluids have been assigned symbols by the International Standards Organization, which identify the fluid as to type. This coding is now being used on storage containers and product data sheets. The ISO designation and matching fluid description can be found in Table 8.11.1.

SUMMARY

Fluid power systems are used to transmit power or motion to equipment and machinery. Although petroleum oils are the most commonly used hydraulic fuels, synthetic lubricants are used

TABLE 8.11.1 Classification of Hydraulic Fluids

Symbol ISO-L	*Composition*
HH	Refined mineral oils with no additives
HL	Refined mineral oils with antirust and antioxidation properties
HM	HL type with antiwear properties
HV	HL type with improved viscosity/temperature properties
HS	Synthetic with no specific fire-resistant properties
HETG	Vegetable-based oil
HEPG	Polyglycols
HEES	Synthetic esters
HEPR	Synthetic hydrocarbons
HG	Hydraulic slide way oils
HFAE	Oil-in-water emulsions—typically more than 80% water (coolants)
HFAS	Chemical solutions—typically more than 80% water (coolants)
HFB	Water-in-oil emulsions
HFC	Water-glycol fluids
HFDR	Phosphate esters
HFDU	Polyol esters

more frequently in industrial and mobile applications. Pressurized oils or synthesized hydrocarbons in fluid power systems present a considerable fire hazard, especially where ignition sources are constantly present. Less hazardous hydraulic fluids, referred to as fire-resistant fluids, represent a lower fire hazard than petroleum oils or synthesized hydrocarbons, but all will ignite under certain conditions.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for fluid power systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 30, *Flammable and Combustible Liquids Code*

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Chapter 12

Refrigeration Systems

Henry L. Febo, Jr.

Chapter Contents

Effects of Regulatory Changes
Applications, Classifications, and Basic Operating Principles
Types of Systems and Their Basic Hazards
Hazard Control and Emergency Response

Key Terms

azeotropic, chlorofluorocarbons (CFCs), Clean Air Act, halogenated agents, heat transfer fluid, oxygen depletion potential (ODP), refrigerant, refrigeration systems, zeotropic

Industrial refrigeration systems are usually designed to provide a means for cooling specific locations to temperatures below ambient. Although there are many types of refrigeration systems, they are all heat exchangers, differing only in mechanical and thermal design, employing different fluids for refrigerants. This chapter outlines regulatory changes affecting refrigeration systems and reviews the refrigerant identification and hazard classification schemes. It discusses basic operating principles and identifies some of the more common types of refrigeration systems and associated hazards. Although it does not address the distribution aspects of refrigeration systems used for heating, ventilation, and cooling (HVAC) systems, the machinery room is similar whether the goal is building cooling or process and food refrigeration.

For related topics, see Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems."

EFFECTS OF REGULATORY CHANGES

In 1978 chlorofluorocarbons (CFCs) were banned from use in nonessential aerosols by the United States in an effort to reduce depletion of the ozone layer. However, increased use of CFCs in manufacturing operations resulted in a continuation rather than a reduction of the problem of ozone depletion.

Montreal Protocol (1987) and the Clean Air Act of 1990

The United Nations began to address the problem and called a conference, the Vienna Convention for the Protection of the Ozone Layer (1985), which led to the adoption of the "Montreal Protocol on Substances That Deplete the Ozone Layer" (1987). The protocol became effective worldwide in 1989, which led the United States to enact the Clean Air Act of 1990 that required the total phaseout of CFC production by the year 2000. Later, this date was revised to January 1, 1996. At this time, recycled and reclaimed stocks are the only source of CFC refrigerants. The Clean Air Act also mandated reduction of CFC emissions to the "lowest achievable levels," including a ban on intentional venting and limitations on purge units expelling CFCs into the atmosphere.

Alternative Refrigerants

Alternative refrigerants have been developed and commercialized. Centrifugal chillers that air condition buildings and use R-11, R-113, R-114, and R-12 (CFCs) can be substituted with R-123, R-134a, R-124, and R-22 (HCFCs), depending on whether the chiller is replaced or retrofitted. Reciprocation chillers using R-12 (CFC) can be substituted with R-134a and R-22, again, depending on whether the chiller is replaced or retrofitted. R-13B1 (fluorine/bromine hydrocarbon) and R-503 (a blend of CFCs) are being recommended for industrial process refrigeration applications. These are not "drop-in" replacements. There *could* be incompatibilities with lubricants and residual refrigerant in existing equipment. The issue of incompatibility needs to be properly addressed on any changeover. Further, the regulations require that all personnel handling refrigerants be certified, including service, operating, and installation personnel.

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Beijing Amendment (1999)

The United Nations has continued to modify and update the protocol during a series of subsequent meetings, the last held in Beijing, China, in 1999. The latest accepted amendments to the protocol have adopted new controls on the production of hydrochlorofluorocarbons (HCFCs). HCFCs have been promoted as substitutes for CFCs but they also contribute to ozone depletion. The Beijing amendment mandates production of HCFCs be halted in developed countries by 2020 and developing countries by 2040.

Kyoto Protocol (1999)

An additional international agreement, the Kyoto Protocol (1999), seeks to control the release of greenhouse gases to the environment. Greenhouse gases contribute to global warming. Some alternative refrigerants are covered by this agreement. Since it does not prohibit the use or manufacture of these gases but only controls their release, the impact on refrigeration applications is less severe. Two included classes in the refrigeration area are HFCs (hydrofluorocarbons) and PFCs (perfluorocarbons).

CFC Substitutes

Presently the United States requires CFC substitutes be authorized for use by the Environmental Protection Agency (EPA). This process is administered under the Significant New Alternatives Policy (SNAP) published in the Final Rulemaking (59 FR 13044) on March 18, 1994. It continues to list HCFCs as acceptable CFC substitutes. The EPA continues to expand the list of acceptable substitutes under the SNAP guidelines with the latest rulemaking, Notice 19, in October 2004.

Available alternatives to the use of halogenated refrigerant systems include the following:

1. Ammonia systems
2. Absorption systems
3. Steam-jet systems
4. Systems employing CFC substitutes
5. Hydrocarbon refrigeration systems

The use of ammonia as a refrigerant is affected by a number of regulations of the U.S. Occupational Safety and Health Administration (OSHA) and the EPA. Application of these various regulations is based on specific quantity limits, typically 500 to 1000 lb (227 to 454 kg). One regulation in particular that might have to be considered is OSHA's 29 CFR 1910.119, "Process Safety Management Standard." This regulation applies to any system with over 10,000 lb (4540 kg) of ammonia, quite common in industrial systems.

Facilities should consult a regulatory specialist prior to proceeding with a new or modified installation.

APPLICATIONS, CLASSIFICATIONS, AND BASIC OPERATING PRINCIPLES

Applications

The following brief outline includes many of the principal applications of refrigeration systems:

1. Industrial, refining, and chemical
   a. Controlling vapor pressure of volatiles during distillation, separation, or processing
   b. Shifting solubility relationships to permit segregation and removal of undesired constituents, such as asphalt or wax, in lubricating oils
2. Manufacture, freezing, preservation, and distribution of food products
3. Air conditioning
4. Manufacture, preservation, and distribution of medicine and drugs
5. Environmental testing chambers
6. Cold treatment of metals
7. Industrial testing
8. Miscellaneous
   a. Cold storage of flowers and furs
   b. Ice making and skating rinks

Refrigerant Classifications

Numerical Designation. One does not usually associate low temperatures with fire hazards, but refrigeration systems are of concern for two reasons: (1) some of the fluids used as refrigerants are flammable and (2) some are explosive in critical combination with air. Other refrigerants are toxic and, if they escape during a fire, can cause injury or death or interfere with fire-fighting operations.

Refrigerants are identified by a numerical designation as specified in ANSI/ASHRAE 34, *Number Designation and Safety Classification of Refrigerants.* The number can be up to four digits, with each representing the number of fluorine, hydrogen, and carbon atoms as well as the number of unsaturated carbon-carbon bonds, respectively. The number of chlorine atoms can be inferred, and the number of bromine atoms is designated by an uppercase "B" in the numerical designation.

Commercialized refrigerant blends are designated in either the 400 or 500 series. The 400 series is for zeotropic* blends, with the number identifying the compounds in the blend but not the amount of each. The 500 series is for azeotropic† blends, with the number indicating both the compounds and, by definition, the amounts of each. The 600 series has been assigned to miscellaneous organic compounds and the 700 series to inorganic compounds.

Safety Designation. ANSI/ASHRAE 34 also assigns safety groups to the various refrigerant compounds. The classification consists of two alphanumeric characters (e.g., A2 or B1). The capital letter indicates toxicity, and the arabic numeral indicates flammability. The safety group classification can be represented

*Zeotropic: These blends comprise multiple components of different volatilities that, when used in refrigeration cycles, change volumetric composition and saturation temperatures as they evaporate (boil) or condense at constant pressure.

†Azeotropic: These blends comprise multiple components of different volatilities that, when used in refrigeration cycles, *do not* change volumetric composition and saturation temperatures as they evaporate (boil) or condense at constant pressure.

as in Figure 8.12.1. Complete details of the classification criteria and methods can be found in ANSI/ASHRAE 34.

The safety class changed with the 1992 edition of ANSI/ASHRAE 34. The pre-1992 system evolved over the years and attempted to classify these two independent parameters, that is, toxicity and flammability, with a simple (or modified single) designator (i.e., Group 1, 2, 3a, 3b, 4a, and 4b). The new system is less arbitrary in assignment of the letter for toxicity and number for the flammability index.

A list of the more commonly used refrigerants, some selected properties, and their safety class can be found in Table 8.12.1. The table has been expanded with the addition of several new refrigerants that can serve as replacements for existing high ODP (oxygen depletion potential) materials. Some of the blends have a potential for flammability when mixed with air or enriched oxygen concentrations at temperatures above 212°F (100°C) and elevated pressures even though rated as Safety Class A1. This situation may occur when they are used as a leak testing agent. Several industrial explosions have occurred under these conditions with R-22. To identify those compounds with special flammability considerations that are not included in this document, see the MSDS or the agent supplier. For a complete listing of the covered compounds, refer to the latest edition of ASHRAE 34.

Basic Operating Principles

All refrigeration systems take heat from one space or medium and transfer it to another. To accomplish the transfer, fluids are used that will readily absorb, transport, and release heat under controlled conditions. These fluids used as refrigerants perform in both the liquid and gaseous states. When a refrigerant in a liquid state changes to a gas, it absorbs heat from its surroundings.

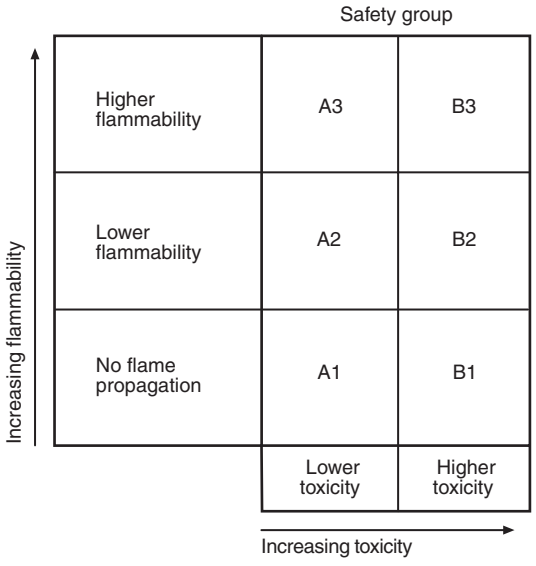

FIGURE 8.12.1 Refrigerant Safety Group Classification (Source: ANSI/ASHRAE 34-2004, *Designation and Safety Classification of Refrigerants*)

Conversely, when a refrigerant in a gaseous state condenses back to a liquid, it releases heat to its surroundings. The most effective refrigerant is a material that can vaporize and condense at the desired temperatures and pressures.

The unit of refrigeration in the United States is known as the ton. It is historically developed from the heat required to melt 1 ton (2000 lb [907 kg]) of ice at 32°F (0°C) during a period of 24 hours. Since the heat of fusion of water is approximately 144 Btu/lb (3.4×10^5 J/kg), a U.S. ton of refrigeration equals 12,000 Btu/hr (3.5 kW).

A refrigeration system consists of a circulating refrigerant, condenser and receiver, a control device, an evaporator, and a compression device (Figure 8.12.2). At the start of a cycle, the refrigerant passes from the receiver at high pressure to the control device, which is an expansion valve where the high-pressure liquid is allowed to expand (thus reducing its pressure and temperature), and then to the evaporator with many coils or tubes that will remove heat from the area or secondary fluid. The compression device, where an outside energy source is used for operation, takes the low-pressure gas, increases its pressure, and then discharges the hot, high-pressure gas into a condenser. Here the gas gives up the heat obtained in the evaporator and compressor and condenses into a liquid, returning to the receiver where the cycle repeats.

TYPES OF SYSTEMS AND THEIR BASIC HAZARDS

Refrigeration systems are classified in two ways: (1) by the type of compression system (mechanical, absorption, steam-jet ejectors) and (2) by the method of cooling the space or substance (direct or indirect).

Mechanical System

Description. A mechanical refrigeration system, where the compression step is achieved by a mechanical compressor, is probably the most common refrigeration system type in use.

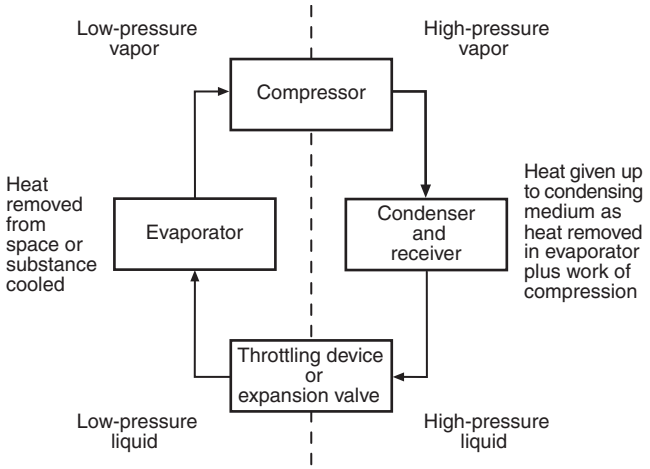

FIGURE 8.12.2 Basic Mechanical Refrigeration System

TABLE 8.12.1 Refrigerant Classification and Selected Properties

Refrigerant	*Name*	*Chemical Formula*	Boiling Point		*Specific Gravity (Air = 1)*	Autoignition Temperature		Flammable Limits and by Volume in Air		*Safety Class*[a]
			°F	*°C*		*°F*	*°C*	*Lower*	*Upper*	
R-11	Trichlorofluoromethane	CCl_3F	76	24	4.79	—	—	—	—	A1
R-12	Dichlorodifluoromethane	CCl_2F_2	–22	–30	4.17	—	—	—	—	A1
R-13	Chlorotrifluoromethane	$CClF_3$	–114	–81	3.60	—	—	—	—	A1
R-13B1	Bromotrifluoromethane	$CBrF_3$	–72	–58	—	—	—	—	—	A1
R-14	Tetrafluoromethane	CF_4	–198	–127	—	—	—	—	—	A1
R-21	Dichlorofluoromethane	$CHCl_2F$	48	9	—	—	—	—	—	B1
R-22	Chlorodifluoromethane	$CHClF_2$	–42	–41	2.98	1170	632	Very weakly flammable		A1
R-23	Trifluoromethane	CHF_3	–116	–82	—	—	—	—	—	A1
R-30	Dichloromethane	CH_2Cl_2	104	40	2.90	1033	556	13.0	23.0	B2
R-32	Difluoromethane	CH_2F_2	–62	–52	1.80	1198	647	12.7	33.4	A2
R-40	Methyl chloride	CH_3Cl	–11	–24	1.80	1170	632	7.0	19.1	B2
R-50	Methane	CH_4	–259	–161	0.60	999	537	5.0	15.0	A3
R-113	Trichlorotrifluoroethane	CCl_2FCClF_2	118	48	6.46	1256	680	Very weakly flammable		A1
R-114	Dichlorotetrafluoroethane	$CClF_2CClF_2$	39	4	5.89	—	—	—	—	A1
R-115	Chloropentafluoroethane	$CClF_2CF_3$	–38	–39	—	—	—	—		
R-116	Hexafluoroethane	CF_3CF_3	–109	–78	—	—	—	—	—	A1
R-123	2,2-dichloro-1,1, 1-trifluoroethane	$CHCl_2CF_3$	81	27	—	—	—	—	—	B1
R-124	2-chloro-1,1,1, 2-tetrafluoroethane	$CHClFCF_3$	10	–12	—	—	—	—	—	A1
R-125	Pentafluoroethane	CHF_2CF_3	–56	–49	—	—	—	—	—	A1
R-134a	1,1,1,2-tetrafluoroethane	CH_2FCF_3	–15	–26	—	—	—	—[b]	—[b]	A1
R-142	1-chloro-1, 1-difluoroethane	CH_3CClF_2	14	–10	1.19	—	—	9.0	14.8	A2
R-143a	1,1,1-trifluoroethane	CH_3CF_3	–53	–47	2.92	1382	750	7.0	19.0	A2
R-152a	1,1-difluoroethane	CH_3CHF_2	–13	–25	—	—	—	3.7	18.0	A2
R-170	Ethane	C_2H_6	–128	–89	1.04	959	515	3.1	2.5	A3
R-E170	Dimethyl ether	CH_3OCH_3	–13	–25	1.62	662	350	3.4	18.0	A3
R-218	Octafluoropropane	$CF_3CF_2CF_3$	–35	–37	—	—	—	—	—	A1
R-236fa	1,1,1,3,3,3- hexafluoropropane	$CF_3CH_2CF_3$	29	–1	—	—	—	—	—	A1
R-245fa	1,1,1,3,3- pentafluoropropane	$CF_3CH_2CHF_2$	59	15	—	—	—	—	—	A1[c]
R-290	Propane	C_3H_8	–44	–42	1.56	871	466	2.2	9.6	A3
R-C318	Octafluorocyclobutane	$-(CF_2)_4-$	21	–6	—	—	—	—	—	NR[d]
R-400	R-12 and R-14 (composition varies)	$CCl_2F_2/C_2Cl_2F_4$	—	—	—	—	—	—	—	A1
R-403B	R-290, 5%, R-22, 56%, & R-218, 39%	$C_3H_8/CHClF_2/CF_3CF_2CF_3$	–57	–49	1.11	—	—	—[e]	—[e]	A1
R-404A	R-125, 44%, R-143a, 52%, & R-134a, 4%	$CHF_2CF_3/CH_3CF_3/CH_2FCF_3$	–52	–47	1.05	—	—	—[e]	—[e]	A1
R-407C	R-32, 23%, R-125, 25%, & R-134a, 52%	$CH_2F_2/CHF_3CF_3/CH_2FCF_3$	–47	–44	—	—	—	—[e]	—[e]	A1
R-410A	R-32, 50%, & R-125, 50%	CH_2F_2/CHF_2CF_3	–64	–53	—	—	—	—[e]	—[e]	A1
R-500	R-12, 73.8%, & R-152a, 26.2%	CCl_2F_2/CH_3CHF_2	–27	–33	—	—	—	—	—	A1
R-502	R-22, 48.8%, & R-115, 51.2%	$CHClF_2/CClF_2CF_3$	–49	–45	—	—	—	—	—	A1
R-503	R-23, 40.1%, & R-13, 59.9%	$CHF_3/CClF_3$	–126	–88	—	—	—	—	—	NR[d]
R-508A	R-23, 39%, & R-116, 61%	CHF_3/CF_3CF_3	–122	–86	—	—	—	—	—	A1
R-508B	R-23, 46%, & R-116, 54%	CHF_3/CF_3CF_3	–127	–88	—	—	—	—	—	A1
R-600	Butane	C_4H_{10}	31	–1	2.06	761	405	1.9	8.5	A3

TABLE 8.12.1 Continued

Refrigerant	*Name*	*Chemical Formula*	Boiling Point *°F*	Boiling Point *°C*	*Specific Gravity (Air = 1)*	Autoignition Temperature *°F*	Autoignition Temperature *°C*	Flammable Limits and by Volume in Air *Lower*	Flammable Limits and by Volume in Air *Upper*	*Safety Class*[a]
R-600a	Isobutane	$CH(CH_3)_2CH_3$	11	–12	2.00	860	460	1.8	8.4	A3
R-611	Methyl formate	$HCOOCH_3$	90	32	2.07	853	456	4.5	23.0	B2
R-717	Ammonia	NH_3	–28	–33	0.59	1204	651	16.0	25.0	B2
R-744	Carbon dioxide	CO_2	–109	–79	1.52	—	—	—	—	A1
R-764	Sulfur dioxide	SO_2	14	–10	2.21	—	—	—	—	B1
R-1150	Ethylene	C_2H_4	–155	–104	0.98	842	450	2.7	36.0	A3
R-1270	Propylene	C_3H_6	–53	–47	1.50	851	455	2.0	11.0	A3

[a]Safety class in accordance with ANSI/ASHRAE 34.
[b]Exhibits combustibility at 5.5 psig (140 kPa) and 350°F (177°C).
[c]This classification is provisional and will be reviewed when additional information is submitted.
[d]NR = Not rated.
[e]Potential flammability at temperatures above 100°C or pressures above atmospheric.

Source: ANSI/ASHRAE 34-2004, *Designation and Safety Classification of Refrigerants,* © American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., http://www.ashrae.org.

The compressor types include reciprocating (horizontal, vertical [Figure 8.12.3], or "V" design), centrifugal (Figure 8.12.4), or rotary screw type. Refrigerants can include any of the fluids shown in Table 8.12.1. Figure 8.12.5 illustrates a typical ammonia refrigeration system, showing the relationship of the major components, such as the compressor, expansion valve, and evaporator.

Hazards. The hazards are primarily related to the refrigerant fluid. Refrigerants with a flammability rating of 1 present no fire hazard but, if released into a confined space, present oxygen depletion hazards to personnel, as would those rated 2 or 3.

Refrigerants with a flammability rating of 2 pose limited fire and explosion hazard, according to the ANSI/ASHRAE 34 classification method. The potential fire and explosion hazards of these fluids should be evaluated before any installation decision is made.

Refrigerants with a flammability rating of 3 are highly flammable. These are used primarily in the petroleum refining and petrochemical industries. Use of these refrigerants requires special design and construction to control the fire and explosion hazards and to minimize the consequences of an unexpected release.

Refrigerants carrying a B toxicity rating present additional personnel hazards that must be recognized and addressed in design and emergency planning.

The equipment used for the compression step will present various hazards not directly addressed in this chapter. These hazards, which include potential for overspeed, overpressure,

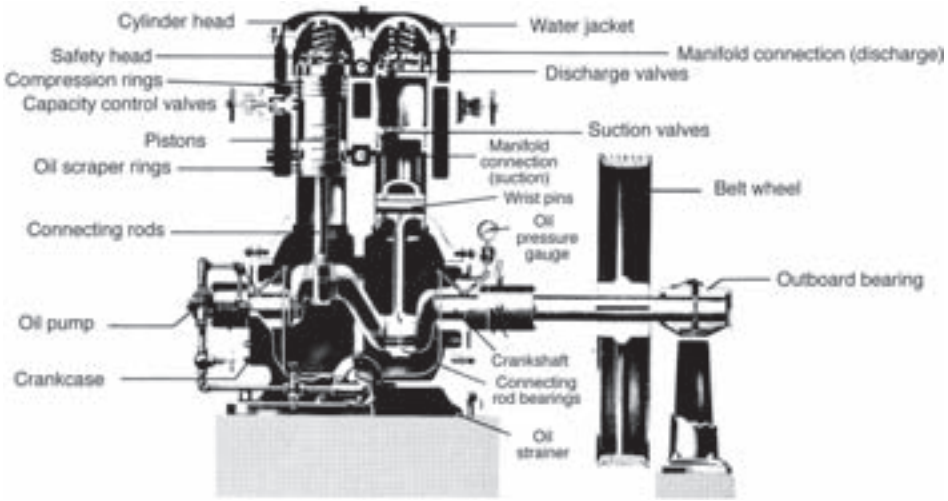

FIGURE 8.12.3 Reciprocating Compressor, Vertical Single Acting (Source: FM Global)

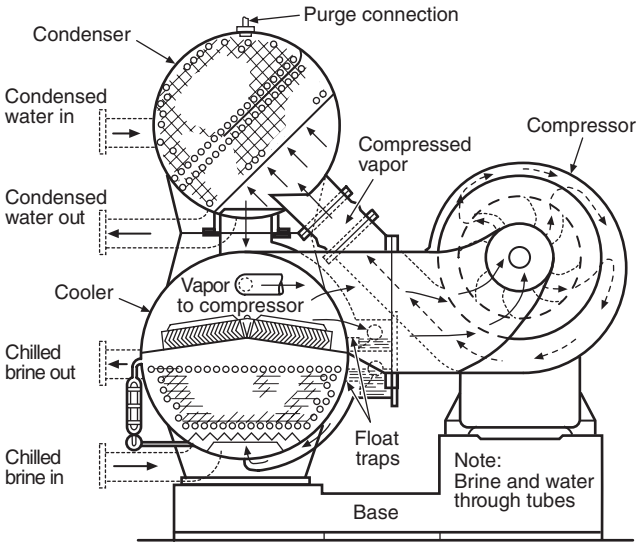

FIGURE 8.12.4 Cross Section of Centrifugal Refrigeration System Showing Refrigeration Cycle (Source: FM Global)

leakage of refrigerants or lubricants, and personnel safety issues, should be recognized in the design and installation phase and addressed in a preventive maintenance program.

Absorption System

Description. The absorption cycle is the oldest known for producing a refrigeration effect. Mechanically, it is the simplest of the systems in common use today. The simple absorption system consists of the basic components shown in Figure 8.12.6, with the absorber, heat exchanger, and generator system serving as the compression step.

The absorption cycle uses an absorbent as a secondary fluid to absorb the primary fluid, which is a gaseous refrigerant that has been vaporized in the evaporator. The evaporation process absorbs heat, providing the needed refrigeration.

The absorption and mechanical compression cycles have in common the evaporation and condensation of a refrigerant liquid, occurring at two pressure levels within the unit. The two cycles differ in that the absorption cycle uses a heat-operated generator to produce the pressure differential, whereas the mechanical compression cycle uses a compressor. Both cycles require energy for operation, that is, heat and a small amount of mechanical energy (a pump) in the absorption cycle and mechanical energy in the compression cycle.

The two most common working fluids presently in use are (1) water-lithium bromide (H_2O-LiBr) and (2) ammonia-water

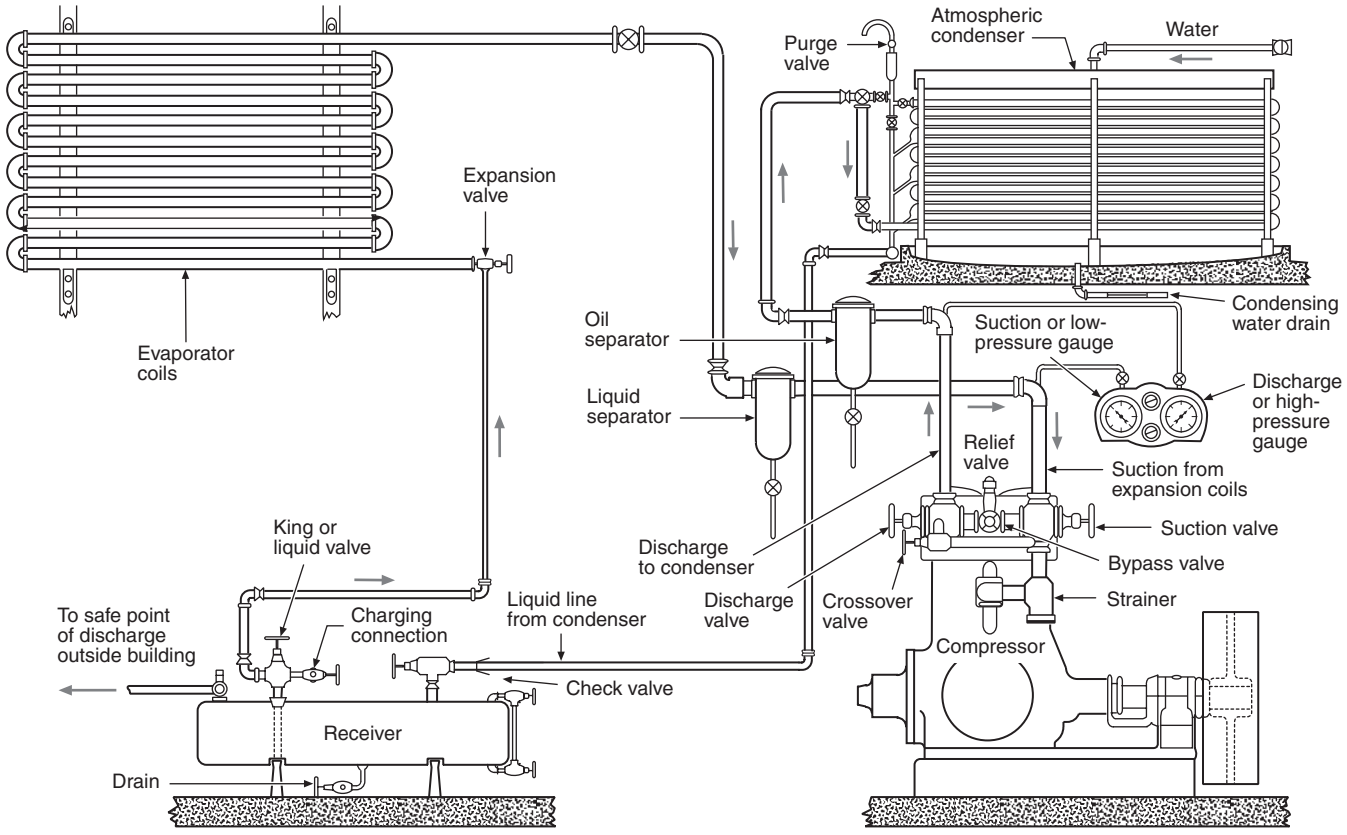

FIGURE 8.12.5 Typical Ammonia Refrigeration Plant (Source: FM Global)

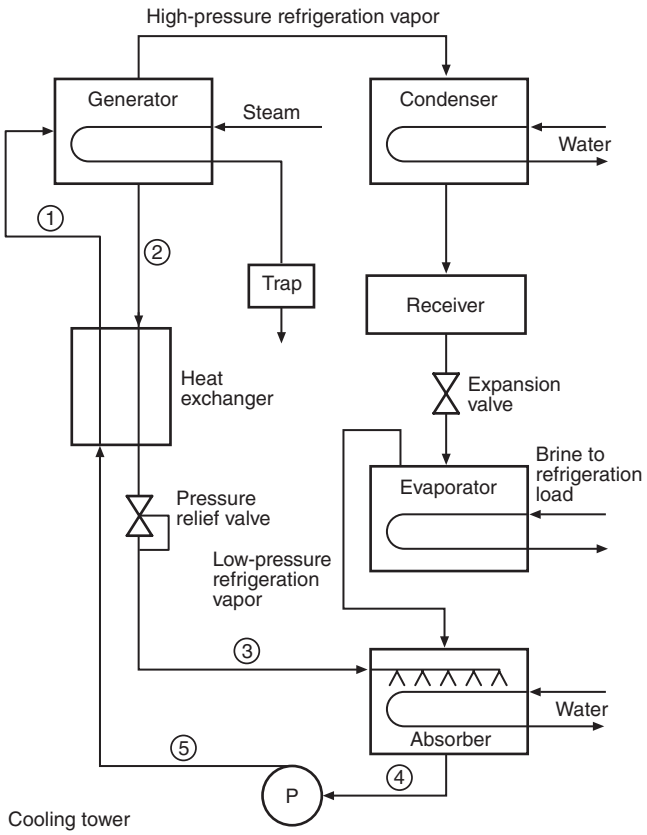

FIGURE 8.12.6 Basic Absorption Refrigeration System (Source: FM Global)

(NH_3-H_2O), where the components are given as refrigerant, then absorbent. Note that in one system water is the refrigerant, whereas in the other it is the absorbent.

The water-lithium bromide is used primarily for air-conditioning applications, whereas the ammonia-water is used for large tonnage industrial applications requiring low temperatures for process cooling.

Water-lithium bromide is a brine that has a subatmospheric vapor pressure at typical cycle conditions. Machines that use water-lithium bromide operate under a vacuum. Conversely, ammonia-water solutions have vapor pressures up to 295 psi (2030 kPa) at cycle conditions. As a result, equipment used for ammonia-water systems requires much stronger vessels.

The heat energy for the generator can come from various sources. These include steam or hot fluids (called indirect fired); clean, hot waste gases (heat recovery, also indirect fired); or flame (direct fired).

Hazards. Lithium bromide is a relatively stable compound (nontoxic, nonflammable, and nonexplosive). If contaminated, it can generally be reclaimed.

Ammonia systems have inherent hazards, as described in the section entitled "Hazard Control and Emergency Response." Similar safeguards in that section would apply.

Steam-Jet Ejector System

Description. The steam-jet (also known as the steam vacuum or steam-ejector) refrigeration cycle has been used for almost 100 years, yet it is one of the least common refrigeration cycles in use today. Its lack of popularity stems, at least in part, from some inherent performance limitations. Several hundred of these units are still in use in such industries as pulp and paper, petrochemical, food processing, and pharmaceuticals, where they are used for air conditioning and process cooling.

The steam-jet refrigeration cycle is similar to the more conventional refrigeration cycles having basic system components, such as an evaporator, compression device, condenser, and refrigerant. Instead of a mechanical compressor, the steam-jet system employs a steam ejector or booster to compress the refrigerant to the condenser pressure level. In the steam-jet refrigeration cycle, water is used as the refrigerant and the cooling effect is produced by the continuous vaporization of a part of the water in the evaporator at a low absolute pressure level.

Figure 8.12.7 shows a simple open, chilled-water refrigeration system. In this open system, refrigerant water is circulated directly to the cooling load. It is possible to have a closed chilled-water system in which a secondary fluid, usually water or brine, is used to serve the cooling load.

Hazards. Due to the simple nature of this system, no unique hazards are presented. Because water is the refrigerant, care is needed to prevent freezing in the evaporator, including operational controls and low-refrigerant-temperature alarms.

Direct Method of Cooling System

In addition to being classified according to the type of compression stage employed, refrigeration systems are further differentiated by how the heat is removed from the cooling load. In direct systems, the evaporator is in direct contact with the product or space to be cooled, or it is in air-circulating passages connected to the area or product. A household refrigerator is an example of a direct system.

Indirect Method of Cooling System

An indirect system uses an intermediate heat transfer fluid, which is first cooled by the refrigerant and then circulated to the material or space. The intermediate fluid is called "brine," because early refrigerating systems used a mixture of sodium or calcium salt and water. Brine has been defined as any liquid cooled by a refrigerant and used for the transmission of heat energy without a change in state. Organic chemical solutions, such as ethylene glycol, as well as brine, are employed in indirect systems.

HAZARD CONTROL AND EMERGENCY RESPONSE

Detailed criteria for installation and arrangement of refrigeration systems are addressed in various national standards and

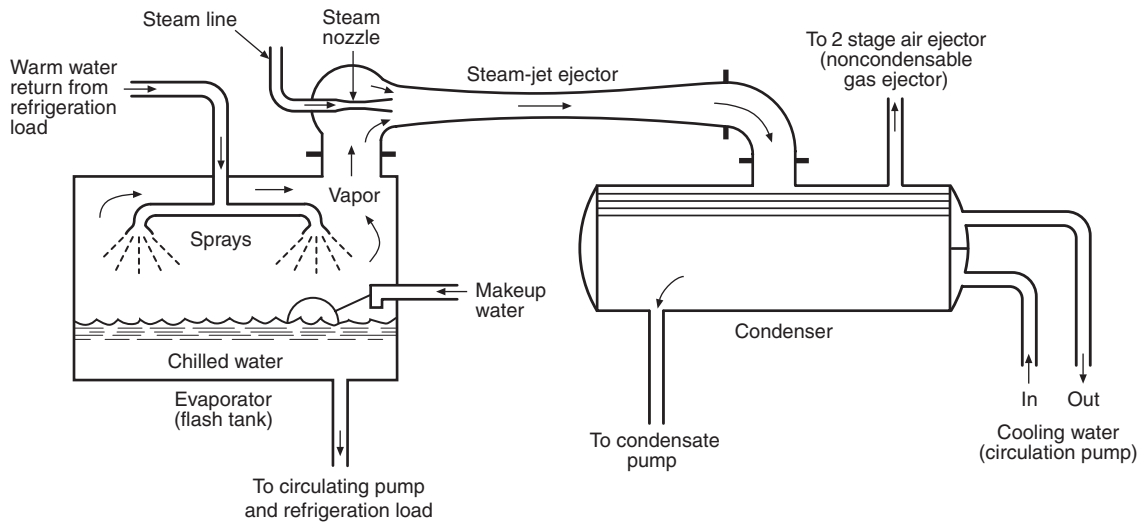

FIGURE 8.12.7 Open, Chilled-Water Steam-Jet Refrigeration System with Surface Condenser (Source: FM Global)

codes (see bibliography). This section summarizes some basic considerations and safeguards. Some of the following criteria might not be practical where small quantities of refrigerants are involved.

Location and Construction

The choice of refrigerant type is limited by some codes, depending on the occupancy of the area where the system is to be installed. Indirect systems can sometimes be used with toxic refrigerants when the machine room can be safely located away from normally occupied areas.

Refrigeration machinery is best located in a separate room, cut off from any adjoining occupancy. In most cases, this room should be limited to containing the refrigeration machinery and controls. Electric switchgear, boilers, fuel fire equipment, and so on should be located in other rooms. Even the noncombustible refrigerants (Classes A1 and B1) can be decomposed by arcs, flames, and hot surfaces, possibly releasing corrosive chlorides and fluorides.

The room construction should be noncombustible. Cutoffs should be 1-hour fire rated for flammability Class 1 and 2 refrigerants, and 2-hour fire rated where flammability Class 3 refrigerants are used.

Where flammability Class 2 and 3 refrigerants are used, the potential for room explosion must be considered. Outdoor locations or rooms of damage-limiting construction (see NFPA 68, *Standard on Explosion Protection by Deflagration Venting*) should be used to minimize damage from an explosion caused by release of these refrigerants.

Ammonia, a flammability Class 2, is often considered exempt from these criteria due to the exemption from using hazardous location electrical equipment (see below). This exemption has proved ill-considered in a number of explosion incidents involving ammonia refrigeration systems.

Electrical Equipment

For flammability Class 1 refrigerants, the major concern for electrical equipment is potential corrosion issues. Best practice is to locate all electrical equipment not directly associated with the refrigeration system to areas other than the machine room. For flammability Class 2 and 3 refrigerants, the machine room should conform to NFPA 70, *National Electrical Code*®. For ammonia, a flammability Class 2 refrigerant, some codes and authorities having jurisdiction allow use of ordinary electrical equipment under either of the following conditions:

1. The machine room is continuously ventilated and failure of the ventilation system sounds an alarm
2. The machine room is equipped with a vapor detector that will automatically start the ventilation system and sound an alarm at a detection level at or below 1000 ppm

Ventilation

For Class A1 refrigerants, natural or mechanical ventilation is necessary for equipment cooling and personnel comfort only. For all other refrigerants, mechanical ventilation is needed. Where the hazard is only toxicity, appropriate guidelines should be followed. Where refrigerant flammability is an issue, continuous mechanical ventilation of 1 $ft^3/min/ft^2$ (0.3 $m^3/min/m^2$) of floor area will minimize the possibility of developing an explosive concentration in the event of normal or minor leakage.

Fire Protection

Control of fire emergencies generally consists of reducing the heat of the fire with water and, if possible, shutting off the gas supply. Water should be applied as a spray from hoses or fixed nozzles.

Where the construction is combustible, or flammable refrigerants are used, automatic sprinklers provide the best and most reliable form of fire protection.

All machine rooms should be provided with portable extinguishers suitable for at least Class B and C fires.

Miscellaneous

To minimize refrigerant release from equipment and piping, a high level of maintenance should be provided, especially where refrigerants are flammable or toxic. In addition, the initial installation should ensure that piping and components are compatible with the refrigerant and installed according to appropriate codes. ANSI/ASHRAE 15, *Safety Code for Mechanical Refrigeration,* details the requirements for piping, pressure relief, and so on. Special care should be taken to protect refrigerant piping from mechanical damage. For large ammonia-based systems (over 10,000 lb [4540 kg]) and those using flammability Class 3 refrigerants, the requirements of the OSHA Process Safety Management standard may apply.

Control of the nonfire emergency is accomplished by directing, diluting, and dispersing the gas to prevent it from coming in contact with people or goods. Simultaneously, steps should be taken to stop the flow of gas. Air, water, and steam are practical media for accomplishing dilution and dispersion. Water, in the form of a spray from hoses or fixed nozzles, is most commonly used for this purpose.

Ammonia presents hazards of fire, explosion, toxicity, and contamination of goods. It can be most severe in the refrigerated area and machine room but can spread to adjoining areas. Emergency planning should address control of the release, protection of personnel, and decontamination or preservation of the stored commodity.

SUMMARY

Industrial refrigeration systems are designed to cool specific locations to below-ambient temperatures by taking heat from one space or medium and transferring it to another. Principal applications of such systems include use in industrial, refining, and chemical processes; in the manufacture, freezing, preservation, and distribution of food products, medicine, and drugs; in air conditioning; in environmental testing chambers; in the cold treatment of metals; in industrial testing; in the cold storage of flowers and furs; and in ice making and skating rinks.

Refrigeration systems are classified by the type of compression system (mechanical, absorption, or steam-jet ejectors) and by the method of cooling (direct or indirect). The hazards of these systems center on the fluids used as refrigerants, some of which are flammable and explosive in critical combinations with air, and some of which are toxic and could cause injury or death during a fire or accidental release.

Basic considerations and safeguards include (1) location, that is, placing refrigeration machinery in a separate room and locating all electrical equipment not directly associated with the refrigeration system elsewhere than in the machinery room; (2) ventilation; (3) fire protection, such as automatic sprinklers and portable extinguishers; and (4) a high level of maintenance.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for refrigeration systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 70, *National Electrical Code®*

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FM Global Property Loss Prevention Data Sheet 7-13, *Mechanical Refrigeration,* Factory Mutual Insurance Company, Johnston, RI, 2007.

Chapter 13

Electrical Systems and Appliances

Robert M. Milatovich

Chapter Contents

Arcing and Overheating in Electrical Systems
Origins of Electrical Fires in Buildings
Codes and Standards
Building Wiring, Design, and Protection
Electrical Household Appliances
Industrial and Commercial Equipment
Electrical Equipment for Outdoor Use
Locations Exposed to Moisture and Noncombustible Dusts
Signaling and Communications Systems
Emergency Systems
Special Occupancy Electrical Problems

Key Terms

ampacity, arc-fault circuit interrupters (AFCI), electric arc, electrical conductor, electrical failure, ground-fault circuit interrupter (GFCI), ground-fault protection (GFP), hazardous (classified) locations, leakage current detection and interruption (LCDI), overcurrent protection, overcurrent protective devices, service entrance (electrical), surge arrester

This chapter discusses electrical systems and appliances. Specific topics include origins of electrical fires; codes and standards; building wiring, design, and protection; electrical household appliances; industrial and commercial equipment; electrical equipment for outdoor use; locations exposed to moisture and dust; signaling and communications systems; emergency systems; and special occupancy installations.

Other chapters in this handbook address related building services, most notably Section 10, Chapter 2, "Heating Systems and Appliances," and Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems." Special considerations for the installation of electrical systems can be found elsewhere in this handbook. See Section 4, Chapter 3, "Concepts of Egress Design"; Section 6, Chapter 11, "Medical Gases"; Section 8, Chapter 8, "Industrial and Commercial Heat Utilization Equipment"; and Section 11, Chapter 6, "Lightning Protection Systems."

If properly designed, installed, and maintained, electrical systems are both convenient and safe; otherwise they can be a source of both fire and personal injury. Electricity can cause a fire if an arc occurs or if electrical equipment overheats and can cause injury or death through shocks and burns.

All references to the *National Electrical Code*® (*NEC*®) in this chapter are to the 2005 edition.

ARCING AND OVERHEATING IN ELECTRICAL SYSTEMS

When an electric circuit carrying a current is interrupted either intentionally, as by a switch, or unintentionally, as when a connection at a terminal becomes loosened, arcing at the switch contacts or heating from the high-resistance connection at the terminal is produced. The intensity of the arc and the energy released depend largely on the current and resistance of the contact at the terminal, as well as the voltage and inductance of the circuit load. The temperature may easily be high enough to ignite any combustible material in the vicinity.

An electric arc may not only ignite combustible material in its vicinity, for example, the insulation and covering of the conductor, but may also melt the metal of the conductor. Embers from burning combustible material and splatters of hot metal may fall on combustible material, setting it on fire.

When an electrical conductor carries current, heat is generated in direct proportion to the resistance (ohms) of the conductor and to the square of the current (amperage). The resistance of conductors used to convey current to the location in which it is used or to convey it through the windings of a piece of apparatus (except resistance devices and heaters) should be as low as practical. Metals, such as copper and aluminum, are used for this purpose. In other instances, such as in electric heaters, electric cooking equipment, and soldering irons, the heat from the current serves a useful purpose.

The heating of electrical conductors is almost never a fire hazard under design conditions. NFPA 70, *National Electrical Code*®, specifies the *ampacity,* or the maximum safe current a

Robert M. Milatovich is a supervising inspector for the Clark County Building Department, Las Vegas, Nevada, principal member of Code Making Panel 17, and past chair of Code Making Panel 20 of NFPA 70, *National Electrical Code*® *(NEC*®*).*

TABLE 8.13.1 Allowable Ampacities of Insulated Conductors, Rated 0 Through 2000 V, 140 to 194°F (60 to 90°C), Not More Than Three Current-Carrying Conductors in Raceway or Cable or Earth (Directly Buried), Based on Ambient Temperature of 86°F (30°C)

	Copper			Aluminum or Copper-Clad Aluminum			
	Temperature Rating of Conductor[a]						
	140°F (60°C)	*167°F (75°C)*	*194°F (90°C)*	*140°F (60°C)*	*167°F (75°C)*	*194°F (90°C)*	
Size (AWG or kcmil)	*Types TW, UF*	*Types RHW, THHW, THW, THWN, XHHW, USE, ZW*	*Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2*	*Types TW, UF*	*Types RHW, THHW, THW, THWN, XHHW, USE*	*Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2*	*Size (AWG or kcmil)*
18	—	—	14	—	—	—	—
16	—	—	18	—	—	—	—
14[b]	20	20	25	—	—	—	—
12[b]	25	25	30	20	20	25	12[b]
10[b]	30	35	40	25	30	35	10[b]
8	40	50	55	30	40	45	8
6	55	65	75	40	50	60	6
4	70	85	95	55	65	75	4
3	85	100	110	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	150	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	190	230	255	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500
600	355	420	475	285	340	385	600
700	385	460	520	310	375	420	700
750	400	475	535	320	385	435	750
800	410	490	555	330	395	450	800
900	435	520	585	355	425	480	900
1000	455	545	615	375	445	500	1000
1250	495	590	665	405	485	545	1250
1500	520	625	705	435	520	585	1500
1750	545	650	735	455	545	615	1750
2000	560	665	750	470	560	630	2000
	Correction Factors[c]						
Ambient Temp. (°C)							*Ambient Temp. (°F)*
21–25	1.08	1.05	1.04	1.08	1.05	1.04	70–77
26–30	1.00	1.00	1.00	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	0.82	0.88	0.91	96–104
41–45	0.71	0.82	0.87	0.71	0.82	0.87	105–113
46–50	0.58	0.75	0.82	0.58	0.75	0.82	114–122
51–55	0.41	0.67	0.76	0.41	0.67	0.76	123–131
56–60	—	0.58	0.71	—	0.58	0.71	132–140
61–70	—	0.33	0.58	—	0.33	0.58	141–158
71–80	—	—	0.41	—	—	0.41	159–176

[a]See *NEC* Table 310.13.

[b]See *NEC* Section 240.3(D).

[c]For ambient temperatures other than 86°F (30°C), multiply the allowable ampacities by the appropriate factor.

Source: NFPA 70, *National Electrical Code,* 2005 edition.

TABLE 8.13.2 Allowable Ampacities of Single Insulated Conductors, Rated 0 Through 2000 V, in Free Air Based on Ambient Air Temperature of 86°F (30°C)

	Copper			Aluminum or Copper-Clad Aluminum			
	Temperature Rating of Conductor[a]						
	140°F (60°C)	*167°F (75°C)*	*194°F (90°C)*	*140°F (60°C)*	*167°F (75°C)*	*194°F (90°C)*	
Size (AWG or kcmil)	*Types TW, UF*	*Types RHW, THHW, THW, THWN, XHHW, ZW*	*Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2*	*Types TW, UF*	*Types RHW, THHW, THW, THWN, XHHW*	*Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2*	*Size (AWG or kcmil)*
18	—	—	18	—	—	—	—
16	—	—	24	—	—	—	—
14[b]	25	30	35	—	—	—	-—
12[b]	30	35	40	25	30	35	12[b]
10[b]	40	50	55	35	40	40	10[b]
8	60	70	80	45	55	60	8
6	80	95	105	60	75	80	6
4	105	125	140	80	100	110	4
3	120	145	165	95	115	130	3
2	140	170	190	110	135	150	2
1	165	195	220	130	155	175	1
1/0	195	230	260	150	180	205	1/0
2/0	225	265	300	175	210	235	2/0
3/0	260	310	350	200	240	275	3/0
4/0	300	360	405	235	280	315	4/0
250	340	405	455	265	315	355	250
300	375	445	505	290	350	395	300
350	420	505	570	330	395	445	350
400	455	545	615	355	425	480	400
500	515	620	700	405	485	545	500
600	575	690	780	455	540	615	600
700	630	755	855	500	595	675	700
750	655	785	885	515	620	700	750
800	680	815	920	535	645	725	800
900	730	870	985	580	700	785	900
1000	780	935	1055	625	750	845	1000
1250	890	1065	1200	710	855	960	1250
1500	980	1175	1325	795	950	1075	1500
1750	1070	1280	1445	875	1050	1185	1750
2000	1155	1385	1560	960	1150	1335	2000
	Correction Factors[c]						
Ambient Temp. (°C)							*Ambient Temp. (°F)*
21–25	1.08	1.05	1.04	1.08	1.05	1.04	70–77
26–30	1.00	1.00	1.00	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	0.82	0.88	0.91	96–104
41–45	0.71	0.82	0.87	0.71	0.82	0.87	105–113
46–50	0.58	0.75	0.82	0.58	0.75	0.82	114–122
51–55	0.41	0.67	0.76	0.41	0.67	0.76	123–131
56–60	—	0.58	0.71	—	0.58	0.71	132–140
61–70	—	0.33	0.58	—	0.33	0.58	141–158
71–80	—	—	0.41	—	—	0.41	159–176

[a]See *NEC* Table 310.13.
[b]See *NEC* Section 240.3(D).
[c]For ambient temperatures other than 86°F (30°C), multiply the allowable ampacities by the appropriate factor.
Source: NFPA 70, *National Electrical Code,* 2005 edition.

TABLE 8.13.3 Allowable Ampacities of Three Single Insulated Conductors, Rated 0 Through 2000 V, 302 to 482°F (150 to 250°C), in Raceway or Cable Based on Ambient Air Temperature of 104°F (40°C)

	Copper		Nickel or Nickel-Coated Copper	Aluminum or Copper-Clad Aluminum	
	Temperature Rating of Conductor[a]				
Size (AWG or kcmil)	*302°F (150°C)* Type Z	*392°F (200°C)* Types FEP, FEPB, PFA	*482°F (250°C)* Types PFAH, TFE	*302°F (150°C)* Type Z	*Size (AWG or kcmil)*
14	34	36	39	—	14
12	43	45	54	30	12
10	55	60	73	44	10
8	76	83	93	57	8
6	96	110	117	75	6
4	120	125	148	94	4
3	143	152	166	109	3
2	160	171	191	124	2
1	186	197	215	145	1
1/0	215	229	244	169	1/0
2/0	251	260	273	198	2/0
3/0	288	297	308	227	3/0
4/0	332	346	361	260	4/0
250	—	—	—	—	250
300	—	—	—	—	300
350	—	—	—	—	350
400	—	—	—	—	400
500	—	—	—	—	500
600	—	—	—	—	600
700	—	—	—	—	700
750	—	—	—	—	750
800	—	—	—	—	800
1000	—	—	—	—	1000
1500	—	—	—	—	1500
2000	—	—	—	—	2000
	Correction Factors[b]				
Ambient Temp. (°C)					*Ambient Temp. (°F)*
41–50	0.95	0.97	0.98	0.95	105–122
51–60	0.90	0.94	0.95	0.90	123–140
61–70	0.85	0.90	0.93	0.85	141–158
71–80	0.80	0.87	0.90	0.80	159–176
81–90	0.74	0.83	0.87	0.74	177–194
91–100	0.67	0.79	0.85	0.67	195–212
101–120	0.52	0.71	0.79	0.52	213–248
121–140	0.30	0.61	0.72	0.30	249–284
141–160	—	0.50	0.65	—	285–320
161–180	—	0.35	0.58	—	321–356
181–200	—	—	0.49	—	357–392
201–225	—	—	0.35	—	393–437

[a]See *NEC* Table 310.13.
[b]For ambient temperatures other than 104°F (40°C), multiply the allowable ampacities by the appropriate factor.
Source: NFPA 70, *National Electrical Code,* 2005 edition.

TABLE 8.13.4 Allowable Ampacities of Single Insulated Conductors, Rated 0 Through 2000 V, 302 to 482°F (150 to 250°C), in Free Air Based on Ambient Air Temperature of 104°F (40°C)

	Copper		Nickel or Nickel-Coated Copper	Aluminum or Copper-Clad Aluminum	
	Temperature Rating of Conductor[a]				
	302°F (150°C)	*392°F (200°C)*	*482°F (250°C)*	*302°F (150°C)*	
Size (AWG or kcmil)	*Type Z*	*Types FEP, FEPB, PFA*	*Types PFAH, TFE*	*Type Z*	*Size (AWG or kcmil)*
14	46	54	59	—	14
12	60	68	78	47	12
10	80	90	107	63	10
8	106	124	142	83	8
6	155	165	205	112	6
4	190	220	278	148	4
3	214	252	327	170	3
2	255	293	381	198	2
1	293	344	440	228	1
1/0	339	399	532	263	1/0
2/0	390	467	591	305	2/0
3/0	451	546	708	351	3/0
4/0	529	629	830	411	4/0
	Correction Factors[b]				
Ambient Temp. (°C)					*Ambient Temp. (°F)*
41–50	0.95	0.97	0.98	0.95	105–122
51–60	0.90	0.94	0.95	0.90	123–140
61–70	0.85	0.90	0.93	0.85	141–158
71–80	0.80	0.87	0.90	0.80	159–176
81–90	0.74	0.83	0.87	0.74	177–194
91–100	0.67	0.79	0.85	0.67	195–212
101–120	0.52	0.71	0.79	0.52	213–248
121–140	0.30	0.61	0.72	0.30	249–284
141–160	—	0.50	0.65	—	285–320
161–180	—	0.35	0.58	—	321–356
181–200	—	—	0.49	—	357–392
201–225	—	—	0.35	—	393–437

[a]See *NEC* Table 310.13.
[b]For ambient temperatures other than 104°F (40°C), multiply the allowable ampacities by the appropriate factor.
Source: NFPA 70, *National Electrical Code,* 2005 edition.

conductor can carry without overheating (Tables 8.13.1 through 8.13.8). Ampacity depends on size of the conductor; temperature of the environment in which the equipment is installed; type of insulation; and location where the conductors are installed, such as in a raceway, in a cable, in the earth, or in free air. Where the specified current is exceeded, the generation of heat causes deterioration of the electrical insulation and may ignite combustibles in contact with or close to the conductors. Apparatus or appliances that use electric conductors as heating elements or use an electric arc to generate heat (e.g., arc welders) can also be fire hazards if improperly installed and used.

The risk of an electrical fire can be reduced by using the proper size conductor for the load, suitable insulation for the environment, and the correct size overcurrent protection (fuse or circuit breaker). Where heat-generating equipment is utilized, the risk of fire can be further reduced by ensuring that sufficient clearances and air circulation are provided to prevent unsafe

TABLE 8.13.5 Allowable Ampacities of Insulated Conductors Rated 0 Through 2000 V, Not More Than Three Single Current-Carrying Conductors Supported on a Messenger, Based on Ambient Temperature of 104°F (40°C)

	Copper		Aluminum or Copper-Clad Aluminum		
	Temperature Rating of Conductor[a]				
	167°F (75°C)	*194°F (90°C)*	*167°F (75°C)*	*194°F (90°C)*	
Size (AWG or kcmil)	*Types RHW, THHW, THW, THWN, XHHW, ZW*	*Types MI, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2 XHHW, XHHW-2, ZW-2*	*Types RHW, THW, THWN, THHW, XHHW*	*Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2*	*Size (AWG or kcmil)*
8	57	66	44	51	8
6	76	89	59	69	6
4	101	117	78	91	4
3	118	138	92	107	3
2	135	158	106	123	2
1	158	185	123	144	1
1/0	183	214	143	167	1/0
2/0	212	247	165	193	2/0
3/0	245	287	192	224	3/0
4/0	287	335	224	262	4/0
250	320	374	251	292	250
300	359	419	282	328	300
350	397	464	312	364	350
400	430	503	339	395	400
500	496	580	392	458	500
600	553	647	440	514	600
700	610	714	488	570	700
750	638	747	512	598	750
800	660	773	532	622	800
900	704	826	572	669	900
1000	748	879	612	716	1000
	Correction Factors[b]				
Ambient Temp. (°C)					*Ambient Temp. (°F)*
21–25	1.20	1.14	1.20	1.14	70–77
26–30	1.13	1.10	1.13	1.10	79–86
31–35	1.07	1.05	1.07	1.05	88–95
36–40	1.00	1.00	1.00	1.00	97–104
41–45	0.93	0.95	0.93	0.95	106–113
46–50	0.85	0.89	0.85	0.89	115–122
51–55	0.76	0.84	0.76	0.84	124–131
56–60	0.65	0.77	0.65	0.77	133–140
61–70	0.38	0.63	0.38	0.63	142–158
71–80	—	0.45	—	0.45	160–176

[a]See *NEC* Table 310.13.
[b]For ambient temperatures other than 104°F (40°C), multiply the allowable ampacities by the appropriate factor.
Source: NFPA 70, *National Electrical Code,* 2005 edition.

TABLE 8.13.6 Ampacities of Two or Three Insulated Conductors, Rated 0 Through 2000 V, Within an Overall Covering (Multiconductor Cable), in Raceway in Free Air Based on Ambient Temperature of 86°F (30°C)

	Copper			Aluminum or Copper-Clad Aluminum			
	Temperature Rating of Conductor[a]						
	140°F (60°C)	*167°F (75°C)*	*194°F (90°C)*	*140°F (60°C)*	*167°F (75°C)*	*194°F (90°C)*	
Size (AWG or kcmil)	*Types TW, UF*	*Types RHW, THHW, THW, THWN, XHHW, ZW*	*Types THHN, THHW, THW-2, THWN-2, RHH, RWH-2 USE-2, XHHW, XHHW-2, ZW-2*	*Types TW, UF*	*Types RHW, THHW, THW, THWN, XHHW, ZW*	*Types THHN, THHW, THW-2, THWN-2, RHH, RWH-2 USE-2, XHHW, XHHW-2, ZW-2*	*Size (AWG or kcmil)*
14	16[b]	18[b]	21[b]	—	—	—	14
12	20[b]	24[b]	27[b]	16[b]	18[b]	21[b]	12
10	27[b]	33[b]	36[b]	21[b]	25[b]	28[b]	10
8	36	43	48	28	33	37	8
6	48	58	65	38	45	51	6
4	66	79	89	51	61	69	4
3	76	90	102	59	70	79	3
2	88	105	119	69	83	93	2
1	102	121	137	80	95	106	1
1/0	121	145	163	94	113	127	1/0
2/0	138	166	186	108	129	146	2/0
3/0	158	189	214	124	147	167	3/0
4/0	187	223	253	147	176	197	4/0
250	205	245	276	160	192	217	250
300	234	281	317	185	221	250	300
350	255	305	345	202	242	273	350
400	274	328	371	218	261	295	400
500	315	378	427	254	303	342	500
600	343	413	468	279	335	378	600
700	376	452	514	310	371	420	700
750	387	466	529	321	384	435	750
800	397	479	543	331	397	450	800
900	415	500	570	350	421	477	900
1000	448	542	617	382	460	521	1000
	Correction Factors[c]						
Ambient Temp. (°C)							*Ambient Temp. (°F)*
21–25	1.08	1.05	1.04	1.08	1.05	1.04	70–77
26–30	1.00	1.00	1.00	1.00	1.00	1.00	79–86
31–35	0.91	0.94	0.96	0.91	0.94	0.96	88–95
36–40	0.82	0.88	0.91	0.82	0.88	0.91	97–104
41–45	0.71	0.82	0.87	0.71	0.82	0.87	106–113
46–50	0.58	0.75	0.82	0.58	0.75	0.82	115–122
51–55	0.41	0.67	0.76	0.41	0.67	0.76	124–131
56–60	—	0.58	0.71	—	0.58	0.71	133–140
61–70	—	0.33	0.58	—	0.33	0.58	142–158
71–80	—	—	0.41	—	—	0.41	160–176

[a]See *NEC* Table 310.13.
[b]See *NEC* Section 240.3(D).
[c]For ambient temperatures other than 86°F (30°C), multiply the allowable ampacities by the appropriate factor.
Source: NFPA 70, *National Electrical Code,* 2005 edition.

TABLE 8.13.7 Ampacities of Multiconductor Cables with Not More Than Three Insulated Conductors, Rated 0 Through 2000 V, in Free Air Based on Ambient Temperature of 104°F (40°C) (For Types TC, MC, MI, UF and USE Cables)

	Copper				Aluminum or Copper-Clad Aluminum				
	Temperature Rating of Conductor[a]								
Size (AWG or kcmil)	*140°F (60°C)*	*167°F (75°C)*	*185°F (85°C)*	*194°F (90°C)*	*140°F (60°C)*	*167°F (75°C)*	*185°F (85°C)*	*194°F (90°C)*	*Size (AWG or kcmil)*
18	—	—	—	11	—	—	—	—	—
16	—	—	—	16	—	—	—	—	—
14	18[b]	21[b]	24[b]	25[b]	—	—	—	—	—
12	21[b]	28[b]	30[b]	32[b]	18[b]	21[b]	24[b]	25[b]	12
10	28[b]	36[b]	41[b]	43[b]	21[b]	28[b]	30[b]	32[b]	10
8	39	50	56	59	30	39	44	46	8
6	52	68	75	79	41	53	59	61	6
4	69	89	100	104	54	70	78	81	4
3	81	104	116	121	63	81	91	95	3
2	92	118	132	138	72	92	103	108	2
1	107	138	154	161	84	108	120	126	1
1/0	124	160	178	186	97	125	139	145	1/0
2/0	143	184	206	215	111	144	160	168	2/0
3/0	165	213	238	249	129	166	185	194	3/0
4/0	190	245	274	287	149	192	214	224	4/0
250	212	274	305	320	166	214	239	250	250
300	237	306	341	357	186	240	268	280	300
350	261	337	377	394	205	265	296	309	350
400	281	263	406	425	222	287	317	334	400
500	321	416	465	487	255	330	368	385	500
600	354	459	513	538	284	368	410	429	600
700	387	502	562	589	306	405	462	473	700
750	404	523	586	615	328	424	473	495	750
800	415	539	604	633	339	439	490	513	800
900	438	570	639	670	362	469	514	548	900
1000	461	601	674	707	385	499	558	584	1000
	Correction Factors[c]								
Ambient Temp. (°C)									*Ambient Temp. (°F)*
21–25	1.32	1.20	1.15	1.14	1.08	1.05	1.15	1.14	70–77
26–30	1.22	1.13	1.11	1.10	1.00	1.00	1.11	1.10	79–86
31–35	1.12	1.07	1.05	1.05	0.91	0.94	1.05	1.05	88–95
36–40	1.00	1.00	1.00	1.00	0.82	0.88	1.00	1.00	97–104
41–45	0.87	0.93	0.94	0.95	0.71	0.82	0.94	0.95	106–113
46–50	0.71	0.85	0.88	0.89	0.58	0.75	0.88	0.89	115–122
51–55	0.50	0.76	0.82	0.84	0.41	0.67	0.82	0.84	124–131
56–60	—	0.65	0.75	0.77	—	0.58	0.75	0.77	133–140
61–70	—	0.38	0.58	0.63	—	0.33	0.58	0.63	142–158
71–80	—	—	0.33	0.44	—	—	0.33	0.44	160–176

[a]See *NEC* Table 310.13.
[b]See *NEC* Section 240.3(D).
[c]For ambient temperatures other than 104°F (40°C), multiply the allowable ampacities by the appropriate factor.
Source: NFPA 70, *National Electrical Code,* 2005 edition.

temperatures and premature breakdown of electrical insulation or ignition of nearby combustibles.

All standards governing electrical equipment include requirements intended to prevent fires caused by arcing and overheating and to prevent accidental contact, which may cause an electric shock. These primary sources of electrical hazards should be kept in mind whenever any work is being done on electric equipment.

TABLE 8.13.8 Ampacities of Bare or Covered Conductors in Free Air, Based on 104°F (40°C) Ambient, 176°F (80°C) Total Conductor Temperature, 610 mm/sec (2 ft/sec) Wind Velocity

Copper Conductors				AAC Aluminum Conductors			
Bare		Covered		Bare		Covered	
AWG or kcmil	*Amperes*	*AWG or kcmil*	*Amperes*	*AWG or kcmil*	*Amperes*	*AWG or kcmil*	*Amperes*
8	98	8	103	8	76	8	80
6	124	6	130	6	96	6	101
4	155	4	163	4	121	4	127
2	209	2	219	2	163	2	171
1/0	282	1/0	297	1/0	220	1/0	231
2/0	329	2/0	344	2/0	255	2/0	268
3/0	382	3/0	401	3/0	297	3/0	312
4/0	444	4/0	466	4/0	346	4/0	364
250	494	250	519	266.8	403	266.8	423
300	556	300	584	336.4	468	336.4	492
500	773	500	812	397.5	522	397.5	548
750	1000	750	1050	477.0	588	477.0	617
1000	1193	1000	1253	556.5	650	556.5	682
—	—	—	—	636.0	709	636.0	744
—	—	—	—	795.0	819	795.0	860
—	—	—	—	954.0	920	—	—
—	—	—	—	1033.5	968	1033.5	1017
—	—	—	—	1272	1103	1272	1201
—	—	—	—	1590	1267	1590	1381
—	—	—	—	2000	1454	2000	1527

Notes:
1. This table is for Overhead Service and Feeder Drops.
2. AAC Aluminum Conductors are conductors which are All Aluminum 1350-H19 Conductors, not the AA-8000 Aluminum Alloy Conductors referenced in *NEC,* Section 310.14.

Source: NFPA 70, *National Electrical Code,* 2005 edition.

ORIGINS OF ELECTRICAL FIRES IN BUILDINGS

Table 8.13.9 provides an overview of structure fires reported to U.S. fire departments from 1994 through 1998 that were coded as caused by electrical failure. This table is limited to fires coded as involving a short circuit, a ground fault, or another electrical failure, so some relevant incidents are likely not counted. Other causes, some of which may include a mix of electrical failures with other fires, are not included. Also, these statistics reflect cause determinations by fire officers on the scene, so some errors of inclusion or exclusion may have occurred.

Electrically powered equipment is involved in several times this number of fires each year (Table 8.13.10, for example, shows total fires involving electrical distribution equipment), including nonelectrical-failure scenarios, such as installing or using equipment with hot surfaces too close to combustibles. Some of these nonelectrical-failure scenarios involve mechanical failure or some other type of equipment failure. But, in fact, even when equipment failure is a proximate cause, nearly all fires involving electrically powered equipment stem from foreseeable or avoidable human error, such as the following.

Improper Installation

Failure to follow manufacturer's installation instructions or to observe all provisions of the *NEC,* including the workmanship provisions, can result in equipment being installed in ways that will lead to overloading, damage to equipment, or excessive heating of nearby combustibles. Mismatching of wire gauge size with equipment wattage or overfusing (using a fuse of too high an amperage rating) are examples.

Lack of Maintenance

Equipment wears out in service. An example is the deterioration of electrical insulation over time. Deterioration can accelerate due to improper installation, excessive heat, adverse environmental conditions, or physical damage. Even when equipment and systems are properly installed, aging can cause deterioration; therefore, periodic inspection and maintenance of electrical equipment should be performed.

Improper Use

Listed equipment that is not installed in accordance with the manufacturer's instruction for its intended use and for the conditions under which it is used can cause fires or injure personnel.

TABLE 8.13.9 Structure Fires Due to Electrical Failure (Annual Average of 1994 Through 1998 Reported Fires)

Equipment Involved in Ignition	*Average Number of Fires per Year*
Heating Equipment	
Central heating unit	1,930
Water heater	1,280
Fixed space heater	1,110
Portable space heater	850
Cooking Equipment	
Stove	1,970
Oven	910
Portable cooking or warming unit	600
Air-Conditioning or Refrigeration Equipment	
Central air-conditioning or refrigeration equipment	940
Refrigerator	960
Fixed local air-conditioning unit	560
Portable air conditioning or refrigeration unit	540
Electrical Distribution Equipment	
Fixed wiring	15,030
Transformer	750
Meter or meter box	890
Power switch or overcurrent protection device (e.g., fuse, circuit breaker)	2,520
Switch, receptacle, or outlet	4,430
Light fixture, lampholder, ballast, or sign	4,890
Cord or plug	6,360
Lamp or lightbulb	740
Unclassified electrical distribution equipment	3,370
Appliance or Tool	
Television, radio, or phonograph	1,440
Dryer	2,310
Washing machine	750
Separate motor or generator	690
Portable appliance designed to produce controlled heat (e.g., iron, electric blanket)	1,120
Portable appliance not designed to produce controlled heat (e.g., can opener, electric razor)	550
Unclassified appliance or equipment	2,500
Special Equipment	
Electronic equipment (e.g., telephone, computer, x-ray)	620
Other	
Vehicle	450
No equipment involved	9,770
Other known equipment involved	5,270
Unknown equipment involved	5,580
Total	81,670

Notes: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Statistics include a proportional share of fires with ignition factors unknown or unreported. "Electrical failure" defined as Ignition Factor 54 (short circuit or ground fault) or 55 (other electrical failure). Numbers rounded to nearest ten. Sums may not equal totals because of rounding error. Individual types of equipment are shown if they accounted for at least 450 fires per year.

Source: National estimates based on NFIRS and NFPA survey.

TABLE 8.13.10 Structure Fires Originating with Specified Electrical Distribution Equipment (Annual Average of 1994 Through 1998 Reported Fires)

Equipment Involved in Ignition	*Average Number of Fires per Year*
Fixed wiring	17,800
Transformer	1,100
Meter or meter box	1,300
Power switch gear or overcurrent protection device (e.g., fuse or circuit breaker)	3,000
Switch, receptacle, or outlet	5,700
Light fixture, lampholder, ballast, or sign	8,900
Cord or plug	8,000
Lamp or lightbulb	3,900
Total	49,700

Notes: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Statistics include a proportional share of fires with equipment involved in ignition unreported or unknown. Numbers rounded to nearest hundred.

Source: Kimberly D. Rohr, *The U.S. Home Product Report (Appliances and Equipment Involved in Fires),* NFPA Fire and Analysis Division, Quincy, MA, Jan. 2002.

Use of equipment listed for dry locations, but installed in damp or wet locations, or general-purpose equipment installed in locations where flammable liquids are used can be sources of ignition. Cords installed in traffic areas or pinched against a wall can be damaged and lead to overheat fires. Lightbulbs with higher wattage than the fixture is rated for can overheat and ignite lamp shades. Many other examples exist.

Carelessness or Oversight

Even momentary lapses of caution in the use of equipment can cause fires. Failure to turn off devices (e.g., space heaters) when no longer needed, dropping combustible objects into equipment, and draping combustible materials over operating equipment (e.g., clothes on a lamp) are all examples.

Some special studies provide additional insights that go beyond the level of detail in Table 8.13.9, although no other sources of representative national fire statistics exist. These studies include the annual tabulations by the International Association of Electrical Inspectors (IAEI) of fire and shock incidents that come to their attention and the several field studies done by the U.S. Consumer Product Safety Commission (CPSC). These studies appear to support a few qualitative observations:

- Many electrical cord fires involve extension cords, as opposed to lamp or other appliance power cords. This fact indicates that extension cords are probably overused as semipermanent extensions of building wiring systems.
- Overcurrent protection device fires appear to involve circuit breakers more often than fuses, both overall and relative to

the degree of use of each type of device. This is notable given that fuses are used primarily in much older homes, where deterioration due to age or damage due to system alterations would be more likely, and that fuses are more susceptible to tampering.

- Color televisions pose a greater fire hazard than black-and-white televisions due to differences in the energy usage of the two types.

CODES AND STANDARDS

All electrical installations in the United States should be made, used, and maintained in accordance with the *NEC* and other National Fire Protection Association (NFPA) standards that apply in special situations—for example, NFPA 70E, *Standard for Electrical Safety in the Workplace;* NFPA 75, *Standard for the Protection of Information Technology Equipment;* NFPA 79, *Electrical Standard for Industrial Machinery;* and NFPA 99, *Standard for Health Care Facilities.* There are also special standards for electrical installations on marine vessels, on aircraft, in hazardous (classified) locations, and in other locations.

National Electrical Code (ANSI/NFPA 70)

The *NEC* provides for the practical safeguarding of persons and property from hazards arising from the use of electricity. The *NEC* was first issued under its present name in 1897. It is revised every three years by the National Electrical Code Committee.

National Electrical Safety Code (ANSI C2)

As interest increased in electrical safety in the United States, a need arose for a code to cover the practices of public utilities and others when installing and maintaining overhead and underground electric supply and communications lines. Accordingly, the first edition of the *National Electrical Safety Code* (*NESC*) was completed in 1916. This code is updated and published by the Institute of Electrical and Electronics Engineers (IEEE).

Canadian Electrical Code

CSA International (CSA) sponsors and publishes the *Canadian Electrical Code (CEC).* This code establishes essential requirements and minimum standards for the installation and maintenance of electrical equipment in Canada. It can be adopted and enforced by electrical inspection departments throughout Canada and was prepared with due regard for the *NEC* and the *NESC.* Its several parts are the Canadian equivalent of the *NEC,* the *NESC,* and the standards of Underwriters Laboratories Inc. (UL) in the United States.

The *National Electrical Code® Handbook*

Although not itself a code or standard that can have the force of law, the *National Electrical Code® Handbook* is a valuable resource in implementing provisions of the *NEC.* The *NEC Handbook* contains the entire text of the *NEC,* supplemented by comments, diagrams, examples, and illustrations that are intended to clarify and explain some of the intricate requirements of the *NEC.* The *NEC Handbook* is published by the NFPA; a new edition is published with each new edition of the *NEC.*

Listed and Labeled Electrical Equipment Manufacturers

Publications are available that list the names of companies making electric appliances and materials that have been listed or labeled by nationally recognized testing laboratories, such as UL, Intertek Testing Services, and other testing laboratories. Devices and materials in the product categories listed have been tested for actual field use in accordance with the *NEC* and against other American National Standards Institute (ANSI) safety standards. The lists are published so that the names of manufacturers of devices that meet test criteria may be readily obtained. UL publishes the *Hazardous Location Equipment Directory,* the *Electrical Appliance and Utilization Equipment Directory,* and the *Electrical Construction Materials Directory.* UL also publishes the *Fire Resistance Directory,* which includes a number of listed methods of protecting penetration of building assemblies, such as walls or floors. They are all published annually by UL with six-month supplements. Certain types of electrical equipment are covered in other testing laboratory directories, such as the *Marine Products Directory.*

There are sections of the *NEC* that influence the design and construction of electric equipment. Most testing labs have complete published standards for most electric fittings, materials, and equipment, including specifications for performance under test conditions and in actual service and further details of design and construction. Other testing laboratories in the United States and Canada that test electric equipment include Factory Mutual Research Corporation (FMRC); U.S. Testing; Applied Research Laboratories; Dash, Straus, and Goodhue; and CSA. Some laboratories stipulate compliance with the *NEC* in testing equipment. (Where no published standards are available for special equipment, arrangements usually can be made with testing laboratories for field testing on an individual basis.)

BUILDING WIRING, DESIGN, AND PROTECTION

This section contains information on various types of building wiring and electrical equipment, including panelboards and overcurrent protection; types of electric conductors; identification of conductors, terminals, and so on; how to calculate loads; and similar subjects.

Service Entrance

Good practice requires that service entrance conductors comply in all respects with the detailed requirements of Article 230 of the *NEC.* Figure 8.13.1 provides typical arrangements of service entrance conductors.

The basic requirement is that a building or other structure can be supplied by only one service. Where more than one service is allowed, however, a permanent plaque or directory that describes all the other services to the building and the area served by each is required to be installed at each service drop

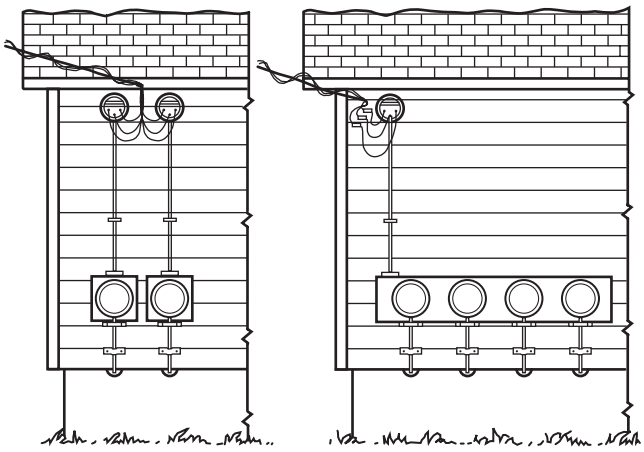

FIGURE 8.13.1 (a) Two Sets of Service Entrance Conductors Tapped from One Service Drop, with Meters Mounted on Outside of Building; (b) Set of Main Service Entrance Conductors Connected to Service Drop and Carried Through a Trough and Through Four Sets of Subservice Entrance Conductors to Each Service Equipment, with Meters Mounted on Outside of Building

or lateral or at each service equipment location. This plaque or directory should be sufficiently durable to withstand the ambient environment.

Where separate services are permitted, such as for fire pumps, emergency or legally required standby electrical systems, optional standby electrical systems, or parallel power production systems, six additional switches or circuit breakers are allowed, in addition to the six service disconnects normally allowed. The intent here is that a disruption of the main building service will not interfere with the operation of fire pump equipment, emergency or legally required standby electrical systems, optional standby electrical systems, or parallel power production systems.

Special permission is required for the installation of more than one service. Expansion of buildings, shopping centers, or industrial plants often necessitates the addition of one or more new services. It may, for example, be impractical or impossible to install one service for an industrial plant with capacity requirements to compensate for any and all future load requirements. It is also impractical to run feeders for extremely long distances, because of high costs and voltage drop problems.

More than one service is allowed for different characteristics, such as different voltages, frequencies, single-phase or three-phase services, or different utility rate schedules. For example, different service characteristics exist between a three-wire, 120/240-V single-phase service and a three-phase, four-wire, 480Y/277-V service. For different rate schedules, a second service is allowed to supply a second meter for specific equipment, such as an electric water heater.

Parallel underground conductors, 1/0 AWG or larger that are connected together at their supply end and at their load end, are considered to be *one* service lateral. These conductors are permitted to supply up to six service disconnecting means installed at one location in a group, as required by *NEC* Section 230.71(A).

All feeder and branch-circuit conductors must be separated from service conductors. Service conductors are not provided with overcurrent protection where they receive their supply; they are protected against overload conditions at their load end by the service disconnect fuses or circuit breakers. The amount of current that could be imposed on feeder or branch circuit conductors, should they be in the same raceway and a fault occurs, would be much higher than the ampacity of the feeder or branch-circuit conductors.

The *NEC* requires that means be provided for disconnecting all conductors in the building from the service entrance conductors. The object is to permit disconnection of all conductors of the service at that location with no more than six operations of the hand (Figure 8.13.2). This requirement applies to all of the service disconnecting means located, or grouped, in one place and each disconnect must be marked to indicate the load served. It does not include service disconnecting means for fire pumps, legally required standby services, or optional standby services, which the *NEC* recognizes as being separate services for specific purposes. These must be sufficiently remote from the one to six service disconnecting means for normal service to minimize the possibility of simultaneous interruption of supply to the building or structure.

The disconnecting means can be either outside or inside the building served and must be at a readily accessible location nearest the point of entrance of the service entrance conductors. It cannot be in a bathroom. A remote-control device may be used to actuate the service disconnecting means, if it is located in a readily accessible location. Service entrance conductors must be of sufficient size to carry the calculated load.

No maximum distance is specified from the point of entrance of the service conductors to the service disconnecting means. The authority enforcing the *NEC* has the responsibility for, and is charged with, deciding how far inside the building the service entrance conductors are allowed to travel before reaching the main disconnecting means.

The length of service entrance conductors should be kept to a minimum inside buildings, because power utilities provide limited overcurrent protection and, in the event of a "fault," the

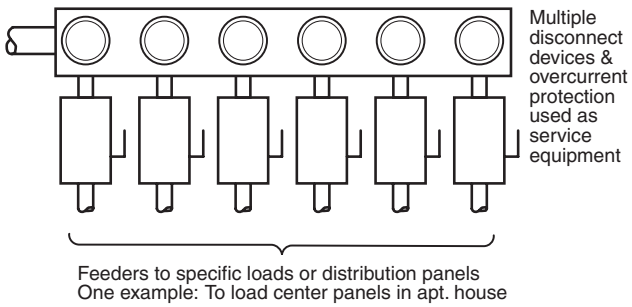

FIGURE 8.13.2 Typical Layout for Multiple Disconnecting Means

service conductors could ignite nearby combustible materials. Some local jurisdictions have ordinances that allow service entrance conductors to run within the building up to a specified length to terminate at the disconnecting means. The authority having jurisdiction (AHJ) may permit service conductors to pass by fuel storage tanks or gas meters to permit the service disconnecting means to be located in a readily accessible location. However, if the authority judges the distance to be excessive, the disconnecting means may be required to be located on the outside of the building or near the building at a readily accessible location that is not necessarily nearest the point of entrance of the conductors.

One set of service entrance conductors, either overhead or underground, is permitted to supply two to six service disconnecting means in lieu of a single main disconnect. A single-occupancy building can have up to six disconnects for each set of service entrance conductors. Multiple-occupancy buildings (residential or other than residential) can be provided with one main service disconnect or up to six main disconnects for each set of service entrance conductors.

Multiple-occupancy buildings may also have service entrance conductors run to each occupancy, with each such set of service entrance conductors having from one to six disconnects.

Where service entrance conductors are routed outside the building, each set of service entrance conductors is permitted to supply not more than six disconnecting means at each occupancy of a multiple-occupancy building. Conductors are considered outside a building where installed under not less than 2 in. (50 mm) of concrete beneath a building or in a raceway encased by 2 in. (50 mm) of concrete or brick within a building. They are also considered outside the building where installed in a transformer vault (Figure 8.13.3).

Service entrance conductors, overhead or underground, are the supply conductors between the point of connection to the service drop or service lateral conductors and the service equipment. Service equipment is intended to constitute the primary means of controlling and disconnecting the electrical supply to the premises' wiring system. At this point, an overcurrent device, which usually consists of circuit breakers or a set of fuses, is required to be installed in series with each ungrounded service conductor.

The service overcurrent device will not protect the service conductors under conditions of short circuit or ground fault on the line side of the disconnect. A degree of protection under these overcurrent conditions is provided by the special requirements applicable to locating and physically protecting the service conductors.

Figure 8.13.4 illustrates the wiring and components of a fire pump circuit designed to comply with the *NEC* and NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection.* Note that the service head protects the conductors

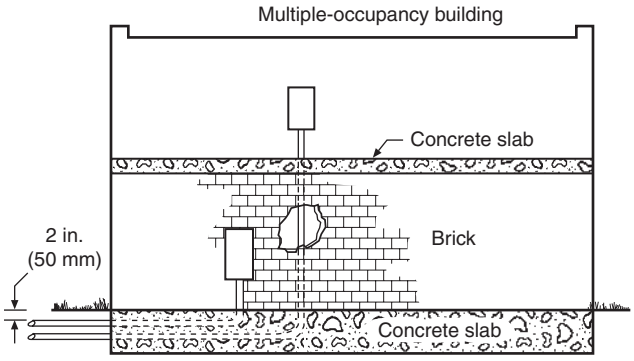

FIGURE 8.13.3 Conductors Installed Under Concrete Beneath a Building or in a Raceway of Concrete or Brick Within a Building

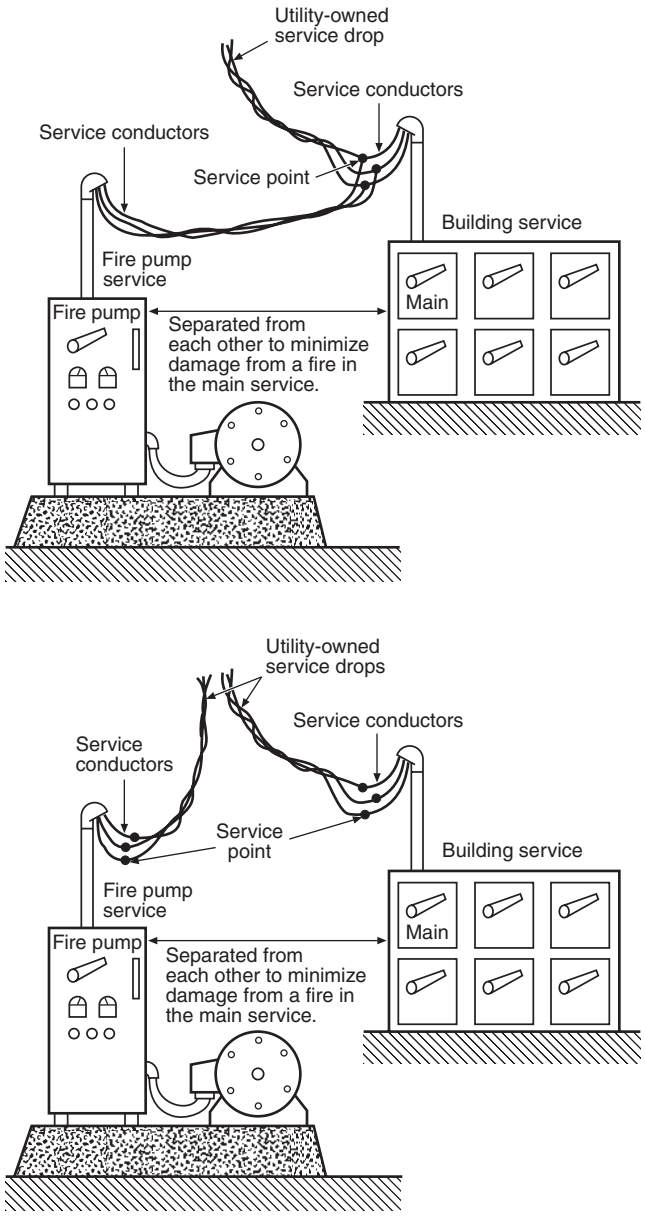

FIGURE 8.13.4 Methods of Connecting Utility-Owned Service Drop Conductors to the Service Entrance Conductors Supplying the Building and Fire Pump Services

against the entrance of water and that the point of connection of the service entrance conductors is below the level of the service head. The pump motor represented is a 100-hp, 460-V, three-phase, squirrel-cage induction type, and its full-load current, taken from *NEC* Table 430.250, is 124 A.

The service conductors, feeder conductors, and branch-circuit conductors are sized for 125 percent of the motor's full-load current rating (124 A at 125 percent = 155 A). According to *NEC* Table 310.16, the appropriate copper wire size for 155 A is a 2/0 AWG, XHHW conductor, which has an allowable ampacity of 175 A; therefore, all the conductors would be sized at not less than 2/0 AWG, XHHW copper. Where the voltage drop at the controller under starting conditions exceeds 15 percent, conductors with an ampacity greater than 155 A are necessary. The locked-rotor current of the motors in the installations illustrated in Figure 8.13.4 is 725 A, derived from *NEC* Table 430.51(B). The power supply protection may consist of either fuses or circuit breakers sized to carry locked-rotor current. In either case, the next standard ampere rating for fuses or circuit breakers is 800 A. Most fire pumps rated 100 hp and over would require a disconnecting means rated at 1000 A or more. However, due to the emergency nature of their use, fire pumps are exempt from the following ground-fault provisions.

Ground-Fault Protection for Equipment (GFP)

Ground-fault protection of equipment (GFP) should not be confused with ground-fault circuit-interrupter protection for personnel (GFCI). Ground-fault protection of equipment on services rated 1000 A or more, operating at 480Y/277 V, was first required in the 1971 *NEC* because of the unusually high number of burndowns that were reported for this type of service. Alternating current, due to its sine wave characteristics, can be a dangerous source of ignition that can ignite combustibles and start a fire. Where the voltage is greater than 250 V to ground, even though the voltage sine wave decreases to zero, the voltage can cause a restrike of the arc, causing continuation of burning at the ground-fault location.

Ground-fault protection of services will not protect the conductors on the supply side of the service disconnecting means, but is designed to provide protection from line-to-ground faults that occur on the load side of the service disconnecting means. An alternative to installing ground-fault protection may be to provide multiple disconnects rated less than 1000 A. For instance, up to six 800 A disconnecting means may be used, and, in this case, ground-fault protection would not be required. The second fine print note (FPN) in *NEC* Section 230.95(C) recognizes that ground-fault protection may be desirable at lesser amperages on solidly grounded systems for voltages exceeding 150 V to ground, but not exceeding 600 V phase-to-phase.

The maximum setting for ground-fault sensors is 1200 A; however, there is no minimum, and it should be noted that setting at lower levels increases the likelihood of nuisance tripping. The *NEC* requirements place a restriction on fault currents greater than 3000 A and limit the duration of the fault to not more than 1 second. This limit will minimize the amount of damage done by an arcing ground fault, which is directly proportional to the time it is allowed to burn.

Where interconnection is made between multiple-supply systems or multiple buildings, care should be taken to ensure that the interconnecting of different systems or buildings does not negate the proper ground-fault sensing by the ground-fault protection equipment. A careful engineering study should be made to ensure that fault currents do not take parallel paths back to the supply system, thereby bypassing the ground-fault detection device.

Physical Protection

Underground service conductors must be protected against physical damage (Figure 8.13.5). Tables 8.13.11 and 8.13.12 give minimum cover requirements for underground installations. (Cover is defined as the shortest distance in millimeters measured between a point on the top surface of any direct buried conductor, cable, conduit, or other raceway and the top surface of finished grade, concrete, or similar cover.)

For circuits over 600 V, there are variations in burial depths shown in Table 8.13.12, under certain circumstances. For example, the burial depth beneath areas subject to vehicular traffic is 24 in. (600 mm). Under airport runways and adjacent areas, the burial depth must be a minimum of 18 in. (450 mm). Lesser burial depths are permitted where access is necessary, or where termination or splicing points are located.

Lightning (Surge) Arresters—Building Wiring

Lightning and surge arresters are not required but may be used, particularly where buildings are supplied by an overhead service and where thunderstorms are prevalent in the area. (See NFPA

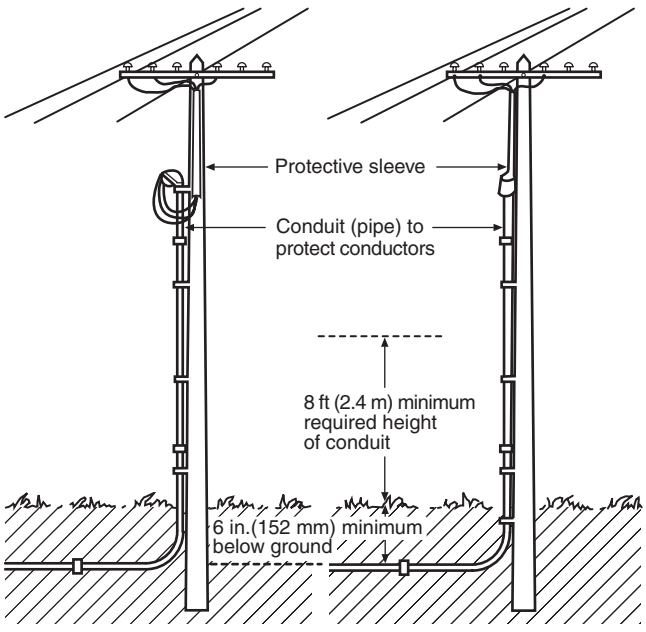

FIGURE 8.13.5 Two Different Configurations Permitted for Connecting to Electric Utility–Owned Service Drops

TABLE 8.13.11 Minimum Cover Requirements, 0 to 600 V, Nominal, Burial in Inches (Millimeters)

	Type of Wiring Method or Circuit									
	Column 1 Direct Burial Cables or Conductors		Column 2 Rigid Metal Conduit or Intermediate Metal Conduit		Column 3 Nonmetallic Raceways Listed for Direct Burial Without Concrete Encasement or Other Approved Raceways		Column 4 Residential Branch Circuits Rated 120 Volts or Less with GFCI Protection and Maximum Overcurrent Protection of 20 Amperes		Column 5 Circuits for Control of Irrigation and Landscape Lighting Limited to Not More Than 30 Volts and Installed with Type UF or in Other Identified Cable or Raceway	
Location of Wiring Method or Circuit	*in.*	*mm*	*in.*	*mm*	*in.*	*mm*	*in.*	*mm*	*in.*	*mm*
All locations not specified below	24	600	6	150	18	450	12	300	6	150
In trench below 2-in. (50-mm) thick concrete or equivalent	18	450	6	150	12	300	6	50	6	50
Under a building	0 (in raceway only)	0	0	0	0	0	0 (in raceway only)	0	0 (in raceway only)	0
Under minimum of 4-in. (102-mm) thick concrete exterior slab with no vehicular traffic and the slab extending not less than 6 in. (152 mm) beyond the underground installation	18	450	4	100	4	100	6 (direct burial) 4 (in raceway)	150 100	6 (direct burial) 4 (in raceway)	150 100
Under streets, highways, roads, alleys, driveways, and parking lots	24	600	24	600	24	600	24	600	24	500
One- and two-family dwelling driveways and outdoor parking areas, and used only for dwelling-related purposes	18	450	18	450	18	450	12	300	18	450
In or under airport runways, including adjacent areas where trespassing is prohibited	18	450	18	450	18	450	18	450	18	450

Notes:
1. Raceways approved for burial only where concrete encased shall require concrete envelope not less than 2 in. (50 mm) thick.
2. Lesser depths shall be permitted where cables and conductors rise for terminations or splices or where access is otherwise required.
3. Where one of the wiring method types listed in columns 1–3 is used for one of the circuit types in columns 4 and 5, the shallower depth of burial shall be permitted.
4. Where solid rock is encountered, all wiring shall be installed in metal or nonmetallic raceway permitted for direct burial. The raceways shall be covered by a minimum of 2 in. (50 mm) of concrete extending down to rock.

Source: NFPA 70, *National Electrical Code,* 2005 edition.

TABLE 8.13.12 Over 600 V, Minimum Cover Requirements

					(4) Rigid Metal Conduit and Intermediate Metal Conduit									
(1) *Circuit Voltage*	(2) Direct Buried Cables		(3) Rigid Nonmetallic Conduit Approved for Direct Burial and Not Under a Building*		(5) All Locations Not Otherwise Specified		(6) Under a Building (Including Rigid Nonmetallic Conduit Approved for Direct Burial)		(7) Under Minimum of 4 in. (102 mm) Thick Concrete Exterior Slab with No Vehicular Traffic and the Slab Extending Not Less Than 6 in. (152 mm) Beyond the Underground Installation (Including Rigid Nonmetallic Conduit Approved for Direct Burial)		(8) Under Streets, Highways, Roads, Alleys, Driveways, and Parking Lots		(9) In or Under Airport Runways, Including Adjacent Areas Where Trespassing Is Prohibited	
	in.	*mm*	*in.*	*mm*	*in.*	*mm*	*in.*	*mm*	*in.*	*mm*	*in.*	*mm*	*in.*	*mm*
Over 600 V through 22 kV	30	750	18	450	6	150	0	0	0	0	24	600	18	450
Over 22 kV through 40 kV	36	900	24	600	6	150	0	0	0	0	24	600	18	450
Over 40 kV	42	1000	30	750	6	150	0	0	0	0	24	600	18	450

*Listed by a qualified testing agency as suitable for direct burial without encasement. All other nonmetallic systems require 2 in. (50 mm) of concrete or equivalent above conduit in addition to above depth.

Source: NFPA 70, *National Electrical Code,* 2005 edition.

780, *Standard for the Installation of Lightning Protection Systems*). Surge arresters are required to be installed on electric and telephone services and on radio and television antenna lead-ins. Installation of such devices serves to minimize damage to solid-state electronic equipment, because such equipment is very sensitive to voltage surges.

Each lead-in from an outdoor antenna to a radio or television set or to an amateur radio transmitting station needs protection from lightning. Antenna discharge units should be installed to provide lightning protection for the equipment. Additional protection from power line surges or from connected communications equipment may also be desirable.

Grounding Requirements—Building Wiring

Dangerous voltages that constitute a fire hazard and a personal injury (shock) hazard can be imposed on electric distribution systems and equipment by lightning, inadvertent contact between low-voltage conductors and a high-voltage primary system, breakdown of insulation in transformers, surface leakage due to dirt or moisture, or by a wire coming loose from its connection.

Grounding one conductor of the electrical system and then grounding all exposed noncurrent-carrying metal parts of the electrical installation that might accidentally come in contact with an ungrounded circuit conductor ensures that a low-resistance path is provided for fault current to actuate the fuse or circuit breaker. The fault current finds a path through the equipment grounding conductor and can cause the operation of an overcurrent device (fuse or circuit breaker) in the ungrounded circuit conductor, thereby eliminating the dangerous condition. The impedance of the fault path must be low enough to permit sufficient current flow to cause the overcurrent device to operate quickly.

The metal enclosures of conductors (metal armor of cables, metal raceways, boxes, cabinets, and fittings) must be grounded. (Article 250 of the *NEC* contains general requirements for grounding electrical installations.) The *NEC* also requires

grounding of exposed noncurrent-carrying metal parts of equipment likely to become energized, where the equipment is operated by persons standing on the ground or on metal surfaces, or where it is operated at more than 150 V to ground. In some cases, the metal frames of electrically heated appliances should also be grounded. The *NEC* also specifies grounding of cord- and plug-connected appliances. These appliances include refrigerators, freezers, air conditioners, clothes washers and dryers, dishwashers, sump pumps, electric aquarium equipment, and portable handheld motor-operated tools—for example, hedge clippers, lawn mowers, snow blowers, and wet scrubbers. Appliances may be exempt from grounding if equivalent protection via double insulation is provided.

If available on the premises at each building or structure served, each item in *NEC* Section 250.52(A)(1) through (A)(6) must be bonded together to form the grounding electrode system. Where none of these electrodes is available, one or more of the electrodes specified in *NEC* Section 250.52(A)(4) through (A)(7) must be used.

A metal underground water pipe with at least 10 ft (3.0 m) of pipe in direct contact with the earth can be used as the grounding electrode (including any metal well casing effectively bonded to the pipe). Interior metal water piping more than 5 ft (1.5 m) from the point of entrance to the building is not allowed to be used as part of the grounding electrode system or as a conductor to interconnect electrodes that are part of the grounding electrode system. However, a metal underground water pipe grounding electrode must be supplemented by an additional electrode of the type specified in *NEC* Section 250.52(A)(2) through (A)(7), in the event that the metal water pipe is replaced by a nonmetallic pipe, thereby maintaining the integrity of the grounding electrode system.

Electrodes permitted for grounding are listed in the *NEC,* Section 250.52(A), and they are (1) metal underground water pipe, (2) metal frame of the building or structure, (3) concrete-encased electrode, (4) ground ring, (5) rod and pipe electrode, (6) plate electrode, and (7) other local metal underground systems or structures.

An example of a grounding electrode is shown in Figure 8.13.6. Piping should be inspected to ensure that there are no intervening insulating joints that might isolate it from the earth. Effective bonding jumpers must be provided around any insulated joints and sections and around any equipment that is likely to be disconnected for repairs or replacement.

Figure 8.13.6 shows an electrical system service neutral conductor grounded by connection to a metal water pipe and supplemented with a driven ground rod. The metal parts of the service equipment are allowed to be grounded by bonding to the neutral (grounded) conductor. The service enclosure is bonded to the grounded neutral conductor at point "B." This connection is often a removable strap or green-colored screw. The service raceway (conduit) is grounded through the metal of the panelboard. Because service equipment is not protected by an overcurrent device, a bonding jumper is one of the methods employed to ensure electrical continuity at service equipment; this electrical connection is indicated at "A." The meter box on the line side of the service equipment is usually grounded by means of the neutral terminal being bonded directly to the meter box and would be required where service-entrance cable is used. The upper portion of the service raceway or cable is grounded through threaded connections to the meter box where metal conduit or electrical metallic tubing is used. The conduit between the meter and panelboard may be grounded by bonding to the meter enclosure or bonding to the panelboard. The branch circuit equipment grounding conductor is connected to ground through the equipment grounding terminal block, which is grounded at point "C." This connection is commonly the mounting screw for this terminal block. The grounding connection shown is an underground water piping system. The connection should be as required by the *NEC.*

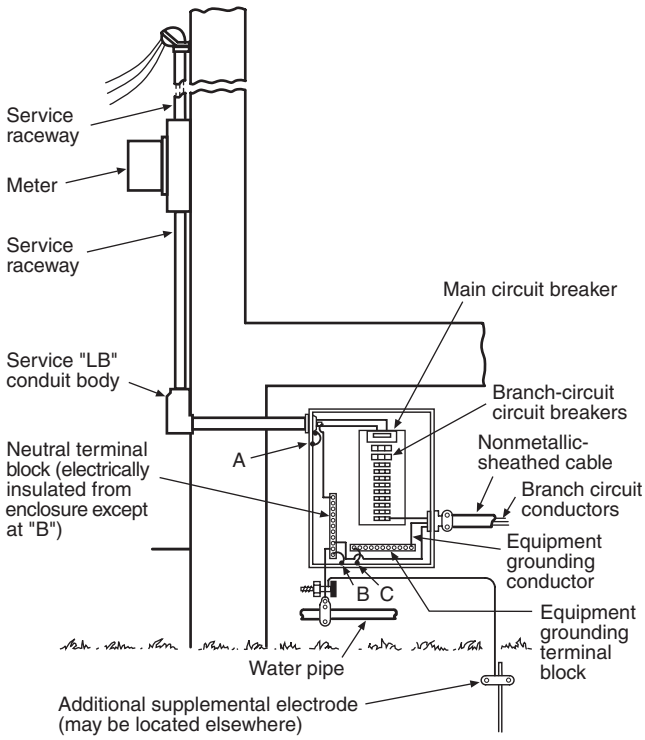

FIGURE 8.13.6 Grounding at a Typical Small Service (ac, Single-Phase, Three-Wire [120/240 V])

Panelboards and Overcurrent Protection—Building Wiring and Equipment

Panelboards. A panelboard consists of an assembly that may include switches, fuses, or circuit breakers that are mounted on copper or aluminum bus-bars, whose function is the control and protection of light, heat, or power circuits. The buses are mounted in a cabinet or cutout box, which may be placed in or on a wall and is accessible only from the front.

The *NEC* does not allow a lighting and appliance branch-circuit panelboard to have more than 42 overcurrent devices installed in any one cabinet or cutout box. Lighting and appliance panelboards are not allowed to have more than two main circuit breakers or two main sets of fuses to protect the buses in a lighting and branch-circuit panelboard (Figures 8.13.7 and 8.13.8). Figures 8.13.9 and 8.13.10 show exceptions to the general rule

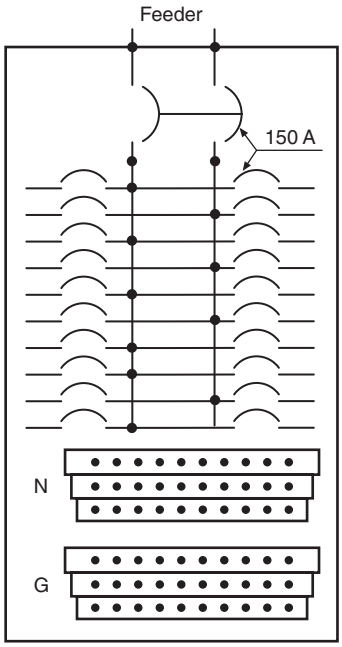

FIGURE 8.13.7 One Main Provided (Two Permitted). Grounding terminal block may not be required, depending on wiring system used.

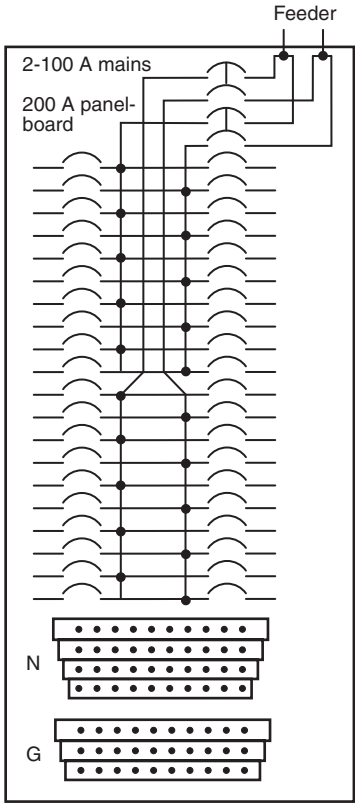

FIGURE 8.13.8 Two Mains Required. Grounding terminal block may not be required, depending on wiring system used.

for individual protection of panelboards. The arrangement shown in Figure 8.13.10 is acceptable only for the service to an existing individual residential occupancy where the panelboard was installed prior to application of the 1981 *NEC* requirements.

Panelboards installed in wet locations need weatherproof cabinets and must be mounted so that there is at least ¼ in. (6 mm) of airspace between the cabinet and the wall or other

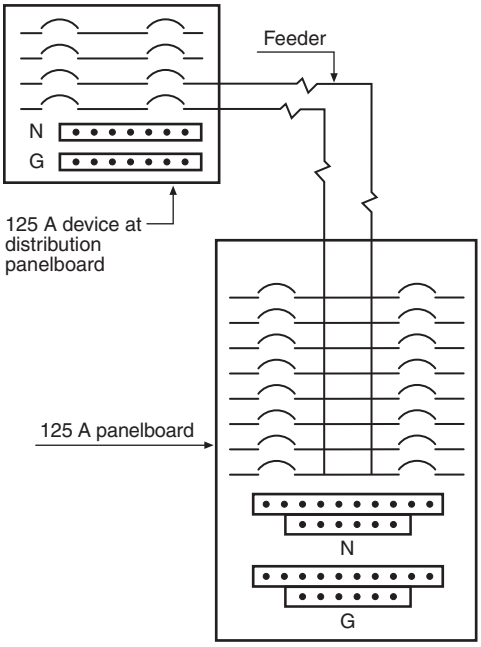

FIGURE 8.13.9 No Mains Required. Grounding terminal block may not be required, depending on wiring system used.

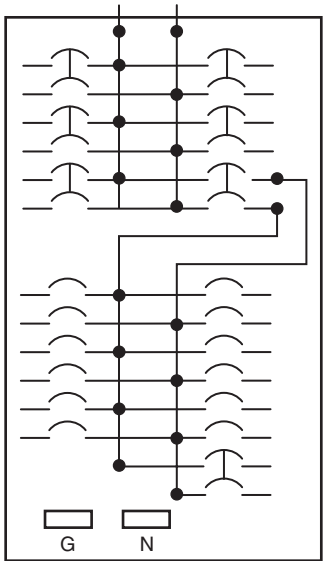

FIGURE 8.13.10 One Service Circuit Breaker in Upper Section Serving as the Main for Lower Section Buses Supplying Branch Circuits

supporting surface. Where located in corrosive atmospheres, equipment must be suitable for the conditions. Special requirements in Chapter 5 of the *NEC* govern installation of panelboards in hazardous (classified) locations.

Overcurrent Protection. Conductors are provided with overcurrent protection to open the circuit, if the current is greater than the value that will cause the conductor's temperature to exceed the temperature of its insulation. Equipment also needs overcurrent protection to minimize the effects of an electrical fault within the equipment, thereby reducing the amount of arcing and ejection of hot metal. No feature of an electrical installation deserves more careful attention and supervision. In general, overcurrent devices should be rated or set in accordance with the tables for conductor ampacity, as shown in Tables 8.13.1 through 8.13.8. They should be installed in each ungrounded conductor of each circuit and feeder, at the point where the conductor to be protected receives its supply. Fixture wires, cords, taps, motor circuits, remote-control circuits, and fire-protective signaling circuits are covered in Articles 240, 430, 725, and 760 of the *NEC*.

Overcurrent Protective Devices

The most commonly used overcurrent protective devices for feeders, circuits, and equipment are fuses and circuit breakers. (Overcurrent and undervoltage relays, and so on, are used on high-voltage, high-current systems.) Thermal motor running overload sensing devices are not considered to be overcurrent protection but are used in the same manner.

Plug Fuses. There are two basic types of plug fuses: (1) the ordinary Edison-base type and (2) the Type S. Either of these may incorporate time delay. An Edison-base fuseholder will take an Edison-base fuse of any size up to a maximum 30 A rating. Plug fuses of the Edison-base type are allowed only for replacements in existing installations where there is no evidence of tampering.

The Type S fuse is designed to minimize tampering or bridging. Adapters are available that fit the Edison-base fuseholders and that, once properly installed, cannot be removed without damaging the fuseholder. The adapters are designed to prevent the use of Edison-base fuses in the fuseholder and to prevent the use of a higher rated Type S fuse in an adapter designed for a lower rating. They also prevent the use of pennies and other common bypassing schemes.

Time-Delay Plug Fuses. Whether of Type S or Edison-base design, time-delay fuses permit short-time current surges, such as motor starting currents, without interruption of the circuit. These momentary surges are harmless unless repeated a number of times at short intervals. This function makes it possible to use Type S fuses in sizes small enough to give better protection than a non-time-delay type, which must be oversized to allow for such surges. In the case of a short circuit or a high-current fault, however, the time-delay type will operate and open the circuit as rapidly or even more rapidly than the non-time-delay type. A representative plug fuse is shown in Figure 8.13.11. The

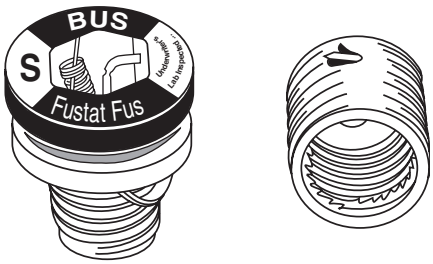

FIGURE 8.13.11 Type S Nonrenewable Fuse (Source: Cooper Bussman)

time-lag type of fuse shown in Figure 8.13.11 is acceptable but not required by the *NEC*. These fuses have been designed to minimize tampering or bridging. The *NEC* specifies that fuseholders for plug fuses of 30 A or less must not be used unless they are designed to accept a Type S fuse or to accept a Type S fuse through use of an adapter.

Cartridge Fuses. Cartridge fuses are of both the time-delay and the non-time-delay types. They are also of the one-time and the renewable link types. When a one-time fuse opens, the entire fuse must be replaced. But when a renewable link fuse opens, the fuse link can be replaced inside the same cartridge unless the cartridge has also been damaged.

Renewable link fuses have two disadvantages: (1) the links can be doubled, tripled, and so on, thereby defeating their purpose and usefulness; and (2) the links, on replacement, can be left with loose connections. A representative cartridge fuse is shown in Figure 8.13.12.

Circuit Breakers. There are two basic types of breakers: (1) adjustable trip and (2) nonadjustable trip. The adjustable-trip type may be of either the air- or oil-immersed type. The setting of the trip point is adjustable between a minimum and a maximum range. This type is usually used only on large installations having qualified operators and maintenance personnel. They are designed to trip when the current reaches that of the setting. The nonadjustable-trip type comes in a molded case, making it extremely difficult or impossible to change its rating. A

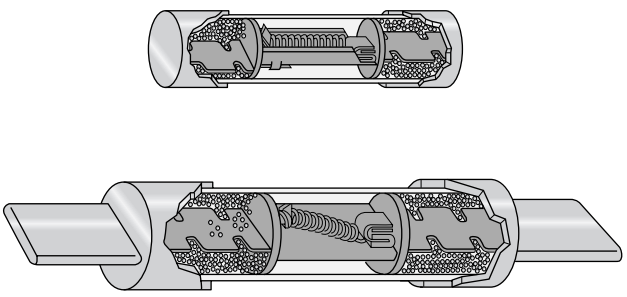

FIGURE 8.13.12 A Fusetron Cartridge-Type Fuse (Source: Cooper Bussman)

molded-case breaker can be of the inverse-time thermal-magnetic type or of the magnetic-only inverse-time type. Inverse-time thermal-magnetic breakers consist of two elements: (1) an electro-magnetic trip element that trips quickly on high fault current and (2) a bimetallic trip element that provides a time delay. Molded-case circuit breakers are designed so that the current has to exceed the rating (as is also true with all types of fuses) before it will trip. Unless it is the thermally compensated type, high ambient temperatures can reduce the current required to trip the circuit breaker (or fuse). A representative nonadjustable circuit breaker is shown in Figure 8.13.13.

Thermal Devices. These are not intended for protection against short circuits, but only for the protection of overload currents of a comparatively lower magnitude unless otherwise designed. An example is overload protection for a motor where short-circuit and ground-fault protection is provided by the branch-circuit fuses or circuit breakers and motor running overload protection is provided by the thermal relay. Another thermal device is the type used in recessed luminaires (lighting fixtures), which temporarily opens the circuit when the luminaire (fixture) exceeds a predetermined temperature. For detailed requirements for motors and other equipment, see Articles 410 and 430 of the *NEC*.

Current-Limiting Overcurrent Protective Devices. These devices are provided in some installations where high current (more than 10,000 A) is available under short-circuit conditions. They are designed so that, when interrupting a specified current, they will consistently limit the short-circuit current in that circuit to a magnitude substantially less than that obtainable in the same circuit if the device were replaced with a solid conductor having comparable impedance (Figure 8.13.14). Fuseholders for current-limiting fuses are designed to make it difficult to install a noncurrent-limiting fuse.

Ground-Fault Circuit Interrupters (GFCI)

Circuit breakers and fuses open a circuit and stop the flow of electricity when the current flow exceeds their ratings. Lighting and receptacle circuits are usually rated 15 or 20 A. Under certain conditions, as little as 20 mA can kill a normal healthy adult; thus, the rating of lighting and receptacle circuits is high, relative to the amount of current that could kill a person.

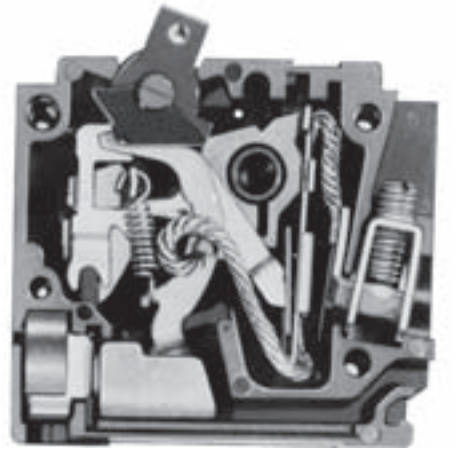

FIGURE 8.13.13 15-A, Single-Pole, 120-V Branch-Circuit Breaker (Source: Eaton's Cutler-Hammer Business)

FIGURE 8.13.14 Class R Current-Limiting Fuses with Rejection Feature to Prohibit Installation of Non-Current-Limiting Fuses (Source: Cooper Bussman)

Ground-fault circuit interrupters (GFCIs) are devices that sense when even a small amount of current passes to the ground through any path other than the proper conductor. When this condition exists, the GFCI trips almost instantly, stopping all current flow in the circuit, including through a person who might be in contact with it.

Simplicity of design is one reason for the reliability of the GFCI. Figure 8.13.15 shows a typical circuit arrangement of a GFCI for personnel protection. Figure 8.13.16 shows types of GFCI units and a GFCI tester.

Currently available GFCIs are set to operate when line-to-ground currents exceed 5 mA. Evaluation standards permit a differential of 4 to 6 mA. Even at trips of 5 mA, it should be clearly understood that the instantaneous current will be higher and any shock during the time the fault is being cleared will be

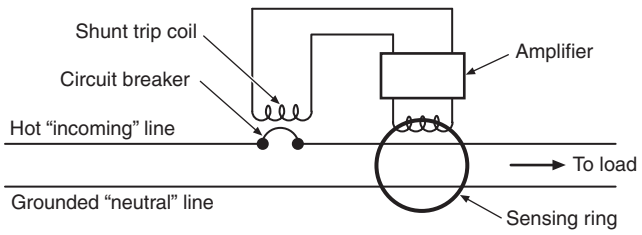

FIGURE 8.13.15 Circuit Arrangement for a Typical Ground-Fault Circuit Interrupter for Personnel Protection

(a)

(b)

(c)

FIGURE 8.13.16 (a) Portable Plug-In Type of GFCI; (b) Raintight GFCI with Open Neutral Protection for Use on Line End of a Flexible Cord; (c) 15 A Duplex Receptacle with Integral GFCI That Also Protects Downstream Loads (Source: Pass & Seymour/Legrand®)

uncomfortable. The key to the ground-fault circuit interrupter is its time-current characteristic. Trip-out time is about ¼₀ of a second (25 msec) when the fault reaches or exceeds 6 mA.

There are two classes of GFCIs—Class A and Class B. The Class A GFCI trips at not more than 6 mA. The Class B GFCI trips when the current exceeds 20 mA and is for use only with swimming pool underwater lighting fixtures that were installed prior to local adoption of the 1965 edition of the *NEC*. The Class A GFCI is used where personnel protection against ground fault is required or desired.

GFCIs at Construction Sites. All 125 V, single-phase, 15-, 20-, and 30-A receptacle outlets must have GFCI protection for personnel or an assured equipment grounding conductor program. Precautions must be taken to aid the efficient operation of GFCIs on construction sites. Most laboratory-tested 120 V appliances have 0.5 mA leakage or less under normal operating conditions. However, moisture and improper maintenance on portable handheld tools, which is common at construction sites, can create conditions under which GFCIs can be expected to trip. Flexible cords with standard attachment plug cap and connector, when dropped in water (e.g., puddles), can be expected to cause leakage currents of 100 to 300 mA or greater, far in excess of GFCI trip currents. Motors with dirty brushes, carbon tracking on commutators, or moisture in the windings contribute to leakage current. A commonsense approach to installing, using, and maintaining GFCI circuits goes a long way toward eliminating nuisance tripping at construction sites. (Actually, tripping under any of the conditions mentioned is not nuisance tripping, but merely a device performing its intended function.)

Moisture is the major culprit in current leakage on wiring and equipment. Panelboards, receptacles, and cord caps and connectors intended for dry locations must not be subjected to wet conditions.

GFCIs in Residential and Commercial Occupancies. The *NEC* requires ground-fault protection for personnel (i.e., a GFCI) on all 125 V, single-phase 15- and 20-A receptacles installed in the following locations in dwelling units: bathrooms, garages and accessory buildings that have a floor at or below grade level not intended as habitable rooms and limited to storage areas, work areas and areas of similar use, the outdoors, unfinished basements, crawl spaces that are at or below grade level, boathouses, receptacles that are installed to serve kitchen countertop surfaces, and receptacles that are located within 6 ft (1.8 m) of the outside edge of a wet-bar sink.

A single or duplex receptacle does not need GFCI protection if (1) it is located within a dedicated space for an appliance that is not easily moved from one location to another and is cord- and plug-connected or (2) it is not readily accessible and supplied by a dedicated circuit for snow-melting or de-icing equipment. In other than dwelling units, receptacles that are installed must have GFCI protection for personnel in all bathrooms and rooftops.

All 125 V receptacles, whether of the parallel blade or twist locking type, that are located within 20 ft (6 m) of a swimming pool, fountain, or outdoor spa or hot tub are required to be GFCI protected. Where spas or hot tubs are installed indoors, receptacles that provide power to the spa or hot tub must be GFCI

protected. Hydromassage bathtubs and their associated equipment are required to be GFCI protected, as well as any receptacles within 5 ft (1.5 m) of the tub. In addition, in all occupancy types, non-GFCI-protected receptacles that are replaced due to damage or other causes that were not previously required to be GFCI protected under previous *NEC* editions must be GFCI protected if the present *NEC* requires it.

Arc-Fault Circuit Interrupters (AFCIs)

Fixed wiring in homes accounted for 13,000 reported structure fires in 1998, with associated losses of 96 civilian deaths and 293 civilian injuries.[1] As early as the mid- to late 1980s, when home wiring fires were averaging 17,000, with more than 150 deaths a year, the U.S. Consumer Product Safety Commission (CPSC) identified arc-fault detection as a promising new technology. Since then, CPSC electrical engineers have tested arc-fault circuit interrupters (AFCIs) and found these devices to be effective.

AFCI Defined. An arc fault is an unintentional electrical discharge characterized by low and erratic current that is capable of igniting combustible materials. Although standard circuit breakers provide overload protection, short circuit protection, and (when specified) ground-fault protection for personnel, they do not provide protection against potential fire hazards that can result from low-level arcing faults.

An AFCI is a safety device that uses electronics to recognize the current and voltage characteristics of arcing faults and interrupts the circuit when the arcing fault occurs. The AFCI is expected to provide enhanced protection from fires resulting from these unsafe wiring conditions. AFCI technology was first used to protect the areas surrounding downed utility lines. Advances in electronic technology make arc-fault protection available for use on 125-V, 15- or 20-A branch circuits.

AFCIs are already recognized for their effectiveness in preventing fires. The current edition of the *NEC* will contain updated AFCI requirements.

Short Circuits and Arcing Faults. Short circuits, also known as faults, are usually high and rapid current flows. Conventional circuit protective devices quickly detect these short circuits. Arcing faults are characterized by low and erratic current flow. Due to these characteristics, arcing faults in damaged cords or cables can continue undetected by conventional circuit protective devices, thus creating hazardous situations such as ignition of nearby combustive materials.

There are three types of arc faults:

- A *parallel arc fault* is an arc resulting from direct contact of two conductors with opposite polarity (e.g., damaged extension cord).
- A *ground arc fault* is an arc between a single conductor and ground (e.g, improperly installed wall receptacle).
- A *series arc fault* is an arc across the break in a single conductor (e.g., cable pierced by a nail).

Arcing can occur and lead to fire in these and the following common situations:

- Deterioration of the insulation due to aging
- Extension cords caught in a doorjamb or crimped between a piece of furniture and a wall
- Deterioration of the cord's insulation by exposure to sunlight or a hot air duct
- Frayed appliance extension cords
- Appliances where the insulation of the internal wires are impaired
- Appliance wire damaged by constant use, bending, and abuse
- Wire stapled too tightly against a stud, severing or damaging insulation
- Overheated cords or wires
- Exposed stranded wiring on an old style plug caps, including frayed and loose wiring
- Receptacles that have loose connections

When unwanted arcing occurs, it generates high temperatures that can ignite nearby combustibles such as wood, paper, and carpets. The AFCI uses unique current sensing circuitry to discriminate between normal and unwanted arcing conditions. Once an unwanted arcing condition is detected, the control circuitry in the AFCI trips the internal contacts, thus de-energizing the circuit and reducing the potential for a fire to occur. An AFCI should not trip during normal arcing conditions, such as those that occur when a switch is opened or a plug is pulled from a receptacle. The AFCI circuit breaker provides protection for the branch-circuit wiring as well as power cords, extension cords, and internal wiring of equipment.

AFCIs can be installed in any single-pole 125 V, 15 or 20 A branch circuit and are currently available as built-in features to circuit breakers. In the near future, other types of devices with AFCI protection will be available. In homes equipped with conventional circuit breakers rather than fuses, an AFCI circuit breaker can be installed in the panel box in place of the breakers. Homes with fuses are limited to receptacle or portable-type AFCIs, which are expected to be available in the near future.

AFCI and GFCI Combination Devices

The AFCI should not be confused with the ground-fault circuit interrupter (GFCI). The GFCI is designed to protect people from severe or fatal electric shocks whereas the AFCI protects against fires caused by arcing faults. The GFCI also can protect against some electrical fires by detecting arcing and other faults to ground but cannot detect hazardous across-the-line arcing faults that can cause fires. Based on U.S. Consumer Products Safety Commission reports, combination devices that include both AFCI and GFCI protection in one unit will become available soon.

Leakage Current Detection and Interruption (LCDI)

The leakage current detection and interruption (LCDI) device is a protective device that is similar to an AFCI and is usually provided, by the manufacturer, in the power supply cord of a piece of equipment. The LCDI is designed to sense any damage in a power supply cord or cord set; if the cord or cord set is

damaged, current begins to leak from the conductor to the shield and interrupts the circuit at a predetermined level of leakage current. The plug-mounted electronics sense the current on the shield and disconnect power in less than 25 milliseconds, faster than a blink of the eye.

Electrical cord fires are a leading cause of residential fires in the United States. Extension cord fires have been and continue to be a major problem. There are many causes of cord fires, including consumer misuse, overload (which damages the insulation of the extension cord), overheating, and aging of the cord.

Consumer misuse is the most common and occurs in an assortment of ways, including leaving the cord to be crushed by pedestrian traffic or by furniture or other heavy items placed on top of the cord, stapling the cord to baseboards, running the cord under the carpet, or leaving it coiled for aesthetic reasons. When the cord is used as a permanent extension of premises wiring, as in the case of the overload condition, the insulation is damaged from the inside out.

Circuit breakers and fuses are designed to protect the fixed wiring. Breakers and fuses allow an overload to exist for a period of time, depending on its inverse-time trip curve; they do not provide overload protection for extension cords.

There are two primary types of cord faults. Series faults (the fault is in series with the load) are partially or completely severed conductors within the cord set. A parallel fault, either line to neutral or a ground fault, is typically caused by damaged insulation. Both of these faults will lead to carbon tracking within the cord set, leakage current, arcing, and then combustion.

Types of Wiring Methods and Materials

The *NEC* recognizes a number of standard wiring methods, some of which are suitable for general use whereas others are suitable only for special purposes. In some localities, regulations restrict the use of some of the wiring methods recognized by the *NEC*. The most widely used wiring methods are rigid metal conduit, rigid nonmetallic conduit, intermediate metal conduit (IMC), electrical metallic tubing (EMT), metal-clad cable (MC), armored cable (AC; trade name "BX"), nonmetallic sheathed cable (NM, NMC, NMS; trade name "Romex"), surface metal and nonmetallic raceways, wireways, busways, underfloor raceways, and cellular metal floor raceways (Figures 8.13.17 through 8.13.20). In some areas of the country, flexible metal conduit (trade name "Greenfield") is used for complete wiring systems. None of these wiring methods should be used for either temporary or permanent work where they do not fully conform to *NEC* safety requirements.

FIGURE 8.13.17 Type UF Sheathed Cable. The insulated conductors are jacketed in parallel and the overall covering must be flame retardant, moisture resistant, fungus resistant, corrosion resistant, and suitable for direct burial in the earth.

Identification of Conductors, Terminals, Circuits, and Branch Circuits

With few exceptions, all interior wiring systems have a grounded circuit conductor that is continuously identified throughout. The identification for conductors of 6 AWG or smaller (except for Type MI cable) should consist of an outer white or natural gray colored insulation. Insulated conductors larger than 6 AWG should have similar identification or be identified by distinctive white markings at their terminations during installation. The grounded conductors of Type MI cable

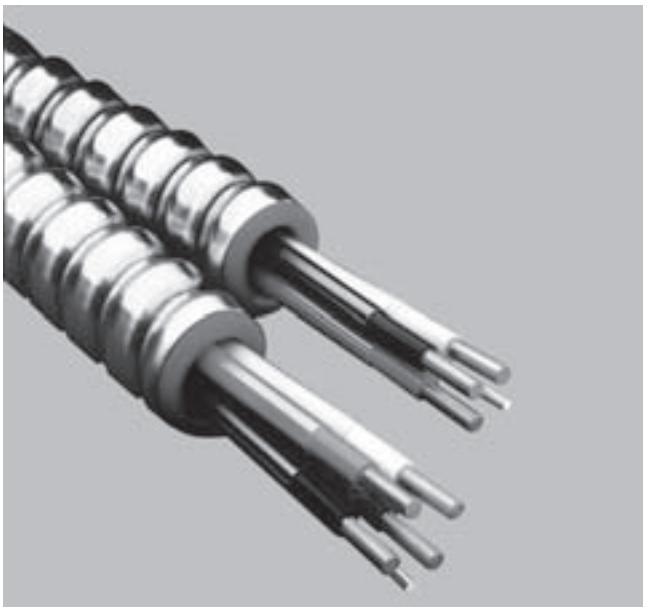

FIGURE 8.13.18 Type AC Cable (Source: AFC Cable Systems, Inc.)

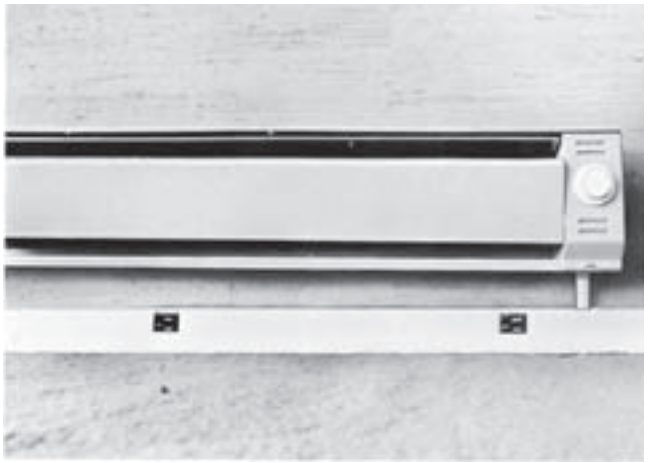

FIGURE 8.13.19 Installation of a Typical Metal Raceway System Showing an All-Steel Baseboard and a Multi-Outlet System (Source: The Wiremold Co.)

FIGURE 8.13.20 Multi-Outlet Assembly Installed to Serve Countertop Appliances (Source: The Wiremold Co.)

are also identified by distinctive markings at their terminations during installation.

In general, the terminals of electrical devices to which a grounded conductor is to be connected are identified by being made of metal substantially white in color, having a metallic plating substantially white in color, or having the word *white* located adjacent to the terminal. If the terminal is not visible, the conductor entrance hole may be colored white. In the case of screw-shell-type lampholders, the (white) terminal is the one that is connected to the screw shell.

Where a terminal is provided for the connection of an equipment grounding conductor, it must be designated by a green-colored hexagonal-head screw or nut, or, if the terminal is not visible, the conductor entrance hole must be marked with the word *green,* or the letter *G* or *GR,* or the grounding symbol (⏚).

Lighting and Appliance Branch Circuits

A branch circuit is that portion of a wiring system extending between the final overcurrent device protecting the circuit and the outlets on the circuit. Branch circuits are further defined as (1) a small-appliance branch circuit supplying one or more outlets to which appliances are to be connected that has no permanently connected luminaires (lighting fixtures) other than those that are part of the appliance, (2) a general-purpose branch circuit supplying two or more outlets for lighting and appliances, and (3) an individual branch circuit supplying only one utilization equipment.

The equipment grounding conductor of a circuit can be bare or insulated. Where it is insulated, it must be identified by a continuous green color or green with one or more yellow stripes. Conductors larger than 6 AWG that are insulated or covered must be identified by stripping the insulation from the exposed length, coloring the insulation green, or covering it with green tape or green adhesive labels.

Ungrounded conductors of different voltages are permitted to be of any color other than green, white, or natural gray. In some special applications, for example, isolated (ungrounded) power systems used in hospital operating rooms, the circuits are identified as follows: isolated conductor No. 1—orange; isolated conductor No. 2—brown.

Lampholders, where connected to branch circuits having a rating in excess of 20 A, must be of the heavy-duty type with a rating of not less than 660 W if of the admedium type, and not less than 750 W if of any other type.

Receptacles, when connected to circuits having two or more receptacles or outlets, must not supply loads greater than the values given in Table 8.13.13. They must not be supplied by circuits of ratings greater than the values listed in Table 8.13.14. Where larger than 50 A, the receptacle rating is not permitted to be less than the branch-circuit rating, except for motor loads.

Individual branch circuits may supply any loads. Branch circuits having two or more outlets may supply only loads as follows.

Branch circuits rated at 15 and 20 A are for lighting units or appliances. The rating of any one cord- and plug-connected appliance must not exceed 80 percent of the branch-circuit ampere

TABLE 8.13.13 Maximum Cord- and Plug-Connected Load to Receptacle

Circuit Rating (A)	*Receptacle Rating (A)*	*Maximum Load (A)*
15 or 20	15	12
20	20	16
30	30	24

Source: NFPA 70, *National Electrical Code,* 2005 edition.

TABLE 8.13.14 Receptacle Ratings for Various Size Circuits

Circuit Rating (A)	*Receptacle Rating (A)*
15	Not over 15
20	15 or 20
30	30
40	40 or 50
50	50

Source: NFPA 70, *National Electrical Code,* 2005 edition.

rating. The total rating of fixed appliances must not exceed 50 percent of the branch-circuit ampere rating when lighting units or other appliances are also supplied.

Branch circuits rated at 40 and 50 A are permitted to supply fixed lighting units with heavy-duty lampholders, infrared heating units, or other utilization equipment in other than dwelling units. Branch circuits rated larger than 50 A may supply only nonlighting loads.

Receptacle outlets in dwelling occupancies, including guest rooms in hotels and motels, should be installed in every kitchen, family room, dining room, living room, parlor, library, den, sunroom, bedroom, recreation room, or similar room or area of dwelling units. Insofar as practical, the outlets should be spaced equal distances apart (Figure 8.13.21). Receptacles should be installed so that no point along the floor line is more than 6 ft (1.8 m), measured horizontally, from an outlet so as to permit a lamp or appliance equipped with a 6 ft (1.8 m) cord to be located anywhere along the wall, in the room.

In guest rooms of hotels, motels, and similar occupancies, the *NEC* allows the receptacle outlets to be located conveniently for permanent furniture layout, with at least two receptacle outlets in a readily accessible location. The total number of receptacle outlets cannot be less than the minimum number that would comply with the provisions of Section 210.52(A) of the *NEC*. Where receptacles are installed behind the bed, the receptacle must be located so that the bed does not contact any attachment plug that may be installed, or it must be provided with a suitable guard. (See the *NEC Handbook* for a better understanding of this requirement.)

Most appliances and portable lamps are provided with flexible cords at least 6 ft (1.8 m) in length. Countertop appliances for use in the kitchen are usually supplied with 2 ft (600 mm) cords. Therefore, the *NEC* requires receptacles to be installed so that no point along the wall is more than 2 ft (600 mm), measured horizontally, from a receptacle. All receptacles that serve countertop spaces are required to be GFCI protected (Figure 8.13.22).

Receptacles installed on 15- and 20-A branch circuits must be of the grounding type and must be effectively grounded. This does not mean that all cord- and plug-connected equipment must be of the grounded type. (See the current *NEC* for specific details on grounding.)

Calculation of Loads

The methods specified in the *NEC* provide a basis for calculating the expected branch circuit and feeder loads and for determining the number of branch circuits required. Where in normal operation the maximum load of a branch circuit will continue

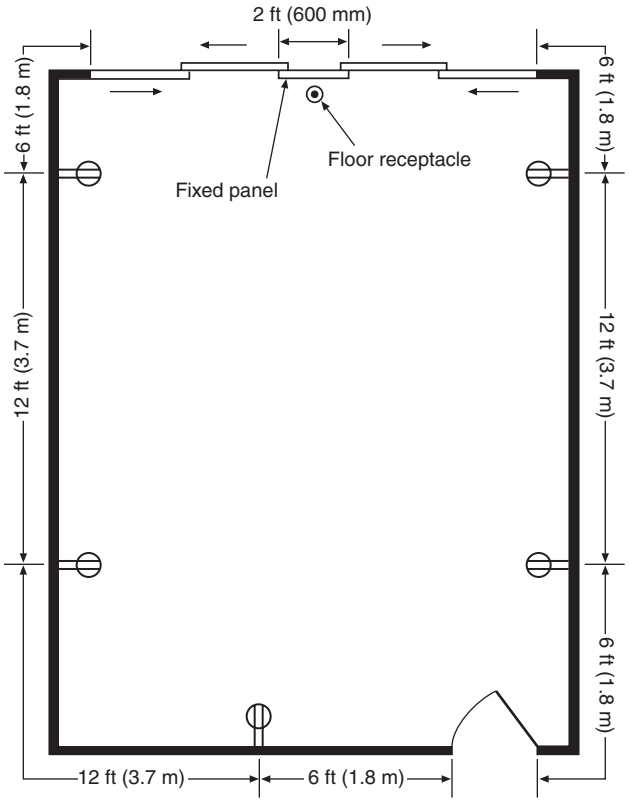

FIGURE 8.13.21 *NEC* Requirements on the Placement of Receptacles in Dwelling Occupancies

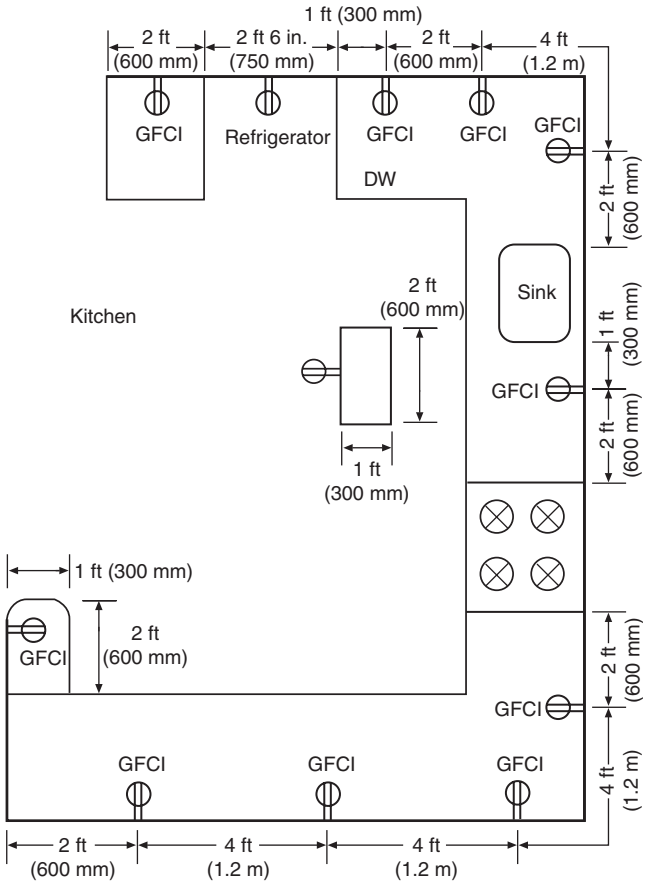

FIGURE 8.13.22 *NEC* Requirements on the Placement of Receptacles at Countertops and Islands in Kitchens and Dining Areas of Dwelling Units

for 3 hours or more, such as store or office lighting, the loads specified must be increased by 25 percent.

The minimum unit lighting loads in volt-amperes (VA) per square foot for various types of occupancies are given in Article 220 of the *NEC*. In determining the load, open porches and garages in connection with dwelling occupancies are not included. Unfinished and unused spaces in dwellings need not be included unless adaptable for future use.

For other than general illumination lighting, general-use receptacles, appliances, and loads other than motor loads, the following minimum unit load should be included for each outlet:

1. Outlets supplying specific appliances and other loads—ampere rating of appliance or load served
2. Outlets supplying heavy-duty lampholders—600 VA
3. Other outlets—180 VA (This does not apply to the small-appliance branch circuit.)

Feeder Loads

Feeder conductors must have sufficient ampacity to supply the load served. The computed load of a feeder must not be less than the sum of all branch-circuit loads supplied by the feeder, subject to the demand factor provisions of the *NEC*. Tables of demand factors for general illumination, electric ranges and other cooking appliances, and for clothes dryers are found in the *NEC*. Table 8.13.15 lists the demand factors that may be applied to that portion of the total feeder load computed for general illumination.

TABLE 8.13.15 Lighting Load Feeder Demand Factors

Type of Occupancy	*Portion of Lighting Load to Which Demand Factor Applies (VA)*	*Demand Factor Percent*
Dwelling units	First 3000 or less at	100
	From 3001 to 120,000 at	35
	Remainder over 120,000 at	25
Hospitals*	First 50,000 or less at	40
	Remainder over 50,000 at	20
Hotels and motels—including apartment houses without provision for cooking by tenants*	First 20,000 or less at	50
	From 20,001 to 100,000 at	40
	Remainder over 100,000 at	30
Warehouses (storage)	First 12,500 or less at	100
	Remainder over 12,500 at	50
All others	Total volt-amperes	100

*The demand factors of this table shall not apply to the computed load of feeders to areas in hospitals, hotels, and motels where the entire lighting is likely to be used at one time, as in operating rooms, ballrooms, or dining rooms.

Source: NFPA 70, *National Electrical Code,* 2005 edition.

An optional method of calculating the load for a single-dwelling unit served by a 120/240 V or 208/120 V system, with feeder or service conductors rated 100 A or greater, is to use the percentage values provided in Table 8.13.16.

Examples of branch-circuit and feeder calculations for other buildings and occupancies are given in Annex D of the *NEC*.

These calculations are not applicable to receptacle outlets required by the *NEC* for dwelling units. The 20 A small-appliance branch circuits and laundry branch circuits in dwelling units are calculated at 1500 VA per circuit. Other receptacle outlets rated 20 A or less in dwelling units are considered part of the general lighting load, based on the area and calculated at 3 VA per ft^2. For receptacle outlets in other than dwelling units, each single or multiple receptacle on a single yoke or strap is considered at not less than 180 VA.

An example from the *NEC* of how to calculate the load in a single-family dwelling is presented to illustrate the principles involved.

For a dwelling that has a floor area of 1500 ft^2 (457 m^2) (exclusive of an unoccupied cellar, unfinished attic, and open porches), a 12 kW range, and 5 kW clothes dryer, the load may be computed as follows:

General Lighting Load: 1500 ft^2 at 3 VA per ft^2 = 4500 VA.

Number of Branch Circuits Required

General Lighting Load:

4500 ÷ 120 = 37.5 A; 37.5 ÷ 15 = 2.5 or three 15 A, 2-wire circuits; or two 20 A 2-wire circuits.

Small-Appliance Circuit: Two 20 A, 2-wire circuits.

Laundry Circuit: One 20 A, 2-wire circuit.

TABLE 8.13.16 Optional Calculation for One-Family Dwelling Unit

Largest of the Following Five Selections

(1) 100 percent of the nameplate rating(s) of the air conditioning and cooling, including heat pump compressors.
(2) 100 percent of the nameplate ratings of electrical thermal storage and other heating systems where the usual load is expected to be continuous at the full nameplate value. Systems qualifying under this selection must not be figured under any other selection in this table.
(3) 65 percent of the nameplate rating(s) of the central electric space heating including integral supplemental heating in heat pumps.
(4) 65 percent of the nameplate rating(s) of electric space heating if less than four separately controlled units.
(5) 40 percent of the nameplate rating(s) of electric space heating of four or more separately controlled units.

Plus: 100 percent of the first 10 kVA of all other load. 40 percent of the remainder of all other load.

Source: NFPA 70, *National Electrical Code,* 2005 edition.

Minimum Size Feeders Required

Computed load	
General lighting	4500 VA
Small-appliance load	3000 VA
Laundry	1500 VA
Total (without range and dryer)	9000 VA
3000 VA at 100 percent	3000 VA
9000 – 3000 = 6000 VA at 35 percent =	2100 VA
Net Computed (without range and dryer)	5100 VA
Range load	8000 VA
Clothes dryer	5000 VA
Net Computed (with range and dryer)	18,100 VA

For 120/240 V system feeders 18,100 ÷ 240 = 75 A. Therefore, feeder size for total load may be selected on the basis of 75 A load. Net computed load exceeds 10 kVA, so service conductors must have a rating of 100 A.

Flexible Cords and Cables

Flexible cords are made for various kinds of service, ranging from wiring for portable lamps to elevator cables. Article 400 of the *NEC* gives a description, the ampacities, and the intended use of the various flexible cords now available. The ampacity of flexible cords is limited by type and gauge of wire used. They must not be overloaded nor their size reduced where the gauge is intended for mechanical strength.

Flexible cords are frequently subject to physical damage and rapid wear. Ground faults or short circuits may occur if the insulation is damaged and the resulting arc may ignite the insulation or nearby combustible material. Replacement of flexible cords as soon as they show damage or appreciable wear is of utmost importance.

Under present labeling practices, only replacement nondetachable power supply cords; range and dryer power supply cords; and cord sets, such as extension cords, carry the label on the product itself. Formerly, the original cords and power supply cords were labeled, and some consumers may have thought a label on the cord of an electrical appliance signified the appliance itself was investigated for safety. Nondetachable cords on new appliances no longer carry a label, so the consumer cannot be misled into assuming that the appliance itself has been tested, which may not be the case.

Flexible cords are not considered by the *NEC* as a wiring method. They are covered in Chapter 4 of the *NEC,* "Equipment for General Use." Flexible cords, including extension cords, are not acceptable as a substitute for the fixed wiring of a structure, but they are acceptable for use in extending the length of a cord on a portable lamp or on cord- and plug-connected appliances. The appliance should be used in accordance with any instructions included with the listing or labeling and the flexible cord itself should be used in accordance with Article 400 of the *NEC.* Flexible cords are not limited solely to "temporary wiring."

Switches

Switches are required for the control of lights and appliances and as the disconnecting means for motors and their controllers. Switches may be of either the air-break or the oil-break type. In the oil-break type, the interrupting device is immersed in oil.

A chief fire hazard in switches is the arcing produced when the switch is opened. This hazard is somewhat greater with oil-break switches. If operated much beyond their rated capacity or if the condition of the oil is poor or its level is not properly maintained, the arc can vaporize the oil, rupture the case, and cause a fire. However, the amount of oil is comparatively small (except in high-voltage equipment) and these switches present no hazard if properly used and maintained.

ELECTRICAL HOUSEHOLD APPLIANCES

Electric Heating Equipment

Electric heating equipment is used widely and it is important that all such devices be tested and listed by qualified electrical testing laboratories. Some fixed spaceheating equipment covered in Article 424 of the *NEC* is acceptable for installation in direct contact with combustible material. Baseboard heaters, for example, have been tested and found to incorporate suitable safeguards against fire hazards that might result from contact with draperies, furniture, carpeting, bedding, and so on, although discoloration or scorching (but no glowing embers or flaming) is possible on adjacent materials. Other electric air heaters, however, may present fire hazards if they come in contact with combustible materials or if they are covered or blocked in any manner. Space heating systems must not be installed where exposed to severe physical damage unless adequately protected, nor in damp or wet locations unless approved for such locations.

A heater installed in an air duct or plenum must be of a type suitable for that purpose. Article 424 of the *NEC* covers installation of heaters for ducts and plenums and such items as airflow reliability, problems of condensation, fan circuit interlock, limit controls, and location of disconnecting means. NFPA 90B, *Standard for the Installation of Warm Air Heating and Air-Conditioning Systems,* also contains details on central systems.

Electric Ranges, Wall-Mounted Ovens, and Counter-Mounted Cooking Units

Each of these devices needs a means for disconnection from all ungrounded conductors of the supply circuit. A separable connector or a plug and receptacle may serve as the disconnecting means for free-standing household ranges. A plug and receptacle connection at the rear base of the range, if accessible from the front by removal of a drawer, is considered satisfactory. Grounding requirements for ranges are covered in Article 250 of the *NEC.*

In new installations, the grounded conductor (neutral) is not allowed as a means of grounding the frame of an electric range or counter-mounted cooking unit. Therefore, the flexible power cord must contain four conductors and a four-blade plug. Where there is an existing branch circuit containing only three conductors supplying a three-wire receptacle, the grounded conductor (neutral) is allowed to be used for grounding the frame of the appliance.

The *NEC* gives the methods for calculating feeder loads for household electric ranges and other cooking appliances.

Refrigerators

Fire problems with refrigerators can include deterioration in service of the fractional horsepower motors used and the possibility of overheating. Refrigerant coils and motors are susceptible to accumulations of lint and oily deposits, so cleanliness is a primary consideration in fire prevention. New devices have sealed motors not requiring oiling or maintenance, but overheating can result from improper use or inefficient cooling of the refrigerant due to coil dirt or damage. Ordinary household or commercial refrigerators must not be used to store flammable liquids. (Refrigerators listed for use in Class I hazardous [classified] locations and for flammable materials storage in laboratories, in accordance with Chapter 10 of NFPA 99 and NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals,* are available.) Exposed noncurrent-carrying metal parts of refrigerators and freezers that are likely to become energized need to be grounded under provisions of the *NEC.*

Room Air-Conditioning Units

Room air-conditioning units have the same fire hazards as other motor-operated appliances. The exposed noncurrent-carrying metal parts must be grounded as required by Article 250 of the *NEC.*

Properly designed portable room air conditioners are protected by an LCDI provided with the cord. The protection is an integral part of the attachment plug or is located in the power supply cord within 12 in. (300 mm) of the attachment plug.

Incandescent Lamps

Because incandescent lamps produce considerable heat, they inherently possess a fire hazard and can ignite combustible material in contact with them. Under normal conditions, with the lamp in an approved lampholder and the fixture properly guarded, the heating hazard is negligible, but ignition of combustible material may result if lamps are surrounded by or laid on such combustible material. Table 8.13.17 presents information on surface and base temperatures of standard lamps in open sockets. The temperature measurements are all taken at an ambient temperature of 77°F (25°C). In most instances where lamps are incorporated in various kinds of lighting equipment, the ambient temperature at which the lamps operate is higher; thus, the surface temperatures of the bulbs are also higher. The bulb temperatures may be further increased if the lamp is in other than a vertical, base-up position. Figure 8.13.23 shows surface temperatures of 100 W A-19 and 500 W PS-35 lamps in various positions but, again, these temperatures were measured in an ambient temperature of 77°F (25°C); so where enclosed in fixtures, the temperatures will be higher. The older style conventional Christmas tree lamps of U.S. manufacture have approximate average bulb surface temperatures at the hottest spot of approximately 260°F (127°C) for the blue and green colors, and somewhat lower for the white, red, and yellow colors.*

*The data in Table 8.13.17 was extracted from the *IES Handbook,* 5th ed., of the Illuminating Engineering Society, and is used here with the permission of the society. The reader is asked to keep in mind the above comments in the text regarding use of data in Table 8.13.17 and Figure 8.13.23.

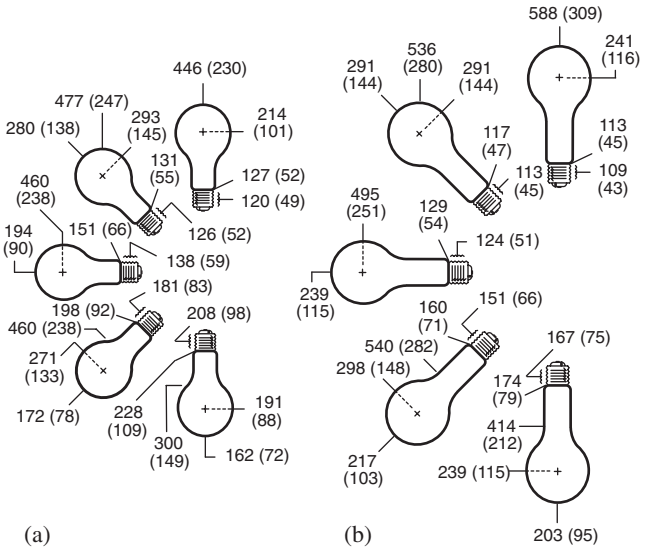

FIGURE 8.13.23 Surface Temperatures of Lamps in Various Positions: (a) 100 W, A-19 Lamp; (b) 500 W PS-35 Lamp

In clothes closets, an open, partially enclosed, pendant, or lampholder with incandescent lamp in a luminaire (fixture) is not permitted to be installed.

In locations where there are flammable vapors or gases, combustible dusts, or readily ignitable fibers or flyings, lamps in fixtures specially approved for the location must be used. Luminaires (lighting fixtures) approved for Class I, Division 1 locations must be marked to indicate the maximum wattage of the lamps for which they are approved, and they must be protected against physical damage by a suitable guard or located beyond the area of potential damage.

Fixed luminaires (lighting fixtures) in Class I, Division 2 locations must be protected from physical damage by a suitable guard or located out of the area of potential damage. Where there is the potential for sparks or hot metal falling from the lamps and igniting localized concentrations of flammable vapors or gases, suitable enclosures or other means must be provided. Where lamp size might be increased so that, under normal operating conditions, the surface temperature of the luminaire (fixture) could exceed 80 percent of the ignition temperature (°C) of the gas or vapor involved, the fixture must be of a type that has been tested for the marked temperature operating range.

Electric Discharge (Fluorescent) Lamps

The operating temperature of a fluorescent tube is lower than that of the glass envelope of the incandescent lamp, but high voltage is often used to start the lamp. This requires the use of transformers, reactors, capacitors, and switches. The heat produced by this equipment must be taken into account, and the equipment properly safeguarded.

Bulb temperatures on the surface of fluorescent lamps average between 100 and 110°F (38 and 43°C) over most of their length, because this is a requirement for efficient light production.

TABLE 8.13.17 General Service Lamps for 115, 120, and 125 V Circuits (Will Operate in Any Position, but Lumen Maintenance Is Best for 40 to 1500 W when Burned Vertically Base-Up)[a]

Watts	*Bulb and Other Description*	*Base*	*Filament*	*Rated Average Life (hr)*	*Maximum Overall Length (in. [mm])*	*Average Light Center Length (in. [mm])*	*Approximate Initial Filament Temp. (K)*	*Max. Bare Bulb Temp. (°F [°C])*	*Base Temp.*[b] *(°F [°C])*	*Approximate Initial Lumen (sec)*	*Rated Initial Lumen (sec per watt*[c]*)*	*Lamp Lumen Depreciation*[d] *(percent)*
10	S-14 inside frosted or clear	Med.	C-9	1500	3½ (89)	2½ (63)	2420	106 (41)	106	80	8.0	89.0
15	A-15 inside frosted	Med.	C-9	2500	3½ (89)	2⅜ (60)	—	—	—	126	8.4	83.0
25	A-19 inside frosted	Med.	C-9	2500	3⅜ (98)	2½ (63)	2550	110 (43)	108 (42)	230	9.2	79.0
40	A-19 inside frosted and white	Med.	C-9	1500	4¼ (108)	2 15/16 (75)	2650	260 (127)	221 (105)	455	11.4	87.5
40	S-11 clear	Intermed.	CC-2V or C-7A	350 500	3 5/16 (59)	1⅝ (41)	2800	570 (299)	390 (199)	477	11.9	—
50	A-19 inside frosted	Med.	CC-6	1000	4 7/16 (113)	3⅛ (79)	—	—	—	680	13.6	—
60	A-19 inside frosted and white[e]	Med.	CC-6	1000	4 7/16 (113)	3⅛ (79)	2790	255 (124)	200 (93)	860	14.3	93.0
75	A-19 inside frosted and white[e]	Med.	CC-6	750	4 7/16 (113)	3⅛ (79)	2840	275 (135)	205 (96)	1,180	15.7	92.0
100	A-19 inside frosted and white[e]	Med.	CC-8	750	4 7/16 (113)	3⅛ (79)	2905	300 (149)	208 (98)	1,740	17.4	90.5
100[f]	A-19 inside frosted and white	Med.	CC-8	1000	4 7/16 (113)	3⅛ (79)	—	—	—	1,680	16.8	—
100	A-21 inside frosted	Med.	CC-6	750	5¼ (133)	3⅜ (98)	2880	260 (143)	194 (90)	1,640	16.9	90.0
100[f]	A-23 inside frosted or clear	Med.	C-9	1000	5 15/16 (151)	4 7/16 (113)	—	—	—	1,480	14.8	—
150	A-21 inside frosted	Med.	CC-8	750	5½ (140)	4 (102)	2960	—	—	2,880	19.2	89.0
150	A-21 white	Med.	CC-8	750	5½ (140)	4 (102)	2930	—	—	2,790	18.6	89.0
150	A-23 inside frosted or clear or white	Med.	CC-6	750	6 3/16 (157)	4⅝ (117)	2925	280 (138)	210 (99)	2,780	18.5	89.0
150	PS-25 clear or inside frosted	Med.	C-9	750	6 15/16 (176)	5¼ (133)	2910	290 (143)	210 (99)	2,660	21.2	87.5
200	A-23 inside frosted or white or clear	Med.	CC-8	750	6 5/16 (160)	4⅝ (117)	2980	345 (174)	225 (107)	4,000	20.0	89.5
200	PS-25 clear or inside frosted	Med.	CC-6	750	6 15/16 (176)	5¼ (133)	—	—	—	3,800	19.0	—

(continued)

TABLE 8.13.17 Continued

Watts	*Bulb and Other Description*	*Base*	*Filament*	*Rated Average Life (hr)*	*Maximum Overall Length (in. [mm])*	*Average Light Center Length (in. [mm])*	*Approximate Initial Filament Temp. (K)*	*Max. Bare Bulb Temp. (°F [°C])*	*Base Temp.*[b] *(°F [°C])*	*Approximate Initial Lumen (sec)*	*Rated Initial Lumen (sec per watt*[c]*)*	*Lamp Lumen Depreciation*[d] *(percent)*
200	PS-30 clear or inside frosted	Med.	C-9	750	8 1/16 (205)	6 (152)	2925	305 (152)	210 (99)	3,700	18.5	85.0
300	PS-25 clear or inside frosted	Med.	CC-8	750	6 15/16 (110)	5 1/16 (132)	3015	401 (205)	234	6,360	21.2	87.5
300	PS-30 clear or inside frosted	Med.	C-9	750	8 1/16 (205)	6 (152)	3000	275 (135)	175 (79)	6,100	20.3	82.5
300	PS-30 clear or inside frosted	Mog.	CC-8	1000	8 5/8 (219)	7 (178)	—	—	—	5,960	19.8	—
300	PS-35 clear or inside frosted	Mog.	C-9	1000	9 3/8 (238)	7 (178)	2980	330 (166)	215 (102)	5,860	19.6	86.0
500	PS-35 clear or inside frosted	Mog.	CC-8	1000	9 3/8 (238)	7 (178)	3050	415 (213)	175 (79)	10,600	21.2	89.0
500	PS-40 clear or inside frosted	Mog.	C-9	1000	9 3/4 (248)	7 (178)	2945	390 (199)	215 (102)	10,140	20.3	—
750	PS-52 clear or inside frosted	Mog.	C-7A	1000	13 1/16 (332)	9 1/2 (241)	2990	—	—	15,660	20.9	—
750	PS-52 clear or inside frosted	Mog.	CC-8 or 2CC-8	1000	13 1/16 (332)	9 1/2 (241)	3090	—	—	17,000	22.6	89.0
1000	PS-52 clear or inside frosted	Mog.	C-7A	1000	13 1/16 (332)	9 1/2 (241)	2995	480 (249)	235 (113)	21,800	21.8	—
1000	PS-52 clear or inside frosted	Mog.	CC-8 or 2CC-8	1000	13 1/16 (332)	9 1/2 (241)	3110	—	—	23,600	23.6	89.0
1500	PS-52 clear or inside frosted	Mog.	C-7A	1000	13 1/16 (332)	9 1/2 (241)	3095	510 (265)	265 (129)	34,000	22.6	78.0

[a]Lamp burning base up in ambient temperature of 77°F (25°C).
[b]At junction of base and bulb.
[c]For 120 V lamps.
[d]Percent initial light output at 70 percent of rated life.
[e]Lumen and lumen per watt values of white lamps are generally lower than for inside frosted.
[f]Used mainly in Canada.

There is a small area of higher bulb temperature directly above the cathode at each end of a fluorescent lamp that ranges from 120 to 250°F (49 to 121°C), depending on the type involved.

Where fluorescent lamps having an open circuit voltage of more than 300 V are installed in dwelling occupancies, they must have no exposed live parts when lamps are in place and when being inserted or removed.

Extreme care is required in mounting fluorescent lamp luminaires (fixtures) containing a ballast on combustible, low-density, cellulose fiberboard. In this case, low-density refers to combustible low-density, cellulose fiberboard tiles or sheets that have a density of 20 lb/ft^3 (320 kg/m^3) or less, and are formed of bonded plant material. It does not include solid or laminated wood or fiberboard that has a density in excess of 20 lb/ft^3 (320 kg/m^3). Luminaires (fixtures) containing ballasts should not be mounted in contact with low-density, cellulose fiberboard, unless specifically listed by a qualified electrical testing laboratory for mounting in that manner. If not so listed, they should be spaced not less than 1½ in. (38 mm) from the surface of the combustible material. A principal hazard is ignition of the fiberboard, which under some conditions can ignite at relatively low temperatures. Integral thermal ballast protection is now provided for fluorescent luminaires (fixtures) installed indoors to protect against ballast overheating as a result of failure of capacitors, lamps, ballast winding shorts, and so on.

Electric (High-Intensity) Discharge Lamps

The operating temperature of a high-intensity discharge lamp, such as a mercury vapor lamp, is usually much higher than the operating temperature of either Edison-base incandescent or fluorescent lamps, exceeding 550°F (288°C) in some sizes. Extreme care is therefore necessary where such lamps are encountered to prevent their contacting combustible material. Although such lamps were at one time used primarily for street lighting and other outdoor lighting applications, their higher lighting efficiency and new designs providing good color correction and lower wattages have resulted in increased use indoors. Such lamps usually require ballasts (transformers), sometimes capacitors, and are designed to fit into Edison-base lampholders. There are, however, self-ballasted lamps that can be substituted directly for incandescent lamps. High-intensity discharge lamps should be used only in luminaires (fixtures) listed by a qualified electrical testing laboratory for their use, as indicated on the luminaire (fixture).

Portable Handlamps

Metal-shell, paper-lined lampholders are not designed to be used as portable handlamps. A fire hazard may result from a defective or worn cord or from the breaking of a lamp. A personnel hazard may result from personal contact with bare spots on the cord or by contact with a live metal lamp socket. Portable handlamps must have a handle of molded composition or other insulating material and a substantial guard attached to the lampholder or handle. Metallic guards must be grounded by means of an equipment grounding conductor that runs with the circuit conductors within the power supply cord. Portable handlamps are not required to be grounded where supplied through an isolating transformer with an ungrounded secondary of not over 50 V.

Portable handlamps used in hazardous (classified) locations must be suitable for the purpose (Figures 8.13.24 and 8.13.25).

FIGURE 8.13.24 Explosionproof Handlamp for Use in Class I Locations (Source: Appleton Electric LLC, EGS Electrical Group)

FIGURE 8.13.25 Portable Handlamp with Grounded Metal Guard and Reflector and Swivel-Type Hook (Source: Daniel Woodhead Co.)

Home Entertainment Equipment

Outdoor antennas and lead-in conductors must be of corrosion-resistant material and securely supported (Figure 8.13.26). They must not be attached to poles or similar structures carrying electric light or power wires or trolley wires, nor should they cross over or be near electric light or power circuits (to avoid accidental contact). Where antennas or lead-in conductors are in proximity of outdoor electric light or power circuits operating at less than 250 V, they must have at least 2 ft (600 mm) of clearance, and at 250 V or more, 10 ft (3.0 m) clearance. Lead-in conductors also must be kept at least 6 ft (1.8 m) from any conductor forming a part of a lightning protection system. The metal sheath of the coaxial cable used for cable television systems must be grounded in accordance with Article 820 of the *NEC,* to avoid electric shock and fire hazards. The sheath must be electrically bonded to the electrical system power ground. Where a separate ground rod is installed for the cable television ground, it must be bonded to the electrical system grounding electrode system or to the electrical service equipment.

Masts and metal structures supporting antennas must be well grounded, and each conductor of a lead-in from an outdoor antenna must be protected by an approved antenna discharge unit. Metal masts on buildings are required by NFPA 780 to be bonded to the nearest lightning conductor (where available). This bonding is normally done with standard lightning conductors.

FIGURE 8.13.26 Dangerous Arrangement of a Lightly Supported Television Antenna in Proximity of Power Lines

Radio interference eliminators and noise suppressors connected to power supply leads and devices, intended to permit an electric supply circuit to be used in lieu of an antenna, should be listed for the purpose by a qualified electrical testing laboratory.

Operating television sets, even solid-state sets, can develop considerable heat, so most cabinets housing such equipment are provided with ventilation openings at the rear and bottom. It is important not to install television receivers so that the desired ventilation is cut off or significantly reduced (e.g., by recessing the set in a wall, bookcase, etc.), unless the receiver is designed for such use.

Clothes Washers and Dryers

These appliances are required to have a means for disconnecting all ungrounded conductors from the supply circuit. A separable cord connector or an attachment plug and receptacle may serve as the disconnecting means.

Electric clothes washers and dryers and similar appliances are usually installed within reach of a person who can make contact with a grounded surface or object. Consequently, the exposed, noncurrent-carrying metal parts of these machines must be grounded to remove the danger of electric shock. Accumulations of lint in dryers and in lint traps also present a potential fire hazard if not periodically cleaned.

Flatirons

These appliances intended for use in residences are required by the *NEC* to be equipped with approved means to limit the temperature. Even with the widespread use of automatic irons, some hazard still remains because satisfactory ironing of many fabrics requires a degree of heat sufficient to cause ignition if the iron is left in contact with some combustible materials for a considerable period of time.

Electrically Heated Pads and Bedding

The user must be warned by means of a marking on the appliance and by instructions packed with it against the common possible abuses that would increase the fire or shock hazard.

Because many fabrics readily absorb moisture, listed pads (unless of the waterproof type) are provided with moisture-resistant envelopes. This envelope should be examined frequently for signs of deterioration. Blankets are normally designed so that they may be laundered; some cannot be dry cleaned (as with Stoddard solvent or perchloroethylene) and are normally labeled "Do Not Dry Clean."

INDUSTRIAL AND COMMERCIAL EQUIPMENT

Furnaces

Industrial furnaces generally employ transformers, which may be either the dry type, askarel-insulated type, oil-insulated type,

or insulated with a less flammable fluid (e.g., dimethyl silicone). Although new transformers are no longer made with askarel (a material containing polychlorinated biphenyl, or PCB), many such transformers are still in use. The *NEC* requires oil-insulated transformers of a total rating exceeding 75 kVA to be located in a fire-resistant vault. Electric furnace transformers that have a total rating not exceeding 75 kVA are permitted to be installed without a vault in a building or room of fire-resistant construction, provided suitable arrangements are made to prevent a fire involving the transformer oil from spreading to other combustible material.

Oil-filled circuit breakers that control arc furnaces are subject to unusually severe duty and, unless frequently inspected and properly maintained, may fail with disastrous results. Circuit breakers on circuits operated at more than 600 V and that are used to control oil-filled transformers must be located outside the transformer vaults. Vents on high-voltage circuit breakers must be piped outdoors. Electric arc furnace circuits, due to the nature of the operation, are also subject to high surge voltages that can cause failure of the arc circuit breakers used. In these cases, shunt capacitors are installed in the circuit to prevent these high-voltage surges.

Inductive and dielectric heat-generating equipment employing high-frequency alternating currents is used in many heat-treating processes. To eliminate both the personnel hazards and fire hazards of such equipment, construction and installation should comply with the special requirements of the *NEC.*

Other hazards of electric furnaces are similar to those of furnaces employing other means of heating.

Motors

Ignition of motor insulation or nearby combustible material can be caused by sparks or arcs when the motor winding short circuits or grounds or when brushes operate improperly. Bearings may overheat because of improper lubrication and sometimes excessive bearing wear allows the rotor to rub on the stator. The individual drives of machines of many different types sometimes make it necessary to install motors in locations and under conditions that are injurious to motor insulation. Dust that can conduct electricity may be deposited on the insulation, or deposits of textile fibers and so on may prevent the normal dissipation of heat. Motors should be cleaned and lubricated regularly. All motor installations should comply with the requirements of the *NEC,* which includes special rules for motors in hazardous (classified) locations.

Machine Tools

The electrical equipment of a modern machine tool or plastics processing machine may vary from a simple single-motor drill press or extruder to a large complicated multimotor automatic machine involving highly complex control systems and equipment. This latter type is generally custom designed and factory wired. Machine tools incorporate many devices and safeguards to provide safety to life, safety from fire, reduction of machine lost time due to replacement of parts, safety to the machine itself, and safety to the work in process.

NFPA 79 covers the specific electrical equipment, apparatus, and wiring furnished as a part of an industrial machine, starting at the electrical supply connection, provided that it is 600 V or less. The *NEC* contains requirements for general application, particularly for protection of several motors on one branch circuit.

Electrical equipment is subject to damage by oil, metal chips, coolants, and moving parts. The fixed wiring to the machines specified in the *NEC* should generally be conductors in conduit, tubing, or Type MI cable. Exceptions are connections to continuously moving parts, which can be extraflexible, multiconductor cable. For flexible connections where small or infrequent movement is involved, as at motor terminals, flexible metal conduit, liquid-tight flexible metal conduit, or liquid-tight flexible nonmetallic conduit is permitted.

Motor Control Center Rooms

Automation of production machinery has greatly increased the use of motors and their related control circuits, resulting in grouping the motor control equipment in relatively large, compartmented metal enclosures. These are specially designed, factory-built equipment, commonly referred to as "motor control centers." They are usually located in large rooms, sometimes referred to as "motor control center rooms." Electrical failures or fires in motor control centers can result in the destruction of the equipment in many compartments of the control center due to rapid temperature rise.

A serious fire hazard can be created if multiconductor circuits are installed stacked one above the other in cable trays. Heat from arcing or a fire in the control center can raise the temperature in the control center room to a point where normally slow-burning cables become readily combustible. A fire in such cables can shut down a process or an entire plant for weeks or months. The *NEC* covers the use and construction of cable trays, and should be strictly followed where this type of support is used.

The number of motor control centers in one room should be limited or arranged so that exposure of a large number of circuits or equipment to any one fire is avoided. Motor control center rooms should be of noncombustible construction, with a roof or ceiling not readily weakened by a major electrical disturbance or fire. In addition to normal ventilation, the room should be provided with emergency ventilation for removal of heat and smoke in event of a severe fire.

Suggested fire protection for motor control center rooms may consist of preaction sprinkler systems or fixed water spray protection to cover exposed cables, fire detectors to initiate an alarm at a central point in the event of abnormally high temperatures or smoke conditions, total flooding carbon dioxide or other gaseous agent system, portable Class C fire extinguishers located at each entrance to the control room, and small hose connections with suitable hose and adjustable spray nozzles readily available near the control room.

Switchboards

Ideally, switchboards are installed in clean, dry locations. They should be under competent supervision and accessible only

to qualified persons. Switchboards operating at voltages over 600 V must be provided with protection to avoid damage from condensation leaks and breaks in piping. Piping for fire suppression is allowed within the electrical room for the protection of the electrical installation. Where it is necessary to install a switchboard in a wet location or outside a building, the enclosure must be weatherproof. Ample space must be provided for maintenance operations, as stipulated in the *NEC*.

Insulated conductors grouped within switchboards, as well as the instrument and control wiring, should have a listed flame-retardant outer covering.

Circuit breakers and switches must have ample ratings for the maximum loads and sufficient interrupting capacity for the maximum short-circuit currents. Contacts of switches and circuit breakers should be kept in good condition and the oil in oil circuit breakers renewed periodically and kept at the proper level.

Capacitors

Capacitors may be insulated with a combustible or a nonflammable liquid. Capacitors containing more than 3 gal (11 L) of flammable liquid must be enclosed in vaults or outdoor fenced enclosures. These safeguards prevent persons from coming into accidental contact or bringing conducting materials into accidental contact with exposed energized parts, terminals, or buses.

Capacitors must have a means of draining the stored energy, such as through a suitable resistance. The residual voltage of a capacitor must be able to be reduced to 50 V, nominal, or less, within 1 minute after the capacitor is disconnected from the source of supply. The discharge circuit must be either permanently connected to the terminals of the capacitor or capacitor bank, or provided with automatic means of connecting it to the terminals of the capacitor bank on removal of voltage from the line. Manual means of switching or connecting the discharge circuit cannot be used. If no means were provided for draining off the charge stored in a capacitor after it is disconnected from the line, a severe shock might be received by a person servicing the equipment, or the equipment might be damaged by a short circuit.

Resistors and Reactors

Except when installed in connection with switchboards or control panels whose locations are suitably guarded from physical damage and accidental contact with live parts, resistors should always be completely enclosed in properly ventilated metal boxes. A resistor is always a source of heat and, when mounted on a combustible wall, a thermal barrier should be required if the space between the resistors or reactors and any combustible material is less than 12 in. (305 mm).

Large reactors are commonly connected in series, with the main leads of large generators or the supply conductors from high-capacity network systems assisting in limiting the current delivered under short-circuit conditions. Small reactors are used with lightning arresters to offer a high impedance to the passage of a high-frequency lightning discharge and aid in directing the discharge to ground. Another type of reactor, having an iron core and closely resembling a transformer, is used as a remote-control dimmer for stage lighting in some of the older installations. Reactors are sources of heat and therefore should be mounted in the same manner as resistors.

Motion Picture Projection Rooms

The provisions of *NEC* Article 540 apply to motion picture projection rooms, motion picture projectors, and associated equipment of the professional and nonprofessional types using incandescent, carbon arc, xenon, or other light sources that develops hazardous gases, dust, or radiation. (For further information, see NFPA 40, *Standard for the Storage and Handling of Cellulose Nitrate Film.*)

All professional projectors should be operated by qualified personnel. A professional projector is a type that uses 35- or 70-mm film that has a minimum width of 1⅜ in. (35 mm) and has on each edge 5.4 perforations per in., or that uses carbon arc, xenon, or other light source equipment that develops hazardous gases, dust, or radiation.

Motor generator sets, transformers, rectifiers, rheostats, and similar equipment for the supply or control of current to projection or spotlight equipment must be located in a separate room, if cellulose nitrate film is used. When placed in the projection room, cellulose nitrate film must be located or guarded so that arcs or sparks cannot come in contact with film. The commutator end or ends of motor generator sets must comply with one of the conditions in *NEC* Section 540.11.

Switches, overcurrent devices, or other equipment not normally required or used for projectors, sound reproduction, flood or other special effect lamps, or other equipment cannot be installed in projection rooms. There are exceptions: (1) In projection rooms approved for use only with cellulose acetate (safety) film, the installation of appurtenant electrical equipment used in conjunction with the operation of the projection equipment and the control of lights, curtains, audio equipment, and so on is permitted. In such projection rooms, a sign reading "Safety Film Only Permitted in This Room" must be posted on the outside of each projection room door and within the projection room itself in a conspicuous location. (2) Remote-control switches for the control of auditorium lights or switches for the control of motors operating curtains and masking of the motion picture screen are permitted to be installed in projection rooms.

Approved projectors of the nonprofessional or miniature type, when employing cellulose acetate (safety) film, may be operated without a projection room. Special rules are also given in the *NEC* to cover electrical installations in motion picture studios, factories, laboratories, stages, or areas of buildings in which work is done on cellulose nitrate film. Provisions include wiring on stages, sets, dressing rooms, viewing, cutting, and patching tables, and film storage vaults.

Cranes and Hoists

Wiring methods and installation of electrical equipment for cranes and hoists are covered in Article 610 of the *NEC*. Where bare contact conductors are objectionable because of the presence of easily ignitable material, current may be conducted to

a crane or hoist via a multiple cable on a cable reel or suitable takeup device.

Where a crane operates over combustible material, the resistors must be placed in either (1) a well-ventilated cabinet of noncombustible material that will not emit flames or molten metal, or (2) a cage or cab constructed of noncombustible material that encloses the sides of the cage or cab from the floor to a point at least 6 in. (152 mm) above the top of the resistors.

Collectors must be designed to reduce sparking between them and the contact conductors to a minimum. When operated in rooms where easily ignitable fibers or materials producing combustible flyings are handled, manufactured, used, or stored, the installation must comply with the special requirements of Section 503.155 of the *NEC*.

All exposed metal parts of cranes, monorail hoists, hoists, and accessories (including pendant controls) should be metallically joined together into a continuous electrical conductor so the entire crane or hoist will be grounded.

Elevators, Dumbwaiters, Escalators, Moving Walks, Wheelchair Lifts, and Stairway Chair Lifts

Installation of electrical equipment and wiring used in connection with elevators, dumbwaiters, escalators, moving walks, wheelchair lifts, and stairway chair lifts are covered in Article 620 of the *NEC*. For further information, see *Safety Code for Elevators and Escalators,* ASME/ANSI A17.1-1996, and *Elevator and Escalator Electrical Equipment Certification Standard,* ASME/ANSI A17.5-1996 (CSA B44.1-1996).

All live parts of electrical apparatus in the hoistways, at landings, in or on cars of elevators and dumbwaiters, in the wellways or the landings of escalators or moving walks, or in the runways and machinery spaces of wheelchair lifts and stairway chair lifts must be enclosed to protect against accidental contact. (See *NEC* Section 110.27 for guarding of live parts [600 V, nominal, or less].) The conductors to the hoistway door interlocks from the hoistway riser must be flame retardant and suitable for a temperature of not less than 392°F (200°C). Conductors must be Type SF or equivalent. Other wiring in raceways must have flame-retardant insulation.

Bonding of elevator rails (car and/or counterweight) to a lightning protection system grounding down conductor(s) is permitted. However, the lightning protection system grounding down conductor(s) cannot be located within the hoistway. Elevator rails or other hoistway equipment cannot be used as the grounding down conductor for lightning protection systems. (See *NEC* Section 250.106 for bonding requirements. For further information, see NFPA 780.)

Traveling cables must be suspended at the car and hoistways' ends, or counterweight end where applicable, so as to reduce the strain on the individual copper conductors to a minimum and must be supported by one of the following means: (1) by its steel supporting member(s), (2) by looping the cables around supports for unsupported lengths less than 100 ft (30 m), and (3) by suspending from the supports by a means that automatically tightens around the cable when tension is increased for unsupported lengths up to 200 ft (60 m).

Unsupported length for the hoistway suspension means is that length of cable as measured from the point of suspension in the hoistway to the bottom of the loop, with the elevator car located at the bottom landing. Unsupported length for the car suspension means is that length of cable as measured from the point of suspension on the car to the bottom of the loop, with the elevator car located at the top landing.

Traveling cables used as flexible connections between the elevator or dumbwaiter car or counterweight and the raceway must be of the types listed in *NEC* Table 400.4 or other approved types.

To reduce the danger of electric shock, the following equipment must be effectively grounded in accordance with the grounding requirements of the *NEC:* (1) metal raceways, Type MC cable, Type MI, or Type AC cable attached to elevator cars; (2) the frames of all motors, elevator machines, and controllers; (3) the metal enclosures for all electric devices in or on the car or hoistway; and (4) the frames of nonelectric elevators if accessible to persons and if any electric conductors are attached to the car.

Each 125 V, single-phase, 15- and 20-A receptacle installed in pits, elevator car tops, and in escalator and moving walk wellways must be of the ground-fault circuit-interrupter type, and all 125 V, single-phase, 15- and 20-A receptacles installed in machine rooms and machinery spaces must have ground-fault circuit-interrupter protection for personnel. A single receptacle supplying a permanently installed sump pump does not require ground-fault circuit-interrupter protection. This protection does not include a GFCI circuit breaker located in a distribution panel; the intent is to allow personnel to reset the GFCI receptacle without climbing around in the dark. Receptacles installed in the machine room are allowed to be protected by either a GFCI receptacle or a GFCI circuit breaker.

Heating Cable

Recognized testing laboratories have listed a number of heating cables for use within buildings. These cables are of the resistance type, primarily designed to be used around water pipes to prevent freezing and facilitate the flow of viscous liquids. The cable is secured to the pipe with straps or wrapped around the pipe with the pitch recommended by the manufacturer. Electric heating cables are required to have a grounded metal outer covering. The pipe and heating cable are usually encased in thermal insulation.

Some units incorporate a thermostat that automatically turns on the heating cable when the temperature drops below a predetermined value. The pipe heating cables are intended to be connected to a permanent supply wiring system. Unless specifically indicated otherwise by marking on the heating cables or in the installation instructions, the heating cables are intended for use only on metallic pipes. Ground-fault protection of equipment must be provided for each branch circuit supplying electric heating equipment; this is not GFCI protection. For industrial establishments where only qualified persons will service the installation and the continued circuit operation is necessary for safe operation of the equipment or process, ground-fault protection is not required, but an alarm indication of a ground fault is required.

Electrical heating cables for outdoor ice- and snow-melting systems are covered in the *NEC* Article 426.

ELECTRICAL EQUIPMENT FOR OUTDOOR USE

Electric equipment that is installed outside of buildings must be weatherproof in design, that is, constructed such that exposure to the weather will not interfere with its successful operation; otherwise it must be enclosed in weatherproof cabinets, enclosures designed to prevent moisture or water from entering and accumulating within them. If mounted on a wall or other supporting surface, there should be at least ¼ in. (6 mm) airspace between the box or cabinet and the supporting surface.

Description of Devices

Electric equipment suitable for outdoor use is tested by recognized electrical testing laboratories. The tests encompass the following: (1) suitability of the materials used and the protective coatings for exposure to sunlight, rain, and snow; (2) effects of heat and cold; and (3) provisions for grounding. The term *raintight,* as used in the *NEC,* is applied to equipment that, on exposure to a beating rain, will not let water enter. The term *weatherproof,* as used in the *NEC,* is applied to equipment that, on exposure to the weather, will still operate successfully. Rainproof, raintight, or watertight equipment can fulfill the requirements for weatherproof equipment where varying weather conditions other than wetness—for example, snow, ice, dust, or temperature extremes—are not a factor.

Electric Signs and Outline Lighting

Electric signs and outline lighting, whether fixed, mobile, or portable, are required to be listed. Except for portable indoor signs, signs and outline lighting equipment are usually constructed of metal or other noncombustible material. The spacing between wood or other combustible materials and an incandescent or high-intensity discharge (HID) lamp or lampholder must not be less than 2 in. (50 mm). Enclosures for outside use must be weatherproof. Signs and outline lighting systems must be constructed and installed so that adjacent combustible materials are not subjected to temperature in excess of 194°F (90°C). All steel parts of enclosures must be galvanized or otherwise protected from corrosion. Signs, troughs, tube terminal boxes, and other metal frames must be grounded in the manner specified in the *NEC.*

Each electric sign (other than cord-connected) and each outline lighting installation must be controlled by an external operable switch or circuit breaker (handle on outside of switch enclosure), which will open all ungrounded conductors. The switch or breaker must be within sight of the sign or outline lighting installation unless it is capable of being locked in the open position.

Portable outdoor electric signs must be equipped with factory-installed GFCI protection. The GFCI must be an integral part of the attachment plug or located in the power supply cord within 12 in. (300 mm) of the attachment plug.

Electric Fences

Wire fences with electrical connections to produce a shock when animals come in contact with them are widely used on farms. To avoid hazard to persons and to livestock, the current and the time interval during which the current is on and off must be limited to values that will not cause fatalities or injuries to persons or animals, while still causing an unpleasant sensation of shock. Fatalities and fires can result from homemade equipment supplied from ordinary lighting circuits. The open circuit voltage need not be limited if the current is properly limited. UL Research Bulletin No. 14 and UL 69, "Standard for Safety Electric-Fence Controllers," give detailed information on these installations.

The output characteristics of some controllers are such that combustible material may be readily ignited when a grounded object occupies a position respective to the energized fence to produce an electric arc. To protect against fire from such a cause, users should determine whether the controller has been designed and tested with respect to this hazard. Electric fence controllers listed in accordance with the requirements of UL 69 have been so tested.

Marinas and Boatyards

Wiring in marinas and boatyards presents special outdoor electric equipment problems, which are covered in Article 555 of the *NEC.* Electric service equipment for floating docks or marinas must be located adjacent to, but not on or in, the floating structure. Metal raceways and metal boxes must not be depended on for grounding; a continuous insulated copper conductor, not smaller than 12 AWG, must be provided as an equipment grounding conductor from outlet boxes and receptacles to the service ground. Electrical equipment and wiring located at gasoline dispensing stations must follow the requirements in Article 514 of the *NEC* and NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages.* Wiring over and under navigable water should be subject to approval by the authority having jurisdiction.

LOCATIONS EXPOSED TO MOISTURE AND NONCOMBUSTIBLE DUSTS

Special electric equipment is required for use where moisture and noncombustible dusts might be present. For years, the *NEC* referred to such equipment as *vaportight,* but this term was dropped from the *NEC* because of confusion in the field between equipment so designated and *explosionproof* equipment. Many users assumed that vaportight equipment was safe to use in atmospheres containing flammable gases or vapors (Class I locations), combustible dusts (Class II locations), or easily ignitable fibers or flyings (Class III locations). To avoid this type of misunderstanding, the term *enclosed and gasketed* was developed for this type of equipment. Some inspection authorities permit enclosed and gasketed luminaires (lighting fixtures) in Class I, Division 2; in Class II, Division 2; and in Class III, Divisions 1 and 2 locations when marked to show the operating temperature and maximum wattage of permissible lamps. The

NEC requires luminaires (lighting fixtures) to be marked for use in wet and damp locations when so used.

SIGNALING AND COMMUNICATIONS SYSTEMS

Communications systems, including telephone, telegraph, fire and burglar alarms, and watchman and sprinkler supervisory systems, usually operate with low voltages and currents and, if kept free from accidental contacts with higher voltage systems, they present no unusual hazards. There are, however, *NEC* requirements for the wiring of these systems if the wiring is in a duct, plenum, or other space for environmental air, because of the hazard of spreading products of combustion from one location to another. There are also *NEC* requirements for separation from other systems, such as lighting and power circuits, to minimize imposing higher voltages and current on the communication equipment and conductors. Where fire-rated walls, floors, or ceilings are penetrated, the integrity of the construction assembly must be maintained by proper sealing around cables to prevent the spread of fire or smoke.

Fire alarm systems are classified as nonpower-limited or power-limited. Nonpower-limited cables (NPLFAs) must be identified and listed as NPLFP, where installed in spaces used for environmental air; NPLFR, where used as a vertical riser from floor to floor or in shafts; and NPLF, where used for general purpose in other than risers, ducts, plenums, or environmental air-handling spaces. Power-limited systems (PLFAs) must be identified and listed with the following markings: FPLP, FPLR, and FPL; these are similar to those of nonpower-limited cables.

Signaling systems and communications systems must be installed in accordance with Articles 725, 760, and 800 of the *NEC,* and *NFPA 72®*, *National Fire Alarm Code®*, which covers the proper electrical wiring and equipment for fire alarm services. *NFPA 72* has cross references to the *NEC.* Telephone communications circuits may be used for completing the fire-protective circuits between the protected premises and fire alarm headquarters.

EMERGENCY SYSTEMS

Requirements for the installation, operation, and maintenance of emergency system circuits and equipment are given in Article 700 of the *NEC.* The systems are intended to supply light and power when the normal supply fails. They are generally installed in places of assembly where artificial lighting is required, such as auditoriums, theaters, sports arenas, and so on, occupied by large numbers of persons (Figures 8.13.27 and 8.13.28). In Figure 8.13.27, the heavy lines represent walls required by typical local building codes to be of fire-rated construction. The light lines represent walls not required by typical local building codes to be of fire-rated construction.

Legally required standby systems installed to serve loads such as heating and refrigeration systems, communications systems, ventilation and smoke removal systems, sewerage disposal, lighting systems, and industrial processes, that, when stopped during any interruption of the normal electrical supply, could create hazards or hamper rescue or fire-fighting operations, are covered in Article 701 of the *NEC.* NFPA 110, *Standard for Emergency and Standby Power Systems,* covers the performance requirements for such systems.

NFPA *101®*, *Life Safety Code®*, specifies where emergency lighting is considered essential for life safety. NFPA 99 gives minimum factors governing the design, operation, and maintenance of those portions of health care facility electrical systems where any degree of interruption would jeopardize the effective and safe care of hospitalized patients. The provisions in NFPA 99 do not supersede the recommendations in NFPA *101* or the *NEC,* which both limit the type of alternative source of electrical power allowable for use to ensure electric power continuity in health care facilities. NFPA 99 recognizes the progressively greater dependence being placed on electrical apparatus for the preservation of life of hospitalized patients and is a guide in the selection of the electrical services for emergency supply to all lighting and power equipment considered essential, and for their design and maintenance in health care facilities.

The sources of electric current that can be used for emergency lighting equipment are (1) storage batteries of suitable capacity, (2) a generator driven by some form of prime mover, and (3) a second electric service separated electrically and physically from the regular service to minimize the possibility of simultaneous interruption of both services. NFPA 99 stipulates that the alternative source of power for health care facilities be prime-mover-driven generators or, where the normal source is an on-site generator, an external utility service may be the alternative source. Means must be provided for automatically energizing emergency lights on failure of the regular lighting system supply. For hospitals, the transition time from the instant of failure of the normal power source to an emergency generator source must not exceed 10 seconds.

Audible and visual signal devices are provided, where practical, to (1) warn of impairment of the emergency source, (2) indicate that the battery or generator is carrying load, (3) indicate when a battery charger is functioning properly, and (4) indicate a ground fault on large 480Y/277 volt systems.

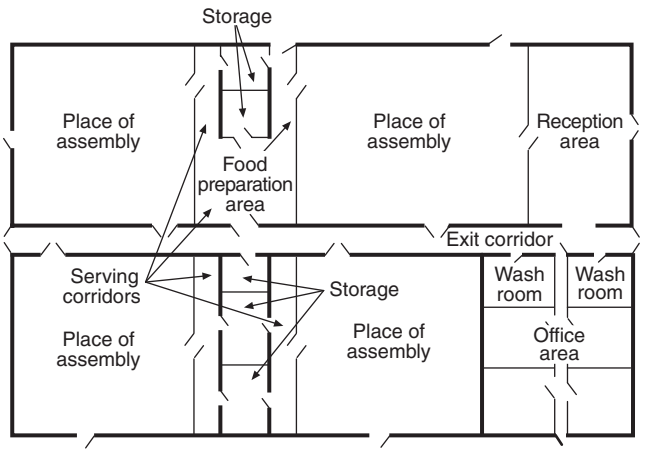

FIGURE 8.13.27 Walls in Places of Assembly Requiring (heavy lines) and Not Requiring (light lines) Fire-Rated Construction by Typical Local Building Codes

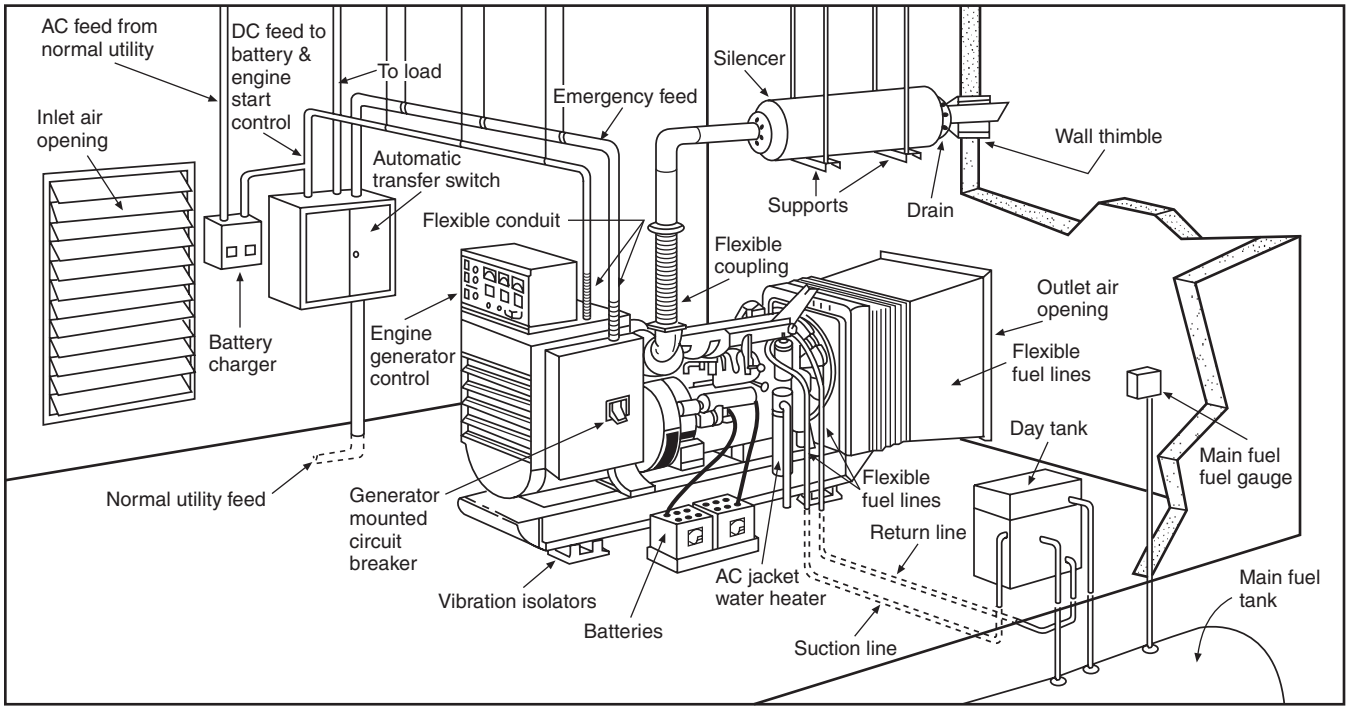

FIGURE 8.13.28 Typical Installation of a Diesel-Powered Standby Generator Such as Might Be Used for Emergency Light and Power Systems

No appliances or lamps, other than those required for emergency use, are to be supplied by the emergency lighting circuits. A good emergency lighting system is designed so that the failure of any individual lighting element, such as the burning out of a lightbulb, cannot leave any space in total darkness.

The emergency lighting circuit wiring is independent of all other wiring and equipment and must not enter the same raceway, cable, box, or cabinet with other wiring except at transfer switches and at exit lighting fixtures supplied from both the normal and the emergency sources.

A transfer switch that supplies emergency power is not allowed to also supply normal loads. Loads other than emergency loads must be supplied from a different transfer switch.

It is good practice to test the complete system on installation and periodically thereafter to ensure it is maintained in proper operating condition. A written record should be kept of such tests and maintenance.

SPECIAL OCCUPANCY ELECTRICAL PROBLEMS

Hazardous (classified) locations and other special problems require individual attention for which the *NEC* has specific recommendations.

Hazardous (Classified) Locations—General

The *NEC* recognizes an additional method of classification of hazardous locations. This method uses zones that are consistent with the rules of the International Electrotechnical Commission (IEC). The method is described in Article 505 of the *NEC.*

Electric power for lighting, motors, controls, and instrumentation, along with their associated wiring, is necessary or desirable in many hazardous locations. Due to the presence of flammable liquids, gases, vapors, combustible dusts, or readily ignitable fibers or flyings in these areas, special electrical equipment and wiring methods are necessary to prevent ignition and to minimize the occurrence of fire and explosion.

A flammable liquid, as it pertains to Article 500 of the *NEC,* is defined as follows: "A liquid having a flashpoint below 100°F (37.8°C) and having a vapor pressure not exceeding 40 psia at 100°F (37.8°C) shall be known as a Class I liquid."

Explosionproof apparatus is defined in the *NEC* as follows: "Apparatus enclosed in a case that is capable of withstanding an explosion of a specified gas or vapor that may occur within it and of preventing the ignition of a specified gas or vapor surrounding the enclosure by sparks, flashes or explosion of the gas or vapor within, and that operates at such an external temperature that a surrounding flammable atmosphere will not be ignited thereby."

In Article 500 of the *NEC,* hazardous (classified) locations are divided into three classes depending on the kind of hazardous material involved; each class is further divided into two divisions according to the likelihood of the potential hazard existing. For the purposes of testing for approval and area classification, various air mixtures (not oxygen enriched) have been grouped on the basis of their characteristics. The groups are given in Tables 8.13.18 through 8.13.21 (statistics from Section 500.3 of

TABLE 8.13.18 Group Classification and Autoignition Temperature (AIT) of Selected Flammable Gases and Vapors of Liquids Having Flashpoints Below 100°F (37.8°C)

		AIT	
Material	*Group*	*°F*	*°C*
Acetaldehyde	C[a]	347	175
Acetone	D[a]	869	465
Acetonitrile	D	975	524
Acetylene	A[a]	581	305
Acrolein (inhibited)[b]	B (C)[a]	455	235
Acrylonitrile	D[a]	898	481
Allyl alcohol	C[a]	713	378
Allyl chloride	D	905	485
Ammonia	D[a]P[c]	928	498
n-Amyl acetate	D	680	360
sec-Amyl acetate	D	—	—
Benzene	D[a]	1040	560
1,3-Butadiene[b]	B (D)[a]	788	420
Butane	D[a]	550	288
1-Butanol	D[a]	650	343
2-Butanol	D[a]	761	405
n-Butyl acetate	D[a]	790	421
iso-Butyl acetate	D[a]	790	421
sec-Butyl acetate	D	—	—
Butylamine	D	594	312
Butylene	D	725	385
Butyl mercaptan	C	—	—
n-Butyraldehyde	C[a]	425	218
Carbon disulfide[d]	—[a]	194	90
Carbon monoxide	C[a]	1128	609
Chlorobenzene	D	1099	593
Chloroprene	D	—	—
Crotonaldehyde	C[a]	450	232
Cyclohexane	D	473	245
Cyclohexene	D	471	244
Cyclopropane	D[a]	938	503
1,1-Dichloroethane	D	820	438
1,2-Dichloroethylene	D	860	460
1,3-Dichloropropene	D	—	—
Dicyclopentadiene	C	937	503
Diethyl ether	C[a]	320	160
Diethylamine	C[a]	594	312
Di-isobutylene	D[a]	736	391
Di-isopropylamine	C	600	316
Dimethylamine	C	752	400
1,4-Dioxane	C	356	180
Di-*n*-propylamine	C	570	299
Epichlorohydrin	C[a]	772	411
Ethane	D[a]	882	472
Ethanol	D[a]	685	363
Ethyl acetate	D[a]	800	427
Ethyl acrylate (inhibited)	D[a]	702	372
Ethylamine	D[a]	725	385
Ethyl benzene	D	810	432
Ethyl chloride	D	966	519
Ethylene	C[a]	842	450
Ethylenediamine	D[a]	725	385
Ethylene dichloride	D[a]	775	413
Ethylenimine	C[a]	608	320
Ethylene oxide[b]	B (C)[a]	804	429
Ethyl formate	D	851	455
Ethyl mercaptan	C[a]	572	300
n-Ethyl morpholine	C	—	—
Formaldehyde (gas)	B	795	429
Gasoline	D[a]	536–880	280–471
Heptane	D[a]	399	204
Heptene	D	500	260
Hexane	D[a]	437	225
2-Hexanone	D	795	424
Hexenes	D	473	245
Hydrogen	B[a]	752	400
Hydrogen cyanide	C[a]	1000	538
Hydrogen selenide	C	—	—
Hydrogen sulfide	C[a]	500	260
Isoamyl acetate	D	680	360
Isoamyl alcohol	D	662	350
Isobutyl acrylate	D	800	427
Isobutyraldehyde	C	385	196
Isoprene	D[a]	743	395
Isopropyl acetate	D	860	460
Isopropylamine	D	756	402
Isopropyl ether	D[a]	830	443
Isopropyl glycidyl ether	C	—	—
Liquefied petroleum gas	D	761–842	405–450
Manufactured gas (containing more than 30% H_2 by volume)	B[a]	—	—
Mesityl oxide	D[a]	652	344
Methane	D[a]	999	537
Methanol	D[a]	725	385
Methyl acetate	D	850	454
Methylacetylene	C[a]	—	—
Methylacetylene-propadiene (stabilized)	C	—	—
Methyl acrylate	D	875	468
Methylamine	D	806	430
Methylcyclohexane	D	482	250
Methyl ether	C[a]	662	350
Methyl ethyl ketone	D[a]	759	404
Methyl eormal	C[a]	460	238
Methyl eormate	D	840	449
Methyl isobutyl ketone	D[a]	840	440
Methyl isocyanate	D	994	534
Methyl mercaptan	C	—	—
Methyl methacrylate	D	792	422
2-Methyl-1-propanol	D[a]	780	416
2-Methyl-2-propanol	D[a]	892	478
Monomethyl hydrazine	C	382	194
Naphtha (petroleum)[e]	D[a]	550	288
Nitroethane	C	778	414
Nitromethane	C	785	418
Nonane	D	401	205
Nonene	D	—	—

(continued)

TABLE 8.13.18 Continued

Material	Group	AIT °F	AIT °C
Octane	D[a]	403	206
Octene	D	446	230
Pentane	D[a]	470	243
1-Pentanol	D[a]	572	300
2-Pentanone	D	846	452
1-Pentene	D	527	275
Propane	D[a]	842	450
1-Propanol	D[a]	775	413
2-Propanol	D[a]	750	399
Propionaldehyde	C	405	207
n-Propyl acetate	D	842	450
Propylene	D[a]	851	455
Propylene dichloride	D	1035	557
Propylene oxide[b]	B (C)[a]	840	449
n-Propyl ether	C[a]	419	215
Propyl nitrate	B[a]	347	175
Pyridine	D[a]	900	482
Styrene	D[a]	914	490
Tetrahydrofuran	C[a]	610	321
Toluene	D[a]	896	480
Triethylamine	C[a]	—	—
Tripropylamine	D	—	—
Turpentine	D	488	253
Unsymmetrical dimethyl hydrazine (UDMH)	C[a]	480	249
Valeraldehyde	C	432	222
Vinyl acetate	D[a]	756	402
Vinyl chloride	D[a]	882	472
Vinylidene chloride	D	1058	570
Xylenes	D[a]	867–984	464–529

[a]Material has been classified by test.
[b]If equipment is isolated by sealing all conduit (trade size) ½ in. or larger, in accordance with Section 501.5(A) of the *NEC,* equipment for the group classification shown in parentheses is permitted.
[c]For classification of areas involving ammonia, see "Safety Code for Mechanical Refrigeration," ANSI/ASHRAE 15, and "Safety Requirements for the Storage and Handling of Anhydrous Ammonia," ANSI/CGA G2.1.
[d]Certain chemicals may have characteristics that require safeguards beyond those required for any of the above groups. Carbon disulfide is one of these chemicals because of its low autoignition temperature and the small joint clearance to arrest its flame propagation.
[e]Petroleum naphtha is a saturated hydrocarbon mixture whose boiling range is 68 to 274°F (20 to 135°C). It is also known as benzine, ligroin, petroleum ether, and naphtha.

Sources: NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas.* Autoignition temperatures listed above are the lowest value for each material as listed in NFPA's *Fire Protection Guide to Hazardous Materials,* which was originally NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids,* or as reported in an article by Hilado, C. J., and Clark, S. W., *Chemical Engineering,* Sept. 4, 1972. NFPA 325 has been officially withdrawn from the National Fire Codes®; the information is still available in NFPA's *Fire Protection Guide to Hazardous Materials.*

TABLE 8.13.19 Selected Nonconductive Dusts Classified as Group G—Ignition Sensitivity Equal to or Greater Than 0.2; Explosion Severity Equal to or Greater Than 0.5

	Minimum Cloud or Layer Ignition Temperature* °F		°C
Agricultural Dusts			
Alfalfa meal	392		200
Cellulose	500		260
Cinnamon	446		230
Cocoa, natural, 19% fat	464		240
Corn	482		250
Corncob grit	464		240
Corn dextrine	698		370
Cornstarch, commercial	626		330
Cork	410		210
Cottonseed meal	392		200
Garlic, dehydrated	680	NL	360
Malt barley	482		250
Milk, skimmed	392		200
Potato starch, dextrinated	824	NL	440
Rice	428		220
Rice bran	914	NL	490
Rice hull	428		220
Safflower meal	410		210
Soy flour	374		190
Soy protein	500		260
Sucrose	662	Cl	350
Sugar, powdered	698	Cl	370
Wheat	428		220
Wheat flour	680		360
Wheat starch	716	NL	380
Wheat straw	428		220
Woodbark, ground	482		250
Wood flour	500		260
Yeast, torula	500		260
Chemicals			
Acetoacetanilide	824	M	440
Adipic acid	1022	M	550
Anthranilic acid	1076	M	580
Azelaic acid	1130	M	610
2,2-Azo-bis-butyronitrile	662		350
Benzoic acid	824		440
Benzotriazole	824	M	440
Bisphenol-A	1058	M	570
Chloroacetoacetanilide	1184	M	640
Diallyl phthalate	896	M	480
Dihydroacetic acid	806	NL	430
Dimethyl isophthalate	1076	M	580
Dimethyl terephthalate	1058	M	570
3,5-Dinitrobenzoic acid	860	NL	460
Diphenyl	1166	M	630
Ethyl hydroxyethyl cellulose	734	NL	390
Fumaric acid	968	M	520
Hexamethylene tetramine	770	S	410
Hydroxyethyl cellulose	770	NL	410
Isotoic anhydride	1292	NL	700

TABLE 8.13.19 Continued

	Minimum Cloud or Layer Ignition Temperature*		
	°F		°C
Chemicals *(continued)*			
Paraphenylene diamine	1148	M	620
Paratertiary butyl benzoic acid	1040	M	560
Pentaerythritol	752	M	400
Phthalic anhydride	1202	M	650
Salicylanilide	1130	M	610
Sorbic acid	860		460
Stearic acid, aluminum salt	572		300
Stearic acid, zinc salt	950	M	510
Sulfur	428		220
Terephthalic acid	1256	NL	680
Drugs			
Aspirin	1220	M	660
Gulasonic acid, diacetone	788	NL	420
Mannitol	860	M	460
l-Sorbose	698	M	370
Vitamin B1, mononitrate	680	NL	360
Vitamin C (ascorbic acid)	536		280
Dyes, Pigments, Intermediates			
Green base harmon dye	347		175
Red dye intermediate	347		175
Violet 200 dye	347		175
Pesticides			
Crag No. 974	590	Cl	310
Dieldrin (20%)	1022	NL	550
Dithane	356		180
Ferban	302		150
Manganese vancide	248		120
Sevin	284		140
Thermoplastic Resins and Molding Compounds			
Acetal resins			
Acetal, linear (polyformaldehyde)	824	NL	440
Acrylic resins			
Acrylamide polymer	464		240
Acrylonitrile polymer	860		460
Acrylonitrile-vinyl chloride-vinylidene chloride copolymer (70-20-10)	410		210
Methyl methacrylate polymer	824	NL	440
Methyl methacrylate-ethyl acrylate copolymer	896	NL	480
Methyl methacrylate-ethyl acrylate-styrene copolymer	824	NL	440
Methyl methacrylate-styrene-butadiene-acrylonitrile copolymer	896	NL	480
Methacrylic acid polymer	554		290
Cellulosic resins			
Cellulose acetate	644		340
Cellulose triacetate	806	NL	430
Cellulose acetate butyrate	698	NL	370

	Minimum Cloud or Layer Ignition Temperature*		
	°F		°C
Thermoplastic Resins and Molding Compounds *(continued)*			
Nylon (polyamide) resins			
Nylon polymer (polyhexamethylene adipamide)	806		430
Polycarbonate resins			
Polycarbonate	1310	NL	710
Polyethylene resins			
Polyethylene, high-pressure process	716		380
Polyethylene, low-pressure process	788	NL	420
Polyethylene wax	752	NL	400
Polymethylene resins			
Carboxypolymethylene	968	NL	520
Polypropylene resins			
Polypropylene (no antioxidant)	788	NL	420
Rayon resins			
Rayon (viscose) flock	482		250
Styrene resins			
Polystyrene molding cmpd.	1040	NL	560
Polystyrene latex	932		500
Styrene-acrylonitrile (70-30)	932	NL	500
Styrene-butadiene latex (>75% styrene; alum coagulated)	824	NL	440
Vinyl resins			
Polyvinyl acetate	1022	NL	550
Polyvinyl acetate/alcohol	824		440
Vinyl chloride-acrylonitrile copolymer	878		470
Vinyl toluene-acrylonitrile butadiene copolymer	936	NL	530
Allyl resins			
Allyl alcohol derivative (CR-39)	932	NL	500
Amino resins			
Urea formaldehyde molding compound	860	NL	460
Urea formaldehyde-phenol formaldehyde molding compound (wood flour filler)	464		240
Epoxy resins			
Epoxy	1004	NL	540
Epoxy-bisphenol A	950	NL	510
Phenolic resins			
Phenol formaldehyde	1076	NL	580
Phenol formaldehyde molding compound (wood flour filler)	932	NL	500
Polyester resins			
Polyethylene terephthalate	932	NL	500
Styrene modified polyester-glass fiber mixture	680		360
Polyurethane resins			
Polyurethane foam, no fire retardant	824		440

(continued)

TABLE 8.13.19 Continued

	Minimum Cloud or Layer Ignition Temperature*		
	°F		°C
Special Resins and Molding Compounds			
Ethylene oxide polymer	662	NL	350
Ethylene-maleic anhydride copolymer	1004	NL	540
Petroleum resin (blown asphalt)	932		500
Rubber, crude, hard	662	NL	350
Rubber, synthetic, hard (33% S)	608	NL	320

Notes: Cl: cloud ignition temperature is shown; NL: no layer ignition temperature is available and the cloud ignition temperature is shown; M: dust layer melts before it ignites, and the cloud ignition temperature is shown; S: dust layer sublimes before it ignites, and the cloud ignition temperature is shown.

*Normally, the minimum ignition temperature of a layer of a specific dust is lower than the minimum ignition temperature of a cloud of that dust. Because this is not universally true, the lower of the two minimum ignition temperatures is listed. If no symbol appears between the two temperature columns, then the layer ignition temperature is shown.

the *NEC* and tables from NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*). For Group A, B, C, and D materials with flashpoints of 100°F (38°C) and higher, see NFPA 497. For a more complete table of Group G dusts and information on Group E dusts, see Table 8.13.18 and NFPA 497.

Group G includes combustible dusts, such as wood, flour, grain, corn starch, cocoa, food, chemical, and plastics dusts. Coal, coke, and carbonaceous dusts are classified in Group F. Group E includes metal dusts and other dusts of similarly hazardous characteristics.

Determining the proper group classification for flammable gases and vapors involves a determination of explosion pressures and maximum safe clearance between parts of a clamped joint under several conditions and comparison of the values obtained with those obtained for materials that have already been evaluated.

Listed equipment is marked to show the class, group, and operating temperature, or temperature range, referenced to a 248°F (120°C) ambient. The temperature range, if provided, is indicated by identification numbers, as shown in Table 8.13.22. The identification numbers are marked on equipment nameplates.

The ignition temperature of a liquid, solid, or gaseous substance is the minimum temperature required to initiate or cause self-sustained combustion, independent of the heating or heated element. The flashpoint and the ignition temperature are not the same, and the flashpoint is always lower than the ignition temperature.

Because there is no consistent relationship among explosion properties, explosion pressure, maximum experimental safe gap, minimum ignition energy, and ignition temperature, testing requirements for groups and classes are independent of each other.

TABLE 8.13.20 Selected Carbonaceous Dusts Classified as Group E—Ignition Sensitivity Equal to or Greater Than 0.2; Explosion Severity Equal to or Greater Than 0.5

Material[a]	Minimum Cloud or Layer Ignition Temperature[b] °F		°C
Aluminum, atomized collector fines	1022	Cl	550
Aluminum, A422 flake	608		320
Aluminum-cobalt alloy (60-40)	1058		570
Aluminum-copper alloy (50-50)	1526		830
Aluminum-lithium alloy (15% Li)	752		400
Aluminum-magnesium alloy (downmetal)	806	Cl	430
Aluminum-nickel alloy (58-42)	1004		540
Aluminum-silicon alloy (12% Si)	1238	NL	670
Boron, commercial-amorphous (85% B)	752		400
Calcium silicide	1004		540
Chromium, (975) electrolytic, milled	752		400
Ferromanganese, medium carbon	554		290
Ferrisilicon (885, 9% Fe)	1472		800
Ferrotitanium (19% Ti, 74.1% Fe, 0.06% C)	698	Cl	370
Iron 98% H_2 reduced	554		290
Iron 99% carbonyl	590		310
Magnesium, Grade B, milled	806		430
Manganese	464		240
Tantalum	572		300
Thorium, 1.2% O_2	518	Cl	270
Tin, 96%, atomized (2% Pb)	806		430
Titanium, 99%	626	Cl	330
Titanium hydride (95% Ti, 3.8% H_2)	896	Cl	480
Vanadium, 86.4%	914		490
Zirconium hydride (93.6% Zr, 2.1% H_2)	518		270

[a]Certain metal dusts may have characteristics that require safeguards beyond those required for atmospheres containing the dusts of aluminum, magnesium, and their commercial alloys. For example, zirconium, thorium, and uranium dusts have extremely low ignition temperatures (as low as 68°F [20°C]) and minimum ignition energies lower than any material classified in any of the Class I or Class II groups.

[b]Normally, the minimum ignition temperature of a layer of a specific dust is lower than the minimum ignition temperature of a cloud of that dust. Because this is not universally true, the lower of the two minimum ignition temperatures is listed. If no symbol appears between the two temperature columns, then the lower ignition temperature is shown. "Cl" means the cloud ignition temperature is shown. "NL" means that no layer ignition temperature is available and the cloud ignition temperature is shown.

Source: NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*.

The operating temperature markings specified in Table 8.13.22 are not to exceed the ignition temperature of the specific gas or vapor to be encountered.

For information regarding ignition temperatures of gases and vapors, see Table 8.13.18, NFPA 497, and NFPA's *Fire Protection Guide to Hazardous Materials.*

TABLE 8.13.21 Selected Carbonaceous Dusts Classified as Group F—Ignition Sensitivity Equal to or Greater Than 0.2; Explosion Severity Equal to or Greater Than 0.5

Material	Minimum Cloud or Layer Ignition Temperature* *°F*		*°C*
Asphalt, (blown petroleum resin)	950	CI	510
Charcoal	356		180
Coal, Kentucky bituminous	356		180
Coal, Pittsburgh experimental	338		170
Coal, Wyoming	—		—
Gilsonite	932		500
Lignite, California	356		180
Pitch, coal tar	1310	NL	710
Pitch, petroleum	1166	NL	630
Shale, oil	—		—

*Normally, the minimum ignition temperature of a layer of a specific dust is lower than the minimum ignition temperature of a cloud of that dust. Because this is not universally true, the lower of the two minimum ignition temperatures is listed. If no symbol appears between the two temperature columns, then the layer ignition temperature is shown. "CI" means the cloud ignition temperature is shown. "NL" means that no layer ignition temperature is available and the cloud ignition temperature is shown.

Source: NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*.

TABLE 8.13.22 Temperature Identification Numbers

Maximum Temperature *°F*	*°C*	*Identification Number*
842	450	T1
572	300	T2
536	280	T2A
500	260	T2B
446	230	T2C
419	215	T2D
392	200	T3
356	180	T3A
329	165	T3B
320	160	T3C
275	135	T4
248	120	T4A
212	100	T5
185	85	T6

Classes on Divisions of Hazardous Locations

Complete definitions of the several classes and divisions of hazardous (classified) locations and the methods of wiring and types of electrical equipment to be used in each are covered in detail in the *NEC*. Rules applying specifically to commercial garages, aircraft hangars, gasoline dispensing facilities and service stations, bulk storage plants, finishing processes, and areas in health care facilities containing flammable anesthetics are also covered in the *NEC*.

Class I, Division 1. This division includes locations in which (1) ignitable concentrations of flammable gases or vapors can exist under normal operating conditions; (2) ignitable concentrations of such gases or vapors may exist frequently because of repair or maintenance operations or leakage; or (3) breakdown or faulty operation of equipment or processes might release ignitable concentrations of gases or vapors, and might also cause simultaneous failure of electrical equipment in such a way as to directly cause the electrical equipment to become a source of ignition. Motors and other rotating electrical machinery, luminaires (lighting fixtures), most switches, circuit breakers, and similar electrical equipment in these locations must be of the explosionproof type or purged type approved for Class I locations of the proper group (see NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment*) (Figures 8.13.29, 8.13.30, and 8.13.31). Approved intrinsically safe equipment and circuits may also be used. These are usually limited to low-energy control, signal, and instrumentation systems.

Class I, Division 2. This division includes locations (1) in which volatile flammable liquids or flammable gases are handled, processed, or used, but in which the liquids, vapors, or gases will normally be confined within closed containers or closed systems from which they can escape only in case of accidental rupture or breakdown of such containers or systems, or in case of abnormal operation of equipment; (2) in which ignitable concentrations of gases or vapors are normally prevented by positive mechanical ventilation, and that might become hazardous through failure or abnormal operation of the ventilating equipment; or (3) that are adjacent to Class I, Division 1 locations, and to which ignitable concentrations of gases or vapors might occasionally

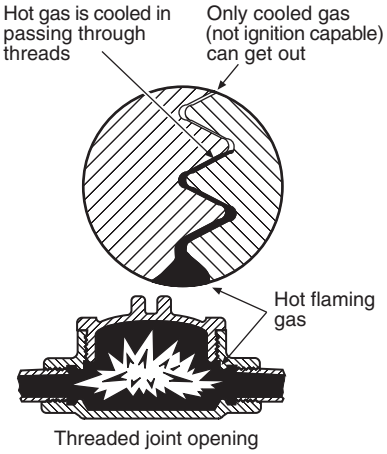

FIGURE 8.13.29 Principle of "Explosionproof" Equipment, Indicating Containment of Hot Gases Within the Enclosure

FIGURE 8.13.30 Typical Luminaire for Use in Class I, Group C and D Locations (Source: Appleton Electric LLC, EGS Electrical Group)

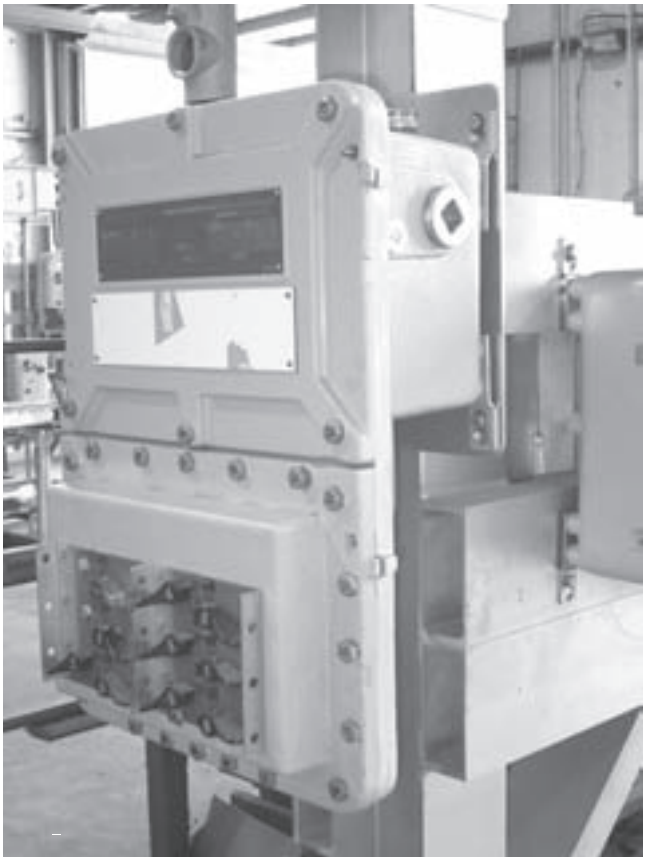

FIGURE 8.13.31 Explosionproof Panelboard (Source: Appleton Electric LLC, EGS Electrical Group)

be communicated unless such communication is prevented by adequate positive-pressure ventilation from a source of clean air, and effective safeguards against ventilation failure are provided. In general, ordinary types of motors that do not have brushes, switching mechanisms, and so on may be installed in these locations, but motors that do have sliding contacts, switches, and so on must have the switches in explosionproof or other type enclosure approved for Class I, Division 2 locations. Lamps that operate at temperatures above the ignition temperature of the gas or vapor involved must have approved explosionproof or purged enclosures. Units located where falling sparks or hot metal from broken lamps might ignite localized concentrations of flammable gases below the Division 2 location must also have suitable enclosures. Switches, circuit breakers, controllers, and other devices that create arcs or sparks and that are intended to interrupt ignition-capable energy in normal operation must either be explosionproof, have their contacts in hermetically sealed chambers, or have contacts immersed in oil. Enclosures for electrical equipment that does not interrupt ignition-capable energy or otherwise represent an ignition source under normal conditions may be of the general-purpose type. Portable lamps must be of the type satisfactory for use in a Class I, Division 1 location.

Class II, Division 1. This division includes locations (1) in which combustible dust is in the air under normal operating conditions in sufficient quantities to produce explosive or ignitable mixtures; (2) where mechanical failure or abnormal operation of machinery or equipment might cause such explosive or ignitable mixtures to be produced, and might also provide a source of ignition through simultaneous failure of electric equipment, operation of protective devices, or from other causes; or (3) in which combustible dusts of an electrically conductive nature may be present in hazardous quantities. Motors must be of an enclosed type approved as dust-ignitionproof for the proper Class II locations. Luminaires (lighting fixtures), switches, circuit breakers, controllers, and fuses that are intended to interrupt current in normal operation must be provided with dust-ignitionproof enclosures approved for the proper Class II locations. Maximum surface temperatures on equipment in Class II locations under actual operating conditions must not exceed the ignition temperature of the dust. See Tables 8.13.19 through 8.13.21 for information regarding ignition temperatures of dusts. For additional information, see NFPA 497.

Class II, Division 2. This division includes locations (1) in which combustible dust is not normally in the air in quantities sufficient to produce explosive or ignitable mixtures, and dust accumulations are normally insufficient to interfere with normal operation of electrical equipment or other apparatus, but combustible dust may be in suspension in the air as a result of infrequent malfunctioning of handling or processing equipment; and (2) where combustible dust accumulations on, in, or in the vicinity of the electrical equipment may be sufficient to interfere with the safe dissipation of heat from the electrical equipment or may be ignitable by abnormal operation or failure of electrical equipment. In general, totally enclosed motors are suitable. Under certain conditions, standard, open-type motors without sliding contacts, switches, and so on may be used in many of

these locations. Fixed lamps and lampholders must have enclosures designed to minimize the deposit of dust and prevent the escape of sparks, burning material, or hot metal. Switches, circuit breakers, controllers, and fuses should be provided with dust-tight enclosures. Division 1 temperature limits also apply to Division 2 locations.

Class III, Division 1. This division includes locations in which easily ignitable fibers or materials producing combustible flyings are handled, manufactured, or used. In general, motors in these locations must be of the enclosed type except that, where only moderate accumulations of lint are present and cleaning and maintenance are satisfactory, self-cleaning, squirrel-cage, textile motors or standard, open-type motors without sliding contacts, switches, and so on may be installed. Lamps and lampholders, switches, circuit breakers, controllers, and fuses must be dust-tight. Maximum surface temperatures under actual operating conditions must not exceed 329°F (165°C) for equipment that is not subject to overloading, and 248°F (120°C) for equipment, such as motors, power transformers, and so on, that may be overloaded.

Class III, Division 2. This division includes locations in which easily ignitable fibers are stored or handled other than in process of manufacture. Motors must be of the enclosed type. Lamps, lampholders, switches, circuit breakers, controllers, and fuses must have enclosures similar to those specified for Class III, Division 1 locations. Division 1 temperature limits apply to Division 2 locations.

Equipment for Use in Hazardous Locations

Equipment for use in Class I, Division 1 hazardous (classified) locations, as defined in the *NEC,* is sometimes referred to as *explosionproof* equipment. The two basic design criteria for explosionproof apparatus for Class I locations are that it (1) withstand internal explosions of flammable gas or vapor-air mixtures and (2) prevent propagation of the internal explosion to the surrounding flammable atmosphere. In other words, it is recognized that surrounding flammable gas or vapor-air mixtures will enter the enclosure of this equipment and the possibility exists of their ignition within the enclosure. To prevent the propagation of flame to the outside surrounding atmosphere, which may likewise contain flammable vapor-air mixtures, the enclosures of this equipment must (1) arrest flame at joints or other openings to the outside, (2) be of sufficient strength to resist (without rupture or serious distortion) the internal pressure, and (3) ensure that the external surface temperature of the enclosure is not high enough to ignite the surrounding gas or vapor. The various gas or vapor-air mixtures vary considerably with respect to (1) the propagation of flames through joints of such assemblies, (2) the pressure developed within the enclosure following ignition, and (3) the ignition temperature of the gas or vapor-air mixture. Thus, equipment should be tested and listed for use, and the various groups listed in Table 8.13.18 should be addressed, as necessary.

Equipment for use in Class I hazardous (classified) locations must also be designed to operate under full load and, in the case of equipment such as motors likely to be overloaded, must operate under overload conditions without developing surface temperatures above the ignition temperature of the flammable gas or vapor with which it is intended to be used.

As an alternative to explosionproof motors, controllers, luminaires (lighting fixtures), switches, or equipment approved for use in Class I locations, it is permissible to use either of the following two designs:

1. *Pressurizing system.* The protected enclosure must be constantly maintained at a positive pressure of at least 0.1 in. water (25 Pa) above the surrounding atmosphere during operation of the protected equipment and if a positive pressure is not maintained in a protected enclosure, a suitable device such as an indicator, alarm, cutoff, or interlock switch must warn the user to take action or must automatically de-energize power from ignition-capable equipment. The type of device should be dependent on the type of pressurization used. An alarm must be provided to indicate failure of the protective gas supply to maintain the required pressure. If Type X pressurized equipment is provided with a protective gas supply, an alarm is not required. Electric motors require at least 10 volumes of air while maintaining a positive internal pressure of at least 0.1 in. water (25 Pa), in order to accomplish proper purging of the voids between windings.

2. *Protective gas system.* The protective gas must be essentially free of contaminants or foreign matter and can contain no more than trace amounts of flammable vapor or gas. Protective gas supplies must be carefully designed to minimize chances for contamination. Air of normal instrument quality, nitrogen, or other nonflammable gas is acceptable as protective gas. Piping for the protective gas must be protected against mechanical damage. If compressed air is used, the compressor intake must be located in an unclassified location. If the compressor intake line passes through a classified location, it must be constructed of noncombustible material, designed to prevent leakage of flammable gases, vapors, or dusts into the protective gas, and protected against mechanical damage and corrosion. In addition, the electrical power for the protective gas supply (blower, compressor, etc.) must be supplied either from a separate power source or from the protected enclosure power supply before any service disconnects to the protected enclosure. When "double pressurization" is used (e.g., a Division 1 enclosed area pressurized to a Division 2 classification that contains ignition-capable equipment also protected by pressurization), the protective gas supplies must be independent.

When either of these designs is used, no external surface of the motors, generators, or other rotating electrical machinery can have an operating temperature (°C) that exceeds 80 percent of the ignition temperature (°C) of the gas or vapor involved, as determined by ASTM E659, "Autoignition Temperature of Liquid Chemicals." Appropriate devices (heat sensors) must also be provided to detect any increase in temperature of the equipment beyond its design limits and then to automatically de-energize the equipment. The detectors and control equipment used are to be suitable for the atmosphere involved without positive pressure; in other words, they must be explosionproof or intrinsically safe if the location is Class I, Division 1.

NFPA 496 provides information for the design of purged enclosures for the purpose of eliminating or reducing within

the enclosure a Class I hazardous (classified) location (gases or vapors in air in quantities sufficient to produce explosive or ignitable mixtures). Protective measures include supplying an enclosure with clean air or an inert gas at sufficient flow and positive pressure to achieve and maintain an acceptable safe level of the atmosphere.

Another alternative is the use of intrinsically safe systems, which are assemblies of interconnected intrinsically safe apparatus, associated apparatus, and interconnecting cables whose parts that are located in hazardous (classified) locations are intrinsically safe circuits. An intrinsically safe circuit is a circuit in which any spark or thermal effect is incapable of releasing sufficient electrical energy under normal or abnormal conditions to cause ignition of a specific hazardous atmospheric mixture in air under prescribed test conditions.

In many cases, the amount of explosionproof, purged, or intrinsically safe equipment required can be reduced through the exercise of ingenuity in the layout of electrical installations by locating much of the equipment in nonhazardous areas. The extent of the hazardous areas is normally defined by the codes and standards relating to the storage and handling of the specific flammable liquids, gases, or solids.

Equipment for use in Class II and Class III hazardous (classified) locations presents a somewhat different problem, because the equipment is designed to be dust-ignitionproof for Class II, Division 1 and for some Class II, Division 2 locations, and to be dust-tight or totally enclosed with telescoping covers for some Class II, Division 2 locations and for Class III locations. It is thus not intended to resist internal explosions of a dust-air mixtures. Such equipment is tested in specific dust-air mixtures to determine that the enclosures are dust-ignitionproof for Class II locations and that overheating does not occur when the device is blanketed with dust or lint and flyings.

Garages, Commercial (Repair and Storage)

The requirements of Article 511 of the *NEC* apply to locations used for the servicing and repair of passenger automobiles, buses, tractors, trucks, and so on in which flammable liquids or flammable gases are used. NFPA 30A and NFPA 88A, *Standard for Parking Structures,* should also be consulted in connection with further classifications of, and the fire protection recommendations applying to, garages. The specific hazardous (classified) areas in these garages are defined in the *NEC.*

Aircraft Hangars

Where aircraft containing gasoline, jet fuels, or other flammable liquids are stored or serviced, the specific (classified) hazardous areas are as defined in Article 513 of the *NEC.* Reference should also be made to NFPA 409, *Standard on Aircraft Hangars,* for guidance on the construction and protection of these structures.

Motor Fuel Dispensing Facilities

This occupancy group includes locations where gasoline or other volatile flammable liquids or liquefied petroleum gases are transferred to the fuel tanks or auxiliary fuel tanks of self-propelled vehicles. Reference should be made to NFPA 30, *Flammable and Combustible Liquids Code,* and NFPA 30A as well as Article 514 of the *NEC* for information on the hazardous (classified) areas and other guidance on fire safety in service stations.

Bulk Storage Plants (Flammable Liquid)

Where gasoline or other volatile flammable liquids are stored in tanks having an aggregate capacity of one carload or more and from which such products are distributed, the hazardous (classified) areas are defined in NFPA 30 and Article 515 of the *NEC.* NFPA 30 also contains many requirements for the safe construction and utilization of bulk storage plants.

Spray Application, Dipping, and Coating Processes

The *NEC* hazardous (classified) locations requirements apply to areas where paints, lacquers, or other flammable finishes are regularly or frequently applied by spraying or dipping, or by other means and where volatile flammable solvents or thinners are used, or where readily ignitable deposits or residues from such paints, lacquers, or finishes may occur. Further information regarding safeguards for finishing processes are contained in NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials,* and NFPA 34, *Standard for Dipping and Coating Processes Using Flammable or Combustible Liquids.* NFPA 33 also governs chopper-gun and hand-layup production of glass fiber reinforced plastics. Hazardous (classified) areas with respect to flammable vapors are defined in Article 516 of the *NEC.*

Chemical Plants

In chemical plants where flammable liquids or gases are processed or handled, NFPA 497 provides information on the extent of the hazardous (classified) location.

Anesthetizing Locations

The use of flammable anesthetics in health care facilities has been greatly reduced; however, there may be some older facilities that still use them. Special rules apply in hospital operating rooms and other locations where flammable anesthetics are or may be administered to patients. Article 517 of the *NEC* defines the anesthetizing location as follows: "Any area of a facility that has been designated to be used for the administration of any flammable or nonflammable inhalation anesthetic agent in the course of examination or treatment, including the use of such agents for relative analgesia."

In a flammable anesthetizing location, the entire area is considered to be a Class I, Division 1 location extending upward to a level 5 ft (1.52 m) above the floor. The remaining volume up to the structural ceiling is considered to be above a hazardous (classified) area.

Any room or location in which flammable anesthetics or volatile flammable disinfecting agents are stored shall be considered to be a Class I, Division 1 location from floor to ceiling.

For further information on the subject of flammable anesthetics, reference should be made to Chapter 3 of NFPA 99.

Places of Assembly, Theaters, Areas of Motion Picture and Television Studios, Performance Areas, and Similar Locations

In places of assembly, theaters, areas of motion picture and television studios, performance areas, and similar locations where numbers of people congregate, it is important that the electric equipment be properly designed and installed. The general rules of the *NEC,* as well as its special requirements for these occupancies, should be followed in installing the equipment. NFPA *101* should be consulted for further information on use of emergency lighting.

SUMMARY

Electricity can result in fire if an arc occurs or if electrical equipment overheats, potentially causing injury or death through shock and burns. The risk of fire from electrical systems and appliances is incurred by improper installation, lack of maintenance, improper use, and carelessness, such as failure to turn off a device when no longer needed. The manufacture, use, and maintenance of electrical installations are governed in the United States by the *National Electrical Code* and other NFPA standards. These standards cover a wide variety of systems, locations, equipment, and procedures, ranging from building wiring, design, and protection to signaling and communications systems. Adherence to the requirements of these standards ensures that electrical systems and appliances are designed, installed, and maintained properly, thus reducing the risk of fire.

BIBLIOGRAPHY

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1. Rohr, K. D., "The U.S. Home Product Report (Appliances and Equipment Involved in Fires)," National Fire Protection Association, Fire Analysis Division, Quincy, MA, Jan. 2002.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for electrical systems and appliances discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

Fire Protection Guide to Hazardous Materials
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*
NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*
NFPA 34, *Standard for Dipping and Coating Processes Using Flammable or Combustible Liquids*
NFPA 40, *Standard for the Storage and Handling of Cellulose Nitrate Film*
NFPA 70, *National Electrical Code®*
NFPA 70B, *Recommended Practice for Electrical Equipment Maintenance*
NFPA 70E, *Standard for Electrical Safety in the Workplace*
NFPA 72®, National Fire Alarm Code®
NFPA 75, *Standard for the Protection of Information Technology Equipment*
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 79, *Electrical Standard for Industrial Machinery*
NFPA 88A, *Standard for Parking Structures*
NFPA 90B, *Standard for the Installation of Warm Air Heating and Air-Conditioning Systems*
NFPA 99, *Standard for Health Care Facilities*
NFPA *101®*, *Life Safety Code®*
NFPA 110, *Standard for Emergency and Standby Power Systems*
NFPA 409, *Standard on Aircraft Hangars*
NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment*
NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*
NFPA 501, *Standard on Manufactured Housing*
NFPA 501A, *Standard for Fire Safety Criteria for Manufactured Home Installations, Sites, and Communities*
NFPA 780, *Standard for the Installation of Lightning Protection Systems*
NFPA 1192, *Standard on Recreational Vehicles*
NFPA 1194, *Standard for Recreational Vehicle Parks and Campgrounds*

SECTION 9

Processes and Facilities

Amy Beasley Spencer

9.1 Woodworking Facilities and Processes
9.2 Spray Finishing and Powder Coating
9.3 Dipping and Coating Processes
9.4 Plastics Industry and Related Process Hazards
9.5 Metalworking Processes
9.6 Welding, Cutting, and Other Hot Work
9.7 Storage and Handling of Grain Mill Products
9.8 Protection of Records
9.9 Semiconductor Manufacturing
9.10 Oilseed Solvent Extraction Plants
9.11 Protection of Wastewater Treatment Plants
9.12 Fire Protection of Laboratories Using Chemicals
9.13 Fire Protection of Telecommunications Facilities
9.14 Electric Generating Plants
9.15 Nuclear Facilities
9.16 Mining and Mineral Processing
9.17 Oxygen-Enriched Atmospheres

Section 9 gathers chapters dealing with fire protection of various processes and highly specialized facilities that in earlier editions of the *Fire Protection Handbook*® were located in the very large section entitled "Fire Prevention." The relocation of chapters to the smaller "Processes and Facilities" section groups similar information for more convenient access. The first nine chapters primarily cover processes, whereas the last eight chapters address specialized facilities.

Chapter 1, "Woodworking Facilities and Processes," addresses the fire protection problems that are unique to wooden product manufacturing facilities and processes.

Spray application of coatings is a process basic to the manufacture of a broad variety of fabricated products. Chapter 2, "Spray Finishing and Powder Coating," explains types of coatings, the equipment and components associated with both spray finishing and powder coating, and hazard control for both fluid spray and powder coating processes. The treatment of coating processes continues in Chapter 3, "Dipping and Coating Processes." That chapter discusses dipping and coating processes, equipment that uses flammable and combustible liquids, the inherent hazards and means of hazard reduction, and fire protection for dipping and coating processes.

The goal of Chapter 4, "Plastics Industry and Related Process Hazards," is to provide an overview of the plastics industry, what constitutes a plastic, the terminology used in the industry, the types of processing techniques used to produce a product, the hazards that exist when producing that product, and the steps that the industry and government have taken to provide a safe working environment for the personnel working within the facility and those people living nearby.

Chapter 5, "Metalworking Processes," explains the metalworking process, considers alternative means of machining, and identifies hazards (such as cutting fluid, lubricating oil, and metal dust) and safeguards.

NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work,* defines hot work as "work involving burning, welding, or a similar operation that is capable of initiating fires or explosions." Chapter 6, "Welding, Cutting, and Other Hot Work," discusses prevention guidelines and safety precautions, contract operations, processes using electricity or oxyfuel gas, thermal spraying, and special situations.

Chapter 7, "Storage and Handling of Grain Mill Products," deals with grain mill products and explains grain elevator design before discussing dust control, relevant fire and explosion hazards, and safeguards.

Chapter 8, "Protection of Records," outlines storage options, including bulk storage, mobile shelving, and open shelf storage, and discusses extinguishment, including damageability and salvage of records.

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Chapter 9, "Semiconductor Manufacturing," considers both preproduction and production processes, as well as fire hazards, health hazards, and hazard control.

The second half of Section 9 concentrates on specialized facilities, beginning with Chapter 10, "Oilseed Solvent Extraction Plants," which discusses plants that house devices such as desolventizer-toaster (D-T) units, rotary coolers, and rotary steam tube dryers.

Wastewater treatment plants are covered in Chapter 11, "Protection of Wastewater Treatment Plants." The chapter covers operations and equipment, general and process hazards, fire and explosion mitigation, and fire protection measures for wastewater treatment plants.

Strategies for protection of laboratories using chemicals are explored in Chapter 12, "Fire Protection of Laboratories Using Chemicals." This chapter describes passive and active fire protection strategies for laboratories, as well as safe storage and handling of chemicals, chemical waste, and compressed and liquefied gases.

Chapter 13, "Fire Protection of Telecommunications Facilities," discusses protection against fire in the public and private telecommunications networks in the United States and Canada. This chapter describes many industry changes, their potential impact on fire risk, and methods to assess fire risk and determine appropriate fire protection programs.

The next two chapters deal with power facilities. The purpose of Chapter 14, "Electric Generating Plants," is to help the reader achieve a well-developed fire safety program tailored to the needs of an electric generating plant. This chapter offers guidance on how to develop a program that addresses life safety, continuity of operations, and property protection for individuals who are responsible for the design, construction, operation, and protection of electric generating plants that are fueled by fossil fuels, alternative fuels, and hydroelectric plants. Chapter 15, "Nuclear Facilities," discusses nuclear reactors, radiation machines, radioactive materials, and radiation exposure, in addition to fire protection concerns.

Chapter 16, "Mining and Mineral Processing," discusses typical surface and underground mining methods, the excavation and distribution equipment used in mining, and the various and typical mineral concentration or coal preparation processes used to convert mined materials into intermediate or final consumer products. Fire and explosion hazards presented by the mining and processing of coal and metal and nonmetal ores as well as structural and construction materials are the focus.

The section closes with Chapter 17, "Oxygen-Enriched Atmospheres." Such atmospheres are commonly used in medical applications, industrial processes, underwater tunneling and caisson work, deep-sea exploration, space flight operations, and commercial and military aviation. This chapter discusses the fire hazards that may be associated with oxygen-enriched atmospheres and presents methods that can reduce and protect against fire hazards.

Chapter 1

Woodworking Facilities and Processes

John M. Cholin

Chapter Contents

Forest Products Industry
Process Hazards Management
Woodworking Processes
Fire Prevention
Fire Protection

Key Terms

deflagration, design brief, dust collection system, explosion, fire prevention, flammable liquid, flammable solvent, forest products, heat transfer fluid, process hazard, wood products, wood waste, woodworking

After millennia of civilization and technological progress, wood—humanity's first structural material—remains the favorite material for the construction of both our homes and the furnishings we choose to live with. The demand for wooden products has not diminished with the introduction of plastics as some had predicted; it has increased. For example, timber product consumption (in industrial round wood consumption) increased 70 percent from 1960 to 1997.[1] With the ever-increasing demand for wooden products, there has been a continued growth in the forest products industry.

The tens of thousands of timber-based manufacturing facilities average 20 to 30 paid employees apiece.[2] Some forest products firms are housed in old timber-frame structures, whereas others are in new fire-resistive structures—ultramodern facilities with automated processes controlled by computers. Some woodworking facilities are one-person shops whereas others employ as many as 2000 people. Some woodworking shops produce custom-designed high quality furnishing, whereas others produce dimension lumber, paneling, engineered wood products, rifle stocks, knobs, millwork, picture frames, cutting boards, or musical instruments. It is the wide size, age, business volume, and product range, coupled with the inherently combustible nature of wood, that makes fire protection for any woodworking facility a challenge.

This chapter addresses the fire protection problems that are unique to wooden product manufacturing facilities and processes. It will not discuss wood as a material, which is covered in Section 6, Chapter 4, "Wood and Wood-Based Products." Nor will it discuss the fire protection concerns over wooden construction and timber-frame construction under fire exposure. These topics are covered elsewhere. This chapter is devoted to the woodworking facility and the production processes commonly employed in those facilities.

For the purposes of this chapter, a *deflagration* is the propagation of a flame-front through a fuel/oxidizing gas mixture at a velocity that is sufficient to cause an increase in pressure but is slower than the speed of sound in the gas. In the case of most woodworking and wood-processing facilities, the fuel is wood dust, and the oxidizing gas is air. Where the wood particles are relatively large, the flame-front propagates slowly enough that an observer would describe it as a rapidly expanding fireball or flash-fire. However, where the particles are finer, the flame front propagates too fast to discern, and it appears to be an instantaneous burst of flame. When a deflagration occurs within a building, room, or other enclosure, the expansion of the hot combustion product gases produces so much pressure that the enclosure ruptures. For the purposes of this chapter the rupture of an enclosure due to the development of excessive pressure within from a deflagration is called an *explosion.*

For related topics, see Section 6, Chapter 1, "Fire Hazards of Materials"; Section 6, Chapter 4, "Wood and Wood-Based Products"; Section 6, Chapter 8, "Dusts"; Section 8, Chapter 7, "Heat Transfer Systems and Fluids"; and Section 21, Chapter 4, "Vehicle Fueling Using Gaseous Fuels."

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FOREST PRODUCTS INDUSTRY

The forest products industry is often categorized based on the type of product produced. Forest products are commonly divided into four general categories:

1. Primary forest products
2. Secondary forest products
3. Tertiary forest products
4. Pulp and paper

Primary forest products, including structural timbers, dimensioned lumber, shingles, and veneers, are produced from a wide variety of tree species. Only cutting and drying are required to derive these products from the raw log. Primary forest products are usually produced in facilities that are dedicated to a specific product and situated close to the forest source. The primary product is then shipped as a commodity to various producers of either secondary or tertiary forest products. There are exceptions to this general scheme of things. Some *secondary forest products,* such as plywood, particle board, flake board, oriented strand board, and fiberboard, are produced in large centralized facilities that consume logs in their raw form as well as chips and wood waste shipped in from other locations.

Other secondary forest products, including millwork, knobs, spindles, paneling, glue-laminated beams, composite wood joists, and dowels, are made from the primary dimension stock in separate facilities or portions of larger entities that produce the tertiary product. Each of these forms of wood has specific structural characteristics that make them the material of choice for specific applications. These products are referred to as "secondary" because processes subsequent to cutting and drying are necessary to create the product, yet the product is still not in a form that is normally consumed at the retail level.

The majority of the primary and secondary forest products are consumed as raw material for *tertiary forest products,* forest products that are consumed at the retail level. The most obvious examples of tertiary forest products are houses and furniture. Lumber, a primary forest product, is cut and shaped into wooden components that are then assembled with other components to ultimately become a finished piece of furniture.

The final category is *pulp and paper.* Paper production is generally a wet process, where wood particulate is suspended in a water-based slurry. The fire hazards associated with paper production are unique to pulp processing and paper manufacture and are not addressed in this chapter.

PROCESS HAZARDS MANAGEMENT

Process Hazards Analysis (PHA)

In general, woodworking and wood-processing facilities represent both a fire and explosion hazard. In order to manage that hazard down to an acceptable level of risk, the entire process and facility should be analyzed in an orderly process where the hazards associated with each stage in the process are identified and documented. Once all of the hazards are documented, the relevant metrics required for the management of the hazard should be identified and quantified. Then a hazard management method can be selected to manage the fire or explosion hazard down to an acceptable level. This stepwise analytical process is generally referred to as a *process hazards analysis* (PHA). A prudent facility operator should perform a process hazards analysis on her or his facility to identify those areas where there is a demonstrable fire or explosion hazard.

Hazard Management Strategy

Once the analysis has been performed and reduced to a document, a hazard management strategy can be developed. The hazard management strategy is derived from the quantity and physical nature of the fuel, the type of ignition sources present, and the expected nature and extent of the resulting fire. These factors will dictate whether the ignition can be reliably prevented. If it cannot, what fire suppression or extinguishing methods will be necessary and sufficient to prevent the extension of the fire? This thought process leads to a hazard management strategy, usually documented in the form of a *design brief.*

Implementation and Maintenance

With a strategy in place the next step is implementation. Ignition prevention features are added where appropriate. Fire suppression and extinguishing systems are designed and installed where they are needed. Where the process hazards analysis identified a potential for a deflagration, the means to manage the explosion hazard are selected and installed. Finally a maintenance program is adopted to maintain the performance of the hazard management assets.

Ignition Process

In a woodworking or wood-processing facility, the process hazards analysis will almost invariably identify both fire and deflagration hazards. The fuel, wood, is ubiquitous. Virtually all woodworking processes involve reducing the size of a piece of wood through mechanical means. Whenever mechanical work is done on matter, heat is liberated. This is a principle of physics called the work/heat equivalence. Consequently, one must anticipate the liberation of heat whenever wood is processed. If this heat is allowed to accumulate in a sufficiently small mass of wood, the temperature will increase until it reaches the point where exothermic pyrolysis begins. Once exothermic pyrolysis begins, usually approximately 536°F (280°C), the reaction liberates more heat than it consumes, and it will continue without additional energy input.[3] Ignition has been achieved, and the wood will char. Such temperatures can easily be achieved from frictional heating through the use of powered cutting and shaping tools. Figure 9.1.1, for example, shows a milling cutter that was turned blue, indicating a temperature in excess of 600ºF (316ºC), during a routing operation that led to the ignition of a fire in the dust collection system. If conditions conducive to sustained combustion are maintained, wood brought to this temperature will ultimately break into open flame. Consequently, every mechanized woodworking process represents a very real ignition hazard.

Machinery that performs cutting, sanding, milling, sawing, or grinding operations on wood will occasionally ignite

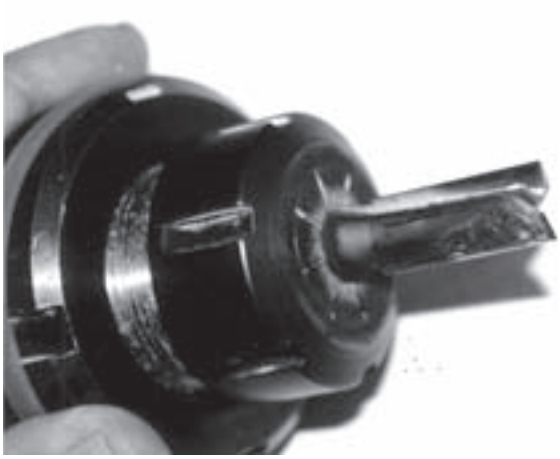

FIGURE 9.1.1 Milling Cutter Turned Blue from High Temperature During a Routing Operation (Source: J. M. Cholin Consultants, Inc.)

the particulate being generated. The heat liberated by the friction attendant to the cutting operation is the ignition source. The probability of spark generation is related to both the wood species and the woodworking process. In general, species that exhibit wide variations in density are prone to produce more sparks. The feed rate of a saw or milling machine is generally adjusted for the average density of the species. When the cutter encounters an abnormally hard portion of a board, excessive heat is generated. The other important species-dependent factor is the average hardness of the wood. The harder the wood, the more likely it is to generate sparks when maximum recommended feed rates are exceeded.

Some generalities can be made regarding the relative tendency of various species to present a spark generation problem, but only in the context of the process. The hardwoods maple, hickory, cherry, and white oak are commonly viewed as representing a high probability of spark generation in the context of milling and cutting. Other hardwoods, including beech, red oak, birch, yellow poplar, and ash, have represented less of a problem.

The softwoods tend to be less prone to spark generation in sawing and milling. The theory is that the resin in the softwood chips can evaporate with a cooling effect, whereas hardwoods lack these resins, and consequently, ignite. However, in sanding operations, the resinous softwoods tend to load the abrasive grit much more aggressively than do the nonresinous hardwoods. This results in a tendency of resinous softwoods to generate sparks several orders of magnitude higher than that of hardwoods in the sanding operation.

Management of Wood Waste

Since most woodworking processes produce waste wood as a by-product of the size reduction to the desired size and shape, wood-waste management is a major design and operational concern. Wood waste exists over a wide range of particle sizes, from board-size pieces to fine powdery dust. Management of wood waste is a ubiquitous problem throughout the forest products industries. Fine wood particulate is very easily ignited. When suspended in air, it burns very aggressively, producing a deflagration.

When wood particulate exists in a mass or pile, such as an accumulation on a floor, it can smolder for extended periods of time (days), producing a charring mass. As soon as sufficient air, at sufficient velocity, is provided to suspend the particulate in the air a deflagration can result. The accumulation of wood dust and wood-waste particulate is a serious problem that plagues almost every forest products facility.

WOODWORKING PROCESSES

There are many distinct types of woodworking equipment. Each has specific operating characteristics that make it both an ignition source and a generator of wood particles that are relatively easy to ignite. Despite this fact, it is important to note that, collectively, only about one-fourth of reported fires in woodworking facilities, based on 1994–1998 structural fire data, had any type of processing equipment involved in ignition. One-third of fires involved no equipment at all. A significant share of the reported fires were caused by cutting and welding operations, heating equipment, and electrical distribution equipment. It is important not to overlook common hazards while addressing special hazards.

The combustibility of wood-waste dusts is the basis for the concern with the generation of sparks by woodworking machinery. NFPA 664, *Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities,* addresses both the fire and explosion prevention and protection features for each principal type of woodworking process. In many cases, particular types of woodworking processes present unique fire protection problems. The reader is urged to consult this standard before undertaking a design of a wood-processing facility.

Raw Material Storage

The storage of wood products represents a fire protection challenge, as large quantities of inherently combustible material are commonly stored in a single location. The storage material can consist of logs, chips, stuck lumber (wood stacked for drying), dense packed lumber, or panels. Regardless, once ignited, the fire has a tremendous fuel load available to it and, if proper precautions are not observed, the fire can rapidly become impossible to extinguish.

Fire protection criteria for bulk wood storage are found in NFPA 1, *Uniform Fire Code*™. This standard addresses indoor storage of lumber at retail and wholesale locations, as well as outdoor storage of timbers, logs, and chips. It states that large undivided piles, congested storage conditions, delayed fire detection, inadequate fire protection, and ineffective fire-fighting tactics are the principal factors that allow fires to escalate to large losses.

Fire Prevention Program. NFPA 1 also states that the fire hazard potential inherent in forest products storage operations,

with their large quantities of combustible materials, can best be controlled by a positive fire prevention program under the direct supervision of top management and should include the following:

1. Selection, design, and arrangement of storage yards or areas and materials-handling equipment based on sound fire prevention and protection principles
2. Systems for early fire detection, transmission of alarm, and fire extinguishment (see *NFPA 72®*, *National Fire Alarm Code®*)
3. Fire lanes to separate large piles and to provide access for effective fire-fighting operations
4. Separation of yard storage from mill operations and other exposing properties
5. An effective fire prevention maintenance program, including regular yard inspections by trained personnel

Danger of Deflagration and Explosion. NFPA 1 provides specific recommendations for pile size, separation between piles, and water supply for each type of storage. Where dry wood particulates are stored in silos, bunkers, and bins, there is also an explosion hazard. Loading operations usually produce suspensions of fine wood particles (dust) in the ullage space above the top of the fuel. Unloading operations often are accompanied by cavitation deep within the fuel mass. When such cavities collapse a dust suspension is created. If there is any burning material present when either of these two dust-suspending circumstances exists, that material can serve as the ignition source for a dust deflagration.

Consequently, it is advisable to monitor the material being conveyed into such storage vessels for burning material (sparks or embers). This is usually done with a spark detection system that is coupled with an intermittent water spray extinguishing system mounted on the in-feed conveyor or conveyors. In some cases the spark detection system is used to activate diverter valves to divert the flow to a safe location known as a *fire dump,* rather than rely on extinguishment of the ember(s) in the particulate flow stream.

Storage of Lumber. Where lumber and panels are stored indoors, they should be oriented horizontally, not vertically. Furthermore, indoor lumber and panel storage should be kept separate from other combustibles, neat and free of clutter or extraneous material. Lumber should be kept in dense-packed units until used, as this practice minimizes the exposed surface area and hence the heat release rate in the event of an ignition.

Dimension Cutting

Dimension cutting usually occurs at a specialized facility called a sawmill. Raw logs are first debarked and then cut to one of several standard working lengths. The bark is collected beneath the debarker and usually transported to a collection silo by a belt conveyor. The log is then squared on at least two sides. The slabs taken from the log to square it are waste and are either diverted to a pile for residential firewood or introduced into a wood-waste system via a hog. (A hog is a high-power mill that reduces large pieces of wood to chips, splinters, or flakes.) The squared-up log is then run through the saw and converted into rough green dimension stock.

When raw logs are reduced to green dimension stock, the moisture content in the wood is usually in excess of 25 percent. This moisture content is generally considered sufficiently high to make ignition of the stock being cut unlikely. However, the sawdust that accumulates beneath and around the saw will rapidly air dry to a moisture content of approximately 10 percent. At this moisture content wood is readily ignitable. The inherently ignitable state of the sawdust in the vicinity of the saw constitutes the most serious fire hazard associated with the sawing operation.

Rough sawing does introduce ignition sources from "inclusions" in the log. These inclusions run the gamut from arrowheads, bullets, nails, and sugar-taps to stones and knots. Although larger mills may have either radio frequency or ultrasonic metal detectors monitoring the logs being fed to the saw, inclusions can still occasionally be hit by the saw. This generally produces large quantities of heat, resulting in the ejection of sparks, embers, or broken saw teeth into the sawdust that has accumulated in the vicinity of the saw. The removal of wood waste, including sawdust, is an important means of managing the fire hazard in the sawmill. Usually the hazard is managed with the installation of a wood-waste removal system to prevent accumulations of wood dust in the sawmill.

Drying

Most tree species yield green wood with a moisture content between 30 and 50 percent water, by weight. As green wood dries, it shrinks. Consequently, green wood is generally deemed unusable as a structural material and must be dried before it can be used. Most wood intended to be used as *dimension stock* is kiln dried to a moisture content of between 5 and 7 percent. Wood chips, flakes, and strands intended for use in particle board, oriented strand board, flake board and similar engineered wood products are often brought to lower moisture contents to aid in the adhesion efficiency of the glues used to form these products.

In the lumberyard, boards are individually inspected and built into hacks for drying and handling. A *hack* is a stack of green boards in layers with a narrow gap between adjacent boards, created by thin sticks called *kiln sticks* or *stickers.* The stickers provide for the flow of air between layers of boards.

Lumber hacks are usually approximately 14 ft (4.3 m) long, 6 to 8 ft (1.8 to 2.4 m) wide, and from 4 to 6 ft (1.2 to 1.8 m) in height. Hacks are stacked by forklift trucks, back to back and as high as 16 ft (4.9 m). The honeycomb construction and the resulting easy access to combustion air make it almost impossible to extinguish a fire in a lumber hack once it is underway. Consequently, aisle widths in both the staging and storage area, as well as the kiln should be sufficiently wide to allow fire-fighting equipment to maneuver effectively.

Dry Kilns. The kiln (Figure 9.1.2) removes the moisture from the lumber in a manner that minimizes the differences in rate of shrinkage throughout the board. The hacks are placed into the kiln. Once fully loaded the kiln temperature is raised, often as high as 300°F (149°C), and the humidity is maintained at

FIGURE 9.1.2 Typical Wood Kiln Used for Drying Dimension Stock (Source: J. M. Cholin Consultants, Inc.)

100 percent. Once the entire stack of lumber has attained the kiln temperature, the humidity is allowed to decrease slowly, while the temperature is maintained. This drives the moisture from the wood without causing cracks (called *checks*), warping, twisting, or other defects in the dried planks. The hacks of kiln-dried (KD) lumber emerge from the kiln (Figure 9.1.3) after a period of usually several weeks having a uniform moisture content throughout the board. For most wood species a moisture content of approximately 7 percent is considered ideal for use in construction, furniture, and other tertiary forest products.

Veneer driers are a special subset of kiln. They are designed to dry the thin plies of wood used in the manufacture of plywood and decorative paneling. The plies usually range in thickness from ⅛ in. (3.2 mm) down to 1/32 in. (0.8 mm). The thinness of the ply aids in rapid drying. The plies are loaded onto racks which move through the kiln.

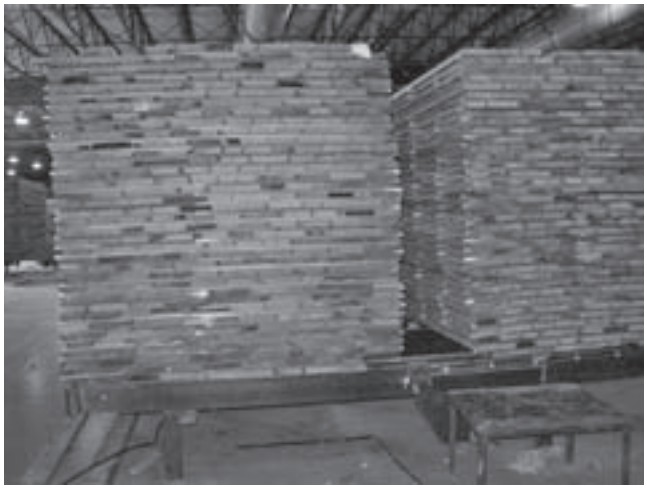

FIGURE 9.1.3 Two Hacks from a Dry Kiln (Source: J. M. Cholin Consultants, Inc.)

While the drying of lumber and veneers does not involve reducing the size of the lumber, it does involve heating a cellulosic combustible material to a temperature close to 392°F (200°C), a temperature usually taken to be sufficient for the onset of endothermic pyrolysis.[2] Furthermore, the productivity of the kiln is measured by the number of board feet of lumber that exit the kiln per unit of time and per quantity of heating fuel consumed. This creates a financial incentive to run the kiln as hot as possible.

Rotary Drum Driers. The drying process for wood particulates used in engineered wood products such as particle board, medium density fiberboard (MDF), flake board, and oriented strand board (OSB) is radically different. Particles are usually dried in rotary drum driers. Figure 9.1.4 is a photograph of a rotary drum drier. Figure 9.1.5 is a schematic diagram of the

FIGURE 9.1.4 Rotary Drum Drier (Source: Energy Unlimited, Inc.)

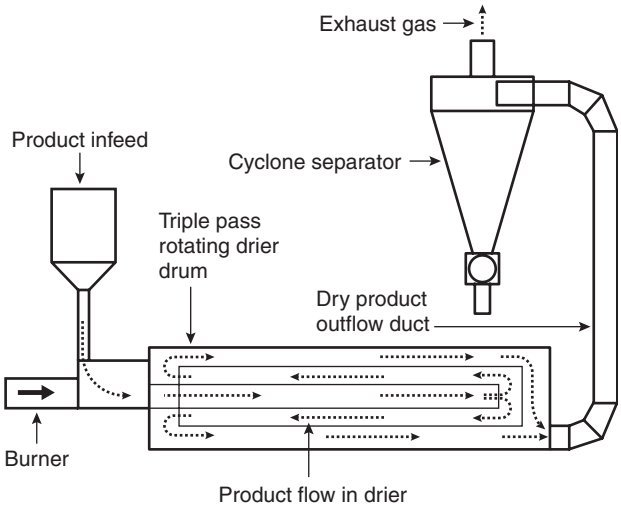

FIGURE 9.1.5 Schematic Diagram of a Rotary Drum Drier (Source: J. M. Cholin Consultants, Inc.)

rotary drum drier with flue gas and particulate flow. Most rotary drum driers are *direct-fired,* meaning that the drying fluid is flue gas taken directly from a burner, often fueled with wood waste. The flow of the flue gas is used to pneumatically convey the wood particulates through the dryer, driving the moisture out of the particulates as the flue gas flows past the particles. The flue gas and water vapor are usually separated from the wood particulates in a cyclone separator.

The operation of a rotary drum drier must be carefully controlled. Usually the flue gas enters the drier at a temperature close to, if not above, the ignition temperature of the wood. By closely controlling the flue gas temperature and flow rate compared to the particulate flow rate and rotational speed of the drier, the operator can dry the particulate down to the target moisture content without igniting any of the particulate. However, imbalances in the operating parameters can lead to ignition of the wood particulates by the drying process. This fact makes it very important to have a well-thought-out fire detection and extinguishing strategy for the conveying and storage equipment downstream from this type of drier. Usually spark/ember detection and intermittent water spray extinguishing systems are used to manage the frequency of sparks entering the production space and deflagration hazard management measures are used to manage the explosion hazard associated with downstream conveyors and storage vessels.

Wood-Waste Particulate. Driers, regardless of type, often use heat generated from the combustion of wood waste. Wood-waste particulate is usually collected from a number of sources, including sawdust, planer chips, and the discharge from a wood hog. The wood waste is conveyed to a storage silo. As boiler fuel is needed, the wood particulate is then conveyed to the boiler via a pneumatic conveyance system or screw conveyor.

Wherever wood is handled as a particulate solid, the potential for fire and deflagration exists. This will be covered in detail later under wood-waste management. NFPA 664 includes detailed fire protection requirements for the various types of wood-drying equipment in common use. These criteria focus on the fire hazard in drying operations handling lumber and veneers. NFPA 664 also addresses explosion prevention in drying operations handling fine particulates.

Veneer Cutting

The object of veneering is to obtain more square feet of visually appealing or usable wood from a log. In general, there is less waste generated in veneering than in the dimension sawmill. However, there is still waste in the form of sawdust, veneer flakes, veneer strands, bark, flattening slabs, and cutoffs. This waste represents a fire hazard similar to that in the sawmill. Management of the fire risk depends on the wood-waste removal system to minimize the accumulation of wood waste in the site. This will be covered in detail later under wood-waste management.

Veneer mills are unique in that the size reduction is performed with knives rather than saws. Veneer logs are often air dried for an extended time period prior to processing. They are then cut to length prior to slicing with knives. Veneer is cut either by a rotary machine or a rift machine. The rotary machine turns the log and slices a thin layer from the circumference as it rotates. Rift cut veneer is produced by slicing along the length of a log that has been sawn down its middle. As the veneer comes off the log, it is transported via conveyor to a dryer where it is rapidly brought to the nominal 7 percent moisture content. Most commercial hardwood veneer is a nominal 1/32 in. to 1/24 in. (0.8 to 1.1 mm) thick, whereas softwood veneers and plies vary from 1/24 in. (1.1 mm) for face ply to 1/8 in. (3.2 mm) for core plies. As a consequence of thinness, drying of veneer occurs quite rapidly. The dried veneer is either stacked flat and baled for shipping or transported via conveyor belt to a paneling facility, where it is laminated into multi-ply material or onto a composite wood core.

Veneer-cutting operations require very large mechanical forces. These forces are generated by large electrical motors or hydraulic systems that introduce additional ignition mechanisms and attendant fire hazards.

Panel Manufacture

The need to obtain greater quantities of useable product from each tree has created an environment in which tremendous strides have been made in the manufacture of panels from wood particulate. Whether particle board, oriented strand board (OSB), flake board, medium-density fiberboard (MDF), or plywood, manufactured panels continue to comprise a significant portion of the wood used in the United States and abroad. Panels employ a mixture of wood particulate or, in the case of plywood, thin plies of wood and petroleum-based adhesive resin to produce a product that provides many of the structural advantages of wood at a reduced cost.

In the production of traditional dimensioned lumber, almost 25 percent of the wood in the tree ends up as waste. By the time traditional dimensioned stock is turned into a finished product, another 25 percent is lost as waste. The use of manufactured panels reduces the waste overhead considerably by reducing the entire log to particulate and reassembling the log into a flat panel that is more conducive to efficient use.

Reduction of Log to Particulate. The first step in the panel manufacturing process is the reduction of the log to "small" particles. In the case of plywood manufacture, the small pieces are thin plies of wood. In the case of flake board, OSB, MDF, and other products, the log is chipped and, in some cases, hogged to produce a particulate of a predetermined target average particle size. In many cases, wood particulate is purchased from third-party producers and trucked in from diverse sources. In this case, there is the potential for the importation of burning material into the facility from a third-party supplier. This potentiality must be considered in the fire protection strategy for the particle board facility.

Particulate Storage and Drying. The wood particulate for particleboard is usually stored in large piles outdoors until needed. The particulate is first screened to remove stones, grit, tramp metal, and particles that are both too large and too small. The particulate is then dried to an acceptable moisture content, usu-

ally below the 7 percent usually preferred for dimension lumber. In the case of plywood production, the drying is carried out in veneer dryers. In the case of the other types of panels, such as particle board, the drying is carried out in dryers specifically designed for the type of particle being processed, such as rotary drum dryers, mentioned previously. Each type of dryer presents its own fire hazard as heat is used to drive off the water in the wood. Particular attention should be paid to the source of heat for the dryers. Occasionally, dryers employ either heat transfer fluid (HTF) or steam as a source of heat. (See Section 8, Chapter 7, "Heat Transfer Systems and Fluids.") However, many dryers are direct-fired. Dryer heat sources can represent a serious source of ignition. Once the wood particulate is dried, it is often classified by particle size and stored as dry particulate in intermediate storage silos or bunkers.

Panel Assembly. The dry wood particulate is conveyed from intermediate storage to a blender, where it is mixed with a thermoset adhesive resin. One or more flat layers are then extruded down onto a wide stainless steel belt. The layers of wood particulate are called the *mat.* The mat is conveyed to the press and compressed at high pressure and heat to form the finished board.

In particle board manufacture both gang and continuous presses are used. In the gang press a large number of layers of the wood particulate mat are sequentially stacked, separated by a stainless steel divider sheet, into the press. The press then closes and both heats and compresses the layers of wood particulate mat, causing the thermoset resin to react and glue the particles together into a single panel. After the requisite press time the press opens, and the panels are removed and conveyed to a panel cooler.

Continuous presses use a set of long continuous stainless steel bands between which the wood particulate mat is extruded. These two bands, one beneath and one above the mat, slide into the press where the heat and pressure are applied as the bands slide through the press. As the bands leave the press, a long, continuous panel results. As the panel exits the press it is cut to length and conveyed to the panel cooler.

Since the press uses both heat and pressure, there are concerns over the presence of the heat transfer fluid (HTF), usually called thermal oil in the forest products industries, and hydraulic fluids used by the press. As a general rule, continuous presses are larger, much more costly, and use far more HTF at higher pressures than the sequential gang presses they replace. All of these factors make fire protection much more demanding.

Plywood. The process for making plywood is similar to that for particle board. A ply is laid down, sprayed with adhesive, and covered with the next ply, the process continuing until the intended number of layers are in place. The press then closes, and heat and pressure are applied to cause the adhesive to react, producing a panel.

As for the particle board presses, the heat source for the press is usually HTF. HTF represents a serious fire hazard whenever it is used. Usually it is used at temperatures above its flashpoint and is pumped from the heating plant to the utilization equipment at both high pressure and high volumetric flow rate. In the event of a leak this can result in the release of a combustible liquid above its flashpoint as an atomized spray or rapidly expanding pool over large portions of the facility. This is an obvious and serious fire hazard.

Each of the operations in producing a panel product involves specific fire protection problems, usually associated with the type of equipment used. The fire protection engineer or specialist must study the specific process and its equipment in detail to identify the fire hazards and the most cost-effective means of managing the fire risk.

Milling

Rough-sawn dimension stock serves as a raw material for the production of lumber. Most dimension stock is milled to standard nominal dimensions, such as 2 in. (5 cm) by 4 in. (10 cm) or 1 in. (2.6 cm) by 6 in. (15.4 cm). Milling involves passing the stock through edgers, jointers, and planers, all of which have hardened steel cutters rotating at high speed that cut away enough wood to assure a smooth, straight, and flat surface on all four faces. Often short sections of plank are joined end-on to form a long plank. This process involves the use of finger joiners. Finger joiners produce interlocking fingers on the ends of boards allowing them to be joined end-to-end with glue to make longer pieces.

Other secondary milling operations further reduce the lumber to pieces with specific cross-sections for door stiles, door frames, window frames, window sills, moldings, tongue and groove flooring and paneling, and other special uses. These specific cross-sections are produced by mills with cutters that have been precisely ground to produce the desired shape.

Milling produces large quantities of wood chips and dust. The high speeds of the cutters and the high feed rates make the generation of sparks and embers the rule rather than the exception. This reality complicates the problems in the wood-waste management for the site. The wood waste must be removed from the milling machine to prevent an accumulation of chips, yet the wood-waste stream is likely to contain embers.

NFPA 664 includes detailed fire protection and explosion prevention requirements for wood-waste handling systems (dust collection systems). Although the chips from milling operations are generally too large to support a deflagration, there is usually a sufficiently high concentration of fine dust mixed with the chips that these portions of the dust collection system should be evaluated for explosion hazard.

Cutting

As lumber is used as a raw material in tertiary forest products facilities, one of the most common processes is cutting to component dimension. Cutting across the grain of the board is called cross-cutting, and cutting parallel to the grain is called ripping or resawing. The by-products of cutting are sawdust, block scraps from cross-cutting, and kerf scraps from resawing.

The cutting creates a severe fire ignition exposure, as dry stock is processed by a machine that can transfer large quantities of energy into the fine wood waste created by the machine. The sawdust is produced at elevated temperatures and is easily

ignited. This is especially true of facilities that process woods with large variations in density in a single board or billet. When the wood density increases, the feed rate must be reduced to keep operating temperatures below the auto-ignition temperature of the sawdust. In mechanized facilities, the feedback from the saw to the feeding unit may not be sufficiently responsive to assure adequate control over cutting temperature in the workpiece. The result is sparks and embers in the sawdust stream from the unit when knots, crotches, burls, and butts are encountered in the cut. This is especially common in resawing.

High saw speeds and high feed rates make the generation of sparks and embers in the cutting operations a common occurrence. As in milling, this complicates the problems of wood-waste management for the site. The wood waste must be removed from the saw to prevent an accumulation of chips, but this waste stream is likely to contain embers. As stated previously, NFPA 664 includes detailed fire protection and explosion prevention requirements for wood-waste handling systems. Although the sawdust from cutting operations is generally too large to support a deflagration, like milling operations, there is usually a sufficiently high concentration of fine dust mixed with the chips that such dust collection systems should be evaluated for explosion hazard.

Turning

Turning has historically represented somewhat less of a fire risk than other shaping methods. However, when billets of wood with wide variations in density or glue-ups are used, there is an ignition potential. Part of the difficulty with turning is that the roughing, final shaping, and sanding are often done at the same location, without removing the workpiece from the lathe. This introduces a very wide range of dust particulate into the waste removal system, increasing the likelihood of a dust collector fire. Previous comments regarding the potential for explosion in wood-waste handling systems apply here as well. See NFPA 664 for applicable requirements.

Laminating

Laminating covers a very wide range of processes. There is an incredible range of surfaces, substrates, and adhesives in use today. Some lamination surfaces are themselves engineered materials consisting of multiple layers of different materials, all integrated into a single layer with advanced adhesives. Amendments to the Clean Air Act have placed pressure on laminators to reduce volatile organic compound (VOC) emissions (see Section 21, Chapter 4, "Vehicle Fueling Using Gaseous Fuels," for a discussion of volatile organic compound emissions). Consequently, many toluene- and xylene-based glues have been replaced with casein, acrylic, and urethane adhesive systems. These adhesive systems are typically heat activated and are applied at a very high solids content.

Application of the adhesive is usually performed at a spray station. Adhesive application does not involve the complexities of spray finishing. Overspray is easily controlled and electrostatic spraying is rarely employed, due to the poor electrical conductivity of wood-based substrates. Once the adhesive is applied, the laminate facing is applied, and the adhesive is activated by applying both heat and pressure, either by passing the laminate through heated rollers or placing the laminate in a heated press. The heat source for the heated rollers or press is usually either steam or heat transfer fluid. Combustible heat transfer fluids have been known to provide an ignition source when lines have ruptured while at elevated temperature and pressure.

Sanding

Each component that is to become an exposed part of a finished assembly must be smooth and free of sharp edges. This is achieved by sanding. The sanding operation is particularly hazardous because of the fineness of the dust created. The final form and surface quality of virtually all wooden products are achieved by sanding. A wide variety of sanding machines are used in the tertiary forest products industries, from hand-held random orbital sanders for finish sanding to wide-belt abrasive planers capable of taking over ⅛ in. (3.2 mm) in a single pass. The sanding machine shown in Figure 9.1.6 is being used to smooth the surface of furniture legs and represents the small end of the size range in sanding machines.

Dust Collection. Sanding operations probably represent the greatest hazard to the modern forest products plant. Sanders can produce large quantities of dust at the same time they generate high temperatures from the sanding operation. Usually pneumatic conveying systems are used to pull the sander dust from the sander toward a dust collector. Generally, the dust collection system is designed to operate at dust concentrations well below the minimum explosible limit for the wood dust generated by the sander. However, when an extremely large reduction in panel thickness must be achieved, the dust concentration in the duct can exceed the minimum explosible concentration (MEC). This renders the atmosphere within the duct deflagrable and the dust collection system an explosion hazard.

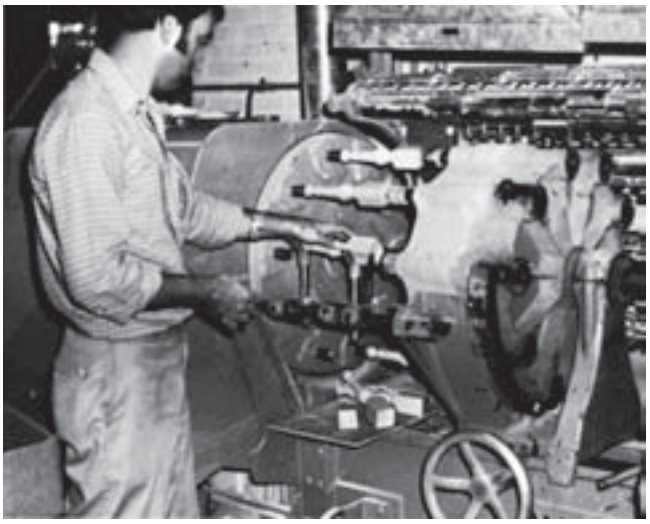

FIGURE 9.1.6 Sanding Machine Smoothing the Surface of Furniture Legs

Deflagration Prevention Systems. Under these circumstances explosion prevention strategies must be provided for the dust collection ducts and the dust collector. Dust collection systems serving sanders should always be designed to operate well below the MEC at the worst-case operating condition, removal of the maximum depth of cut at the maximum feed rate. While this design strategy introduces additional cost into the dust collection system by requiring large air flows in large diameter ducts, it eliminates the need for explosion prevention systems on the ducts. See NFPA 664 for additional information.

The larger sanding machines also are capable of producing substantial quantities of heat, which vaporizes resins and extractives in the wood; these vapors then condense on the interiors of the dust collection system ducts, coating the interior surface over time. The grit on the sanding belt can become "loaded" with compressed wood dust, forming a composite material that can achieve red-hot temperatures as it is rubbed across the stock.

Sander dust, vaporized resins, and red-hot bits of wood/resin composite are all picked up by the dust collection system. The pneumatic wood-waste ducts running from the sanders to the dust collector are frequent sources of fire. The four-head abrasive planer shown in Figure 9.1.7 represents the large end of the size range of sanding machines. Note the number of dust removal ducts rising from the top of this machine.

Glue-Up/Assembly

The glue-up and assembly of tertiary forest products is the least hazardous portion of the production facility. Although glues have traditionally been dissolved in mineral spirits, toluene, or other volatile organic compounds, the new polyurethane and acrylic adhesives are not.

Finishing

Years ago, finishing operations represented a more serious concern than they usually do today. The concern over VOC emissions has made finishes using nitrocellulose, toluene, xylene, and methylethyl ketone (MEK) vehicles far less common than they once were. New acrylic, urethane, and water-based finishes are replacing the older finishes in most large-volume facilities.

FIGURE 9.1.7 Four-Head Abrasive Planer (Source: J. M. Cholin Consultants, Inc.)

Many of the larger, more modern woodworking plants employ as many as 20 spray booths in a conveyorized finishing operation, using about 20,000 to 40,000 ft^2 (1900 to 3700 m^2) of floor space. Ovens for curing the finished pieces operate at approximately 250°F (121°C). Due to the competitive pressure to produce a flawlessly finished product, multicoat finishes are customary, necessitating curing ovens operating at high temperatures and air flows and overnight storage between coats to ensure finish quality.

The lower-volume, smaller facilities are often found to still be using older finishing procedures based on volatile vehicles. Wherever volatile flammable liquids are used, there is the possibility of a fire. The principal flammable solvents used in wood finishing are listed in Table 9.1.1 with their approximate flashpoints.

All of the materials listed in Table 9.1.1 are prone to electrostatic ignition under certain circumstances. Furthermore, fires can be caused when flammable vapors come in contact with lighting fixtures, heaters, sparking motors, electrical switches and other well-known sources of ignition.

Finished Products Storage

The storage of finished forest products naturally varies with the type of product. However, the storage areas should be protected in a manner consistent with the combustible loading that can be achieved in a storage area used for the storage of furnishings or other cellulosic combustibles.

Wood-Waste Management

Most forest products production processes generate wood waste. By the time parts have progressed through rough milling and finish machining, approximately 50 percent of the original log has been reduced to waste.

Large chips, chunks, board ends, resaw kerfs, and lumber scraps account for approximately 35 percent of the wood waste. The larger pieces are usually conveyed by belt conveyor, front-end loader or wheelbarrow to a hog. The wood hog reduces large pieces of wood waste to chips, splinters, or flakes, which can be conveyed pneumatically. Larger facilities operate hogs that can consume entire wood pallets and tree trunks, reducing them to a shower of chips. The outlet of the hog is usually connected via a high-power fan to a pneumatic conveying duct, which transports the chips to a silo for storage.

TABLE 9.1.1 Flashpoints of Flammable Solvents

Solvent	*Flashpoint °F*	*Flashpoint °C*
Acetone	–4	–20
Methylethylketone	16	–9
Naphtha VM&P	50	10
Xylene	81	27
Toluene	40	4

Dust Collection. All the previously described wood shaping and cutting processes also generate wood chips, shavings, and dusts, which are gathered by the dust collection system. This particulate material is usually removed from the machine producing it via the dust collection system. The dust collection system consists of ducts extending to each of the woodcutting machines, a large fan to provide the motive force, and a dust collector. The chips and dust are sucked up by the dust collection system and are conveyed while suspended in air to a dust collector where the wood chips and dusts are separated from the conveyance air.

There are two general designs of dust collection systems common in the forest products industries. The first is the single-stage system, shown in Figure 9.1.8. This system consists of a single dust collector either in the form of a cyclone separator or a combination cyclone/bag filter unit. The second is a two-stage system, shown in Figure 9.1.9. This system usually consists of a cyclone separator followed by a bag type filter house, usually referred to as a "baghouse."

Cyclone separators remove the larger particulate matter from the air stream. However, they cannot remove fine dusts efficiently enough to be practical where conveying air is being returned to the workplace. If conveying air is returned to the workplace, a design decision that is usually selected to save on the cost of heating or cooling the facility, a filter must be used to remove the fine, dusty particulates. The filter usually consists of an array of cloth bags in a steel enclosure, the baghouse. The baghouse removes wood dust having particle sizes larger than the weave of the cloth.

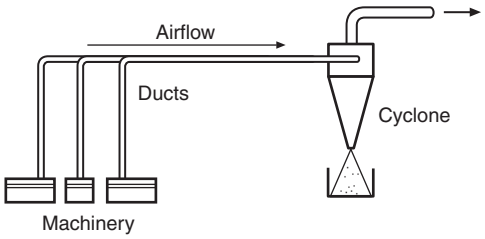

FIGURE 9.1.8 Single-Stage Collection System Consisting of a Cyclone Separator

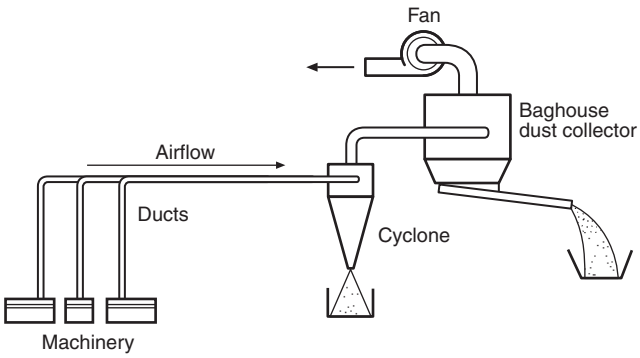

FIGURE 9.1.9 Two-Stage Collection System Consisting of a Cyclone Separator and a Baghouse

Most facilities have two-stage systems. Historically, they began as single-stage systems, using only a cyclone to separate the larger, usable wood waste from the air stream and exhausting the conveying air to the outside. Subsequently, a baghouse was added, allowing the return of the heated conveying air back to the facility. Newer facilities are now often designed with a single-stage cyclone/baghouse combined unit, where the bottom of the unit acts as the cyclone separator and the upper portion contains the bag-type filters (Figures 9.1.10. and 9.1.11).

In many installations, about 80 percent of the air used by the dust collection system is returned to the plant. Return of this air into the plant atmosphere can cut down on the air make-up requirement and reduce plant heating needs. However, it introduces serious fire protection concerns that must be addressed.

Fire and Explosion Hazard Management. Dust collection systems and the dust collectors at the ends of these systems represent a serious fire and explosion hazard because wood dust suspended in air can deflagrate on ignition. In the context of U.S. standards, a *deflagration* is the rapid propagation of a flame front through a fuel/air mixture at a rate that is sufficient to cause a pressure front but slower than the speed of sound in the unreacted medium. An *explosion* is the rupture of a containment enclosure due to the excessive pressure produced by a deflagration. The deflagration is the process and the explosion is the result. European standards apply a different definition to the terms *explosion* and *deflagration* than U.S standards.

Requisite Conditions for Deflagration. To produce a deflagration four basic conditions must exist concurrently as shown in Figure 9.1.12. First there must be present a combustible particulate solid of sufficiently small particle size. The rate of combustion is controlled by surface area, and the smaller the

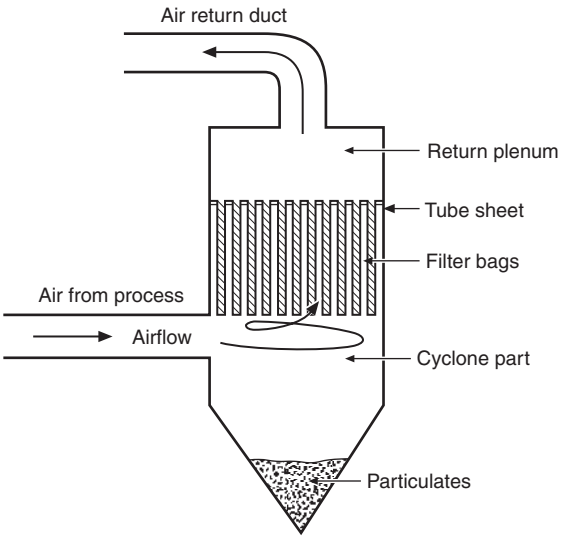

FIGURE 9.1.10 Single-Stage Dust Collector with Combination Cyclone Separator and Baghouse (Source: J. M. Cholin Consultants, Inc.)

FIGURE 9.1.11 Single-Stage Dust Collector Installation (Source: J. M. Cholin Consultants, Inc.)

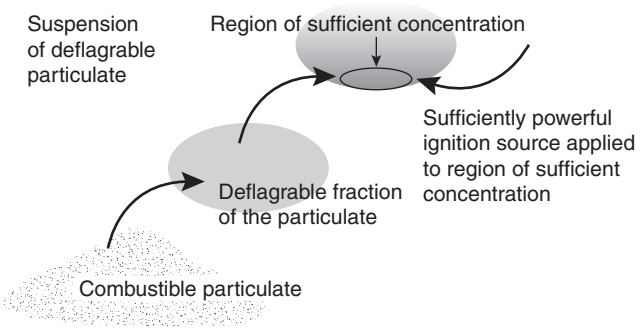

FIGURE 9.1.12 Basic Conditions Required for Deflagration (Source: J. M. Cholin Consultants, Inc.)

particle size the greater the surface area to mass ratio. In general, particles must have an equivalent diameter of less than 420 microns to be capable of supporting a deflagration. Second, the particulate must be suspended in the air. This state exposes the maximum particle surface area to the atmosphere and the oxygen needed to carry out the combustion reaction. Third, the suspension of combustible particulates must have a concentration of particles, measured in units of mass per unit volume, sufficient to propagate a flame front. Each particulate has its own MEC. In this day and age, MEC is usually expressed in terms of grams per cubic meter (g/m^3), but older references might express it in terms of ounces per cubic foot. Finally, there must be a competent igniter. The source of ignition must be capable of introducing sufficient energy per unit of time and unit of volume to bring the dust/air mixture to its auto-ignition temperature. Thus the ignition source must be quantified in terms of a power density measured in watts per unit volume. This value is usually derived experimentally. Consequently, where the energy investment and concentration are both sufficient, a deflagration will propagate through a suspension of wood dust in air.

Deflagrable Fractions. Particulates with equivalent diameters greater than 420 microns will not produce a deflagration. These particulates will still burn, but the rate of combustion will be too slow to result in the generation of potentially dangerous pressure. Where a broad range of particle sizes exists, only the sub-420 micron fraction is generally deemed capable of deflagration. The remainder will burn but can actually serve as a flame-quenching fraction, reducing the probability of a propagating deflagration if the concentration of the nondeflagrable fraction is large compared to the deflagrable fraction. The extent of the quenching phenomenon can only be quantified, at this time, by testing.

For the deflagrable fraction, the general rule is that as particle size decreases, the maximum deflagration pressure, P_{max}, increases. Likewise, the maximum rate of pressure increase, dP/dt_{max}, increases. The volume-normalized rate of pressure increase, K_{St}, often called the *dust constant,* also increases. These are all artifacts of the higher rate of combustion for finer particulates due to the larger surface area per unit of mass.

Particulate Size. The finer the particulate the more easily ignited it is. Ignition behavior is usually quantified by determining the minimum ignition energy (MIE). Consequently, one can see that the finer the particulate the more hazardous it is. This observation is valid until the particle sizes decrease below approximately 20 microns. Decreases in particle size below 20 microns generally do not increase the hazard associated with a particulate.

Particle size is usually determined by using standard sieves. If the particulate passes through the sieve it is ascribed a nominal diameter equivalent to the opening in the sieve. This method works well for particulates that are essentially spherical or cubic in particle shape. Unfortunately, wood particulates are rarely round or cubic in shape. Consequently, when working with wood particulates the designer must use equivalent particle diameter rather than actual diameter. The equivalent particle diameter is the diameter of a round particle that has the same surface area to volume ratio as the particulate under consideration. Highly elongated and fibrous particles will behave as if they were much smaller because of the larger average particle surface area to average volume ratio they have. The net result is that simple sieve analyses can lead to dangerous underestimation of the hazard posed by wood particulates. Figure 9.1.13 shows a photomicrograph of wood dust from a particle board plant showing fibrous particle shapes that are typical of wood dusts.

Particulate Concentration. Wherever there exists a sub-420 micron fraction of wood particulate that can attain suspension in

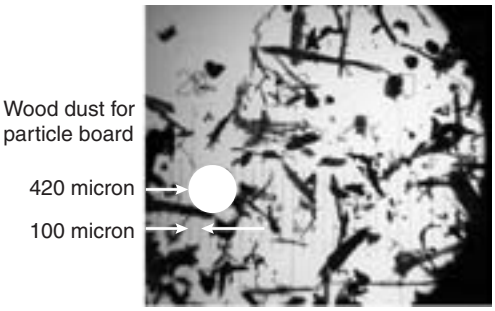

FIGURE 9.1.13 Photomicrograph of Wood Dust (Source: J. M. Cholin Consultants, Inc.)

the air at concentrations above the MEC, a deflagration hazard exists and must be managed. Since both cyclones and baghouses separate wood waste from the conveying air, there is a continuous concentration gradient within these units as a normal part of their operation. The concentration gradient effectively guarantees that some portion of the interior volume of the cyclone or baghouse used as a dust collector has an environment capable of supporting a deflagration. Most cyclones are not designed to separate the fine "deflagrable" dust from the conveying air under normal operating conditions, but they will produce an environment capable of deflagration during startup and shutdown. The baghouse is designed to collect fine particulate and conditions conducive to a deflagration exist during startup, normal operations, and shutdown.

Dust collectors that employ filter media (i.e., baghouses) also must have some means of removing accumulated dust from the media while operating. Otherwise, the media becomes clogged with dust and the flow of air through the media lessens, decreasing the ability of the entire system to efficiently transport wood waste from the point of generation to the collector. To address this problem, dust collectors are usually equipped with bag shakers or reverse pulse cleaners to periodically remove the accumulated dust from the surface of the filter bags and maintain filtration efficiency. A concentrated dust cloud is produced inside the operating dust collector during the bag cleaning cycle. If burning material exists within the dust collector when the bag cleaning cycle occurs, it is likely that a deflagration will result. Figure 9.1.14 shows the bag cleaning cycle in a baghouse that produces a dust suspension at regular intervals, which can lead to a deflagration.

Returned Dust. Dust collectors are *not* 100 percent effective in removing dust from the air. To varying degrees, all dust collection systems remove only the larger, less-combustible wood particles, allowing the finest particles to pass through the filter medium and back into the production facility. This results in an accumulation of ultrafine wood dust on many of the undisturbed, upward facing, horizontal surfaces in production shops (Figure 9.1.15). As the efficiency of the dust collection system is improved in an effort to keep the facility cleaner, the combustibility of the dust in the collector increases, making it more likely that it will be the site of an explosion. The combustibility of the residual dust that passes through the filter, returning to the occupied space, also increases. In short, the better the dust

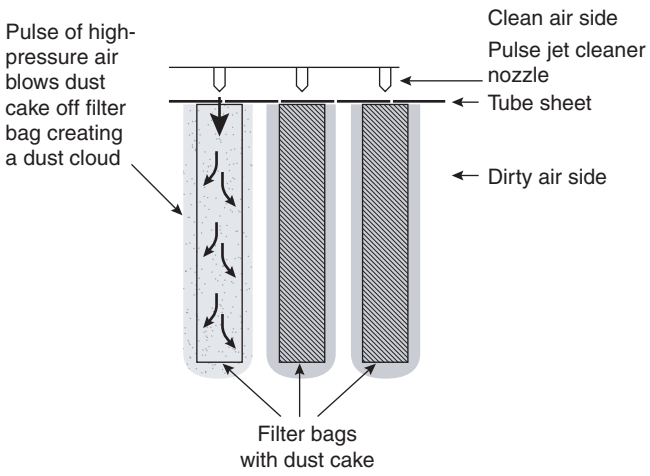

FIGURE 9.1.14 Bag Cleaning Cycle (Source: J. M. Cholin Consultants, Inc.)

FIGURE 9.1.15 A Dangerous Accumulation of Very Fine Dust on the Upward-Facing Surfaces of the Ducts Can Be Seen Here (Source: J. M. Cholin Consultants, Inc.)

collection system, the finer the dust returned to the facility and the greater the fire hazard.

The fire hazard does not go away if there is no dust collection system. If the wood chips and dusts are not collected, the employees are exposed to the health risks associated with inhaling the dust. The dust is simply free to migrate throughout the workplace. In this circumstance, whenever someone drops a plank or otherwise causes the dust to billow up, there is the possibility that the dust cloud will ignite. The choice is between an explosion and fire hazard distributed throughout the facility or an explosion and fire hazard concentrated in a specific spot. The explosion and fire hazards are always there.

Process Heat Production

One of the major fire hazards in the modern wood-processing facility is the process heat production equipment. Often, the heat used to fabricate particle board, plywood, laminates, and

other engineered wood products is transferred from the point of generation to the point of utilization by means of HTF, sometimes referred to as "thermal oil." These systems are operated at temperatures that usually exceed the flashpoint of the fluid. Any release of the fluid poses an immediate threat of fire. Furthermore, these systems usually contain large quantities of HTF and pumps designed to circulate it through transfer piping at high flow rates.

NFPA 664 includes detailed fire protection criteria for heat transfer or thermal oil systems. It provides for a performance-based design or a prescriptive design. In performance-based designs, NFPA 664 requires that the hazard be assessed on the basis of the "largest credible spill," taking into account the total quantity of oil available, maximum flow rate through the utilization piping, system instrumentation for detecting a loss of fluid from the system, automatic shutdown controls and interlocks, the presence of trained personnel that can reliably isolate portions of the system, and the spatial organization of the facility. The assessment should determine the worst-case spill area, considering the ability to limit flow as well as the ability of the structure to contain a spill. This assessment will lead to a quantification of the spill area and hence the fire suppression capacity needed to control the fire resulting from an ignition. Once the extent of the hazard has been assessed, the consequences of the fire should be evaluated based on the life safety threat, probable property loss, and interrupted operations loss. A design is then developed to limit the loss to a level acceptable to the authorities having jurisdiction, who represent the public, and all involved stakeholders.

In the prescriptive design approach, NFPA 664 includes extensive detailed criteria for the design of systems that have been developed over many years of experience. These design criteria generally achieve the performance expectations of most operators. Regardless of the design method selected, these HTF systems must be designed and maintained properly.

FIRE PREVENTION

Design

The fire safety of a new facility can be improved substantially by addressing fire prevention concerns during the layout of the production area. Significant fire safety improvements can be made in most existing facilities by reorganizing the layout. Where the process hazards analysis determines that a fire or explosion hazard exists, the facility design should be modified to eliminate, if possible, or minimize those hazards.

Separation of Processes. Processes that are likely to cause ignition should be moved away from processes or areas where there is significant fuel loading or fuels of elevated combustibility. Whenever possible, fire-resistive separations equipped with listed fire doors at each penetration should be installed between the wood shaping/cutting, finishing, assembly, and storage areas.

Since most of the commonly used wood finishes have a solvent of flammable liquid, there is an increased fire hazard wherever finishes are stored or applied. The facility, regardless of size, should be organized to keep flammable vapors out of confined spaces and away from ignition sources. All flammable materials should be stored and used in compliance with NFPA 30, *Flammable and Combustible Liquids Code.*

Space Heaters. The use of fixed or portable space heaters to supplement building heat introduces ignition sources throughout the facility. The heating plant should be designed to eliminate any need for space heaters. Appliances that produce controlled heat, such as glue pots and bending irons, should be restricted to specific dedicated areas that are dust free and physically separated from cutting, shaping, and sanding machines, as well as from inventory storage and finishing areas.

Electrical Hazards. Properly grounded electrical outlets, suitable for the electrical classification of the area, should be installed where electric power is needed. Extension cords, three-wire to two-wire adapters ("cheater plugs"), cube taps, and outlet extenders should be replaced with permanent electrical service in compliance with NFPA 70, *National Electric Code®*.

Tramp Metal. Provisions should be made to prevent the introduction of foreign material, such as stones and tramp metal, into dust collection systems. These tramp materials can become heated as they collide with the steel walls of the pneumatic conveying system duct and cause ignition where they come to rest in the hopper section of either a cyclone or dust collector. Where floor sweep pick-ups are connected to the dust collection system, they should be equipped with magnets or other equivalent means of preventing the introduction of ferrous material into the dust collection system.

Fans and Blowers. Fans and blowers represent a potential ignition source in the dust collection system. The surface of large blocks of wood and knots can reach ignition temperature when they strike the impeller of a fan. NFPA 664 establishes criteria regarding when wood particulate is permitted to pass through a fan. Green material, material with a moisture content of 25 percent or greater, is permitted to flow through fans. Dry material is not permitted to flow through a fan without providing fire detection and extinguishment downstream from the fan. When dry, deflagrable wood particulate passes through a fan, both fire and explosion protection should be installed on downstream dust collectors.

Dust Collectors. NFPA 664 also establishes a number of requirements on the design of the facility, especially as it relates to the dust collection system and pneumatic conveying systems used to transport particulate material. One of the requirements is that dust collectors be of noncombustible construction and situated outside the structure. Furthermore, if cleaned conveying air is to be returned to the facility interior, a listed spark detection system activating an abort gate is required (see NFPA 664). Figure 9.1.16 shows an abort gate diverting an airstream to the outside, preventing passage of flames and combustion gases into the facility via the clean air return duct.

Reducing the Risk of Dust Collection System Fires. Several other design methods can reduce the likelihood of a dust collection system fire. They do not eliminate the possibility of a fire but do reduce the probability. They are derived from the fundamentals of spark physics. A small wood particle (such as

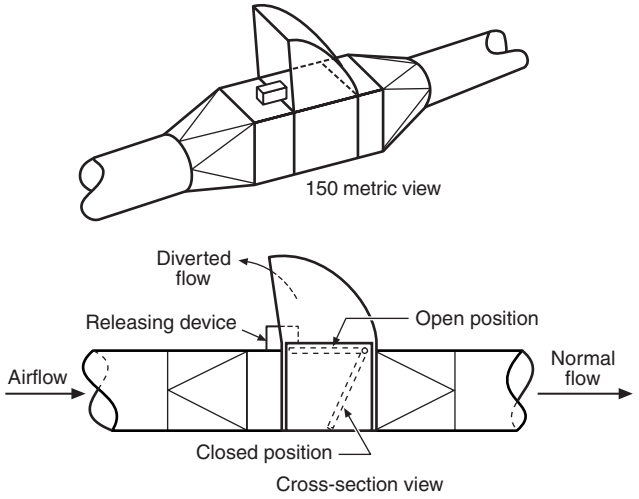

FIGURE 9.1.16 Abort Gate Diverting Airstream to the Outside (Source: J. M. Cholin Consultants, Inc.)

sander dust) is easily ignited, but it burns out very quickly, since the individual particle consists of very little fuel. Large wood particles (such as router chips) are harder to ignite, but will burn for a longer period of time, sometimes long enough to survive until they reach the dust collector (baghouse). For this reason, there is added fire risk when fine sander dust and larger chips from routers, planers, and saws are conveyed together in the same duct. That risk can be reduced by conveying fine dust and large chips in separate ducts until they reach the collector.

The same strategy holds true for separating the lines that come from the sanding of finished surfaces or resinous woods and the sanding of unfinished surfaces or nonresinous woods. The resins in the finishing materials tend to load up grit on the belts. When the resin/wood composite reaches ignition temperature, it can ignite the nonresinous dust in the line. Finally, longer ducts provide more opportunity for the ember or spark to burn out before it reaches the dust collector, where the continuous concentration gradient exists that is conducive to the development of a deflagration leading to an explosion. These steps will only reduce the probability of a dust collector fire; they will not eliminate the possibility.

Equipment Maintenance

There are ignition hazards associated with electrically powered woodworking machines, both stationary and portable. Switches can wear out and start "arcing." Power cords can become worn and frayed. Bearings can fail and overheat. All of these are possible electrically generated ignition sources. Lighting can also be the cause of excessive heat or catastrophic electrical ignition. Frayed power cords, arcing switches, clogged ventilation ports, worn bearings, worn belts, misaligned pulleys, and misaligned guards and fairings around moving parts have all been identified as sources of ignition. Corrective action should be taken as soon as these conditions become evident.

Cutting tools should be maintained as sharp as practical. This improves both productivity and the fire safety of a facility. Sharper tools cut more cleanly, producing less dust and chips with smoother surfaces, both factors that reduce the fire risk. Furthermore, a sharp tool produces less heat during the cutting process, making it less likely that the cutting process will raise particles to their auto-ignition point. Cutters should be kept sharp and there should be a specific quantitative method (such as motor current demand or cut roughness) of determining when sharpening is needed.

Finally, abrasive cutters, such as sanding belts and discs, should be kept clean, in good repair, and free of "loading" of compressed wood dust. A specific quantitative method for determining when abrasive belts should be replaced should be developed and enforced. Overall grit thickness can be used to infer the degree of grit wear and breakdown. When a belt becomes loaded, it can generate tremendous frictional heating that will readily ignite the dust produced by the sanding operation. Excessive abrasive belt temperatures can cause the cloth backing of the belt to fray, resulting in catastrophic failure of the belt. When a belt fails, shards of sanding belt material are often ejected into the dust collection system ducts, where they can strike sparks as they pass down the duct.

Heating Systems

Furnaces and other sources of space heat should use a source of combustion air that is isolated from the air in the woodworking facility. Most furnaces use ambient interior air as their source of combustion air. The furnace burns fuel to produce hot flue gas, which passes through a heat exchanger on its way up the chimney. Interior cool air is passed across the heat exchanger, absorbing heat in the process and is then forced into the interior space (Figure 9.1.17).

If wood dust is allowed to mix with the combustion air, it will ignite, potentially upsetting the inflow of air into the combustion chamber and sending flames into the production area. This is especially true of gas-fired space heating units, commonly found in industrial spaces. This concern can be addressed by installing a fresh combustion air inlet duct, running from the outside to the furnace air inlet, as shown in Figure 9.1.18. This will prevent wood dust from invading the combustion airstream of the furnace.

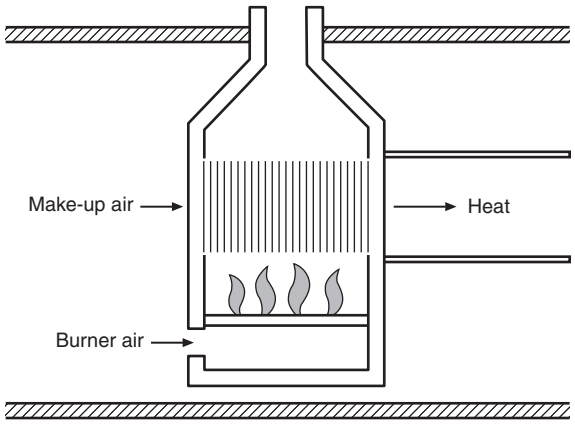

FIGURE 9.1.17 Simplified Hot Air Furnace (Source: J. M. Cholin Consultants, Inc.)

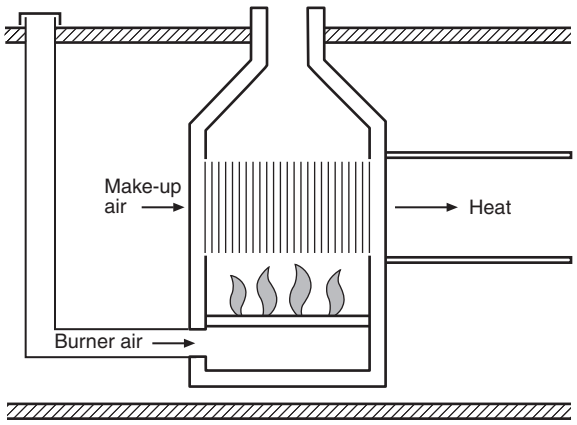

FIGURE 9.1.18 Modified Furnace/Heater (Source: J. M. Cholin Consultants, Inc.)

Regular inspection of the heating system is advisable. Furthermore, routine facility inspections during the winter months should be conducted to prevent the use of small portable space heaters, as these units present a much higher hazard of fire than engineered central heating. Production employees often try to solve local discomfort problems with portable space heaters. A facility auditor who understands fire hazards can remove the space heaters while encouraging work on a more systematic solution, through adjustments to the central heating.

Personnel/Procedures

Safe operating procedures should be established and reviewed on a regular basis. Out-feed from all cutting and sanding machines should be monitored on a regular basis to identify any machines that are cutting too hot. The need for adjustments to feed rates and cutting implement maintenance are often first noticed by scorching and burning of the wood as it is cut. The staff should be properly trained in the correct method of installing and achieving proper alignment of abrasive belts.

There are procedural ways to manage the ignition risk represented by electrically driven machinery. The single least-reliable, most failure-prone component in the entire electrical system are the switches. Since the on/off electrical switches of equipment are operated often, they represent a potential source of electrical failure. To avoid having a switch fail in the "On" position, the facility should be equipped with a dedicated set of circuit breakers for the machinery, enabling those responsible for the facility to turn off the source of electrical energy before leaving for the night. An alternative, where small machinery operating at 110 V ac is used, is an "unplug when you're done" policy. If such a policy is in place it should be monitored by management to ensure that all equipment is disconnected when not in use.

A specific location should be reserved for lunch break. This limits the probability that small appliances such as coffee makers are placed in uncontrolled locations. Furthermore, small cooking devices such as coffee pots, microwave ovens, and hot plates should be powered through switched outlets that are de-energized when the lights are turned off. Smoking should not be allowed in a woodworking facility. Improper disposal of smoking materials still represents a pressing threat to any woodworking facility.

Welding and Hot Work. Welding should be performed in accordance with NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work.* Welding should be controlled and carefully monitored. When welding is performed, small pellets of molten metal fly off from the material being welded. If these land on combustible material, a fire can result. It often takes several hours for the fire to develop. Every year, buildings burn down due to latent sparks from welding. Welding should not be performed unless and until the area is thoroughly cleaned of all wood and wood waste and the appropriate fire-extinguishing equipment is in place. A fire watch, maintained for at least two hours after the welding has ended, should be required whenever welding is performed, regardless of how small the needed repair is.

Housekeeping. The wood dust that is an inescapable part of a woodworking facility is a combustible material that represents a serious and extensively distributed fire and explosion hazard. Every effort must be made to minimize the accumulation of wood dust on upward-facing horizontal surfaces and to routinely remove all dust that evades preventative measures.

An efficient, properly constructed dust collection system is the first step in keeping dust levels under control. However, no system is 100 percent effective. Routine vacuum cleaning of the entire facility is of paramount importance. Under no circumstance should high-pressure air be used to "blow down" a work area as a routine part of the production process while production equipment and other sources of ignition are energized. This merely stirs up the dust and will cause the finest, most combustible fraction of the dust to be deposited in the highest, most difficult to clean spaces. Blow-down is permitted during production shutdowns, when all equipment is de-energized. Often this is the only practical way to dislodge the dust from high spaces. As a general rule, the finest, most hazardous dust will accumulate on upward-facing surfaces near the ceiling. This dust cannot be allowed to accumulate, as it is the fuel for the secondary deflagrations that cause the most injuries and fatalities when explosions occur.

The heat exchanger in the furnace/heaters should be kept clean. The surface of the heat exchanger will get hot enough to ignite surface dust or dust in the air. This is especially true in the autumn when the furnace/heaters are turned on for that first cold morning of the year.

FIRE PROTECTION

Sprinkler Coverage

In general, woodworking facilities are highly combustible environments, filled with wood and/or fabric-covered finished and semifinished goods, as well as other raw materials. Automatic sprinkler coverage is considered the most appropriate general area protection for woodworking facilities. However, in some older buildings, it may be difficult to achieve full protection. In 1994–1998, 54 percent of reported structure fires in wood,

paper, and related product manufacturing facilities were in buildings with sprinklers, a percentage that is typical of manufacturing in general.

NFPA 13, *Standard for the Installation of Sprinkler Systems,* requires design of sprinkler systems to be based on Ordinary Hazard-Group 3 design rules for the woodworking machinery spaces. Other areas, such as finishing rooms and upholstery rooms, should be designed for these special occupancies. They often require designs based on a higher density, involving larger pipe sizes and closer spacing of sprinkler heads. Whenever possible, these processes should be located in separate buildings or separated from each other by fire-rated construction with openings protected by automatic fire doors.

The degree of protection needed can vary from facility to facility, but a basic recommendation is that a yard system of mains and hydrants capable of supplying at least 1000 gpm (3.78 m^3/min), enough to sustain four 2½ in. (64 mm) hose streams simultaneously, should be installed in accordance with NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances,* as appropriate. If conditions warrant, expanded supplies and larger fire stream appliances might be needed for effective fire control. Unobstructed fire lanes are needed in the yards, so that fire equipment can approach the lumber piles. NFPA 1 provides requirements for the protection of stored lumber, logs, and chips.

In facilities where heat transfer fluid is used for hot presses, such as in panel manufacturing, sprinkler protection is required. NFPA 664 provides explicit criteria for the safe design of these systems and the fire protection for them. The presence of a heat transfer fluid system in a wood-processing facility increases the fire hazard considerably because of the added fuel and the speed with which the fire can extend beyond the point of origin due to the horizontal flow of burning oil across floors and equipment. It is important to keep in mind that woodworking and wood-processing facilities represent not only a fire hazard, but an explosion hazard as well.

Protection Strategies

Fire protection is used to manage the fire hazard. Explosion prevention is used to manage the explosion hazard. As a general rule, the installation of fire protection does *not* make a major contribution to the management of the explosion hazard. Similarly, the installation of explosion prevention equipment does *not* generally contribute to the management of the fire hazard. The prudent facility operator will employ both protection strategies. NFPA 664 provides detailed fire protection and explosion prevention criteria for each general type of process equipment found in the modern forest products production facility. These include particle size reduction equipment (mills, grinders, and hogs), veneer and fiberboard dryers, rotary dryers, flash-tube dryers, kilns, finish dryers, pollution control equipment, silos and storage bins, and various types of hot presses.

Portable Fire Extinguishers

Portable fire extinguishers should be installed in accordance with the requirements of NFPA 10, *Standard for Portable Fire Extinguishers,* and any local codes. There is a wide diversity in the types of fires that are apt to occur in a woodworking plant. Fires that require the use of Class A, Class B, and Class C extinguishers are abundant.

There should be water or aqueous film-forming foam (AFFF) extinguishers for the wood storage and general production areas. Dry chemical agent extinguishers should be used for the finishing areas and wherever combustible or flammable liquids are stored or used. Dry chemical extinguishers would also be preferable for use on electrical equipment. Gaseous extinguishers, including both clean agent and carbon dioxide (CO_2) units should *not* be used in a woodworking shop. When these units are discharged, the jet of extinguishing agent gas can cause a great deal of turbulence in the surrounding air. This turbulence can lift any wood dust in the vicinity of the discharge into suspension, resulting in a dust cloud. This is an extremely dangerous situation. If the suspended wood dust contacts the flame, a deflagration will probably result.

ABC dry chemical is often called a "universal dry chemical." However, a given extinguisher's effectiveness varies greatly with the fuel. Although a given extinguisher could easily extinguish a 10-ft-diameter (3.1-m) combustible liquid fire, it would not be able to extinguish a fire in a stack of wood pallets the same size. Nevertheless, ABC dry chemical is electrically nonconductive and effective on two-dimensional wood, paper, and combustible liquid fires. It is an excellent choice as a general-purpose fire extinguisher for most of the areas in the woodworking environment. In the finishing areas, there is a concentration of combustible liquids, and it is appropriate to use a fire extinguisher that is optimized for that fuel. Type BC sodium bicarbonate dry chemical extinguishers are generally recommended for this type of service. The ABC unit will extinguish flammable liquid fires, but might not be as effective as the BC-type units. Sodium bicarbonate units are not very effective on wood and paper fires. Consequently, they should only be used on fires involving flammable and combustible liquids and gases.

AFFF is excellent on wood and paper and on combustible or flammable liquids. However, foams are not as effective on three-dimensional fires—fire where the fuel is stacked vertically. AFFF is also electrically conductive. These factors often limit its applicability. However, AFFF is generally considered a good choice for stockrooms and veneer, lumber, and corrugated cardboard storage areas.

The diversity of combustible materials does introduce some risks associated with fire extinguishers. Their placement and signage should be designed to minimize the likelihood that the wrong type of unit will be used.

Finishing

A principal hazard in the spray application of finishes involves flammable and combustible liquids, their vapors or mist, and combustible residues in spray booths. Spray booths that are properly constructed in accordance with NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials,* and with adequate mechanical ventilation, are the ideal way to discharge vapor to a safe location. Minimizing all sources of ignition in the spraying area and constantly supervising the overall finishing process are essential to a safely conducted operation.

NFPA 33 provides the minimum compliance design criteria and operating procedures for spray application of flammable coatings. This standard should be applied to all finishing areas.

Mechanical ventilation of the spraying area should remove solvent vapors and control overspray. The ventilation system should maintain a sufficient average velocity over the entire open face of the booth to entrain and confine overspray to the booth interior. In some larger facilities, the spray booths exhaust over 25,000 cfm (708 m^3/min). This necessitates careful management of the make-up air demand.

Curing ovens associated with finishing processes are generally classified in accordance with NFPA 86, *Standard for Ovens and Furnaces,* as continuous Class A ovens. These are enclosures that operate at nominal atmospheric pressure and in which there is an explosion or fire hazard due to the presence of flammable volatiles and combustible residues. The oven exhaust system is usually vented to a solvent recovery system prior to discharge to the outside.

Explosion Hazard Management

Wherever there is wood dust, there is an explosion hazard. Furthermore, the single deflagration leading to the rupture of a single compartment or enclosure is the exception rather than the rule. In most woodworking facilities, a fire that does not involve a cloud of wood dust suspended in air can be adequately controlled with a properly designed sprinkler system. However, in woodworking and wood-processing facilities, the fire protection specialist must also have systems in place to deal with the contingency of a deflagration involving suspended wood dust.

Typical Progression of a Dust Explosion. Most explosion events involve multiple deflagrations, occurring in rapid succession, each more powerful and damaging than its predecessor. It is critical that the fire protection strategy be designed to interrupt this progressive development. The progressive nature of explosions in woodworking facilities relies on the presence of a source of additional fuel in the form of accumulated fugitive dust in the facility interior. Usually, fugitive dust accumulates over the years within the facility building. The finest dust is found highest in the interior space, on upward-facing surfaces of beams, pipes, electrical conduit, and wall ledges. Even the pores of cement block used to construct walls harbor fine dust. This combustible material fulfills the critical precondition of ample available fuel. Where this precondition is met, the stage is set for a propagating chain of deflagrations that can lead to the destruction of the facility.

Primary Deflagration. Most explosion events begin as a single deflagration within a piece of equipment. It could be a mill, hog, sander, dust collector, dust bin, chip silo, or other such enclosed equipment. Figure 9.1.19 shows the beginning of an explosion event as an unmanaged deflagration within enclosed equipment.

When this initial deflagration occurs it produces an acoustic wave that radiates from the locus of the initial deflagration at the speed of sound through the structure (Figure 9.1.20). The speed of sound in air is usually taken to be 1100 ft/sec (330 m/sec), whereas the speed of sound through steel and concrete is closer to 15,000 ft/sec (4560 m/sec).

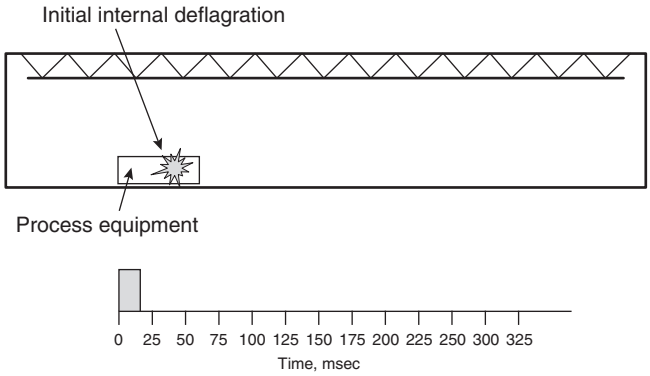

FIGURE 9.1.19 Beginning of an Explosion Event Within Enclosed Equipment (Source: J. M. Cholin Consultants, Inc.)

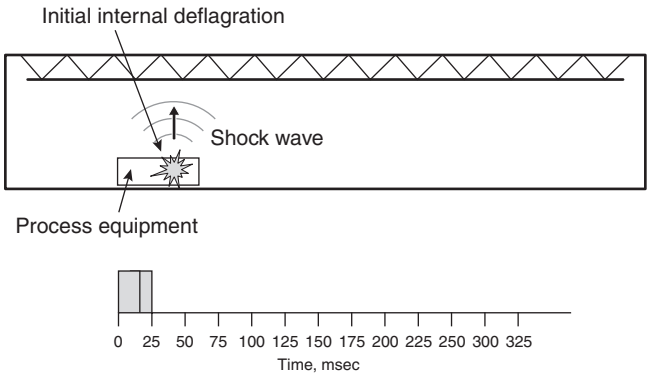

FIGURE 9.1.20 Acoustic Impulses Traveling Through a Building (Source: J. M. Cholin Consultants, Inc.)

Every component of the structure is to some degree elastic. The floor slab flexes, walls vibrate, and the roof deflects as the acoustic wave from the initial deflagration propagates through the building (Figure 9.1.21). This movement propels accumulated fugitive dust from its resting place into the interior airspace. In Figure 9.1.22, the rebound of the building compartment or enclosure suspends accumulated fugitive dust into dust clouds. This process occurs in a fraction of a second, producing dust clouds throughout the facility. Since the acoustic wave through the building travels many times faster than the wave through the air, dust dispersions occur throughout the facility. When the enclosure containing the initial deflagration ruptures and its flame front exits the enclosure, it extends into the building interior where there are already-established dust dispersions. For example, Figure 9.1.23 shows that when a deflagration within the enclosure produces more pressure than the enclosure can withstand, it ruptures, releasing the flame to the building interior.

Secondary Deflagration. When the flame from the initial deflagration, moving at a velocity substantially lower than the

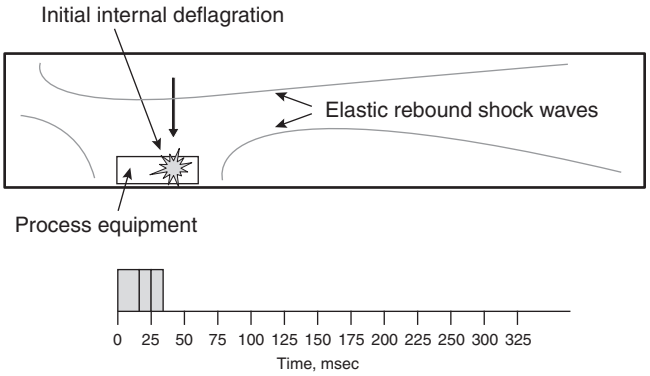

FIGURE 9.1.21 Elastic Rebound of the Building (Source: J. M. Cholin Consultants, Inc.)

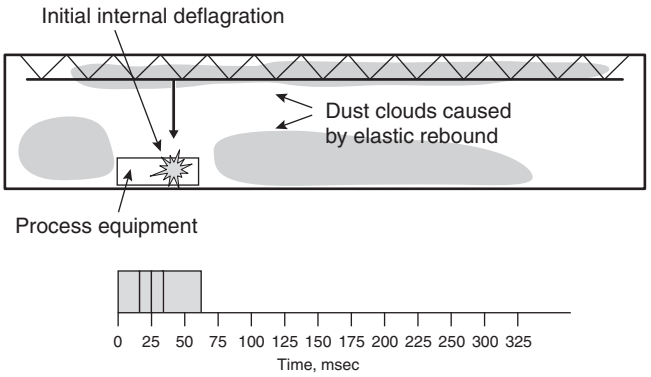

FIGURE 9.1.22 Suspension of Accumulated Fugitive Dust into Dust Clouds (Source: J. M. Cholin Consultants, Inc.)

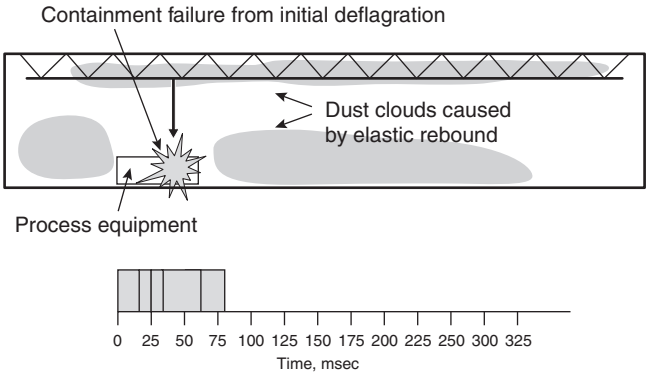

FIGURE 9.1.23 Rupture of Enclosure Caused by Deflagration (Source: J. M. Cholin Consultants, Inc.)

acoustic wave, impinges on any portion of any of the dust clouds produced by the acoustic wave, a secondary deflagration is usually ignited. This secondary deflagration usually occurs within a building compartment where there might be occupants. For example, Figure 9.1.24 shows a situation in which the flame

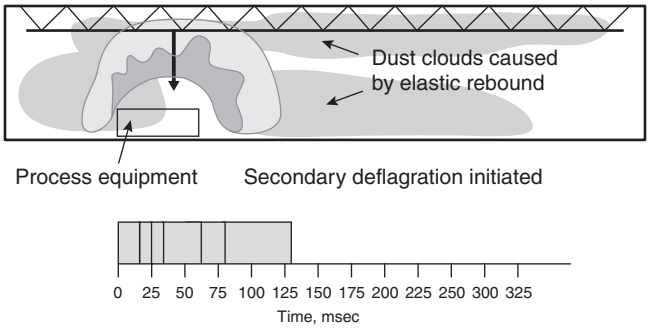

FIGURE 9.1.24 Flame Front from Initial Deflagration Ignites a Secondary Deflagration (Source: J. M. Cholin Consultants, Inc.)

front from the initial deflagration ignites a secondary deflagration within the building compartment.

The deflagration within the building compartment propagates through the dust/air mixture of the dust dispersions. The combustion of the wood dust liberates huge quantities of heat, causing the air within the building to rapidly expand. The rapid expansion of the air within the building increases the pressure and causes the building envelop to rupture. Since the weakest part of the building envelope is usually the wall-to-roof joint, this joint is often the first to fail. Figure 9.1.25 diagrams a situation in which the deflagration within the building pressurizes the building until it ruptures at a wall-to-roof seam. As the pressure within the building continues to build, the roof might even lift from its points of attachment to the walls. The failure of the walls and roof allow the combustion product gases to vent to the outside (Figure 9.1.26).

Eventually the dispersed fuel in the air within the building is consumed and the combustion product gases cannot support the roof any longer and it falls back down onto the building slab (Figure 9.1.27). Even if the building does not collapse, numerous residual fires have been ignited and often the fire suppression sprinkler system has been damaged to such an extent that it is no longer capable of controlling these fires. This process can pro-

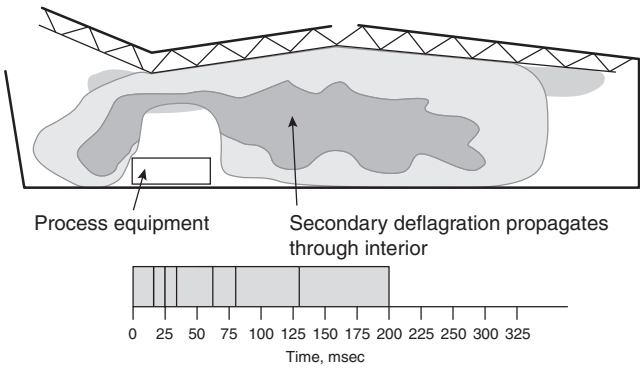

FIGURE 9.1.25 Deflagration Ruptures Wall-to-Roof Seam (Source: J. M. Cholin Consultants, Inc.)

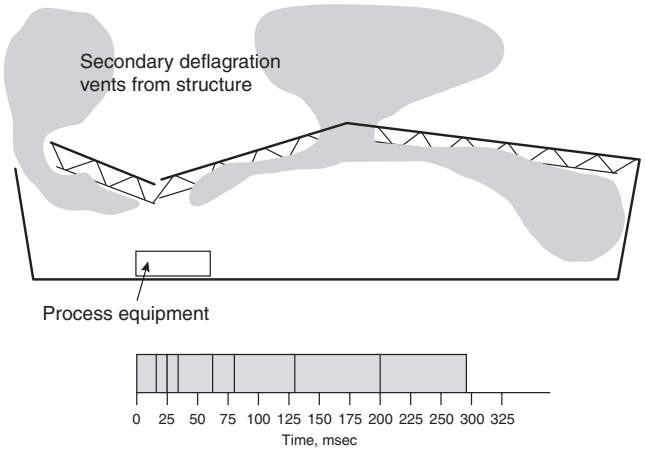

FIGURE 9.1.26 Deflagration Gases Vent to the Outside (Source: J. M. Cholin Consultants, Inc.)

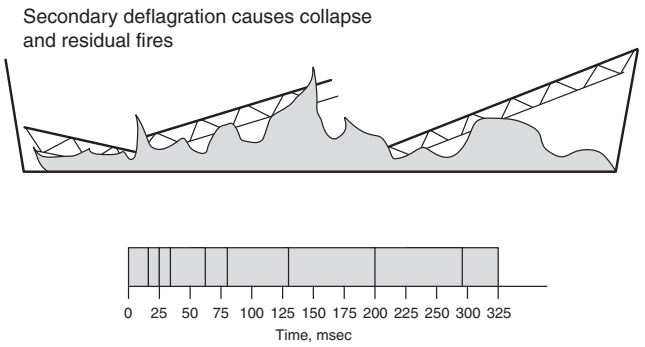

FIGURE 9.1.27 Building Collapse on Escape of Deflagration Gases (Source: J. M. Cholin Consultants, Inc.)

duce multiple deflagrations of increasing severity, even resulting in the catastrophic failure of the building structure. Furthermore, the secondary deflagrations often occur in occupied portions of the building, resulting in severe burn injuries to those occupants.

Hazard Management. Critical in this process is the dust accumulation within the facility. If the dust accumulations are held below that which is sufficient to fuel a deflagration, the process does not go forward. Consequently, in NFPA 664, the hazard analysis hinges on determining where a deflagration hazard exists. A deflagration hazard is deemed to exist wherever there are accumulations of dust of sufficient depth to render the compartment deflagrable or where dust dispersions exist due to normal operations. As part of the process hazards analysis, each compartment in the facility and each point in the process and dust collection system should be evaluated for the presence of a deflagration hazard. Where the deflagration hazard exists, protective features should be employed to mitigate that hazard.

Managing Combustible Concentration. Since the source of ignition is inherent in wood-processing equipment, there is no alternative to proactively managing the deflagration and explosion hazard. Process-generated ignitions are usually introduced into the dust collection system along with the wood particulate being produced by the process equipment. Consequently, one management tool is to design the dust collection systems so that they operate at wood dust concentrations well below the MEC. For most wood particulates, the MEC is approximately 30 to 60 g/m^3 (0.03 to 0.06 oz/ft^3). If the pneumatic system is designed to operate with dust concentrations well below this level of fuel loading, a deflagration cannot propagate through the duct, and spark detection and extinguishment systems can be used to prevent sparks from reaching the dust collector where deflagrable conditions exist. Where the dust loading is at or above the MEC, there is no alternative to considering it to be a deflagrable environment and measures to manage the effects of deflagrations in the duct must be employed.

The fact that many dust collectors have been operating for decades without a fire does not justify a lack of protection for both the employees and the facility from a dust collector fire or explosion. In the context of the dust collection system, the "fire" is an ember or "spark," sometimes as small as a BB (approximately 0.177 in. [4 mm] in diameter) produced by the wood working machinery that has been picked up by the dust collection system.

In some cases, the machinery in the modern forest products facility can generate an endless succession of sparks. As many as dozens of sparks per hour have been detected in some facilities. Even though the conveying velocity might be several thousand feet per minute, under normal circumstances most of the sparks burn out. They are quenched as they collide with the walls of the duct, with large wood chips, or with resinous material in the duct. Most sparks do not survive enough long to reach a location where they can ignite a dust cloud. Perhaps only one in a million sparks generated will survive the journey from its source to the dust collector.

Dust Collector Fires. There are some management options that can reduce the probability of a spark reaching the collector. However, the laws of probability predict that a fire will occur in every dust collector handling wood particulates sooner or later. Once the burning material, the spark, enters the dust collector, it encounters one of four possible fates. First is that it impinges on the filter media and initiates a fire on the surface of the media. In this scenario, as soon as the next automatic bag cleaning cycle occurs, a dust cloud will be produced adjacent to the surface fire on the filter media. This usually leads to a deflagration within the dust collector interior.

The second possibility is that the burning material falls to the bottom of the collector. As it falls, it passes through the continuous dust concentration gradient between the airspace and the accumulated dust in the hopper section of the dust collector. If the spark is sufficiently large, it can ignite the dust suspension in the hopper section, resulting in a deflagration within the dust collector interior.

The third potentiality is that the spark ignites the filter media and the resulting fire burns through the filter media before the bag cleaning cycle begins. As the fire burns through the filter media it will cause a pressure drop across the filter

media. With the loss of pressure, there is no longer a force holding the dust to the surface of the media, and the dust begins to fall to the bottom of the collector. As the dust falls, it creates a dust suspension that could encounter the flames of the fire and ignite. However, it is possible that it might not necessarily lead to a deflagration. The last possibility is that the burning material burns out without igniting a sustained fire.

It is important to keep in mind that a deflagration will not result every time a spark is introduced into a dust collector. It is rare that a single spark has sufficient energy and can deliver sufficient power to ignite a deflagration. It is more likely that it will initiate a fire within the dust collector. With the air movement providing plenty of atmospheric oxygen, a fire that develops on the filter media can rapidly involve the entire collector interior. In this case, the heat release is very rapid and if the dust collector is equipped with a fire suppression sprinkler system, the release of heat from the combustion of the filter media could actuate a sprinkler head. Unfortunately, if the sprinkler system is a dry pipe system there is a remote possibility that the exhausting of air from the dry pipe system could force dust into suspension and yield a deflagration. However, this last concern has not yet been validated by postincident investigations.

If the dust collector is located outside the facility and is deemed expendable, then there is no compelling need to protect it. The only need is to prevent the deflagration flame front from entering the building via the dust collection system ductwork. When the inlet duct interior is nondeflagrable, this need is usually fulfilled by installing backflash dampers on the inlet ducts from the facility to the dust collector. To prevent the flow of flame back into the facility via the return air ducts, abort gates are installed on the return air ducts to divert flame and burning material to a safe outside location. When the inlet duct interior is deflagrable, provisions must be made to prevent the propagation of a deflagration in the duct upstream from the dust collector to the factory interior. Deflagration flame front velocities are generally at least an order of magnitude greater than conveying air velocities, so the airflow makes little, if any, contribution to preventing deflagration propagation from a dust collector into the factory interior.

Since most woodworking facilities rely on the operability of the dust collector, the expendable dust collector is the exception rather than the rule. Furthermore, since there is no guarantee that an ignition will result only in a fire, there is no alternative to designing the dust collector with provisions to deal with a deflagration.

Dust Collector Deflagration Management. There are three practical means of dealing with the deflagration in the collector. The first is deflagration venting designed in accordance with NFPA 68, *Standard on Explosion Protection by Deflagration Venting.* The second is venting the deflagration through a listed dust retention/quenching vent assembly designed, installed, and maintained in accordance with NFPA 69, *Standard on Explosion Prevention Systems.* The third is deflagration suppression designed, installed, and maintained in accordance with NFPA 69.

These solutions deal only with the potentiality of deflagration—not fire. Prudent design practice dictates that dust collectors be protected from both fire and deflagration; both a fire protection system and a deflagration management system will be needed. Usually the fire protection is implemented with either a sprinkler system or a water deluge system.

Protecting the Facility and Occupants from the Dust Collector. NFPA 664 provides requirements for the protection of dust collection systems based on whether the dust collection system represents a fire hazard or an explosion hazard. In many cases, a single dust collection system will represent both and must be protected for both hazards.

Life safety objectives are addressed with protective features that address both the potential for deflagration and fire. Where pneumatic conveying air is to be recycled back into the facility, a means must be provided to prevent flame and combustion product gases from being conveyed into the facility in the event of a fire. This is important for two reasons. First, if smoke and combustion gases are conveyed into the facility, the occupants are immediately placed at risk. Secondly, the flow of the hot combustion gases into the facility can produce a hot layer of smoke and gas at the ceiling plane, especially if the return air discharge is located at or near the ceiling (usually the case). Under these circumstances the flame from the dust collector fire is conveyed back into the facility where the most easily ignited, most hazardous dust is located, at the ceiling plane. Even if this does not ignite a deflagration at the ceiling plane, it has the potential to cause numerous sprinkler heads (if present) to operate. But sprinkler systems are designed to supply a finite number of heads, based on the presumption that a fire in a given location is producing a plume that forms a ceiling jet. When flame and gas from the dust collector fire move across the ceiling, all of the heads might operate, exceeding the capacity of the system riser. This sets the stage for potential failure of the system to control the fire.

Abort Gates. The recycling of flame into the facility by way of the return air duct is usually prevented with an abort gate situated at the dust collector exhaust. Usually, spark detection is used to actuate the abort gate. The spark detection is usually installed on the dust collection system ducts at one of two locations relative to the dust collector. One location is on the inlet to the dust collector. Figure 9.1.28 shows a minimum code-compliant implementation of spark detection for return air abort, with spark detectors located on the inlet to the dust collector. The detector actuates the abort gate whenever a spark enters the dust collector.

While this approach is the safest, it is not always practical. Where the spark detectors are located a long way from the dust collector, excessive downtime due to nuisance activations must be considered. A second location is in the exhaust duct, as shown in Figure 9.1.29. This location relies on the fact that when a fire is ignited in the filter media bits of burning wood dust and filter material from a dust collector fire begin to flow back toward the facility via the return air duct. These bits of burning material are easily detected with spark detectors. The specifics relating to how spark detection systems are designed and installed are addressed in *NFPA 72®, National Fire Alarm Code®.* Activation of an abort gate is a remedial action necessary to secure the life safety and property of the site. Consequently, a listed protected premises

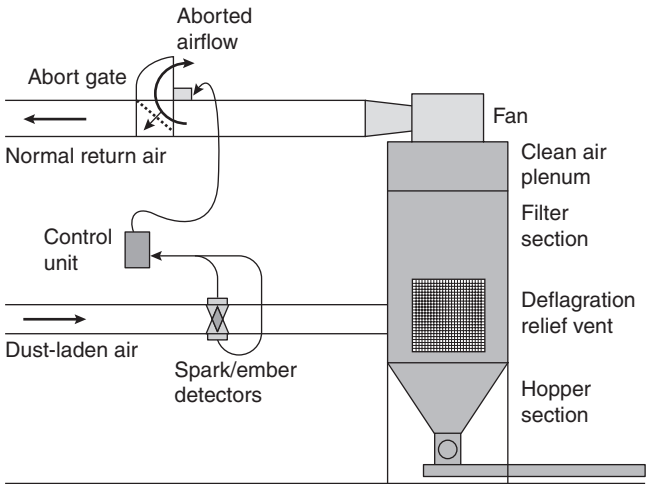

FIGURE 9.1.28 One Minimum Code-Compliant Implementation of Spark Detection for Return Air Abort (Source: J. M. Cholin Consultants, Inc.)

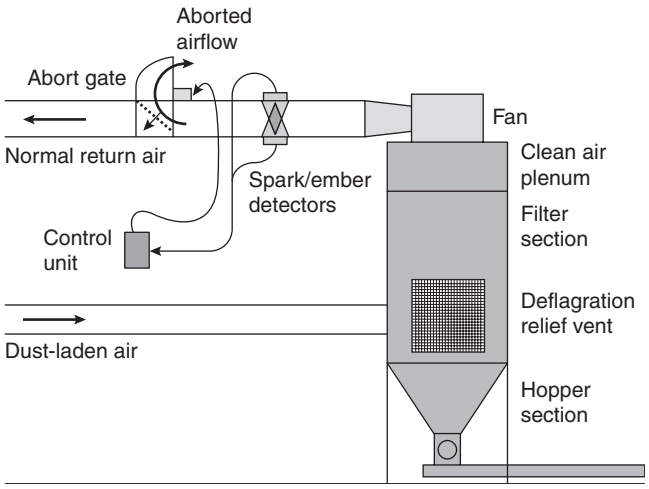

FIGURE 9.1.29 An Alternative Minimum Code-Compliant Implementation of Spark Detection for Return Air Abort (Source: J. M. Cholin Consultants, Inc.)

fire protective signaling system control panel, listed as a releasing device, is required for the activation of the abort gate.

This system does nothing to protect the dust collector itself. Once the abort gate has operated, the occupants of the building and the building itself are considered adequately protected, and the dust collector is allowed to burn. Since the dust collector is of noncombustible construction, it represents, in theory, a limited fire threat. The air moving through the dust collector serves as a heat transfer medium. As the filter media (bags) are consumed, the probability of a dust deflagration becomes increasingly remote. Prudent design dictates that whenever a return air abort gate is tripped, the automatic bag cleaning feature of the dust collector be shut down also. This reduces the probability that a fire in the dust collector will transition to a deflagration because of a dust/air suspension caused by the operation of the bag cleaning feature.

Dust Collector Rupture. In the context of a dust collector deflagration, the life safety objectives require the prevention of the catastrophic rupture of the dust collector and the prevention of flame extension into the facility interior by way of the inlet ducts and the return air ducts. Prevention of the dust collector rupture is usually achieved by either venting the dust collector to a safe outside location, following the guidelines in NFPA 68, or with deflagration suppression systems designed, installed, and maintained in accordance with NFPA 69. These deflagration control measures reduce the pressure in the dust collection system and should be adequate to limit flame extension via the ductwork.

Spark Detection and Extinguishment Equipment. This represents the minimum code compliant protection for the woodworking facility dust collector. This does not represent the commonly accepted best design practice. In most cases additional spark detection and extinguishment equipment is installed to minimize downtime and preserve the capital investment in the dust collection system. Spark detection is usually used in conjunction with an automatic intermittent water spray extinguishing system to quench sparks before they enter the dust collector.

The typical spark detection and extinguishing system consists of three basic components, shown in Figure 9.1.30, each listed by a nationally recognized testing laboratory as a system:

1. Set of spark/ember detectors mounted on the duct
2. Water spray extinguishing unit mounted downstream from the detectors
3. Control panel to provide power to and receive signals from the detectors and to provide power to actuate the extinguishing unit

Spark detection and extinguishing systems rely on the extreme sensitivity and speed of response of spark detectors to detect sparks as they travel down the pneumatic conveyor duct, often at speeds as high as 6000 ft/min (30 m/sec). When the detector detects the radiant emissions from the spark, it signals the control unit. The control unit energizes the solenoid of a water spray extinguishing unit. The extinguishing unit establishes a water discharge pattern within the duct to quench the spark as it arrives at the extinguishing unit location (Figure 9.1.31).

The distance between the detector and the extinguishing unit must be carefully computed, based on the duct diameter, conveying air velocity, and the response time parameters of the spark detectors, extinguishing unit, and control panel. Likewise, there is usually a minimum distance between the dust collector and the extinguishing unit. This distance is determined by the conveying air velocity, duct diameter, and water pressure. Failure to properly compute these factors renders the system of limited value, as it then becomes possible for the spark to pass the extinguishing unit before the water discharge has established an effective extinguishing concentration in the duct.

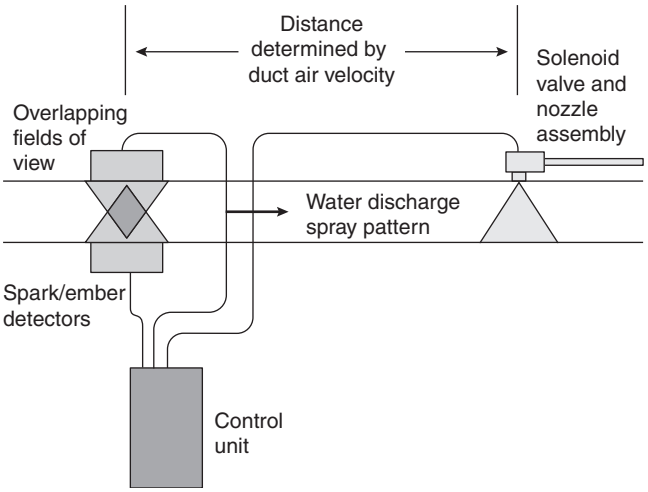

FIGURE 9.1.30 Basic Spark Detection and Extinguishment System Design (Source: J. M. Cholin Consultants, Inc.)

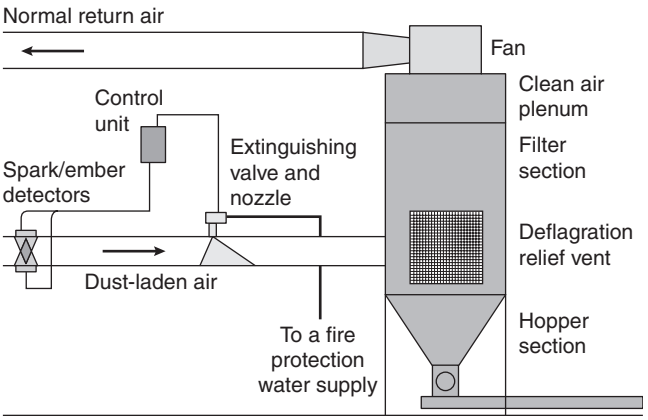

FIGURE 9.1.31 Spark Detection and Extinguishing System Protecting the Inlet to a Dust Collector (Source: J. M. Cholin Consultants, Inc.)

Limitations to Spark Detection Systems. Spark detection and extinguishing systems are listed as integrated systems to be installed on the inlet pipes that convey dust to the collector. Each duct entering the dust collector must be monitored. The principal concern is the protection of the collector from sparks entrained in the airflow. Each time a spark is detected, the extinguishing unit is energized and a spray of water is established in the duct. The control panel is equipped with a timer, which controls the duration of the water discharge usually to a period between 3 and 15 seconds. After this brief spray, the extinguishing unit is de-energized and the system waits for the next spark. The air movement is not shut down. The whole dust collection system continues to operate. The water discharge is normally limited to less than approximately 6.6 gal (25 L), a quantity that readily evaporates in the dust collection system airflow.

Spark detection and extinguishing systems are applicable only when the concentration of combustible dust within the pneumatic conveyor duct is below the MEC. Where ducts are operating above the MEC, the dust/air mixture is capable of propagating a deflagration. There is the potential that a spark could ignite a deflagration in the duct. If this occurs the spark detection system would be of little value for several reasons. First, deflagration flame fronts move at speeds substantially greater than the normal conveying velocity of the dust collection system. Since the distance between the spark detectors and the extinguishing unit is based on normal conveying velocity, this greater speed would mean that the flame front would pass the extinguishing unit before a water spray pattern had been established. Secondly, the quantity of water delivered by extinguishing units has not been evaluated for capability of quenching a deflagration flame front. There is no basis to conclude that the intermittent water spray unit listed for spark quenching provides sufficient extinguishing water density to quench a deflagration flame front. Finally, deflagration flame fronts in ducts tend to accelerate until they exceed the speed of sound, turning into a detonation. Consequently, ducts in which a deflagration can occur must be protected with either deflagration venting or deflagration suppression systems.

Spark detection and extinguishing systems are one tool available to the facility designer to manage the fire hazard inherent in the modern woodworking and wood-processing facility. They are usually used as part of an overall fire protection strategy. A spark detection and extinguishing system located on the inlet lines detects and quenches the sparks in the wood particulate stream, preventing burning material from entering the collector. A second set of spark detectors is used to actuate the abort gate to prevent smoke, flame, and burning material from re-entering the facility from the collector and to shut off the automatic bag cleaning facility on the dust collector. This design concept is shown in Figure 9.1.32. In some cases, the second set of spark detectors is employed to actuate a water deluge system in the dust collector.

In general, it is not recommended that a single set of spark detectors on the inlet side of the collector be used to actuate the

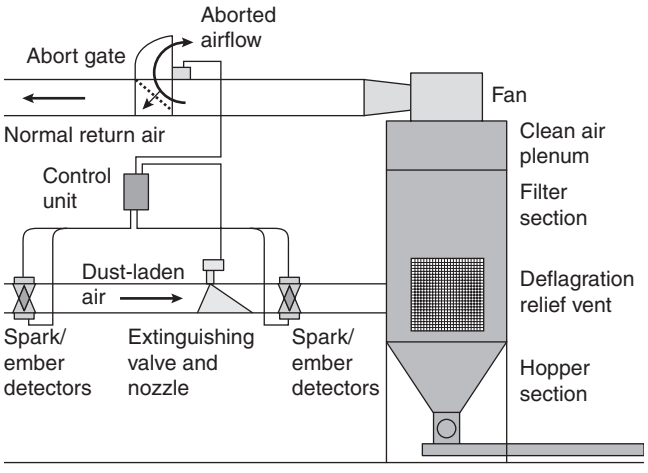

FIGURE 9.1.32 Typical Spark Detection and Extinguishing System for Managing the Hazards Associated with a Dust Collector (Source: J. M. Cholin Consultants, Inc.)

abort damper on the outlet side. In many woodworking operations, sparks are a regular occurrence, and a properly operating spark detection system will detect several sparks per day under normal conditions. Once the abort damper has operated, the air movement must be shut down to enable the manual reset of the damper. This is a serious inconvenience if it happens too frequently. Furthermore, the interruption of the air movement through the dust collector allows all the dust that has adhered to the filter bags to fall down into the bottom of the collector. If there is any burning material within the collector, the air shutdown could cause a fire to transition to a deflagration.

Spark detection and extinguishing systems can make very significant reductions in the hazard associated with pneumatic wood particulate conveying systems, subject to one important caveat. Spark detection and extinguishing systems cannot be used where deflagration conditions exist in the ducts. When deflagration conditions exist in the ducts, explosion prevention systems that meet the requirements of NFPA 69 or deflagration venting designed in accordance with NFPA 68 must be employed. Spark detection and extinguishing systems should be thought of as fire-extinguishing systems that reduce the probability that burning material will enter the dust collector.

In general, a spark detection system does not "completely protect" a dust collection system, the dust collector, or the facility it serves. The spark detection and extinguishing system covering the inlet lines and the detection activating an abort gate on the air return lines address a substantial part of the fire risk. However, a properly protected dust collection system will include either deflagration vents installed in accordance with NFPA 68 or explosion prevention and protection systems installed in accordance with NFPA 69 to address the contingency of a deflagration in the collector producing a flame front that travels too fast to be diverted by the abort gate. Furthermore, a sprinkler system in the dust collector installed in accordance with NFPA 13 should be considered, as it will probably limit the structural damage to the dust collector in the event of a fire and hence facilitate the return to operation.

Other Design Approaches. Some fire protective design concepts should be carefully scrutinized before using them to protect dust collectors for combustible particulate solids. The use of heat detectors to actuate a gaseous extinguishing system can increase the hazard rather than reduce it. In a 50,000 cfm (1400 m^3/min) dust collection system, at standard temperature and pressure, it takes a fire of about 15.3 Btu/sec (16 kW) to produce a 1°F (0.556°C) increase in the temperature of the air flowing through the collector. Fixed temperature heat detectors generally require temperature increases on the order of 50°F (27.8°C) before operating. Differential temperature detection systems are rarely stable when the threshold differential is less than 10°F (5.5°C). Using the 10°F (5.5°C) temperature differential, such a system could be expected to initiate response when the fire had achieved a heat output of 153 Btu/sec (approximately 160 kW). This is equivalent to a pool of burning gasoline of approximately 1.0 ft^2 (0.1 m^2). If the air movement through the collector is disrupted (by the discharge of an extinguishing agent and the shutdown of the air movement necessitated to attain and maintain extinguishing concentration) while a fire of this magnitude exists within the collector, a deflagration is likely. A similar set of concerns should be addressed in the event that water deluge actuated by heat detection is contemplated.

SUMMARY

The nature of wood as a raw material and the methods employed to convert that raw material into a finished product contribute to a substantial level of fire hazard in woodworking facilities. In addition, the production methods produce large quantities of wood particulate that are easily ignited and in many cases can deflagrate. These factors demand an aggressive loss prevention posture in woodworking facilities.

The fire risk inherent in a forest products processing facility can be very effectively managed through conscious facility design, operations, and fire-protective systems. Woodworking facilities can be designed to minimize the opportunities for ignition by organizing the production process to keep combustibles away from ignition sources, compartmentation of the facility, properly designed wood-waste management systems, and utilization of automatic sprinklers. Operational policies can contribute to the reduction of fire risk, especially through a strictly enforced housekeeping program. Finally, the proactive protection of the wood-waste/dust collection system can reduce the probability of an explosion to acceptable levels.

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3. Cholin, J. M., "Everything You Didn't Know You Wanted to Know About Spark/Ember Detection But Are About to Learn," *The Moore-Wilson Signaling Report,* Focus Publishing Enterprises, Bloomfield, CT, serialized over 5 issues, Mar. 1993.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on woodworking facilities and processes discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™*
NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 72®, National Fire Alarm Code®
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 664, *Standard for Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities*

Chapter 2

Spray Finishing and Powder Coating

Don R. Scarbrough

Chapter Contents

Types of Coatings
Spray Process Equipment and Components
Powder Coating Process Equipment and Components
Fluid Spray Process Hazards and Control
Powder Coating Process Hazards and Control

Key Terms

coating operations, finishing process, fluid coatings, fluidized bed, limited finishing workstation, overspray, powder coatings, spray area, spray booth, spray gun, spray process, spray room

Spray application of coatings is a process basic to the manufacture of a broad variety of fabricated products. Factories frequently operate at least one paint spray booth. Regardless of the purpose for which the coating is applied, flammable or combustible materials are commonly used in the process. Fires in paint operation areas develop very quickly, have high heat release rates, and produce large volumes of toxic smoke. The risk of fire can be kept to an acceptable level through a combination of efforts directed at the control of sources of ignition, the control of ignitable atmospheres (vapor- or powder-air mixtures), limitation of available fuel, isolation of the process, explosion prevention, and provision of an adequate means for extinguishing a fire. Simply stated, the person who manages his or her process safely must do those things that will tend to prevent a fire from starting and those things that will limit the size of any fire that does occur to a scale that can be quickly extinguished with immediately available resources. If these things are done, the process can be operated with minimal risk to life and property.

For related topics see Section 9, Chapter 3, "Dipping and Coating Processes"; and Section 9, Chapter 4, "Plastics Industry and Related Process Hazards."

TYPES OF COATINGS

Fluid Coatings

Flammable and combustible fluid coatings have been in industrial use for many years. Their use involves familiar fire risks, discussed here at some length.

Waterborne coatings, which are enjoying expanded use, present somewhat of an enigma; namely, many formulations that exhibit a flashpoint do not have a fire point and will, therefore, not sustain a flame. Although these materials do not present fire hazards typical of flammable liquids, their dried residues are combustible and must be managed as such. ASTM D4206, *Standard Test Method for Sustained Burning of Liquid Mixtures by the Seta Flash Apparatus (Open Cup),*[1] sets forth a procedure useful to determine whether a given material, as a liquid, will support flame. If it does, it should be treated as a flammable liquid.

The most familiar atomizing device for fluid coatings is the air spray gun, which uses jets of high-pressure air to break up fluid into a fine mist. The high-volume, low-pressure (HVLP) spray gun is an adaptation of the air spray gun that produces a somewhat coarser spray, thereby reducing the fine mist. Another device commonly seen in high-volume production processing is the airless atomizer, which generates a spray of fluid by hydraulic means without using compressed air. Fluid pressures used with this type of atomizer range from 300 psi (2068 kPa) to approximately 7000 psi (48,265 kPa).

Air and airless atomizers are also used in electrostatic spray operations. For this process, the appropriate atomizer is built into a spray gun that has a high-voltage electrical input. Voltages applied to the charging electrode range from approximately 35,000 V to somewhat over 100,000 V.

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There is less overspray with the electrostatic method than with the air or airless spray methods because the charged atomized particles are attracted to the grounded workpiece.

A third type of atomizer depends on electrostatic forces for its operation. In its most common configuration, a sharp-edged disc with a diameter of 6 to 12 in. (150 to 300 mm) is mounted with its axis oriented vertically and is then charged electrically to about 100 kV. The disc is spun about its axis while the coating fluid is poured slowly onto the surface. Centrifugal force spreads the fluid into a thin film and carries it to the sharp edge of the disc, where the film is disrupted by electrostatic forces and sprayed in a 360 degree pattern. Workpieces are carried to the process zone by a conveyor and collect coating as they pass through. A form of this device that has gained popularity has the disc developed into the form of a cup or bell 2 or 3 in. (50 or 76 mm) in diameter that rotates at a high speed—sometimes approaching 60,000 rpm. Bell atomizers are frequently seen mounted in banks of 6 to 12 units at a single spray station.

Powder Coatings

A coating process that has gained broad acceptance is the application of organic coatings in the form of dry powder. In this process, the powder is first suspended in air and then charged electrostatically from a dc power supply operating between 60 and 120 kV. The powder is then directed toward the grounded workpiece and held in place by electrostatic forces. The powder is formed into a continuous coating as it melts during passage through a process oven. The powder coating process differs substantially from the fluid coating processes because no organic solvents are used and no readily ignitable residues are produced.

Electrostatic application of powder is most commonly accomplished with spray guns. These spray guns are simple devices to which a mixture of powder and air is fed through a single tube. A separate cable connected to the gun provides the high voltage necessary for operation of "corona-type" guns, whereas those that operate by frictional charging (referred to as "tribocharging" guns) require no external source of high voltage.

Workpieces having dimensions less than approximately 4 in. (102 mm) or that are configured as long ribbons or cables can be powder coated with a device known as an electrostatic fluidized bed. In this process, powder is held in a container having an open top and a porous bottom through which an upward flow of air causes the powder mass to levitate or "fluidize." Charging electrodes near the surface or beneath the fluidizing plate impart an electrical charge to the powder. Electrically grounded workpieces pass over the surface of the bed and collect a coating of powder. The coating is then cured in a baking oven.

Although they are not widely used, there are techniques for applying dry powder coatings without the use of electrostatics. These processes typically involve preheating the workpiece to a temperature substantially above the melting point of the powder and then applying the powder, either by dipping the workpiece into a fluidized bed or by spraying air-suspended powder directly onto the hot surface of the workpiece. The powder melts immediately on contact and flows to form a film, which is subsequently cured in a bake oven.

SPRAY PROCESS EQUIPMENT AND COMPONENTS

Fluid Supply

Air spray guns draw their coating fluid from either small cups mounted on the guns or through hoses connected to larger pressurized containers called paint tanks or pressure pots that have capacities varying from ½ to 60 gal (2 to 227 L). In very high production arrangements, the coating can be fed by a pump from a bulk tank. Fluid pressures between 3 and 75 psig (21 and 517 kPa) are customary.

To ensure satisfactory results, industrial coating mixtures are usually modified shortly before spraying by the addition of solvents to adjust viscosity. A safety tank or container is used to reduce the possibility of a flammable liquid spill while handling or transporting this blended material.

Spray Guns and Devices

Among the various forms of industrial air spray guns, the two most commonly used are the pistol grip hand spray gun and the machine-mounted automatic air spray gun. Air is supplied to the hand spray gun through one hose, while fluid is either hose fed or drawn from a gun-mounted container (Figure 9.2.1).

Electrical grounding of airless spray guns to drain off static electricity generated during spraying is provided through a wire or conductive layer built into the fluid hose. A manual safety lock is usually provided on hand units to secure the trigger and prevent accidental actuation.

Handheld and automatic electrostatic spray guns have electrically nonconducting extensions at the front end to insulate the

FIGURE 9.2.1 Hand Air Spray Gun with Fluid Supplied from 2 qt (1.9 L) Pressure Pot (Source: DeVilbiss)

energized components from the grounded parts. In addition to being connected to coating fluid and air supplies, these guns are also connected to high-voltage power supplies. Voltage at the atomizer is in the 30 to 75 kV range for handheld units and in the 30 to 120 kV range for automatic units. In hand spray guns of this type, the cable carrying the high-voltage power to the gun also supplies an electrical ground for the pistol grip and trigger. To prevent electrical sparking from accidental contact of the charged elements of the gun with a grounded object, the cable is usually terminated at the gun in an electrical resistance on the order of 75 to 250 MΩ (megohm). In a more recent development, the high-voltage power supply has been integrated into the gun, thereby eliminating the high-voltage cable. Some automatic electrostatic spray guns are not equipped with a high-impedance termination but rely on the process control approach of maintaining separation between gun and workpiece to prevent electrical sparking.

Figure 9.2.2 shows an electrostatic disc surrounded by chairs hanging from a conveyor loop. Immediately above the disc is its motor drive. Partially obscured, at the top of the illustration, is a device that moves the disc up and down, enabling it to coat workpieces over the entire height of the carriers. Separate electrical and fluid inputs are remotely controlled. Discs are commonly equipped with variable voltage power supplies that can be adjusted over a range of approximately 50 to 120 kV. Because considerable electrical energy is stored on the disc, adequate distance must be maintained between it and the workpiece to prevent sparking.

Spray Booths

A spray booth is a power-ventilated structure used to enclose a spraying operation. Although in most cases the booth structure physically surrounds the spray operation, some configurations leave the spray operation unenclosed and surround the operation with a controlled stream of air drawn into the booth.

The most popular type of spray booth is the "open face" or "open front" arrangement. It is a boxlike structure that has one open side. The ventilation system associated with the booth may provide an airflow horizontal to the floor (cross draft) or vertical to the floor (downdraft) as demanded by process requirements.

For some operations, such as production finishing of automotive bodies, a tunnel spray booth is used (Figure 9.2.3). This structure is virtually always arranged with vertical downdraft ventilation and a horizontal floor-mounted conveyor running the length of the tunnel. Makeup air is introduced through special ductwork and air diffusers in the ceiling.

Limited Finishing Workstations

A type of spray enclosure, referred to in NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*, as a "limited finishing workstation," is gaining acceptance for use in automotive repair shops and similar uses. Originally developed to control dust from surface preparation operations, such as sanding and grinding, these limited finishing workstations are allowed to enclose limited spray application, if certain requirements of NFPA 33 are met.

Limited finishing workstations differ from spray booths structurally in that the enclosing walls are usually not walls at all but movable curtains. In addition, the units might or might not exhaust to the building exterior and some are mounted on wheels to facilitate movement around the shop. NFPA 33 limits the total amount of material that can be sprayed in any 8 hour period to 1 gal (3.8 L). Refer to NFPA 33 for the requirements that must be met for these units to be used for spray application.

Special-Purpose Enclosures

Continuous Coaters. Continuous coater enclosures are individually engineered for a specific coating process. Within the

FIGURE 9.2.2 Electrostatic Disc (Source: ITW Ransburg)

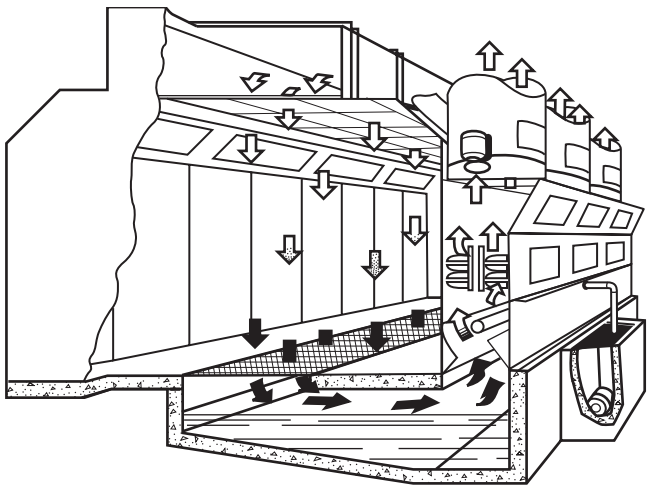

FIGURE 9.2.3 Tunnel Booth Configured for Downdraft Ventilation

coater enclosure is an array of spray guns that apply coatings to workpieces that pass through the coater at conveyor speeds between 100 and 600 ft/min (30 and 183 m/min). The interior of the coater is not exhausted, but the entry and exit vestibules are equipped with exhaust shrouds to capture any vapors or minor amounts of overspray that drift out from the main enclosure. Most of the overspray is collected in a sump and drawn off through a pumping system, which recycles the coating into the coating process.

Decorating Machines. These machines are used in conjunction with masking devices to paint stripes or other patterns on workpieces, such as automobile grilles and side moldings. The mask is mounted in the opening beneath a row of cylinders at the front of the machine, and the workpiece is placed face down on the mask. When the operating cycle is started, air-driven pistons in the row of cylinders clamp the work to the machine. Spray guns inside the cabinet automatically tilt in one direction and travel the length of the workpiece. At the end of the workpiece, the spray guns tilt in the opposite direction and travel back to the starting point. The air-driven clamps automatically release the work at the end of the operation.

An exhaust system draws fresh air in through the grille at the front of the machine, and internal filters remove overspray from the air-vapor stream before it is exhausted. Because the process is totally enclosed, the risk of escaping vapors or overspray and subsequent ignition is significantly diminished.

Spray Rooms

The size, shape, and weight of some workpieces might make the use of spray booths impractical. When this case occurs, an entire room dedicated to the spray process is a legitimate alternative. Such rooms, called spray rooms, are classified as hazardous areas. Power ventilation removes the combustible vapors that are released during the process, but velocities are not high enough to capture particulate matter. Therefore, overspray is permitted to settle to the floor where it accumulates as a combustible residue until it is removed by a mechanical cleaning process. Vapor removal systems are most effective when the exhaust intake is located along one wall within 1 ft (300 mm) of the floor and the makeup air is introduced along the opposite wall.

Open-Floor Spraying

A spray operation conducted without a spray booth and in an area not separated from general factory operations by a partition is called open-floor spraying. Depending on the quantity of volatiles to be released in the operation and existing ventilation within the building, forced ventilation might or might not be provided. Whether forced or not, adequate ventilation must be provided to prevent accumulation of flammable concentrations of vapor. Particulate overspray materials are allowed to settle to the floor and their residues are removed by mechanical means. Ignition sources incidental to other factory operations are a great concern whenever open-floor spray techniques are used, and it is common to establish a buffer zone surrounding the spray area for about a 20 ft (6 m) radius to separate processes.

Overspray Collectors

Vapor and overspray removal systems associated with spray booths or enclosures typically include a fan to create an airflow and a collection system that separates and collects particulate matter from the airstream, then exhausts vapors to the exterior of the building. Overspray collectors can generally be placed into one of four categories, as follows.

Baffle Maze. The baffle maze consists of a series of flat panels arranged in a staggered pattern through which the airstream is directed. A substantial portion of its particulate burden is removed by direct impaction and collection on the surface of the dry baffle panels where it remains until removed by mechanical cleaning. Such systems are of limited efficiency and permit appreciable amounts of fine particulates to pass through.

Dry Filter. Collectors using paper or fiberglass filter elements are called dry filters and are popular for low- to intermediate-volume spray operations. The typical filter used in this type of collector is a replaceable element approximately 20 in. (508 mm) square and perhaps 2 in. (51 mm) thick. Secondary cloth filters might be found mounted in the plenum behind the primary filters to provide more efficient capture of fine particles. Particulate residues are permitted to accumulate on the filter until a significant obstruction of the airflow through the filter is noted. Then the fouled filters are discarded and replaced.

Waterfall and Cascade Scrubbers. Where high-volume spray coating operations are conducted for several hours a day, waterfall or cascade scrubbers are commonly used. The exhaust airstream either is scrubbed directly by sprays of water coming from nozzles or follows a path that takes it through several stages of waterfall. Figure 9.2.4 is an example of one variation of this type of scrubber. Particulate matter is accumulated in a water tank from which it is removed either manually or automatically by a sludge removal device.

Chemical compounds must be added to the water to prevent paint residues from adhering to the walls or clogging nozzles, thereby creating open channels through the water curtain. Air passing through these open channels will not be adequately cleansed and will carry particulate matter into the exhaust system; the particulate matter can then be deposited on the lining of the exhaust stack, on exhaust fan blades, or on the roof of the building.

Venturi Scrubbers. Perhaps the most efficient overspray collector is the venturi scrubber. This device directs the exhaust airflow through a narrow throat (venturi) through which a high-velocity spray of water is also directed. Virtually all particulate matter is extracted from the airstream and trapped in the water. The water is processed through a tank where residues are removed by settling and skimming. The same chemical compounds mentioned in the discussion of the waterfall-type scrubber must be added to the water used in this system to prevent plugging and blocking of nozzles. Figure 9.2.5 is a schematic of a venturi scrubber.

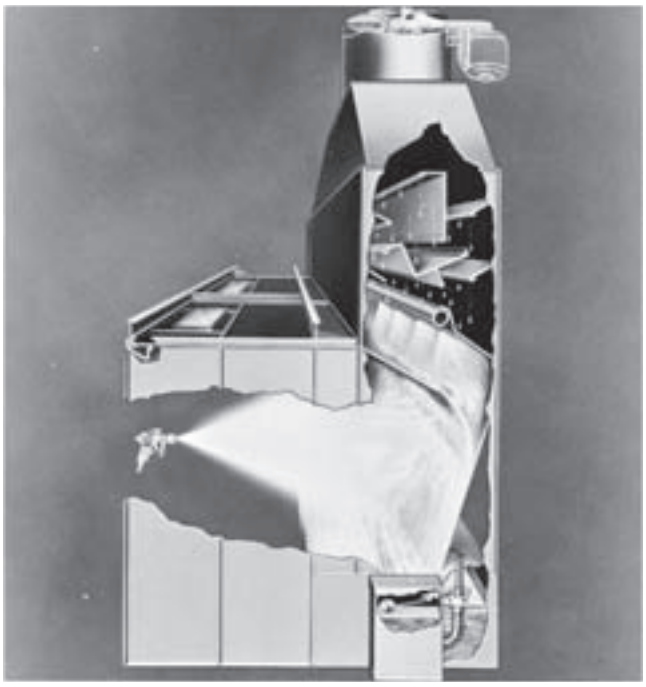

FIGURE 9.2.4 Water Wash Booth (Source: Team Blowtherm)

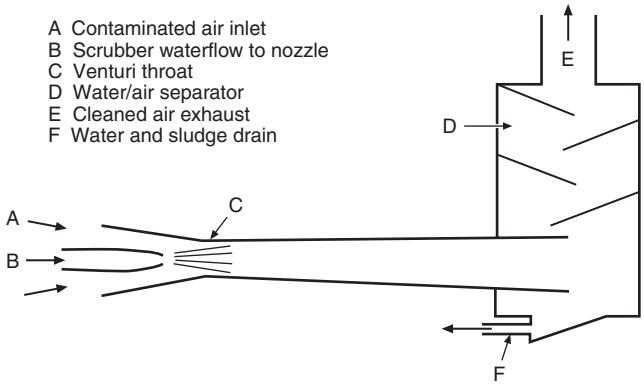

FIGURE 9.2.5 Venturi Scrubber

POWDER COATING PROCESS EQUIPMENT AND COMPONENTS

Spray Process

The powder coating spray process utilizes a device called a feeder that mixes powder with air and supplies the mixture to the spray guns. The powder is contained in a fluidized bed or in a hopper having a cone-shaped bottom. Feeders might supply a single gun or several guns with a separate ejector for each gun.

The most common coating powder is epoxy powder, but others include acrylic, polyester, vinyl, nylon, butyrate, polyolefin, and alkyd. These powders are shipped from the manufacturer to the user in containers of 25 to 1000 lb (11.34 to 453.6 kg). They may be classified as ordinary combustibles and, as such, may be stored without requirements for extra hazard protection.

FIGURE 9.2.6 Automatic Powder Gun (Source: Nordson Corp.)

Spray guns used for the electrostatic application of dry powders do not differ greatly in appearance from guns used for the electrostatic application of fluids (Figure 9.2.6). Because no atomization is required, the functions of the spray gun are simply to control the shape of the spray pattern and to impress a high-voltage charge on the powder cloud. Powder and electrostatic power input connections can be made at the rear of the barrel or from below to the base of the grip and the forward portion of the barrel. Connections to automatic guns typically are made at the rear. Guns having integrated power supplies have no high-voltage cable but are commonly powered through a lightweight cable carrying about 12 V.

Electrostatic power supplies rectify stepped-up common ac line voltage inputs, either 115 or 230 V, to produce dc output ranging from 30 to 100 kV. Several automatic guns may be connected to a single power supply. For handgun applications, however, a separate power supply is provided for each gun, and each supply has a control circuit that prevents the voltage from being energized unless the trigger is actuated.

The interconnection between power supply and spray gun is usually made through a high-voltage coaxial cable. At the termination of the cable within the spray gun, the charging circuit is connected to the gun electrode through a 75 to 250 MΩ resistor. In operation, a faint blue glow, called a corona, is developed around the end of the electrode that is projected through the front of the gun. Individual powder particles are charged as they pass through the corona.

In a class of equipment commonly referred to as tribocharging guns, no external power supply or cable is used (Figure 9.2.7). These devices generate static charge directly on the surface of the powder granules through frictional contact between the high-velocity airborne granules and internal surfaces of the apparatus.

FIGURE 9.2.7 Automatic Tribo Gun (Source: Nordson Corp.)

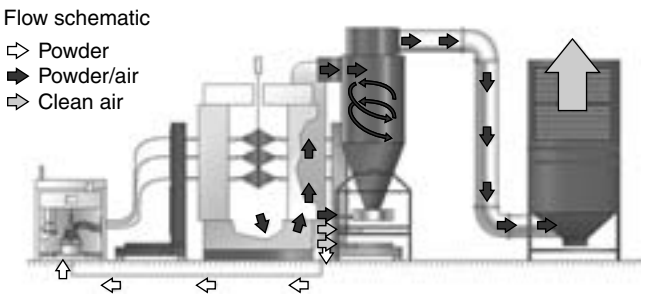

FIGURE 9.2.8 Automatic Recycle of a Single-Color Powder-Coating System Showing Booth, Collector, Fan, and Filter

A common facility in which electrostatic powder spray operations are conducted is a spray booth with a hopper bottom through which exhaust air is drawn into a ductwork that leads to a powder collector. A cloth or fabric filter within the collector separates the powder from the airstream. Powder separated within the collector falls to the bottom of the hopper from which it is extracted and is subsequently reintroduced to the feeder for the spray guns. A basic outline of this arrangement is shown in Figure 9.2.8.

In some installations, a cyclone is placed in the airstream between the booth and the filter collector. This device uses centrifugal force to separate larger particles from the airstream prior to filtration.

A more recent development is the integration of the spray booth and powder recovery system into a single structure (Figure 9.2.9). In this equipment, cartridge-type filters and the exhaust fan are built into the structure of the spray booth. The ductwork, which conventionally would separate the booth from

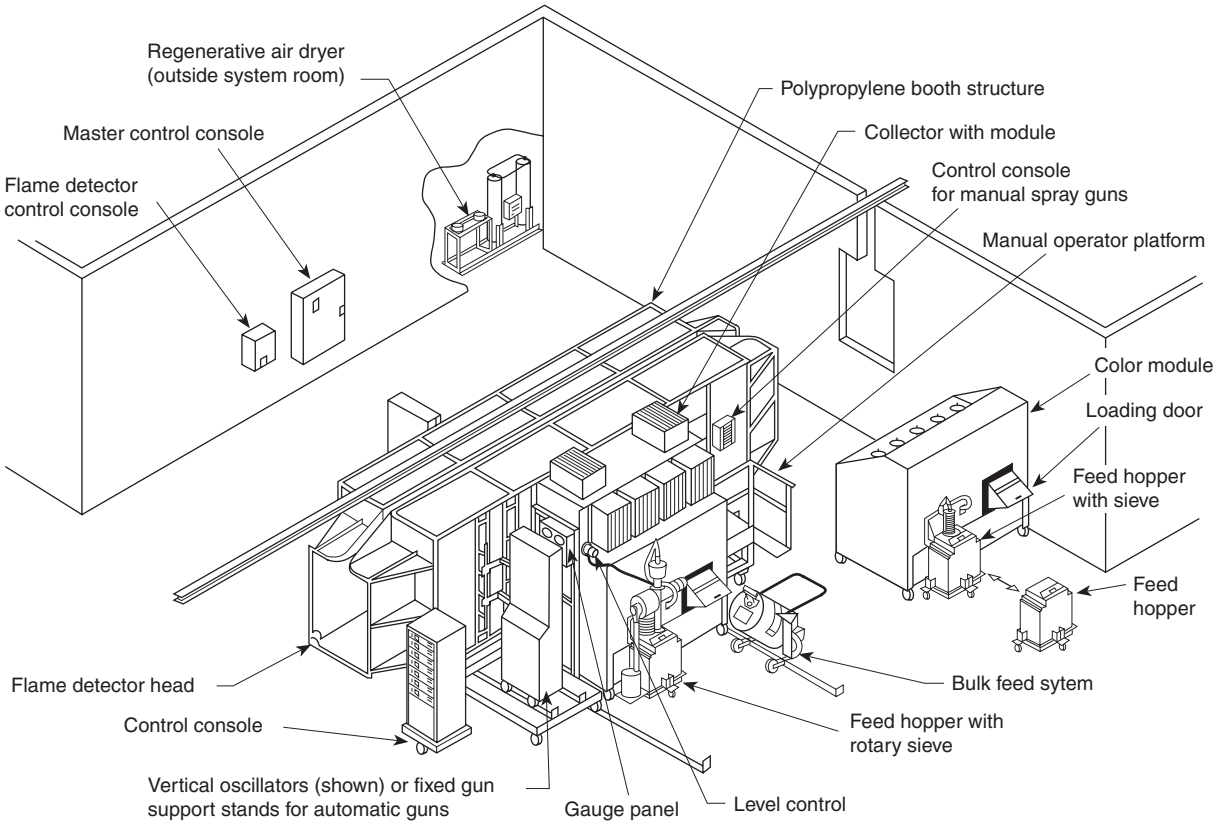

FIGURE 9.2.9 Integrated Powder Spray Booth/Recovery System

the powder collector, is eliminated. Collected powder is pneumatically pumped from the hoppers immediately beneath the recovery filters directly back to the spray gun feeders. Within the last three decades this arrangement has gained dominance in new installations. A further development that has gained broad acceptance is the use of flame-retardant plastics for the spray enclosure. Many of the powder booths currently manufactured have plastic walls and roof panels.

Electrostatic powder coating can also be conducted within an enclosure commonly referred to as a pipe coater. The device consists of a steel enclosure, a ring of automatic electrostatic powder spray guns, and a conveyor. The workpiece, typically a pipe or structural steel form, enters at one end, passes through a cloud of coating powder, and leaves the coater at the opposite end. The workpiece is preheated to a temperature above the melting point of the powder, so the powder will fuse on contact. The coater is provided with an exhaust system and powder recovery filter system similar to that used with the booth arrangement described in connection with Figure 9.2.9.

Fluidized Bed

Fluidized beds are constructed in a wide variety of sizes. They have vertical walls (typically steel) and a porous floor (textile or plastic). Air flows upward through the floor and through the powder. When the airstream is adjusted properly, the powder will behave as a liquid, flowing readily around and contacting all surfaces of any object that is dipped into it. It will immediately fuse to a workpiece that has been preheated above the melting point of the powder. After the workpiece has been removed from the bed, it is placed in an oven to complete the curing of the coating.

An electrostatic fluidized bed has a series of high-voltage electrodes near the surface of the fluidized powder mass or, alternatively, below the fluidizing plate. Grounded workpieces, which might or might not be preheated, pass above the surface of the fluidized bed and are coated electrostatically, then cured in a bake oven. (Dipping is not required.)

Both regular and electrostatic fluidized bed arrangements usually are provided with peripheral air exhaust systems that collect any powder grains escaping the bed and prevent their distribution into the general factory area (Figure 9.2.10).

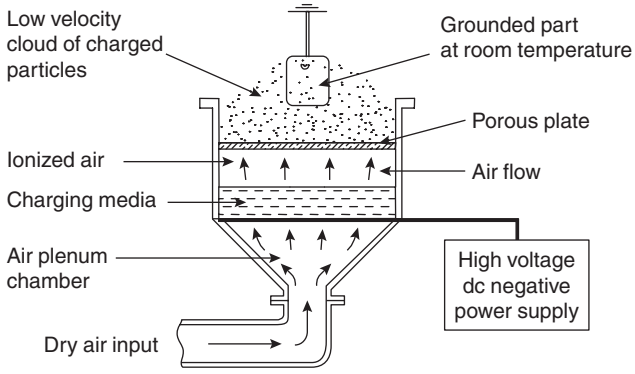

FIGURE 9.2.10 Fluidized Bed Feed Hopper (Source: Nordson Corp.)

FLUID SPRAY PROCESS HAZARDS AND CONTROL

Materials and supplies used in organic spray finishing processes are usually flammable or combustible, are often toxic, and, in some cases, might be highly reactive or unstable. For these reasons, spray finishing operations are considered hazardous, and suitable preventive and protective measures should be taken to minimize the hazards.

Fire Prevention

Hazard Identification. Materials' hazards should be identified as soon as they arrive in the facility, and personnel should be trained on these hazards. A detailed method of identification is contained in NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response.* The NFPA 704 system provides for the identification of five degrees of health, flammability, and reactivity hazards, including special hazards for consideration during emergency response, such as water reactivity or oxidizer status.

Storage and Handling. Bulk supplies of flammable liquids should be stored outdoors away from buildings or in special indoor storage facilities. Smaller quantities are then brought indoors to a mixing room where they are prepared for use. The mixing room should be located adjacent to an outside wall provided with explosion-relief vents and should be isolated from the rest of the building by fire-resistant construction. The room should have sufficient mechanical ventilation to prevent the development of flammable vapor concentrations in the explosive range. To prevent rupture of the container due to fire exposure, all flammable liquid containers of greater than 5 gal (19 L) capacity that are kept indoors should be equipped with a special plug that incorporates a pressure relief valve, a vacuum-relief valve, and a flame arrester. See NFPA 33 for additional requirements.

Prepared coating materials are transported from the mix room to the spray area in containers or through piping. Containers should be equipped with tightly clamped lids that will retain vapors and liquids in the event the container is upset. Piping should be identified as process pipe containing flammable materials, and a shutoff valve should be installed at each point where a hose is connected to the system. Emergency stop controls and fire alarm interlocks are very important to keep runaway pumps from continuing to feed a fire after hoses have been burned off. All piping, pumps, and supply and receiving vessels must be electrically grounded and bonded to prevent accumulation of dangerous static electrical charges during transfer of fluids.

Quantities of flammable or combustible liquids kept in or near process areas should be limited to the amount needed for one working shift at a time. The materials should be put in closed containers equipped with appropriate pressure relief devices and flame arresters at all openings. These materials are best kept outside the spray booth and separated from it by several feet (1 or 2 meters) to prevent them from becoming involved in a spray booth fire.

Flammable or combustible liquids should never be transferred from one container to another by the application of air pressure to the original shipping container. Pressurizing such containers might cause them to rupture, creating a serious flammable liquid spill. Any pressure vessels used should be designed specifically for such use or should be manufactured in conformance with the American Society of Mechanical Engineers' (ASME) *Code for Unfired Pressure Vessels.*[2]

Fluid hoses connected to some electrostatic equipment must have a special structure to resist both fluid and high-voltage electrical stresses that result from use of electrically conductive paint. If ordinary hose or tube is substituted for this use, electrical failure of the hose wall will lead to pinhole failures and ignition of fires.

Control of Vapors and Overspray. Limitation of vapors and overspray to the smallest practicable area is accomplished through the combination of process enclosures and power ventilation systems. Ventilation systems should be checked frequently to ensure they are operating properly and that specified flow rates are being maintained.

Ignition Sources. All sources of ignition should be barred from, or controlled in, areas defined as Division 1 or Division 2 in NFPA 70, *National Electrical Code®*. The careless use of smoking materials and improperly supervised welding or flame cutting operations pose significant threats to a fluid-coating applications system. A hot work permit system and prohibition of smoking should be in practice. See NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work.*

To minimize chances of ignition, open flames, spark-producing equipment, and any exposed surfaces exceeding ignition temperature of the material being sprayed should be prohibited in either Division 1 or Division 2 areas. No equipment or process capable of producing sparks or hot particles should be located above or adjacent to those areas classified as hazardous unless partitions or other means of separation are provided.

All electric wiring and equipment, unless specially designed and manufactured for use in hazardous areas, can be regarded as potential ignition sources. Only those devices and wiring types listed for this use should be installed or used in areas classified as hazardous. To accommodate failure, electric lighting fixtures located above a classified area should be totally enclosed or provided with a guard that will prevent hot particles from dropping into the hazardous area. Exhaust fans should be nonsparking and conform to Air Movement and Control Association (AMCA) Class C requirements.

Static electricity remains a common source of flammable vapor ignition in electrostatic spray finishing operations. Energized electrodes send generous amounts of electrical charge into the air, and they then collect on surrounding surfaces. Accumulation of this charge can raise a surface to a high voltage. Electrostatic spray systems should be equipped with electrical interlocks to de-energize the electrostatic power supply any time the spray guns are not actually spraying. Most modern electrostatic spray guns that are listed for use with flammables include a charging circuit that limits the energy of a discharge arc to a value below that which is sufficient to cause ignition.

Electrostatic ignition can be prevented by electrically bonding together all the elements of a fluid transfer or spray system along with the workpiece and all other electrically conductive objects located within 10 ft (3 m) of the charged elements and then grounding the bond. Additional information on bonding and grounding can be found in NFPA 77, *Recommended Practice on Static Electricity.*

Human beings are also conductors of electricity; thus, the spray operator cannot be overlooked in the grounding process. Gripping the grounded spray gun with the bare hand or wearing shoes with electrically conductive soles, provided the floor is grounded, are two workable methods for grounding the operator. Even in the absence of electrostatic equipment, dangerous static electrical charges can be generated by the simple act of walking across a spray area floor that is covered with sticky paint residue. The charging mechanism is identical to that seen in the more familiar act of walking across a wool or nylon carpet on a dry day: a spark and shock result when a doorknob or switchplate is touched. That spark is quite capable of igniting flammable vapors.

Static electrical charge is also generated by the operation of nonelectrostatic air and airless spray equipment, resulting in discharge sparks from either the spray apparatus or the object being sprayed. To prevent ignition of fires from such discharges, electrical bonding and grounding of apparatus and the sprayed object is necessary.

Housekeeping. Residues of spray materials are a solid form of readily ignitable fuel. A routine maintenance program should provide for the periodic removal of overspray residue from walls, floor, and ceiling of the spray booth, room, or area, as well as from conveyors and the interior of ventilation ducts. Residue buildup on conveyors may become particularly hazardous by acting as electrical insulation, which interferes with workpiece grounding. Contaminated spray booth filters should be either removed from the building as soon as they have been replaced or kept immersed in water until disposal, as they present a serious spontaneous heating hazard. Only a few hours of "fermenting" is required for a waste container holding paint-fouled filters or rags to become so hot that it bursts into flame. Alternately, the spontaneous heating hazard can be eliminated by curing the paint in fouled filters or rags by processing them through a paint bake oven before disposal.

Operator Training. Operating personnel should be thoroughly trained when they begin the job and should be given periodic additional training to maintain their appreciation of the hazards involved, to teach them hazard control procedures, and to educate them in new processes. They should be aware of the inherent hazards of the spray materials being used, particularly if the materials are toxic, chemically unstable, or reactive. They should also be familiar with the system of hazard identification that is employed. Operators should be drilled in proper operating, bonding and grounding, emergency, and maintenance procedures.

Fire Protection

Areas in which fluid spray processes are conducted and areas where coatings and solvents are mixed or stored should be separated from other plant operations by appropriate distance or partitions. Automatic sprinklers inside spray booths, inside ventilation ducts, and at the ceiling contribute considerably to the control of fire. In open areas, draft curtains extending down from the ceiling around spraying operations, along with smoke and heat vents, will slow the "mushrooming" of hot combustion gases along the ceiling and, thus, limit the number of sprinklers that will activate. This scenario will concentrate sprinkler discharge into the area where it is most needed and will minimize smoke and heat interference with fire-fighting efforts.

Fire in the paint spray pattern radiates heat at an extremely high rate.[3] Temperature of surfaces 3 ft (900 mm) from the spray gun have been shown to rise more than 150°F (66°C) per second. Residues exposed to such radiant heating ignite within a few seconds.[3] Fast-acting optical flame detectors have been shown capable of interrupting spray within a small fraction of a second, thereby preventing ignition of surrounding residue. NFPA 33 requires such detectors for automatic electrostatic installations.

Any fluid transfer or supply system for flammables, whether driven by pump or by pressure vessel, should be arranged with emergency shutdown provisions and an interlock with the fire alarm and flame detector to interrupt flow in the event of fire or accidental spill, thereby limiting available fuel. "Panic button" actuators should be located at the operator control station and at the exit door.

Hoses should be constructed of material that has a nominal resistance to fire. For example, polyethylene tubing will melt immediately when exposed to fire, whereas rubber hoses will be more resistant. Polytetrafluoroethylene (PTFE) hoses are even more fire resistant.

Portable fire extinguishers and standpipe hoses are useful against fires involving small spray operations. The rate of fire development across residue accumulations can be very high, however. It must be recognized that in only a few seconds a fire can grow to a size that will be beyond portable extinguisher control, particularly in spray booths of the baffle- or the dry-filter type or in operations where paint residues are permitted to accumulate on the floor. For enclosed or semi-enclosed coating processes, such as in continuous coaters or automatic decorating machines, automatic fire-extinguishing systems can be used to flood the interior of the machines.

A spray booth and its exhaust ductwork should maintain structural integrity (i.e., not collapse) during a fire of nominal proportions so that the major portion of flame, heat, and fire gases produced will vent from the building through the exhaust ductwork. This venting diminishes the chances of fire spread in the building that will interfere with egress and access to the seat of the fire by members of the fire service. Exhaust fans and air makeup units should remain in operation during fire conditions to maximize smoke removal. Spray booths and their exhaust ductwork are required by various codes and standards to be constructed of steel, masonry, or other material of equivalent fire resistance. Survivability of booth structure is considerably enhanced by the cooling effect of water from sprinklers inside the stack and booth. The probability that heat from a fire within a booth and stack will ignite nearby combustible materials can be reduced to an acceptable level by reasonable clearances between any combustible structure or stored materials and the surfaces of the booth or stack. (For recommended clearances, see NFPA 33.) Spray rooms are usually required to be separated from other occupancies within the same building by walls, floors, and ceiling structures with a minimum 2 hour fire resistance rating.

POWDER COATING PROCESS HAZARDS AND CONTROL

Powder coating operations using combustible organic powders are classified as hazardous processes because the powders can burn vigorously when suspended as airborne dusts and can explode when confined. There are no flammable vapors in the powder coating process. The energy required to ignite a cloud of air-suspended coating powder is from 100 to 1000 times higher than that required to ignite flammable vapors. Powder deposited onto workpieces or booth walls or lying on the floor is not readily ignitable.

Fire Prevention

Storage and Handling. Coating powders that are kept in shipping containers are not customarily classified as hazardous materials and are commonly stored under conditions appropriate for ordinary combustible materials. Reasonable care is required in the handling and movement of the powder containers because a fire hazard could be created should the containers be broken and the powder distributed as an air-suspended cloud of dust.

Waste powder is commonly packaged into fiber drums or cardboard cartons lined with plastic bags and shipped to a landfill for disposal in accordance with Environmental Protection Agency (EPA) regulations. If the waste container has been processed through a baking cycle, the waste powder will have fused into a solid block of plastic that is no longer vulnerable to scattering or dispersion in air if the container is broken.

Spilled powder pickup and routine cleanup are usually accomplished with an industrial vacuum approved for use with combustible dust. Explosions have occurred when unapproved vacuums (with open-frame universal motors and sparking commutators) were used.

Coating Operations. Virtually all spray powder coating processes are conducted in spray booths that are more tightly enclosed and permit considerably less overspray to escape than those booths used for fluid coating processes. All connections in the hoses and piping associated with pneumatic transfer equipment should be routinely checked to confirm that they are secure and that ground connections are in place. Breakage of any such connection during operation could create a substantial hazard by blowing powder into the workspace air outside the process enclosure.

To prevent the escape of powder, the spray booth must have adequate ventilation that provides effective capture velocity at

all its openings. Minimum average velocities are considered to be in the vicinity of 60 ft/min (18 m/min). Interlocks should be installed to permit operation of the powder application equipment only while the ventilation equipment is in operation and, similarly, to permit operation of the electrostatic power supply only during the time the powder is actually being applied.

Ignition Sources. The control methods for ignition sources for powder coating are similar to those for spray finishing. Electrical apparatus in the Division 1 area should be listed for use in Class II, Division 1 locations; in the Division 2 area, wiring and apparatus should be dust tight and not have hot surfaces. Explosionproof wiring and apparatus (i.e., equipment listed for Class I areas only) are not appropriate.

Static accumulations on electrically isolated conductive objects are a major potential cause of fires in electrostatic powder coating installations. Metal workpieces suspended from conveyor hangers that do not provide an effective electrical circuit between the workpiece and ground pass through the coating process zone while discharging hot electrical sparks. Ungrounded metal blowpipes, or "wands," used for booth cleaning may become highly charged by tribo effect during use, and discharges from the pipe can ignite the powder being blown from the floor of the booth. Propagating brush discharges within thin-wall nonconductive transfer hoses and within grounded metal ductwork of dust collector systems, where thermoplastic powder has impact fused to form a nonconductive coating at a duct elbow or wye, have ignited the powder cloud within the hose and the duct. This sparking can ignite the powder cloud and flames will be sustained by the continuing flow of powder and air. Some application equipment will discharge incendiary sparks when approached too closely by a grounded object. Proper use of this type of equipment requires safeguards to prevent any grounded object from approaching the electrically charged high-voltage elements closer than twice the sparking distance. Discharge sparks that do occur during use of this type of equipment may be traceable to improper racking of parts on a conveyor or swinging of the conveyor racks. To reduce the probability of a small fallen part being drawn into a duct and producing mechanical sparking, grillwork at the intake of any exhaust duct is highly recommended, and magnetic devices can be added to catch tramp metal. A hot work permit system and prohibition of smoking should be in practice.

Fire Protection

Protective measures for powder coating installations are (1) keep the powder collector from becoming involved in a fire that has originated in the spray operation, (2) equip the collector with pressure relief vents and ductwork in order to prevent its rupture in an explosion, (3) protect the building from heat and pressure effects that would be generated by an explosion, and (4) provide sprinklers or other approved fire suppression systems to control a persistent fire.

To prevent a fire in a powder spray booth from spreading through connecting ductwork, the ventilation system is usually arranged to keep powder concentrations in the ductwork below one-half the minimum explosible concentration (MEC). In those cases in which fire has persisted in the spray booth for periods ranging beyond approximately 15 seconds, however, the powder collector is threatened by glowing embers that have formed in the spray fire. These glowing embers are independent of powder concentration and are capable of igniting the powder collector.

Powder collectors can be protected by a fast-acting flame detector within the spray booth, interlocks to shut down equipment, and a fast-acting damper to interrupt airflow in the duct between the spray booth and the powder collector. In operation, this apparatus will recognize any flame that has ignited in the spray booth and respond quickly (within ½ second) to the flame by shutting down all process equipment energy supplies (including electricity and compressed air) and by closing the ductwork damper. This same equipment can be arranged to extend the response sequence by discharging an inerting gas into the dust collector.

Use of multispectral "smart" flame detectors from one manufacturer has been monitored for several years (millions of hours of operation) in industrial service. Although fires ignited many times, not a single case of damage resulted when the detector system was properly installed and maintained. Use of optical flame detectors was initiated in 1974–1975. Prior to that time, fires and explosions resulting in damage were common. Since then, incidents (about a dozen total) involving damage have all been found to have either:

1. No detectors or detectors bypassed
2. Inoperable (not maintained) detectors
3. Detectors installed with line of sight to the guns obstructed

For those application systems that require operation with combustible concentrations of powder in the ductwork between the application area and the powder collector, the potential exists for almost instantaneous explosion of the collector whenever a fire occurs in the application area. Such systems should either be equipped with appropriately engineered suppression systems or designed in such a manner that the powder application and collection equipment will be fire and explosion resistant.

Airborne clouds of powder in a confined space will burn at far higher rates than in an unconfined space. Because the interior of a conventional dust collector is a confined space, steps must be taken to accommodate the sudden pressurization and volumes of smoke and fire gases that will evolve in the event of ignition. The usual protective technique used is to install automatic pressure relief vents in the collector housing. These vents will open should ignition occur and allow the combustion products to escape, thereby limiting pressure development. When the collector is located within a building, ductwork is usually required to direct the vented combustion products to the exterior of the building or to a safe location. Vent ductwork must be kept short. Lengths in excess of 10 ft (3 m) are of questionable value.

When a collector explosion occurs, fire, clouds of unburned powder, and molten globules of partially burned powder are projected from pressure relief openings and from spray booth openings. If vented into a building, a major secondary explosion may occur, resulting in catastrophic damage.

If powder escapes from the collector into the building during normal operation, it can collect on horizontal surfaces and create a potential for a secondary explosion. The primary explosion may disperse powder into the air in suspension where it could be ignited by flames or embers that persist from the initial combustion. If a substantial quantity of powder is thrown into suspension by the primary explosion, the secondary explosion could be considerably more serious than the primary. Protection is achieved primarily through (1) maintenance of process equipment, (2) procedures, and (3) scrupulous housekeeping to collect any powder that does escape.

The dust explosion hazard is virtually eliminated (through elimination of the confined space necessary to form an explosion) in an integrated spray booth/collector of the type shown in Figure 9.2.9 and in other apparatus incorporating the same design principles. This class of equipment, because it operates without explosion risk, needs no explosion vent or ductwork. However, flame detectors are still needed—when automatic spray guns are used—to quickly interrupt powder feed in the event of fire and thereby limit heat damage and formation of toxic smoke.

After ignition of a spray gun powder cloud or a fluidized bed, the flame can usually be extinguished almost instantly by simply turning off the spray gun feeder or the air supply to the fluidized bed. The normal velocity of the feed systems exceeds typical flame-front propagation velocities and flame; therefore, it does not backstream in hoses from guns to feeders, even though powder concentrations in hoses may exceed MEC.

Automatic sprinkler systems are commonly required in factory areas where powder coating operations take place, as well as within the booth and collector. Because sprinklers have rather long operating delays relative to the duration of a powder fire (in a system equipped with automatic flame detectors), it is common for powder fires to be extinguished by shutting down the equipment before sprinklers can activate.

In those cases in which small fires have persisted in spray booth residues, portable water fire extinguishers or sprinklers arranged to protect the filter cartridges or bags have been found to be adequate.[3] *Adequate* means damage did not extend beyond the collector when water was used to suppress the fire. The unpublished research includes privately conducted experimental fires (hundreds), and immediate (within one day) fireground investigations of accidental industrial fires (several dozen) in powder systems. No formal consolidation of these results has been written.

Fire Experience

Investigations of explosions and fires in powder coating operations that resulted in damage have shown, in virtually every incident known to the author, that flame detectors were absent, were disconnected, or were mounted so that they could not see the spray gun fire. Dirty lenses or deliberately covered lenses were frequently seen. In addition to flame detector deficiencies, powder collector explosions resulted from powder concentrations in the ductwork that were above the MEC because of (1) increases in the application rate to more than double the original design rate and (2) decreases in airflow through the system due to improper filter maintenance and replacement practices. Replacement of wear components with other than parts supplied or authorized by the original equipment manufacturer (such as hoses, ejector throats, filters, or electrostatic gun parts) has, in several cases, led to ignition.

SUMMARY

A broad variety of fabricated products undergo a process in which flammable or combustible fluid or powder coatings are spray applied. Air spray guns draw their coating fluid from small cups mounted on the guns or through hoses connected to pressurized containers. In the powder coating spray process, a feeder mixes powder with air and supplies the mixture to the spray guns. The spray booth is a power-ventilated structure in which the spraying operation takes place; the spray enclosure can be individually engineered for a specific coating process. Vapor and overspray removal systems typically include a fan and a collection system that exhausts vapors to the exterior of the building. In a fairly recent development in powder coating, the spray booth and powder recovery system are integrated into a single structure. Because materials and supplies used in organic spray finishing processes are usually flammable or combustible and in some cases highly reactive or unstable, spray finishing operations are considered hazardous and require suitable preventive and protective measures.

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2. (ASME) *Code for Unfired Pressure Vessels,* American Society of Mechanical Engineers, New York.
3. Unpublished research by the author.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for spray finishing and powder coating discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*

Chapter 3

Dipping and Coating Processes

John Katunar III

Chapter Contents

The Processes
Process Hazards
Hazard Reduction
Fire Protection

Key Terms

combustible liquid, curtain coating, dip tank, electrostatic detearing, exhaust system, flammable liquid, flow coating, process tank, roll coating, tank

The flammable and combustible liquids used in dipping and coating operations have tremendous heat energy and heat release capabilities, which, if not properly protected, can cause rapid property destruction when involved in a fire. The heat of combustion of flammable liquids is approximately two and one-half times that of an equivalent weight of wood.[1] In addition, heavy concentrations of smoke and products of combustion can develop. These factors make fire fighting extremely difficult. This chapter discusses dipping and coating processes, equipment that uses flammable and combustible liquids, the inherent hazards and means of hazard reduction, and fire protection for dipping and coating processes. It does not, however, discuss toxicity or industrial hygiene.

See also Section 6, Chapter 12, "Flammable and Combustible Liquids"; and Section 9, Chapter 2, "Spray Finishing and Powder Coating."

THE PROCESSES

Applications

Dipping and coating processes include, but are not limited to, finishing, impregnating, priming, cleaning, and other similar operations by which materials are immersed in, passed through, or coated by flammable or combustible liquids. Processes vary widely and range from the cleaning of small parts in small quantities of liquid to an automated coating process that uses a very large tank containing a flammable or combustible liquid. As is the case with any potentially hazardous operation, a complete evaluation of the process and an understanding of the properties of the liquid(s) in use are essential.

Equipment

The equipment associated with basic dipping and coating processes (such as dip tanks, flow coaters, curtain coaters, roll coaters, solvent cleaners, electrostatic detearing, and vapor degreasers) have similar hazards. Process equipment that is utilized in dipping and coating operations include conveyors, pumps and piping systems, flammable or combustible liquid storage tanks, ovens, liquid heaters or heat exchangers, agitators, detearing equipment, and ventilation and exhaust systems. Exhaust systems can include energy recovery devices and environmental protection devices. Auxiliary equipment should be selected and installed with full consideration of the inherent process hazards.

Dip Tanks. Dipping processes are used to apply coating material, or to accomplish other specific applications, through the immersion of the workpiece in a tank, vat, or container of flammable or combustible liquids. Dip tanks are liquid containers of various sizes and shapes designed for the specific process. Tank sizes vary from a small exposed surface area to a very large exposed surface area. Dip tanks, their drainboards, and their covers should be constructed of noncombustible material, such as heavy gauge steel, reinforced concrete, or masonry. They should be designed for the process and liquid involved, with consideration given to the static head of the liquid contained, corrosion, mechanical damage, and ease of maintenance and repair. Spill or exposure fires could weaken tank supports, possibly causing tank collapse. Therefore, supports for large tanks should

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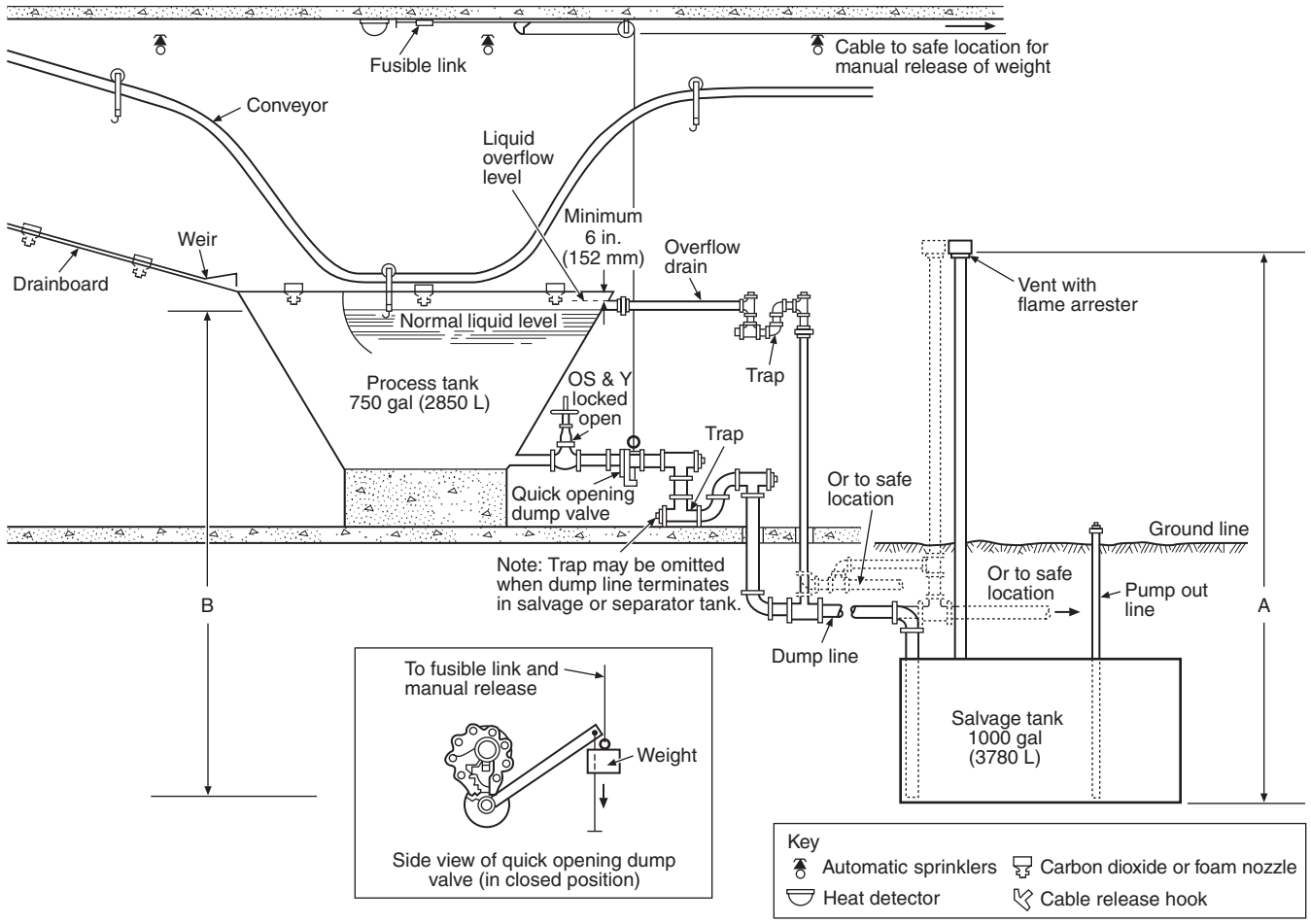
be reinforced concrete or protected steel with a fire resistance rating of at least 1 hour.

Figure 9.3.1 is an example of a typical dip tank process system. The salvage tank is shown below grade and outside of the building, as allowed by NFPA 30, *Flammable and Combustible Liquids Code*. However, below-grade salvage tanks are strongly discouraged due to environmental regulations, confined space rules, clean out difficulties, and the need for some form of periodic inspection and supervision. Also, salvage tanks should not be located in below-grade areas within a building if flammable liquids are handled or used in the process.

Flow Coaters. Flow coaters apply the coating material from nozzles or slots in an unatomized state onto the material being coated. This typically involves an enclosure or tunnel arrangement. Figure 9.3.2 is an example of a flow coating process, which is protected by a typical total flooding carbon dioxide system. The excess coating material is collected in a trough or sump below the workpiece, returned to the reservoir, and recirculated to the nozzles by a pump. The nozzles can be fixed or oscillating. The more nozzles used, the larger the reservoir and pump capacities required, and the greater the solvent loss. The workpiece usually enters and leaves through conveyor openings, and a drip tunnel is used in place of the drainboards that are used with dip tanks. The tunnel is enclosed on all sides, except for the conveyor opening, and is sloped toward the trough or sump. Airborne solvent concentration in the tunnel is sometimes used to keep the coating from drying before it gets to the oven.

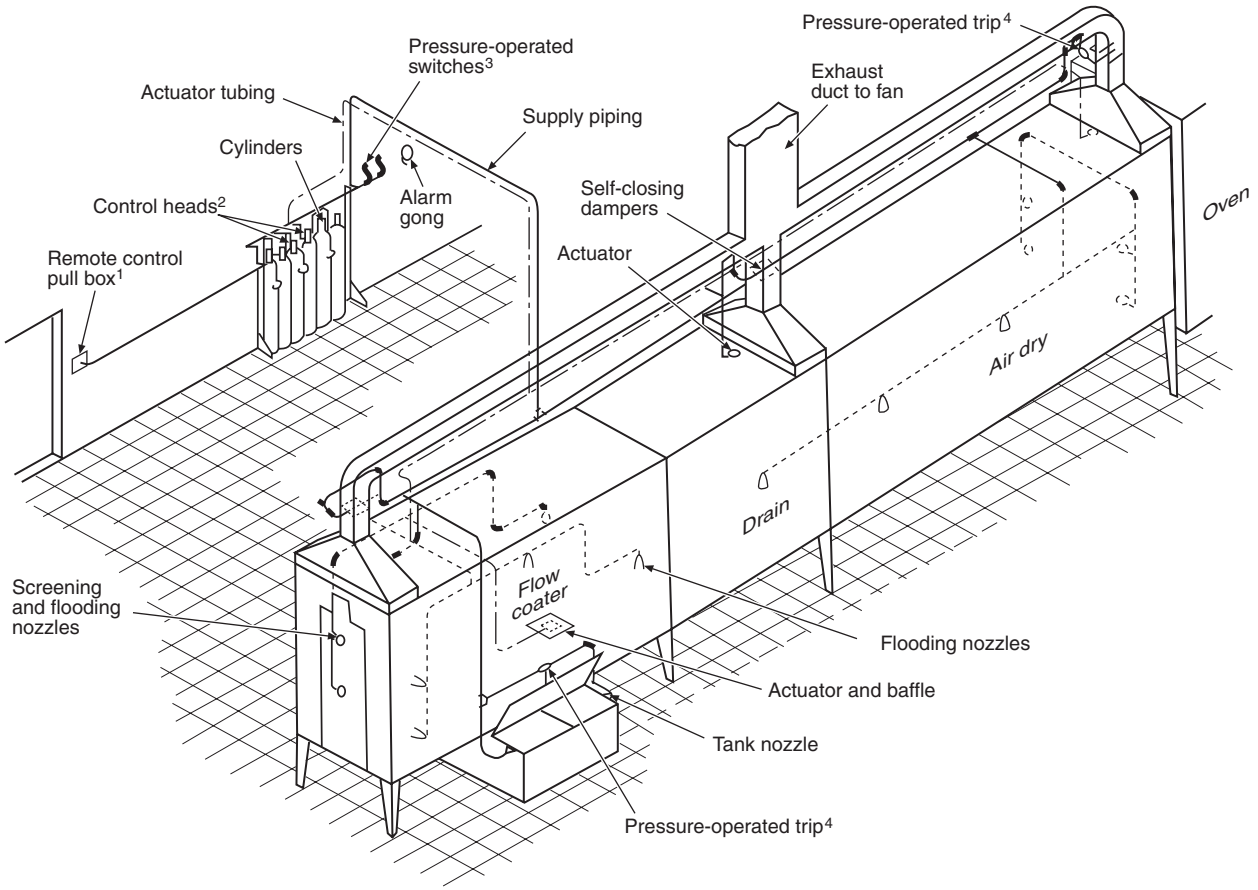
Curtain Coaters. Curtain coaters apply a coating material to flat or slightly curved workpieces. Figure 9.3.3 is an example of a curtain coating process. Coating material is pumped from a reservoir to a coating head, which has a small reservoir with a dam or weir forming one side. Coating material that is pumped to the head overflows the dam and forms a continuous vertical stream, which drops down onto the workpiece. The excess coating material drops into a trough and returns to the reservoir, then it is recirculated.

Roll Coaters. Roll coaters apply a coating material by bringing the workpiece into contact with one or more liquid-coated rollers. Figure 9.3.4 is an example of a roll coating process. The



Note: A is greater than B but discharge is at least 12 ft (3660 mm) aboveground.

FIGURE 9.3.1 Dip Tank, Drainboard, and Conveyor System



Notes:

1. Normal manual pull-box control and cable.
2. Pneumatic control heads with emergency manual controls.
3. Pressure-operated switches to shut down exhaust fan, pumps, conveyor, and so on, and sound alarm.
4. Pressure-operated trips to release self-closing dampers in exhaust duct and self-closing cover on paint tank.

FIGURE 9.3.2 Flow Coater Protected by a Typical Carbon Dioxide Total Flooding System That Can Be Either Manually or Automatically Activated

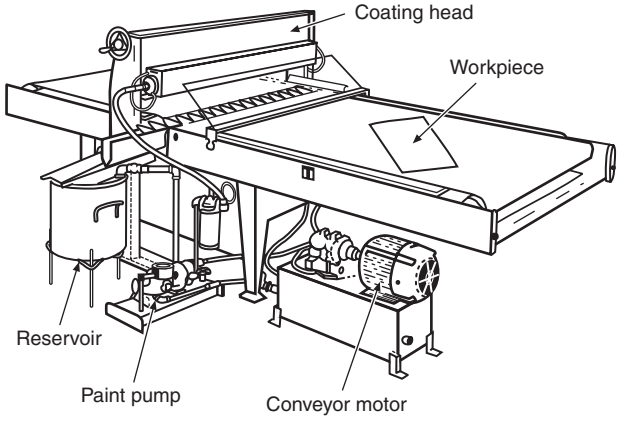


FIGURE 9.3.3 Curtain Coater

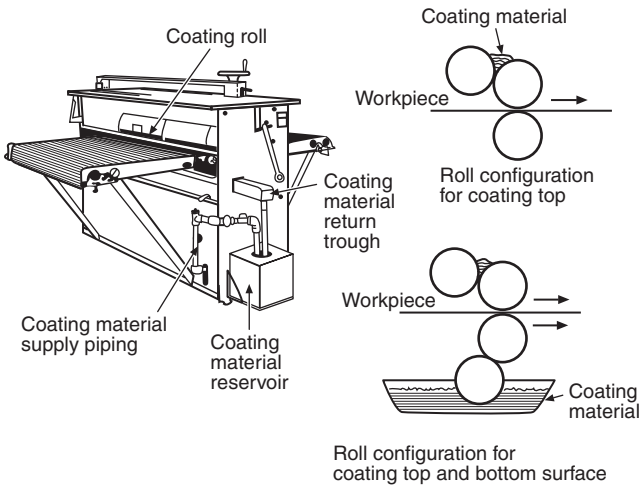


FIGURE 9.3.4 Roll Coater

coating material comes from an open pan or from a nip formed by two rollers. Coating material is supplied from a reservoir by a pump and piping system.

Solvent Cleaning and Distillation Units. Solvent removes material from an object using processes such as immersing, soaking, spraying, agitating, or ultrasonics.

Electrostatic Detearing. This is process whereby excess wet coating material is removed from the bottom edge of a dipped or coated object by passing it through an electrostatic field.

Peripheral Vapor Containment. This is a process that cools the perimeter of a vapor degreaser tank near the top for the purpose of condensing a saturated vapor blanket from boiling flammable solvent. Figure 9.3.5 is an example of a degreasing process.

Secondary Enclosure. This is an enclosure or guard constructed around but separate from a dipping and coating process whose purpose is other than fire protection, confinement of a possible fire, or confinement of vapor or mists.

PROCESS HAZARDS

Dipping and coating of articles or materials by passing them through flammable and combustible liquids involves the inherent danger of fire and explosion. Generally, the severity of the hazard increases with use of lower flashpoint liquids, increased depth or quantity of liquid, increased surface area of liquid, increased rate of vapor generation, and increased accumulation of combustible residues in and around process equipment. (Characteristics of flammable and combustible liquids are discussed in detail in Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids.")

The severity of the hazard is determined by (1) ease of ignition and (2) rate of flammable vapor generation from the liquid surface and from surfaces of freshly coated articles, floors, drain or drip boards, and ancillary equipment. Two factors for consideration in further evaluation of hazards are (1) the intensity and burning characteristics of the flammable vapor evolved and (2) the probability of fire spread from radiated heat or from the flow of burning liquids because of a container rupture, boilover, or overflow.

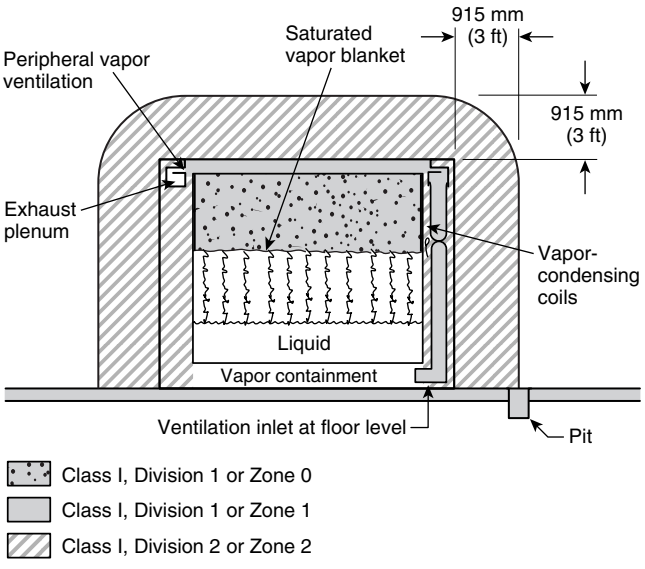
Flammable liquid vapors are usually denser than air and, therefore, flow to low points. They can travel great distances before reaching an ignition source that can cause flashback to the process area.

Flammable liquids are often less dense than and immiscible in water. During fire-fighting operations, water applied to such liquids can cause overflow and float the burning liquid away from the process to other areas.

Flammable and combustible liquids can be transported by closed containers, approved portable tanks and intermediate bulk containers, approved safety cans, or a piping system. All pumps, meters, pipe, fittings, and so on should be approved for handling of the liquids used in the dipping and coating process. If the dip tank is filled from the top, the discharge opening of the fill pipe should be within 6 in. (150 mm) of the bottom of the tank. If a pump is used to fill the tank, the pump should be arranged with a relief valve to prevent overpressurizing the system. Process tanks should have a limit device to prevent overfilling of the tank.

According to NFPA 34, *Standard for Dipping and Coating Processing Using Flammable or Combustible Liquids,* the volume of Class I, Class II, or Class IIIA liquids stored in a listed storage cabinet or cabinets is limited to (1) one storage cabinet with total volume of 120 gal (454 L) in a process area, (2) a total aggregate volume of 360 gal (1350 L) in storage cabinets in a single fire area, (3) a total aggregate volume of 360 gal (1365 L) in each group of cabinets in the same fire area for an industrial occupancy if a minimum separation of 100 ft (30 m) is maintained between each group, and (4) a total aggregate volume of 720 gal (2700 L) in storage cabinets stored in a single group for an industrial occupancy if the building is protected by an approved automatic sprinkler system.

According to NFPA 34, Class I and Class II liquids should only be transferred between their original shipping containers and process equipment within a building by (1) containers with a capacity of 5 gal (19 L) or less, (2) approved safety containers, (3) a closed piping system, (4) an approved pump located on top of a portable tank or container, or (5) gravity through a listed, self-closing valve or self-closing faucet.



Definitions

Freeboard: The distance from the maximum solvent or coating material level to the top of the tank.

Freeboard ratio: The freeboard height divided by the smaller of the interior length or interior width of the tank.

FIGURE 9.3.5 Electrical Area Classification for Open Dipping and Coating Process with Peripheral Vapor Containment and Ventilation—Vapors Confined to Process Equipment

HAZARD REDUCTION

Hazards inherent in dipping and coating operations can be reduced by properly locating the processes, installing ventilation

and exhaust systems, eliminating ignition sources, and providing proper maintenance and periodic inspections. Special equipment design, employee training, proper fire protection systems, and effective fire prevention procedures will also help to reduce process hazards.

Process Location

The principle of segregating hazards to confine fires and limit damage is fundamental in the selection of locations for dipping and coating operations. The personal safety of workers and other building occupants as well as the potential exposure of large values must also be considered.

Dipping and coating processes should be separated from other operations, materials, or occupancies by location, fire walls, or fire partitions. A preferred location for dipping and coating operations is a detached or cutoff one-story sprinklered building of fire-resistive construction. When operations are located on upper stories, floors should be made liquid-tight and equipped with drains to a safe location. Dipping and coating operations should not be located below grade, directly over basements, or near pits or trenches, because liquid drainage and vapor removal will be difficult to achieve. Curbs and trapped drains should be provided to control liquid flow where necessary.

When, due to its nature, the process cannot be cut off, it should be located in an area that is clear of combustible storage and separated from other important processes. Combustible floors, ceilings, and surrounding walls should be protected to minimize fire exposure. Noncombustible curtain boards should be installed around the perimeter of the process area and extended downward from the roof level as far as is practical. Also, curbs should be installed on the floor to minimize the potential flow of liquids to other areas. This arrangement should offer a minimum level of process separation from adjacent areas.

Because flammable and combustible liquid fires generally develop rapidly and release large amounts of heat, automatic roof vents are desirable. Roof vents allow heat and smoke to escape, improving the chances of fire control by automatic sprinklers or the fire department.

When processes are located in confined areas and highly flammable or unstable liquids are used, deflagration relief venting might be necessary to lessen potential losses. Venting can be in the form of lightweight walls and roofs or explosion-relieving wall panels, roof latches, and windows. For more detail, see NFPA 68, *Standard on Explosion Protection by Deflagration Venting.*

Careful evaluation of the process is necessary in selecting the proper location for dipping and coating operations. Small dipping and coating operations should be considered in the same light as the larger operations, because it is often the small operation that produces a major fire loss. Figures 9.3.6 and 9.3.7 show common location features of dipping and coating operations. In Figure 9.3.6, the tank is located near an outside wall and is cut off from the main plant areas by fire-resistive construction. In Figure 9.3.7, the tank is located in the main plant area and is cut off by draft curtains and curbing. The heat and smoke vents should limit opened sprinklers to those near the fire and therefore reduce smoke damage.

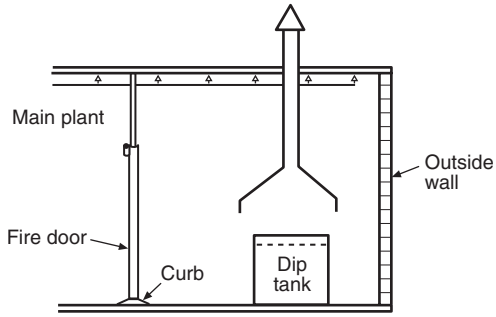


FIGURE 9.3.6 Most Satisfactory Arrangement for Location of Dipping and Coating Processes

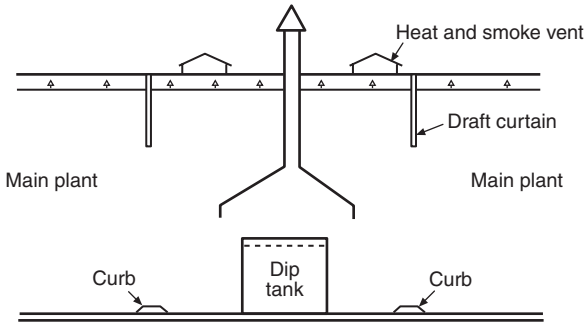


FIGURE 9.3.7 Satisfactory Arrangement for Location of Dipping and Coating Processes

Figure 9.3.8 shows unsatisfactory location features for this process, in which the tank is not cut off from the main plant area. In this situation, water from hose streams will leak down through the floor and damage the finished product.

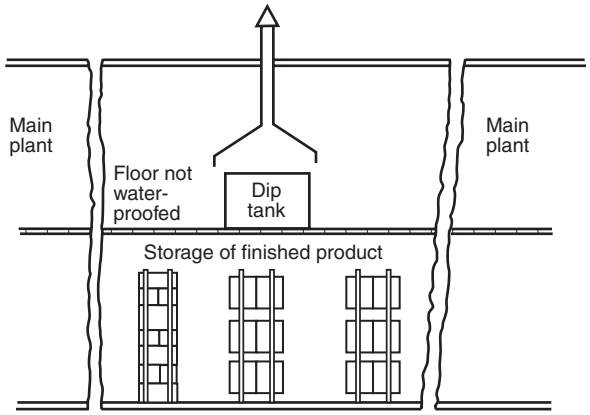


FIGURE 9.3.8 Unsatisfactory Arrangement for Location of Dipping and Coating Processes

Ventilation and Exhaust Systems

Ventilation is defined as movement of air that is provided for the prevention of fire and explosion and is sufficient to prevent accumulation of vapor-air mixtures in concentrations over 25 percent of the lower flammable limit.

When processes involve liquids that emit flammable or combustible vapors, ventilation is necessary to limit the vapor source to the smallest practical space possible. The vapor source created by dipping and coating processes is defined as the liquid exposed in the process and on the drainboard. Also, any dipped or coated object from which it is possible to measure vapor concentrations exceeding 25 percent of the lower flammable limit at a distance of 1 ft (305 mm) in any direction from the object.

The vapor area is defined as any area in the vicinity of: (1) a dipping or coating process and its drainboards, (2) associated drying or conveying equipment, (3) the interior of any exhaust plenum or any exhaust duct leading from the process, or (4) other associated equipment that could contain a flammable vapor concentration exceeding 25 percent of the lower flammable limit during operation or shut-down periods. The extent of the vapor area of a process depends on the properties of the liquid, such as vapor pressure, flashpoint, boiling point, and evaporation rate, along with the characteristics of the process, the liquid surface area, and the wetted surface area of the object being coated as well as the process equipment. Figure 9.3.9 shows the difference in exposed wetted surface area between two dip tank operations using the same quantity of liquid. With all else being the same, the process shown in the upper part of the figure would generate a greater volume of vapor and have a higher rate of heat release than that in the lower part. In this comparative example, the dip tank with the smaller liquid surface area would offer a greater fire hazard.

Vapor areas for each process should be kept as small as is practical but should not extend more than 5 ft (1.5 m) from the vapor source. The extent of a vapor area can be determined with a combustible gas analyzer. The concentration of vapors in the exhaust air stream should not exceed 25 percent of the lower flammable limit. A properly designed enclosure, including ventilation system capable of confining all vapors to the enclosure, may be necessary. A theoretical ventilation rate can be determined when the liquid usage rate is known. Because vapor concentrations vary widely from one process to another, a standardized exhaust ventilation system cannot be designed for all operations. The prime objective is to limit the vapor area to the smallest space possible and to prevent dead air spaces or pockets where vapors can accumulate. Freshly dipped or coated objects should be dried only in spaces or enclosures that are adequately ventilated.

Because flammable vapors are typically denser than air, low-point peripheral ventilation systems are usually more desirable than overhead hood arrangements. Two types of design are shown in Figure 9.3.10. The least efficient system is the overhead, or canopy, hood that allows migration of vapors to other areas.

When exhaust systems are considered, the ratio of air to vapor is important. However, the effectiveness of exhaust air in picking up and diluting the vapor is often lost in design. Entrain-

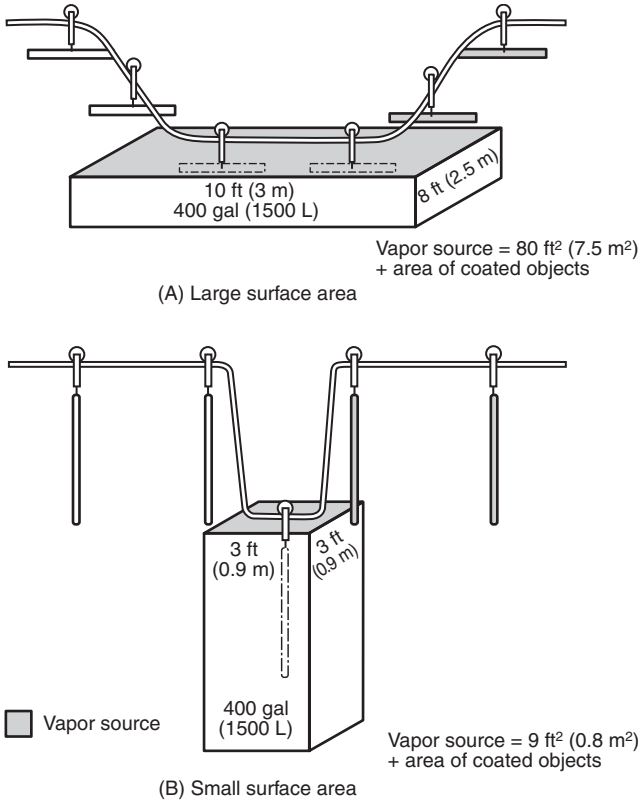


FIGURE 9.3.9 Difference in Vapor Source Area Between Two Dip Tanks with Same Coating Volume

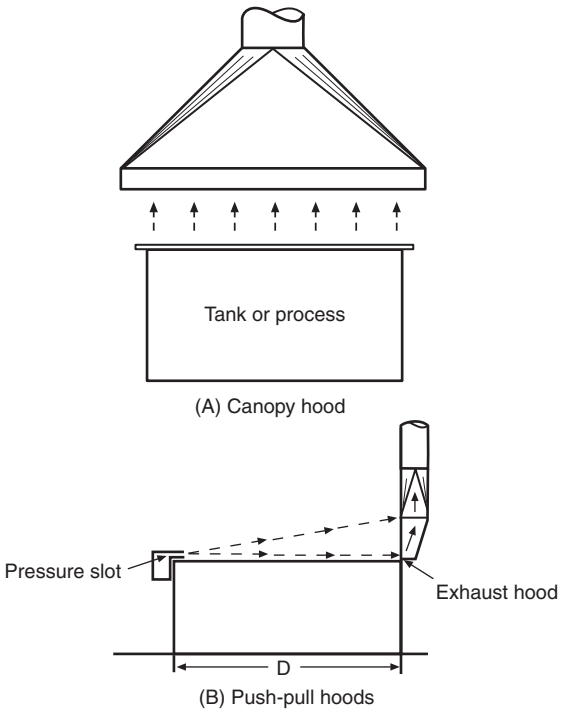


FIGURE 9.3.10 Ventilation Systems Used for Open Process Tanks

ment velocity with mixing action becomes the key to efficient use of exhaust air. Exhaust rates per square foot or square meter typically range from 50 to 200 ft^3/min (15 to 60 m^3/min) based on wetted surface area. Effective entrainment of vapor often requires slot velocities of 1000 to 2000 ft^3/min (28 to 56 m^3/min).[2]

Several of the important considerations when designing or evaluating ventilation systems for dipping and coating processes follow:

1. Ventilation should be kept in operation at all times while dipping or coating processes are conducted and for a sufficient time thereafter to allow vapors to be exhausted until the vapor area no longer constitutes a vapor source.

2. Automatic processes should be interlocked to shut down the operation in the event of a ventilation system failure.

3. The supply of makeup air should be sufficient to allow efficient operation of the exhaust fans and to minimize dead air spaces.

4. Ideally, each exhaust system should discharge directly outdoors. When exhaust streams must be treated to satisfy environmental protection requirements or when energy conservation measures are used, individual and/or direct discharge of each system might not be practical. Manifold systems increase the hazard. Therefore, manifold exhaust systems should be specifically evaluated including development and enforcement of strict preventive maintenance procedures. Reactive materials and coatings should not be used when ducts are connected to a manifold.

5. Exhaust air should not be recirculated as makeup air in occupied spaces. It could be recirculated to unoccupied areas, but only if solid particulates have been removed, concentration of vapors in exhaust stream are less than 25 percent of the lower flammable limit and monitored by approved detector, and the process stops automatically if vapor concentration exceeds 25 percent of the lower flammable limit.

6. Exhaust ducts should not discharge near air intakes, nor should they discharge less than 6 ft (1.8 m) from any exterior wall or roof. Exhaust ducts should not discharge within 25 ft (7.6 m) of combustible construction. Also, exhaust ducts should not discharge in the direction of an unprotected opening in any noncombustible or limited-combustible construction that is within 25 ft (7.6 m) of the discharge point.

7. Exhaust ducts should be equipped with enough access doors to facilitate inspection, maintenance cleaning, and access to fire protection devices.

8. Ducts and fasteners should be of noncombustible or limited-combustible construction, such as steel or masonry. Other materials of construction could be used in cases where the conveyed materials are not compatible with steel. These ducts should be substantially supported to prevent collapse under fire conditions. They should be installed with adequate clearance from combustibles. Dampers should not restrict exhaust ventilation to below minimum safe levels.

Ignition Sources

The key to minimizing the hazard of fire or explosion from vapor-air mixtures in dipping and coating processes is maintaining vapor concentrations less than 25 percent of the lower flammable limit using properly designed ventilation systems. Without vapor (fuel) and air (oxygen) properly mixed, ignition cannot take place even though sources of ignition are available. Since it is almost impossible to keep processes free of flammable vapor-air mixtures in the explosive range, sources of ignition should be eliminated or equipment should be designed for use in hazardous areas containing ignitable atmospheres or combustible residue.

Electrical Equipment. Where Class I liquids are used, or where Class II or III liquids are used at or above their flashpoint temperatures, electrical equipment should conform to the requirements for hazardous locations as outlined in NFPA 70, *National Electrical Code*® (*NEC*®). The *NEC* classifies areas in which special types of electrical equipment must be used. In the case of dipping and coating processes, the classified areas are measured from the vapor source, which may be the liquid surface (open tank) or wetted surfaces (freshly coated workpieces, drainboards, floors). The space containing hazardous vapor concentrations normally extends laterally and upward a short distance from the vapor source, and then downward to the floor, because the vapors are usually denser than air.

For open processes, classified areas are shown in Figures 9.3.11, 9.3.12, and 9.3.13. Class I, Division 1 (Zone 1) electrical equipment is required within a radial distance of 5 ft (1.5 m) from the vapor source and within a horizontal distance of 25 ft (7.6 m) from the vapor source when the equipment is in pits. If a pit is not vapor-stopped at a point 25 ft (7.6 m) from the vapor source, the entire pit is considered a classified area. Class I, Division 2 (Zone 2) electrical equipment is required 3 ft (0.9 m) beyond Division 1 (Zone 1) in all areas down to 3 ft (0.9 m) above the floor. In the space between the floor and 3 ft (0.9 m) above the floor, the Division 2 area extends 20 ft (6.1 m) beyond the Division 1 (Zone 1) area. An exception to these electrical requirements is tanks containing 5 gal (19 L) or less and having 5 ft^2 (0.5 m^2) or less of exposed surface area. Vapor concentrations during operating and shutdown periods cannot exceed 25 percent of the lower flammable limit. These small installations generally present less of a hazard and ordinary electrical equipment is permitted, if it is located more than 8 ft (2.4 m) from the vapor source.

For enclosed processes, classified areas are shown in Figure 9.3.14. Class I, Division 1 (Zone 1) electrical equipment is required within the enclosure. Class I, Division 2 (Zone 2) electrical equipment is required within 3 ft (0.9 m) in all directions from any opening in the enclosure and extending to the floor.

For open containers, locate supply containers, waste containers, and solvent distillation units that contain Class I liquids in a ventilated area. Hazardous classified areas are shown in Figure 9.3.15. Class I, Division 1 (Zone 1) electrical equipment is required within 3 ft (0.9 m) in all directions from the container and extending to the floor. Class I, Division 1 (Zone 0) electrical equipment is required inside any tank or container that contains Class I liquids. Class I, Division 2 (Zone 2) electrical equipment is required for 2 ft (0.6 m) beyond the Division 1 (Zone 1) area and extends 10 ft (3.1 m) horizontally beyond the Division 1 (Zone 1) area up to a height of 18 in. (458 mm) above the floor.

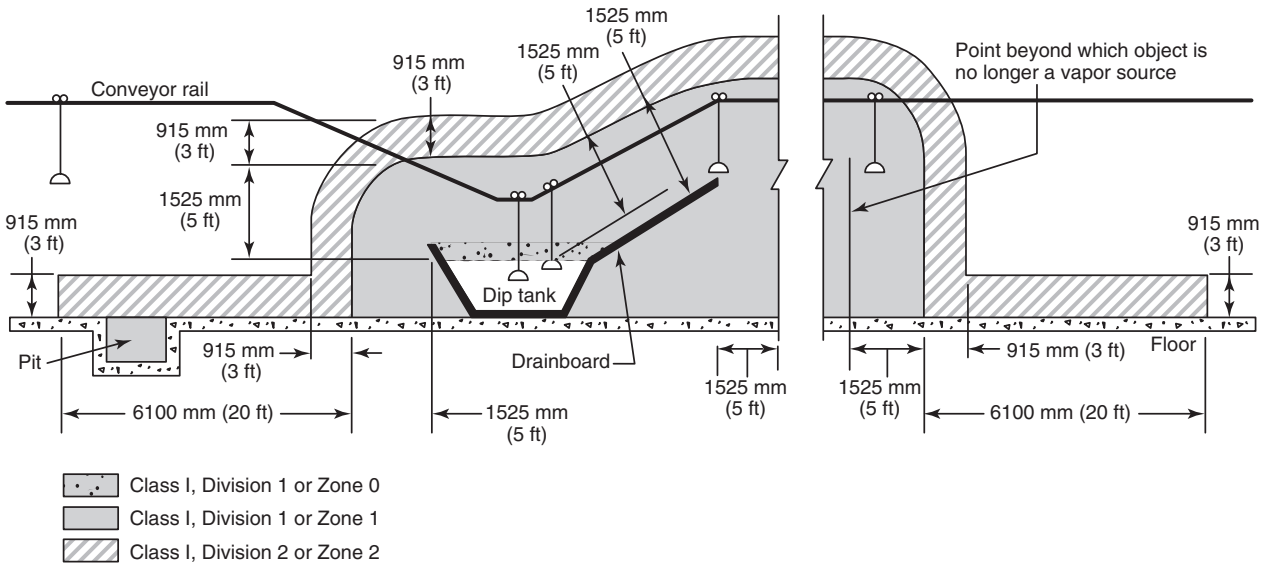


FIGURE 9.3.11 Class I, Divisions 1 and 2, Hazardous Locations for a Dipping Operation

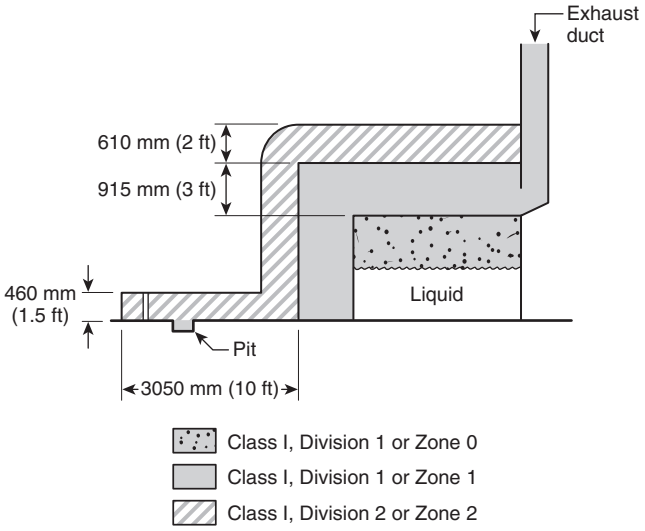


FIGURE 9.3.12 Electrical Area Classification for Open Dipping and Coating Process with Partial Peripheral Vapor Containment and Ventilation—Vapor NOT Confined to Process Equipment

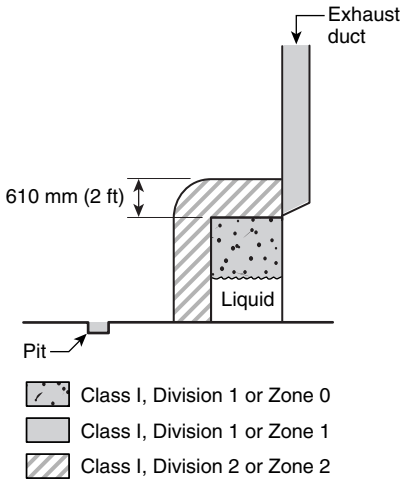


FIGURE 9.3.13 Electrical Area Classification for Open Dipping and Coating Process with Partial Peripheral Vapor Containment and Ventilation—Vapors Confined to Process Equipment

It is usually undesirable to install electrical equipment in the vicinity of dipping and coating operations. In such locations, the equipment would be subject to deposits of combustible residue, which would complicate maintenance and cleaning procedures. However, if electrical equipment must be installed in such locations, it should be a type that can be exposed safely to flammable vapors and combustible residues as explained above. Wiring in rigid conduit or in threaded boxes or fittings containing no taps, splices, or terminal connections is permitted in both residue and vapor areas.

Fixed lighting fixtures located outside of, but above, classified areas should be protected against physical damage. These fixtures should be arranged, so that they do not become sources of ignition for flammable vapors.

In areas where the electric service is supplied from overhead wires and lightning is a fairly common occurrence, protection against lightning-induced surge voltages should be provided. In the absence of lightning protection, high surge voltages could enter vapor areas and create high-energy ignition sources. Suitable protection includes lightning arresters, interconnection of all grounds, and surge protection capacitors.

Under abnormal conditions, overheating and arcing can occur in electrical circuits and equipment. Therefore, it is important that electrical circuits and equipment servicing dipping and coating processes have the proper overcurrent

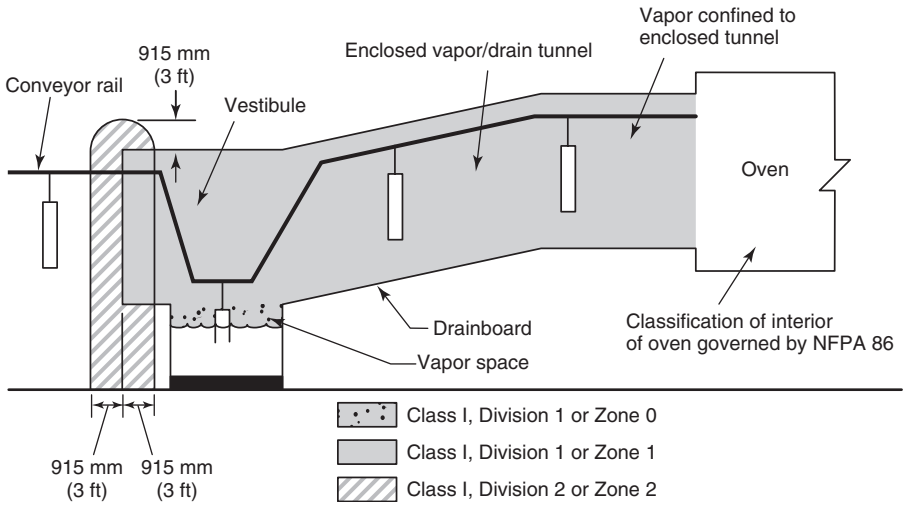


FIGURE 9.3.14 Electrical Area Classification Around Enclosed Processes

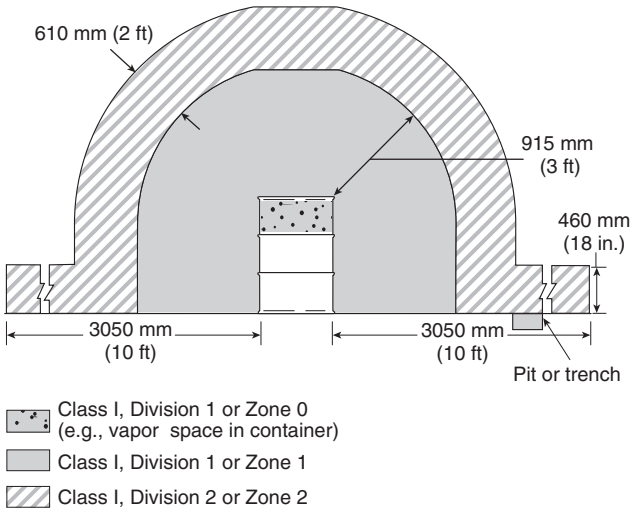


FIGURE 9.3.15 Electrical Area Classification Around an Open Container

protection, are grounded, and receive regular preventative maintenance.

Dipping and coating processes are frequently changed when new coating materials are introduced, production demand is increased, and new equipment is installed. Quite often, unsafe electrical installations and poor maintenance habits creep into the production process. It is common to find extensions connected to additional fans and lighting that are not suitable for use in classified hazardous areas.

Other Ignition Sources. Open flames, spark-producing processes, and equipment whose exposed surfaces exceed the autoignition temperature of the dipping or coating liquid should not be located in the dipping and coating process area or in surrounding areas. Ovens located directly above or adjacent to dipping and coating operations have been the ignition source for many reported fires. This equipment should be located as far as practical from dipping and coating operations, with noncombustible partitions provided when reasonable distances cannot be maintained. Exhaust systems of ovens and dryers located directly above or adjacent to dipping and coating processes should be interlocked, so that heating and process equipment cannot function unless all ventilation equipment is in operation. Indirect heating systems, which do not normally present ignition sources, are usually preferred in drying operations. (For more information on heating systems, see Section 8, Chapter 8, "Industrial and Commercial Heat Utilization Equipment.")

Dipping and coating processes often involve the use of conveyors, rollers, collectors, festoon dryers, and other devices that move the workpiece or liquid through the process. Flowing liquids and materials moving through a process can generate static electricity. A static electric charge can accumulate on process equipment and develop a difference in electrical potential sufficient to cause a spark containing enough energy to ignite flammable vapor-air concentrations. Static elimination by bonding and grounding of the process equipment, or by humidification or ionization of the local atmosphere, is essential in reducing the hazard of fire or explosion. (See NFPA 77, *Recommended Practice on Static Electricity*.)

Of equal importance is the prohibition in hazardous classified areas of equipment and processes that are not essential to dipping and coating operations but that are potential ignition sources. Included in this category are cutting and welding operations, portable heaters, spark-producing (ferrous) tools, and smoking. Nonferrous tools are available as are nonferrous rotating parts for exhaust fans. If hazardous maintenance operations, such as cutting or welding, must be performed in the vicinity of dipping or coating processes, it is imperative that these hot work operations are in accordance with recognized good practices and performed by competent personnel under strict supervision. "No Smoking" signs in process areas must be properly posted and the restrictions enforced. (See NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*.)

Special Design Considerations

Hazards of dipping and coating operations can be reduced if special design features are implemented for the process equipment. Many flammable and combustible coatings are less dense than and immiscible with water. In the event of fire, water from hose streams or sprinkler systems could cause an overflow of liquid from the tank unless certain design precautions have been implemented. Examples of special design considerations for dipping and coating equipment and systems are discussed in the following paragraphs.

The top of the dipping or coating tank should be at least 6 in. (150 mm) above the floor, and the liquid surface should be at least 6 in. (150 mm) below the top of the tank. Tanks that exceed 150 gal (570 L) capacity or 10 ft^2 (1 m^2) of liquid surface area should be equipped with a trapped overflow pipe leading to a safe location. This overflow pipe should be capable of handling either the maximum rate of delivery of process liquid or the maximum rate of automatic sprinkler discharge, whichever is greater. In any case, overflow pipes should never be less than 3 in. (75 mm) in diameter.

Dipping and coating equipment should be constructed of noncombustible materials. For tanks that exceed 500 gal (1900 L) capacity or 10 ft^2 (1 m^2) of liquid surface area, the supports should have a fire resistance rating of at least 1 hour.

Larger tanks, having a capacity of 500 gal (1900 L) or more, should be equipped with a bottom drain of sufficient size to empty the tank in 5 minutes. If gravity flow is not practical, pumps may be used to empty the tank. The drain should be operable manually and automatically. However, if a manual drain release is used, it should be located at a safe and accessible area. Drains should be trapped and flammable liquid should discharge to a closed, vented salvage tank or to a safe location outside and away from all buildings. If, due to increased hazard or by nature of the operation, bottom drains cannot be provided, the process should be cut-off or fully diked. Fire protection for this area should be both an automatic special extinguishing system and sprinklers.

Where a salvage tank is utilized, a pumping arrangement should be provided for removal of the contents. The capacity of the salvage tank should be greater than the capacity of the dipping or coating tank. Further requirements are included in NFPA 30.

Conveyor systems used in dipping and coating processes should be arranged to stop automatically in the event of a fire, excess temperature indication, or failure of the ventilation system. Heating systems should be arranged to stop automatically in the event of excess temperature indication or if the level of liquid in the tank exceeds or falls below a safe level.

Heating and cooling units for flammable or combustible liquids should be of an approved type for the specific process design and maintained per manufacturer's instructions. Heating systems should be automatically shut down if the coating material liquid level is higher or lower than specified operating levels. In processes where there is a possibility of flammable liquids being heated above their boiling points or to within 100°F (55°C) of their autoignition temperatures, suitable excess temperature limit controls are needed to prevent rapid vapor buildup and possible autoignition. Controls should limit the surface temperatures of heated workpieces to at least 100°F (55°C) below the autoignition temperature of the coating material used.

Solvent distillation units having distillation chambers or still pots that do not exceed 60 gal (227 L) capacity and are used to recycle Class I, Class II, or Class IIIA liquids should be approved for the purpose and used only in locations per their listing or approval. These units should only be used to distill liquids for which they have been approved.

Limit controls, such as liquid level devices, meters, and timers, should be used to prevent overfilling of tanks where automatic filling is designed into the process. If pumps are used, they should be interlocked to shut down in the event of fire.

Where the dipping or coating equipment is enclosed for the purpose of confining vapors and mists, all panels for light fixtures or for observation should be heat-treated glass, laminated glass, wired glass, or hammered-wired glass, and the panels should be sealed to confine vapors or mists to the enclosure. This does not apply for secondary enclosures such as those installed for environmental purposes to capture low-level fugitive emissions or for observation purposes as vision panels.

Maintenance, Training, and Inspection

Location, ventilation, equipment design, and the elimination of ignition sources are key to the reduction of the hazards in dipping and coating processes using flammable and combustible liquids. Similarly, preventative maintenance, training, and regular inspection of equipment are essential to safe operations. Unfortunately, due to production schedules, changes in processes, and turnover of personnel, these essentials are sometimes neglected, resulting in unsafe operating conditions.

Areas in the vicinity of dipping and coating processes should be kept free of accumulations of combustible residues and unnecessary combustible materials. Spontaneous ignition, due to oxidation or exothermic reaction between various coating components, can readily occur if excess residue accumulates in work areas, ducts, duct discharge points, or other areas. When excess residues accumulate in such locations, operations should be discontinued until conditions are corrected.

Cleaning operations should be conducted with ventilation systems in operation. Cleaning solvents for dipping and coating equipment should have flashpoints above 100°F (38°C) or not less than that of materials normally used in the process.

Combustible coverings (e.g., thin paper or plastic) and strippable coatings are often used to facilitate cleanup of drippings and residues. Use of these coverings increase the amount of combustibles in the process, which could be offset by improved housekeeping and ease of cleaning. Suitable containers should be provided for the disposal of waste and rags used for cleaning. Waste containers should be emptied at least once per day or at the end of each shift.

The size and complexity of dipping and coating operations can vary widely, but, in all operations, the personnel involved should be instructed in the potential safety hazards inherent in the particular process. The nature of the process and operational criteria, maintenance, protection, and emergency procedures

should be included in the employee-training program. Also, there should be thorough instruction regarding proper flammable liquids handling procedures and safeguards. It is desirable to record such training and provide refresher instruction from time to time to ensure continuity and proper action in the event of an emergency.

Depending on the size and nature of the process, periodic (usually at least monthly) inspection should be made of dipping and coating processes. Inspections should include noting the condition of equipment covers, overflow pipe inlets and outlets, bottom drains and valves, electrical wiring and equipment, grounding and bonding connections, ventilation equipment, and fire extinguishing equipment. Inspections and protection equipment tests should be documented and conducted using an appropriate inspection form. Defective equipment and unsafe conditions should be corrected promptly.

FIRE PROTECTION

In spite of the considerable care taken in the operation of dipping and coating processes that use flammable and combustible liquids, fires and explosions do occur. Thus, fire protection and suppression equipment are necessary.

Damage on small processes can be as severe as in large operations. Less consideration is usually given to the location of small processes, and they might be in areas that expose high values or combustible construction. Some form of protection is usually required for all dipping and coating processes.

The simplest device for extinguishing a fire in a process tank is a self-closing cover, which cuts off the fire's air supply. Normally the cover is held open by a cable and fusible link. When exposed to the heat of a fire, the solder in the fusible link melts, releasing the cover and allowing it to drop tightly in place over the tank (Figures 9.3.16 and 9.3.17). Covers should be kept closed when the process is not in operation. Automatic sprinklers are often provided at ceiling level and can provide adequate protection for small processes and where combustible coatings are used with a limited liquid surface area exposure. Sprinklers are intended to help control the fire, prevent damage to the building, and allow effective manual fire fighting. Automatic sprinklers are often required as backup to special fire extinguishing systems. Sprinklers are essential protection for the building and to help control the fire at equipment, where larger dipping and coating processes are installed.

Automatic fire extinguishing systems are needed for dipping and coating processes, including enclosed processes, open processes with peripheral vapor containment and ventilation, and for process tanks exceeding 150 gal (570 L) or 10 ft^2 (1 m^2) in liquid surface area. The fire extinguishing system should be designed to simultaneously discharge to all protected areas of the process. In many cases, a connected reserve supply of extinguishant should be provided.

For dip tanks, the fire extinguishing system should protect the tank, drainboard, freshly coated objects or materials, pumping equipment, and exhaust ventilation ducts. Where processes involve considerable volumes, large liquid surface areas, or large wetted areas of low flashpoint materials, fire-extinguishing systems should be provided. Fire-extinguishing systems should be provided for tanks having capacities in excess of 150 gal (570 L) or surface areas greater than 10 ft^2 (1 m^2). Suitable protection systems use foam, carbon dioxide, or dry chemical as the extinguishing medium. For liquids having flashpoints above 140°F (60°C), water spray systems may be used. All systems should operate automatically and manually. The complexity and value

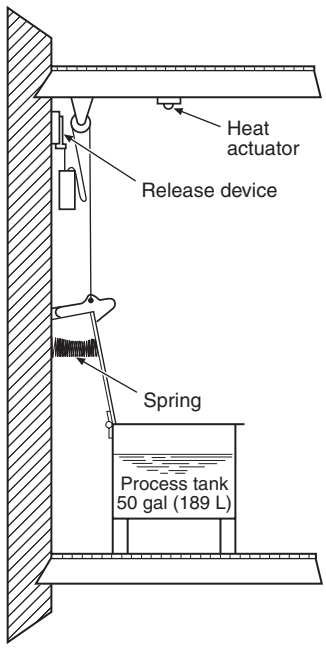


FIGURE 9.3.16 Small Process Tank with an Automatic Cover

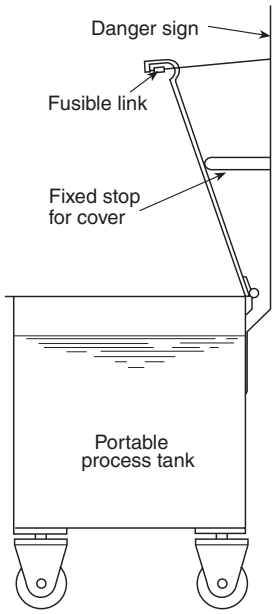


FIGURE 9.3.17 Portable Tank with an Automatic Cover

of some processes and/or the absence of sprinklers as backup often make it desirable to provide redundancy in protection systems.

For flow coaters, the system should protect open tanks, vapor drying tunnels, and exhaust ventilation ducts. Pumps that recirculate the coating material should be interlocked to stop in the event of fire. For curtain coaters and roll coaters, the system should protect the coated objects or material and open troughs and/or tanks containing coating material. Pumps that recirculate the coating material should be interlocked to stop in the event of fire.

For a small process with an open tank of less than 150 gal (570 L) capacity or less than 10 ft^2 (1 m^2) of liquid surface area, an automatic (and manually operable) closing tank cover or fire extinguishing system is needed. Covers should be of noncombustible construction and overlap the tank by at least 1 in. (25 mm). The operating and support mechanisms for the cover should be noncombustible. Drainboards should be designed so that they do not interfere with the automatic closing of the cover. Covers should be kept closed when the process is not in operation.

In the event of fire, preventing overflow of the tank due to sprinkler discharge is necessary. This can be accomplished by arranging drainboards to prevent sprinkler discharge from flowing into the tank, by automatic closing covers for the tank, or by providing an overflow pipe from the tank (Figures 9.3.18 and 9.3.19).

Ventilation and exhaust systems for dipping and coating processes should be interlocked with the fire alarm system and should remain in operation during any fire alarm conditions. However, shutdown of ventilation systems and closing of dampers in ducts might be necessary if the process is protected by a special fire extinguishing system.

Dipping and coating process areas should be equipped with portable fire extinguishers suitable for use on flammable and combustible liquids fires. Due to the flash fire conditions that can prevail in flammable liquids fires, emergency response personnel should be trained to act immediately to affect both automatic and manual protection methods to fight the fire to achieve rapid control and limit possible injury and damage. Fire-fighting efforts should be restricted to the level of personnel training and the company's selected level of emergency response. Also, these efforts should be coordinated with the local public fire authorities.

SUMMARY

Dipping and coating processes vary in the application of equipment and the hazard associated with the specific process. This chapter pertains to the processes, equipment, hazards, and fire protection of dipping and coating operations that use flammable and combustible liquids. Typical equipment is dip tanks, flow coaters, curtain coaters, and roll coaters. Properly designed ventilation systems for the process and classified electrical equipment for specific areas are critical to the safe operation of these processes. Also, there are special design considerations for these processes to reduce the hazard.

Because flammable or combustible liquids are normally involved in dipping and coating operations, elimination of the source of ignition and/or properly ventilating to reduce vapor-air mixture concentrations are the best method to avoid a fire or explosion event. Properly designed automatic fire extinguishing systems are necessary for most dipping and coating operations. An automatic sprinkler system is often provided to protect the building and to control fire spread in the vicinity of the dipping and coating process.

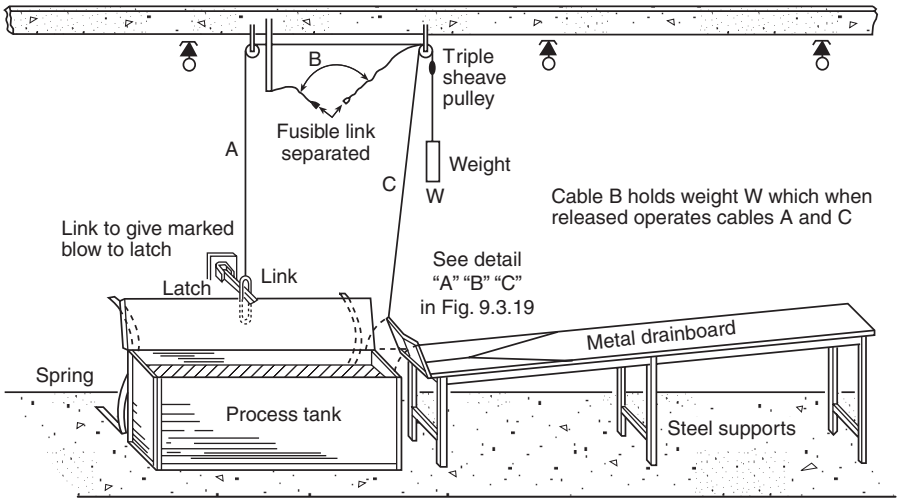


FIGURE 9.3.18 Process Tank, Automatic Cover, and Drainboard, with Drainboard Arranged to Prevent Interference with Latch Cover. The link in cord "B" has separated, weight "W" has lifted the hinged section of the drainboard, and the latch is about to release the cover.

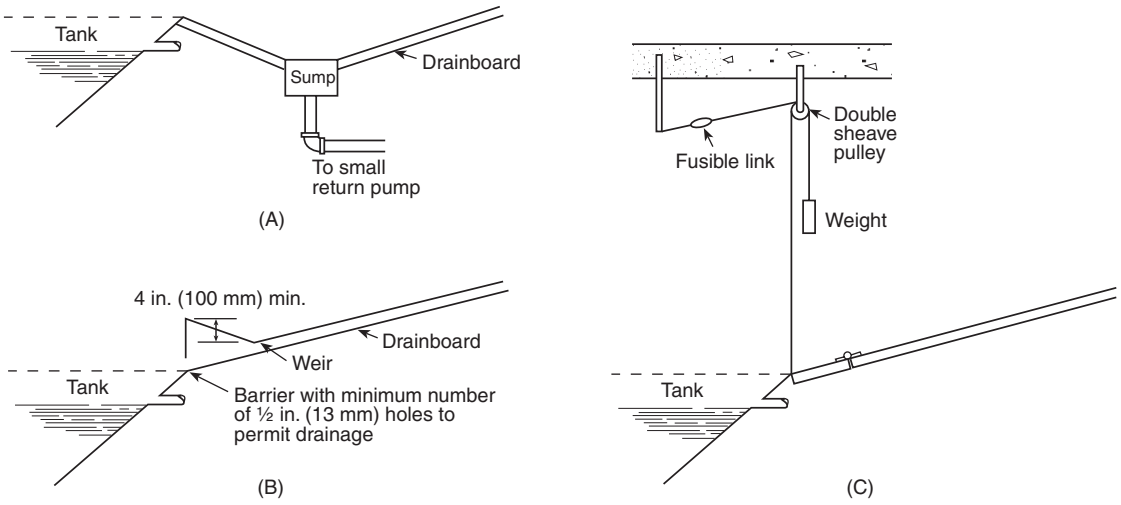


FIGURE 9.3.19 Suggested Arrangement to Prevent Sprinkler Discharge onto Drainboard from Entering Tank. A and B are most effective for other than paint process tanks. If used for aerosol process tanks, drain holes and piping should be cleaned frequently to prevent clogging.

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2. *Industrial Ventilation—A Manual of Recommended Practice,* 22nd ed., Committee on Industrial Ventilation, Cincinnati, OH, pp. 10-93–10-118.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on dipping and coating processes discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 34, *Standard for Dipping and Coating Processes Using Flammable or Combustible Liquids*
NFPA 35, *Standard for the Manufacture of Organic Coatings*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electric Code®*
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 326, *Standard for the Safeguarding of Tanks and Containers for Entry, Cleaning, or Repair*
NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors, and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*

Chapter 4

Plastics Industry and Related Process Hazards

George Ouellette

Chapter Contents

Overview of the Plastics Industry
Plastics Processing
Raw Materials
Production Process
Fire Hazards
Safeguards

Key Terms

dusts, flammable solvent, foam plastic, plastic (class of), polymerization, static electricity, thermoplastics

The goal of this chapter is to provide an overview of the plastics industry, what constitutes a plastic, the terminology used in the industry, the types of processing techniques used to produce a product, the hazards that exist when producing that product, and the steps that industry and government have taken to provide a safe working environment for the personnel working within the facility and those people living nearby.

OVERVIEW OF THE PLASTICS INDUSTRY

Alexander Parkes unveiled the first human-made plastic in London in 1962. It showed great promise, except for the high cost of production. Since then the plastics industry has become a rapidly growing worldwide business. Today there are approximately 30 major classes of plastics or polymer groupings, with numerous variations within each individual plastic grouping.[1–4]

With many large plastic producers selling licenses to their technology, many small producers have joined the industry. They have built production plants worldwide to generate the products needed by the various regions of the world. Recent growth has been significant in China, Latin America, the Middle East, and Central and Eastern Europe. There has also been growth in the United States as companies have invested heavily to remain competitive. According to the American Plastics Council (APC), in 2004 production in the United States and Canada grew to 115.2 billion lb (52.4 billion kg) and this total continues to increase each passing year. But as there is growth in production of plastic in the United States, a massive influx of finished plastics from China has resulted in loss of jobs and the closure of a number of U.S. facilities.

Plastics are a basic material of use—on a par with metals, glass, wood, and paper. They have become increasingly important to advanced concepts in building and construction, aerospace, communications, electronics, packaging, fibers, and transportation, as well as medicine and the arts. As the number of applications for plastics grows, so has the possibility of the exposure of plastics to fire.

A plastic is any one of a large and varied number of materials consisting wholly or in part of combinations of carbon with oxygen, hydrogen, nitrogen, and other organic and inorganic elements. In most cases, the plastic is produced from a single "mer" unit, also known as monomer. These mer units are low molecular weight formations of organic elements. By chemical reaction or polymerization, these single mer units are connected to each other to form long polymer chains of high molecular weight. It is the high molecular weight polymer chains that provide the plastic with its unique properties and its ability to be processed and formed.

Although solid in the finished state, at some stage in its manufacture a plastic is liquid, molten, or softened and thus capable of being formed into various shapes, mostly through the application of either heat or pressure or a combination of both. Whatever their properties or form, however, plastics fall into one of two groups: (1) thermoplastics or (2) thermosets (Table 9.4.1).

Thermoplastic resins can be repeatedly softened and hardened by heating and cooling without a major chemical change taking place. There might be some breakdown of the long molecular

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TABLE 9.4.1 Examples of Plastics Materials

Thermoplastic		Thermoset	
ABS (acrylonitrile-butadiene-styrene)	*Polyethylene*	*Epoxy*	*Silicones*
A combination of three different monomers—acrylonitrile, butadiene, and styrene gas—suitable for tough products; has good electrical insulating qualities; used to make automobile front grilles, household appliance components, and business machine and telephone components	Tough; excellent chemical resistance and electrical insulating quality; near zero moisture absorption; used for packaging, molded housewares, and toys	Excellent for chemical resistance, electrical properties, and dimensional stability; will bond metals, glass, hard rubber, etc.; used for aircraft components, tanks, and electrical and electronic assemblies	Long-term heat resistant, water repellent, electrical insulator, and mineral acid resistant; used in the electrical and electronics industry; insulation in meters and generators and induction heating apparatus

chains resulting in a decreased molecular weight and reduced viscosity of the product when reprocessed.

Thermoset resins, when heat treated, undergo a chemical reaction, sometimes going from a liquid to a solid. Once a solid is thermoset, it cannot be softened by further heating without causing a significant chemical change that will forever alter the material.

The diversity of major classes of plastics or polymer groups has made plastics applicable to an extremely broad range of end uses and products. Yet, paradoxically, this diversity has also made it difficult to grasp the concept of a single family of materials encompassing such a far-reaching span of physical and chemical properties and fire hazard characteristics.

Additional information on the formation of these various types of plastic and elastomeric materials can be found in Section 6, Chapter 13, "Polymeric Materials." For additional information on fire hazards, see Section 6, Chapter 8, "Dusts"; Section 6, Chapter 12, "Flammable and Combustible Liquids"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 8, Chapter 4, "Automated Equipment"; Section 8, Chapter 7, "Heat Transfer Fluids and Systems"; Section 8, Chapter 8, "Industrial and Commercial Heat Utilization Equipment"; Section 8, Chapter 13, "Electrical Systems and Appliances"; Section 10, Chapter 1, "Emergency and Standby Power Supplies"; Section 10, Chapter 2, "Heating Systems and Appliances"; Section 11, Chapter 1, "Waste Handling and Control"; Section 11, Chapter 2, "Housekeeping Practices"; and Section 18, Chapter 6, "Deflagration (Explosion) Venting." For additional information on the hazards of the polymerization or synthesis plant, see Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 7, Chapter 3, "Storage of Gases"; and Section 7, Chapter 4, "Storage and Handling of Chemicals."

PLASTICS PROCESSING

The plastics industry as a whole has four broad areas of processing: (1) polymerization or synthesis, (2) manufacturing, (3) conversion, and (4) fabrication. Although each area of processing is basically distinct, each can be conducted at the same or different locations, and each area has its own types and levels of hazards.

The first step is the polymerization or synthesis of the product in which the feedstock or the monomer is reacted in a reactor to form the basic polymeric material. This step is where the mer units, along with catalysts, donors, and gases, set off a chemical reaction in the reaction chambers. The degree of polymerization or reaction determines the form of the basic plastic material. In this step, the basic material can be in the form of powder, granules, or viscous liquid.

An example of the polymerization of ethylene to polyethylene is shown in Figure 9.4.1, in which the *N* represents the number of mer units that are reacted. With the addition of each mer unit, the molecular weight of the product increases and the form of the product begins to change. In the case of polyethylene, the ethylene monomer is a gas with a molecular weight of 28. At 6 mer units the product is a liquid, at 35 mer units the material is a grease, at 140 mer units a wax, and at 430 mer units it has a molecular weight of 12,000 and is in the form of a hard resin. Further increases in the number of mer units result in higher

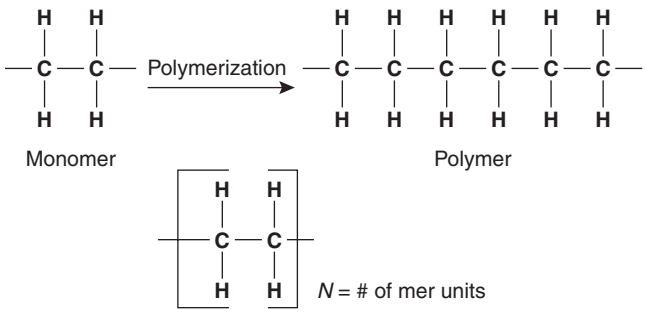

FIGURE 9.4.1 An Example of Conversion of Ethylene Mer Units to Polyethylene

molecular weights, which affect the processability, physical and mechanical properties, and the chemical resistance.[5]

The hazards of the polymerization or synthesis plant are basically those of a chemical plant. (See Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 7, Chapter 3, "Storage of Gases"; and Section 7, Chapter 4, "Storage and Handling of Chemicals.") Additional information may be obtained from American Petroleum Institute Standard 500 and U.S. Department of Labor Occupational Safety and Health Administration Standard 29 CFR 1910.119 on Highly Hazardous Chemicals.

Because of the large amounts of gases and flammable liquids used in the polymerization step, it would be considered the most hazardous. Major disasters, including the 1984 incident in Bhopal, India, the 1989 explosion at Phillips Petroleum Company in Pasadena, Texas, the 1990 fire at BASF in Cincinnati, Ohio, and the 1991 incident at IMC, Sterlington, Louisiana, have shown that safety is a critical issue during this part of the process.

In the manufacturing step, the basic polymeric material is processed into a different form that can be easily handled in subsequent processing steps. The most common process used is compounding. In compounding, the basic polymeric material might be blended with colorants, rubber, other types of polymeric materials, fillers, reinforcements, flame retardants, or other additives to modify the physical, mechanical, optical, rheological, or chemical properties of the material or to protect it from harsh environments, such as heat or ultraviolet (UV) light. The subsequent properties of the compounded product will have a major influence on the type of conversion technique used to convert the material into the final application that is sold to the customer.

Conversion of the plastics materials into useful articles by molding, extrusion, foaming, or casting usually involves heating the plastic so it will flow into a shape that is retained when the plastic is cooled. In the case of thermoplastics there are normally no chemical reactions taking place. With thermosetting resins, the chemical reaction to cross-link the material to put it in its final unchangeable form is a significant part of these operations. The plastics industry refers to these operations as "processing" or "converting."

Fabricating encompasses the largely mechanical operations of bending, machining, cementing, welding, heat sealing, decorating, and polishing plastics.

These four areas (i.e., polymerization or synthesis, manufacturing, conversion, and fabrication) accurately categorize the fire hazards that can be encountered in the plastics industry. It is important to recognize, though, that the synthesis, or manufacturing, of a given plastic might be much more hazardous than its molding or extrusion. It is also crucial to recognize that some plants doing only nominal converting and/or fabricating may also be conducting chemical operations with flammable or reactive materials. One example is the overlapping of molding and synthesis operations in a plant that impregnates liquid polyester resins into reinforcing glass fibers for molding boat hulls or containers.

This chapter discusses the manufacturing and conversion phases of the plastics, recognizing, of course, that in some instances hazards associated with all four phases of the industry may be carried on in one location.

Basic Hazards

Most plastics are combustible organic compounds that can burn under certain conditions. Concern must be directed at the inherent combustibility of plastic formulations influenced by the basic polymers used, the nature of plastic additives, the form the final product takes, and the conversion of feedstock plastics into finished articles. Concern must also be shown for the hazards associated with combustible dusts, flammable solvents, electrical faults, hydraulic fluids, the storage and handling of large quantities of combustible raw materials and finished products, and housekeeping within the processing area. (See the chapters in this handbook that specifically discuss these hazards.)

Terminology

Before discussing the converting of plastic feedstocks into finished products and the associated hazards, certain process terms and definitions are provided:

Additive: Any material added in small amounts to basic resins or compounds to alter properties. Additives can be dyes, pigments, plasticizers for flexibility, fibers to reinforce, antioxidants to protect the polymer from degradation by heat, UV stabilizers to protect the polymer from ultraviolet light, lubricants to aid flow into or release from a mold, or fire retardants.

Binders: The resins in a plastic mixture that hold together all of the other ingredients

Blowing agent: Any substance that alone or in combination with other substances is capable of producing a gas by thermal or chemical action, resulting in expansion of the plastic, formation of a cellular structure, and reduction in density of the final part

Blown tubing: A thin film made by extruding a tube and simultaneously inflating it with air while hot; distention may be 20 times the diameter of the extruded tube

Casting: Flowing liquid material into a mold or against a substrate with little or no pressure, followed by solidification and removal of the formed object

Compound: An admixture of polymer with all the materials necessary for the finished product

Cure: To change the properties of the polymeric system into a more stable, usable condition by the use of heat, radiation, or reaction with chemical additives

Decomposition: The breakdown or change of a material into other chemical compounds

Depolymerize: To decompose macromolecules into simpler compounds

Elastomer: A macromolecular material that at room temperature returns rapidly to approximately its initial dimensions and shape after substantial deformation by a weak stress and release of the stress

Extrusion: The process of passing molten plastic under pressure through a die to form a continuous profile; the equipment is called an extruder

Fabrication: The making of articles by machining, cementing, heat sealing, or thermoforming of preformed sheets, rods, or tubes. The term is used in contrast to *processing.*

Fiber: The polymer is present in the form of essentially continuous cylindrical rods of very small diameter.

Fillers: Relatively inert materials added to plastic to modify physical properties and/or to reduce its cost. For example, fillers might be used to increase heat resistance and alter the dielectric strength. A wide variety of products are used, for example, wood flour, cotton, sisal, glass, talc, calcium carbonate, and clay.

Film: A general term for sheets of plastic not more than 0.01 in. (0.25 mm) thick, regardless of the process used to make them

Fines: Materials that are finely divided into small particles and are characterized by high surface area per unit volume or unit mass. These can also be called dust or powder.

Finishing: The removal of burrs, flash, gates, and defects from plastic articles, and also the development of a desired surface texture

Flash: Unwanted projections from molded articles resulting from flow of plastic into the gap between matching parts of a mold. (The term has no fire connotation.)

Flash ignition temperature: The minimum temperature at which sufficient flammable gases are emitted from the polymer and ignited when an external ignition source is applied[6]

Foam (cellular plastic): A plastic with numerous cells dispersed throughout its mass. Rigid foams have rapidly reached large-volume production as thermal insulation boards for construction, cups for hot and cold drinks, trays for prepackaged meats, and shock-resistant packaging; flexible foams are used for furniture padding and insulation of outer garments.

Foaming agent: See *blowing agent*

Forming: The process in which the shape of plastic pieces, such as sheets, rods, or tubes, is changed into a desired configuration

Laminate: A composition of several layers of material(s) firmly held together by heat and pressure, bonding, or impregnation

Layup: In reinforced plastics, an assembly of layers of resin-impregnated material ready for processing

Lubricant: Material added to improve feeding of powder or granules into molding or extrusion machines, to improve flow of molten plastic through machines and into molds, or to prevent adhesion of plastic to molds; the last of these uses is called "mold release." Typical lubricants are zinc stearate, carnauba wax, and silicone oil.

Molding: The process of forcing plastic into a cavity to achieve a desired shape

Molecular weight: The sum of the atomic weights of all the atoms in a molecule

Monomers: A simple compound usually containing carbon and of low molecular weight, which can react to form a polymer by combination with itself or with other similar molecules or compounds

Oligomer: A polymer consisting of only a few monomer units, such as dimer, trimer, tetramer, or their mixtures

Peroxide: A chemical with a single oxygen-to-oxygen bond with a specific half-life or rate of decomposition; added to the plastic during compounding to control the process rheology of the product

Plasticizers: Materials added to plastic to make the finished product more flexible or to facilitate compounding. Some plasticizers increase the combustibility of the plastic whereas others serve as flame retardants.

Plastics: Materials that contain as an essential ingredient an organic substance of large molecular weight, are solid in their finished state, and at some stage in their manufacture or processing into finished articles can be shaped by flow

Polymer: A substance consisting of molecules characterized by the repetition of one or more types of monomeric units

Polymerization: The process by which molecules of a monomer are made to respectively combine with other monomers. The result is a much longer chainlike molecule.

Processing: The converting of polymers into useful articles by molding or extrusion from granules, depositing film from solvent, or laminating resin and reinforcement. Most often the molding operation uses heat, but it is largely or entirely a physical rather than a chemical process.

Reinforced plastic: A plastic with a fibrous filler that significantly increases flexural, impact, or tensile strength. Additives are usually glass, cotton, or nylon fibers. Reinforced plastics can be thermoplastic granules for injection molding or materials using large areas of reinforcement as in layup molding or pulp molding.

Resin: A solid, semisolid, or pseudosolid organic material that often has high molecular weight and that exhibits a tendency to flow when subjected to stress and usually has a softening or melting range. However, common usage of the term in the plastics industry does not always conform to the definition. The term is often used for uncured fluid thermosetting materials, for some chemically modified material resins, and often synonymously with the terms *plastic* and *polymer.*

Rheology: The flow characteristics of a material, including viscosity

Self-ignition temperature: The minimum temperature at which self-heating properties of the material lead to ignition or ignition occurs of itself, in the absence of any additional ignition source[6]

Sheeting: A form of plastic in which the thickness is very small in proportion to length and width; similar to film except the thickness is greater than 0.01 in. (0.25 mm) in thickness

Thermoplastic: A plastic that can be repeatedly softened by heating and hardened by cooling through a temperature range characteristic of that plastic, and that in the softened state can be shaped by flow into articles by molding or extrusion

Thermoplastic elastomers: A diverse family of rubber-like materials that, unlike conventional vulcanized rubbers, can be processed and recycled like thermoplastic materials

Thermoset: A plastic that, after having been cured by heat or other means, is substantially infusible and insoluble

Viscosity: The property of resistance to flow of the material

RAW MATERIALS

Many plastic feedstocks are derivatives of petroleum or gas recovered during the refining process; for example, ethylene monomer (a widely used feedstock) is derived in gaseous form from petroleum refinery gas, liquefied petroleum gases, or liquid hydrocarbons (Figure 9.4.2).

The monomer is subjected to a chemical reaction, known as polymerization, that causes the small molecules to link together into increasingly longer molecules. Chemically, the polymerization reaction has turned the monomer into a polymer (the reason that names of so many plastics materials begin with the prefix *poly*). The polymer, or plastic resin, must next be prepared for use by the processor, which will turn it into a finished product. In some instances, it is possible to use the plastic resin or feedstock as it comes out of the polymerization reaction. More often, however, it is transformed into a form that can be more easily handled by the processor and more easily handled in processing equipment. The most common solid forms for the plastic resin are pellets, granules, flakes, and powder. Some feedstocks are also available as semisolids (e.g., pastes) or as liquids (for casting).

PRODUCTION PROCESS

The ways in which plastics can be processed into useful end products are as varied as the plastics themselves.

Common Elements

Though the processes differ, there are common elements. In the majority of cases, thermoplastic compounds in the forms of pellets, granules, flakes, and powder must be melted by heat so they can flow. Pressure is usually involved in forcing the molten plastic into a mold cavity or through a die, and cooling must be provided to allow the molten plastic to harden. With thermosets, heat and pressure are also most often used. In their case, however, heat serves to trigger a chemical reaction and causes the thermosetting resin to cure (set) in the mold under pressure. When thermoplastic or thermoset resins are in liquid form, heat, pressure, or both need not necessarily be used; however, in many casting techniques intended for high-speed production, they do play a role.

Basic Processes of Manufacturing Systems

The following descriptions of processes cover the basics of the major manufacturing systems. It should be recognized, however, that there are variations in virtually every process.

Blow Molding. This process is generally used only with thermoplastics. It is applicable to the production of hollow plastics products, such as bottles, automotive cooling reservoirs, and automobile fuel tanks. Blow molding involves melting the thermoplastics resin and then forming the molten, highly viscous polymer into a tube-like shape (known as a parison). The ends of the tube are then sealed, and air is injected into the tube. The tube, in a softened state, is inflated inside the mold and forced against the walls of the mold, where it cools, solidifies, and is ejected from the mold. Figure 9.4.3 is a diagram of continuous extrusion blow molding. The plastic parison (in cylindrical shape) is extruded from the die into a mold, which closes on the parison (knife cuts the parison off from the extrudate). The mold then rotates to the second station where air is injected into the parison (still hot and, therefore, formable) to blow it out to the shape of the inside mold cavity. At the third station, the

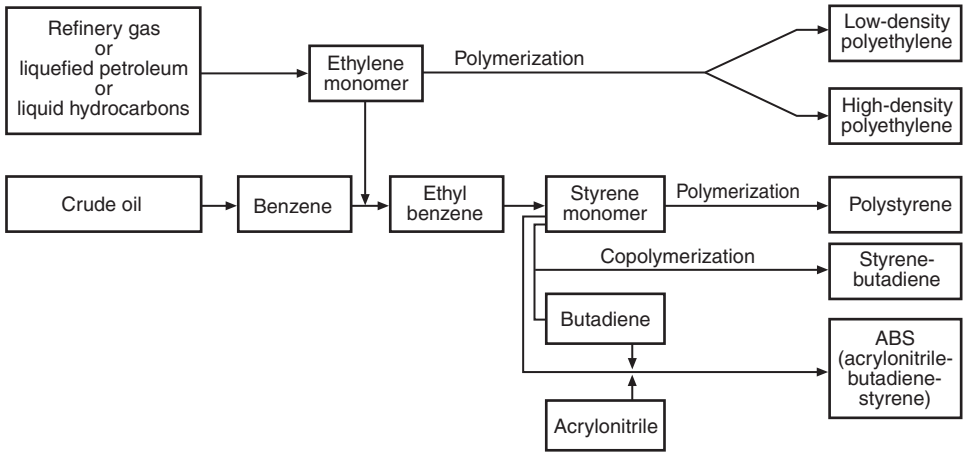

FIGURE 9.4.2 Ethylene's Role in the Manufacture of Polyethylene, Polystyrene, and Styrene Copolymers

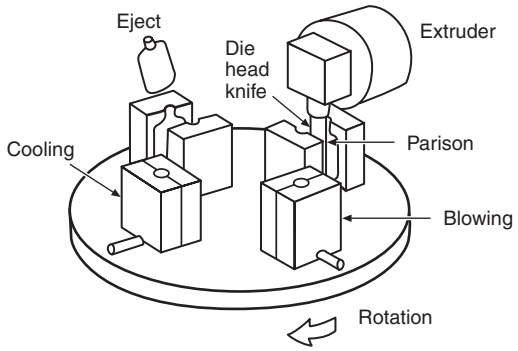

FIGURE 9.4.3 Continuous Extrusion Blow-Molding Setup, Using a Rotating Horizontal Table

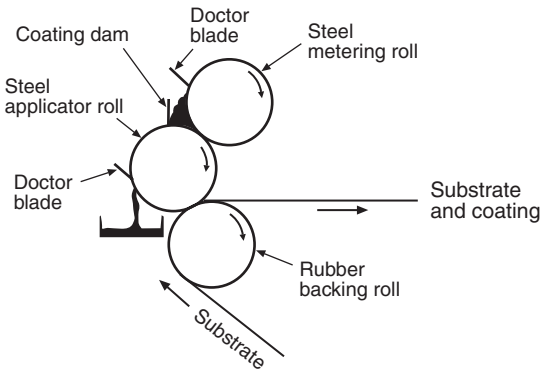

FIGURE 9.4.4 Typical Coating Setup, Known as a 3-Roll Nip-Fed Reverse Roll Coater

blown part is allowed to cool and set. The mold finally rotates to the last station where the finished part (in this case, a bottle) is ejected from the mold.

Calendering. Calendering can be used to convert thermoplastics into film and sheeting or to apply a plastic coating to textiles or other supporting materials. In calendering of film and sheeting, the material is initially processed in a kneading mixer or extruder to melt or soften it for further processing. The plastic compound is then passed between a series of three or four large, heated, revolving rollers running at different speeds to reduce the thickness of the material, forming it into a sheet or film.[7]

Casting. Casting can be used with both thermoplastics and thermosets to make products, shapes, rods, and tubes by pouring a liquid monomer-polymer solution into an open mold or a closed mold, where it finishes polymerizing into a solid. Pressure need not be used with the casting process, unlike the molding process. The starting material in the casting process is usually in liquid form rather than solid form.

Coating. Coating is accomplished by using either thermoplastic or thermosetting materials. The coating may be applied to metal, wood, paper, glass, fabric, leather, or ceramics. There are a number of techniques by which the coating may be applied. Figure 9.4.4 illustrates a 3-roll nip-fed reverse roll coater. In this setup, plastic feeds from the dam, through the nip, and between the steel metering and applicator rolls, rotating in the same direction. At the bottom of the applicator roll, plastic is laid on top of the substrate (e.g., fabric, paper, etc.) as it comes in contact with the substrate at the nip between the applicator roll and backing roll (which carries the substrate up from the bottom of the setup). A doctor blade is used to scrape off excess plastic from the applicator roll. Another technique is extrusion coating where the material is heated, melted, and extruded directly onto the substrate.

Compounding. Mixing additives into previously formed resin, using kneading mixers, screw extruders of varied design, masticating rolls, or calenders, is called compounding. Rolls and kneaders are heated by high-pressure steam or heat transfer fluids.

Screw extruders have largely displaced rolls and kneaders for compounding, because they provide better control, continuous output, and less exposure of hot plastic to air. The extrudate is cooled normally in a water bath and then chopped into pellets, which are easily used in other downstream processing operations.

Compounding for flexible polyvinyl chloride (PVC) packaging uses high-intensity mixers and ribbon blenders. The mixer spins the resin at high speed. This generates heat, which softens the resin and allows it to accept plasticizers, stabilizers, and so on. After absorption at 190 to 240°F (88 to 116°C), the batch drops to a blender to cool for storage or extrusion.

Compression Molding. Compression molding is the most common method of forming thermosetting materials. It can also be used for thermoplastics. Compression molding is simply the squeezing of material into a desired shape by applying heat and pressure to the material in a mold. In the case of thermoset resins, the material is heated until curing of the material takes place and the part is ejected from the mold hot. For thermoplastics, after the heat and pressure are applied to the part for a certain length of time to ensure complete flow within the mold, the mold is cooled, normally under pressure, to allow the material to solidify before ejection from the mold.

Figure 9.4.5 illustrates a simple two-piece compression mold. Plastic molding material is loaded into the lower half (cavity) of the heated mold (shown at top). The top half of the mold (mold force) is then lowered, and the two halves are brought together under pressure (shown below). The softened molding material is, thus, formed into the shape of the cavity and allowed to harden with further heating or cooling. The mold is then opened and the part is removed.

Extrusion. Extrusion is employed to form thermoplastic materials into continuous sheeting, film, tubes, rods, profile shapes, or filaments and to coat wire, cable, and cord. Figure 9.4.6 illustrates a basic single-screw extruder, in which plastics pellets (or powders) are fed into the hopper, through the feed throat, and into a screw that rotates in a heated barrel. The rotation of the screw (which is powered by the drive motor) conveys the plas-

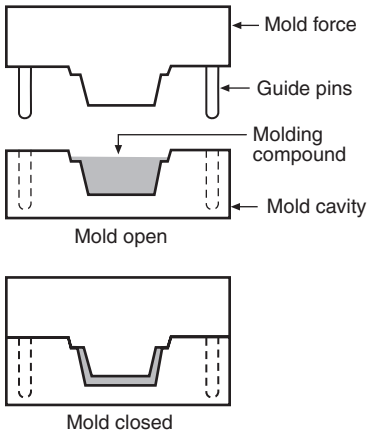

FIGURE 9.4.5 Basics of a Simple Two-Piece Compression Mold

tic forward for melting and delivery through the breaker plate (reduces the rotary motion of the melt), through the adapter, and into the die, which dictates the shape of the final extrudate. The final size of the extrudate is determined by the speed of the downstream take-off equipment.

Foam Plastics Molding. In foam plastics molding, foams can be used in casting, calendering, coating, rotational molding, flow molding, and even injection molding and extrusion. Figure 9.4.7 illustrates a setup for steam-chest molding. Among the many variations in molding foamed plastics is this setup for steam-chest molding expandable styrene beads into products such as foam cups, novelties, building products, and so on. In this operation, the expandable beads, containing a blowing agent, are preexpanded with steam, then screened to remove large clumps. The expanded beads are next blown into a storage hopper and allowed to dry and stabilize. From here, they feed into the final mold where steam is again used to complete expansion of the beads so that they fill the mold and fuse together. Water is used for cooling, prior to opening the mold and removing the finished foamed styrene part. The manufacture of foamed products is discussed in more detail later in this chapter in the section Flammable Solvents.

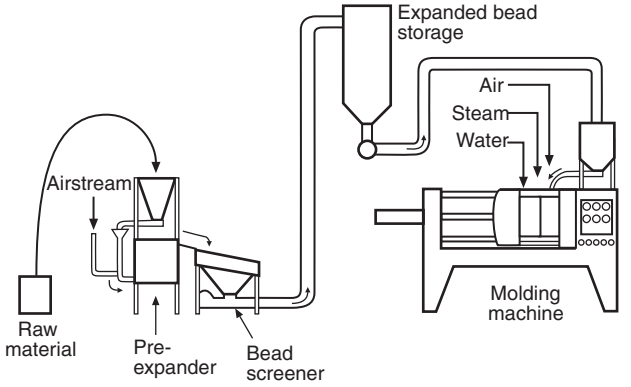

FIGURE 9.4.7 Setup for Steam-Chest Molding

High-Pressure Laminating. High-pressure laminating is a process that uses thermosetting plastics to hold together reinforcing materials, such as cloth, paper, wood, or glass fibers. Heat and pressures of at least 200 psi (1.4 kPa) are used to produce the laminated product.

Injection Molding. Injection molding is the method of forming objects from pelletized, granular, or powdered plastics, most often of the thermoplastic type, in which the material is fed from a hopper to a heated chamber in which it is softened, after which a ram or screw forces the material into a mold. Pressure is maintained until the mass is hardened sufficiently for removal from the mold. Figure 9.4.8 illustrates an injection molding machine with a reciprocating screw. Plastic pellets feed through the hopper into the screw (much like the screw in an extruder) where they are compacted, melted, and pumped by the rotation of the screw past the nonreturn flow valve to the front of the screw, where the molten material is allowed to accumulate. At the proper time in the molding cycle the rotation of the screw is stopped. The amount of molten plastic in front of the screw is injected into the mold, using the screw as a plunger activated by the hydraulic injection cylinder. In the mold, the molten plastic flows throughout the cavity, completely filling it. The plastic is then allowed to cool and harden, the mold is opened, and the finished part removed. The back end of the machine shown in

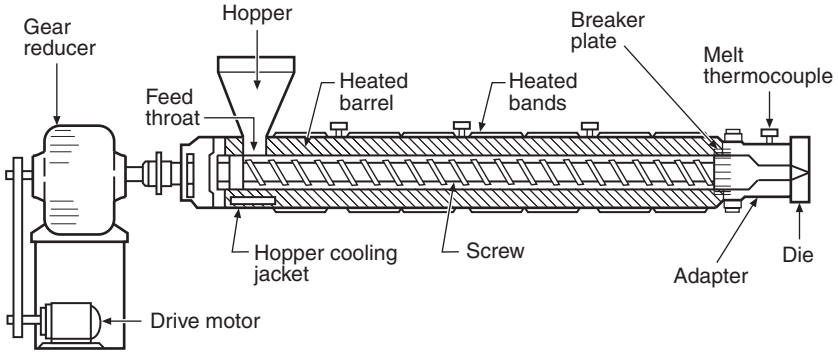

FIGURE 9.4.6 Basic Single-Screw Extruder

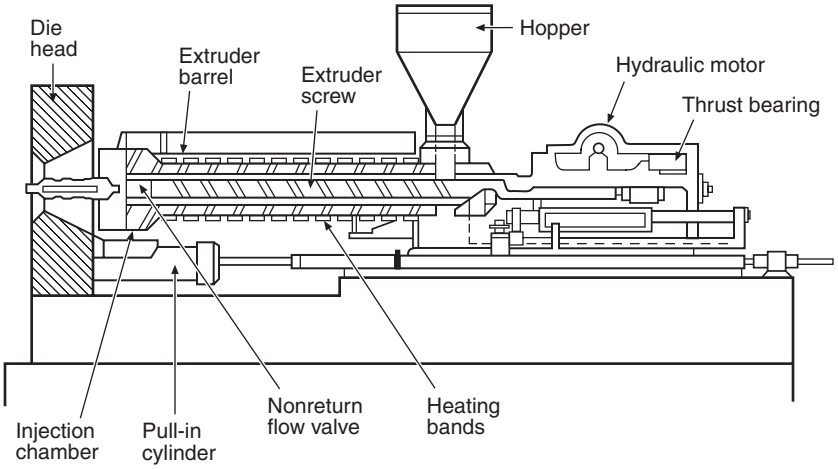

FIGURE 9.4.8 Injection Molding Machine (Reciprocating Screw)

this figure contains the motors and drives needed to power the machine.

Low-Pressure Laminating. Low-pressure laminating is a process that uses thermosetting plastics to hold together reinforcing materials, such as cloth, paper, wood, or glass fibers. Heat and pressures of less than 200 psi (1.4 kPa) are used to produce the laminated product.

Reaction Injection Molding (RIM). Reaction injection molding is a technique used primarily for molding polyurethane elastomers or foams into end products with solid integral skins and cellular cores. Basically, two or more pressurized reactive streams are impinged together under high pressure in a mixing chamber. The resulting mixture is then injected, under low pressure, into a mold. There the reaction begins and continues until the liquid mixture has set up into a solid or cellular finished product.

Reinforced Plastics Processing. In reinforced plastics processing, resins (acting as binder material) are combined with reinforcing materials (usually in fibrous form) to produce composite products having exceptional strength-to-weight ratios and outstanding physical properties. The resins may be either thermosets or thermoplastics.

Figure 9.4.9 illustrates the technique of matched-die molding. Basically, it is a compression molding process in which resin and glass fibers are shaped into the finished product under heat and pressure between the two halves of a mold (male and female halves). The glass-fiber reinforcements are laid over the male mold in the form of a "preform," a combination of glass and resin preformed before molding to the basic shape of the part to be molded. Additional liquid resin mix is added before the mold is closed.

Rotational Molding. Rotational molding is a process used to make hollow one-piece parts such as plastic barrels. Finely powdered plastic or molding granules are placed in a cavity that is rotated about two axes to distribute the plastic. While it is rotating, the mold is heated to melt the plastic and then cooled to solidify the part.

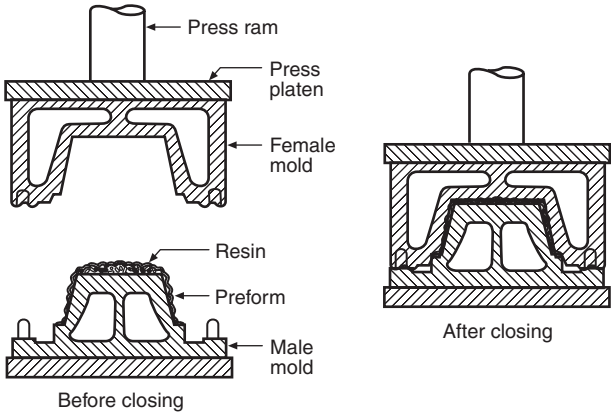

FIGURE 9.4.9 Matched-Die Molding Technique for Producing Reinforced Plastic Parts

Thermoforming. In thermoforming, thermoplastic sheeting is heated to its softening temperature and forced against the contours of a mold by mechanical means (e.g., tools, plugs, solid molds, etc.) or by pneumatic means (e.g., differentials in air pressure created by pulling a vacuum between the sheet and mold as in vacuum forming or by using the pressures of compressed air to force the sheet against the mold as in pressure forming). The part cools in the mold and is removed.

Figure 9.4.10 illustrates a variation on the thermoforming of plastic sheets known as plug-assist vacuum forming. In operation, the plastic sheet is clamped in place and heaters move in to heat the sheet top and bottom to soften it (A). Heaters are then withdrawn, and the frame holding the sheet is lowered down to contact the mold. At this point, the plug-assist is lowered into the softened sheet, stretching it down to the bottom of the mold cavity (B). After the plug-assist has reached its closed position,

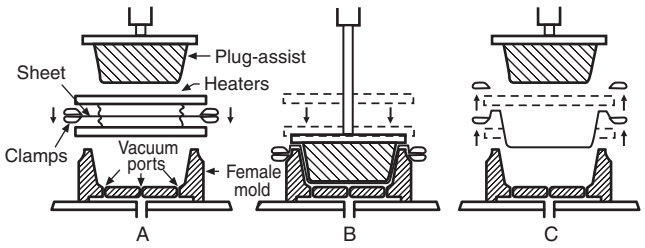

FIGURE 9.4.10 Variation on the Thermoforming of Plastic Sheets Known as Plug-Assist Vacuum Forming

a vacuum is drawn through the ports to pull the stretched sheet completely into the cavity and finish the forming. Next, the plug-assist is withdrawn, the formed sheet is cooled, and the clamps are opened to remove the formed part from the frame (C).

Transfer Molding. Transfer molding is most generally used for thermosetting plastics in a process similar to compression molding. The molding material is placed in a pot at the top of a closed mold and a plunger is used to force the material into the gates, runners, and cavities of the mold. Heat is used to cure the material, and the part is then removed.

FIRE HAZARDS

The sections that follow describe hazards that are specific to the plastics industries. The reader should understand that the hazards common to most industrial operations are also important. For additional information on fire hazards, see the chapters referenced at the beginning of this chapter.

Plants converting feedstocks into finished products are subject to a variety of hazards that can result in explosions and fire. The broad area of hazard involves the presence of combustible dusts (commonly called fines), flammable and combustible liquids, high-heat elements, static electricity, hydraulic and heat transfer fluids, and failure to observe good storage and housekeeping practices.

Dusts

Although when in solid massive form many plastics can be difficult to ignite and will not continue to burn on removal of an exposing flame, nearly all will burn rapidly in the form of dust and, if dispersed in air, can be explosively ignited by a spark, a flame, or a surface that is heated above the material's flash ignition temperature. The higher the ratio of surface area to unit volume or unit mass will significantly increase the possibility of ignition. Dust explosions should be considered possible when operations use pulverized plastic, convey larger granules through pneumatic conveying systems, or produce dust by machining or sanding in finishing work. Additives, such as wood flour or finely ground dyestuffs, also require safeguarding when being added to plastics.[6]

Plastic pellets for injection or extrusion molding are commonly known as molding powder. In reality they are not pulverized material but are cubes or cylindrical pellets. They are usually screened to remove finer particles to permit more uniform feeding to machines, and they are free from the hazard of dust explosion. However, dust (fines) can be generated by abrasion of these particles when conveyed in a long pneumatic conveying system.

Trimmings from injection molding, such as runners, sprues, and flash, are cut too small for reuse alone or for blending with fresh (virgin) molding pellets. This cutting is called "regrinding," although it is a shearing and impacting action deliberately intended to avoid making dust and fine particles. Regrinding usually generates some fine powder, and dust hazards should be considered when considerable regrinding is done.

Compounding of resins with such additives as dyes, pigments, fillers, mold-release or flow-improving lubricants, plasticizers for flexibility, ultraviolet or heat stabilizers, or modifying resins is also a source of dust hazards. For rapid mixing, most of these are charged to mixing equipment as fine powders, and dust explosions are possible with any of these ingredients. Some compounding, especially for reclaiming of once processed materials, is done at molding machines in plastics plants of all types.

Incorporation of wood flour, cotton flock, or other combustible fillers usually increases the explosibility of dust. Incorporation of low percentages of fire retardants has but little effect on explosibility of dusts. These fillers have a lower flash ignition temperature than the plastics in which they are used, making them more susceptible to spark or flame.

It is important that the escape and dispersion of dust into the atmosphere of a converting plant be kept to a minimum. Equally important is that provisions are made to reduce the possibility of ignition, relieve explosion pressure, and confine and control fire. Guidance in controlling dust explosion hazards in plastics plants is found in NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling to Combustible Particulate Solids.* Other applicable standards are NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* and NFPA 69, *Standard on Explosion Prevention Systems.*

Flammable Solvents

Flammable organic solvents are found in nearly every plastics plant. They are used in very small quantities to apply adhesives, lacquers, or paints to molded or fabricated items or to clean tools or surfaces contaminated by resin; in large amounts to coat plastic on cloth, paper, leather, or metal; or on metal belts from which a dried film will be stripped. There might be increased hazard when solvents are applied to plastics, particularly when printing or coating on fast-moving films, because plastics usually have high electrical resistivity; they generate and retain static electric charges more readily than paper or cotton fabric.

Small plants are increasing their use of solvents for the preparation of both rigid and flexible foam plastic. The plastic is moistened with solvent and heated above the boiling point of the solvent in a closed mold or extruder. On release of pressure, the boiling solvent expands the resin and produces a bubbled structure. Another type of foaming process heats a resin containing

a chemical additive that evolves gas, usually nitrogen, carbon dioxide, or steam. Either the solvent or the chemical agent is called a blowing agent. The most common rigid foam is made from beads of polystyrene moistened with about 10 percent pentane or a similar hydrocarbon. The pentane does not soften and expand the resin at room temperature but does so at the low-pressure steam temperature used in molding to shape or in extruding as sheet. It is imperative that sources of electric spark or flame be avoided. Resin is usually shipped from the manufacturer with the hydrocarbon blowing agent already mixed with it. Containers will have free vapor of pentane and should be opened outdoors or with good exhaust ventilation. Expanded articles should be aged under forced hot air to remove nearly all the flammable blowing agent before shipping.

Flexible urethane foams for upholstery and garments or rigid foams for pour-in-place construction or refrigeration insulation are blown by steam and carbon dioxide generation, which are by-products of the formation of the urethane resin from basic ingredients. Urethane foams of lower density can be made with a low-boiling hydrocarbon in the resin mixture to increase the expansion.

Foams of polyvinyl chloride, used in garments and upholstery, are usually called "expanded vinyl," because the extent of foaming is limited to provide an essentially continuous outer surface. These are commonly made with the chemical blowing agent azodicarbonamide, also called azobisformamide. Above 300°F (149°C) it provides nitrogen gas at a controlled rate, is essentially nonhazardous in the proportions used, and does not give off flammable vapors. Drums of the reagent should be cooled with water when exposed to fire.

Improper handling of flammable liquids can cause serious fires in plastics plants. Failure to recognize the importance of preventing electrostatic spark, explosion-proof electrical equipment, and vapor removal systems has been the most frequent cause of flammable liquid fires. NFPA 30, *Flammable and Combustible Liquids Code,* NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials,* NFPA 35, *Standard for the Manufacture of Organic Coatings,* NFPA 70, *National Electrical Code®*, NFPA 77, *Recommended Practice on Static Electricity,* and NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids,* contain further information on safeguards to observe in the handling and use of flammable liquids as they might apply to the plastics industry.

Heating Elements

Molding and extrusion operations for both shaping and compounding have hazards associated with local overheating of electrical components. Operating temperatures normally range from 300 to 650°F (149 to 343°C), depending on the plastic being processed. The upper temperature range is beyond that practical for heat transfer fluids, so electric resistance heating is almost universally employed. Heater bands are required to melt or soften the resin in the feed section and at the upstream end of the extruder barrel. Heater bands along the barrel heat the material to higher temperatures to melt and make the material less viscous, so it can flow from the die. It is not uncommon for temperature controllers to stick, permitting resistance heaters to exceed the temperature set for the thermocouple controller. In most cases, the character of extrudate will markedly change—and, thus, warn the operator—well before heater bands get hot enough to be a source of ignition.

Some areas within equipment might not be regularly purged by flow of the plastic feedstock. Material remaining in such areas can be subject to excessively high temperature or be kept too long at a normally acceptable temperature. Decomposition can then take place, resulting in the release of gases that might be combustible. It is good practice to start heating such equipment first at the downstream end to ensure fluidity of material and, hence, relief of pressure. Never walk in front of an extruder when it is heating up to prevent burns from the material should it exit the die at high pressure.

Cleanliness in molding and extruding areas is vital to reduce the hazard of ignition from overheated bands where flammable vapors might be generated.

Electrical wiring in heat processing equipment on plastics machines should be installed in accordance with applicable provisions of *NEC®*.

Static Electricity

Many operations in plastics plants can generate static electricity through friction, heat, or pressure. Because plastics are such good electrical insulators, static electricity on them can rapidly build up to spark discharge—a hazardous condition if dust or flammable vapors are present. Operations that can generate static electricity include stripping of films from production or printing equipment, or rapid passage of films across rolls or guides. Belts for power transmission also are a significant source of static electricity discharge. Because of their low water absorption and high resistivity, plastics cannot have their electrostatic charge dissipated by high ambient humidity as practiced in cotton, wool, and paper mills.

There are three methods of neutralizing static electricity: induction, grounding, and ionization. The most common method of induction is the use of tinsel. Tinsel must be used properly if it is to work, and remember it can never reduce or neutralize static electricity to zero. Tinsel must have a conductive metal core, be properly grounded, be stretched tight, and be ¼ in. (6 mm) from the material to be neutralized.[8] Grounding is important for personnel who handle plastic. Without grounding, each time they touch a charged plastic part they increase the potential voltage on their bodies. Eventually, the potential becomes great enough to allow discharge to any convenient ground, causing a shock. The same is true of the equipment if it is not properly grounded. The third method is ionization, which generates positive and negative ions to neutralize the positive or negative ions that exist on the plastic's surface.

Care should also be given to separating vapor and dust hazards from machines where static electricity ignition sources could develop. NFPA 77 is a good source for the safeguards to use in protecting against static electricity hazards.

Hydraulic Pressure Systems

Hydraulic systems are used to clamp molds and to provide pressure to rams or screws that force molten plastic into molds by

compression, transfer, or injection molding. The molten plastic can be at pressures up to 30,000 psi (207 MPa), but the hydraulic systems are normally less than 2000 psi (13.8 MPa). Petroleum fluids have been used in plastics operations where heating elements are generally below 600°F (315°C). (The same fluids have a poor fire incident record in die casting of metal parts because the molten metal is generally at a much higher temperature than the ignition temperature of the fluid.)

Fire-resistant water-glycol or water-oil emulsions or "synthetic" fluids are available for hydraulic systems. Substituting fire-resistant fluids for petroleum fluids should follow the recommendations of the manufacturers of hydraulic system components.

Storage Arrangements

The fire hazards of plastics in storage, whether as feedstocks for the manufacturing, conversion process or as finished articles, are determined by their chemical composition, physical form, and storage arrangement. The physical form may be formed, foam, solid sheet, film, fiber, pellets, flakes, random-packed small objects, bags, or cartons. The storage of plastics generally should not exceed a maximum height of approximately 20 ft (6.1 m). The hazard of a particular plastic in any form of storage arrangement is the same whether it is encapsulated or nonencapsulated. If fire occurs, large quantities of smoke are usually generated, making manual fire fighting difficult and venting desirable in building construction consideration. In addition to smoke, many plastics give off gases that are volatile and toxic, including carbon monoxide, which is the leading cause of death in a fire.

Plastics, such as fluorocarbons, unplasticized polyvinyl chloride, and phenolics, can be protected the same way as any Class III commodity (wood, paper, and natural fiber cloth), regardless of their physical form or storage arrangement. Pellets and small objects can be protected the same as Class IV commodities.

Thermoplastics that present a fire hazard include polystyrene and acrylonitrile-butadiene-styrene (ABS), as well as polyurethane, polyethylene, polypropylene, plasticized polyvinyl chloride, and thermosets such as polyesters, although all of these to a lesser extent. These plastic materials will either continue to react or melt or break down (depolymerize or undergo decomposition) into their monomers or lower molecular weight compounds, acting and burning like flammable liquids. With some, after polymerization the unstabilized powder may be stored before it is later compounded. During this time in storage there may be some decomposition where heat is liberated by this reaction. If the heat is not lost to the environment, the bulk material increases in temperature, which leads to an increase in the rate of decomposition and increased heat until it reaches a self-accelerating decomposition temperature.[9] During storage of these powders, it is important that the temperature of the material containers be monitored to ensure that decomposition does not reach a point where it becomes a hazard.

When containers of these materials are subject to the heat of a fire, the decomposition or depolymerization becomes rapid, and the lower molecular weight oligomer fractions act like flammable liquids. With these materials, storage areas with high sprinkler discharge densities over relatively large areas are necessary to protect these types of plastics. In the form of foamed material, these plastics present the most severe fire hazard, because they can be ignited more easily and burn more rapidly.

One-story buildings without basements are preferable for storage of plastics materials because of greater efficiency for fire fighting, ventilation, and salvage operations. Plastics should be stored, handled, and piled according to their fire characteristics.

Housekeeping Practices

Housekeeping is basic to good fire safety. Good housekeeping practices reduce the danger of fire simply because they are time-proven methods of controlling the presence of unwanted fuels, obstructions, and sources of ignition. Approved containers should be provided and properly maintained for the disposal of refuse and rubbish. Spills of flammable liquids or combustible materials should be promptly cleaned up and properly disposed. Removal of combustible dust and lint accumulations from walls, ceilings, and exposed structural members is necessary. Smoking control, in addition to sensible regulations, also requires receptacles for spent smoking materials. Areas containing flammable liquids, vapors, or combustible plastics materials, as well as areas used for processing, manufacturing, or storage, must be clearly identified to prohibit smoking or the use of open-flame devices.

In some cases, trying to have a perfectly clean area can also result in a fire or injury to personnel. Personnel must understand that plastics are thermal insulators, which means it takes energy and time to heat a plastic and also requires a considerable amount of time to cool it down. Although the surface of the material might solidify and cool, the interior of the material remains very hot and might possibly still be molten. In both the extrusion and injection molding operation a quantity of material is always purged from the machine in order to get the equipment to the desired conditions necessary to make a good product. This large mass of purged material must be put in a safe area away from the personnel to prevent tripping hazards and the potential of serious burns. Purged material should never be placed in rubbish containers until it has completely cooled. Placing it in a container with other materials that have flash and self-ignition temperatures below that of the plastic could result in a fire.

SAFEGUARDS

Good fire protection starts with the fire-safe design of the plant or warehouse or inspection and modification of the existing facilities. Sprinkler-protected, noncombustible construction is appropriate for buildings occupied for storage, processing, and manufacturing of combustibles such as those involved in the plastics industry. Automatic sprinklers, standpipe and hose systems, and water-type portable extinguishers should be supplemented by fire extinguishers and special automatic systems suitable for flammable liquid fires and electrical fires, where these hazards exist.

Consideration should be given to the provision of roof vents, particularly in large one-story warehouses of manufacturing plants.

Besides design of the processing facility, the personnel working in the plant or warehouse must be trained to react in the proper manner should fire or explosion occur.

Building Construction

Long, narrow buildings provide greater ease in protection and fire fighting than large, square buildings. One-story buildings without basements are preferable to multistory buildings that could be subject to the spread of fire from lower to upper floors.

Large properties are best subdivided into separate fire areas to limit the spread of fire. Storage and manufacturing areas particularly need to be separated from each other by walls with sufficient fire rating to protect each area and occupancy from the other in case of fire. Preferably, fire walls should be without openings, but if openings are necessary, protection can be provided by self-closing or automatic fire doors suitable for openings in fire walls. Generally, a single fire area should not exceed 50,000 ft^2 (4645 m^2).

Fire Control Systems

An alarm system that alerts building occupants, notifies fire departments, and activates automatic suppression equipment is a necessary protection feature. Rapid extinguishment can be achieved by providing plastics processing equipment, conveyors, and manufacturing machinery subject to ignition or explosion with automatic fire-, smoke-, or explosion-detecting devices to initiate an alarm and to activate automatic suppressing systems (water spray, foam, dry chemical, carbon dioxide, or halogenated extinguishing agents).

Sprinklers are the most important single system for automatic control of fires in plastics plants. Among the advantages of automatic sprinklers is the fact that they operate directly over a fire and that smoke, toxic gases, and reduced visibility do not affect their operation. Automatic sprinklers, standpipes, and fire hose connections depend on an adequate water supply delivered with the necessary pressure to control fires.

Training of Personnel

Well-trained personnel minimize the possibility of a fire or explosion occurring and if a fire or explosion does occur their knowledge of what to do in that emergency situation can be lifesaving and possibly minimize the extent of damage.

In an emergency all persons at a plant should know their responsibilities. For some personnel, the main responsibility might be to evacuate the facility; for others, it might be to assist in containing a small fire until the fire department arrives or providing medical aid to those injured.

Before an emergency occurs, personnel should be thoroughly trained in the material safety data sheets (MSDSs) for each plastic, additive, and solvent that they use. The MSDS explains the potential hazards of each material should a fire occur.

Training should make each person aware of the location of fire alarm switches, fire extinguishers, and electrical panels containing switches for main power to the equipment. Something as simple as shutting off electrical power removes an energy source for the fire. Dumping water from an extruder cooling bath onto burning or smoldering plastic might be all that is needed to extinguish a potentially larger problem.

Properly trained personnel react—they do not panic. Proper training should be a top priority of all companies involved in the manufacture, conversion, or fabrication of plastics.

SUMMARY

Plastic is any one of a large and varied number of materials consisting wholly or in part of combinations of carbon with oxygen, hydrogen, nitrogen, and other organic and inorganic elements. Plastics fall into one of two groups: thermoplastics, which can be repeatedly softened and hardened without a major chemical change taking place, and thermosets, which undergo a chemical reaction when heat treated and cannot be softened again. The four broad areas of processing include (1) polymerization; (2) manufacturing; (3) conversion of the plastics materials into useful articles by molding, extrusion, foaming, or casting; and (4) fabricating, which encompasses the mechanical operations of bending, machining, cementing, decorating, and polishing.

Besides the hazards common to most industrial operations, hazards specific to the plastics industry include combustible dusts, flammable and combustible liquids, high-heat elements, static electricity, hydraulic and heat transfer fluids, and failure to observe good storage and housekeeping practices. Good fire protection for plastics facilities include fire-safe building design; automatic sprinkler systems, standpipes, and fire hose connections; an alarm system that alerts building occupants, notifies fire departments, and activates automatic suppression equipment; and well-trained personnel who know what their responsibilities are in an emergency.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for extrusion and molding processes discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems*
NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*
NFPA 35, *Standard for the Manufacture of Organic Coatings*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA *101®*, *Life Safety Code®*
NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*

Chapter 5

Metalworking Processes

Paul G. Dobbs

Chapter Contents

The Metalworking Process
Alternative Means of Machining
Fire Hazards
Safeguards

Key Terms

cutting fluid, cutting tool, electric discharge machine (EDM), electrochemical machining (ECM), lubricating oil, machine tool, metal dust, metal powder, metalworking

This chapter describes the various methods used to shape, dimension, and finish metals. These include tool, electrical discharge, and electromechanical machining. The fire and explosion hazards of the various processes, metals, and fluids are indicated and the proper safeguards discussed.

For related topics, see Section 6, Chapter 8, "Dusts"; Section 6, Chapter 9, "Metals"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 8, Chapter 1, "Air-Moving Equipment"; and Section 8, Chapter 11, "Fluid Power Systems." For more information, the Bureau of Mines publishes a bulletin on the explosibility of metal dusts.[1]

THE METALWORKING PROCESS

The metalworking process includes shaping, dimensioning, or surface finishing of a wide variety of metals. The operations include turning, planing, shaping, slotting, milling, sawing, boring, drilling, grinding, abrasive cutting, filing, threading, reaming, broaching, deburring, lapping, chamfering, spinning, and so on. Some of these same operations and equipment are also used to work on other-than-metal materials, such as plastics or wood. These other materials likely would increase the hazard of the operation; however, the extent of that increase, or the additional protection that might be necessary, is not covered in this chapter.

On cursory observation of a machining operation, it would appear there are few, if any, fire hazards about which to be concerned. This is deceptive, for there are aspects of machining that require careful and constant attention. The fire record is full of experiences that point to the need for considerable pre-incident planning and preventive action. The principal hazards involve the coolants/lubricants used for the lubrication of the cutting tools and the possible combustion of the cuttings (chips) and fine particles (fines) that are produced as the workpiece is shaped and cut. The three principal sources of ignition directly associated with the operation are (1) the heat generated by the work being done, (2) the friction created by the cutting tool, and (3) the spontaneous oxidation of materials used. Other possible sources of ignition include smoking materials; hot surfaces such as furnaces and torches; electric sparks or arcing; and impact ignition of certain pyrophoric surface compounds that sometimes form during the earlier stages of fabrication. It is important to remember that nearly all metals will burn in air under certain conditions, depending on size, shape, and quantity.

The machining operation can be broken down into five components for the purpose of analyzing the hazards present: (1) machine tool; (2) cutting tool; (3) raw materials; (4) oils, including cutting oils, lubricating oils, and hydraulic oils; and (5) machine cuttings and their collection systems.

The Machine Tool

The modern industrial machine tool can be a single-motor machine, such as a drill press, or it can be a very large multimotored automatic machine with a highly complex electronic-control system. Stock can be brought as needed to an individual machine where a worker then mounts it to the machine and initiates the operation manually. More likely there is some degree of automation in these

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operations, and, in many cases, several machines can be located in close proximity to facilitate the easy movement of stock from one machining operation to the next. Almost all machines are electric-motor operated and likely contain some lubricating oils and grease. Electrical supply to this equipment is generally 480 V or less; however, some larger equipment will operate at higher voltages.

In almost all cases, the lubricating oil for the machine is self-contained (i.e., in the unit). Although the amount might be significant (50 to 100 gal [189 to 378 L]), it is generally not a significant hazard. The containment structures for these oils are usually substantial, and leaks are rare.

The electric motors and the lubricating oils systems on the machines usually do not alone constitute a hazard sufficient to warrant any automatic protection. However, portable Class BC extinguishers should be available in the area.

Traditionally, the machine tool is a stand-alone piece of equipment, usually operated manually by a trained operator, who sets up the stock, then controls the cutting operation. In the modern industrial setting, this arrangement has gradually given way to numerically and digitally controlled equipment, leading to more sophisticated electronic equipment in the vicinity of these operations. Today most machine tools rely on numeric control (NC), computer numerically controlled (CNC), programmable logic controller (PLC), or other microprocessors to function. Usually, this equipment does not itself present a significant fire hazard, but it does present an additional loss potential from fire exposure. Malfunction or failure of the automatic control equipment can also create hazardous situations in the operation of the machine tool, leading to fires. A significant number of fires in these occupancies have "automatic failure" cited as their cause, so reliability of this control equipment is also important. In addition, modern electronic equipment due to its value and fragile construction is more susceptible to damage from exposure fires. This potential for increased loss due to exposure fires should be included in the evaluation of automatic protection in occupancies that include such equipment.

Cutting Tool

The cutting tool can be either fixed in place while the stock is moved past it, such as on a lathe, or the tool itself can be moving, such as in a mill, surface grinder, or boring machine. The tools can be pointed or bladed and can be of hardened high-carbon steel, high-speed steel, hard ceramics, or steel tipped with hard metal carbides of tungsten, cobalt, tantalum, or other hard metallic elements. Grinding abrasives are usually alundum or silicon carbide grains bonded with resin or ceramics and pressed into the shape of wheels. These cutting tools shape the raw materials into the finished part. They can also represent a point of ignition, as they can develop significant heat from the friction of the work they are performing. Dull tools not only increase the requirement for power and influence the quality and tolerance of the work being done, but also can be the ignition source of fires in machines. Dull tools tend to produce finer particles that are more readily combustible or explosive than the larger chips generally produced by sharp tools. Cutting tools normally do not require any special protection. Of course, if they are transported on wood pallets or in cardboard cartons or other combustible containers, those materials might necessitate the provision of sprinkler protection where they are being stored.

Raw Materials

The raw materials arriving at a machining plant can be in the form of clean castings, forgings, rough-cut plate, rolled or drawn bar or merchant mill stock, fabrications, tubes, or rolled or extruded shapes. In general, these raw materials have significant mass and so can be considered as noncombustible unless exposed to massive fire. This applies even to the light metals that are known to be more readily combustible when they have a large surface-to-mass ratio. In most cases, though, the raw materials do not present any significant combustible loading. However, the packaging materials used in the transport of these materials must be considered, and, if sufficient combustibles are present, automatic sprinkler protection should be provided as necessary.

Other raw materials include cutting, lubricating, and hydraulic oils; cutting tools; and so on. Bulk shipments and storage of combustible oils should be handled in accordance with accepted standards. Further discussion of these hazards can be found in Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids."

Hazard potentials can change significantly once the raw materials are subjected to the metalworking processes. The type of operation the stock is subject to determines the size of pieces of that material that will be removed in the form of chips or fines. Chips and fines significantly increase the surface-to-mass ratio of the material, and, in some cases, they can become subject to spontaneous ignition or to ignition from outside sources. Table 9.5.1 shows the combustibility of fine powders of various metals and the amount of energy needed to initiate combustion. Almost all metals have some degree of combustibility, and, in the case of such materials as aluminum, magnesium, and titanium, they can represent a very significant hazard. As mentioned, some chips in cuttings are subject to spontaneous ignition. Zirconium and uranium powders can ignite spontaneously. Spontaneous ignition in such apparently noncombustible materials as iron and steel borings and turnings has been recorded in scrapyards and in the holds of ships carrying scrap. In these cases, fires have occurred where the heat of oxidation cannot be dissipated sufficiently to the surrounding atmosphere to prevent the development of ignition temperatures in these materials. In most normal situations, though, this should not be a problem.

Some metals, for example, magnesium and titanium, resist the normal extinguishing methods, such as automatic sprinklers, fire hoses, or regular portable extinguishers. When these materials are being used, special dry-powder extinguishers rated for Class D fires should be available nearby for use, if needed.

Cutting Fluids

Cutting fluids are often used in metalworking operations. Fluids can include various oils, soluble oils, semisynthetic fluids, and synthetic fluids. On the machines, lubricating oils and/or greases are often used to facilitate the operation of the equipment. Coolant/lubricants are often used to cool and lubricate the tool and stock at the point of operation, facilitating smoothness of the cut, life of the tool, and removal of chips and cutting fines. These

TABLE 9.5.1 Ignition and Explosibility of Metal Powders

Metal	Ignition Temperature Cloud Layer °F	Ignition Temperature Cloud Layer °C	Minimum Explosive Concentration oz/ft^3	Minimum Explosive Concentration g/m^3	*Minimum Ignition Energy Dust Cloud (mJ)*	Maximum Pressure *psig*	Maximum Pressure *kPa*	Maximum Rate of Pressure Rise *psi/sec*	Maximum Rate of Pressure Rise *Pa/sec*	*Explosibility*[a] *Index*
Aluminum	650	343	0.045	45	50	73	503	20,000	508	>10.0
Magnesium	620	327	0.040	40	40	90	620	9,000	228	>10.0
Zirconium	20	–7	0.045	45	15[b]	55	379	6,500	146	>10.0
Titanium	330	165	0.045	45	25	70	482	5,500	140	>10.0
Uranium	20	–7	0.060	60	45[b]	53	365	3,400	86	>10.0
Iron	440	227	0.200	200	72,305	45	310	600	15	0.1
Zinc	680	360	0.500	500	960	48	331	1,800	45	<0.1
Bronze	370	188	1.000	1,000	—	44	303	1,300	33	—
Copper	700	371	—	—	—	—	—	—	—	<0.1

[a]Index of Explosibility: none: 0; weak: 0.1; moderate: 0.1 to 1.0; strong: 1.0 to 10; severe: 10.
[b]In this test, 1 g of powder was used. Larger quantities ignited spontaneously.
Source: U.S. Bureau of Mines, "Explosibility of Metal Dusts," Bulletin RI-6516, U.S. Bureau of Mines, Washington, DC, 1964.

oils vary from alkaline aqueous solutions to light petroleum distillates and compounded oils. They are usually liberally applied to the point of operation for the mentioned purposes. Typical application methods include flood application, jet application, and mist application. After the fluid has performed its function at the work point, it is collected, separated from the chips, filtered, and reused. The cleaning and filtering equipment can be either self-contained to the machine itself or part of the larger central system that interconnects many machines. Essentially all of the oil-based and compounded cutting fluids are combustible to some degree. Of course, as with other combustible liquids, these oils must be heated above their flashpoint to be ignited.

Compounded oils that are acidic or contain organic additives that can oxidize and then become acidic with use should not be used for the machining of magnesium and certain other metals, because the acid can react with the metal to release hydrogen. In these cases, only uncompleted mineral oils should be used. Water-oil emulsions are also used as cutting fluids, especially where only light machining operations are taking place. In the emulsion state these oils are nearly noncombustible. Before being mixed with water or if they come out of emulsion, as might happen if the water evaporates from the emulsion, the hazard becomes that of the oil itself. Nevertheless, water-oil emulsions or other noncombustible oils should be used wherever possible to reduce hazards. Where regular cutting oils are used, the quantity and extent of use should be evaluated and automatic sprinkler protection considered.

In some cases where additional cooling is required, mineral oil, kerosene, or other materials having lower flashpoints are sometimes used. If these fluids are utilized within close proximity of their flashpoint (50°F [10°C]), special extinguishing systems, such as local applications of CO_2 or other gaseous extinguishents or dry chemical systems, should be considered.

With all the application methods, but especially the jet and mist application of cutting oils, an increased hazard is presented by the atomized material created by the application method and the machining operation itself. This can make ignition easier than under ordinary conditions. Additionally this atomized oil can drift from the equipment and condense on other machines, floors, and building structural members. Housekeeping in the surrounding areas is important in these instances, as severe fires can develop and spread over wide areas utilizing these oils. This is most significant where oil deposits have accumulated on vertical surfaces, such as the sides of equipment and building columns. Where such accumulations occur, periodic cleaning of these areas is important. Adequate enclosures and exhaust ventilation to remove this oil spray and mist should be provided.

Where central oil collection and cleaning systems are provided, the dirty oil is often collected in floor trenches that can interconnect numerous machines. If these systems are used, they should be tightly covered, or, preferably, fixed piping systems should be utilized. Where floor trenches are utilized, they create an avenue for spreading fire from one piece of equipment to the next; therefore, some form of automatic protection, such as sprinklers or carbon dioxide systems, should be considered. The central cleaning system will generally have quantities of oil present sufficient to warrant at least automatic sprinkler protection in the area. Provisions for overflow of the oil tanks in these areas caused by water from sprinklers or fire hose should be provided, channeling to a safe area.

As one of the purposes of the cutting fluid is to remove heat from the work area, the temperature of the return oil to the workstation should be checked regularly to ensure that it does not approach its flashpoint. Where oil from a central system is pumped back to individual workstations, provisions should be made for manual or, preferably, automatic shutoff of the oil supply. Automatic shutoff can be actuated by sprinkler waterflow detection, or other automatic fire detection systems.

Automatic ceiling sprinkler protection should be provided where combustible cutting oils are used on a general basis. This protection should be installed on an ordinary-hazard basis, with adequate water supplies provided.

Many machine tools employ hydraulic devices for various control actuators. Oil pressures used can vary from four hundred to several thousand psi (400 psi equals approximately 42 kPa). The reservoirs and pumps for the hydraulic oil can be either self-contained, that is, contained within the machine itself, or part of a larger central system.

Nearly all hydraulic oils are combustible to some extent, even though there are some less hazardous hydraulic fluids that significantly reduce the fire hazard. These less hazardous fluids will burn when released at high pressure and then brought into contact with a source of ignition. However, they do not sustain combustion when that ignition source is eliminated.

The fire resulting from a high-pressure hydraulic oil leak is usually a very intense torchlike flame that characteristically has a very high rate of heat release. Causes of hydraulic oil release can be deteriorated flexible hoses; failure of pipe joints, especially if threaded connections are utilized; or failure of valve packing or gaskets.

One of the easiest ways to dramatically reduce the intensity of a hydraulic oil leak fire is simply to shut off the oil supply. However, experience has shown that if there is a failure in a pressurized oil system, especially one that results in an intense fire, personnel in the area are likely to run for safety without shutting down the pump. For this reason, remotely located emergency shutoff switches should be provided, or, as a more positive step, automatic shutoff should be provided. Automatic shutdown can be provided by low-level switches in the main oil reservoir; an excess flow switch; a flame-actuated detector; a fixed-temperature release, such as a fusible link or thermostat provided in the vicinity of the equipment; or through interconnection to a sprinkler waterflow switch. In most cases where significant hydraulic oil systems are utilized, automatic sprinkler protection should be provided. If the building is not sprinklered completely, the system should extend for at least 20 ft (6 m) beyond all areas of hydraulic usage. Suitable Class BC portable extinguishers are also necessary throughout these areas.

Welded connections should be used wherever possible to eliminate the possibility of leaks from threaded joints. Tubing should be used in preference to pipe. Piping or tubing should be securely fastened in place, and flexible hoses should be kept clear of all objects and not allowed to bend in excessively tight turns. Routine maintenance checks of all hydraulic system components should be made and necessary repairs or corrective action taken on a timely basis. Leaks should not be allowed to continue, and good housekeeping should be maintained around all equipment.

Most petroleum-based hydraulic oils have a flashpoint between 350 and 600°F (177 and 315°C). Less hazardous hydraulic fluids also have flashpoints in a similar range; however, they do not sustain combustion when the ignition source is removed. These fluids are generally of the oil-water emulsion type, water and glycol type, or purely synthetic fluids. Each type has characteristics that cover nearly the entire range of operating temperatures and gasket and seal materials used in conjunction with petroleum-based oils. (See Section 8, Chapter 11, "Fluid Power Systems," for further information on the hazards and safeguards associated with hydraulic pressure systems.) It is important to ensure that the fluid being used is compatible with the seals, gaskets, and packing in the system. If a less hazardous fluid is being retrofilled to an existing system, this compatibility factor becomes especially important.

Machine Cuttings

All machining operations result in the creation of chips, which will vary widely in character, size, and configuration, depending on the operation being performed, the feed and speed of cutting, and the intrinsic characteristics of the metal being cut. Frequently, cuttings and chips appear to be quite large and heavy, and, for this reason, it is often an erroneous assumption that they do not constitute a fire hazard or an explosion hazard. However, a significant amount of fines can be obscured by the more obvious heavy chips.

Combustibility depends on the combustible character of the metal and on the ratio of the exposed surface of the cutting or chip to its mass. The thinner the cutting and the smaller the particles, the greater the likelihood of fire. Table 9.5.1 indicates that relatively small amounts of energy are needed to initiate combustion in some fine metal powders.

The accumulation of chips, cuttings, or fine particles should never be permitted at the machine. They should be removed and placed in a noncombustible container and suitably stored. In small, single-machine operations, the removal of chips is often done manually. In the larger integrated and automated operations, central collection systems are often used.

Where heavy chips and cuttings are generated, they are often mechanically separated from the cutting fluids and stored in some suitable container until disposed. Heavy chips represent the hazard attributable to the particular metal involved. In addition, there is the likelihood that cutting oil residue remains on these chips and that hazard must also be considered in determining protection for the storage and handling of these materials.

Where high-speed operations, harder metals, or grinding and more precise finishing operations are used, much smaller chips and finer particles of the metal are often generated. The removal and collection of these particles is often accomplished with a pneumatic transport system. These systems usually consist of hoods over the work area, connected by ductwork to a central material/air separator. These separators can be in the form of cyclone collectors, bag collectors, wet collectors, and electrostatic precipitators.

Because of the flow of a significant amount of fine particles in the system, it should be designed with explosion hazards in mind, especially when dealing with the more combustible metals. The system should be designed so that at no time will the fine dust concentration approach the minimal explosible concentration (MEC) of the dust. Ductwork should be designed and constructed so that it can contain the pressure buildup from an explosion without failing. Bag-type collectors are usually not utilized for collection of fine metal dust, because they inherently provide the optimum condition for rapid and complete combustion. Any combustible filter medium would tend to catch the particles of combustible or explosive metals and hold them in an envelope of oxygen; therefore, all that would be necessary to initiate a fire or explosion would be a very small amount of energy, such as an electrostatic discharge.

Wet collectors for fine metal dusts should be used only after careful consideration. Many light-metal dusts react with

water to produce highly explosive hydrogen gas. Wetted sludge of these metals is also highly explosive, unless it is kept submerged in the water. Figure 9.5.1 is a schematic diagram of a water-precipitation-type collector. It is intended to show only some of the features that should be incorporated in the collector design. The collector may be used for all combustible metal dusts. Further discussions of this aspect of metalworking operations can be found in Section 6, Chapter 8, "Dusts," and Section 8, Chapter 1, "Air-Moving Equipment."

ALTERNATIVE MEANS OF MACHINING

There are other processes used for the shaping and finishing of metals that require no cutting edge as such.

Electric Discharge Machining

The most important and widely used of the alternative processes is the electric discharge machine (EDM). Electric discharge machining is a process for metal removal by electric arc discharge. In this machine, an electrode is placed in close proximity of the workpiece and is bathed in a continuous flow of dielectric fluid. A direct current of up to 400 A at 400 V is pulsed from the control unit, and a current flows from the electrode through the dielectric fluid to the workpiece. Each pulse partially ionizes the dielectric fluid and causes a submerged spark that melts into and dislodges a small metal particle. Thus, the required shape is created by this eroding process. A continuous flow of the dielectric fluid is maintained to remove the metal particles. The fluid is filtered before being recirculated to the work area. The filtration system can either be proprietary to an individual machine or a part of a larger central system. The principal hazard associated with this operation is the dielectric fluid, which almost always is combustible. Flashpoints can be as low as 200°F (93°C). Under normal work conditions, there is a sufficient level of oil above the electrode to quench the spark and prevent the ignition of the oil. However, if the oil level is allowed to become too low, the electrode arc can become a ready source of ignition.

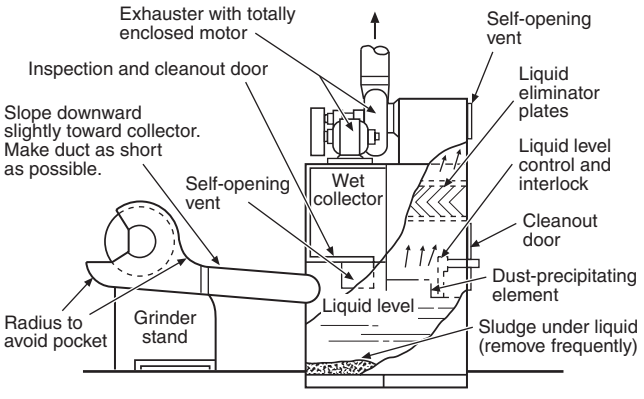

FIGURE 9.5.1 Water-Precipitation-Type Collector for Use in Collecting Dry Combustible Metal Dust Without Creating Explosive Dust Clouds or Dangerous Deposits in Ducts or Collection Chambers

Several large losses have occurred in recent years that have been associated with EDM operations. These losses highlight the importance of maintaining proper fluid levels in the machine and the need for proper precautions when central oil filtration systems are utilized. Because fires within the individual machine work areas are generally confined to a particular piece of equipment, it is important to keep some separation between these machines. At least 5 ft (1.5 m) is considered the minimum clearance to prevent fire spread from one machine to the next. Due to the quantities and combustible nature of the dielectric fluid, automatic sprinkler protection on an ordinary-hazard basis should be provided throughout areas of this occupancy. Suitable Class BC portable extinguishers are also necessary and should be provided within close proximity of these machines.

In order to prevent operation of the machine when there is insufficient fluid to cover the electrode, a low-level interlock should be provided within the work tank. If gravity flow of fluid to the work tank is provided, then automatic-closing fusible-link-operated shutoff valves should be provided to close off the flow of oil in the event of fire.

Significantly greater hazard is created in EDM operations where there is a central oil filtration system. Where these systems are used, at least a 1-hour fire-rated cutoff should be provided to separate these operations from the remaining occupancy. A manual emergency shutoff switch controlling the central oil system should also be provided and located in an area that would be easily accessible during a fire at either the central oil system or the EDM work station. Oil flow between the filtration system and EDM should only be within rigid or flexible metal piping. No plastic or rubber hoses should be utilized, unless specifically listed for such application.

Electrochemical (Electrolytic) Machining

Electrochemical or electrolytic machining (ECM) is a process in limited specialized use. It operates by anodic dissolution in an electric cell in which the workpiece is the anode and the tool is the cathode. The electrolyte (usually $NaNO_3$ aqueous solution) flows at a high rate through the gap (usually between 0.10 and 0.60 mm) between the cathode and the workpiece. A direct current of 50 to 2000 A at 4 to 30 V is imposed. At 1000 A, the rate of metal removal is approximately 1 $in.^3$ per min (16,387 mm^3/min). Current densities of 20 to 200 A/cm^2 are employed. The workpiece is dissolved (according to Faraday's Law) producing in the workpiece a negative mirror image of the cathode tool. This process is sometimes used in finishing dies and molds and in finishing turbine blades and vanes.

FIRE HAZARDS

The principal hazards encountered in a machining operation include the following:

- Chip fires at the machine, where ignition is caused by the heat of metalworking, friction of the chip against the tool, or both
- Spontaneous combustion of cuttings
- Combustion of coolant/lubricants
- Fine particles that are either combustible or explosible

- Reaction of certain metals with water or other agents
- Combustion of pressurized hydraulic fluids used for the actuation of machine tools and/or their accessories
- Combustion of oil vapors deposited on building structures
- Combustion of oil-saturated floors
- Combustion of dielectric fluid in EDM equipment

The principal sources of ignition are the following:

- Smoking materials
- Heat of cutting
- Spontaneous oxidation
- Hot particles from grinding, dressing of grinding wheels, and welding and cutting
- Hot surfaces, such as furnaces and torches
- Electrical sparking or arcing
- Impact ignition of certain pyrophoric surface compounds, which sometimes form during the earlier stages of fabrication (e.g., magnesium nitride, which sometimes appears on the surface of castings and can explode under the impulse of a very minor impact)

SAFEGUARDS

Building Construction

Buildings that house metalworking processes should be of fire-resistive or noncombustible construction with a noncombustible roof deck. If the building is large, it should be subdivided by fire walls to limit the spread of fire.

Buildings in which machining operations are performed should be regularly inspected for the accumulation of oily deposits and/or fine combustible metal particles. Cleaning should be undertaken before hazardous accumulations develop. All electrical control equipment, particularly those for numerical control or computer-directed control of machines, should be housed in vapor-tight enclosures. The equipment itself should be inspected at regular intervals and cleaned when necessary. If possible, control equipment should be located in a separate room, cut off by at least 1-hour-rated walls.

Fire Protection

The need for sprinkler protection should be carefully considered. It will depend largely on the combustible characteristics of the building structure, especially the floors and roof deck, and the extent of the hazard posed by the metalworking machine or raw material as previously discussed. Small fires at machines can be best controlled with portable extinguishers of the correct classification. If proper housekeeping is practiced, the fire hazard from cuttings and turnings can be minimized.

Combustible Metals

The more combustible metals should never be machined unless a suitable fire extinguisher is immediately available to the machine operator. It is important to remember that extinguishers for Class A, B, and C fires are generally ineffective for burning metal or metal dust. Only extinguishers rated for Class D fires should be used on burning metal. When they are used, extreme care must be exercised to ensure that the emergent force of the extinguishing agent or the action of its application to the fire is not sufficient to create an explosive metal dust cloud.

For their own safety, it is most important that all workers thoroughly understand the hazards involved and be properly instructed so that they fully understand the possible consequences of unconsidered or improper action under stress. In many instances, it is highly desirable that local fire fighters, who would normally respond to an alarm, be similarly instructed.

SUMMARY

Metalworking processes do not generally represent a high-hazard occupancy. However, this occupancy can be deceptive as hazards do exist involving the coolants and lubricants used on the tools and in the machines, with some of the metals themselves, and with the support systems for the machining and forming operations. Hazards can also exist for the storage of supplies, such as the cutting and lubricating oils, as well as from the packaging materials used in conjunction with the raw materials and finished products.

BIBLIOGRAPHY

Reference Cited

1. U.S. Bureau of Mines, "Explosibility of Metal Dusts," Bulletin RI-6516, U.S. Bureau of Mines, Washington, DC, 1964.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on metalworking processes discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 34, *Standard for Dipping and Coating Processes Using Flammable or Combustible Liquids*
NFPA 70, *National Electrical Code®*
NFPA 70B, *Recommended Practice for Electrical Equipment Maintenance*
NFPA 72®, National Fire Alarm Code®
NFPA 75, *Standard for the Protection of Information Technology Equipment*
NFPA 79, *Electrical Standard for Industrial Machinery*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 480, *Standard for the Storage, Handling, and Processing of Magnesium Solids and Powders*
NFPA 484, *Standard for Combustible Metals*
NFPA 505, *Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operation*
NFPA 801, *Standard for Fire Protection for Facilities Handling Radioactive Materials*

Chapter 6

Welding, Cutting, and Other Hot Work

Revised by
August F. Manz ❑ Mark E. Blank

Chapter Contents

Prevention Guidelines and Safety Precautions
Contract Operations
Processes Using Electricity
Oxyfuel Gas Processes
Thermal Spraying (THSP)
Safeguards
Special Situations and Additional Precautions

Key Terms

cutting equipment, demolition, fire prevention, fuel gas, hot work, oxyfuel, permit-authorizing individual (PAI), thermal spraying, welding and cutting

Hot work is defined by the NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work,* as "Work involving burning, welding, or a similar operation that is capable of initiating fires or explosions." This work can involve temporary or permanent operations that produce flames, sparks, or heat. Some examples of hot work are as follows:

- Cutting
- Welding
- Grinding
- Using powder-driven fasteners
- Thawing pipes
- Hot riveting and allied processes
- Roofings applied by torch and regulated by the requirements of NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations*
- Similar applications producing or using spark, flame, or heat

In most cases, damaging hot work fires occur when companies, employees, or contractors fail to follow proper hot work safety guidelines. It is not that individuals performing the hot work are irresponsible. They simply can and do make mistakes, or they are not aware of the hazards and the steps that are necessary to mitigate or prevent a hot work fire.

Torch fires accounted for 1 percent of reported 1999–2002 structure fires in the United States, including 1 percent of home structure fires and 3 percent of nonhome structure fires. Torches were involved in 7 percent of the reported structure fires in industrial and manufacturing properties. Of the torch fires coded by type of torch from 1999–2002, 71 percent of the nonhome structure fires but only 43 percent of the residential structure fires were due to cutting or welding torches. Torches were involved in an average of 74,000 reported structure fires per year. However, education, training, and on-the-job training can significantly reduce the potential for welding, cutting, and other hot work fire.[1]

For related topics, see Section 6, Chapter 10, "Gases"; Section 7, Chapter 3, "Storage of Gases"; and Section 9, Chapter 5, "Metalworking Processes."

PREVENTION GUIDELINES AND SAFETY PRECAUTIONS

Hot work fires are preventable. Established hot work fire prevention guidelines are designed to help people stop and think about the fire hazard potentials that can exist in an area before placing themselves and the facility where they are working in harm's way. These guidelines are as simple as taking the following precautions:

- Implementing hot work permit systems (a precautions checklist highlighting important steps to take during hot work operations)

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- Using alternative methods to hot work
- Relocating the hot work activity to safe/designated areas

In some cases, conditions within a facility are just so inherently dangerous that hot work cannot be conducted safely and should be avoided.

To achieve effective hot work management, proper planning, training of personnel involved, and adequate supervision are necessary components to reduce the risks of hot work. For instance, discussing hot work projects prior to performing any job is a crucial first step. Facility owners and contractors should work together to ensure there is a clear understanding of the fire hazards that exist within the area where hot work will be conducted. Hot work operations should always be supervised by trained personnel to ensure unsafe conditions do not develop. The fire watch should be trained in use of fire protection equipment and facility emergency communication procedures should the need arise.

Due to readily available ignition sources that hot work operations openly create, it is imperative to adhere to every safety precaution, including the following:

- Properly isolating a welding operation with listed/approved welding curtains
- Following hot work guidelines in NFPA 241 for torch-applied roofing systems
- Wearing proper fire-resistive clothing to prevent personal injury

Every hot work safety precaution is important and should be followed. Sometimes hazards within a facility are apparent, like exposed storage or well-labeled flammable liquid operations. But many times, hazards within a facility are not obvious, even to seasoned hot work professionals. Combustible concealed spaces in walls or floors; combustible insulation within walls; heating, ventilation, and air conditioning air-intake vents in floors/walls/ceilings; and open/abandoned piping or conduit extending through walls or between building floors all represent potential hidden fire hazards to hot work operations. Sparks and molten slag can fly or roll long distances, igniting hidden unprotected combustible materials like wall insulation, dust or lint accumulations above suspended ceilings, or flammable vapor accumulations in an adjacent area. Sparks from hot work also can settle into wall or floor openings that are not easily seen, or sparks can be drawn into ventilation ductwork where combustible materials can be ignited and smolder undetected for hours before finally breaking out into fire. The key is not taking any facility hazard for granted and not taking shortcuts in established hot work fire prevention guidelines.

With hot work, four factors must be kept in mind:

1. The two sides of the fire triangle that are always present, that is, a source(s) of ignition and air to support combustion. The other controllable element is the combustible material.

2. The shop's familiarity with hot work as an activity. A shop that performs welding or cutting operations on a routine basis in a fixed location can develop confidence and reinforce safe habits more easily than a shop that performs welding or cutting only occasionally and in a variety of different temporary locations. On the other hand, facilities that conduct hot work on a regular basis need to be careful about becoming complacent of the hot work hazards that are present within their plant.

3. The kind of process and equipment used and their potential fire effect. Cutting, as well as certain arc welding operations, produces literally thousands of ignition sources in the form of sparks and hot slag.

4. The supervision and training of the operator. Is the operator trained in the proper use of the equipment and mindful of the exposure? Who has knowledge of and has assessed the risks involved in bringing a torch into the work area and has authorized its use there? Is there a designated fire watch to support the operator in maintaining the hot work area in a fire-safe condition?

CONTRACT OPERATIONS

The trend toward outsourcing facility maintenance and renovations can influence the risks associated with hot work. A contractor must have the technical expertise to perform hot work, have a full understanding of fire prevention and the specific combustible hazards within a client property. Before starting any hot work job, contractors and their clients should discuss the planned project completely, including the following topics:

- The type of hot work that will need to be conducted
- Procedures for isolating the hot work to prevent fire hazards
- Identification of personnel to be assigned as the fire watch for the hot work operations
- Facility emergency notification procedures
- Available manual fire fighting tools (like portable fire extinguishers and small hose stations)
- Identification of all areas where hot work is not allowed
- Review of any requirements for completion of hot work by a certain time each day

However, it is recognized that premises management might not always have expertise in hot work and therefore would need a knowledgeable designated agent or contractor to act on its behalf. Examples of those who might not have the expertise can include owners of small retail shops, a small apartment complex manager, or a grocery store owner who has no knowledge of hot work safe practices. Management should ensure that the contractor has evidence of financial responsibility, which can take the form of an insurance certificate or other document attesting to coverage or responsibility.

PROCESSES USING ELECTRICITY*

Arc Welding (AW)

Arc welding (AW) applies to a number of processes that use an electric arc as the heat source for melting and joining metals. The arc is a useful tool because its heat can be concentrated

*The descriptions in the sections "Processes Using Electricity" and "Oxyfuel Gas Processes" are adapted from publications of the American Welding Society.

and controlled quite effectively. Frequently, but not always, a filler metal must be used to obtain a good joint. The arc is struck between the metals to be welded and an electrode, which is maneuvered along the joint or remains stationary while the work is moved beneath it. The electrode may be consumable or nonconsumable. If the latter, a separate rod or wire may be used as the filler metal. Consumable electrodes supply their own filler metal by melting. The molten metal and weld zone can be protected from atmospheric contamination by use of a supplementary shielding gas or a shielding atmosphere produced by decomposition of a flux, which is used with certain types of electrodes and wires.

Shielded Metal Arc Welding (SMAW). This simple well-known process is widely used with ferrous-based metals (Figure 9.6.1). It produces coalescence of metals by heating them with an arc between a flux covered metal electrode and the weld pool. The process is used with shielding gases from the decomposition of the electrode covering, without the application of pressure, and with filler metal from the electrode. The process requires an alternating or direct current power supply, power cables, and an electrode holder. Shielded metal arc welding can be performed readily in remote, unusual, or confined locations. Consequently, this process is widely used in such industrial applications as construction, shipbuilding, and pipeline erection. Fairly simple portable units are frequently used in maintenance and field construction work. It is also commonly known as "stick welding," "covered electrode welding," and sometimes simply as "arc welding."

Gas Metal Arc Welding (GMAW). The GMAW process uses a continuous filler metal electrode, which functions as one terminal of the arc, and a gas to shield the arc and the weld metal. The shielding gas depends on the base metal and process variations. It can be an inert gas, such as argon or helium; an active gas, such as carbon dioxide; or mixtures involving these gases with additions of hydrogen, nitrogen, or oxygen. Overall, this process can be used to join just about any metal in any configuration of joint. Gas metal arc welding is commonly referred to as MIG welding, an acronym for metal inert gas welding, even though active gases are also employed. Process variations include short circuiting metal transfer (GMAW-S) and pulse transfer (GMAW-P).

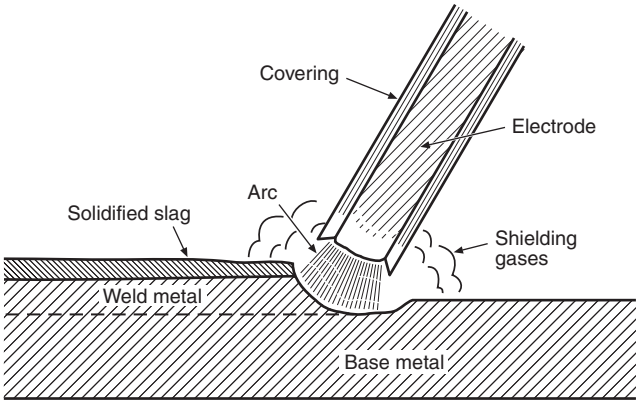

FIGURE 9.6.1 Typical Shielded Metal Arc Welding Operation

Flux Cored Arc Welding (FCAW). Although the FCAW process is similar to gas metal arc welding in equipment used and types of applications, tubular rather than solid electrodes are used. Minerals and alloys in the tube core assist in weld protection, and many such electrodes are intended for use with shielding gases. Other kinds of cored electrodes are self-shielding and produce their own protective envelope without an auxiliary shielding gas.

Gas Tungsten Arc Welding (GTAW). The GTAW process is similar to gas metal arc welding and flux cored arc welding, but it uses a nonconsumable tungsten electrode for one pole of an inert gas-shielded arc. Filler metal may be used. The most common inert shielding gases are argon and helium. Equipment required comprises a power supply, welding torch, source of inert gas, suitable pressure regulators and flowmeters, and connecting hoses. Gas tungsten arc welding is commonly referred to as TIG welding, an acronym for tungsten inert gas welding. It also is called "heliarc" welding and "argon arc" welding. In Europe it can be called WIG welding, where the "W" stands for *Wolfram,* which is the German word for "tungsten."

Plasma Arc Welding (PAW). PAW is characterized by the plasma state, wherein the temperature of a gas is raised until the gas becomes at least partly ionized, enabling it to conduct an electric current. It uses a constricted arc between a nonconsumable electrode and the weld pool (transferred arc) or between the electrode and the constricting nozzle (nontransferred arc). A plasma arc torch incorporates an electrode and an orifice through which a flow of gas forms the arc plasma. Secondary gas, which flows through an outer nozzle cup arrangement that encircles the arc plasma orifice, shields the arc and the weld. Typical shielding gases are argon, helium, and mixtures of argon with hydrogen or helium. Filler metal may or may not be used. Equipment required is not unlike that for gas tungsten arc welding, with necessary differences in power supply and control, torch design, and gas supply and control.

Submerged Arc Welding (SAW). In the SAW process the arc and molten metal are shielded by molten flux and a layer of unmelted flux granules. A continuously fed electrode is submerged in the flux. The arc is submerged below the flux. The process is used without pressure. Radiation and fumes are minimal and fire hazard potential is likewise relatively minor compared to other processes.

Resistance Welding (RW)

Welding heat for resistance welding (RW) is created by resistance to flow of current through the parts being joined. Resistance welding is generally used to join two metal pieces that might have different thicknesses and composition. Electrodes conduct current through the pieces, which are clamped or rigidly held together to provide good contact and pressure at the joint.

Flash Welding (FW)

Although defined by the American Welding Society (AWS) as resistance welding, flash welding (FW) is considered a process unto itself. Heat is created by a flashing action at the interface. Pressure is applied after heating, resulting in the expulsion of metal, formation of a flash, and usually a significant shower of sparks. Applications usually involve butt welding rods or bars end to end or edge to edge. The process is almost always automatic. Flash welding machines vary significantly in size, some being large enough to weld sheets in a steel mill.

Electroslag Welding (ESW)

Electroslag welding (ESW) is a process used primarily for vertical position welding. This process uses a slag, which is electrically conductive while molten, to protect the weld and melt base-metal edges and filler metal. An arc is needed to start the process by melting the slag and preheating the work because the unfused, solid slag is nonconductive. Once the process is started, the arc is no longer necessary, and resistance to current flow through the molten slag produces the heat to sustain the process.

Arc Cutting (AC)

Arc cutting (AC) applies to a group of thermal cutting processes that, like the kindred welding processes, melt the metals to be cut by heating them with an arc struck between an electrode and the workpiece.

Air Carbon Arc Cutting (CAC-A). The CAC-A process uses electrodes comprising a mixture of graphite and carbon, which might also be coated with a copper layer to improve current-carrying capacity. Metal melted by the arc is blown away by a jet of compressed air supplied by conventional compressors, usually at about 80 psi (550 kPa). Current is provided by standard electric welding power supply units rated for CAC-A duty or special power units.

Plasma Arc Cutting (PAC). The PAC cutting process achieves cutting action with an extremely hot jet of ionized gases at high velocity. The high-velocity hot jet is produced by forcing an arc and gas through a small orifice. Arc energy confined to a small area melts the metal, and the jet of highly heated, expanding gases forces the molten metal from the cutting area. High-arc voltages, special power supplies, and water-cooled torches are required. Air, nitrogen, argon-hydrogen, argon-nitrogen, and argon-helium gases are commonly used.

OXYFUEL GAS PROCESSES

Oxyfuel Gas Welding (OFW)

Oxyfuel gas welding (OFW) uses the heat of combustion of a fuel gas and oxygen flame, at high temperatures, to melt the workpiece base metal and filler metal. The flame (except for oxygen-hydrogen) is readily adjusted to provide a "neutral," oxidizing (excess oxygen), or carburizing* (excess fuel gas) environment. The type of flame used depends on the materials being welded.

TABLE 9.6.1 Flame Temperatures of Fuel Gases with Oxygen

Gas	Neutral Flame Temperature °F	Neutral Flame Temperature °C
Acetylene	5589	3087
Methyl acetylene-propadiene (stabilized)	5301	2927
Propylene	5250	2900
Hydrogen	4820	2660
Natural gas-methane	4600	2538
Propane	4579	2526

Acetylene remains the preeminent welding fuel because it has the highest flame temperature of all the fuel gases. Other fuel gases or mixtures, such as methyl acetylene-propadiene (stabilized), have found acceptance. Other hydrocarbons (propane, propylene, butane, natural gas-methane) are not suitable for welding ferrous metals. Hydrogen has a low flame temperature and heat content, and its flame, which is colorless, is difficult to adjust for oxygen-fuel gas ratio. Oxy-hydrogen welding does have application for welding lead, which is frequently but erroneously called lead burning. Table 9.6.1 shows neutral flame temperatures of some fuel gases.

With the exception of acetylene, neutral flame temperatures are significantly lower than the maximums, so it is not possible to melt and control the weld, except perhaps for thin sheet metal. At maximum temperatures, the flames are strongly oxidizing and not usable because of deleterious metal oxide formation in the weld metal. Use of methyl acetylene-propadiene (stabilized) requires special procedures.

Brazing and Braze Welding (BW)

Brazing. This is broadly defined by the AWS as a group of welding processes in which the base metal is heated but not fused and the joining is accomplished with a filler metal having a liquidus temperature above 840°F (450°C) and below the solidus temperature of the base metal. Moreover, brazing is characterized by the filler metal being distributed through a closely fitted joint by capillary action.

Braze Welding (BW). Braze welding is of more significance as it relates to fire prevention because of its frequent use in repair and maintenance activities. It differs from brazing in that capillary action in the joint is not a factor; the filler metal is laid down in a groove or fillet at the point of application. The edges of the joint are heated to a dull red color, flux is used, and filler metal is supplied by a bronze rod. However, the base metal is not melted, only the filler metal melts. The process is widely

*Sometimes carburizing flames are called reducing flames.

used on ferrous metals, as well as on copper and nickel alloys. Sometimes it provides a solution to the problem of joining dissimilar metals.

Hard Soldering. This common but incorrect term is used to describe brazing with a silver-base filler metal. The operation is often performed with an oxyfuel gas torch, as in assembling copper pipe joints with silver brazing alloy. Many times, however, the oxygen is not pure gas but is supplied as air, as in the air-acetylene torch. Thus, only one small gas supply cylinder is needed, enhancing portability.*

Surfacing

In surfacing the oxyfuel gas flame (usually oxyacetylene) is used not in a true welding sense but rather to deposit a layer of filler metal on a base metal to obtain certain surface properties or dimensions. Bronze may be used, but more frequently the process is one of hard facing, where the deposited layer is a special alloy that will greatly prolong the life of parts subject to extreme wear or abrasion. Surfacing can also be accomplished by use of arc welding and thermal spraying processes.

Oxyfuel Gas Heating Operations

There are numerous industrial and commercial operations that regularly employ an oxyfuel or air-fuel flame but do not involve a joining or severing operation. The flame and the nature and location of these operations can, nonetheless, represent an appreciable fire potential. Some such operations are as follows:

Forming. Heating (ironwork, piping, etc.) to facilitate bending, shaping, or straightening

Annealing, flame hardening, flame softening. Use of the flame in a controlled manner to obtain specific properties

Flame priming. Heating to remove scale and rust in preparing metal surfaces for painting

Flame descaling. Heating (generally a steel mill application) to remove scale from bars, billets, slabs, and so on, to facilitate machining or inspection

Other applications. Paint burning, glass finishing, leather edging, babbitting, or antiquing of wood

Oxyfuel Gas Cutting (OFC)

The term oxyfuel gas cutting (OFC) describes a group of oxygen cutting processes named by the specific fuel gas used (e.g., oxy-acetylene cutting, or OFC-A and oxy-natural gas cutting, or OFC-N) for severing metals by the reaction of high-purity oxygen with the metal at elevated temperatures. Burning iron in oxygen produces iron oxide, normally a solid, but the oxide melts at a temperature below the melting point of iron or steel and runs off as slag. A variation in the process is oxyfuel gas gouging, wherein a relatively low-velocity oxygen jet permits gouging or grooving of a metal surface in a reasonably smooth, well-defined manner.

Oxyfuel Gas Welding and Cutting Equipment

Basic elements are fuel gas and oxygen supplies, pressure regulators, conduits (hoses or piping) to convey the gases, and a torch to mix and burn the gases in controlled fashion and provide the oxygen jet used in cutting operations. In its simplest form, the equipment comprises a cylinder each of fuel gas and oxygen, a pressure regulator on each cylinder, hoses, and a torch (Figure 9.6.2). A steel mill, however, might have a major installation for cutting and welding operations (Figure 9.6.3). Fuel gas might be supplied from large multicylinder manifolds (possibly truck mounted and replaceable), from storage tanks for liquefied fuel, or from a public utility natural gas main. Oxygen might be supplied from the mill's own on-site oxygen-generating plant, from storage tanks for liquid oxygen or high-pressure gas or both, or from multicylinder manifolds. A major installation might also have an extensive fixed-piping distribution network and consuming devices running the gamut from simple hand torches to sophisticated steel-conditioning machines.

Auxiliary—but necessary—equipment includes standardized[2] fuel gas and oxygen hose connections, standardized hose,[3] protective equipment for service piping systems, and shutoff valves at points (station outlets) where gas is withdrawn from the piping system. Protective equipment for piping, which may

FIGURE 9.6.2 Portable Welding Outfit with Oxygen and Acetylene Outfits Chained to an Easy-Rolling Cylinder Truck (cutting attachments not shown) (Source: ESAB Welding and Cutting)

*The air-fuel gas flame, particularly air-acetylene, also finds significant use in soldering, commonly called "soft soldering," which by definition involves a filler metal that melts below 840°F (450°C). Plumbing jointwork, refrigeration piping, and heating and ventilating duct assemblies are applications where the air-fuel gas flame is used. Equipment portability is an advantage—but it may also signify access to places where fire prevention is not easily accomplished and is easily overlooked, because a single-joint operation can be done in a matter of minutes.

FIGURE 9.6.3 Large Stationary Oxyfuel Gas Cutting Machine in Operation (Source: ESAB Welding and Cutting)

be installed at one or more locations, should prevent the backflow of oxygen into the fuel gas supply system and vice versa, the passage of flame flashback into the fuel gas supply system, and the development of pressures in excess of system component ratings. In some systems, backflow prevention devices also may be required at station outlets. (See NFPA 51, *Standard for the Design and Installation of Oxygen–Fuel Gas Systems for Welding, Cutting, and Allied Processes.*)

Welding torches have inlet connections and valves for each gas at the rear of the handle (Figure 9.6.4). The gases are controlled by inlet valves and thoroughly mixed before issuing from the torch tip. Cutting torches are similar but provide passageways and separate valving for supplying and controlling the cutting oxygen jet at the center of the tip.

Mechanized cutting is common. Equipment varies from relatively simple, portable machines, used for straightline work and perhaps circles and some irregular shapes, to highly sophisticated multitorch machines that can trace (by photocell, laser beams, or other electronic means) intricate shapes and accurately and simultaneously produce a number of parts of the same shape.

THERMAL SPRAYING (THSP)

Closely allied to welding are several processes known collectively as thermal spraying,* in which finely divided metallic or nonmetallic materials are deposited in molten or near-molten condition to form coatings. Special "guns" are used (Figure 9.6.5). In flame spraying (FLSP), an oxyfuel gas flame is used to melt the coating material, and an auxiliary compressed gas can be used to assist in atomizing and propelling coating material to the workpiece.

Arc spraying (ASP) employs an arc between two consumable electrodes of coating material, plus auxiliary compressed

*"Thermal spraying" is the American Welding Society's preferred terminology for "metal spraying" or "metalizing."

FIGURE 9.6.4 Typical Cutting Torch. All control valves are located at the rear of the body. (Source: ESAB Welding and Cutting)

FIGURE 9.6.5 Thermal Spray Gun (Source: American Welding Society)

gas to atomize and propel the coating particles. Plasma spraying (PSP) uses a nontransferred plasma arc as the heat source and for propelling the coating material. In detonation flame spraying, the coating material is melted and propelled by the controlled explosion of fuel gas and oxygen.

SAFEGUARDS

Although it is beyond the scope of this chapter to describe all the fire prevention considerations that are tied into proper equipment design, installation, and maintenance, some significant items have been selected for specific attention.

Equipment Preparation and Condition

Oxyfuel Gas Equipment. Equipment meeting recognized standards (e.g., torches, cylinder manifolds, pressure regulators, pipeline protective devices, etc.) should be used.

Since oxygen is a far more powerful oxidizer than air, oxygen equipment must be kept clean (i.e., free of oil, grease, and other combustible contaminants). Materials that burn in air will burn violently in pure oxygen at normal pressure and explosively in pressurized oxygen. Also, many materials that do not burn in air will do so in pure oxygen, particularly under pressure. Consequently, it is widely recognized good practice to reserve equipment for oxygen service only.

Proper storage of gas cylinders is important (see NFPA 51). Cylinders should be moved and handled in accordance with recognized practices, for example, those of the American National Standards Institute (ANSI) and the Compressed Gas Association (CGA) (see Bibliography). There are many such recognized practices, and their importance varies with working locations and conditions. However, cylinders should always be supported or located in such a way that they cannot be knocked over. Ruptured cylinders can explode.

Oxyfuel gas cutting and welding equipment should be tested periodically for leaks (Figure 9.6.6). Testing frequency depends on the specific kind of equipment involved and how often it is used. Hose connections are known possible trouble spots. Also, experience has shown that fires can occur at fuel gas cylinder-to-regulator connections simply because someone failed to tighten the joint properly. The ignition of leaking gas at this point can in turn cause the release of cylinder safety devices, especially with acetylene cylinders fitted with fusible plugs, thereby releasing more gas and increasing the size of the fire.

Only standard welding hose should be used.[4] It should be frequently inspected for burns, cuts, worn places, abrasions, and similar defects. Taped repairs are unacceptable. Replace the damaged hose, or, if feasible, cut out the affected area and insert a proper splice. When repairs to equipment such as torches and regulators are required, they should be carried out by trained, skilled mechanics.

FIGURE 9.6.6 Checking Equipment for Leaks Before Operating an Oxyfuel Gas Outfit. After pressurizing both hose lines (with torch valves tightly closed), test for leakage at the following points, using an approved leak-test solution: (1,2) acetylene cylinder connection and acetylene cylinder valve spindle, (3) acetylene regulator-to-hose connection, (4) oxygen valve spindle, (5) oxygen cylinder connection, (6) oxygen regulator-to-hose connection, (7,8) hose connections at the torch, and (9) torch tip (for leakage past the torch valves). Later, after lighting the torch, check for leakage at the throttle valve stems (A,B) and at the welding head-to-torch handle connection (C). (Source: ESAB Welding and Cutting)

Arc Welding Equipment. When using arc welding equipment, the following should be addressed to avoid accidents, electric shock, or equipment damage:

- Use equipment meeting recognized criteria, such as that provided by ANSI, National Electrical Manufacturers Association (NEMA), and Underwriters Laboratories Inc. (UL). Installation, including incoming power lines and grounding of the machine frame or case, should comply with NFPA 70, *National Electrical Code*®, with particular attention to Article 630, "Electric Welders," and with ANSI/AWS Z49.1, *Standard for Safety in Welding, Cutting, and Allied Processes.*
- Proper storage and handling procedures for cylinders of shielding gases should be observed.
- At each work location, cylinders should be supported or located in such a way that they cannot be knocked over accidentally. Precautions must be taken that the cylinders are not grounded.
- Cable sizes should be adequate for current and anticipated duty cycles. Sustained overloading of inadequate cables can burn away insulation. Cables should be inspected frequently for wear and damage and properly repaired or replaced when necessary.

Precautions for the Work Area

Hazardous sparks and globules of molten metal, or hot slag, are produced by welding, cutting, and other hot work operations. Sparks from cutting, particularly oxyfuel gas cutting, are generally more hazardous than those from welding, because the sparks are more numerous and travel greater distances. In a sense, they are jet propelled by the oxygen or airstreams used in cutting processes. Oxyfuel gas flames and electric arcs are inherent and obvious ignition sources, as are hot workpieces or sections cut from the base workpiece.

Isolation of Combustibles. Either isolation or protection of combustibles is essential, for they may be exposed to sparks that fall through cracks or other openings in floors and partitions. If those sparks are of sufficient mass to retain heat for a time, they may ignite combustibles. The following are the minimum recommended requirements for combustible control within a 35 ft (10.6 m) cutting or welding work area:

- Move all combustibles a safe distance away—at least 35 ft (10.6 m)—and be sure that there are no openings in walls, ceilings, or floors within a 35 ft (10.6 m) radius.
- For situations in which combustibles are within a 35 ft (10.6 m) sphere of the point of operation, be alert for cutting conditions that could propel sparks overhead or downward.
- Move the work to a safe location.
- If none of the foregoing steps is possible, protect the exposed combustibles with suitable fire-resistant guards and provide a trained fire watcher with extinguishing equipment readily available.

For situations in which combustible materials cannot be relocated beyond the 35 ft (10.6 m) safe separation distance, the following are some of the precautions that should be implemented:

- Shield combustible flooring with wet sand, listed/approved hot work blankets/pads, or sheet metal.

- Clean up the area, especially oily deposits and trash.
- Cover/shield any storage or other combustibles that cannot be moved with listed/approved hot work blankets or welding curtains.
- Block off any duct openings to prevent sparks from traveling to other areas or to ignite deposits/linings within the ductwork.
- Cover or fill any openings in exposed walls, flooring, and ceiling with noncombustible materials or listed/approved fire-stop material.
- Clean dust and deposits outside and inside enclosures and ducts.
- Close all doors and fire doors around the hot work area.
- Check for gaps under doors or along their sides to prevent sparks from getting through that could ignite combustible material outside the hot work area.
- Relocate combustibles away from the opposite sides of the walls being worked on.
- If hot work occurs at an elevated location (i.e., on the building frame, the ceiling, or the underside of the roof), provide a listed/approved hot work blanket under the work area.
- Relocate the hot work to a designated area devoted exclusively to hot work, which isolates the area from the rest of the facility with noncombustible screens or partitions.

Special Hazards. For operations involving special hazards of combustible dusts, flammable liquids, or flammable gases, special precautions should be taken before any hot work is initiated in these areas. All processing equipment/systems should be shut down, cleaned, and equipment purged of all combustible/flammable contents before hot work is authorized. See appropriate NFPA codes for additional guidance.

Factors to Consider. The steps that have been described are only a partial solution to the problem of preventing cutting, welding, and other hot work fires. There are other important factors to consider. Are there any inconspicuous combustibles in an area proposed for cutting and welding operations? What conditions must be met before cutting and welding operations can take place? Who has the responsibility for authorizing the work to proceed? Are cutters, welders, and their supervisors properly trained in the use of their equipment and in emergency procedures should a fire occur? If an outside firm is engaged to do cutting and welding work, chances are that its employees will be unfamiliar with the premises and its contents. That is why they must be briefed on the conditions in the areas where they will work.

Facility Management Responsibilities. Based on the fundamental but necessary understanding that workers, their supervisors or permit-authorizing individuals (PAIs), and facility management share the responsibility for fire safety, the following paraphrased version of NFPA 51B should be helpful. It is adapted in the following list for convenience; this list should not be used in place of NFPA 51B.

1. Management must establish areas designed and authorized for hot work and/or designate a PAI to authorize hot work in areas not specifically designed for such processes. This management designee must require trained fire watchers where the potential exists for a significant fire to develop. Fire watchers must also be required where appreciable quantities of shielded combustibles are less than 35 ft (10.6 m) away; where wall or floor openings within 35 ft (10.6 m) expose combustibles in adjacent areas; or where combustibles adjacent to opposite sides of partitions, ceilings, or roofs are likely to be ignited by heat from the work. Management must select contractors with a view to their awareness of risks and the quality of their personnel. Management must also advise contractors of the presence of flammable materials or other hazardous conditions on the property work site.

2. The PAI of hot work (e.g., the plant manager, plant maintenance foreman, contractor, or contractor's foreman) in areas not designed for such processes must be assigned the following responsibilities:

   a. Determine what combustible materials are present at the work site.
   b. If necessary, have the work or the combustibles moved, or have the combustibles shielded.
   c. Issue authorization in the form of a written hot work permit.
   d. See that the worker is aware of the authorization and conditions.
   e. See that fire watchers are available when required.
   f. Make a final check for fires one-half hour after completion of welding or cutting operations in cases where a fire watcher was not required.

3. Workers must have the PAI's approval before starting hot work, must handle their equipment safely, and must continue to work only so long as approval conditions do not change.

4. There are a number of precautions to be observed during hot work:

   a. Hot work must not be permitted in flammable (explosive) atmospheres; near large quantities of exposed, readily ignitable materials; in areas not authorized by management; or on metal partitions, walls, or roofs with combustible covering or with combustible sandwich-type panel construction.
   b. Floors must be free of combustibles, such as wood shavings. If the floor is of combustible material, it must be kept wet or otherwise protected.
   c. If combustibles are closer than 35 ft (10.6 m) to the welding or cutting process and the work cannot be moved or the combustibles relocated at least 35 ft (10.6 m) away, they must be protected with flame-resistant covers or metal guards or curtains. This also applies to walls, partitions, ceilings, or roofs of combustible construction (Figure 9.6.7).
   d. Openings in walls, floors, or ducts must be covered if within 35 ft (10.6 m) of the work.
   e. Cutting or welding on pipes or other metal in contact with combustible walls, partitions, ceilings, or roofs must not be performed if close enough to cause ignition by heat conduction.

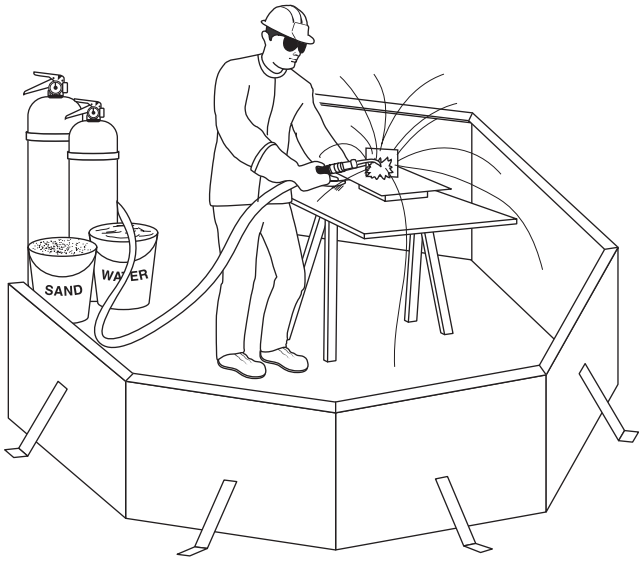

FIGURE 9.6.7 Safe Work Procedures

f. Charged and operable fire extinguishers must be readily available. Trained fire watchers must be posted. In the absence of fire watchers, an important minimum step is to check the work area and adjacent areas carefully for at least one-half hour after completion of welding or cutting to detect possible smoldering fires. Consider extending the time when conditions seem more hazardous.

SPECIAL SITUATIONS AND ADDITIONAL PRECAUTIONS

Containers (Including Piping)

Welding or cutting on containers can cause—and has caused—explosions or fires with potential for deaths or serious injuries. Any container can contain or might have contained a combustible. Therefore, all containers must be considered hazardous unless they have been tested and found safe, cleaned, or rendered inert. Therefore, it is essential that flammable liquids, solids, or vapors be removed from containers by some type of adequate cleaning procedure before welding or cutting.

Depending on the application, it might be necessary or desirable to supplement the cleaning with inerting, water flooding, or periodic testing (for flammables) of the atmosphere within the container. With some materials, water washing or flushing might be sufficient; others might respond to steam cleaning; some might require alkaline cleaners (trisodium phosphate or caustic soda); some might call for more specialized cleaning methods. Heavy, viscous liquids and solids can be especially difficult to remove completely. Residues are especially hazardous because they can volatilize or decompose into flammable products by the heat of the torch or arc. For details concerning these hazards, see AWS F4.1, "Recommended Safe Practices for the Preparation for Welding and Cutting of Containers and Piping."

Jacketed Containers and Hollow Parts

There are some similarities between the hazards of cutting or welding jacketed containers or other hollow workpieces and hazards of cutting or welding containers. Air confined inside an unvented hollow part will expand when heated and pressure will increase. Since hot metal rapidly loses its strength, the container or hollow piece could burst with explosive force at the focus of the cutting or welding work. Be suspicious of closed metal parts that seem unusually light. Drilling a vent hole before heating the part may be necessary (Figure 9.6.8).

Hot Tapping

Occasionally, there are situations in which emergency repair or the complete impracticality of emptying and cleaning demands welding or cutting on a container while it holds flammable gas or liquid (e.g., a natural gas transmission pipeline or utility distribution system). Schemes to accomplish such hot tapping with relative safety have been developed. (See ANSI B31.8, *Gas Transmission and Distribution Piping Systems,* and API Publ 2201, "Procedures for Welding or Hot Tapping on Equipment Containing Flammables.") Needless to say, any such work must be performed only by specially trained and qualified staff, using recognized and authorized methods.

Public Exhibitions and Demonstrations

Special and enhanced fire safeguarding is necessary when welding or cutting is performed at trade shows and exhibitions. Characteristically, places of public assembly, such as auditoriums and hotel exhibit halls, and concentrations of people are involved. When welding or cutting work is planned in such exposures, the fire department must have prior notification, operations must be under the control of a qualified person, gas cylinders must be

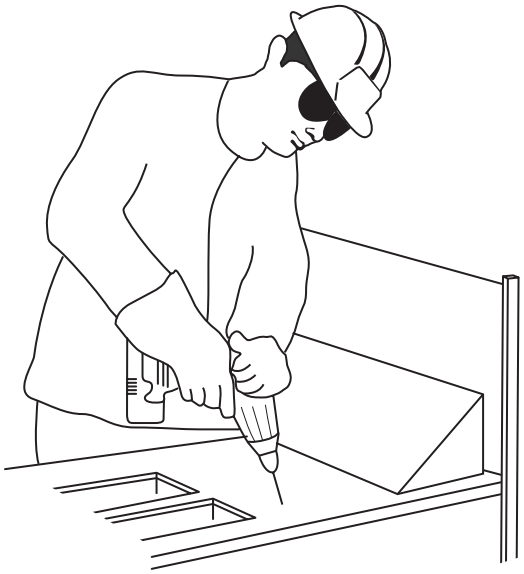

FIGURE 9.6.8 Vent Hole Drilling

charged to only one-half their maximum permissible content, storage sites for gas cylinders must have special restrictions, and fire-extinguishing equipment must be appropriate to the situation.

Personnel Protection and Ventilation

One aspect of welding and cutting fire protection that is sometimes overlooked or inadequately considered is the safety of the operator, helpers, or nearby workers. Flame-resistant gloves and clothing, aprons of leather or other durable flame-resistant material, cape sleeves or shoulder covers with skull caps under helmets or with goggles for overhead work, leggings for heavy work, and high-top safety shoes are generally recommended. Trousers should not be turned up or cuffed on the outside, front pockets on clothing should be eliminated, and sleeves and collars kept buttoned to prevent sparks from entering and lodging in such places. Outer clothing should be free of oil and grease. Cotton clothing may be worn if the cotton is chemically treated to reduce its combustibility (Figure 9.6.9).

Adequate ventilation must be provided wherever welding, cutting, and other hot work are performed to protect the operator from inhaling noxious gases and fumes. Potentially hazardous materials might exist in certain fluxes, coatings, and filler metals. In some cases, general natural draft ventilation is adequate. Other operations require forced-draft ventilation, local exhaust hoods or booths, or personal respirators or air-supplied masks. A good reference for additional information on personal protective equipment (PPE) and ventilation is ANSI Standard Z49.1. It also contains a great deal of general safety information on welding, cutting and allied processes.

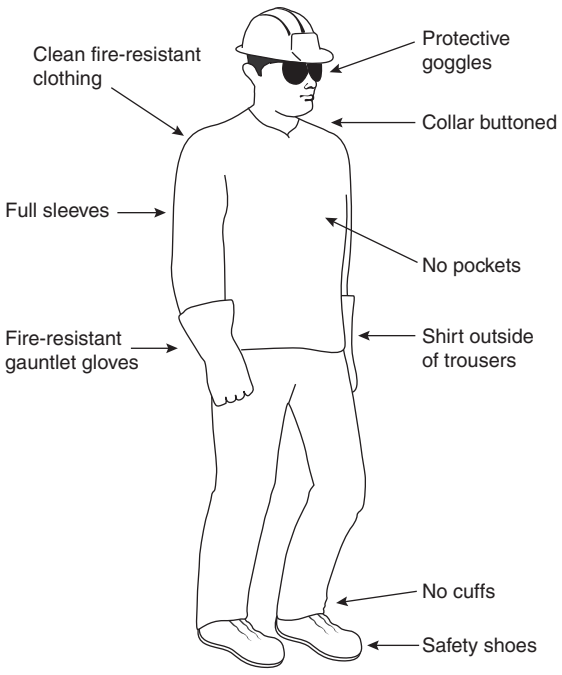

FIGURE 9.6.9 Welder Protection

Oxygen, since it accelerates combustion, must never be used to cool the worker, ventilate a confined space, or dust off clothing. Tests and experience have shown that oxygen-saturated clothing or clothing in an oxygen-enriched atmosphere will literally burn in a flash, with extremely serious and sometimes fatal results.

Manufacturers' Recommendations

Procedures given in manufacturers' instructions for setting up, connecting, lighting or starting, adjusting, and maintaining equipment have specific, safety-oriented purposes. These procedures should be followed. In addition, precautions and safe practices publications with valuable information about fire and personnel safety are available from equipment suppliers.

SUMMARY

Hot work includes welding, cutting, and allied processes that are capable of producing a spark, flame, or heat. Because it is not possible to cover all of these processes, this chapter has focused on the more common ones. First discussed were processes using electricity, such as arc welding, resistance welding, flash welding, electroslag welding, and arc cutting. Next oxyfuel gas processes were described, including oxyfuel gas welding, brazing and braze welding, surfacing, oxyfuel gas heating operations, and oxyfuel gas cutting. Then thermal spraying was discussed. The second half of the chapter examined the recommended safeguards and fire prevention considerations that should be undertaken, including the handling and storage of equipment and various work area precautions. Although the potential for hot work fires is great, education, training, and on-the job practice can reduce the potential significantly.

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4. *Specifications for Rubber Welding Hose,* IP7, Rubber Manufacturers Association, Washington, DC, and Compressed Gas Association, Arlington, VA.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for welding, cutting, and other hot work discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 51, *Standard for the Design and Installation of Oxygen–Fuel Gas Systems for Welding, Cutting, and Allied Processes*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*

NFPA 70, *National Electrical Code®*
NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations*
NFPA 306, *Standard for the Control of Gas Hazards on Vessels*

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CGA P-1, "Safe Handling of Compressed Gases in Containers," Compressed Gas Association, Arlington, VA.
NEMA EW-1, "Electric Arc Welding Power Sources," National Electrical Manufacturers Association, Washington, DC.

Chapter 7

Storage and Handling of Grain Mill Products

Revised by
James E. Maness ■ Lee M. Sargent

Chapter Contents

Modern Elevator Design
Raw Materials
Storage
Handling
Elevators
Dust Control
Fire Hazard
Explosion Hazard
Safeguards

Key Terms

bucket elevator, conveyor, dust collection system, dust explosion, grain, grinding, oilseed

The grain industry includes the movement, storage, and processing of grains—such as wheat, corn, oats, and sorghums—and oilseeds—such as soybeans and sunflower seeds. The industry can be separated into two broad segments: (1) grain elevator operations and (2) millers or processors. Grain elevators are facilities that receive, store, and distribute whole grains and oilseeds for direct use, process manufacturing, or export. Grain elevators receive directly from the farmer and can be classified as either "country" or "terminal" elevators, with terminal elevators further categorized as inland or export facilities. Their end product is virtually identical to their raw material, with only minimal cleaning, drying, and blending and, in some cases, fumigation to preserve and meet product quality standards. Grain millers and processors, on the other hand, take whole grains as their raw material and process these into products, such as animal feeds and feed ingredients, cereals, flour, starch, meal, vegetable oils, corn sugars, and brewery products. The discussion that follows is primarily aimed at the grain elevator segment of the industry and those portions of grain milling and processing that handle and store grains or dry milled products.

For related topics, see Section 2, Chapter 8, "Explosions"; Section 6, Chapter 8, "Dusts"; and Section 17, Chapter 8, "Explosion Prevention and Protection."

MODERN ELEVATOR DESIGN

The growth of the grain industry in the United States has paralleled the phenomenal growth in production, consumption, and export of grains and oilseed products. This growth has been the result of many factors, the most important of which is the ideal temperate climate of the United States for producing these agricultural commodities. The favorable climate combined with the mechanization of farming, the development of high-yielding hybrids, the use of fertilizers, the free market system, and uniquely efficient storage and transportation systems have affected the growth. Table 9.7.1 indicates the dramatic rate of growth in harvested grain and oilseed crops.

In the last three decades there has been much consolidation of the industry, resulting in fewer facilities operating at greater efficiency handling and processing larger crops at a faster rate. Table 9.7.2 gives the structure and productivity of various sectors of the U.S. industry in terms of the number of facilities and their capacity and/or production.[1] All sectors shown in Table 9.7.2 handle grain and grain products and generally have a grain elevator portion in their operations. Figure 9.7.1 shows a major export elevator in the New Orleans, Louisiana, area. The facility was built in the early 1980s to replace a facility that had a major explosion. Many new design concepts were used, including elimination of bucket elevators and use of inclined belt conveyors, and elimination of the headhouse and use of turnheat distributors rather than bin galleries.

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Lee M. Sargent, P.E., is chair and chief executive officer of Todd & Sargent, Inc., an Ames, Iowa, based company which specializes in the design and construction of feed mills, flour mills, grain elevators, and similar structures. An Iowa State University civil engineering graduate, Mr. Sargent chairs NFPA's Technical Committee on Agricultural Dusts.

TABLE 9.7.1 Production of U.S. Grains and Oilseeds in Thousands of Bushels

Year	*Corn*	*Wheat*	*Soybeans*	*Total (1000 bu)*
1950	3,131,009	1,026,755	287,010	4,444,774
1955	3,184,836	938,159	371,276	4,494,271
1960	4,352,668	1,363,443	558,778	6,274,889
1965	4,084,342	1,315,613	845,608	6,245,563
1970	4,151,938	1,351,588	1,127,100	6,630,626
1975	5,828,961	2,122,459	1,547,383	9,498,803
1980	6,641,841	2,374,306	1,792,062	10,808,209
1985	8,875,453	2,424,115	2,099,056	13,398,624
1990	7,933,068	2,738,574	1,921,787	14,685,000
1995	7,374,000	2,186,000	2,152,000	14,961,463
2000	9,968,358	2,223,440	2,769,665	15,907,212
2005	11,112,072	2,104,690	3,086,432	16,303,194

For SI units: 1 bushel = 0.0352 m^3.
Wheat is 60 lb/bu.; soybean is 60 lb/bu.; corn is 56 lb/bu.
1 metric ton = 2240 lb.
Source: National Agricultural Statistics Service, U.S. Department of Agriculture.[2]

TABLE 9.7.2 U.S. Grain-Handling Facilities and Capacities as of June 2001

Type of Facility (Commercial)	*Estimated Number of Facilities*	*Annual U.S. Characteristics (Estimated for each industry segment)*
Grain elevators		
Country elevators	10,835	198.8 million tons storage capacity
Terminals	700	42 million tons storage capacity
Export elevators	60	9.3 million tons storage capacity; 120,000 tons/hr handled; exports 115 million tons of commodities
Soybean crushing	93	Crushes 50 million tons of soybeans; daily crush 143,000 tons
Cottonseed crushing	35	Crushes 4.93 million tons
Sunflower crushing	7	Crushes 4,755 tons/day capacity
Feed mills	6,723	Produces 164.7 million tons of feed
Wheat flour mills	237	Mills 31 million tons of wheat; daily production capacity 75,000 tons of flour
Dry corn mills		
Degerminating	15	Grind capacity 3.78 million tons of corn
Full seed	55	Grind capacity 280,000 tons of corn
Wet corn mills	24	Processes 33.6 million tons of corn; produces 15 million tons of corn sweeteners
Total no. of facilities	18,784	

For SI units: 1 ton U.S. = 0.907 ton metric.

The awareness of dust explosion hazards has caused a transformation in the design and construction of grain elevator facilities during the last 20 years, from the totally enclosed concrete structured headhouse (which contains much of the handling and cleaning equipment) to construction of open towers. This awareness has greatly increased because of (1) the severity and frequency of explosions that occurred in the late 1970s and early 1980s,[3] (2) grain industry efforts to research the causes and prevention of grain dust fires and explosions, and (3) the promulgation of the Occupational Safety and Health Administration (OSHA) rule 29 CFR 1910.272 regarding grain-handling operations. Figure 9.7.2 shows the results of a dust explosion at a Houston, Texas, area export elevator in 1976. The facility had two headhouses—one at each end of an array of concrete silos. The building in the foreground was a bagging shed. Figures 9.7.3 and 9.7.4 show the results of other dust explosions.

Information and new concepts learned about grain dust fires are reflected in NFPA 61, *Standard for the Prevention of*

FIGURE 9.7.1 Export Elevator, New Orleans, Louisiana

FIGURE 9.7.2 Damage to a Major Export Elevator in the Houston, Texas, Area

FIGURE 9.7.3 Destructive Explosion and Fire at This Council Bluffs, Iowa, Facility in 1981

FIGURE 9.7.4 Explosion at a Burlington, Iowa, Facility in 1987, Causing Extensive Damage and Leveling the Headhouse

Fires and Dust Explosions in Agricultural and Food Products Facilities, which combines four NFPA standards used prior to 1995, that is, NFPA 61A, NFPA 61B, NFPA 61C, and NFPA 61D.

RAW MATERIALS

Grain and oilseeds consist primarily of starch or carbohydrates, protein, fiber, and various vegetable oils, all capable of burning under very specific conditions. In their raw, whole-kernel states, these commodities are stable and not readily subject to combustion if protected from moisture, insects, and fungi. So-called spontaneous combustion is a product of microbiological spoilage created by fungi combined with certain levels of moisture and temperature.[4] The incidence of this source of ignition of fires and explosions in grain elevators is rare, although it has been known to occur. Good grain industry practice is to store grains at moisture and temperature levels that keep the grain from deteriorating, thus minimizing the possibility of spontaneous combustion.

The probability of fires and explosions at grain-handling facilities is directly related to the increase in the amount of starch and other particles that are released when grain kernels are broken either during handling or processing. For example, artificial drying of corn can introduce stress cracks into the corn kernel, which leads to increased breakage during subsequent handling. Unless controlled, this breakage can result in increased levels of grain dust in the grain and can increase the risk of fires and explosions during grain operations.

As size reduction of the grain kernel proceeds, the susceptibility to fires and explosions increases dramatically.[5] The frequent handling of grain from farm to consumer progressively creates more broken kernels and, hence, more dust. Reduction in particle size also occurs as an integral part of the milling and processing operations.

Since grain is essentially handled as a bulk commodity, the economies of scale continue to dictate larger and more automated handling units. The grain is normally transported in bulk by truck, rail, barge, and ship. Only a small fraction of the grain is bagged, consisting primarily of seed stocks and bagged commodities for export to a few emerging nations that are not equipped to discharge bulk vessels.

STORAGE

There are numerous types and configurations of bulk grain storage facilities. Structures that consist of upright concrete silos, wood bins, steel silos, and steel tanks can generally be unloaded using gravity flow. A combination of traditional elevator design with new concepts to help minimize explosions and limit damage is shown in Figure 9.7.5. The concrete elevator is a traditional headhouse with concrete silo complex. However, bucket elevators have been extended outside and vented. Steel tanks with conveyors are used to store grain. The gallery above the bins houses enclosed drag conveyors.

In addition to conventional warehouse structures, there are structures, referred to as flat storage, which do not totally empty by gravity and require manual labor or special power equipment to remove residual grains. Further, outdoor temporary piles are used during harvest periods to store the grain. Many facilities serve a multipurpose function, including the operation of other related agricultural businesses, such as seed and fertilizer distribution.

The size of the storage structure is determined by the nature of an individual facility's operation. Individual bins may range from 1000 bushels (35.2 m^3) to 2,000,000 bushels (70,400 m^3) or even larger. The largest single facility has a total storage capacity exceeding 45,000,000 (1,524,000 m^3) bushels.

Grain temperature systems are often used to monitor grain temperature and quality and to detect spontaneous heating at facilities that store grains for long time periods. In addition, storage systems are often equipped with aeration systems to help maintain grain temperature, moisture content, and quality.

FIGURE 9.7.5 Combination of Traditional Elevator Design with New Concepts to Minimize Explosions and Limit Damage

HANDLING

The primary function of a grain handler, other than storage and quality preservation, is conveying grain horizontally and vertically into and out of the storage facility. Conveyors common to most bulk handling industries are used in this process. The following discussion shows how these conveyors are used in the grain industry and highlights modified designs tailored to grain industry needs.

Belt Conveyors

The most common conveyor employed to move grain horizontally from point to point is the trough-belt conveyor. By virtue of the wide choices of speeds and belt widths available, any desired volume, within reason, can be accommodated in this manner. Belt conveyors are used to meet large production capacity needs, often exceeding 20,000 bushels per hr (bph) (700 m^3/hr) upwards to 80,000 bph (2800 m^3/hr) at large export elevators. Belt conveyors are generally highly reliable with low maintenance requirements. The fire hazards associated with these conveyors are the combustible rubber belting material, the tendency of dust to be liberated at grain transfer points (belt to belt or to other equipment or storage), and mechanical failure due to poor maintenance. The fire hazard can be reduced with the use of flame-resistant belting[6] and good maintenance procedures. The dust hazard can be mitigated with the use of enclosures, aspiration, belt speed control, or a combination of these. Newer designs often totally enclose the belt with critical bearings kept outside of the enclosure. These designs control the dust by containment and aspiration.

Chain Conveyors

Alternatives to the belt conveyor include the *en masse,* drag, or chain conveyors, which are totally encased in a housing that prevents the escape of dust. These are usually of more limited capacity and convey at reduced linear speeds with much deeper grain depths. Normally, only the loading point or discharge point needs to be aspirated. Their higher energy use (than belt conveyors), increased maintenance, and installation costs are major factors when considering drag conveyors for use.

Screw Conveyors

The helical screw conveyor is a standard for low-volume conveying for short distances. The grain industry generally uses screw conveyors for handling materials such as dust or small product streams. A major drawback to screw conveyors is that they can cause damage to whole grain, adding to grain breakage.

Bearing failure is also a prime concern and requires periodic inspection and lubrication.

Pneumatic Conveyors

The milling portion of the industry uses pneumatic conveying systems extensively. These are especially effective for confinement and movement of finely ground commodities in a complex processing operation requiring multipoint pickup or distribution. There can be some concern about static electricity buildup and discharge if the systems are not properly grounded and maintained.

ELEVATORS

Bucket Elevators

The common principle used in grain elevator design is that of elevating the commodity to the highest optimum point, then permitting the material to flow by gravitational force down through the various garners, hopper weighing scales, cleaners, and finally through spouts into storage compartments (Figure 9.7.6). Use of gravity flow not only makes efficient use of the energy required to move the mass, but eliminates re-elevating and rehandling, which can cause increased breakage and damage to the kernel or seed. Grain quality is often monitored by using automatic grain samplers to collect representative samples during gravitational grain flow. Each subsequent rehandling contributes to reducing the quality of the grain and generation of additional quantities of fine particles and dust. The bucket elevator (or "leg" as it is referred to in the industry) is the primary equipment used to gain these elevations. Inclined belts have been used in several large terminals, but are often impractical for most smaller facilities because of the large amount of land they require.

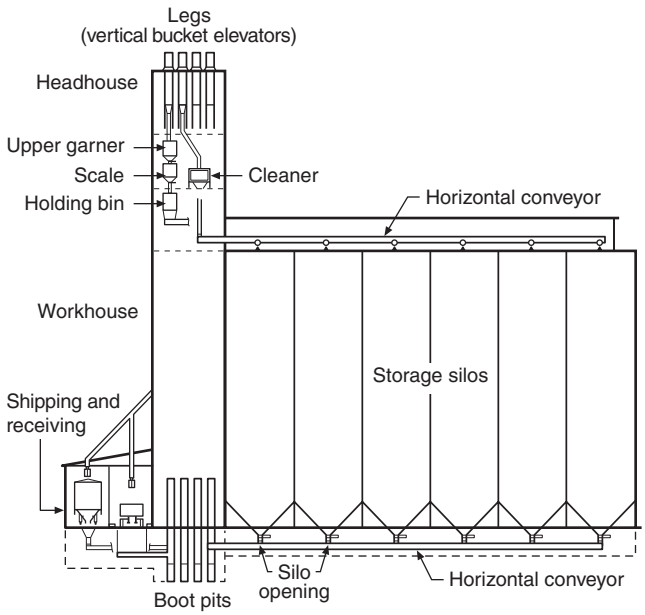


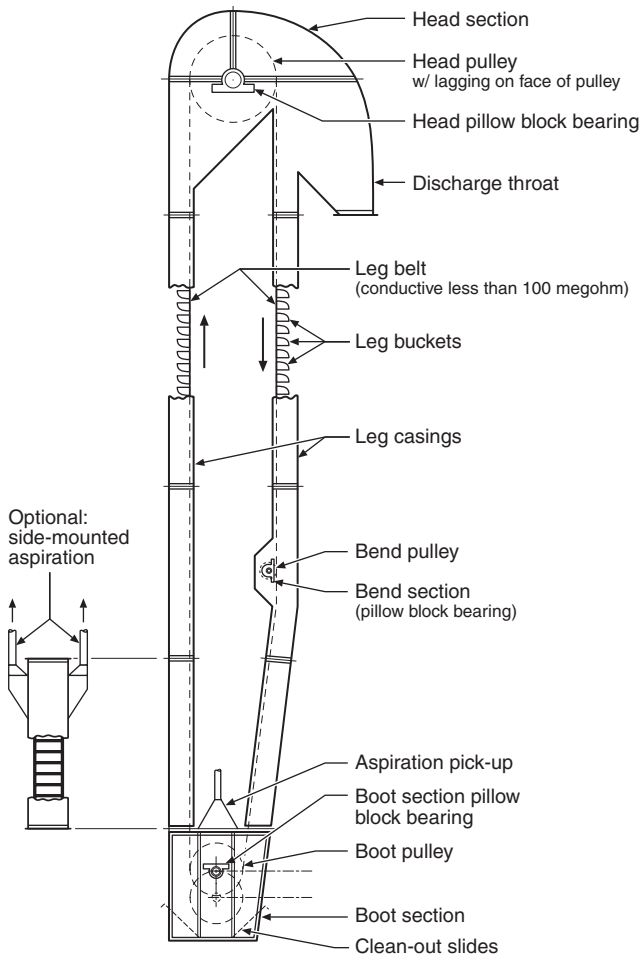
FIGURE 9.7.6 Traditional Concrete Elevator Design

The bucket elevator is the workhorse of the industry and requires special attention as an explosion hazard. The dust concentration within a bucket elevator is likely to be above the minimum explosive concentration (MEC) in some portions of the bucket elevator during normal operations. This combined with the pumping action of the buckets moving in a confined enclosure, mechanical components that can fail (bearings, alignment, etc.) and the high amount of mechanical energy inherent in its operation have led to its identification as the principal ignition source in explosions.[7,8] For these reasons, it is becoming industry practice to locate new bucket elevators outside of totally enclosed headhouse structures (Figure 9.7.7). (NFPA 61 contains explosion venting recommendations for outside-located bucket elevators.) Where "legs" cannot be installed outside, they can be provided with deflagration venting to the outside or be equipped with explosion suppression in addition to other safety devices (Figure 9.7.8).

Spouting and Lining

Grain and oilseeds are very abrasive and can rapidly erode steel conveying spouts used to channel the flow through elevators. For very long grain drops, a grain-retarding device (dead box)

FIGURE 9.7.7 Outside Free-Standing Bucket Elevators with Steel Tank Storage



Notes:

1. Capacity can be a few hundred bushels per hr to 60,000 bushels per hr (2100 m^3 per hr).
2. Belts can have multiple rows of buckets (metal or plastic, plastic is preferred) across them.
3. Take up can be gravity or screw style.
4. Capacity is belt speed x bucket capacity.
5. Head pulley is normally lagged.
6. Legs can be in excess of 200 ft (60 m) tall.
7. Legs interconnect the entire headhouse when placed inside.
8. Slow motion devices are used to detect overload for belt slippage.
9. Bearing and alignment rub blocks with thermocouple establishes temperature monitoring.
10. Casings and head sections can be vented when leg is outside. Head sections of inside legs can often be vented to the outside.

FIGURE 9.7.8 Bucket Elevator

can be used to slow down the grain and reduce breakage and dust generation.

The abrasive nature of grain creates an almost constant demand for maintenance to eliminate leaks and dust emissions. While patching and repair are adequate temporary measures, they seldom fully restore a spout. An alternative has been the wide use of abrasion-resistant liners that can be totally replaced without disrupting the outer spout. Materials most commonly used are abrasion-resistant alloy steel plates and high-density synthetic plastics (most frequently used), such as polyethylene or urethane, and certain ceramics. These can usually be formed or molded to the contour of the spouts and bolted into place without the need for welding or other heating devices. Although the high-density plastics are not easily ignited, they can burn and must be removed or protected whenever welding or cutting is conducted on the spout.

Shipping and Receiving

The first and last adjuncts to a grain storage elevator are the machinery and structures needed to unload or load the grain from and into a carrier. Wherever a truck, railcar, barge, or ocean vessel shipping/receiving system is used, these operations are at ground level, partly or completely in the open, and usually connected to the main storage structure with an underground tunnel beneath the discharge receiving hopper or with an overhead bridge.

The free-fall of grain through open spaces into receiving hoppers presents a unique dust control problem influenced by surface winds and the lack of sufficient enclosures to contain the dust emission. The problem is less of an explosion or fire hazard than a nuisance, as the dust can fly about, since the operation is essentially an open-air one. Environmental laws and regulations have required the same attention to these ground-level emissions as to elevated sources of emissions, which can present greater concerns.

Grain Drying

The principal processing operation at most grain elevators is that of drying the grain to moisture levels low enough to preserve quality during storage or to meet grain standards. Many types of dryers are used in the industry, with batch dryers or continuous flow dryers being the most common. Continuous flow dryers are either column (which allow continuous flow of grain through a screened column while hot air is passed perpendicular to the grain flow) or rack dryers (where grain flows down an air plenum with hot air flowing up through the cascading grain flow) (Figure 9.7.9).

The typical modern grain dryer is direct-fired, that is, the heat of the burned fuel is directed into a stream of air that is passed directly through the moist grain. The fuels used are principally natural gas, fuel oil, or vaporized liquid propane. Although dryers are designed to minimize fire hazards, inadequate maintenance and improper operations can result in ignition of the grain being dried. Examples of causes of these fires are the failure to properly and frequently remove excessive accumulations of dust and combustible materials from the inside of the dryer or the occurrence of blockages to the flow (such as a broken bucket from a "leg"), allowing the grain to overheat.

The resulting "hang-ups" and overdried materials and particles readily ignite when burner temperature gets too hot or small embers are entrained in the plenum air. The multiple severe grain dryer fires and explosions of 20 to 25 years ago have not recurred, reflecting the installation of a number of safety devices and improved operating procedures.

Ideally, a grain dryer should be housed in a structure completely removed from the storage facility. Inside-located bulk

FIGURE 9.7.9 Commercial Column Grain Dryer

grain dryers are prohibited by OSHA in 29 CFR 1910.272(p), unless located in a separate fire area or protected by explosion suppression. Dryers must also be equipped with certain automatic safety controls that shut off fuel for power failure, provide flame or exhaust air movement interruption, and stop the feed to the dryer if excess temperature occurs in the exhaust section of the dryer. The grain is fed to the dryer from an elevated source, and returned from the dryer to storage in a second separate conveyance for distribution into silos. Locating a direct-fired dryer away from the storage unit itself, as well as good operating procedures, minimizes the risk of more serious fires or explosions within the silo structure. In cases where a dryer serves solely to heat grain without cooling, the hot grain is often cooled in the storage silos by fans forcing ambient air up through the grain mass until air-temperature equilibrium is reached. (See Chapter 8 of NFPA 61 for additional dryer recommendations and requirements.)

The grain temperature typically should not exceed 150°F (65.5°C) in a drying operation (corresponding to a hot-air drying temperature between 180 and 200°F [82 and 93°C]), thus avoiding heat damage to the kernels.[3] As the wet grain is heated, the evaporating water at the surface of the kernels has a cooling effect that prevents the kernels from overheating. The heated air leaving the dryer is in a near-saturated state, and some coarse dust and fine particles can escape with it.

Grain Cleaning

Another important activity in some grain-handling facilities is scalping and cleaning of grain through the use of aspiration and/or screening systems to remove extraneous material from the grain, such as bits of stalks, stems, seed pods, husks, corn cobs, weed seeds, or fine broken grain particles. These materials not only affect the quality of the grain but are also more prone to ignition than the grain itself by virtue of their extremely dry state and high fiber content. In some cases, green weed seeds and plant particles can cause additional heating concerns. The grain is cleaned by passing it over vibrating, rotating, or gyrating screening devices or stationary gravity screens for simple size separation. A positive air aspiration system can be used prior to the screening system. Aspiration is often used to remove dust generated by the grain movement within screen-type cleaning systems. Fires associated with cleaners can occur due to lack of maintenance and components coming loose and rubbing, causing frictional heat.

Grinding and Cracking

Some grain facilities serve specialty industries that require grain to be cracked or ground. This entails the use of hammer mills or grinders to accomplish the size reduction, particularly in feed, processing, or milling operations.

Hammer mills can be sources of fires and dust explosions, which can be transmitted through aspiration connections. The hammer mill is frequently used to grind corn and other feed grains in preparing feeds. Care must be taken to remove foreign objects, especially stones and metallic objects, from entering the grinding mechanisms with the use of screening and magnetic devices.

DUST CONTROL

Supplementing the conveying, elevating, drying, screening, sampling, weighing, and storage activities is the dust control process. Each point of grain transfer and handling can produce suspended dust. A complete dust control system at an elevator consists of a combination of methods, such as proper and periodic housekeeping, good maintenance to prevent grain leaks in equipment and spouting, the enclosure of grain-handling equipment to prevent the escape of dust, the reduction of grain-handling speeds, and the use of active dust control provided by mechanical dust collection systems to reduce fugitive emissions. In some cases, oil additives have been sprayed on grain to help reduce grain dust emissions during handling.

Mechanical dust collection continues to be the primary means used to control fugitive dust emissions. The dust collector most commonly employed is the "baghouse" or fabric filter, wherein the dust-laden air is passed through filter media and exits virtually dust-free (up to 99.99 capture efficiency). The dust is recovered in the filter housing, stored in a remote bin or tank, and can sometimes be sold as a by-product of grain for use by the animal feed industry. Often the dust must be given away to avoid disposal and freight costs. Most often the dust is returned to the grain stream in such a manner so as not to create additional airborne dust. However, at export facilities, dust returned to the grain is prohibited once it has been placed in a storage bin or tank. Mechanical dust systems are complex processing operations with self-cleaning devices for the bags, automatic discharge mechanisms, and continuous conveying to disposal points or storage tanks.

The cyclone collector was commonly used prior to clean-air laws, but is used less frequently for controlling dust emissions. Nevertheless, they continue to be relied on for preventing product losses and serve as a separator for dust aspirating systems. Cyclones are not as efficient in capturing smaller particle emissions. Collection efficiencies vary greatly, ranging up to 80 percent for low-efficiency cyclones and up to 95 percent for high-efficiency cyclones. For fine particles, efficiency is only 50 to 60 percent. The cyclone is still often used in conjunction with some dust systems by being located ahead of bag filters to remove and recover very large particles for re-entry into the grain or product streams. The remaining fine dust particles are then collected in bag filters for disposal or for readmission into the operation where circumstances and practices permit.

Dust collection systems can be a fire hazard because they concentrate the dust in specific pieces of equipment and can serve as a path for flame or explosion transmission to interconnecting equipment and areas. For this reason, dust filters should be located outside and should be equipped with deflagration vents to minimize possible damage should an explosion occur. Alternatively, dust systems can be located in separate explosion-vented rooms or be equipped with explosion suppression systems.

Dust systems must be periodically inspected for proper operation. Pressure gauges are often installed to monitor the performance of the unit. Excessive pressure drop across the bags can indicate that filter bags need to be changed or cleaned out. Low pressure can indicate a broken bag or improper operation of the unit.

FIRE HAZARD

Although dust explosions receive the most attention and awareness regarding hazards at grain-handling facilities, there are a number of other fire hazards at these facilities. Fires are much more numerous than dust explosions. Fires often precede a dust explosion; ignition sources include improper welding and cutting, failed bearings, overheated or failed electrical equipment, and mechanical failures.

Fires can occur in nearly any area of a grain facility, particularly where potential ignition sources are present, such as motors, drives, bearings, and electrical equipment. Areas of grain facilities where fires might occur include the dryer, motor control rooms, bucket elevators, conveyors, storage bins, grinding or milling areas, and offices. Potential fuel sources for fires in grain-handling facilities vary depending on construction, equipment, and types of operations.

Generally speaking, grain facility structures are constructed of noncombustible materials, such as concrete and steel. Older facilities may have some wood construction.

The following materials can serve as fuel sources at grain handling facilities: dust, grain, grain screenings, plastics, lubricants and grease, fabric cloth materials, rubber belts, polyvinyl chloride (PVC), conveyor and bucket elevator belting, roofing materials, propane and natural gas, and electrical wiring coverings. Many of these materials are not peculiar to the grain industry and, in fact, are common in most industrial facilities. However, grain dryer fires, conveyor belting fires, bucket elevator fires, and grain fires provide unique fire challenges. Fire challenges can be dealt with as described in the National Grain and Feed Association's publication, entitled *Emergency Preplanning and Firefighting Manual: A Guide for Grain Elevator Operators and Fire Department Officials.* Some typical considerations and factors to consider for several types of grain facility fires are discussed below.

The grain dryer's most potentially severe fire hazard is that of igniting the grain or grain dust and extraneous material that has accumulated on ledges and surfaces inside the dryer. The large amount of heat needed—in some dryers, more than 20,000,000 Btu/hr (21.12 million kJ/hr)—combined with the large size—up to 80 ft (24.4 m) high—requires good operating procedures and proper maintenance of safety devices, such as temperature sensors, UV flame detectors, limit switches, and fuel cutoff devices.

In addition to the preventive measures used to reduce the possibility of a grain dryer fire, each elevator must have an emergency plan for dealing with a fire. The size and unique design of a grain dryer make fighting the fire with hose streams difficult. Probably the most effective consideration in fighting a dryer fire is moving the burning grain to a safe area away from the elevator where water can be selectively applied. In some cases, small smoldering fires in dryers can be removed manually by shoveling the smoldering material into a bucket and removing it to a safe location. For modern grain dryers, a means can be provided for unloading (emergency dumping) of the dryer contents to a safe location so a fire exposure is not created for adjacent buildings, structures, or equipment. One common method is to place a door or chute on the dryer discharge conveyor for emergency dump purposes.

The hazard of grain itself igniting must also be addressed from a preventive, as well as a fire fighting, standpoint. Preventive measures are basically to keep open flame (e.g., welding, torch cutting, cigarettes) and hot surfaces or objects away from the grain. Once grain ignites, it can become quite difficult to extinguish and, if the extinguishing method creates a dust cloud, an explosion is likely. A permit system should be used to control hotwork, such as welding and cutting. The application of large amounts of water in a storage bin will not only deteriorate the grain, but, in the case of soybeans, could cause enough swelling

of the soybeans to rupture the bin itself. A bucket elevator fire is of great concern, since internal dust concentrations can result in a dust explosion. Elevator management should consider meeting with local fire departments to review emergency procedures should a grain fire occur.

Conveyor belting fires are difficult to deal with because of the intensity of the fire and the amount of smoke and vapors given off. Belting fires once ignited are difficult to put out and require large amounts of water to control. If a belting fire cannot be extinguished, consideration can be given to cutting the belt and dropping it to isolate the fire and prevent it from spreading.

Grain bin fires can be particularly difficult to deal with depending on the fire's location and the quantity of grain involved. Bin fires should be approached as a potential explosion hazard. Air sources, such as aeration fan openings and portals, should be sealed off to limit the source of oxygen. If water is applied into the bin, a fog spray is recommended to wet down the dust on top of the bin, including any accumulations under the bin top roof, being careful not to create a dust cloud. Small surface fires can be extinguished using a fog nozzle and removed from the top manually or with the use of a pneumatic evacuator. Fires on the top surface of grain in concrete silos can be controlled by using carbon dioxide to blanket the top of the grain. However, the use of carbon dioxide to extinguish deep-bedded fires is often not successful. If burning or suspect grain is allowed to flow from the bin, it should be directed to the outside by spouting or conveyed to the outside using portable augers or evacuators. Suspect grain should never be handled in bucket elevators or other enclosed equipment. Deep-bedded fires in grain bins or inside large grain storage structures can be the most difficult to deal with because of the amount of grain to be handled and the difficulty of locating and accessing the fire. If a pipe or hose can be probed to the fire area, it is possible to apply water to that portion of the grain mass. It is nearly impossible to apply water to the grain surface to put out deep-bedded fires, and the application of excessive amounts of water can create structural hazards and can destroy grain that can otherwise be reclaimed. In large flat structures, it might be possible to remove the grain with mobile equipment (front-end loaders) or to selectively unload portions of the grain mass to access the fire.

In all cases of dealing with a grain fire in storage structures, a careful plan should first be established to deal with such fires, following these principles: (1) stop the grain flow; (2) seal off all openings that allow oxygen to reach the fire, including shutting down aeration or roof exhaust fans; (3) use fogging nozzles to wet down dust and grain; (4) do not allow high-pressure water streams to be applied that could create dust clouds; (5) carefully consider how suspect or burning grain will be removed from storage; and (6) do not needlessly expose anyone to the fire or a dust explosion hazard.

Another potential fire hazard in grain elevator operations is the use of propane and natural gas. Both are used for grain drying or comfort heating. They present a serious fire hazard in grain operations because of the presence of below-grade areas in grain elevators and because the heavy rail or truck traffic can cause deterioration in underground pipes. If a break occurs, the gas or propane vapors can seep into the below-grade tunnels until discovered or ignited. Elevator management should insist that such gas and propane lines be installed according to NFPA codes, and maintained regularly.

EXPLOSION HAZARD

Dust explosions must certainly be considered the number one hazard in the grain industry. The first recorded grain dust explosion incident is reported to have occurred in 1785.[5] However, recognition of dust explosions was not common until the late 1800s. Figure 9.7.10 shows the number of dust explosions, injuries, and deaths that have occurred from 1976 through 2005. Figure 9.7.11 indicates a trend that the incidence of dust explosions and their severity have continued to decrease from 1976

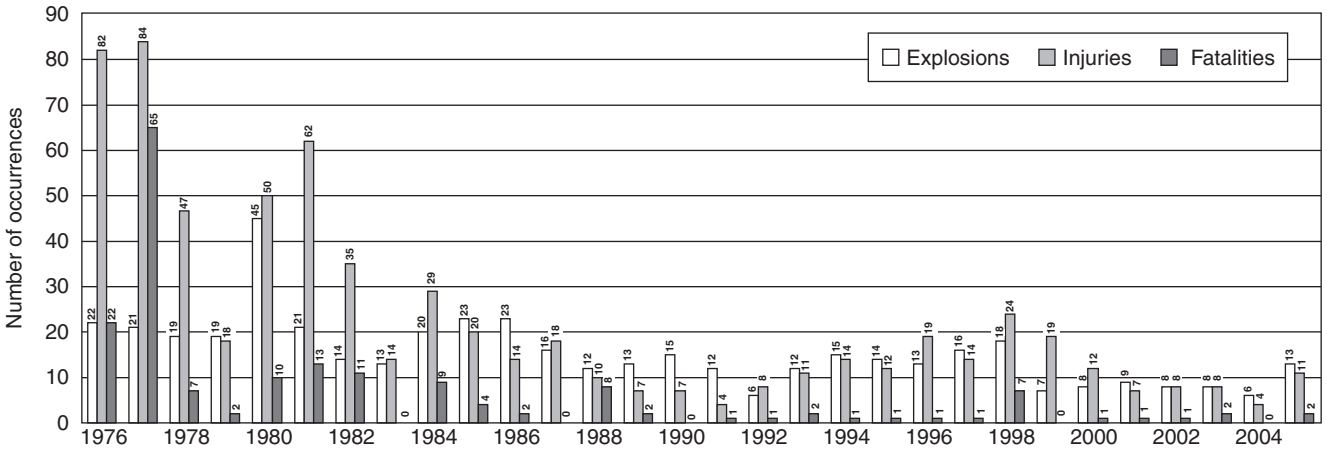


FIGURE 9.7.10 U.S. Agricultural Dust Explosions, 1976–2005 (Source: Schoeff, R. W., Kansas State University, in cooperation with FGIS-USDA)

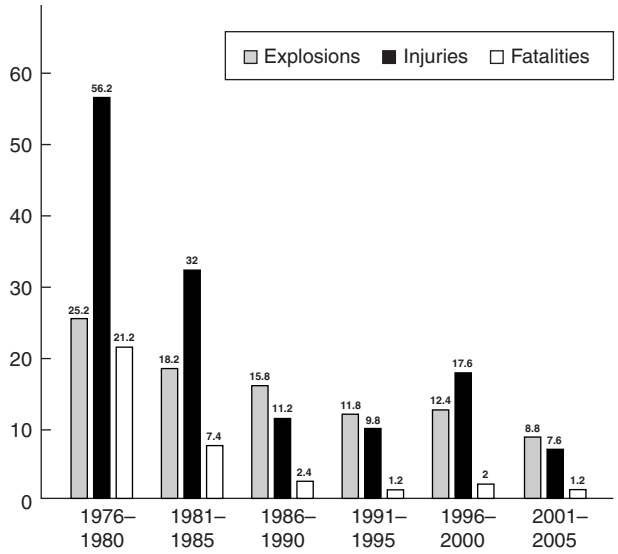


FIGURE 9.7.11 U.S. Agricultural Dust Explosions in 5-Year Increments, 1976–2005 (Source: Data compiled from Jacobsen et al.[9] and Lilienfeld[10])

through 2005. Table 9.7.3 shows the locations of primary dust explosions, indicating that bucket elevators, storage bins, hammer mills, dust collectors, and enclosed equipment are the areas where explosions often initiate. Figures 9.7.2 through 9.7.4 show the severity and type of damage that can occur from grain dust explosions.

Explosion Characteristics

Secondary explosions occur when the primary explosion pressure wave disturbs dust layers, creating a dust cloud that is ignited by the flame front, causing a more severe and damaging explosion. The flame front travels much slower than the pressure wave, which may allow reaction time to avoid fire and explosion hazards. Table 9.7.4 indicates the probable ignition sources that have been identified in the past explosions. Welding and cutting operations, fires, overheated bearings, and electrical failures are among the most frequent explosion ignition sources. An analysis of available information for dust explosions during the period from 1958 through 1995 is presented in Table 9.7.5. Incidents during the time period between 1995 to 2000 appear to show similar trends for probable location and cause of the primary explosion, but evaluation of available data has not yet confirmed this.

Research on Explosions

As a result of increases in grain dust explosion incidents and fatalities in the late 1970s and early 1980s, the industry, through the National Grain and Feed Association, established a Fire and Explosion Research Council to increase the industry's understanding of known causes of explosions and to conduct research into the basic factors contributing to grain dust explo-

TABLE 9.7.3 Probable Location of Primary Dust Explosion, 1958–1978, 1984–1985, 1988–1989, 1991, and 1992–1995

Location	*No. of Facilities*	*Percent of Facilities*
Unknown	146	41.2
Bucket elevator	105	29.6
Storage bins or tanks	19	5.4
Hammer mills, roller mills, or other grinding equipment	18	5.1
Dust collector	14	3.9
Other areas inside elevator	12	3.3
Other areas inside equipment	11	3.0
Headhouse	9	2.5
Adjacent or attached feed mill	8	2.2
Grain dryer	3	0.8
Inside electrical equipment	2	0.6
Outside and adjacent to facility	2	0.6
Pellet collector	2	0.6
Tunnel	2	0.6
Other	2	0.6
Sample size	355	100.0

Source: Data for 1958–1978 from U.S. Department of Agriculture.[11] Data for 1984–1995 from Schoeff.[12]

TABLE 9.7.4 Probable Ignition Sources, 1958–1978, 1984–1985, 1988–1989, 1991, and 1992–1995

Source	*No. of Facilities*	*Percent of Facilities*
Unknown	154	43.4
Welding	51	14.4
Fire other than welding or cutting	22	6.1
Overheated bearings	17	4.7
Miscellaneous	15	4.3
Tramp metal	13	3.6
Friction sparks	13	3.6
Other spark	12	3.3
Electrical failure	12	3.3
Unidentified foreign objects	10	3.0
Friction from choked "leg"	8	2.3
Lightning	7	2.0
Faulty motors	5	1.5
Extension cords in "legs"	4	1.2
Static electricity	4	1.2
Fire from friction of slipping belt in "leg"	3	0.8
Rubbing-pulley	3	0.8
Smoking material	2	0.5
Sample size	355	100.0

Source: Data for 1958–1978 from U.S. Department of Agriculture.[11] Data for 1984–1995 from Schoeff.[12]

TABLE 9.7.5 Grain Dust Explosion Factors

Type of Facility Involved in Explosions		Commodity Handled at Time of Explosion	
Facility	*Percent*	*Commodity*	*Percent*
Grain elevators	65.5	Corn	49.5
Feed mills	15.3	Sorghum	7.3
Corn processors	6.2	Wheat	7.3
Flour mills	3.1	Soybeans	5.2
Rice mills	2.8	Rice	4.7
Others	7.1	Corn starch	3.6
		Barley	2.6
		Others	19.8
Total	100.0		100.0

sions. This research has revealed a number of options for helping to prevent explosions and created a better understanding of their causes. Major accomplishments of research included better guidelines for venting of explosions in bucket elevators and the use of explosion suppression systems to control bucket elevator explosions. Figure 9.7.12 shows a dust explosion test of a bucket elevator conducted by Fenwall, Inc., for the National Grain and Feed Association in 1979. Vents were located along the "leg" casing and in the head section. The testing determined venting criteria to be used on bucket elevators. Also tested was the use of explosion suppression systems. Explosion venting of grain bins and grain galleries was also studied, resulting in a better understanding of explosions of these structures. Figure 9.7.13 shows a dust explosion test conducted in Norway by Dr. Rolf Eckhoff. The research tested explosion venting of grain bins. The large fireball, at the top, shows the initial venting. The flame beginning to come out of the right side shows the bin splitting open on the side. This illustrates the difficulty of venting elongated grain bins. Because of their large length to cross-sectional width or diameter ratio, these structures are difficult to explosion vent, except for mild or limited explosions.

Bearings were identified as a significant factor in dust explosions, requiring good maintenance practices. Metal sparking and electrostatic sparking were also studied. The research showed that electrostatic sparks were not generally a problem, except under special circumstances where there was high charge generation and poor grounding. The major problem with metal sparking was determined to be high-speed grinding equipment and frictional sparks from mechanical failures or objects becoming lodged in equipment. In addition to the above, the research focused on identifying design methods that could be used to help minimize grain dust explosions.

Elements of a Dust Explosion

The elements of a grain dust fire or explosion are almost axiomatic; namely, that to be initiated and sustained there must be fuel, oxygen, and an ignition source. To have an explosion,

FIGURE 9.7.12 Dust Explosion Test of a Bucket Elevator

a fourth element, confinement (which confines the rapidly expanding heated gases of combustion within a constraining enclosure until the pressures exceed the ultimate strength of the enclosure), is necessary (Figure 9.7.14).

The precise circumstance under which an explosion of a grain dust will occur is a complex combination of dust particle size; concentration in the air (oz/ft^3 [g/m^3]); the energy of the ignition source; and less easily determined factors, such as the moisture content of the dust (or percent relative humidity of the air) and the actual composition of the dust. Dust from each agricultural commodity has its own explosion characteristics. Although researchers have not agreed precisely on the limits of the various characteristics of a particular dust, their conclusions are generally within an acceptably narrow range. Studies of explosibility of agricultural dust show that the minimum explosive

FIGURE 9.7.13 Dust Explosion Fire Testing Explosion Venting of Grain Bins

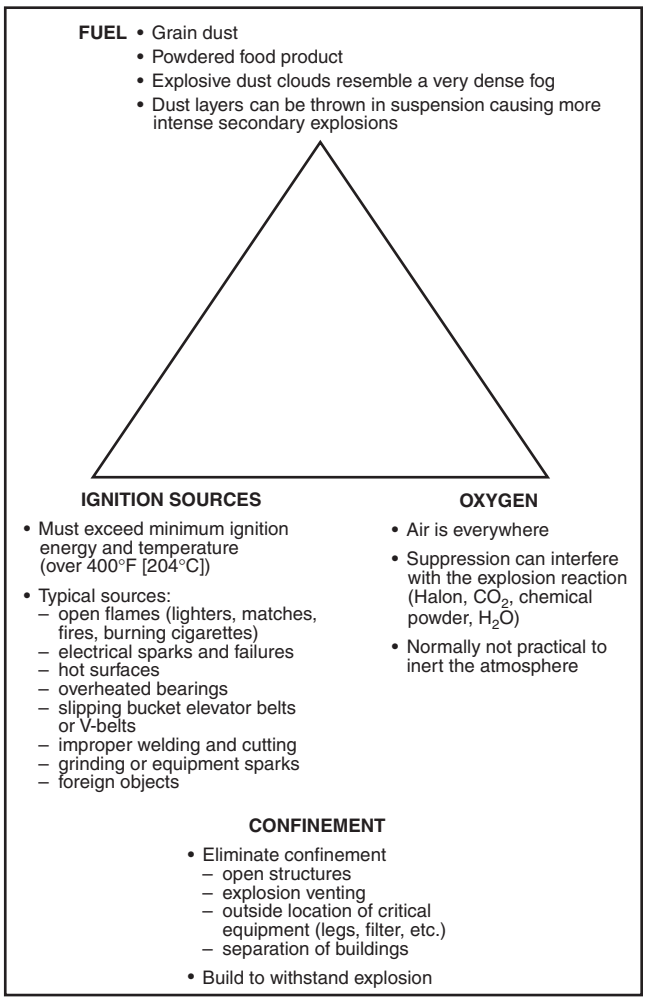


FIGURE 9.7.14 Dust Explosion Elements

concentration needed for an explosion ranges from 0.025 to 0.5 oz/ft^3 (25 to 500 g/m^3).[9] Grain dust generally varies from 0.025 to 0.055 oz/ft^3 (25 to 55 g/m^3) (Table 9.7.6). Suspended dust concentrations of this type represent a severely dense cloud through which a 100 W light bulb cannot be seen at a distance of approximately 9.8 ft (3 m) or one's hand cannot be seen at arm's length. Such dust concentrations make breathing extremely difficult. Some of the highest dust concentrations occur inside bucket elevators, grain bins, scale garners, and other enclosures. Maximum explosive pressures can exceed 100 psi (690 kPa), with the maximum rate of rise of pressure approaching up to 8500 psi/sec (58,608 kPa/sec), which is an indication of the intensity and speed of a grain dust explosion. When the rate of rise of pressure is higher, explosions are more severe.

Fuel. Dust particles emanating from various emission points within a grain elevator are of varying composition and of a wide range of sizes. It is generally agreed by researchers that particle sizes below 100 microns constitute the greatest hazards.[10] A considerable portion of the dust within the elevator environment is smaller than 100 microns. Larger particles tend to settle out rapidly (Table 9.7.7).

Although it seems improbable that such a dense cloud would exist within the ambient space of an elevator structure where personnel are present, such concentrations have been measured within the confines of bucket elevators and can also occur in conveyor housings, bins being loaded, silos, dust collecting systems, and connecting spout work.

The mechanism of an explosion depends on the immediate heat release of a burning particle to ignite and support the burning of adjacent particles.[5] As this rapid spread of flame proceeds from particle to particle, pressure waves and thermal expansion of the air can create an intense shock sufficiently strong to rupture the typical reinforced concrete structure. In studies performed by the U.S. Bureau of Mines,[9] the maximum pressures for corn dust are greater than 100 psig (gauge pressure of 690 kPa). Concrete structures found in elevators can usually withstand no more than 25 psig (172 kPa). Most grain-handling

TABLE 9.7.6 Dust Explosibility Properties

Material	Lower Explosive Limit (g/m^3)	Minimum Ignition Energy (J)[a]	Minimum Ignition Temperature (°C)		Maximum Explosive Pressure (psi)[b]	Maximum Rate of Pressurize (psi/sec)[b]
			Cloud	Layer		
Coffee	85	0.16	410	240	44	500
Corn	45	0.04	400	250	95	6000
Corncobs	30	0.04	400	190	110	5000
Grain (Mixed)	55	0.03	430	230	115	5500
Soy	35	0.05	520	190	99	6500
Sugar	35	0.03	350	220	91	5000
Wheat	55	0.06	480	220	103	3600
Wheat Starch	25	0.02	380	210	105	8500
Flour	50	0.05	380	360	95	3700
Coal, Pittsburgh	55	0.06	610	ND	83	2300

[a]1 cal = 4.187 J.
[b]1 psi = 6.895 kPa.
ND = Not determined.
Source: Lilienfeld.[10]

TABLE 9.7.7 Size Distribution

Dust size (μm)	Dump Pit (Mostly Beeswings) Retained on		Belt Loading (Mostly Starch Dust) Retained on		Main Elevator (60:40 Mixture Beeswings, Starch) Retained on		Beans Dust Retained on				
	%	% cum	%	% cum	%	% cum	%	% cum	Mesh	in.	mm
+150	94.8	94.8	—	—	56.0	56.0	16.0	16.0	+100	—	—
150–100	3.7	98.5	—	—	11.3	67.3	12.1	28.1	100	0.0059	0.150
100–74	1.1	99.6	—	—	7.0	74.0	13.4	41.5	150	0.0041	0.104
74–38	0.4	100.0	—	—	6.0	80.0	9.2	50.7	200	0.0029	0.074
38–21	—	—	31	31	6.0	86.0	16.3	67.0	450	0.0017	0.043
21–16	—	—	28	59	5.0	91.0	16.0	83.0	630	—	—
16–8	—	—	22	81	4.0	95.0	11.0	94.0	937	—	—
8–6	—	—	10	91	3.0	98.0	4.0	98.0	1,875	—	—
6–4	—	—	3	94	2.0	100.0	2.0	100.0	2,300	—	—
4–2	—	—	2	96	—	—	—	—	4,500	—	—
2–1	—	—	3	99	—	—	—	—	6,250	—	—
0–1	—	—	1	100	—	—	—	—	12,500	—	—
Total	100.0	—	100.0	—	100.0	—	100.0	—	—	—	—

Source: Matkovic.[13]

equipment enclosures fail at pressures less than 6 psig (gauge pressure of 41.4 kPa).

Suspended dust is not the only fuel with which to be concerned. Dust accumulation on floors, walls, rafters, and equipment can become suspended if disturbed by vibration, fires, or small explosions. If this accumulated dust is suspended in sufficient concentration, the resulting explosive dust concentration can become ignited and progress into an explosion. This resuspended dust can encompass large volumes and propagate explosions through an entire elevator. This illustrates the importance of keeping overhead surfaces and ledges clean of excessive dust accumulations.

Ignition Sources. The second most important element of a grain dust explosion is ignition of the suspended dust cloud by a source of energy of sufficient intensity and duration. One ignition source is improper use of welding and cutting equipment. Other potential ignition sources include fires and heat caused by the frictional energy of mechanical equipment, such as bucket elevators, bearings, and belt drives. Heat or arcing caused by the failure of electrical equipment, such as lighting, motors, and wiring, has also been identified as an ignition source. Miscellaneous ignition sources include open flames from matches or smoking, space heaters, lightning, and internal combustion engines on vehicles such as industrial trucks.

Torches and electric arcs used for hot work represent one of the most intense energy sources used at grain facilities. These sources can quickly ignite dust and construction materials. Welding and cutting is also a concern in the grain industry, because many elevators do not have full-time maintenance personnel. This results in unsupervised contractors performing welding operations within the grain elevators. These contractors might be unfamiliar with the fire and explosion potential of grain dust and need to be monitored by elevator management. A formalized hot work welding and cutting work permit should be established to help control hot work operations.

The majority of known locations of explosions in grain elevators stem from the bucket elevator, so it would follow that this single piece of equipment presents the most serious ignition hazard to the grain handler.[7,8] This conveyance produces ignition energy in a number of ways. Overloading or stalling of the belt generates intense frictional heat on the revolving drive pulley. This has been known to burn the belting to the point of failure, allowing the severed and flaming pieces to drop within its housing. Failure of belt splices could lead to the same results.

Misalignment of belts can cause the "leg" casing to become hot enough to ignite combustible materials, such as dust or lubricants. The misaligned belt itself probably does not get hot enough to ignite while it is moving, since it has the chance to cool as it moves, but might ignite after the equipment is turned off and the belt is stationary next to the hot casing.

Another potential ignition source associated with bucket elevators is overheating bearings. Some older conveyor designs have tail or head pulley bearings located inside of the casings. If these bearings overheat, they can provide sufficient heat for ignition of static or suspended dust. Even bearings located outside of casings can ignite layered dust, which can be drawn into the "leg" casing by the dust collection aspiration or the "air pumping" action of the "leg" itself.[7]

Extraneous foreign material, such as scrap metal, tools, wood, stones, or pieces of concrete, is also a concern within a bucket elevator. Such material might or might not produce sparks with sufficient energy to ignite dust, but certainly can result in plugged spouts, damage to the belting, or deformation of the elevating buckets. When this occurs, the chances of belts stalling or continuous frictional rubbing are increased. The use of grating to reduce foreign objects from entering the grain receiving pit and subsequent handling equipment is common at most facilities. Most grates are set 2½ in. (63.5 mm) apart, with varying lengths of the opening. The grate size can be adjusted for the commodity; for example, a smaller opening can be used for wheat than for soybeans in southern locations or for receiving corn cobs. Many processors, millers, and grain export facilities rely on magnets on the receiving grain stream to capture tramp metal.

Nonconductive belting moving over the pulleys in bucket elevators can create significant static electricity on the buckets. Research indicates that sufficient energy to initiate a dust explosion is not released from this static discharge, but prudent practice is to reduce this static accumulation by using electrostatically conductive belting and good grounding practices.[14] OSHA calls for belting to have a surface resistivity less than 100 megohms. Rubber belting has typical resistivity of 1 megohm, and PVC belts are typically 15 megohms in resistivity.

The energy inherent in electrical systems is extremely high, but can be minimized as an ignition source by strict adherence to the provisions of NFPA 70, *National Electrical Code*® for the appropriate hazardous area classification. For areas that have an exposure to higher levels of airborne and layer dust, electrical equipment is normally rated as explosion proof for Class II, Division 1, Group G areas. Other areas can be rated for electrical equipment that is suitable for Class II, Division 2 (dust-tight), Group G locations. Many in the industry choose to utilize electrical equipment that has a dual rating for Class II, Divisions 1 and 2, Group G areas to avoid the problem of the wrong equipment getting in an area. The importance of proper electrical equipment applies to both fixed and portable equipment. This consideration is important for portable electrical devices, lighting, low-voltage control circuitry, extension drop-lights, and communications equipment.

Oxygen. The oxygen concentration required for a dust explosion is the same as that found in the atmosphere. Using inert gases in equipment to reduce the oxygen concentration enough to prevent explosions has been suggested, but has limited application due to the large size and volume of grain-handling equipment. Processing equipment, such as hammer mills, may be more likely candidates for inerting.

Confinement. As with all dust explosions (except detonations), the pressures generated after ignition of a grain dust explosion increase until the fuel or oxygen is consumed or until the explosion is vented. If there is no confinement (i.e., unlimited venting), explosion pressures are minimal and the incident should more properly be called flash fire. On the other hand, as confinement increases, the explosion pressures can build up to levels over 100 psig (690 kPa). Grain elevator structures and equipment cannot withstand pressures anywhere near these levels, so considerable damage will occur, unless these pressures can be vented. Due to structural considerations, most existing grain elevators would be nearly impossible to retrofit with adequate venting, but newly designed elevators are adaptable to increased venting and the resulting reduction in explosion confinement. Deflagration venting must be done to the outside of the facility to avoid secondary explosions or danger to personnel. Although the levels of recommended venting are not always possible, some venting is better than no venting when feasible to help eliminate pressure development during an explosion.

An alternative to deflagration venting is explosion suppression, during which a chemical is injected into equipment during the early stages of explosion development to stop the process. The chemical can interfere with the combustion reaction, or inert the environment (CO_2), or cool the process with a water spray. Suppression systems can be specifically engineered for a piece of fixed equipment.

The construction of structures and equipment that can totally contain an explosion is generally not practical, with the exception of hammer mills, which can often withstand the explosive pressures. However, the transmission of pressures and flames to connecting equipment can present explosion problems.

The only other means of dealing with confinement is to provide separation between buildings and structures to help minimize the propagation of an explosion. NFPA 61 recommends that a separation of 100 ft (30.5 m) be provided between personnel-intensive areas and concrete elevator headhouses and silos. Some exceptions are allowed, based on the location of bucket elevators (outside), type of construction (damage limiting), or property size. The concept of separation can be taken into account for major modifications or new facilities, but is often impractical for existing facilities.

SAFEGUARDS

Building Design

NFPA 61 can assist designers of grain-handling facilities. The standard devotes considerable attention to the physical structure. NFPA 61 is not intended to apply to existing facilities, which might have been constructed prior to its publication; however, major modification or expansion made to an existing facility should enhance safety to life and property. The following discussion summarizes industry trends concerning the design of new facilities.

The traditional design approach to grain elevator facilities has been to construct upright storage silos of reinforced concrete or steel. The facility has a high contiguous structure known as a headhouse, with inside-located bucket elevators to elevate the grain high enough to pass through necessary scales, samplers, garners, cleaners, and distributors by gravity into the storage bins. Figure 9.7.6 illustrates the traditional grain elevator design. Structures are constructed of noncombustible materials. There has been a constant evolution of facility design to meet the larger grain productions and to be able to handle higher flow rates with more automation. Higher throughput facilities have evolved to load unit trains in excess of 100 railcars (3300 bushels [119 m^3] per railcar) or several barges (up to 60,000 bushels [2160 m^3] each) a day. Equipment has also changed to meet these new demands. Facility owners have also been concerned with safety and the elimination of fire or dust explosion hazards and make changes, as resources permit.

Modern design has moved toward the elimination of the enclosed elevator headhouse.[15,16] Bucket elevators are placed outside the facility or inside structural steel or reinforced concrete frameworks to eliminate the element of confinement (Figure 9.7.15). The bucket elevators then elevate the grain to the top of storage to distributors that connect to turnheads, which spout directly into bins or to enclosed conveyors, which move the grain to bins, eliminating the enclosed gallery above the bins (Figures 9.7.16, 9.7.17, and 9.7.18). Some large terminals, particularly export facilities, have used inclined belt conveyor systems in lieu of bucket elevators (see Figure 9.7.1). These incline designs convey the grain to separate weighing and cleaning towers. Enclosures, such as dust collectors, bucket elevator housings, and ancillary structures, are often designed to relieve explosion pressure waves as much as possible, should such an incident happen. This is not always physically possible, because of the very nature of the configuration of the enclosure.

FIGURE 9.7.15 Open Tower Structure and Deflagration Relief Venting in Corpus Christi, Texas, Public Elevator

FIGURE 9.7.16 Headhouse Concept Eliminated in This Superior, Wisconsin, Elevator

According to NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* numerous methods have been proposed for calculating the vent area for an enclosure. Some venting models have used the surface area of the enclosure as a basis for determining vent area. Analysis of available data shows that such methods overcome certain deficiencies of previous methods of calculating vent area.

The use of doors, windows, multiple explosion-relief panels, and light-gauge structural coverings on steel structures is a

FIGURE 9.7.17 Naples, Illinois, Terminal Elevator Company with Deflagration Venting Technology Incorporated on Bucket Elevators and Headhouse Structure Left Open on One Side

practical approach to an acceptable design. Stairwells and elevator shafts, where they are enclosed, should be protected with approved fire doors.

Fire walls of approved design can be provided to separate the grain-handling function from adjoining grain-processing operations, such as flour milling, preparation for oil extraction, feed milling, or grinding. Where tunnels, basements, or other underground structures can be avoided, the alternate use of ground-level or aboveground structures can give opportunity for maximum openings to the atmosphere.

Where sufficient land area is available, the placement of structures for weighing, cleaning, and other operational functions can be remote from silo storage and interconnected with inclined belt systems.

All surfaces, bin bottoms, and spout inclinations should be designed to be self-cleaning when the grain or grain products flow. Structural ledges, beams, or other horizontal surfaces should be designed, where practicable, with an inclination of a minimum of 60 degrees from the horizontal to prevent gradual buildup of static dust. Where possible, design should accommodate the washing down of accumulated dust on vertical walls and overhead structures with water.

Where possible, the placement of bucket elevators, in open air, apart from the structure should be considered. Additionally, office buildings, employee break rooms, maintenance shops, inspection labs, and control rooms should be located remote from concrete structures when constructing new elevators.

Mechanical Design

Many devices are available to detect, warn, and control faulty operation of mechanical equipment or their components. Many of these systems were neither available nor sufficiently developed for use in Class II, Group G, dust atmospheres until recent years. Among them are hot-bearing sensors, speed indicators, alignment devices, level-sensing gauges, slowdown detectors, overflow alarms, and pressure gauges, all of which can serve to indicate or react to malfunctioning units. Particularly important among these are the speed indicator and alignment devices for monitoring bucket elevators. If properly designed, installed, and monitored, these devices can prevent ignition from stalled and rubbing belting.

A combination of mesh screens, grating, scalpers, or magnets will prevent large extraneous material and metal from entering into the grain handling machinery. Depending on individual elevators, permanent or electromagnets, large-mesh screening, grizzlies, and specific gravity separators might be appropriate. Their use is particularly important just prior to the point where the grain enters hammermills or other types of grinders.

FIGURE 9.7.18 Country Elevator in O'Neill, Nebraska, Featuring an Outside Located Bucket Elevator and Elimination of Gallery

Dust Control Measures

The need for adequate dust control has been established. Dust control in elevators, however, should not be limited to installation of dust collection systems, but should be a systematic approach to dust control. This systematic approach should include designs that limit the amount of dust liberated from the grain, mechanical dust collection at grain transfer points where dust occurs, containment of dust to selected points where mechanical dust collection can be effective, reduction of dust concentrations within equipment, maintenance of dust collection equipment, and manual housekeeping to complement mechanical dust control.

The design of dust collection systems must provide sufficient capture velocity at the point of emission, particularly at conveyor loading and discharge points. Design must also provide sufficient air velocity (typically between 3500 and 4000 ft/min [1068 to 1220 m/min]) within the ducts to prevent settlement of the particles and subsequent plugging. Blast gates and fresh-air inlet dampers are necessary to balance the airflow to all points served by the system so that starving of some remote emission points is avoided. Operators must understand the dust collection systems, so that they can monitor and maintain their effectiveness on a daily basis.

If a baghouse or fabric filter is used, the porosity of the filter media must be maintained to avoid diminishing the airflow. High humidity and fine dust particles can form a cake on the bags and reduce the air passage. In such instances, replacement or laundering of the bags is necessary (see NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids,* and NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids,* for further information on the application and design of air-moving systems).

Containment of dust to selected points or the proper return of the dust downstream of the capture point not only makes the mechanical dust collection system more effective, but also limits the amount of manual housekeeping effort needed to reduce accumulated dust.

Typical methods to reduce dust liberation from grain include reducing the distance and velocity grain is allowed to free fall onto conveyors or from spouting. (Choke feeding, where possible, is the best approach to limit grain velocity). Reduction of conveyor belt speeds and adequate belt tension can both be effective dust control methods where horizontal belt conveyors are used. Well-designed transition points that do not have abrupt changes in direction can also limit the amount of dust liberated from the grain. Additives, such as soybean or mineral oil, are used as an additional method to control dust.

Regardless of the facility design or amount of mechanical dust collection, manual housekeeping efforts are important in grain elevator facilities. Although safe levels of accumulated dust are impossible to determine, housekeeping programs at each facility should be designed to keep the dust accumulation at the lowest feasible level. This housekeeping program should focus on not only grain dust but also any type of combustibles to reduce the possibility of their providing an ignition source for a dust explosion. Good maintenance to spouts and other equipment leaking grain dust is also an essential element to explosion prevention. In addition, proper safety procedures must be followed to avoid ignition sources while blowing down overhead ledges. Some facilities use vacuum systems to clean overhead and floor areas in lieu of blow down or they use periodic wash down of some areas, such as reclaim tunnels. Further, new techniques are sometimes used to pressurize key areas of a facility to prevent dust from escaping the equipment.

Electrical Design

Electrical wiring and equipment in grain dust environments should be installed in accordance with the appropriate articles in NFPA 70. These articles need to be thoroughly understood by those installing or maintaining electrical equipment in a grain

elevator facility. Individual paragraphs in these articles cover equipment requirements for maximum surface temperature, transformers and capacitors, surge protection, wiring methods, switches/breakers, and so on; motors; ventilating piping; utilization equipment; lighting equipment; flexible cords; receptacles and plugs; signal and communication systems; live parts; and grounding. No attempt is made here to paraphrase these articles. The reader is encouraged to review the most current edition of NFPA 70.

Away from the technical requirements of NFPA 70, the development of economical and miniaturized electronic components for use in Class II, Group G atmospheres has made the operation and control of grain elevators more sophisticated and less labor intensive. Remote control of the entire facility from a centralized control center is now a reality in new installations. This technological advance has dictated the need for redundant detection of malfunctions, since people are no longer in an operating area to observe the minute-by-minute activity.

The more common safeguards include electrical interlocking to simultaneously shut down all activities in a sequenced fashion when one unit of a sequentially connected operation fails. Annunciator panels can display the exact cause of shutdown to the operator. Ammeters and load indicators can depict the exact weight being carried by conveying equipment. Spring-return pneumatic devices can activate shutdown conditions even in a total power failure. Fully electronic scales now safely transmit millivolt differentials, detected by a load cell or strain gauge, to a remote amplifier for direct conversion into information on weight.

Maintenance

A preventive maintenance program is essential not only to ensure trouble-free operation and to minimize breakdowns, but, in grain elevator facilities, it is also a critical safeguard for eliminating ignition sources. This preventive maintenance program should include lubrication of bearings, checking of belt splices, replacement of bent or missing bucket elevator cups, and the early remedy of leaking, worn-out spouting.

Dust filters should be checked frequently for plugging, excessive pressure drop, and worn or poorly sealed rotary airlocks. Ductwork in the aspiration system should be free of plug-ups and bent ducts, and blast gates should be opened or closed consistent with system balancing.

Electrical junction boxes should be kept closed and lighting fixture protective globes kept in place. Whenever maintenance work on the electrical systems is performed, qualified personnel should ensure that the power is disconnected or that hazardous dust concentrations are not present.

Welding and any other hot work should be rigidly controlled by facility management. The use of a written "hot work permit" is generally the best system to ensure that hot work is not performed in the presence of explosive dust concentrations. This is particularly important with contractors whose employees might not be aware of the dust explosion hazard.

Improved maintenance diagnostic equipment can also be effective in monitoring equipment that could become an ignition source for an explosion. This diagnostic equipment includes bearing temperature monitors, bearing vibration monitors, and infrared analysis of electrical and mechanical equipment.

Fire Control Systems

Grain elevators have few applications where traditional automatic sprinkler systems would provide much protection. The nature of the explosion hazard is such that, even if sprinklers are installed, the lines would likely be ruptured by the shock waves. Additionally, explosions are normally initiated so rapidly that fusible links would have insufficient time to react. Combine this ineffectiveness with the lack of combustibles present and the catastrophic damage that could result from water leaks sweeping into grain storage bins, and it becomes clear that general-purpose automatic sprinkler systems would do little to mitigate damage from an explosion hazard. There are, however, several specific applications where sprinklers, fixed water spray nozzles, and explosion suppression systems can be effective. Strategic location of fire extinguishers throughout the facility and near major potential ignition sources, such as major drive units, is important to allow personnel to deal with small incipient fires before they create more serious concerns.

Wood elevators, which have a significant fire hazard potential, as well as the explosion hazard, are the major exception where automatic sprinkler installation can be justified. Additional specific applications where sprinklers or fixed water spray nozzles can have some benefit are (1) within the drive pulley enclosure of bucket elevators; (2) at remote, elevated belt gallery structures where manual fire fighting would be impossible; (3) in some tunnel areas where access is difficult; and (4) within some grain dryers in which, because of design, it would be impossible to use hose streams effectively.

Explosion suppression offers the grain industry a possible tool to reduce the number of explosions. Explosion suppression technology (i.e., rapid detection of incipient explosion and immediate introduction of suppressing agent) has been used effectively in other industries for some time. Recent research efforts directed at applying the technology to the grain industry have resulted in the development of self-contained explosion suppression devices that are suitable for installation on bucket elevators.[17] Application of hose streams within an elevator where the possibility of a dust explosion exists must be a well-considered endeavor. Any application of high-pressure water or use of a fire extinguisher that disperses accumulated dust must be avoided to prevent an airborne dust concentration that could be ignited.

SUMMARY

Much of the preceding discussion is a reiteration of concepts and principles known by the grain-handling industry. The devices, systems, and machinery now available are much more extensive than in earlier years. There are over 10,000 grain elevators in the United States, ranging from crossroad country stations to newly constructed export facilities. Many of these newer facilities have incorporated the devices mentioned above.

In spite of this, grain dust explosions still occur although at a lower incidence rate than in past years. In many instances, the

exact location of the primary explosion and ignition source are not precisely known. However, this much is known: the initial explosion has the characteristic of transmitting pressure waves, vibration, and air movement throughout the facility, which could result in other deposited dust being thrown into suspension. This additional dust might have been lodged on the ledges, beams, walls, floors, and inaccessible places and is exposed to the progressing flame front. The result is a series of additional explosions known as secondary explosions.[18]

In summarizing the potential hazards associated with the handling and storage of grain, one must remember that dust is a powerful fuel. Constant awareness and proper training of all who work in the facilities is essential to continue the recent trend of reduced numbers of explosions. Prudent consideration of the inherent dangers requires respect, care, and adherence to building codes and regulations in the design and construction of each facility. Once the facility is built and operating, each day requires positive management appreciation of the inherent dangers, and action to ensure that all those working in the facility understand the basics of proper operations, maintenance, safety, housekeeping, and training.

If it is assumed that some dust will always be present within the grain elevator facility, the elimination of the explosion hazard can only be accomplished by controlling the dust and removing its ignition sources.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the storage and handling of grain mill products discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 31, *Standard for the Installation of Oil-Burning Equipment*
NFPA 36, *Standard for Solvent Extraction Plants*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 54, *National Fuel Gas Code*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 72®, National Fire Alarm Code®
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA *101®*, *Life Safety Code®*
NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment*
NFPA 505, *Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operations*
NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*
NFPA 780, *Standard for the Installation of Lighting Protection Systems*

Chapter 8

Protection of Records

Revised by
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Chapter Contents

Storage Options
Damageability and Salvage
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Fire Risk Analysis
Fire Risk Reduction
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Fire Prevention and Emergency Planning
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Relevant Fire Experience

Key Terms

archives, bulk storage, Military Personnel Records Center, mobile shelving, open-shelf storage, records, records center, storage

Although the explosive growth in the use of personal computers promised us a "paperless office," the reality is a massive increase in the total volume of paper records that are generated, plus an acceleration of electronic records. This increase has intensified the problems involved in protecting records from fire. Traditional fire-resistive containers, such as insulated file cabinets, safes, and vaults, have not lost any of their capabilities to protect paper records. In fact, recent advances have introduced devices that can safeguard magnetic and photographic records. In many cases, however, the volume of records material has become so great that it is considered impractical to invest in either the devices or the space that is required to safeguard all the records to the level of protection that is justified. New methods of records storage have been developed that use the maximum cubic capacity of the area assigned to records storage. Some of these storage arrangements not only place the records at risk but also contain sufficient fire potential to be a danger to the structure and all other operations housed in it.

This chapter discusses ways of identifying and classifying valuable records to determine the amount of protection, justified by their value, against fire and its associated perils. The relative susceptibility of various records to flame, heat, smoke, and water exposure is discussed. Because water damage can be a serious by-product of fire containment efforts, information on salvaging water-soaked documents is provided. The different ways in which the risk of extensive loss of valuable records can be mitigated are considered. Protection against perils not associated with fire is not discussed.

Detailed discussions of the best ways to provide maximum reasonable protection for records are contained in NFPA 232, *Standard for the Protection of Records,* most recently updated in 2007. NFPA 232A, *Guide for Fire Protection for Archives and Records Centers,* was discontinued. The material suitable for enforcement or guidance has been incorporated into NFPA 232. Further information can be found in "Protecting Federal Records Centers and Archives from Fire,"[1] and the reference book *Protecting the Library and Its Resources.*[2]

Adequate provisions must be maintained for the safety of persons in records storage facilities. This can be a particularly difficult task when the facility is designed to provide maximum security of its contents against illegal entry. However, emergency exits are necessary to ensure life safety for persons in the records area in case of fire, even at some compromise in security.

For related topics, see Section 16, Chapter 5, "Sprinkler Systems for Storage Facilities"; Section 17, Chapter 1, "Carbon Dioxide and Application Systems"; Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems"; Section 19, Chapter 2, "Structural Integrity During Fire"; Section 20, Chapter 16, "Storage Occupancies"; and Section 20, Chapter 17, "Library and Museum Collections."

STORAGE OPTIONS

Bulk Storage

Bulk storage of records creates a fire hazard in itself. Bulk storage describes any sizable collection of records not contained in vaults, safes, or insulated cabinets. This includes collections of

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records ranging from small file rooms to the largest archives or records centers. Storage methods include, but are not limited to, file cabinets; various types of shelving, including open shelves and mobile shelves; palletized cardboard boxes; transport cases; miscellaneous cardboard boxes; and devices for unusually shaped records, such as blueprints, magnetic tapes, photographic film, and other media. Locations range from an area within a general office complex to specially built records facilities. It is not uncommon to house record collections in basements or attics of public buildings, in office buildings, in converted factory or warehouse buildings of various constructions and levels of quality, in public warehouses, underground, including storage in mines, and in facilities protected against war-time perils.

Open-Shelf Storage

The trend toward making the maximum use of available space in buildings has often resulted in using open-shelf storage methods, normally with the records held in either file folders or various kinds of cardboard boxes. Typically, the racks of records face each other across 25 to 30 in. (600 to 750 mm) aisles. The aisle exposure presents a wall of paper made up of the sides of boxes or loose ends of paper sticking out of file folders. They can be easily ignited by any ignition source, such as a match, a cigarette, a portable heater, faulty fluorescent ballast, or by an exposed incandescent lightbulb. Paper ignites at a relatively low temperature. Ignition of a few pieces of paper on a filing cart, for instance, can readily transmit ignition to the boxes.

Attempts have been made to develop economical methods for increasing the flame resistance of the typical records center cardboard boxes. A popular method is coating the box with an intumescent type of fire-retardant paint. Such paint, properly applied, will substantially delay actual ignition of the cardboard box material. However, since intumescent paint does not effectively react to heat under about 400°F (204°C), the temperature of any modest exposure fire (such as might occur on a file cart) will weaken the paper in the box to the point where the box will break open under the weight of the paper it contains and expose the ordinary combustible contents of the box to ignition.

An additional consideration for fire protection and storage professionals is the lack of control of the contents of the cardboard boxes used for storage. Typically the owner of the records to be stored packs the boxes off site. The boxes are then picked up, transported to the storage site, and placed onto shelves or racks by the storage provider. The boxes are most likely never inspected as to contents and arrangement. Regardless of any contractual requirements that may exist between the owner of the records and the storage provider, effective control of what is actually in the storage box is not with the parties responsible for storage and protection.

Full-scale fire tests were conducted in December 1974 in untreated boxes of paper records stored on open steel shelves 13 ft (4 m) high.[1] Sprinklers were adequate to control the fire, but the fire developed very rapidly anyway. From a small ignition source, flames reached the top of the rack in 4½ minutes. Eight seconds later, the facing array of boxes across the 30 in. (0.75 m) aisle flashed into flame from top to bottom. The first sprinkler had a 286°F (141°C) rating* and activated in a little more than 5 minutes. By then, the ceiling temperature directly over the fire had reached 1900°F (1038°C). The direct cause of the intense fire was rupture of the walls of the cardboard cartons and the release of the contents. Paper records exfoliated into the aisle and many burned while falling. A test was conducted with an identical arrangement, except that unboxed files were oriented perpendicular to the aisle, which exposed the edges of paper to easy ignition. In this test, fire spread at a leisurely pace and did not develop into an intense fire. The basic difference in the rate of fire growth between these two fire tests was that in the second test, the paper could not exfoliate into the aisle and no fire storm resulted. The progress of the fire can also be dramatically changed by changing sprinkler temperature ratings, response time, and sprinkler drop size characteristics.[3] Some sprinklers especially designed for fast response to fire exposure would be expected to reduce fire spread, heat rise, and extent of fire damage under similar conditions.

It is important to note that many agencies, both public and private, require that records stored on their behalf be oriented perpendicular to the aisles. However, effective control of the paper arrangement within the boxes is given to the individuals actually placing the files in the storage boxes. The people who develop economics associated with efficient box placement and storage configurations give little thought to the arrangement of the paper files within the boxes.

During a test conducted in December 1999[4] in 30 ft (9 m) high shelving, a single ½ in. (12.5 mm) 155°F (68°C) quick-acting in-shelf sprinkler controlled the fire, which at the time of sprinkler activation had a flame height of 12 ft (3.7 m) above the floor on each side of the aisle. Box fronts were failing and exfoliation of records was in process. The operating sprinkler was located above the lower catwalk, but flaming had not reached the lower catwalk; exfoliation had not started above the catwalk and falling paper was limited to the building floor.

This test was successful in meeting the test criteria of controlling the fire with considerably fewer destroyed records than allowed in the test criteria. It is quite possible that a rerun of this test could result in ignition and exfoliation above the catwalk and operation of two or three additional sprinklers and still have a perfectly acceptable outcome. Quick-acting water spray sprinklers are very well suited to controlling a records fire. The trickiest part is locating in-stack sprinklers so they are activated

*Bulk storage of records has generally been classified as warehousing occupancy and having little need of life safety provisions. Automatic sprinkler protection is usually optional. Prior to the Military Personnel Records Center (MPRC) fire,[1] the U.S. National Archives was setting a trend by providing sprinklers in new storage facilities and retrofitting existing facilities as funds became available. At that time, archivists were extremely nervous about installing water pipes above their valuable paper records. In the effort to alleviate their concerns, fire protection engineers offered sprinklers of low sensitivity (286°F [141°C]), which allowed larger fires to develop but were unlikely to operate accidentally on hot days. Such a system, designed to prevent fires from crossing aisles and jumping to the third row, was perfectly acceptable to archivists. Today, most archivists accept sprinkler protection as a given and show interest in low-temperature (155°F [68°C]) quick-acting sprinklers that may limit fire damage to 50 boxes or less.

by the strong thermal columns early in a records fire, while not having solid ceiling as a heat collector.

In other tests of high-piled storage conducted by Underwriters Laboratories Inc. (UL)[5] and tests of 6 ft (1.5 m) high archival shelving arrangements conducted by the GSA, the fire, at the end of an early and relatively short development stage, preheated a sufficient amount of the exposed boxes so that fire development characteristics changed suddenly, temperatures rose quickly, and the flame enveloped large areas. Neither of the tests involved exposed loose paper typical of systems with open-shelf filing.

In open-shelf storage, the close proximity of the opposing sides of the aisle can result in increased radiant heat feedback and flaming ignition of evolved gases across the narrow aisle. The severity and rapidity of fire development are accelerated by increased stack height and slowed by increased aisle width. Fire development is highly influenced by the amount of open space in the shelving; no means of estimating the effect of vacant space has been suggested.

Properly designed automatic sprinklers will control the fire, but factors that speed fire development and penetration increase the amount of information loss and the amount of irrecoverable damage.

Mobile Shelving

A class of storage devices, known variously as mobile shelving, track files, compaction files, moveable files, and so on, consists of open-shelf units mounted on tracks. In use, all of the shelves are pushed together except that one aisle is left open for access to two units. To access another unit, shelf units are moved on the tracks until access to the desired unit is gained. Units can be designed to move electrically or manually. The shelves that are pushed together form continuous horizontal tunnels through which fire can communicate, except where shelves are built with continuous transverse dividers. Mobile shelving containing combustibles should be protected by overhead sprinklers.

A fire in the open aisle of mobile shelving is similar to a fire in open-shelf storage of comparable height and is readily controllable by overhead sprinklers. When a fire elsewhere in the mobile shelving array is sheltered from sprinkler application, it is a deep-seated burrowing fire. Full-scale fire tests conducted in 1978 indicate that a fire in a tunnel formed by shelving can develop and spread very slowly. When shielded from direct sprinkler discharge, fire is likely to continue spreading through the entire array unless the shelf unit has internal metal dividers.[6] Although protection by sprinklers alone might permit fire involvement of the entire array, the fire is very likely to be confined to that single array. Overhead sprinklers provide adequate protection for a building containing mobile shelving and they prevent fire from jumping to other arrays.[7]

In addition to sprinkler protection, a smoke detection system is suggested in mobile shelving areas not continuously occupied to provide a fire warning well in advance of sprinkler operation. Early-warning smoke detectors can help limit the extent of fire damage in mobile shelving if skilled forces are quickly available during nonoperating hours.

The U.S. National Archives and Records Administration has opened a very large facility in College Park, Maryland, employing state-of-the-art mobile shelving. The facility is about 1.9 million ft^2 (176,500 m^2) in size, protected throughout with wet-pipe automatic sprinklers, augmented in records storage areas with smoke detection. Approximately 520 mi (840 km) of mobile shelves are provided for records storage. Typical shelving units are 8 ft (2.4 m) high and about 20 ft (6.1 m) in length. Shelves are electrically propelled, opening at the selected aisle, but during closed hours and during a fire alarm, shelves are automatically parked a few inches apart. Each shelf is thereby directly accessible to sprinkler water from overhead sprinklers that will operate by heat from a fire in the array. Smoke detectors ensure prompt response to an incipient fire and open the array to sprinkler control and extinguishment.

Automated Files

Program libraries (e.g., open-reel tapes, tape cassettes, etc.) are normally stored in a separate room adjoining a main-frame computer room. A code-conforming library has its own fire separation walls, protected openings, and separate fire extinguishing module(s). Program tapes are manually accessed. Automated file systems are in use, in which a relatively unlimited number of cassette-type programs or record tapes are stored in a series of modules within the computer room. At the command of the computer, a desired tape is mechanically accessed from storage, transported and installed in the proper slot in the computer, removed, and returned to storage. NFPA 75, *Standard for the Protection of Information Technology Equipment,* requires that these tape libraries, being a severe unprotected hazard to the computer and peripherals, be sprinklered internally.

Plastic Media

The combustibility or flammability of magnetic media and its containers is a prime concern when such media are stored in bulk quantities. Generally, acetate and polyester-based tapes do not present a hazard any more severe than paper. Polystyrene cases and reels, however, present a severe fire hazard condition because they have a high fuel value, a high heat release rate, and shed water. Storage systems designed to safeguard materials of cardboard or paper composition cannot be relied on to adequately protect materials involving large quantities of polystyrene. If the containers are made of another plastic, the condition might vary, although most thermosplastics exhibit similar properties. In any case, it is necessary to limit the height and extent of the storage of reels encased in plastic or to design special protection systems for them.

Fortunately, it appears that open-reel data storage is a declining technology, but huge quantities remain in storage and constitute a major self-exposure and exposure to other records. Computer records are being stored on an increasing variety of magnetic and optical media in widely varying formats. The main trend is the dramatic increase in information density each change involves. This factor has serious implications for the archivist, for fire prevention/control, and for the owner of the information. Loss of a records box or its volume equivalent filled with records

on paper would approximate the contents of a file drawer. Loss of an equal volume of CD-ROMs might represent the loss of an entire vault filled with paper records. The current format of DVD-ROMs is up to 70 times the data density of CD-ROMs. The increase in information density also implies that minor dimensional changes (e.g., due to slight overheating) could make the information forever unreadable. Even minor smudges can make some media unreadable until cleaned. It is evident that reasonable protection can be achieved only by storing duplicate records in widely separated locations not subject to a single fire.

DAMAGEABILITY AND SALVAGE

Ordinary paper records survive reasonably well when exposed to most of the effects of fire, except direct exposure to flaming. With rare exceptions, burned paper records represent a total loss, whereas a high recovery rate is practical where the records have been exposed only to water, high humidity, smoke, and moderately high temperatures of about 350°F (177°C). While exfoliated pages burn nearly instantaneously, packed paper files burn slowly at the edges. Prompt extinguishment of packed files leaves the information largely intact, and near total recovery of wet paper with charred edges is possible. Nonpaper records media tend to be more susceptible to damage than paper.

Photographic Records

Photographic records, whether they are on traditional acetate, glass base, or any special base, consist of an image held in place by an emulsion. The image can be distorted or destroyed under any condition that loosens the emulsion. Tests have demonstrated that these emulsions will not withstand high temperature and humidity conditions, and that they are particularly susceptible to steam.[8,9] The traditional insulated safe or insulated filing device depends on the water of crystallization in the insulation material to limit the internal temperature and might be vented into the interior of the device. Therefore, it is expected that a steam atmosphere at 212°F (100°C) or higher will exist within the records protection equipment under severe fire exposure. The tests demonstrated that such exposure would damage or destroy the information on photographic media. A high degree of safety, however, can be achieved by placing the photographic media inside a steel can and sealing it with a moisture-resistant tape before storage within a record container.

The fire problem with photographic records that are stored in bulk facilities is similar to that encountered with paper records, except in salvage efforts it is important to give priority to the photographic records. While the cold water used in extinguishing the fire will not immediately attack the photographic emulsion as would steam, it will tend to cause some softening. If salvage efforts are not undertaken immediately, there is a tendency for the emulsion to stick to adjacent material and damage the image.

Magnetic Media

The more common magnetic records consist of magnetic impulses retained in an iron oxide or similar deposit held to an acetate, polyester, or similar plastic-based material. The tapes are usually wound on polystyrene or similar plastic reels and contained in polystyrene cases. This is particularly true of many tapes used with electronic computer systems. The security of the record is primarily related, as with photographic records, to the stability of the emulsion. Even minor distortion is severe in the case of magnetic records, since machines cannot make subjective judgments regarding distortion. If the emulsion is softened by the heat from fire, for example, there is a tendency for the layers of tape to stick to each other on the reel and to be destroyed in efforts to unreel. A tape can be considered safeguarded only up to temperatures in the range of 125°F (52°C) and in relative humidity not exceeding 85 percent.

Salvage

The problem of recovering wet records is the same whether they are damaged by a fire, or some other source, such as flood, hurricane, heavy rainstorm, roof leakage, spilled liquids from operations located above, or a breakdown of any of the numerous water or steam systems in the building. It is generally recognized that virtually any wet paper records can be recovered, provided prompt and proper action is taken.

Good sources for further information on salvaging records are contained in NFPA 909, *Code for the Protection of Cultural Resource Properties—Museums, Libraries, and Places of Worship,* as well as "Salvaging and Restoring Records Damaged by Fire and Water,"[10] *Managing the Library Fire Risk,*[11] "After the Water Comes,"[12] and *Procedures for Salvage of Water-Damaged Library Materials.*[13]

RECORDS STORAGE

Factory-Built Devices

Limited quantities of valuable records can be stored in factory-built records protection equipment, such as insulated records containers, fire-resistant safes, insulated filing devices, and insulated file drawers. These devices are available in varying degrees of resistance to fire, heat, and impact, and the degree of protection to be specified for a particular application will depend on the severity of the exposure and the items to be stored. The test procedure applicable to this equipment and the ratings employed are described in UL 72, *Tests for Fire Resistance of Record Protection Equipment.*[14]

Records protection equipment is classified in terms of two elements: (1) an interior temperature limit and (2) a time in hours. Three temperature limits are employed: 350°F (177°C), regarded as a suitable limit for paper records; 150°F (66°C), regarded as a limiting temperature for photographic records; and 125°F (52°C), regarded as suitable for most magnetic media. The time limits employed are ½, 1, 2, 3, or 4 hours. The complete rating, consisting of the two elements, indicates that the specified interior temperature limit is not exceeded when the record container, safe, or filing device is exposed to a standard test fire as described in UL 72,[14] for the length of time specified.

Ratings are assigned to the various categories, as follows:

Insulated Records Containers

Class 125—4 hours
Class 125—3 hours
Class 125—2 hours
Class 125—1 hour
Class 150—4 hours
Class 150—3 hours
Class 150—2 hours
Class 150—1 hour
Class 350—4 hours
Class 350—3 hours
Class 350—2 hours
Class 350—1 hour

Fire-Resistant Safes

Class 125—4 hours
Class 125—3 hours
Class 125—2 hours
Class 125—1 hour
Class 150—4 hours
Class 150—3 hours
Class 150—2 hours
Class 150—1 hour
Class 350—4 hours
Class 350—3 hours
Class 350—2 hours
Class 350—1 hour

Insulated Filing Devices

Class 125—1 hour
Class 125—½ hour
Class 150—1 hour
Class 150—½ hour
Class 350—1 hour
Class 350—½ hour

Insulated File Drawers

Class 125—1 hour
Class 150—1 hour
Class 350—1 hour

Insulated records containers and fire-resistant safes must protect contents from heat to an extent described in the requirements, before and after a fall from 30 ft (9 m). Insulated filing devices, which are not drop-tested, are not required to have the strength to endure such an impact.

Insulated records containers, fire-resistant safes, insulated filing devices, and insulated file drawers must sustain sudden exposure to high temperatures to an extent described in the requirements without the unit exploding as a result of such exposure.

Ordinary uninsulated steel files and cabinets provide only a limited measure of protection from an exposure fire, as heat sufficient to char contents is quickly transmitted to the interior. However, they can be very useful where the major fire exposure is from the records themselves. They are commonly used for records having no extraordinary value. They are also used for the organized storage of valuable records in protected facilities, including vaults, file rooms, and document buildings. A records vault or file room in which all records are kept in metal file cabinets is much safer than one in which the records are kept in cardboard boxes on open shelves. If an ignition occurred in an open file drawer, fire development would likely be very slow. An ignition in open-shelf files, however, could be beyond manual control within a few minutes.

Files and cabinets made of wood, fiberboard, or other combustible materials can release their contents in a fire, adding to the fire hazard. They should not be used in valuable records storage.

Vaults and File Rooms

Standards for the construction of fire-resistive vaults and file rooms are contained in NFPA 232. The term "vault" refers to a completely fire-resistive enclosure up to 5000 ft^3 (142 m^3) in volume, used exclusively for records storage, with no work to be carried on inside. It is equipped, maintained, and supervised to minimize the possibility of a fire starting within and to prevent a severe fire of long duration on the outside from entering, provided the vault door is closed. Vaults are designed to fire resistance classifications 4 and 6 hours, indicating that, under standard test conditions, heat will not rise above a specified temperature inside and the construction will withstand both the exposure fire and the application of fire hose streams during that period. Vaults are constructed in the field and do not carry a testing laboratory label. Vault doors, however, are laboratory tested and carry ratings conforming to the vault construction in which they are to be used. (See NFPA 232.) Unlike some other fire doors, vault doors limit the temperature on the interior face to 350°F (177°C) during fire exposure, so that paper stored in contact with the door would not be in danger of ignition. Provisions in NFPA 232 require sprinklers in vaults.

Vaults usually contain a substantial fuel load and by their nature are normally used to store only vital and important records. The internal contents of some vaults are more of a fire hazard than any external exposure. In recognition of this situation, vault standards permit sprinkler systems, lighting, and low-energy circuits, with suitable safeguards. Installation of smoke detectors and/or sprinklers to detect and extinguish a vault fire impose a minor permissible increase in ignition sources. A fire within an unprotected vault can be disastrous unless it is immediately discovered and extinguished with portable fire-fighting devices. Fire extinguishers of the water type or fire hose, or both, should be outside the vault in an accessible location near the door.

Additional protection is gained by storing particularly sensitive documents in protected filing devices *inside* vaults. Be careful that fire exposure is not increased thereby, such as installing the safe in a vault occupied by open-shelf filing.

A standard fire-resistive file room is defined as an enclosure not exceeding 50,000 ft^3 (1416 m^3) in volume and 12 ft (3.66 m) in height, designed to a fire resistance classification of 2, 4, or 6 hours. The volume and height limitations restrict the quantity of records exposed to destruction by fire in a single enclosure and reduce the possibility of fire originating within the enclosure.

File room doors are labeled as to their fire resistance following a laboratory test under the procedures of UL 155, *Tests for Fire Resistance of Vault and File Room Doors,*[15] but the ratings are only for ½ or 1 hour. Door openings shall be protected with listed file room doors that have a minimum rating that is equal to the rating of the walls. These ratings anticipate that paper and other combustibles will not be stored nearer than 3 ft (0.9 m) from the unexposed face of the door, nor 6 in. (152 mm) to the side from the door jambs.

Lighting, heating, ventilation, and so on are permitted inside file rooms, as are filing cabinets and furniture, provided they are noncombustible. Although it is not to be used as a working space for other than filing purposes, the file room is more susceptible to a fire ignition than a vault. Due to this vulnerability, installation of automatic fire detection and fire control systems should be considered in relation to the values involved. Automatic sprinklers are required in file rooms having open-shelf filing, unless all storage is held in records protection equipment.

Records Centers and Archives

Bulk storage of records in buildings set aside for the specific purpose or in major portions of other buildings (in rooms exceeding the 50,000 ft^3 [1416 m^3] fire-resistive file room limitation) should comply with the recommendations set forth in NFPA 232. For facilities of this size, where the most severe hazard might not be from a fire exterior to the facility but from a fire starting and spreading entirely within the records storage area, the level of fire-resistive construction and protection must be individually determined. Within such a facility, secondary operations might have to be segregated from the actual storage by fire-resistive construction. Full-scale fire tests of 14 ft (4.3 m) high open-shelf records storage in a sprinklered facility indicated the likelihood of ceiling temperatures in excess of 1200°F (649°C) for periods of up to 8 minutes when using standard 286°F (141°C) sprinklers.[1] Lightweight bar joist roofs often present in records centers are vulnerable to early collapse unless additional precautions are taken, such as might be provided by developments in large-drop sprinklers, quick-response sprinklers, or fireproof coatings for the steel. In a full-scale test in 30 ft (9 m) high storage, a single quick-operating, 155°F (68°C) sprinkler held the fire in check for an extended period of time before extinguishment was completed with a handheld hose.[4] A thorough fire risk analysis by qualified personnel should be conducted due to the high fire potential from the concentration of combustibles and the probability of loss of large volumes of valuable documents.

Recent changes in the rack and storage arrangements for records centers have led to several important changes to NFPA 232. Records centers have been defined as being of two types: compartmented and noncompartmented. A compartmented records center is defined as having a storage compartment area of less than 40,000 ft^2 (3715 m^2). Fire separation between compartments should have no less than a 2 hour fire resistance rating if the area does not exceed 40,000 ft^2 (3715 m^2), and 3 hour fire resistance rating if the area exceeds 40,000 ft^2 (3715 m^2). Noncompartmented records centers should have height and area limitations as determined by the applicable building code.

FIRE RISK ANALYSIS

Maximum possible protection is not desirable for the bulk of what comprises records storage. Most records can be reconstructed, duplicates are often available in other locations, and their loss might not create any substantial hardship. The value of certain irreplaceable documents warrants especially sophisticated protective measures to preserve a single sheet of paper. The great majority of records in a particular collection, however, might dictate consideration of less-than-optimum methods of records protection and anticipation of potential small fire losses, yet still provide a high degree of assurance against a significant loss.

Classification of Records

A records protection program should be based on an inventory that determines type, volume, rate of acquisition, duplication of data, rate of disposal, and class of importance of the records. The responsible party, records manager, or archivist should determine which, if any, of the records need a higher level of protection as provided by the different classes of records storage. Valuable records can be generally classified in one of two ways to assess their value:

1. *Vital and archival records.* These records are irreplaceable; records having high historic value (archives); records where reproduction does not have the same value as an original; records that give direct evidence of legal status, or ownership; records needed to sustain a business or avoid delay in restoration of production, sales, or service; and records of accounts receivable.
2. *Important records.* These are necessary records that can be reproduced from original sources only at considerable expense or loss of time.

Other records might be useful but should be kept well separated from vital and important records because they could constitute a fire exposure in and of themselves.

Fire Risk Evaluation Factors

In considering the protection of valuable records, the following four basic items must be evaluated:

1. The probability that the building containing the records, as well as neighboring operations, will have a fire outside the records storage activity that will spread to the records. Determining the probability of such fire hazards will involve consideration of building construction, contents, possible fire causes, and general features of fire protection that might stop a fire that originated elsewhere before it reaches the records. (See Section 19, Chapter 2, "Structural Integrity During Fire.")
2. The probability of a fire starting within the records storage activity. This includes assessing the ignition sources, vulnerability to arson, the susceptibility of the records or their containers to ignition, and factors facilitating the spread of fire.
3. The quantity of fuel the records represent, particularly as it relates to available or proposed capability for fire extin-

guishment, and the structural stability of the storage arrangement and the building enclosure.
4. The susceptibility of the records to damage from fire, fire effects (heat, smoke, vapors, etc.), and fire-extinguishing efforts (principally water damage and impact damage from hose streams and other extinguishing devices, and physical disruption from manual fire fighting).

When records must be housed in a building that might burn around them, properly rated vaults and containers can give reasonable protection against the external fire exposure. The hazard of the records themselves, such as those stored within a vault, file room, segregated floor or section of a fire-resistive building, or records center, can be substantial. For example, a fire involving military records of 19 million U.S. servicemen occurred in an unsprinklered, six-story, fire-resistive building. The top floor, where the fire started, was completely destroyed. Fire-fighting efforts prevented the fire from spreading downward. Had the fire started on a lower floor, it is likely that the entire building would have been lost.[1]

The protection methods described in this chapter yield protection guidelines commensurate with the hazard and the sophistication of the protection systems. The degree of fire risk and the potential for loss in collections not suitable for cabinet or vault storage may require evaluation by a person knowledgeable in this type of analysis.

FIRE RISK REDUCTION

Since most records media are combustible, 100 percent effective protection is not feasible and efforts should be directed to reducing the risk of fire and its associated effects. One of the most effective means for limiting the disastrous effects of a fire in a records storage facility is to prepare duplicates and store them away from the originals where they will not be subject to the same incident. Often the duplicate copy is on microfilm, which is inexpensive, easily transported, and easily stored at a remote facility. Once a duplicate has been prepared, the value of the original is reduced considerably, unless the original document is required for legal purposes or is of intrinsic or historic value. If the duplication is complete, up-to-date, and easily accessible, then reduced protective measures may be justified for both the original and the duplicate collection.

If the prior generation of computer records is stored remote from the current generation, the effect of loss of the current records in use at a computer center would be reduced. Although they are not exact duplicates, the existing earlier records still greatly simplify the task of reconstructing current records.

Protective Containers

Heavily insulated, massive vaults, safes, and filing cabinets are the traditional way to safeguard vital and archival records against the effects of fire. The practice of encapsulating the records so that they are fully protected against the greatest potential fire exposure is still viable. Containers are available that will keep the internal temperature and humidity as low as necessary to retain the data on magnetic tape and other temperature-sensitive media.

Vaults are usually used where the volume of valuable records is large. They are often the only practical method of protection in non-fire-resistive buildings where the probable fire severity exceeds the rated endurance of 4 hour safes. Safes are used for smaller volumes of records where it is necessary to have records near their point of use, where the cost of vault construction would be prohibitive, or where the building does not lend itself to vault construction.

Protective containers for records are rated by tests under standard fire conditions. They are rated according to the time elapsed before the interior of the container reaches 350°F (177°C). This time factor provides a measure of safety, since the ignition temperature of most paper is somewhat higher.

Records containers rated for interior temperatures that do not exceed 150°F (66°C) and relative humidity that does not exceed 85 percent at temperatures above 120°F (49°C) are available. Containers rated with these more stringent requirements are intended to provide protection for films, magnetic tapes, plastic media, and similar materials. The development of new and different records materials, however, requires a careful evaluation of their characteristics to ensure proper protection. An important limitation on this type of container is that it is not subjected to the traditional drop test while containing magnetic or similar media records. The device should not be considered capable of safeguarding magnetic and similar records in any building that could collapse in a fire and cause debris to fall on the container, nor should the container itself be subject to falling several floors.

Table 9.8.1 indicates the approximate fire resistance that can be safely expected from various types of records containers exposed to a fully developed fire. The protection provided varies considerably, depending on design and materials. Thickness of insulation alone does not give a reliable indication of fire resistance, which can be determined accurately only by tests.

Patterns of records container performance in real fires were analyzed in depth in a special five-year study done by NFPA five decades ago.[16] Although the statistics from that era might no longer be representative, the leading factors of

TABLE 9.8.1 Fire Resistance of Records Containers

Insulated records vault doors	2, 4, and 6 hours
Insulated file room doors	½ and 1 hours
Steel-plate vault doors with inner doors	About 15 minutes
Steel-plate door without inner doors	Less than 10 minutes
Modern safes	1, 2, and 4 hours
"Old-line," "iron," or "cast-iron" safes, 2 to 6 in. wall thickness	Uncertain
Insulated records containers (files and cabinets, etc.)	½, 1, and 2 hours
Containers with air space or with cellular or solid insulation less than 1 in. thick	10 to 20 minutes
Uninsulated steel files, cabinets, wood files, wood or steel desks	About 5 minutes

For SI units: 1 in. = 25.4 mm.

contents destruction are probably the same ones one would find today. They are listed next in order of frequency from the old study:

- Container exposed to fire beyond its capacity to withstand (mostly unlabeled containers, some 1 hour containers, a few 2 hour containers, no 4 hour containers)
- Obsolete design or construction of unlabeled container
- Container submerged in water
- Container door left open

The first two of these were cited much more often than the second two, which underlines the importance of selecting the right containers for the fire hazard in the first place. As one might expect, the longer the time rating, the more likely the container was to preserve the contents.

Early Warning Concept

Records administrators might consider a sprinkler system as optional when they plan records protection. A smoke detection system coupled with manual response, once highly favored by archivists and librarians as a full substitute for sprinkler protection, is now considered to be only a useful supplement to sprinklers under favorable conditions. In a slowly developing fire, a well-designed smoke detection system can give an advance warning before heat-responsive devices, such as automatic sprinklers, operate. If manual fire extinguishment is mobilized by a manned emergency center, it might be able to attack the fire before it gains headway. Whether manual extinguishment causes more or less damage than sprinklers depends on the skill of the responding force and how the fire progresses while the responding force is mobilizing. In any case, although automatic detection and manual extinguishment can be valuable adjuncts to automatic sprinklers, they would not constitute an acceptable alternative to automatic sprinkler protection under most conditions found in records storage.

Smoke detectors in records storage are particularly useful when the area is unoccupied. Spot-type detectors on high ceilings are unlikely to be activated until smoke from a smoldering fire completely permeates the air, or flaming fire gains sufficient headway to drive a column of smoke and heat to the ceiling. Therefore, in-rack detection or projected beam detectors should be considered.

Smoke detection systems might not be appropriate in open-shelf records storage, where fire development is likely to be very rapid. They might provide supplementary protection in high-value collections, particularly if measures have been taken to slow down development of a fire (such as storage in totally closed metal containers), or burning material is prevented from falling off shelves. Smoke detection equipment can be useful in unoccupied areas of mobile shelving or other arrangements in which combustible contents are sheltered from sprinklers, or storage arrangements slow the spread of fire. Heat detection, either spot type or line type, can be located near or in the racks. This type of detection might be more suited where a rapidly spreading fast-burning fire is expected, and especially if the smoke or heat detection system is connected to activate an extinguishing system.

Smoke detection systems are also used to activate extinguishing systems, such as carbon dioxide, halon, water mist or high-expansion foam. They are used to activate preaction sprinkler systems, which are sometimes installed to prevent accidental water damage.

Duct detectors are used to shut down fans, activate dampers, or initiate smoke control measures. Detectors are also used to cause held-open doors to close and to stop conveyors, in a variety of single-purpose actions.

Heat detectors can perform most of the same duties as smoke detectors but usually with a much longer time lag. An extended time lag is sometimes desirable, such as in the opening of a sprinkler, or the release of a special extinguishing agent.

Handheld Extinguishing Appliances

Even if the facility is equipped with an automatic extinguishing system, manual fire control devices should be provided for staff use. Fire extinguishers are most often encountered. The preferred types are those containing clear water as the extinguishing agent. Although carbon dioxide extinguishers do not leave a residue or dampen documents, they are not effective on the deep-seated fires likely to occur in records storage. Although the use of halon extinguishing agents is being phased out worldwide, they are still used extensively in record storage systems. Halon extinguishers have the same limited extinguishing ability as carbon dioxide, in that they are ineffective on deep-seated fires. The user of halons should also be aware of the toxicity of the agent and avoid high concentrations of it. Although national standards rightly limit human exposure to the various halons, there is no mechanism, except the knowledge and alertness of the extinguisher operator, to manage the extent of exposure to halon. Most extinguisher users, however, are unaware of this hazard and are at risk of overdose. Multipurpose dry chemical extinguishers can be provided, but they leave considerable residue and have only limited effectiveness on deep-seated fires.

Water hose lines can supplement, or be used instead of, fire extinguishers. To minimize water damage, rubber-lined hose with an adjustable water spray, straight stream, and shutoff nozzle is preferable in records storage areas. Its use greatly expands the fire-fighting capabilities of the staff. Hose lines connected to carbon dioxide or halon storage tanks or cylinders have been used. However, these systems should not be undertaken without extensive training and appropriate protective equipment because the danger to the fire brigade is much greater than with the use of hand extinguishers containing the same agent.

AUTOMATIC EXTINGUISHING SYSTEMS

A variety of automatic fire extinguishing systems are suitable for records storage protection; the choice depends on the economics of a particular situation and the degree of sophistication desired. All of the extinguishing systems described are loss initiated; the system does not detect and begin extinguishment until a fire is established and a fire loss has occurred. Systems that are more sensitive and reactive are available for highly specialized requirements. A large increase in cost and rate of false operation should be expected. Increased maintenance is usually required

in more sophisticated systems to attain the reliability inherent in standard sprinkler systems.

Automatic Sprinklers

Automatic sprinkler systems are the most common type of automatic protection. They are effective in records storage fire incidents in limiting both fire and water damage. Water is discharged only in the immediate vicinity of the fire and salvage techniques have been perfected to the point where recovery of wetted items is no longer unusual. Accidental opening of a sprinkler is rare. The probability of water damage from an accidental discharge can be further reduced using a preaction sprinkler system where water does not enter the piping until a fire detector operates. Preaction systems introduce additional failure modes, which could be unacceptable. A more sophisticated variation is a system where the water supply valve cycles on and off, depending on the actual presence of fire as sensed by a detector in the fire area. Also available are sprinklers that cycle on and off individually, but the piping remains filled with water. However, the increased cost of these systems must be weighed against the value of the records being stored. "On-off" sprinklers have a troubled record in long-term use.

Water Mist Systems

"Mist" nozzles, long used in cotton processing factories to raise humidity, reduce static electricity sparking, and reduce incidence of flash fire in accumulations of fine fibers, are being used in a relatively new type of sprinkler system. Parallel developments are being pursued for two types of application. In one model, a small array of open mist nozzles are supplied through a valve controlled by heat or smoke detectors. Many arrays are installed in a large area. In another model, individual nozzles are activated by an internal valve controlled by an integral heat detector.

Installation of a water mist system should be undertaken only under a person experienced in design, installation, and testing of water mist protection for records storage facilities.

Foam Systems

High-expansion (hi-ex) foam can provide some credible assurance of controlling a fire that might escape sprinkler control. Hi-ex foam has the ability to overcome a well-established fire. Like gas extinguishment, to do its job hi-ex foam must fill the entire fire compartment, totally submerging the fire, and continue refilling at a rate adequate to completely replace the foam broken down by the fire. Water damage to any single item will be low, but all items within the room or fire area involved will be affected.

If provided to justify the use of caverns and multistory buildings for records centers, hi-ex foam should be required to demonstrate, by full-scale testing, the ability to overcome a fire spreading beyond sprinkler control in a 250,000 ft^3 (7100 m^3) records module. (Caution: A previous full-scale test was fully successful except that all the records box identifying labels slid off onto the floor—a disaster for records keepers.[17])

Hi-ex foam can be used as a backup for sprinkler failure if adequate reliability factors are built into the design of the system. Inadequate water supply is an important cause of sprinkler failures; such a lack would also cause a hi-ex system failure. Closed valves are the leading cause of sprinkler failures and are a symptom of poor maintenance, which could affect a hi-ex system at a number of points (e.g., water valves, foam valves, air fans, and directional dampers). All sorts of failure modes affect foam systems. Whether to rely on the sprinkler waterflow alarm for activating the hi-ex system or to provide an entire separate heat detection system is a design decision. A smoke detection system designed to activate hi-ex foam seems to be much too reactive.

Carbon Dioxide Systems

A few automatic total flooding carbon dioxide systems having a high rate of discharge have been installed in records storage or library areas. A properly designed system should promptly control fire with limited damage. To be successful, a high concentration of gas must be maintained for an extended period. The concentration must be maintained until a deep-seated fire cools below its ignition temperature. The operation of such systems, however, involves a hazard to life and must be delayed until the area to be flooded is cleared of people. See Section 17, Chapter 1, "Carbon Dioxide and Application Systems," for additional information.

Halon Systems

The manufacture of Halon 1301 (bromotrifluoromethane) and various related Freon™ gases (used in fire protection, refrigeration, and air conditioning) are being phased out rapidly by international treaty because of concern for ozone depletion in the upper atmosphere. Several substitute gases have been proposed for fire extinguishment, none of which has so far received universal acceptance.[18] See Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems" for additional information.

Existing automatic total flooding halon systems utilize flame-inhibiting liquefied gas under pressure. Halon 1301 is being marketed for use in specially engineered systems for the protection of valuable records. The primary advantages are that the gaseous agent leaves no residue and is only mildly toxic in the concentrations in which it is used. Occupants, however, should not be unnecessarily exposed to Halon 1301. Deep-seated smoldering fires will not be extinguished by halon, as it inhibits flaming only.

System Reliability

All fire control systems are subject to failure when various conditions are exceeded or not met. Gaseous systems have a number of possible failure modes that are unique to them, although this does not necessarily imply an unusually high failure rate in practice. An independent detection system must work and must be correctly linked to the gas release. Usually, electric power is required for the detection system, linkage, and release to operate. The gas containers must be filled and connected to distribution piping. If the room has been enlarged since the system was installed, the gas volume applied may be inadequate. If any of

the doors fail to close properly, a critical amount of gas may escape. If the ventilating system continues to operate, critical duct dampers fail to close, a window remains open or gets broken, or walls are breached for construction, a critical amount of gas may escape. If fire fighters open doors to assist in extinguishment, a critical amount of gas may escape. If deep-seated fires are not extinguished prior to gas dissipation, rekindling of the fire may be beyond the control of manual forces if no connected reserve gas supply is available for reapplication.

High-expansion foam systems have similar detection and activation vulnerabilities. They are especially vulnerable to loss of power because substantial power is required to operate the large fans used to generate the foam. Foam is also subject to blockage by doors, walls of stock, and fabric curtains. It is also somewhat vulnerable to loss of containment, although not nearly to the extent of gaseous systems.

Water-based systems (sprinklers, foam, water mist, etc.) are subject to failure because of closed water supply valves, pipe obstructions, and lack of adequate water pressure. Pumper connections are provided for the fire department to supplement the water supply, especially to restore pressure loss caused by other fire department operations.

FIRE PREVENTION AND EMERGENCY PLANNING

Although detection and extinguishing systems are important, particularly for the bulk storage of valuable records, the first line of defense remains a good fire prevention and risk reduction program. Good housekeeping, orderliness, maintenance of equipment, and prohibition of smoking in records storage and handling areas are fundamental principles of good records management.

An emergency action plan that is kept current and practiced is essential to limit damage in case a fire occurs. Staff personnel cannot be expected to approach a fire and use extinguishers or hose lines effectively without adequate training. Fire-resistive containers and vaults are of much greater value if there has been training in procedures for fire emergencies. The following suggestions apply:

1. Records should be returned to their places of safety accurately, quickly, and without confusion or oversight. If there is no standard records protection, the best plan is to have the most important records carried out of the building. Drills are valuable to train employees to meet emergencies.
2. Records belonging in vaults or safes should never be left out overnight.
3. Important materials that belong under protection should not be allowed to accumulate on desks.
4. Because records normally safeguarded are often unprotected while temporarily on loan, copies instead of the originals should be loaned, and the originals retained in safe storage.

PROTECTION LIMITATIONS

The prototypical records center used to be a single-story warehouse complex consisting of 40,000 ft^2 (3715 m^2) modules separated by 4 hour rated brick fire walls, sprinklered and unsprinklered. Wide roadways separated the warehouses in all directions; an uncontrolled fire in any warehouse was unlikely to be transmitted to any other warehouse. Also, if a fire grew out of control in any one module, the fire department could breach the walls and roof of the unit out of control to reduce the heat acting on the fire wall separations and allow water applied externally by hose streams to cool the exposed fire walls, providing a good chance of saving the contents of the rest of the warehouse.

In multistory warehouses, basement storage, and especially mine storage, these options are severely limited. A fire that has grown, for whatever reason, out of control of sprinklers and of inside fire fighting is not likely to be stopped at the fire barriers of the module. Available heat and smoke venting is not at all likely to be adequate, and there is no place for a fire department to combat the fire from outside.

Now, records storage centers are growing bigger and taller, as structural rack assemblies change and automated storage and retrieval equipment is developed. Fire fighting operations can be inhibited by the sheer size of a facility and the associated difficulty in physically finding and getting to the fire.

Multistory Buildings

Success in limiting the fire to a segment of the multistory building by fire department activity is dependent on the fire location. No traditional fire-resistive building will survive a module burnout (a 7 to 15 hour fire exposure); an exception was the top floor MPRC fire.[1] (Even in that fire the 10 in. [250 mm] reinforced roof was destroyed by the fire, which performed the useful task of greatly increasing the venting performed by the windows.) Fire fighters prevented the fire from propagating downward. Had the fire originated on another floor, the unsprinklered, heavy reinforced concrete building would have collapsed because of impact loading caused by floors above collapsing into the fire. All the records in the building would have burned completely. Because of lack of sprinklers, a fire starting on the first floor would have been out of control by manual fire fighting by the time the fire department arrived and the kind of success enjoyed in the Chicago fire would have been negated from the outset.

Modules are generally inaccessible from the outside; an exception was the ground floor of the Chicago Records Storage Facility fire.[19] The fire department was able to breach the entire south wall and apply hose streams from the outside to control and eventually extinguish the fire, while maintaining sufficient control for other fire fighters to defend fire doors on each end of the fire module and to cool the floor above the fire to prevent paper ignition. In a multistory building, providing ventilation is difficult on any story except the top floor and the first floor.

Cavern Storage

Caverns selected for records storage are clean and dry, with essentially no air movement. They are prized as low-maintenance facilities with no heating or air-conditioning required. Lighting is limited to task lighting and safety lighting; therefore, ultraviolet light exposure is not a problem. A minimal water supply is maintained for the comfort of a small staff. The location is

usually remote, reducing security requirements and simplifying visitor control.

Basic fire protection features, however, are lacking. Open-shelf records storage requires the following:

- A professionally designed sprinkler system
- Reasonably sized fire-resistive subdivisions
- A robust water supply, such as 250,000 to 1,000,000 gal (946,350 to 3,785,400 L) of water in a ground tank or reservoir, pressurized by two or more automatic fire pumps of 1000 or 1500 gpm (3785 or 5700 L/min) capacity or pressurized by elevation
- A large professional fire department with strong backup
- The capability of ventilating large amounts of smoke and heat to the outside

Providing the sprinklers and the subdivisions is the easy part. The remaining fire protection features are difficult or impossible to attain in cavern settings; nevertheless, they are vital to the safe storage of records.

After a fire is controlled by sprinklers, it requires the following:

- Overhaul and extinguishment by the fire department
- Smoke removal by the fire department and the small environmental system
- Data recovery by the staff and outside auxiliaries

For a fire beyond control with sprinklers or an unsprinklered fire, the fire walls should contain the fire in the module of origin for 4 hours; however, before the fire spreads throughout the module of origin, smoke and heat will migrate, filling the cavern and making it dangerous and eventually impossible to remain in. Because of limited means to dump smoke and heat to the outside, the fire will continue to grow until it involves all the cavern contents. The cavern might be inaccessible for months. Nothing will remain to salvage.

Caverns are usually remote from any substantial water service. (A credible private water service would consist of the storage supply and fire pump capacity stated earlier.) Caverns are also usually remote from the services of a large, well-organized fire department. This may be a superfluous problem, because there is no safe place for a fire department to operate inside a cavern, and there is little a fire department can do from outside a cavern.

Caverns have no outside venting capacity. Without the possibility of massive smoke and heat venting, a hi-ex foam system might be designed to provide adequate backup fire extinguishment.

Burnout of a module releases massive quantities of heat and smoke that must somehow be vented directly to the outside to avoid a total cavern burnout. Venting into the cavern itself does not permit manual fire fighting. Hi-ex foam is a candidate for limiting a fire to a module, given sprinkler failure, because there is no possibility of adequately venting a module fire to the outside and there is no natural drainage for sprinkler discharge. Failure of sprinklers to control a fire for any reason would likely result in quick abandonment and total burnout of the entire cavern contents unless hi-ex foam provides adequate backup.

None of the mine storage locations assessed for records storage occupancy show potential for venting facilities.

Basement Storage

Basements have all of the downside features of caverns, with two exceptions. They are not necessarily located in remote places; they might be served by superior fire departments and perhaps a strong water supply. The fire department can operate to some extent from the outside, with limited inside travel. Otherwise, basements are very difficult to ventilate in a fire and, given a serious fire, can be very dangerous to fire fighters.

Failure to control a records fire in a basement creates a very serious risk of the loss of the building and all the contents. Existing multistory buildings might be candidates for high-expansion foam backup, in which a single hi-ex system with automatically controlled directional ductwork is designed to protect one of a group of modules.

RELEVANT FIRE EXPERIENCE

Military Personnel Records Center (MPRC) Fire[1]

The unsprinklered Military Personnel Records Center (MPRC) fire in Overland, Missouri, where the service records of 19 million World War II military men and women were destroyed was not the ultimate records center fire—not even for that building. The MPRC fire was limited because it occurred on the top floor. Had it occurred on a lower floor, the building windows could have permitted it to spread to the upper floors. The floors above the out-of-control fire could have been too much of a hazard for fire fighters to occupy, to prevent flames outside the windows from igniting paper stacks inside the windows. Later in the fire, the flooring directly above the fire could have actually become too hot to stand on. The atmosphere could have been too hot to endure, and the floor could have begun to fail and sag, precipitating imminent total collapse of the building. Descending floor and heavy stacks of paper could have imposed impact loading on the floors below. Partial or total building collapse could have broken the building apart and spread the fire to all floors, at which time the loss of the building and all the contents could have been assured. This description was taken from a report about the MPRC building 6 months before the actual fire. The fire that subsequently occurred in July 1973 was on the top floor and relatively easy to prevent propagating downward. Although the entire top floor was destroyed, the fire was fortunately never a serious threat to the rest of the building.

Chicago Records Storage Facility Fire[19]

On Tuesday, October 29, 1996, an alarm was sounded for a fire in an automatic sprinkler–protected records archive building shortly before 2 p.m. Before the fire was declared under control nearly 10 hours later, it had reached the fourth alarm level with a commitment of 17 engines, 9 trucks and tower ladders, a squad, and several additional special pieces of equipment. The last fire company left the scene about 5 p.m. on November 7, 1996, and a full box alarm assignment was involved in overhaul operations for over 24 hours after the fire. Damage consisted of the total loss of thousands of record storage boxes and their contents,

water and smoke damage to thousands of other boxes, the loss of steel storage racks, and structural damage to the fire area and adjacent fire divisions. The value of the lost records and the cost to restore salvageable records were still being determined at the time this investigation was conducted. The loss of the racks and storage boxes themselves is estimated at over $3 million. The cost of structural damage and replacement of the destroyed front wall has been estimated at over $2 million. Early assessments of the total dollar loss have been set at over $50 million.

Aggressive fire department interior and exterior operations contained the fire to the 35,000 ft^2 (3250 m^2) compartment of origin. The fire area contained storage of cardboard-boxed records in approximately 28 ft (8.5 m) high metal racks with solid shelves. Automatic sprinklers were provided at the ceiling level only. Salvage of records had not been decided at the time of this report.

The successful control of this fire can be attributed to the performance of the fire separation walls supported by a large fire suppression force. Effective pre-incident planning and standard operating procedures also contributed. Companies supported the automatic sprinkler systems by supplying pressurized water at siamese connections and protected openings in the fire separation walls with hose streams. The availability of a good water supply to support the numerous hand lines and master streams as well as the automatic sprinkler systems was important to the overall tactical plan. The fire report did not emphasize removal of an outside wall as a key element in saving the facility.

In this fire the Chicago Fire Department kept the automatic sprinkler system operating for days. The sprinklers were still discharging water as outside contractors were overhauling and removing the building contents with heavy equipment. Their tactics and support of the sprinkler system are good examples for other fire departments to study.

Iron Mountain Fires, South Brunswick, New Jersey[20]

After the fire in Chicago, serious fires occurred in four other records storage facilities. Two of these fires also resulted in the total loss of the contents, even though both buildings were protected by automatic sprinkler systems. In addition to the loss of the contents, both of these buildings were destroyed.

Three of the fires, all determined to be the result of arson, occurred between March 10 and March 19, 1997, in two adjacent records storage buildings in South Brunswick, New Jersey. Both buildings were operated by the same company and were part of 117 record storage sites operated countrywide. One building with its contents was totally destroyed.

The first two fires occurred on March 10 and 17, 1997, in the same building, which contained an estimated 250,000 record storage boxes. Both of these fires were controlled by the automatic sprinkler systems and fire department operations. The automatic sprinkler protection included a strong hydraulically calculated overhead system and in-rack sprinklers. Boxes were stored on steel shelves and racks in a similar configuration to that used in Chicago. The exact storage height was not available. The Monmouth Junction Fire Department was still on the scene of the March 17, 1997, fire when the third fire occurred.

The March 19, 1997, fire was reported at 10:20 a.m. in a building located around the corner from the one above. The building, constructed of concrete walls and metal roof, contained an estimated 850,000 record storage boxes. Storage was on steel shelves and racks with intermediate catwalk levels. The exact storage height was not available. Automatic sprinklers were installed at the ceiling and in the racks following the same design that controlled the previous fires. Flames penetrated the roof of the building by early afternoon in the third fire and reached 100 ft (30 m) in the air by 8 p.m. that night.

West Pittston, Pennsylvania, Records Center Fire[21]

A records center fire occurred on May 5, 1997, in West Pittston, Pennsylvania, located between Scranton and Wilkes-Barre. The center was a single-story, 44 ft (13 m) tall, noncombustible building with a ground floor area of about 78,000 ft^2 (7250 m^2). The original section was built in 1995; an addition was completed approximately 6 months before the fire. The center was protected throughout by a ceiling-level-only dry-pipe automatic sprinkler system.

Record storage boxes were arranged on solid metal shelves in double- and single-row metal racks to a height of 42 ft (12.8 m). Intermediate-level grated metal walkways were provided to access the boxes. The arrangement was similar to the rear section of the Chicago Records Center building. The company operated nine other records storage buildings throughout four states.

The building had ceiling-only automatic sprinklers (none in the racks). The sprinklers did not control the fire; it spread throughout the structure resulting in a total loss.

National Archives Fires[22]

Two recent fires at the Washington Regional Records Center serve as a demonstration of the combination of records protection based on research, outstanding disaster planning, local fire department involvement, employee dedication, and official support. A midafternoon fire on February 29, 2000, was controlled by joint action of automatic sprinklers and elements of the Prince George County Fire Department. While the fire was still underway, employees were spreading salvage covers, directing fire fighters to ventilation equipment, moving out smoldering boxes, and beginning records salvage. As soon as the fire was out, salvage and cleanup were started, fire watches were set, and drying equipment was ordered in. Although about 3500 ft^3 (100 m^3) of records were wet down, only about 50 boxes were lost. On April 5 another fire occurred, about quitting time, this time affecting about 700 ft^3 (20 m^3) of records with much the same employee response. Cleanup was quicker because the specialized equipment was still on the scene from the first fire. The cause of both fires was arson by a part-time employee.

SUMMARY

Protecting records from fire and other hazards has become more challenging in recent years because of the increase in the vol-

ume of records and the frequent necessity to use the maximum cubic capacity of storage areas. Provisions must be taken not only to minimize the risk to records but also to protect the safety of persons in records storage facilities. The provisions taken depend on the nature of the records themselves and on the means of storage used. Since there is no 100 percent effective way to provide protection or to salvage damaged records, it is recommended that duplicates be stored at another site.

It is vital that effective maintenance and service of all passive and active fire protection systems be provided on a regular basis. Impairments to any system must be corrected in a timely manner.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the protection of records discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 72®, National Fire Alarm Code®
NFPA 75, *Standard for the Protection of Information Technology Equipment*
NFPA 232, *Standard for the Protection of Records*
NFPA 909, *Code for the Protection of Cultural Resource Properties—Museums, Libraries, and Places of Worship*

Chapter 9

Semiconductor Manufacturing

Revised by
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Chapter Contents

Preproduction Process
Production Process
Semiconductor-Related Developments and Guidelines
Hazard Control in Semiconductor Manufacturing
Fire Hazards
Health Hazards

Key Terms

cleanroom, integrated circuit, mask production, pyrophoric gas, semiconductor, silicon

Producing a state-of-the-art semiconductor device, also known as an integrated circuit (IC) or chip, is truly an extraordinary process. Integrated circuits are based on silicon, a fundamental component of sand, which is a tetravalent, nonmetallic element that occurs in combined form as the second most abundant element in the earth's crust next to oxygen. It is processed through several hundred steps into devices that are used in a wide range of applications.

Silicon has the same crystalline structure as diamond, but is only as hard as glass. It is also a semiconductor, which means it is halfway between a conductor, which carries electricity easily (like the copper wire used in domestic lighting circuits), and an insulator, which prevents electricity from flowing (like the plastic sheath around the wires). Its conductivity can be easily altered by adding minute quantities of other chemicals (called "dopants") to its crystalline structure. Other semiconductor materials include gallium arsenide, germanium, indium arsenide, and a combination of sapphire and silicon. The use of silicon is currently the most popular, but gallium arsenide technology continues to gain popularity. This is because gallium arsenide can move electricity faster than silicon and can generate light impulses, which silicon cannot do.

In addition to the production of electronic circuits, electrooptical and electromagnetic devices are also produced. These devices are made on wafers in cleanrooms with similar processes. Photocells for converting light energy to electrical energy and sensors for measuring ultraviolet (UV), visible, and infrared (IR) electromagnetic waves are made using the deposition, photolithography, and etching processes. Electromagnetic devices, such as read-write heads for magnetic disc drives, are also made using similar processes in clean rooms.

The loss potential as the result of a fire in a semiconductor manufacturing plant can be enormous. A large facility can cost $2–3 billion to construct and equip. Add to this the value of completed and in-process wafers, which are very susceptible to damage from fire and smoke, and the potential disruption in production schedules, product distribution, and business interruption, and the potential for loss can be staggering.

The in-process or finished devices generally present no unique hazard. In contrast to this, the manufacturing process presents several unique hazards to production workers and fire fighters. Acids, alkalis, flammable liquids, flammable gases, pyrophoric gases, and toxic gases are common in semiconductor manufacturing facilities.

For related topics, see Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 7, Chapter 3, "Storage of Gases"; and Section 9, Chapter 12, "Fire Protection of Laboratories Using Chemicals."

PREPRODUCTION PROCESS

Semiconductor devices have extremely small circuit patterns. A single particle of microscopic dust can ruin a chip. Because of this, the devices are fabricated in a cleanroom. A room can be considered a cleanroom if it can maintain a particle level of fewer than 100,000 particles larger than 0.5 µm

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(0.00002 in.) in size per ft^3 (0.028 m^3) of air. Such a room would be designated a Class 100,000 cleanroom. The most advanced semiconductors today require cleanrooms of Class 1 design. This means the room frequently is designed to a specification of fewer than 1 particle larger than 0.12 µm (0.000005 in.) in size per ft^3 (0.028 m^3) of air. In contrast to this, normal urban air has particle counts in the range of 5,000,000 particles per ft^3, and smoke generated from a fire can have 1 trillion particles per ft^3. The human body can release up to 2,000,000 particles per minute into the atmosphere.

Crystal Production

Crystal production involves the growing of silicon crystals in electrically heated, argon-atmosphere vacuum furnaces operating at a temperature above 1400°F (760°C). As with all crystal growing, a seed crystal is required to set the process in motion. When the growing process is complete, the silicon ingot is brought to room temperature and the seed is removed from the crystal. Years ago the diameter of the ingot was only ½ in. (13 mm). Today, 6 in. (150 mm) and 8 in. (200 mm) ingots are common and 12 in. (300 mm) versions are now widely used.

In the cut and grind operation, the ends of the polysilicon crystal are removed and the uneven exterior is ground to achieve uniformity. The silicon ingot is then sliced into wafers with a multiwire saw that make numerous cuts at once or with a diamond-edge circular saw. The saw slices the ingots into 14 to 30 mil (0.36 to 0.76 mm) wafers (i.e., about the thickness of a business card). About 28 wafers are cut from each inch of the ingot.

After being sliced, the wafers are lapped to remove the saw marks. The wafers are mounted to the lapping equipment, which features an abrasive slurry on a revolving disc. An acid etch process performed in plastic wet benches follows to remove the lap marks.

Wafers are then polished with a diamond paste to a mirrorlike finish. Finally, the wafers are given a thin surface layer of either silicon dioxide, in an oxidation furnace (metal oxide semiconductor [MOS] process), or silicon, in an epitaxial reactor (bipolar process). At this point, the wafers are ready for building of the circuits on the silicon substrate. Most chip manufacturers purchase wafers from an outside supplier, but some facilities make a small number of wafers needed for processing.

The gallium arsenide crystal is more brittle and it is more difficult to grow a single gallium aresenide crystal than a silicon one; therefore, 2 in. (50 mm), 3 in. (75 mm), and 4 in. (100 mm) wafers are typically used. Gallium arsenide circuits are sometimes grown on germanium wafers because the cost of germanium is lower. Crystals and wafers are generally not produced at the semiconductor manufacturing site. Raw wafers are purchased from outside vendors.

Mask Production

Mask production involves transferring a large circuit drawing to a glass plate called a mask. The mask may contain hundreds of exact reproductions of the original art work and is used later to recreate the pattern on the surface of the wafer. Each mask contains the pattern for a single layer of the circuit; therefore, many individual masks are used to fabricate the entire integrated circuit or chip. The mask surface can be an emulsion, chrome, iron oxide, or silicon monoxide. Most masks are fabricated from chrome on glass. Reticle and electron beam technology are two different techniques used to produce masks. Companies that specialize in mask making supply the majority of masks to the semiconductor industry. Several large semiconductor manufacturers fabricate their own masks.

The circuit design process starts with determining the intended function of the circuit. A logic diagram of the circuit is developed and then translated to a schematic diagram that shows the location of the various components. The circuit components are then translated to their relative final dimensions, as they will be formed in and on the surface of the wafer. A sophisticated computer-aided design (CAD) system then draws a composite picture of the circuit surface, showing all the sublayer patterns.

Reticle Technique. A reticle, which is an emulsion or chrome photoplate that is selectively exposed to light in a pattern generator, is a miniaturized reproduction of one layer of the circuit. The actual size of the pattern on the reticle is normally 10 times the final size of the pattern on the wafer. The computer tape from the digitizing operation instructs the shutter system to open and close, exposing the reticle in the exact pattern of the original drawing.

The pattern on the reticle is transferred to the mask in a step-and-repeat operation. The reticle is positioned over one corner of the photoresist coated mask blank, and a light source transfers the pattern on the reticle into the photoresist. After the first pattern is transferred, the machine "steps" the reticle to the next position and repeats the pattern in the next location. This process continues until the entire mask surface is filled with the reticle pattern.

Electron Beam Technology. Electron beam technology is used to make masks that produce more advanced circuits. An electron beam writer is similar to a scanning electron microscope. The coated mask is placed in a vacuum chamber and an electron beam is directed at it. The pattern information stored on the tape at the digitizing operation is used to direct the electron beam to the correct locations to expose the photoresist. The pattern is written onto the mask without a reticle.

PRODUCTION PROCESS

In the manufacturing or fabrication process, selected areas of the integrated circuit chip are made to be either conductors or insulators, thus creating electrical circuits, transistors, capacitors, and so on. Highly sophisticated manufacturing techniques allow circuit patterns as narrow as 5 millionths of an inch (⅛ µm) in width. The circuit patterns are applied in sequential layers, one on the other. Forty or more layers of circuit patterns might be combined on a single chip, depending on chip design. A modern microprocessor chip might contain over 10 million individual transistors and capacitors per square centimeter of silicon wafer. See Figure 9.9.1 for an illustration of the general production process.

Fabrication Process Steps

The fabrication process involves repeated steps of applying photoresist, photomasking, developing, etching, doping, and deposition. These processes are typically performed in cleanrooms.

Applying Photoresist. Photoresist and its developer are the largest volume solvents within the fabrication area. Negative photoresist, a photosensitive polymer suspended in a flammable organic solvent base such as xylene or toluene, is used to coat the wafer in preparation for transferring the pattern of the circuit from the mask to the wafer. The wafers are coated with a small quantity of photoresist and then rapidly rotated on a spinner, which spreads the photoresist into a thin uniform layer on the wafer. Photoresist materials are classified as either negative or positive, depending on whether the solubility in the developer decreases (negative) or increases (positive) on exposure to an ultraviolet (UV) light source. Since photoresist is sensitive to light, it is shipped and stored in and dispensed from brown glass or plastic bottles.

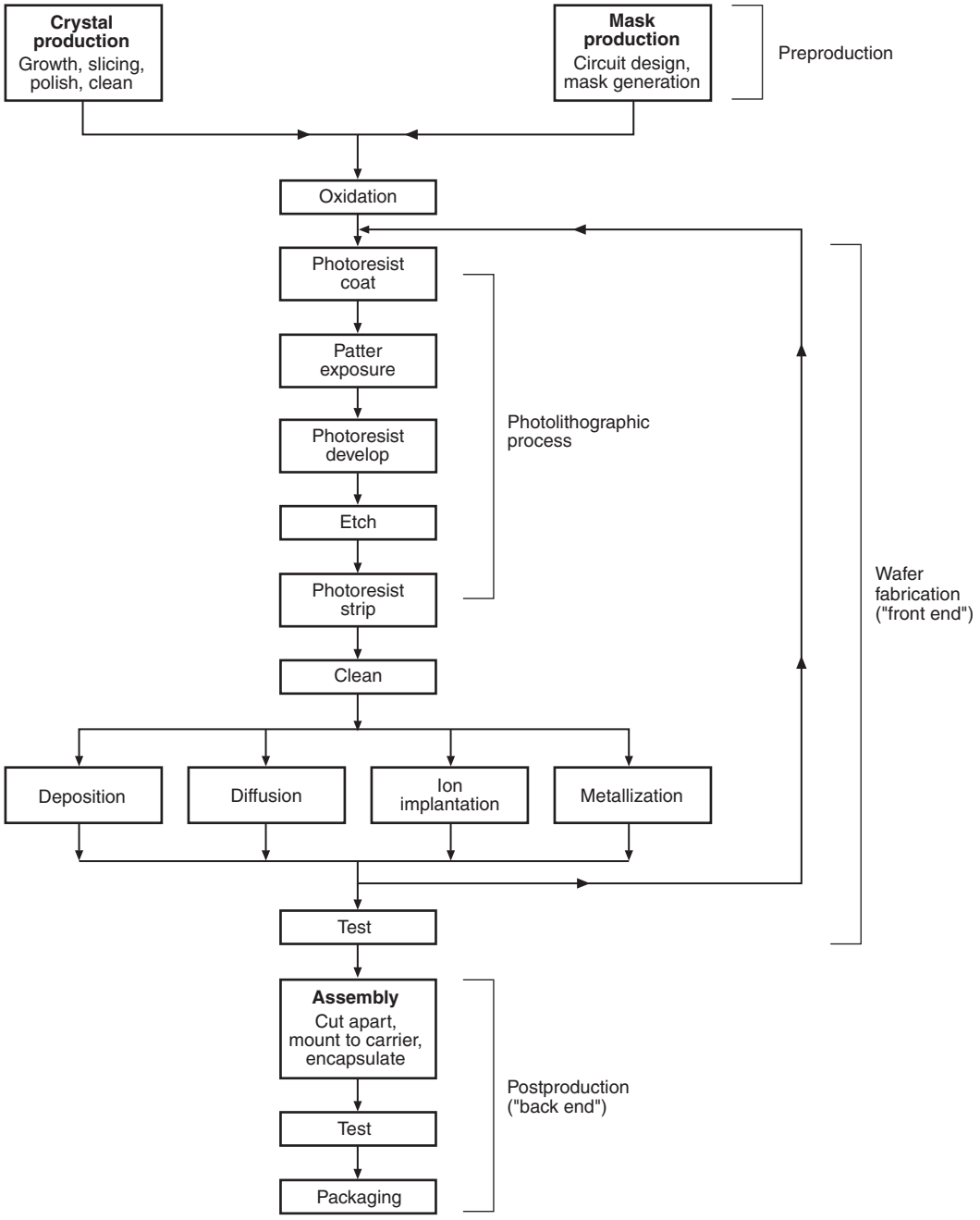

FIGURE 9.9.1 Semiconductor Manufacturing Process

Photoresist adjuncts, which consist of a variety of chemical liquids and gases, are used to promote the adhesion of the photoresist coating to the wafer. Hexamethyldisilazane (HMDS) is the most widely used chemical for adhesion and is spun onto the wafer surface prior to photoresist application.

After the wafers are coated with photoresist, they are "soft baked" to cause a portion of the solvents in the photoresist to evaporate. Methods used to soft bake include hot plates and the following types of ovens: convection, vacuum, moving belt IR, microwave, and conduction belt. After the baking has been concluded, the actual photomask process takes place.

Photomasking. Photomasking is a process of alignment and exposure. The types of equipment used for this process can vary in size, overall appearance, method of operation, and equipment cost. Equipment includes contact aligners, projection aligners, wafer steppers, and wafer scanners. The wafer is placed onto the machine and a specific patterned mask plate is placed over the wafer. The wafer is then aligned with the mask plate and exposed through the action of the shutter of the machine, which opens to allow UV light to hit the unmasked portion of the wafer.

Developing. After the wafer has been aligned and exposed, the next step is developing it. In the development process, a machine similar to a spinner is used. The developing is done by chemicals, which are sprayed onto the wafer. The spray washes away the nonexposed resist (areas where the light was not allowed to pass through the mask plate) while the exposed, or polymerized, resist remains. The preferred developing chemical for negative photoresist is xylene. A Stoddard solvent may also be used in certain cases. Positive photoresist is developed in an alkaline solution, such as potassium hydroxide, sodium hydroxide, or tetramethyl/ammonium hydroxide.

Other flammable solvents also used in the wafer fabrication process include butyl acetate and isopropyl alcohol, which are used as washes for wafers after they have been developed with negative resist. Deionized (DI) water is more commonly used with positive photoresist as a postdeveloping wash.

Etching. Etching removes layers of silicon dioxide, metals, and polysilicon, as well as photoresists, according to the desired patterns delineated by the photoresist. The two major categories of etching are wet and dry chemical, with wet etching used predominantly. Wet etching involves solutions containing etchants, usually acid mixtures at the desired strength, which react with the materials to be removed. Plastic wet benches and plastic exhaust ductwork are typically used in wet etching operations. Dry etching involves the use of reactive gases containing chlorine or fluorine under vacuum in a highly energized chamber, which also removes the desired layers not protected by photoresist.

Doping. To form the junctions where current will flow, a controlled number of impurities or dopants must be introduced into a selected region of the wafer by either diffusion or ion implantation. Diffusion is a high-temperature (1652 to 2372°F [900 to 1300°C]) process in which the dopants are introduced into the surface layer of the semiconductor material to change its electrical characteristics. Diffusion is the most established method of applying dopant material.

Ion implantation is a technique for doping impurity atoms into an underlying substrate by accelerating the selected dopant ion toward the silicon target through an electrical field. Ion implantation is often preferred over standard diffusion methods because it is more precise, faster, and less expensive. Annealing is usually required following ion implantation because of the structural damage caused by bombardment of the substrate by the accelerated ions.

The need for annealing after ion implantation has led to the development of a technology called rapid thermal processing (RTP). This process, which takes place in seconds, eliminates the need for a minutes-long process in a tube furnace, which has undesirable side effects of migration of dopant atoms within the wafer. Also, every time a wafer is heated near diffusion temperatures and then cooled down, crystal dislocation occurs, which can result in circuit failures. In the single wafer RTP tool, radiation heating (usually from tungsten halogen lamps) is very rapid, and the body of the wafer never comes up to temperature. Annealing can take place without undesirable side effects. The trend to small feature sizes on wafers has also lead to thinner layers. Thermally grown gate oxide layers now can be less than 100 Å thick. Rapid thermal oxidation (RTO) tools are similar to the RTP annealing tools, but they have an oxygen atmosphere in the chamber rather than an inert gas. RTP technology is used in various oxide, nitride, and silicon layer processes.

Deposition. Deposition is the process of placing additional layers onto the wafer surface, either by chemical vapor deposition (CVD) or physical vapor deposition (PVD). CVD is the process of causing a thin film to form on a substrate through the chemical reaction of various gases. CVD is usually promoted by the heating of the substrate, either at atmospheric pressure or at low pressure (LPCVD). Epitaxy, which represents a special form of chemical vapor deposition, is the process of depositing a crystalline layer having the same structure as that of the substrate. Often, epitaxial layers are grown with intentionally added impurities, such as boron or phosphorus. These impurities change the electrical conductivity of the crystalline silicon.

The photoresist application, photomasking, developing, etching, doping, and deposition processes are repeated many times until the complete circuit is produced. A typical photolithographic sequence using negative photoresist is shown in Figure 9.9.2. The sequence is as follows:

1. A pattern is etched onto a silicon dioxide layer that has been grown on to the surface of the wafer.
2. The wafer is coated with photoresist.
3. The coated wafer is exposed to ultraviolet light through the patterned mask.
4. Exposure renders the exposed photoresist insoluble. The unexposed photoresist is removed in the developing process, leaving a patterned area of silicon dioxide exposed.
5. The exposed silicon dioxide is removed by etching. The remaining hardened photoresist protects the unexposed silicon dioxide from the etchant.

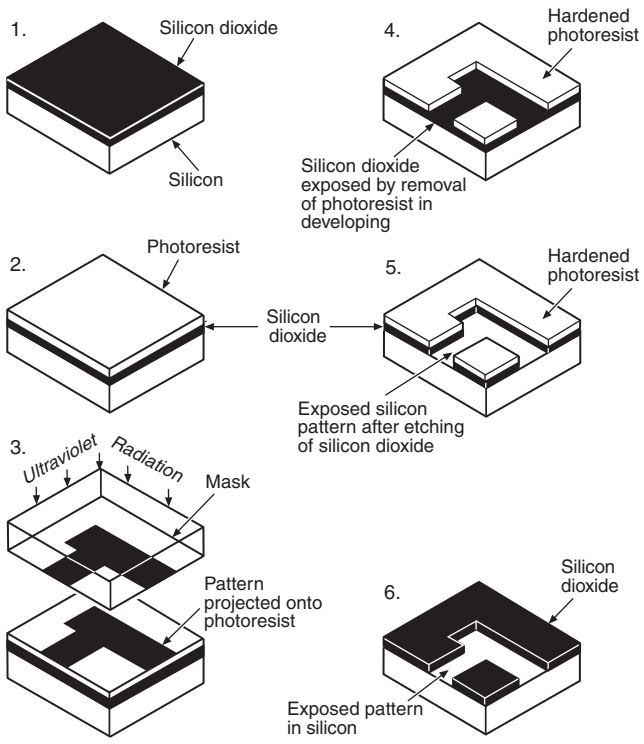

FIGURE 9.9.2 Photolithography

6. The remaining photoresist is stripped away in a chemical bath leaving a pattern on the surface of the wafer.

Metallization. After the final diffusion step, the devices that have been fabricated into the silicon wafer must be connected to perform circuit functions. This process is known as metallization. Metallization provides a means of wiring or interconnecting the uppermost layers of integrated circuits by depositing complex patterns of conductive material, which route electrical energy within the circuits. To do this, a PVD process is used in which a conductive metal is either sputtered or evaporated over the front of the wafer. A photoresist pattern is then aligned over the metal and some of it is etched away, leaving the desired metal coverage. The most common metals used for metallization are aluminum, nickel, chromium, gold, copper, silver, titanium, tungsten, and platinum.

Testing

The final step in the wafer form of integrated circuit manufacturing is testing. During the electrical test (e.g., die sort, wafer sort, wafer probe), each integrated circuit or chip is tested for its ability to perform the operations for which it was designed. As each chip is tested, a computer records information about it. If a chip is not acceptable, that is, if it fails any one or more of the tests, a small droplet of ink is automatically placed on the chip so that the bad, or inked, chip can be discarded when the wafer is separated into individual chips.

300 mm Wafer Processing Fabrication Facilities

Semiconductor manufacturing using 12 in. (300 mm) wafers are now common with over 40 such facilities now operating. The ability to fabricate more than twice as many chips on a 300 mm versus 200 mm wafer has led to significant cost savings per wafer. Many new 300 mm facilities are under construction and discussions have begun regarding the move to 450 mm wafers.

Front-Opening Unified Pod (FOUP). The main differences in 300 mm versus 200 mm fabrication facilities (fabs) are related to the high level of automation. Whereas interbay (between bays) material handling systems are common in 200 mm fabs, 300 mm fabs have automated intrabay (within bays) material handling systems. Due to the weight (8 kg) of a 24-wafer lot front-opening unified pod (FOUP), personnel movement of the FOUPs will generally not occur. Overhead hoist vehicles (OHV), automated guided vehicles (AGV), or rail guided vehicles (RGV) are used for intrabay transport.

FOUPs are staged in stockers (Figure 9.9.3) which are self-contained vertical storage units located inside cleanrooms. FOUPs in use today are generally constructed of combustible plastics and represent a significant fire hazard when located inside a stocker as confirmed by large-scale fire testing conducted by FM Global.

Fire protection options for stockers include automatic sprinkler protection, high-sensitivity smoke detection/gaseous fire suppression, or nonfire propagating FOUPs. FM Global Test Standard 4911, *Approval Standard for Wafer Carriers for Use in Cleanrooms,* provides test criteria for the rating of a FOUP as nonfire propagating. Special engineered plastics are needed to pass the requirements of Test Standard 4911.

Ceiling Heights. The minimum requirement for ceiling heights in 300 mm fabs is 14.8 ft (4.5 m) and can reach as high as 22.9 ft

FIGURE 9.9.3 Wafer Stocker and Associated Automated Materials Handling System (Source: Copyright FM Global. Reprinted with permission. All rights reserved.)

(7 m). The minimum height is necessary to allow move-in clearance for tools with heights approaching 11.5 ft (3.5 m). Ceiling heights lower than 14.8 ft (4.5 m) do not allow adequate automation track clearance configurations so that tools can pass without track removal.

In the event of a fire, these higher ceiling heights would result in a longer response time for a typical fab sprinkler system. In addition, the fire will actually be larger in terms of heat release rate (HRR) at the time of sprinkler response. This situation should be reviewed to ensure sprinkler arrangements take into account the longer response times.

Processing Tools. 300 mm processing tools are 1.0 to 1.5 times larger than comparable 200 mm tools. In addition, subfab support equipment is also greater in size. This will result in greater amounts of tool construction materials. If noncombustible and/or fire safe plastics are not used for tool construction, this will result in an increase in fire loading.

Electrical Demand. Another change is increased electrical demand for major tools, particularly in the etch area (208V and greater than 250A), which is driving more 480V supply and distribution to tools. Electrical interconnects between tools and support equipment are major considerations in equipment facilities routing between floors. The increase in power creates greater fire ignition source energy. This and the fact that there are fewer operators in the fab increases the likelihood of potential fire ignition along with delayed discovery by operators.

SEMICONDUCTOR-RELATED DEVELOPMENTS AND GUIDELINES

NFPA 318, *Standard for the Protection of Semiconductor Fabrication Facilities*

NFPA 318 was first published in 1992 and is currently a 2006 edition. The standard applies to any semiconductor facility that contains a cleanroom or "clean zone" and it provides a set of reasonable requirements to protect such facilities from a fire or related hazards. The standard includes requirements for the following:

- Construction, including seismic protection
- Fire protection, including sprinkler system design criteria and detection system design criteria
- Ventilation (air supply and recirculation) systems and local exhaust systems
- Production and support equipment, including required interlocks, electrical system design, and specific requirements for process liquid heating systems

NFPA 318 also addresses the storage and handling of chemicals used in semiconductor manufacturing processes. Topics include delivery systems for flammable and combustible liquids, both bulk and containers, as well as disposal of waste liquids. Particular attention is paid to storage and handling of cylinders of hazardous gases and bulk silane storage systems. NFPA 318 contains extensive references to relevant standards and guidelines of other organizations, such as FM Global and Semiconductor Equipment and Materials International (SEMI), as described later in this chapter.

The 2006 edition of NFPA 318 contains a new chapter addressing quantity limits for hazardous materials following coordination of this information with *NFPA 5000®, Building Construction and Safety Code®*.

NFPA 1, NFPA 318, and *NFPA 5000®*

There are cross references among NFPA 1, *Uniform Fire Code™*, NFPA 318, and *NFPA 5000.* NFPA 318 references NFPA 1 and *NFPA 5000* relative to hazardous materials storage, usage and handling, fabrication area separation walls, emergency power requirements, and hazardous chemical/gas room separation walls. NFPA 1 references NFPA 318 relative to new and existing facility compliance to NFPA 318. *NFPA 5000* states that buildings in semiconductor fabrication facilities that contain cleanrooms must be constructed in accordance with NFPA 318.

Semiconductor Equipment and Materials International (SEMI)

Semiconductor industry organizations such as the Semiconductor Equipment and Materials International (SEMI) also produced fire protection guidelines. Up to the year 2000, the industry has followed Section 19 of SEMI S2-93, *Safety Guideline for Semiconductor Manufacturing Equipment,* which provided a prescriptive and limited scope regarding fire protection. Most operators were accepting the use of UL 94 V-0, developed for small plastic appliances, to evaluate the combustibility of their large polypropylene plastic tools. UL 94 V-0 was never intended to be applied to semiconductor manufacturing tools, especially those enclosed in present-day huge minienvironments. The plastic tools in these chambers can be constructed of thousands of pounds of plastics, which in most cases is shielded from the facility automatic sprinkler systems.

SEMI S14. SEMI S14-0200, *Safety Guidelines for Fire Risk Assessment and Mitigation for Semiconductor Manufacturing Equipment,* was originally published in February 2000. The purpose of the document is to assess the risks to equipment that might be created by fire and to allow for performance-based alternative methods to reduce or mitigate those risks. The guideline is intended to apply to all semiconductor manufacturing equipment in the fabrication area air-flow space, possibly including the subfabrication area. The document is intended to be used in the design of new equipment, but can also be used to categorize and report the risks for existing equipment in a facility. It is not intended to be used to evaluate the fire sources that can start outside of a piece of equipment. The document does not assess or review any regional or local regulations and is not intended to be used as a code document. The following hierarchy, or cascade, of correction should be used whenever possible, as this emphasizes the concept of a proactive rather than a reactive solution:

1. Taking steps to eliminate the hazard or to replace combustible material with noncombustible material

2. Using a nonpropagating material of limited combustibility
3. Reducing the hazard by using detection, suppression, or another mitigation method, including power shutdown

S14 provides a formalized approach to evaluating various potential fire hazards and their risks, provides a standardized method of categorizing and reporting those risks to the user, and gives some minimum requirements for risk reduction or mitigation methods. SEMI S14 has been revised several times and the most current version is SEMI S14-0704.

SEMI S2. SEMI S2, *Environmental, Health, and Safety Guideline for Semiconductor Manufacturing Equipment,* is a safety guideline intended as a set of performance-based environmental health and safety (EHS) considerations for semiconductor manufacturing equipment. SEMI S2-0703A contains an extensive section on fire protection. According to SEMI S2-0703A's Section 14, equipment fire risk is to be assessed and reported, as are the risk mitigation features that are incorporated. It allows for optional fire risk reduction features, depending on the plant's level of risk acceptance. The prescriptive components are limited to those the supplier and user communities consider common to most equipment. There is also a description of how some of the features are to be provided, but the direct inclusion of these is only prescribed if risk assessment finds them to be necessary.

When risk reduction is considered, materials of construction are high on the list. Noncombustible material should be used whenever possible, with the second choice being materials that do not propagate flame. It advocates that the selection of materials be based on minimizing fire risk, but also recognizes that materials must be compatible with process chemistries. The hazards from the materials of construction might be reduced, for example, by using barriers of noncombustible materials to separate combustible materials from sources of ignition.

Another method of risk reduction is a fire detection and suppression system, which is to be included only if the need is indicated by the risk assessment. The components of the fire detection and suppression system should be suitable for use in process equipment, certified by an accredited testing laboratory, installed in accordance with appropriate standards, and capable of interfacing with the facility systems.

HAZARD CONTROL IN SEMICONDUCTOR MANUFACTURING

Most of the potential hazards encountered in semiconductor manufacturing plants are commonly found in other industries as well. Plating operations, crystal growing, flammable liquids, and flammable gases all present hazards that are widely recognized and for which effective loss prevention controls are established.

There are, however, several hazards that are not widely encountered in other industries. Pyrophoric gases, toxic materials (gases, liquids, and solids), radio frequency fields, ionizing radiation, and special handling techniques required for certain chemicals due to purity constraints are examples of uncommon potential hazards that might be encountered in semiconductor manufacturing facilities.

General Safeguards

Semiconductor manufacturing cleanrooms should be located in buildings of fire-resistant construction and must be equipped with a fully automatic, fast-response sprinkler system. The cleanroom should be cut off from other areas of the plant by fire-rated construction having a minimum rating of 1 hour. Because of the high values present, additional compartmentation is highly desirable. Ventilation systems, including recirculating and exhaust systems, should be independent of ventilation systems in adjoining compartments.

Recirculating air systems should be designed with the flexibility to shut down in the event of a fire or chemical spill. Exhaust systems serving processes using toxic materials should continue running during such incidents. This will allow continued removal and treatment of potentially dangerous fumes and vapors from the cleanroom, as well as assist in smoke removal. Most of these exhaust systems contain treatment processes to remove or neutralize the chemical(s) in the exhaust stream. Caution should be used in placing automatic sprinklers inside ducts used for fume and vapor exhaust, because sprinklers may significantly reduce the exhaust flow through the duct when sprinklers are operating. This could be undesirable in exhaust systems handling toxic fumes or vapors.

Fire extinguishers and hose stations should be provided. The minimum extinguisher capability should be distributed on an extra-hazard schedule in fabrication areas. (See NFPA 10, *Standard for Portable Fire Extinguishers.*) Carbon dioxide (CO_2) fire extinguishers are the most common type used in cleanrooms. Dry chemical extinguishers are not recommended for use in cleanrooms, because the powdered extinguishing agent used in these extinguishers will contaminate an area of the cleanroom where it is discharged, causing many wafers in the area to be contaminated beyond salvage. Most of the equipment will require meticulous and expensive cleaning to remove the powder, and the high-efficiency particulate air (HEPA) filters will probably have to be replaced at great expense. In specific isolated situations, combustible metal extinguishing powders, such as MET-L-X, might be appropriate for processes using combustible metals.

Selected process equipment or wet benches may be considered for protection with fine water spray or gaseous extinguishing systems (such as CO_2 or FM-200). However, process constraints should be evaluated when this option is considered.

Cleanroom Overview

The fabrication or main part of the semiconductor manufacturing process is performed in Class 1–10,000 cleanrooms (Figure 9.9.4). The two basic methods of constructing a cleanroom are the built-in-place method and the modular method.

Built-in-place rooms are based on a custom design and all construction is on site. These rooms are the most practical approach for larger, permanent installations. Prefabricated or modular construction uses manufactured, modular components that can be connected to one another in a variety of ways.

FIGURE 9.9.4 Clean Bay Service Aisle (Source: Copyright FM Global. Reprinted with permission. All rights reserved.)

In either modular or built-in-place construction, the mechanical systems must be custom designed and installed. The cleanroom air-handling system includes the make-up air system and the recirculation system. The concept of laminar air flow is used in nearly all semiconductor cleanrooms. Laminar flow occurs when air is made to flow in unidirectional layers. The air flow velocity in a cleanroom ranges from 40 to 100 ft/min (0.2 to 0.5 m/sec). Depending on the velocity, up to 10 air changes per minute might occur. Typical air flow volumes for new cleanrooms, whether recirculated at work stations, modules, or large global air systems, range from about 20 to 50 cfm/ft^2 (6 to 15 m^3/min/m^2) of clean room. This assumes that 60 percent of the cleanroom is made up of service corridors with less stringent requirements.

The method of returning the air from the cleanroom to the recirculation fans is accomplished through sidewall vents, a perforated raised floor, or a perforated raised floor opening into a basement plenum. Sidewall returns are openings in the walls of the work area that are used as the path for return air. A perforated raised floor is a perforated deck raised 1 to 4 ft (0.3 to 1.2 m) above the structural floor of the room. The space between the perforated deck and the solid floor forms a path for air return. In the last case, perforations in the structural floor allow air flow directly into the basement of the building, which is used as an air return path.

The air supplied to the cleanroom is usually a mixture of recirculated air and make-up air that compensates for leakage and exhaust losses. Since the recirculated air is cleaner and closer to the desired temperature and humidity, a high ratio (80 to 95 percent) of recirculated-to-make-up air is provided.

The cleanroom is typically kept under a slight positive pressure of about 0.15 in. (40 Pa) water. This is done to maintain airflow from the cleanroom to the outside if there is any air leakage or if a door or other passage is opened. If outside air were to rush in, it would bring millions of airborne contaminants with it.

FIRE HAZARDS

Flammable Liquids

A number of fairly common flammable liquids are used in chip fabrication processes. Most are alcohols and alcohol-based mixtures. When these liquids are to be used in direct wafer processing (i.e., in contact with the wafer), absolute purity of the liquid must be maintained. As in the cleanroom atmosphere itself, a single microscopic particle can contaminate the chip, rendering it useless.

Storage and handling of flammable liquids should generally follow the principles outlined in NFPA 30, *Flammable and Combustible Liquids Code.* Special precautions are necessary to handle flammable materials safely. These include carts designed specifically to transport containers safely from the flammable liquid storage room to the cleanroom. These carts hold the containers firmly upright and can even contain the contents in the event of leakage. Regardless of container construction, flammable liquids not being used should be stored in listed flammable liquid storage cabinets. Personnel training and restricted travel routes for the carts between storeroom and cleanroom should be provided.

In some cases, the flammable liquid is piped into the process equipment. The bulk supply will vary in size and location according to process requirements. Appropriate safeguards must be taken to ensure stability of the pipe system. Bulk dispensing in closed, dual-contained systems is prevalent throughout the industry.

Flammable and Pyrophoric Gases

Some of the gases used in semiconductor manufacturing are either flammable or pyrophoric (i.e., ignite spontaneously on contact with air). The gases might be pure, or they might be found as mixtures, with a carrier gas such as hydrogen or nitrogen. Pyrophoric and toxic gases should be placed outside the plant. Gas may be piped to the cleanroom in welded, stainless steel tubing. Process equipment using high concentrations of pyrophoric gases, such as silane, should be equipped with exhaust gas conditioning in the exhaust stream. The exhaust systems should be equipped with continuous monitoring devices to warn of abnormal conditions.

The burning characteristics of pyrophoric gases, such as silane, dichlorosilane, diborane, and phosphine, are not fully un-

derstood, mostly because the engineering controls provided for these processes have been so successful in eliminating uncontrolled releases. Experience has shown that when a leak occurs in an unconfined area (e.g., outdoors), pyrophoric gases usually ignite on release and subsequently burn in a manner similar to other flammable gases.

The use of the pyrophoric gas silane as a source of silicon in semiconductor manufacturing has grown greatly over the years. The hazards of this material are noteworthy due to the ability of the material to self-ignite with visible flame on release or, in other cases, to be released with either no ignition or delayed ignition occurring, possibly resulting in a detonation explosion. When released into a confined area, such as a gas cabinet, silane has been known to detonate.

Studies conducted by the Compressed Gas Association (CGA) on the release of large quantities of silane have produced technical data. These data have resulted in a CGA publication P32-2000, "Safe Storage and Handling of Silane and Silane Mixtures." The data in P32 have been used to establish minimum separation distances for system installations. These distance limitations minimize risk in the event of an inadvertent release. The distances determined recognize the probability for immediate ignition as well as the probability of latent ignition with its potential explosive effects. It also includes guidance on siting, design of equipment, piping, and controls, fire protection, gas detection, ventilation, and related safeguards. The P32-2000 document has recently been revised and now is called G-13, "Storage and Handling of Silane and Silane Mixtures."

NFPA 318 contains new performance-based guidance on silane gas cabinet ventilation rates, based on FM Global Research testing. Figure 9.9.5 gives average silane concentrations in a ventilated enclosure, and Table 9.9.1 shows silane flow rates through restrictive orifices.

Explanatory appendix material in NFPA 318 gives additional guidance (based on the Compressed Gas Association studies on releases of silane) on separation of bulk silane systems from buildings. The guidance uses performance criteria based on the pressure in the system and the size of the pressure relief valve.

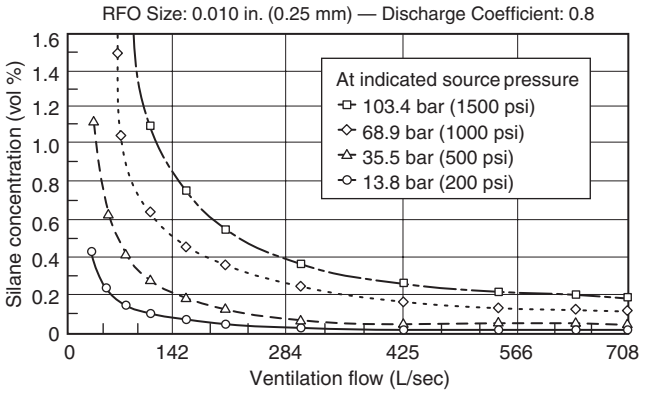

FIGURE 9.9.5 Average Silane Concentration in a Ventilated Enclosure. Notes: 1. If RFO = 0.36 mm (0.014 in.), multiply silane concentration by 2.0. 2. If RFO = 0.51 mm (0.020 in.), multiply silane concentration by 4.0. 3. If RFO = 0.15 mm (0.006 in.), multiply silane concentration by 0.36. (Source: NFPA 318, *Standard for the Protection of Semiconductor Fabrication Facilities,* Figure 8.5.3(C), 2006, p. 318-17)

Cleanroom Furnishings

Workstations, wet benches, and other equipment used in fabrication areas are specially designed to reduce dust accumulation and release of particulates (from the finish treatment) into the room and for compatibility with the chemicals used in or around the equipment. Fiberglass-reinforced plastic ducts for exhaust of corrosive fumes are usually present.

NFPA 318 contains major modifications dealing with fire protection for the tools in the semiconductor cleanroom, which could well be the most significant change to the standard. The requirement says that tools should be of noncombustible construction. An existing exception has been deleted and three new exceptions have been added. The first exception states that small

TABLE 9.9.1 Silane Flow Rates Through Restricted Flow Orifices

RFO Diameter		Source Pressure (bar) (psi)								
mm	*in.*	*103.4 (1500)*	*82.7 (1200)*	*68.9 (1000)*	*55.1 (800)*	*41.3 (600)*	*27.6 (400)*	*13.8 (200)*	*6.9 (100)*	*3.5 (50)*
0.51	0.020	4.72 (10.00)	3.72 (7.88)	2.85 (6.04)	2.05 (4.34)	1.43 (3.020)	0.91 (1.920)	0.45 (0.949)	0.23 (0.497)	0.136 (0.288)
0.36	0.014	2.32 (4.91)	1.82 (3.86)	1.40 (2.96)	1.01 (2.13)	0.70 (1.480)	0.44 (0.941)	0.22 (0.465)	0.11 (0.243)	0.064 (0.136)
0.25	0.010	1.18 (2.50)	0.93 (1.97)	0.71 (1.51)	0.51 (1.08)	0.356 (0.755)	0.23 (0.480)	0.11 (0.237)	0.059 (0.124)	0.033 (0.069)

Notes:
1. The flows through the 0.36 mm (0.014 in.) and 0.25 mm (0.010 in.) RFOs are equal to 49 and 25 percent of the flow through the 0.5 mm (0.020 in.) diameter RFO.
2. Source temperature: 25°C (77°F); downstream pressure: 0 bar (0 psig); discharge coefficient: 0.8.

Source: NFPA 318, *Standard for the Protection of Semiconductor Fabrication Facilities,* Table 8.5.3(C), 2006, p. 318-17.

parts are excluded. The second exception allows the use of listed nonfire propagating materials that are acceptable without internal fire detection and suppression. The third exception allows the use of other control methodologies, such as fire sprinklers or detection and suppression systems. There is also extensive new appendix material regarding the second exception that adds references to the FM Global Test Standard 4910, *Cleanroom Material Flammability Test Protocol,* and UL 2360, *Test Methods for Determining the Combustibility Characteristics of Plastics Used in Semi-Conductor Tool Construction,* for listing materials acceptable for use in cleanrooms without internal fire detection and suppression.

FM Global Test Standard 4910 provides guidance for assessing the fire hazard of materials used in environments highly sensitive to thermal and nonthermal damage, such as within cleanrooms in the semiconductor industry. The test apparatus is recognized in ASTM E2058, *Standard Test Methods for Measurement of Synthetic Polymer Material Flammability Using a Fire Propagation Apparatus (FPA),* and the fire test methodology is recognized in NFPA 287, *Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using a Fire Propagation Apparatus (FPA).* The protocol uses three small-scale tests and, if needed, a large-scale validation test. Small-scale tests are performed in a flammability apparatus, which includes a fire products collector and data evaluation equipment. The tests include ignition tests, fire propagation tests, and combustion tests.

Based on results of the three small-scale tests, the following indices are determined for each material tested:

1. Fire propagation index (FPI): This index is determined by the fire propagation tests and represents the ease or difficulty of fire propagation on the surface of the material, as expected in large-scale fires. Nonpropagating materials have FPI values at or below 6.0.
2. Smoke development index (SDI): This index is defined as the product of the FPI and the yield of smoke for a given material and represents the rate at which smoke is expected to be released during fire propagation. Materials expected to restrict smoke development have SDI values of 0.4 or less.

Materials that meet the flammability protocol criteria require high heat fluxes to be ignited; once ignited, these materials can burn locally in the ignition area, but they will not propagate a fire beyond the ignition zone. Smoke and corrosive products generated from the combustion of these materials are reduced, minimizing nonthermal damages.

Underwriters Laboratories has also developed a cone-calorimeter-based test method as an alternative to the FM Global 4910 oxygen-enriched fire propagation apparatus test protocol. The cone calorimeter is the basis of ASTM E1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter,* and is widely available. It is also the referenced instrument of ISO 5660 and NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter,* and resulted in UL 2360.

The plastic materials tested are identified as nonpropagating—Class 1; limited propagating—Class 2; and slow propagating—Class 3. The individual classifications are defined as follows:

Class 1. Materials that ignite with limited propagation of flame and a demonstrated flame propagation index of 6 or less in the cone calorimeter and flame propagation in the parallel panel test of 4 ft or less. Smoke damage index is 0.4 or less.

Class 2. Materials that ignite with limited propagation of flame in the parallel panel test of less than 8 ft. Smoke damage index is 0.4 or less.

Class 3. Materials that ignite with maximum flame propagation in the parallel panel test of less than 8 ft in the first 10 minutes of the test. Smoke damage index is 1.0 or less.

HEALTH HAZARDS

Although health hazards are also present in semiconductor manufacturing, they are beyond the scope of this handbook. They are mentioned briefly only to acknowledge their existence. For additional information concerning any particular hazard, an industrial hygienist or safety engineer should be consulted. Semiconductor plants should have persons on staff trained in these disciplines.

Several of the gases used, such as arsine, phosphine, and diborane, are highly toxic. The toxicity hazards must be monitored on a continual basis and controlled. In addition to the piping and control systems, the exhaust systems from the process tools should include treatment processes for these materials to avoid release into the atmosphere.

Many of the liquid and solid chemicals used in semiconductor manufacturing are also toxic. Examples include arsenic, various acids, and solvents. Safety considerations including ventilation and employee training are required.

In addition to chemical hazards present in the fabrication area, there are sources of ionizing radiation, laser radiation, radio frequency (RF) energy, and exposure to UV radiation. The machines should have appropriate safety devices and controls incorporated into them and follow the SEMI recommendations for cleanroom equipment.

SUMMARY

Silicon, a fundamental component of sand, is processed through many steps in order to manufacture semiconductor devices, also known as integrated circuits or "chips," which serve a variety of purposes. Several types of fire hazards are associated with semiconductor manufacturing, including hazards that are commonly found in other industries such as flammable liquids and gases. Other hazards are pyrophoric gases, toxic materials, radio frequency fields, and ionizing radiation. General safeguards include cleanrooms located in buildings of fire-resistant construction, fully automatic, fast-response sprinkler systems, recirculating air systems, exhaust systems, fire extinguishers,

hose stations, and specially designed cleanroom furnishings and semiconductor manufacturing equipment.

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NFPA Codes, Standards, and Recommended Practices

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NFPA 1, *Uniform Fire Code™*
NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 70, *National Electrical Code®*
NFPA 75, *Standard for the Protection of Information Technology Equipment*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*
NFPA 287, *Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using Fire Propagation Apparatus (FPA)*
NFPA 318, *Standard for the Protection of Semiconductor Fabrication Facilities*
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Chapter 10

Oilseed Solvent Extraction Plants

C. Louis Kingsbaker

Chapter Contents

Solvent Extraction Process
Hazards of Solvent Extraction
Fire Protection

Key Terms

desolventizer-toaster (D-T) unit, flammable solvent, hexane, oilseed, rotary cooler, rotary steam tube dryer, solvent extraction process

Oilseeds that contain approximately 20 percent oil by weight, such as soybeans, are usually extracted directly. Seeds containing more than 20 percent oil usually are prepared by prepressing to reduce their oil content to 10 to 20 percent. Facilities employing this step are called prepress solvent extraction plants. Some major oilseeds processed this way are cottonseed, rapeseed, flaxseed, corngerm, sunflower, safflower, peanuts, and copra.

Additional information relevant to the solvent extraction process can be found in the following chapters: Section 6, Chapter 8, "Dusts"; Section 6, Chapter 12, "Flammable and Combustible Liquids"; Section 9, Chapter 7, "Storage and Handling of Grain Mill Products"; and Section 11, Chapter 1, "Waste Handling and Control."

SOLVENT EXTRACTION PROCESS

Solvents Used

Commercial hexane is the solvent exclusively used in oilseed extraction because it is relatively easy to desolventize from the extracted meal and oil products, making them nontoxic; it is essentially immiscible with water; and it can be produced from petroleum at a relatively low cost. Commercial hexane consists of a mixture of these petroleum solvents: normal hexane with a weight ranging from about 53 percent to 85 percent (60 percent by weight is a normal average); methylcyclopentane, about 13 percent to 15 percent; methylpentanes, about 22 percent to 25 percent; and dimethylbutanes, about 1 percent. The major disadvantage of commercial hexane is the danger of fire and/or explosion. This danger is overcome by careful design, construction, and operation of the solvent extraction plant.

Other flammable solvents, such as mixtures of aromatic hydrocarbons, are used for extracting lignite, Douglas fir bark, and other special raw materials whose end products are not used by humans for internal consumption.

Description of the Process

Unit operations for extracting all oilseeds are similar, and usually the same equipment can handle the flakes or cakes from these materials. A flow diagram for a typical extraction process is shown in Figure 9.10.1.

For safe storage, oilseeds are brought into the processing plant, checked for moisture content, and dried in a flue gas dryer to about 10 or 11 percent moisture content by weight. To eliminate fire hazards in both the dryer and in the preparation step of the extraction process, seeds are cleaned to remove trash, dirt, and foreign material before they are dried.

The solvent extraction process is continuous. Its rate is usually controlled by measuring at the weigh scale and adjusting the cracking mill feed rolls. The cracking mill splits the hulls and breaks the seeds. Screens and aspiration remove hulls. The seeds are flaked between rollers after passing through a rotary steam tube conditioner. Here they are heated to temperatures between 140 and

C. Louis Kingsbaker is president of C. L. Kingsbaker, Inc., consultants to the oilseed industry.

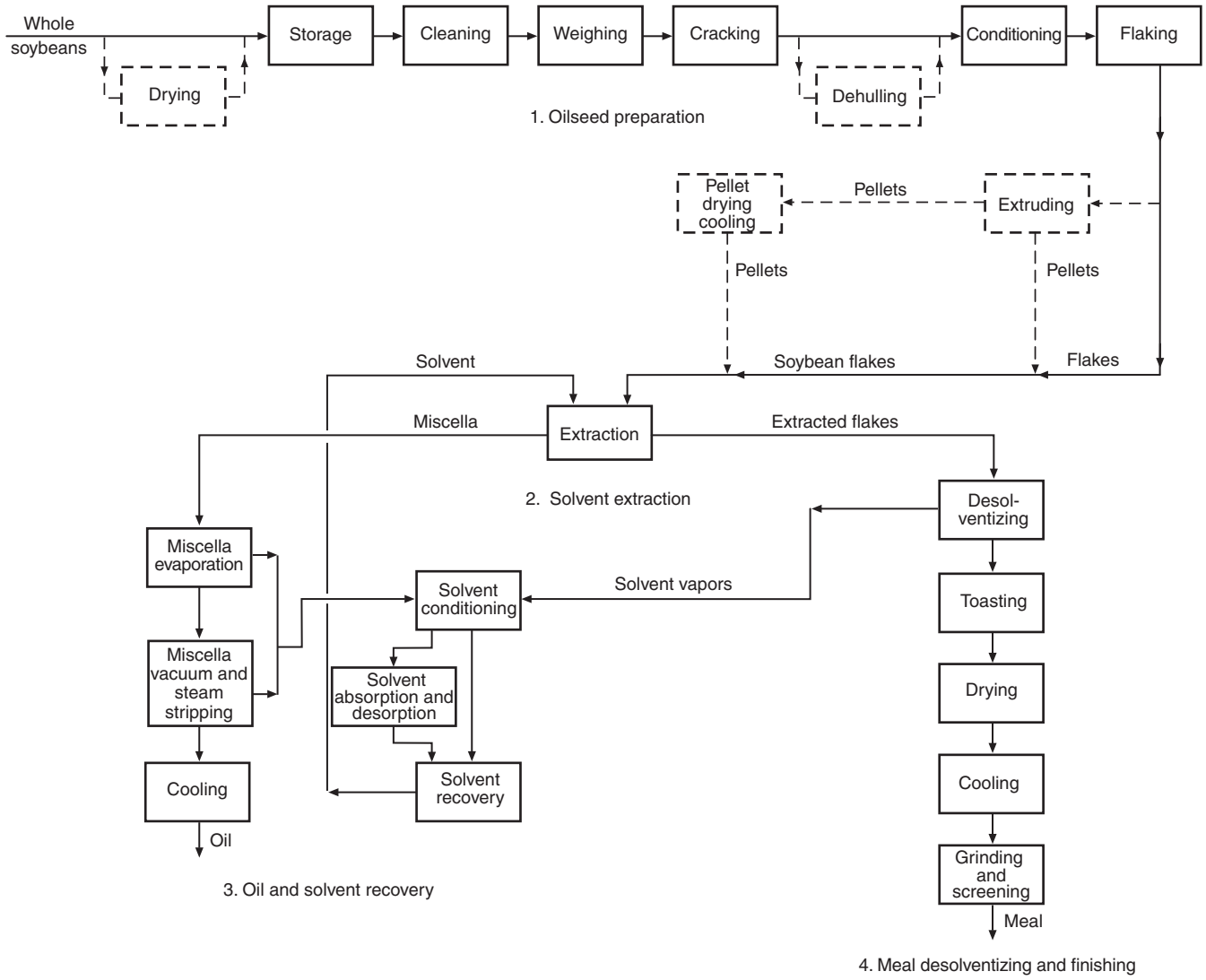

FIGURE 9.10.1 Soybean Solvent Extraction Process

165°F (60 and 74°C) and the moisture content is adjusted to between 10 and 10½ percent.

Due to the demand for high protein soybean meal for poultry and other animal feeds, most U.S. extraction plants remove hulls from cracked soybeans using sifters and aspirators in the separation step. To achieve good separation of hulls from bean meats, typically the bulk moisture is reduced to about 10 percent by weight. The beans are then stored for several days in "tempering" silos to allow the residual moisture to equilibrate. A newer method is to process the beans directly from storage at their normal moisture content by heating them quickly in a fluidized bed dryer. Then the beans are cracked and dehulled while still hot. The meats are then conditioned in a second fluidized bed dryer prior to flaking.

Within the past 15 years, many processors have installed equipment to produce pellets or collets from soybean flakes and other oilseeds. This machine is called an expander and consists of a tubular barrel, a feeding device that takes material into the barrel, a cut flight screw inside the barrel, bolts that protrude from the barrel into the spaces between the discontinuous flights to add shear to the material inside, a die plate at the outlet of the barrel through which the extruded material leaves the machine, and a large motor and drive that powers the unit. Live steam injected into the barrel heats and cooks the oilseed and raises its moisture content. The purpose of using an expander is to rupture additional oil cells and increase the pellet's density when compared to the flake. However, the most important benefit is to greatly improve the drainage of the solvent and miscella (mixture of extracted oil and hexane) streams added to the extractor. With better drainage in the extractor, material leaving the extractor has a lower solvent holdup, which reduces the desolventizing duty in the desolventizer-toaster and saves considerable steam energy. Some plants only expand about 20 to 25 percent of the incoming flakes, whereas others expand 100 percent of the stream. As long as no more than about 30 percent of the flakes are extruded, the pellets can be fed directly back

into the remaining flake stream. But if more than 40 percent of the flakes are pelletized, a dryer-cooler must be provided to reduce the pellets' moisture content and cool them to about 165°F (74°C). Higher oil content oilseeds, such as cottonseed, can be extruded and then extracted without first prepressing them in a screw press.

Hot flakes are delivered to the extractor, which is usually of the continuous percolation type. The liquid solvent enters above the flake bed and drains or percolates through the bed to a compartment below the flakes to be recycled by a pump to another stage of the extractor. Most percolation extractors have six or more extraction stages.

The many types of percolation extractors include vertical basket, rotary, stationary bottom, sliding cell, perforated belt, and rectangular loop extractors. Figure 9.10.2 shows a rectangular loop extractor. Fresh, recovered hexane solvent, heated to about 140°F (60°C), contacts flakes near the extractor's discharge end to remove the remaining oil from the flakes. This solvent, which now contains some oil, is pumped from stage to stage in a direction counter to the flakes' flow and becomes richer in oil with each successive stage. Oil extracted from the flakes and mixed with hexane, which is called miscella, usually has a concentration of 25 to 30 percent by weight when it exits the extractor. The amount of hexane solvent added to the extractor is one part solvent to one part flake, by weight. This is the solvent ratio and ranges from 0.85 to 1.10. The extractor normally operates at 140°F (60°C) and at either atmospheric pressure or at a slight vacuum of ½ in. water gauge (gauge pressure of 124 Pa). A variable-speed drive, or variable-speed motor, controls the extractor speed for changes of plant rate and also bed height in the extractor.

After the flakes move beyond the solvent addition point in the extractor, time is provided for hexane to drain. Extracted and drained flakes are conveyed to equipment to desolventize, toast, dry, and cool the material. Two processing systems are used to accomplish this. The first, which is now being phased out in older plants, requires three individual equipment items: (1) the desolventizer-toaster (D-T unit), (2) a rotary steam tube dryer (D), and (3) a rotary cooler (C) using ambient air to cool the meal. The second system, the counter current D-T-D-C, is normally installed in extraction plants. This single piece of equipment achieves the four processing steps (Figure 9.10.3). It consists of eight trays: two predesolventizing trays (1 and 2); two hollow staybolt trays, often called countercurrent trays (3 and 4); one sparge (5); two drying trays (6 and 7); and one cooling tray (8). Additional trays can be provided for each processing step as needed, depending on plant capacity, or the type of oilseed processed.

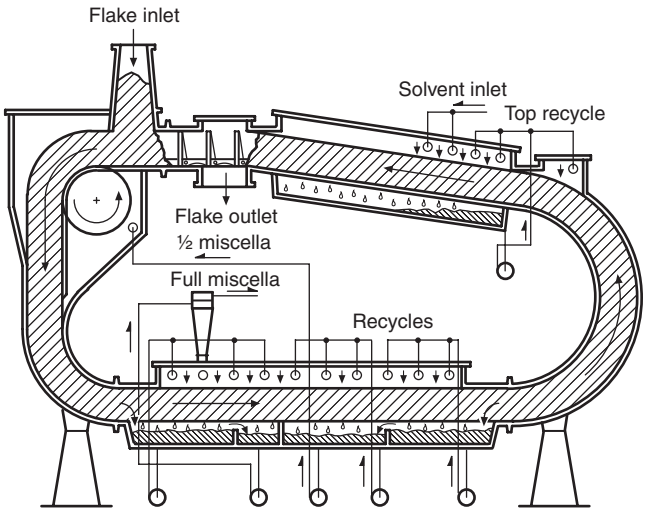

FIGURE 9.10.2 Rectangular Loop Extractor

The processing principles are the same for each type of seed. Open or sparge steam in the desolventizer strips solvent from the flakes. Toasting is accomplished by indirect contact with high-pressure steam in trays 1, 2, 3, and 4 and the open steam. The D-T-D-C is a vertical, cylindrical unit consisting of multiple trays or decks. Flakes drop from tray to tray. Open steam in the top five trays removes solvent. Steam condenses in the flakes, raising the flakes' moisture content. Toasting is also done in these trays, which are also heated by indirect steam.

Usually, the desolventizing step uses about 10 percent excess sparge steam. The D-T-D-C dome's normal operating temperature is about 158 to 165°F (70 to 74°C). The outlet temperature from tray 5 must be at least 221°F (105°C). Lower flake outlet temperature indicates that not all solvent has been removed, which could present a potential safety hazard. Operating pressure at the top of the D-T-D-C should be lower than the pressure in the extractor. This prevents steam vapor from flowing back to the extractor and stops solvent vapor from flowing downward through the outlet of the toasting section. Solvent and excess sparge steam vapors leaving the top of the D-T-D-C are scrubbed with liquid hexane to remove any fine particulates that might be entrained in these vapors, and are condensed, recovered, and reused in the extraction step.

The specially designed rotary valve located at the outlet of tray 5 has a variable speed drive. Its speed controls the operating levels in trays 1 through 5. It also seals tray 5 from tray 6 to prevent drying air from blowing into tray 5 from tray 6. Tray 6 has a much higher operating pressure than tray 5. The rotary valve is a safety device that prevents explosive mixtures of hexane and air from forming in the unit's top five trays.

The desolventized material drops into trays 6 and 7, where it contacts hot air. As the water-moist meal proceeds downwards, heated air is injected through holes in the top of these two trays. The hot air evaporates excess moisture in the meal, and as water evaporates from desolventized meal, its temperature drops. A fan sends atmospheric air through a steam coil air heater and into the trays for drying.

The outlets from trays 6 and 7 each have a gate and sail arrangement. The gate is normally closed until the level in each tray rises high enough to contact a sail at the top of its tray. The sail, located inside the tray, has a shaft that extends through the D-T-D-C shell; the end of the shaft connects externally to the gate at the tray's outlet. When the meal contacts the sail, the sail opens the gate to permit material to exit the tray. This automatically maintains meal levels in the trays.

A steam purge line admits a small quantity of open steam against the rotary valve at the outlet of tray 5. Its purpose is to purge the valve pockets of the hot drying air picked up from tray

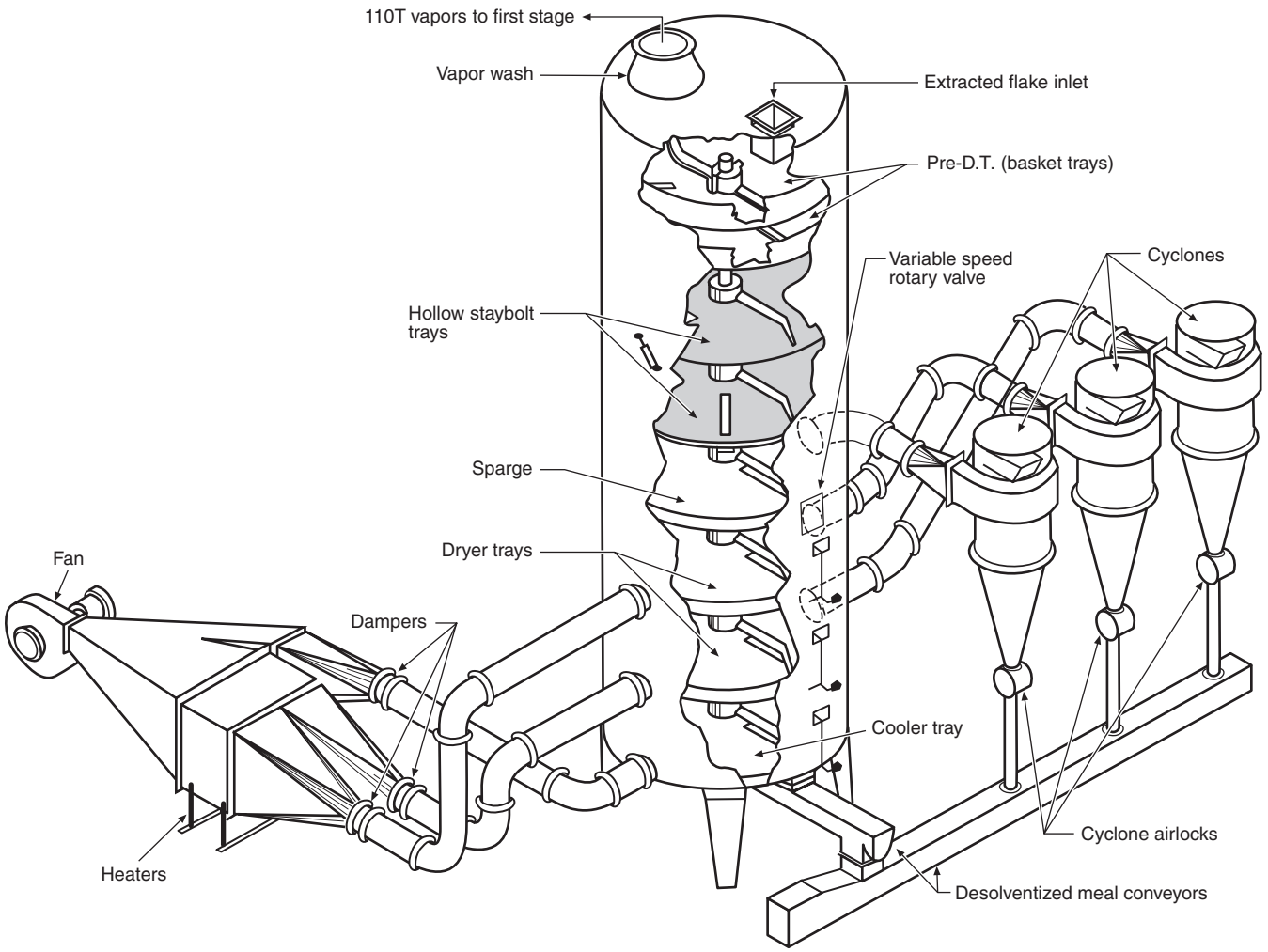

FIGURE 9.10.3 Counterflow D-T-D-C

6 as it turns in its cycle at the top of drying tray 6. The valve pockets, now filled with steam, prevent dryer air from entering the desolventizing zones of the unit and forming explosive mixtures there.

Dried meal from tray 7 drops into tray 8 where it is contacted by a stream of cool, ambient air, in similar countercurrent flow as tray 7 and through holes in the top of the tray deck. The same fan that introduces air into the drying trays sends air to the cooling tray. The meal, dried to a moisture content of 12 percent by weight and cooled to between 115 and 120°F (46 and 49°C), is conveyed to the meal finishing system for sizing by the desolventized meal conveyors. Three cyclones, each with a rotary air lock, remove meal fines from the D-T-D-C drying and cooling air streams.

A low temperature alarm sounds when the meal temperature leaving tray 5 drops to 205°F (96°C). It warns of possible carryover of hexane solvent in the meal leaving the desolventizing-toasting section of the D-T-D-C. If the warning alarm is not heeded and the meal temperature continues to fall, a low temperature shutdown switch automatically stops the inlet feed to the D-T-D-C when this temperature reaches 195°F (90°C). NFPA 36, *Standard for Solvent Extraction Plants,* requires both safety devices.

Oil is removed from the solvent in three stages by two long tube rising film evaporators and a stripping column. The first-stage evaporator operates at a vacuum of about 15 in. (51 kPa) of mercury on the tube side and uses vapors from the desolventizer-toaster to provide heat. Miscella from the first stage evaporator has an oil concentration of about 50 to 60 percent. The second-stage evaporator normally operates at atmospheric pressure, using low-pressure steam in the shell side. Final removal of solvent from the 92 percent miscella out of the second stage evaporator is carried out in a stripping column operating under vacuum ranging from 22 to 27 in. (74 to 91 kPa) of mercury at a temperature of 210 to 240°F (99 to 115°C) and using open or sparge steam at the bottom of the column. The vacuum dries or removes water from the oil, and the sparge steam strips the final traces of hexane solvent.

All solvent is condensed and returned to the solvent separator, along with solvent from the flake-desolventizing step. The solvent separator's 15 minute holding interval allows water condensed in the process to separate from the solvent. The water

flows from the separator to a wastewater evaporator, where it is heated to at least 200°F (93°C) with open steam to remove any entrained solvent, before leaving the plant for a wastewater trap and finally to a sewer. The separated solvent returns to the extractor for reuse.

A low-temperature alarm sounds when the temperature of water leaving the wastewater evaporator drops to 185°F (85°C). It warns that carryover of hexane solvent may enter public sewer systems. If the warning alarm is not heeded, and the wastewater temperature continues to fall, a low temperature shutdown switch automatically stops the extractor drive motor when the temperature reaches 175°F (80°C). NFPA 36 requires both safety devices. There was no such alarm and shutdown device at a soybean plant in Louisville, Kentucky, when a massive quantity of hexane entered the sewers in 1981 and blew up 6 miles (10 km) of the sewer system.[1]

The extractor and all other tanks and condensers in the process are vented to a separate header and into a vent recovery system. This system, which uses an edible mineral oil to absorb vent gases, consists of two columns filled with ceramic or metallic packing. One column absorbs hexane solvent vapors with a flow of cool mineral oil counter to the flow of the vapors. The other column strips the absorbed hexane solvent vapors from the mineral oil with open steam. A condensing system condenses these vapors. The mineral oil recirculates continuously for reuse. A blower on top of the mineral oil absorber removes unabsorbed water and air vapors that discharge into the atmosphere through a flame arrestor. The blower also provides a slight vacuum for all equipment in the extraction system. Maintaining the process at a low vacuum prevents solvent vapors from escaping from the system and entering the extraction building. To prevent similar incidents, extraction plants are now equipped with high-pressure alarms and high-pressure shutdown switches. High pressures in the extractor and the top of the D-T-D-C activate these devices. NFPA 36 also requires extraction plants to install relief valves on vessels such as the extractor, solvent work tank, miscella tank, and solvent-water separator. The relief valve provides emergency venting to relieve excessive internal pressures in case of a fire; it also protects the vessels from being ruptured by high internal pressures. The discharge line from the relief valves to the atmosphere must not be provided with a flame arrestor.

Efficiency of the Process

Most designers of solvent extraction facilities make efficiency guarantees for the process. The guarantees are important not only for the profitability of the process but also for safe plant operation. Exceeding these guarantees indicates potential safety problems, and steps must be taken to correct them. The guarantees given here are typical for the soybean processing industry but do vary considerably when other oilseeds are processed. In a process having a capacity that can be measured in U.S. tons/24 hour day, the following conditions can be expected:

1. Solvent loss of 0.055 percent by weight of beans processed or 0.20 U.S. gal/U.S. ton of beans (0.83 L/metric tonne)
2. Residual oil content of flakes from extractor of 0.5 percent by weight, corrected to 12 percent water by weight on a solvent-free basis
3. Crude oil 0.10 percent of total moisture and volatiles by weight that will not flash at 300°F (150°C) in a closed-cup flash tester
4. Soybean flakes from a meal cooler will not exceed a 0.15 pH rise in urease enzyme activity, measured by the Caskey-Knapp method[2]

HAZARDS OF SOLVENT EXTRACTION

The principal hazards specific to solvent extraction operations are the highly flammable solvents used and combustible dusts associated with storing and handling oilseeds. Ignition sources include arcing electrical equipment, static electricity, and open flame. Ignition can occur during regular operations, maintenance operations, or an emergency. Attempts to operate a facility beyond its design capacity can introduce hazards of abnormal operation.

Normal Operations

Solvent Loss. To prevent fires, it is necessary to keep solvent liquid or vapor from leaving the extraction plant and controlled areas. Hexane solvent vapor is about three times heavier than air and, if not dispersed, could possibly enter areas where an ignition source is present. To be ignitable, the vapor concentration in air must be within its flammable limits—1.2 to 6.9 percent by volume. (Consult Table 9.10.1 for details on the physical properties of typical commercial hexane and isohexane.)

The U.S. Environmental Protection Agency (EPA) has published its national emission standard of hazardous air pollutants (HAP) for vegetable oil production from solvent extraction plants. The standards were issued in 2000 in the U.S. Federal Register. EPA considers solvent extraction plants for vegetable oil production as a major source of *n*-hexane emissions and has classified *n*-hexane as a hazardous air pollutant. Therefore, all existing and new solvent extraction processes that are sources (defined as those facilities with the potential to emit 10 tons (9.1 tonees [2004 lb/tonne] per year or more of *n*-hexane) must meet HAP emission standards. The industry will have three years to comply. The emission loss factors values are 12 operating months rolling averages but permit deductions of losses in accordance with the plant startup, shutdown malfunction (SSM) plan.

The EPA has prepared a list of maximum permissible commercial hexane solvent losses for the different oilseeds processed. These hexane loss factors are stated as U.S. gallons/U.S. ton. The loss quantities range from 0.2 gal/U.S. ton (0.86 L/tonne [2204 lb/tonne]) for conventional soybean processing to 0.7 gal/ton (2.6 L/tonne) for peanut extraction. The new EPA requirements have caused U.S. extraction plants to greatly improve their processing efficiencies and solvent recovery systems. All solvent losses must be calculated to include the plant startups, plant shutdowns, plant spills, and plant breakdowns.

Although a solvent loss of about 0.35 gal/ton (1.5 L/tonne [2204 lb/tonne]) had been considered acceptable for soybean plant operations, a maximum loss of 0.20 gal/ton (0.8 L/tonne) must now be achieved in the United States. Since this low solvent loss is now required in the United States, it is only a matter

TABLE 9.10.1 Physical Properties of Typical Commercial Hexane and Isohexane

Property	*Hexane*	*Isohexane, Mixed Isomers*
Flammable limits (percent by vol.)	1.2–7.7	1.0–7.0
Ignition temperature (ºC)	225	264
Flashpoint (ºC), closed up	–26	–18
Molecular weight	86.2	86.2
Melting point (ºC)	–94	–154
Coefficient of expansion	0.00135	NA
Boiling range at 1 atm (1.0 bar), (ºC)	67–69	56–60
Specific gravity at 60ºF (15.6ºC)	0.68	0.66
A.P.I gravity at 60ºF (15.6ºC)	77.2	82.9
Pounds per gal at 60ºF (15.6ºC)	5.63	5.52
Vapor density (air = 1)	≈3	≈3
Cubic feet vapor per gal liquid at 60ºF, and 1 atm (15.6ºC and 1.0 bar)	25.5	NA
Vapor weight (kg per m^3 at 15.6ºC)	3.48	NA
Vapor weight (m^3 per kg at 15.6ºC)	0.29	NA
Latent heat of vaporization at 1 atm (1.0 bar), (kcal/kg)	79.6	NA
Heat of combustion (kcal/kg) (gross)	11,652	NA
(kcal per m^3 vapor [gross])	10,791	NA
(kcal per kg vapor [net])	45,171	NA
Vapor pressure at 37.8ºC (kPa)	38.1	49.4
Specific heat liquid (kcal per kg-ºC at 15.6ºC)	0.531	NA
Specific heat vapor (kcal per kg-ºC at 15.6ºC)	0.339	NA
Solubility in water (moles per L at 60ºF [15.6ºC])	Negligible	Negligible

NA = Data not available.

Source: NFPA 36, *Standard for Solvent Extraction Plants,* Table B.2(a), 2004, p. 36-17.

of time before these new emission regulations will become enforced in other countries. Solvent extraction plants that operate with low solvent losses are inherently safer than those with higher losses.

Conventional Soybean Extraction Plants. Conventional soybean extraction plants range in capacity from about 1000 to over 5000 U.S. tons (409 to 4545 tonnes [2204 lb/tonne]) per day. Based on a solvent loss of 0.2 gal/ton (0.8 L/tonne) and operating 330 days a year, a plant with a capacity of 1000 tons (909 tonnes) per day would emit about 180 U.S. tons (162 tonnes) of hexane solvent per year. Although a soybean plant with a capacity of 1000 tons (909 tonnes) per day was once considered a large facility, new plants now constructed can have a capacity of over 5000 tons (4545 tonnes) per day. The new 0.2 gal/ton (0.8 L/tonne) EPA regulation for solvent loss is a very strict one, and plant operators will have to be very diligent to meet this low solvent loss requirement.

Large-Capacity Solvent Extraction Plants. Within the past five years many large high capacity soybean extraction plants have been constructed and placed into operation. These capacities range in size from 5500 to 15,400 U.S. tons (5000 to 14,000 metric tonnes) per day. The large plants are located in Argentina, Brazil, and the United States.

When the original NFPA 36 was published in 1959, an extraction plant with a capacity of about 250 tons (225 tonnes) per day was considered a normal average size. A capacity of 1000 tons (909 tonnes) per day was deemed to be a large plant. The committee writing the NFPA 36 Standard at that time never imagined that a 14,000-tonne-per-day plant would be thought of, let alone constructed.

Some of the rules written in the 2004 edition of NFPA 36 are the same as those published in 1959. The NFPA 36 Committee must now review NFPA 36 to determine if changes must be made to specifically cover these newer installations that process such large quantities of oilseeds.

Solvent loss in a soybean extraction plant is a key indicator of possible hazards during normal operation. Solvent loss of 0.055 percent by weight of the material processed is considered within the bounds of efficient operation. If the loss exceeds 0.10 percent by weight, reasons for the increase must be found and corrective action taken. Table 9.10.2 shows the five sources of solvent loss from the conventional soybean extraction process and the percentage of loss attributed to each.

It is of primary importance to prevent flammable solvents from leaving the extraction building and entering the preparation building. This can happen if solvent remains in the flakes after they have been removed from the desolventizer-toaster and sent to the preparation building to be ground, sized, and finished. Because the equipment in this building is not explosionproof, ignition could occur with disastrous results.

TABLE 9.10.2 Sources of Solvent Loss from the Solvent Extraction Process

	Loss (gal/ton)	*Loss (lb/ton)**	*Loss (% by weight)*
Flakes from D-T unit	0.110	0.6084	0.0304
Leaks	0.056	0.3097	0.0155
Vent gas from vent system	0.020	0.1106	0.0055
Oil from oil stripper	0.014	0.0774	0.0038
Effluent from process waste water	—	0.0001	0.0001
Total	0.200	1.1062	0.0553

*Pounds of solvent per ton of material processed.

Startup, Shutdown, and Purging. The startup or shutdown of an extraction plant introduces a transient hazard. The equipment, especially the extractor, is full of air before startup. As hexane solvent is added, the concentration of solvent vapor and air mixture that is inside the extractor passes through the flammable range of 1.2 to 6.9 percent by volume. Two methods eliminate the possibility of ignition by static electricity when using hot liquid to purge the extractor of air. One method is to design the plant so hot vapors from the second stage evaporator flow into and rapidly heat the extractor to 104°F (40°C), thus replacing the air. The advantage of this procedure is to shorten extractor heat-up time, usually about 4 hours, to about ½ hour. Stage pumps do not start until the extractor is hot. The second method is to replace extractor air with carbon dioxide or nitrogen gas before adding hot liquid hexane to the extractor.

Vapor-proof slide gates located upstream and downstream of the extractor are closed during warmup to prevent hexane solvent vapors from flowing back to the preparation building.

A normal or controlled shutdown is accomplished by emptying the extraction plant of all oilseed flakes and hexane liquid and purging the empty extractor or desolventizer-toaster unit with air until the unit cools. Steam purging is used if normal maintenance is required inside the extractor.

If welding is necessary in the extraction area, personnel must take the following precautions:

- Empty all solids and liquids.
- Store hexane from the plant in solvent tanks isolated from the plant.
- Steam purge the extractor, desolventizer-toaster unit, and all equipment containing hexane or miscella.
- Fill all vessels with water.
- Use water to seal flake connections from the extractor and desolventizer-toaster unit to the preparation building.
- Use a portable gas analyzer to locate possible flammable mixtures.

Inert gas is satisfactory for purging an empty extractor before normal startup procedures. Inert gas can also be used for purging during normal shutdown, but steam purging is a surer method than inert gas purging for removing solvent vapor.

Abnormal Operations

Emergency Breakdowns. A serious hazard in the operation of a solvent extraction plant is an emergency breakdown in the extractor when it is full of solvent-laden flakes and cannot be emptied. Quite often the problem can neither be determined nor corrected without someone entering the unit.

The extractor should be cooled to about 104°F (40°C). The required time to do this depends on the extractor size and its specific method of operation. During this time, a plan for correcting the problem should be devised and approved by a supervisor. The extractor must then be purged with air, using the extractor purge blower provided with the unit. The purge blower air flow capacity should be 1 extractor volume air change every 3 minutes, based on an empty extractor. The purge blower must be of sparkproof construction. Inert gas purging of an extractor that has failed under load does not ensure a nonflammable condition will exist. If the extractor is not equipped with a purge blower, the unit should be steam purged for 24 to 48 hours or longer to be sure all hexane solvent inside the extractor has boiled off.

While air purging, air entering the purge blower must be checked with a meter to detect the explosive limits of hexane. Air purging continues until the air reaches 0.25 percent or less of the lower explosive limit (LEL) of hexane in air by volume. The extractor can be entered, but the purge blower keeps operating during the repair process. Persons entering the extractor must wear a safety harness and an air mask, and be supervised at all times. The LEL of the purged air leaving the extractor must be constantly monitored to ensure it is below 0.25 LEL of hexane. External and internal ignition sources must be eliminated because a flammable mixture of hexane and air might exist.

If a D-T-D-C fails under load, the material in the heating trays may overheat and cause a fire. It is important to immediately turn off the indirect steam to these trays when such a failure occurs. Normally, sparge or open steam is piped into the space above the flakes in the heating trays, which can be added to the unit's trays for several hours to desolventize the flakes and to smother smoldering material inside the trays. Doors on each tray are opened individually and their contents raked until the unit is empty and the problem corrected.

Failures. The supply of emergency cooling water should be sufficient to operate the condensers long enough for a safe shutdown. If cooling water fails, the process must be stopped, the steam to the process shut off, and the vapor slide gates closed. Similar steps should be taken in the event of steam or electrical failures.

System Overloads. If a solvent extraction plant capacity increases above its design rating, this creates a hazard, because normally the solvent condensing capacity is insufficient to recover the solvent. This will result in higher vent pressures and the inherent danger that solvent vapors may be forced into the atmosphere or carried out with flakes to form flammable mixtures.

NFPA 36, *Standard for Solvent Extraction Plants,* 2004 Edition

The 2004 edition of NFPA 36, *Standard for Solvent Extraction Plants,* was approved on January 16, 2004, with an effective date of February 5, 2004, and supersedes all previous editions. The following is a list of several major additions and revisions:

1. Revision of 4.5.3 for transfer of solvent, to correlate with NFPA 30, *Flammable and Combustible Liquids Code*
2. Revision of 5.3.2 to require the design and construction of solvent storage tanks to comply with NFPA 30, *Flammable and Combustible Liquids Code*
3. Revision of Section 7.4, Drainage and Spill Control, to provide more specific design requirements for the separation sump; this includes a new paragraph (2) for Section 7.4.2.3; it also includes a new Section 7.4.2.4 on preventing the outflow of oil, solvent, or miscella from the separation sump to the sewer system under emergency conditions or if the liquid seal fails

4. For Section 7.5, Conveying Systems, addition of Sections 7.5.1, 7.5.2, 7.5.2.1, 7.5.2.2 and the addition of Figure 7.5.2 to illustrate typical locations for providing vent openings in conveying systems
5. Revision of Section 7.6, Cooling Towers, allowing flexibility in locating the various types of cooling towers relative to the extraction process
6. Addition of an exception to Section 8.2.6 that permits an automatic control valve to be installed to regulate the pressure in the extractor, but only if the valve meets specified requirements
7. Addition of the physical property data for isohexane to Annex B to recognize its use as an extraction solvent; this is shown in Table B.2(a), Physical Properties of Typical Commercial Hexane and Isohexane (see Table 9.10.1)

The NFPA 36 Committee is considering the installation of a low temperature alarm and a low temperature shutdown switch if the oil temperature from the final oil stripper falls to a dangerous level and also a low vacuum alarm and shutdown switch if the vacuum in the oil stripper drops to a dangerous level. This is to warn of possible excess hexane solvent leaving with the finished oil.

FIRE PROTECTION

Fire protection for solvent extraction plants involves building construction and services, plant layout, fire protection equipment and systems, and safe operating procedures. Detailed guidance can be found in NFPA 36 and in other related standards, guides, and recommended practices listed at the end of this chapter.

Layout and Construction

Structural elements of solvent extraction plants should be laid out so that separation distances adequately isolate or dissipate flammable concentrations of solvent vapor from ignition sources. Figure 9.10.4 shows a typical layout and Figure 9.10.5 illustrates typical locations for the air brake vent opening.

The extraction and preparation buildings should be of fire-resistive or noncombustible construction and equipped with some form of explosion relief. It is important that electrical wiring and equipment be suitable for use in the presence of flammable vapors. All vessels, pipes, tubes, and hoses containing or carrying flammable solvent should be electrically bonded together and grounded to prevent the buildup of a static charge. Portable flammable gas detectors should be available for monitoring the atmosphere.

For a process involving combustible dust, electrical wiring and equipment should be suitable, a dust collecting system should be provided, and protection against static electricity discharges should be installed.

Programmable logic control (PLC) systems along with computers are now being installed to monitor and control the operations of extraction plants. Locating these systems in the extraction building control room is convenient, but since they are not of Class I, Groups C and D, Division 1, construction,

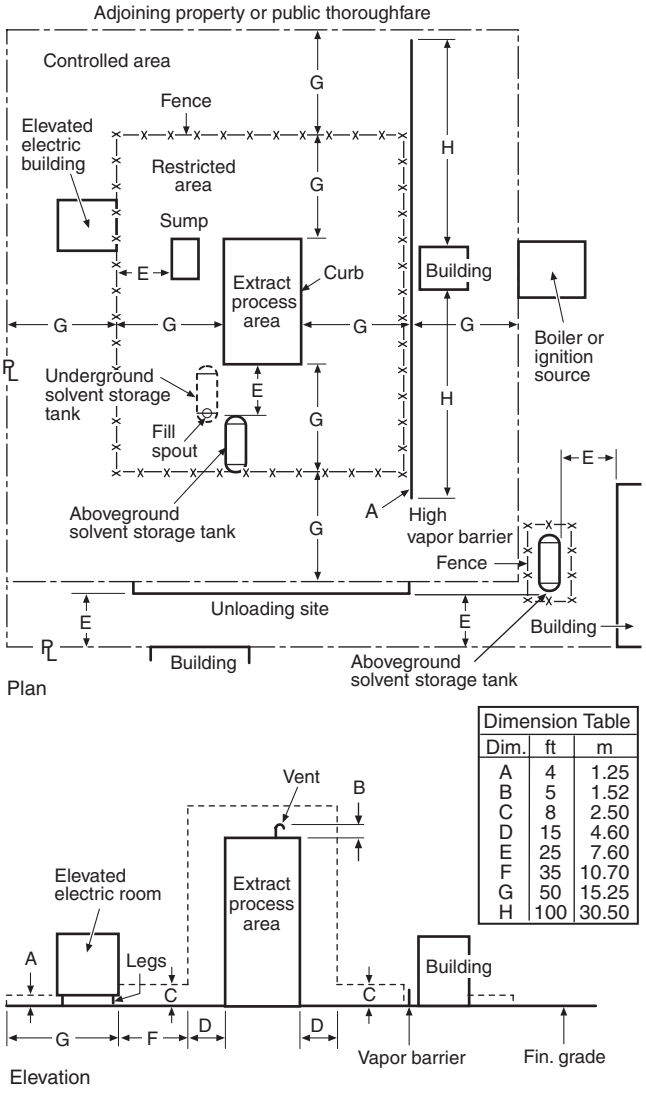

FIGURE 9.10.4 Typical Distance Diagram

special control room design must be provided. In such a design, the extraction plant control room must be designed in accordance with NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment.* Type X purging must be used; this design reduces the classification within the control room from Division 1 to nonhazardous.

Fire Protection Equipment

Water spray, deluge, or foam-water systems—singly or in combination—are suitable for use in extractor buildings. Automatic sprinkler systems are appropriate for use in preparation buildings. Portable fire extinguishers of the proper types and sizes may adequately protect the solvent unloading and storage area, if it is isolated from exposure hazards.

Portable fire extinguishers should be strategically located. The facility may also have standpipe and hose systems equipped with combination nozzles. A system of yard hydrants is an es-

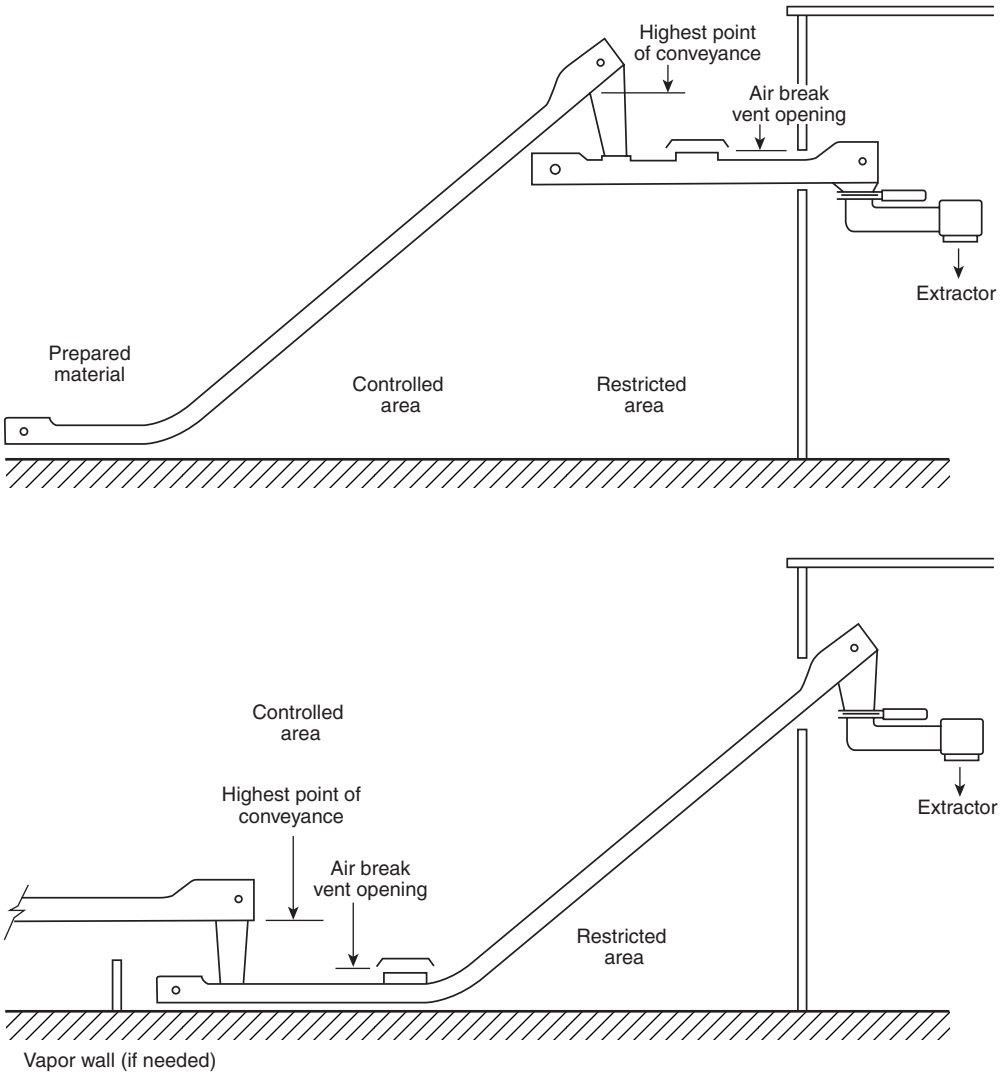

FIGURE 9.10.5 Typical Locations for Air Break Vent Opening (Source: NFPA 36, *Standard for Solvent Extraction Plants,* Figure 7.5.2, 2004, p. 36-12)

sential part of protection. Finally, the available water supply must adequately meet the needs of fixed protection and yard hydrant systems.

Policies and Procedures

It is imperative that solvent extraction equipment be operated in the manner the manufacturer prescribes and that no attempt be made to bypass or defeat safety devices and systems. Company policy should limit the output demanded of the extraction plant and not overtax its design capacity. Policy should also provide for shutdown in the event of excessive solvent loss and for regular maintenance and cleaning operations. If solvent loss increases from 0.095 to 0.135 weight percent per ton, 0.35 to 0.50 U.S. gal/ton (1.5 to 2.1 L/metric tonne) of material processed, an abnormal hazard exists and preventive action must be taken.

Fire prevention is a key factor in any fire protection program. It includes conspicuously posting safety rules and emergency procedures throughout the plant, safety education for new employees, appointment of a plant emergency organization, and a compulsory monthly safety program. A safety system audit program must be implemented to regularly check the workability of all safety devices and controls.

If a fire occurs, appropriate action is to activate fire extinguishing systems (if they are not automatically controlled), activate the plant interlock system to shut down all solids-conveying equipment in the plant, turn off the main steam valve to the extraction plant, leave the area, and notify the fire department.

SUMMARY

Oilseeds, such as cottonseed, rapeseed, flaxseed, corngerm, sunflower, safflower, peanuts, and copra, are processed in solvent extraction plants, using commercial hexane as the solvent.

Other flammable solvents, such as mixtures of aromatic hydrocarbons, are used for extracting lignite, Douglas fir bark, and other special raw materials. The principal hazards in solvent extraction operations are the highly flammable solvents used and combustible dusts associated with storing and handling oilseeds. Fire protection for solvent extraction plants involves building construction and services, plant layout, fire protection equipment and systems, safe operating procedures, and emergency planning.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for oilseed solvent extraction plants discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 36, *Standard for Solvent Extraction Plants*
NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 70, *National Electrical Code®*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 385, *Standard for Tank Vehicles for Flammable and Combustible Liquids*
NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment*

Chapter 11

Protection of Wastewater Treatment Plants

James F. Wheeler

Chapter Contents

Operations and Equipment
General Hazards
Process-Related Hazards
Fire and Explosion Mitigation
Fire Protection Measures

Key Terms

collection and pumping system, denitrification, explosion, fuel gas, sewer, sewer gas, sludge gas, wastewater, wastewater liquid treatment system, wastewater solid treatment system, wastewater treatment

This chapter discusses wastewater treatment processes, process equipment, and their fire and explosion hazards. Traditionally, wastewater treatment process equipment is classified according to the various unit operations being performed. The basic unit processes fall into three categories: (1) collection and pumping, (2) liquid treatment systems, and (3) solid treatment systems. Specific unit processes to consider are pumping station wet wells that handle raw sewage or unstabilized solids, preliminary screening and grit removal processes, primary sedimentation, anaerobic digestion, scum collecting processes, and fuel and chemical handling and storage areas. A considerable variety of makes and models of equipment provide the necessary processing. Consequently, the fire and explosion hazards associated with wastewater treatment processes are much too broad a subject to examine in a single chapter. Therefore, this chapter discusses some basic principles of risk evaluation, mitigation, and fire protection that can be applied generally to individual unit processes and equipment.

The collection and transportation of liquid wastes, known as wastewater, from a community creates a disposal problem that demands a solution that protects the public's health and comfort. The series of closed conduits (pipes) conveying liquid wastes in a municipality is commonly called a sewer system. Among the first historical traces of wastewater collection is the sewer arch at Nippur, India, which was probably constructed about 3950 B.C. Although other examples of ancient sewers exist, the development of the modern wastewater collection system did not begin in the United States until 1805, with the construction of the first large sewer in New York City.[1]

With the collection of wastewater comes the requirements to provide treatment. All methods aim to produce an effluent that can be discharged without nuisance and that can protect human health and the environment. Modern cities and present-day metropolitan centers could not exist as they do without protecting the health and conveniences that comprehensive collection systems and sophisticated treatment facilities afford. As of 2004, in the United States, roughly 16,250 municipal wastewater treatment facilities served 208 million people and treated approximately 45 trillion gallons (170 trillion liters) of wastewater per day. Of the 45 trillion gallons of wastewater treated daily, 57 percent received greater than secondary treatment, 35 percent received only secondary treatment, 5 percent received less than secondary treatment, and 3 percent was not released to surface water.[2] Thousands of industries and businesses also provide their own wastewater treatment services. In addition, millions of people, most living in rural areas, are still served by individual on-site treatment units, such as septic tanks and small aerobic package plants.[3] As development expands into these rural areas, and as on-site septic systems begin to fail and pollute ground water supplies, new collector sewers must be constructed and larger, more complex treatment plants will be required.

Wastewater treatment covers any artificial processes that remove or alter wastewater's objectionable constituents to make it less offensive or dangerous. Early treatment plants included anaerobic lagoons or cesspools, which provided barely primary treatment, or provided treatment simply by dilution. Modern wastewater treatment began in the United States in 1886 with the introduction of the intermittent sand filter. The wastewater treatment industry grew rapidly during

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the early 1900s with the development of aerobic processes, such as the trickling filter and activated sludge treatment.[1]

In addition to conventional pollutants, such as biochemical oxygen demand (BOD) and suspended solids (SS), today's wastewater industry must be prepared to treat hazardous and toxic industrial waste or explosive and flammable materials that may be illegally or accidentally discharged to the collection system. The treatment of these wastes involves highly specialized knowledge of the design, construction, maintenance, and operation of sophisticated equipment and processes. Wastewater treatment is a viable and growing industry that is continually changing as demands for better removal of toxic and hazardous materials increase and more sophisticated and complex chemical and biological processes evolve.

For related topics, see Section 6, Chapter 10, "Gases"; Section 7, Chapter 3, "Storage of Gases"; Section 11, Chapter 1, "Waste Handling and Control"; and Section 17, Chapter 8, "Explosion Prevention and Protection."

OPERATIONS AND EQUIPMENT

In a modern wastewater treatment plant (Figure 9.11.1), treatment of wastewater can be broken into three major components: (1) collection and pumping systems, (2) liquid treatment systems, and (3) solids treatment systems. Each component utilizes different processes and equipment. Each also has specific hazards associated with its particular function.

Collection and Pumping Systems

Collection systems gather wastewater from houses, factories, or other sources and transport it to a central facility for processing. Where the terrain is flat, the collection system may consist solely of gravity piping; however, in most areas the collection system includes pumping. Among the many different kinds of collection systems, the separate sanitary sewer and the combined sewer are most common. The separate sanitary sewer carries wastewater from individual homes and excludes storm water, surface water, and groundwater. Sanitary sewers also collect wastewater from industrial and commercial businesses in the service area. Combined sewers carry both domestic wastewater and storm water, as well as industrial wastewater. Although today only separate sanitary sewers are being constructed, many older cities still have thousands of miles of large combined sewers.

Separate sanitary sewers are generally smaller than combined sewers. Sanitary sewers with diameters of 8 to 48 in. (0.2 to 1.2 m) are common. Combined sewers generally are very large, often 20 ft (6 m) in diameter or larger. These collection systems also include other appurtenances, such as manholes, valve boxes, catch basins, curb inlets, and a variety of other structures. Combined sewers may also have regulators or diversion structures that allow overflow directly into rivers or streams during major storms.

Pumping wastewater has long been a problem because of fibrous and stringy material in the wastewater. Rotary and reciprocating pumps are generally not suited for wastewater pumping, unless the wastewater has been treated to remove solids. Even many centrifugal pumps experience problems handling wastewater solids. Today, solids-handling centrifugal pumps with single-suction volutes can pump most wastewater.[4] These pumps have open impellers, thus creating large passageways, as shown in Figure 9.11.2. These centrifugal pumps can also be equipped with bladeless impellers for pumping unscreened wastewater and sludge. Pneumatic ejectors have also been used successfully for handling small volumes of unscreened wastewater.

A flat efficiency curve is desirable for sewage pumps, because the head against which the pump must work is variable.

FIGURE 9.11.1 Modern Wastewater Treatment Plant

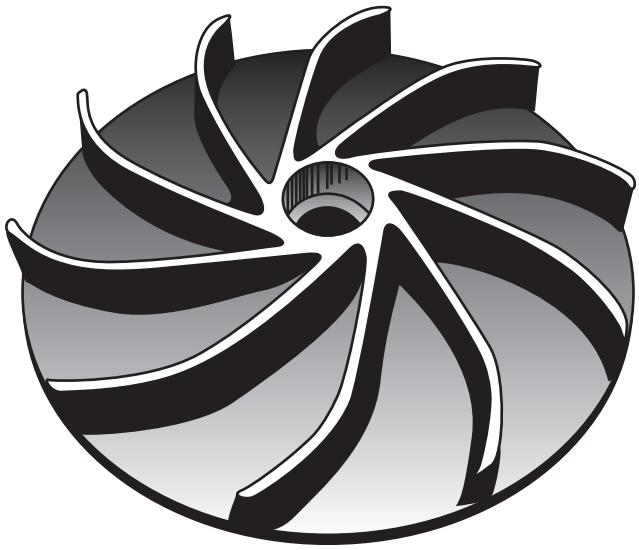

FIGURE 9.11.2 Open Nonclog Impeller for Pumping Raw Sewage

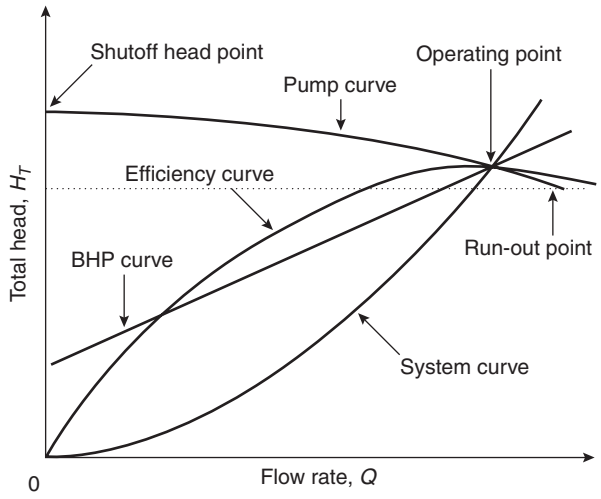

FIGURE 9.11.3 Typical System Head Curve for a Sewage Pump

Figure 9.11.3 illustrates a typical system head curve showing discharge head versus efficiency. The special nonclog impellers used in sewage pumps are generally less efficient than the enclosed impellers used to pump potable drinking water. Since dependability is more important than efficiency in most wastewater pumping applications, slow-speed operation is desirable because it reduces wear on the impeller and increases equipment life.

Most pumping stations have two parts, a dry well and a wet well. The wet well receives and temporarily stores wastewater. Wet wells often contain screens that remove large solids that could damage the pumps. Wet wells may also contain mechanical equipment, fans, lights, and so on. However, most electrical equipment, including motors, pumps, and switches, are placed in the dry well. Most pumping stations have both above and below ground structures, as shown in Figure 9.11.4, although some smaller stations are placed entirely underground, as shown in Figure 9.11.5. Figure 9.11.6 shows a suction lift pump that can be used in either station configuration.

When the required lift is too great for suction lift pumps (approximately 30 ft [10 m]), horizontal or vertical flooded end suction pumps can be mounted in the dry well side of the pumping station (Figures 9.11.7 and 9.11.8). Many large pumping stations use multiple pumps with various capacities designed to handle a wide variation in flow rates. The pumps are generally driven with electric motors that can be mounted horizontally (Figure 9.11.9) or vertically (Figure 9.11.10). The vertical arrangement has the advantage of permitting the motor to be mounted above the pump to safeguard it against flooding. Depending on the service needed, motors can be open drip proof, totally enclosed fan cooled, water resistant, or explosionproof. Pumps can also be connected to diesel or gas-driven engines, for use during emergencies or power failures.

Today many pumping stations use submersible pumps as shown in Figure 9.11.11. These pumps are located in the wet well, thus eliminating the need for a dry well. The discharge

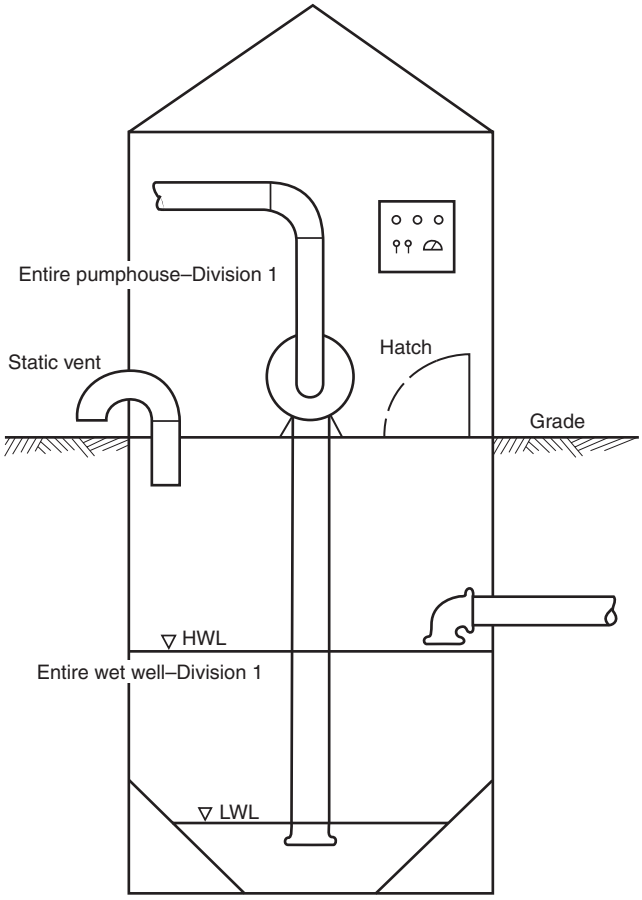

FIGURE 9.11.4 Typical Above/Below Ground Pumping Station

piping can be equipped with quick disconnects so the pumps can be removed from the wet well for servicing without entering the wet well, as shown in Figure 9.11.12. Submersible pumps can be supplied with explosionproof motors for use in hazardous environments.

Where interruption to the normal electric power source is possible, an auxiliary power source is often required. In larger stations, electric generators or gasoline or natural gas engines are provided. The engines connect directly to the pump shaft by means of a right-angled gear drive unit so that either the engine or electric motor can be used by operating a clutch. Some gas engines are dual-fuel compatible and can use either natural gas or methane gas produced at the treatment plant by anaerobic digestion of sewage sludge.

Liquid Treatment Systems

Liquid treatment processes remove objectionable constituents from the wastewater so treated water can be returned to the environment without being offensive or dangerous to public health. The principal components of liquid treatment are preliminary treatment, primary treatment, secondary treatment, tertiary treatment, and disinfection. A typical schematic flow and

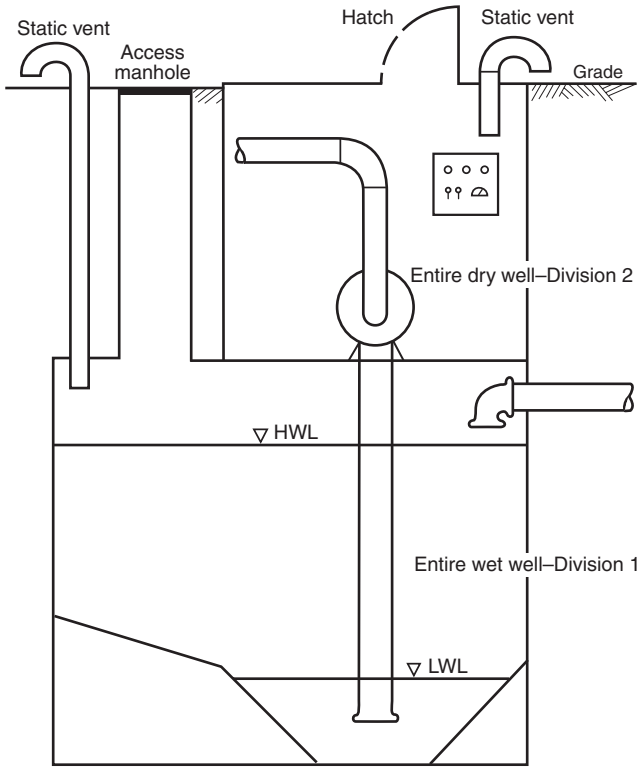

FIGURE 9.11.5 Typical Below Ground Pumping Station

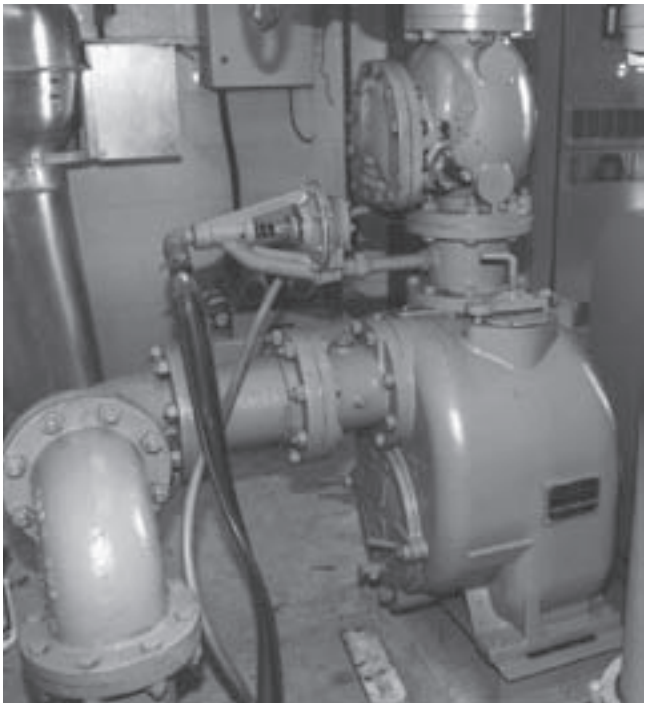

FIGURE 9.11.6 Typical Suction Lift Pump

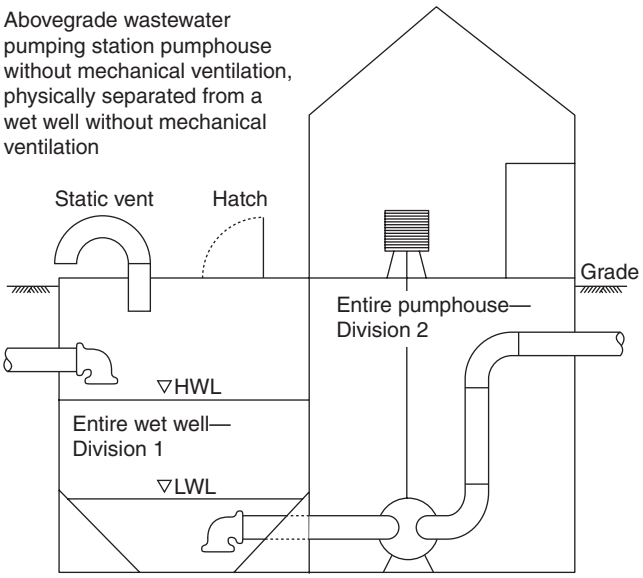

FIGURE 9.11.7 Typical Pumping Station with Vertically Mounted Pumps (Source: NFPA 820, *Standard for Fire Protection in Wastewater Treatment and Collection Facilities,* Figure A-2.19, 1992, p. 820-59)

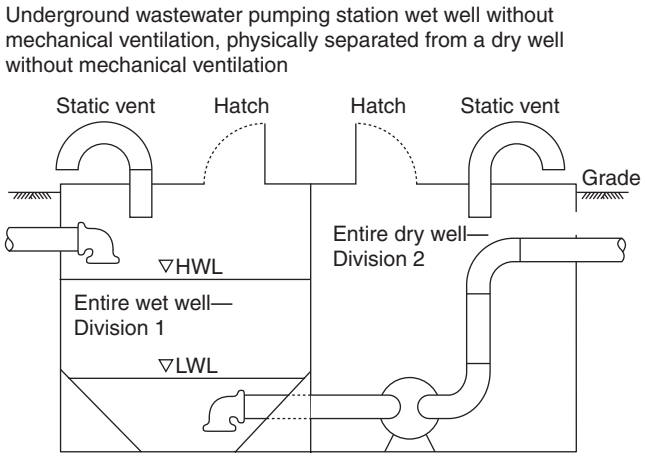

FIGURE 9.11.8 Typical Pumping Station with Horizontally Mounted Pumps (Source: NFPA 820, *Standard for Fire Protection in Wastewater Treatment and Collection Facilities,* Figure A-2.10, 1992, p. 820-50)

process diagram for wastewater treatment is shown in Figure 9.11.13.

Preliminary treatment conditions wastewater as it enters the treatment plant. Preliminary treatment removes materials that might harm or adversely affect the operation of the treatment plant or process equipment. Such material may include lumber, cardboard, rags, stones, sand, plastic, and grit. Methods and equipment used to remove these materials include comminutors, mechanically or manually cleaned bar racks, and bar

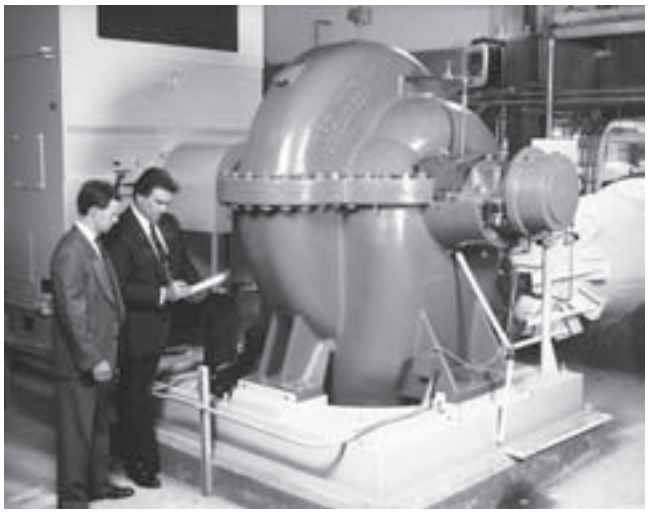

FIGURE 9.11.9 Typical Large Pumping Station with Horizontally Mounted Pumps

FIGURE 9.11.10 Typical Large Vertically Mounted Pump

screens. Particularly in combined sewers, grit and sand washed into the collection system from the street can damage mechanical equipment and adversely affect downstream units, such as sedimentation tanks and digesters. Grit is generally removed by gravity or in aerated grit chambers.

Primary treatment includes first-stage sedimentation, which removes settleable suspended solids, and floating material, such as grease and scum, from the wastewater. Figure 9.11.14 shows a typical primary clarifier. Well-operated primary treatment facilities may remove as much as 60 percent of the influent-suspended solids and 30 percent of the influent biochemical oxygen demand. However, primary treatment does not remove colloidal or dissolved solids. Some treatment plants add chemicals, such as lime, alum, or ferric chloride, to increase colloidal solids removal.

Secondary treatment is intended to reduce the concentrations of remaining suspended solids and dissolved and colloidal organic matter in wastewater. Such material is not removed to any significant degree in primary treatment. A wastewater

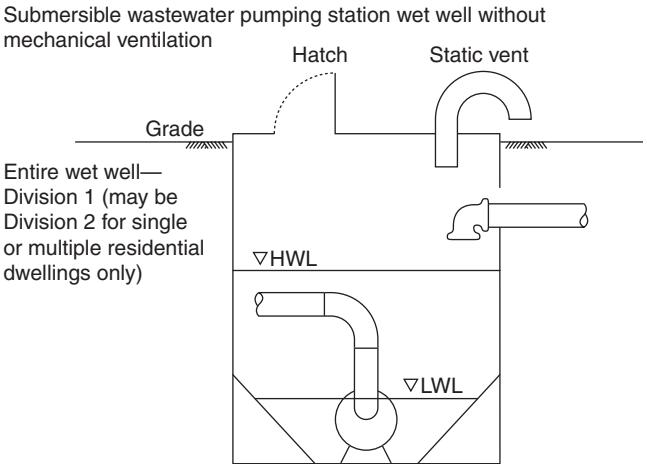

FIGURE 9.11.11 Typical Submersible Pumping Station (Source: NFPA 820, *Standard for Fire Protection in Wastewater Treatment and Collection Facilities,* Figure A-2.2, 1992, p. 820-42)

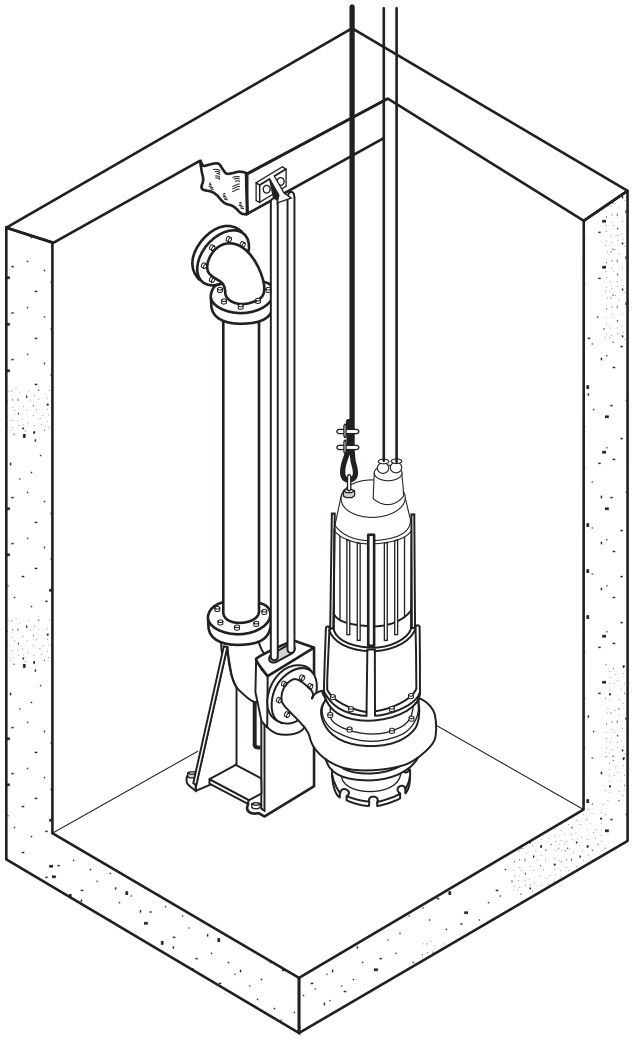

FIGURE 9.11.12 Typical Submersible Pumping Station

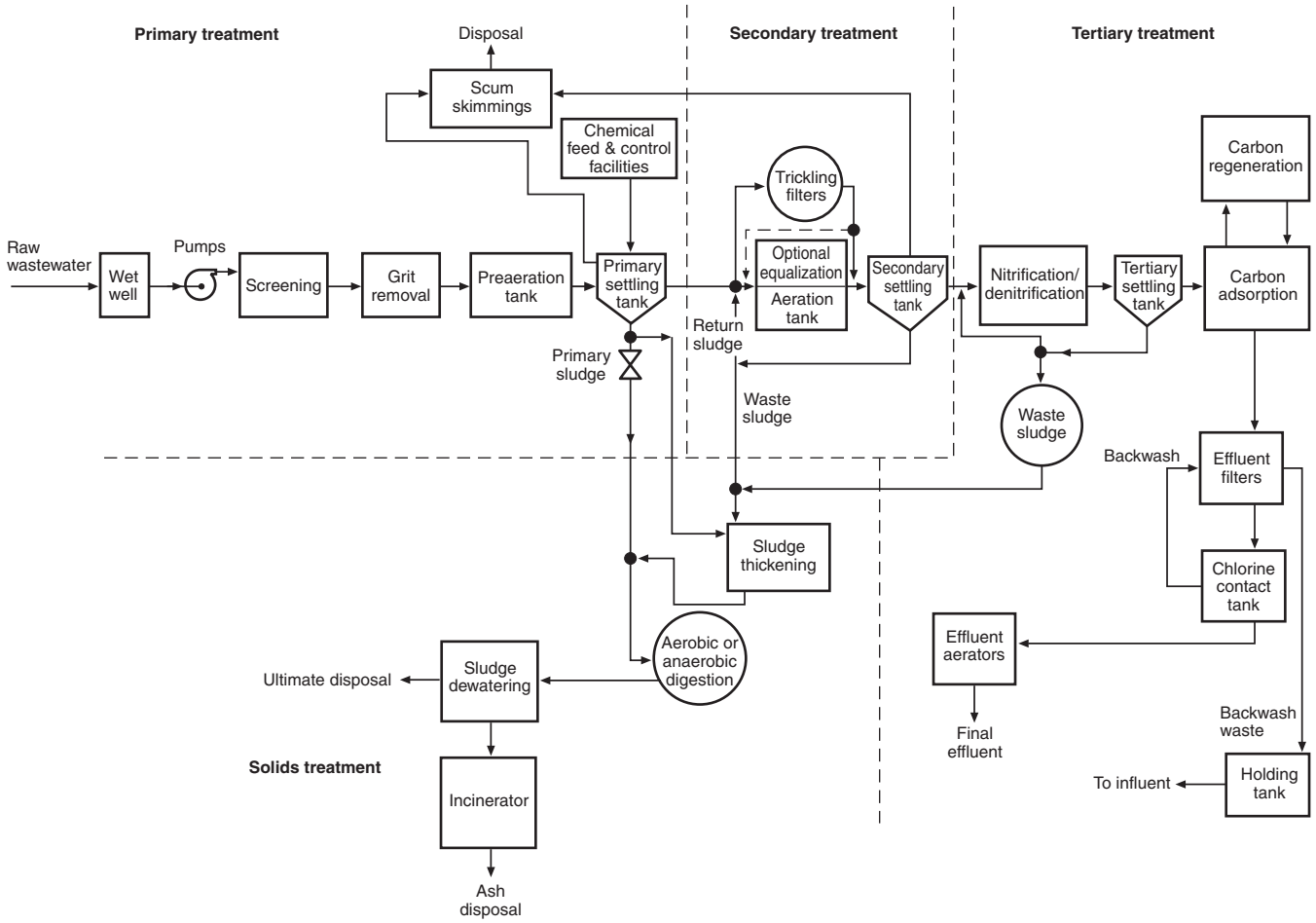

FIGURE 9.11.13 Typical Schematic Flow and Process Diagram (Source: NFPA 820, *Standard for Fire Protection in Wastewater Treatment and Collection Facilities*)

FIGURE 9.11.14 Typical Primary Clarifier

treatment plant having secondary treatment following primary treatment commonly can remove 85 percent of the influent-suspended solids and biochemical oxygen demand of the raw wastewater. Secondary treatment processes may be either biological or physical-chemical.

Most municipal secondary treatment processes are biological. These processes may be classified as fixed film or suspended growth. Fixed film processes include trickling filters, biotowers, and rotating biological contactors (RBC). In these processes a thin biological slime (film) grows on a fixed surface. Figure 9.11.15 shows a typical trickling filter with plastic media. Suspended growth processes include aerobic ponds, oxidation ditches, and a variety of air- and pure oxygen–activated sludge systems. Although not flammable, oxygen-rich atmospheres will greatly accelerate the rate of combustion. In these processes, the biological organisms are suspended in liquid (Figure 9.11.16). In each process, a mixed population of microorganisms establishes in the presence of oxygen. These microorganisms metabolize dissolved organic matter in wastewater and form a biological mass. The effluent from fixed film or suspended growth processes contains suspended biological solids. A portion of these solids called waste sludge is removed from the treated wastewater in a secondary sedimentation tank for further processing. A portion of these solids called return sludge may be recycled to the head of the suspended growth process for additional treatment, as shown in Figure 9.11.13.

In a small number of cases, physical-chemical treatment is used in place of, or combined with, biological unit processes. Physical-chemical processes can include chemical addition,

FIGURE 9.11.15 Typical Trickling Filter with Plastic Media

FIGURE 9.11.16 Typical Activated Sludge Aerated Tank

coagulation, precipitation, and filtration to remove suspended matter, and activated carbon absorption to remove soluble organics. In addition to lime, alum, and ferric chloride, a variety of anionic and cationic polymers also enhance settling in the physical-chemical process.

Tertiary treatment is used, as required, to reduce the concentration of inorganic and organic constituents below concentrations achievable through secondary treatment. Tertiary treatment also includes removing nitrogen and phosphorus by additional unit process operations. Tertiary treatment processes may be physical, chemical, biological, or a combination. A wide variety of chemicals are used in tertiary treatment processes. Most common are lime, alum, ferric chloride, polymers, methanol, chlorine, carbon, ozone, and oxygen.

Disinfection is required to destroy pathogenic bacteria, viruses, and amoebic cysts commonly found in wastewater. Disinfection processes may be chemical (chlorination or ozonation) or physical (ultraviolet irradiation). Chemical disinfection using chlorine is the most widely used means of wastewater disinfection. Ozone and ultraviolet irradiation are produced on site. However, chlorine is generally supplied as a gas or liquid. Smaller plants use chlorine gas in 150 lb to 1 ton (23 to 907 kg) cylinders, while larger plants may use chlorine in bulk from a tank truck or railroad tank car. Today many treatment plants also require dechlorination to protect aquatic plants and animals from the toxic effects of any chlorine remaining in the effluent. The most common chemicals used in dechlorination are sulfur dioxide or activated carbon.

Solids Treatment Systems

Solids treatment processes further treat the sludge or biosolids removed from wastewater by the liquid treatment processes. Sludges withdrawn from the treatment processes are still largely water, as much as 97 percent. The principal components of solids treatment are digestion, thickening, dewatering, and disposal. Figure 9.11.13 shows a flow schematic and process diagram for a typical solids treatment system.

Sludge handling and disposal are often the most difficult, important, and costly parts of wastewater treatment. Sludge may be stabilized either under anaerobic or aerobic conditions. Anaerobic sludge digestion occurs in the absence of free oxygen. The digested solid end product of anaerobic digestion is relatively nonputrescible and inoffensive. The off-gas produced in anaerobic sludge digestion contains about 65 percent methane and may be collected and used as fuel.

Areas around anaerobic digesters and other anaerobic treatment processes are especially dangerous, because they produce combustible gases (Figure 9.11.17). The off-gas produced by anaerobic digestion contains about 65 percent methane and 5 percent hydrogen. Figure 9.11.18 shows a typical egg-shaped anaerobic digester cluster. The off-gas from the anaerobic digester is often collected and used as fuel at the treatment plant. Digester gas handling areas can also present a fire and explosion hazard (Figure 9.11.19).

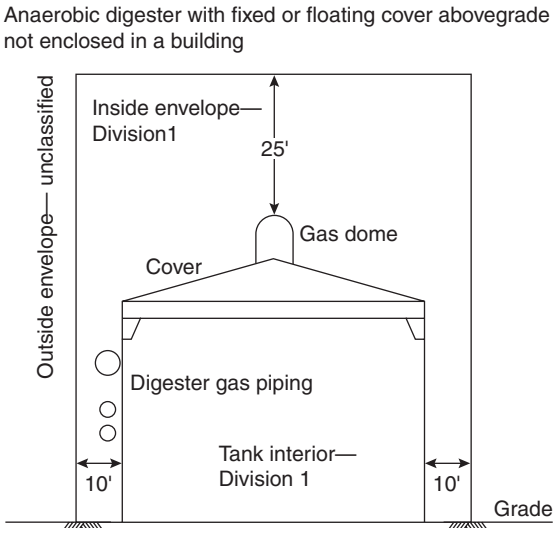

FIGURE 9.11.17 Typical Anaerobic Digester (Source: NFPA 820, *Standard for Fire Protection in Wastewater Treatment and Collection Facilities,* Figure A-4.1, 1992, p. 820-81)

FIGURE 9.11.18 Typical Egg-Shaped Anaerobic Digesters (Courtesy of Appleton Wastewater Treatment Facilities)

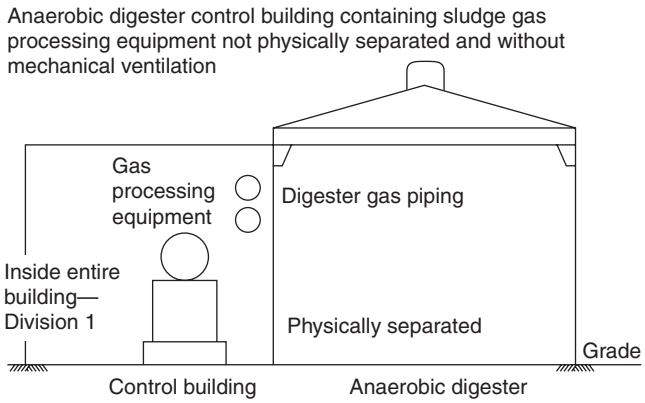

FIGURE 9.11.19 Typical Digester Gas Handling Application (Source: NFPA 820, *Standard for Fire Protection in Wastewater Treatment and Collection Facilities,* Figure A-4.5, 1992, p. 820-83)

Both anaerobic and aerobic digestion results in a reduction in the total volume and weight of excess organic matter. It is often desirable, before final disposal, to reduce further the volume and weight of sludge and to change it from a liquid that is more than 95 percent water to a semisolid form. This dewatering may be accomplished by using drying beds, vacuum filters, centrifuges, filter presses, or mechanical gravity units. The dewatering operation often is enhanced by chemically conditioning the sludge with lime or polymers before dewatering. Conditioning may include a thickening step, which could use gravity or air flotation. Thermal conditioning may also be used to prepare sludge for dewatering.

In smaller plants much of the dewatered and stabilized sludge is trucked to sanitary landfills. Municipal sludge, however, contains essential plant nutrients and useful trace elements. Some treatment plants take advantage of these nutrients and apply the sludge to the land. The sludge can be composted and used as a soil conditioner, or the sludge can be applied as a liquid fertilizer. For larger plants, or where land is not available, sludge is often incinerated. The two most common types of incineration systems are the multiple-hearth furnace and the fluid-bed incinerator. Exhaust gas from the incinerator must be treated carefully to avoid air pollution. The incinerator ash can be toxic and may require special handling and disposal methods.

GENERAL HAZARDS

Many potential hazards may be found in wastewater treatment plants and in the operations they perform. These include explosion and fire hazards, health hazards, and environmental hazards. This discussion, however, deals only with explosion and fire hazards.

Three principal sources of hazards are associated with the wastewater treatment industry. These include materials and chemicals that enter the collection system, materials and chemicals used in the treatment processes, and materials and chemicals produced as by-products of the treatment processes. Hazard sources commonly associated with the wastewater industry include fuel gases, sewer and sludge gases, specialty gases, liquids, solids, dusts, and construction materials.

Fuel Gases

Fuel gases include natural gas, manufactured gas, sludge gas, liquefied petroleum gas–air mixtures, liquefied petroleum gas in the vapor phase, and mixtures of these gases. Some of these gases have specific gravities lower than that of air, so when released they rapidly rise and diffuse above a leakage point. Flammable mixtures are produced when these gases are mixed with air within certain limits, and, since the oxygen content of each gas (when not mixed with air) is generally low, they may also be considered as suffocating gases. In addition, the wastewater treatment plant uses a variety of gaseous, solid, and liquid chemicals that by themselves or mixed with oxygen or other chemicals may be potential sources of fire and/or explosion.

Sewer and Sludge Gases

Sewer and sludge gases are flammable gases resulting from fermentation or decomposition of organic matter. Explosive conditions (especially concerning the anaerobic digestion process) may result when these gases mix with air within certain limits.

Specialty Gases

Specialty gases commonly found in the wastewater treatment plant are used in a variety of operations including (1) laboratory analysis and instrumentation calibration (e.g., hydrogen, methane, etc.); (2) wastewater treatment plant unit processes (e.g., chlorine, ozone, etc.); and (3) welding operations (e.g., acetylene, oxygen, etc.). These gases may provide flammable and/or explosive conditions when either acting alone or mixed with other chemicals.

Liquids

Liquid waste chemical products discharged into the collection system and transported to the wastewater treatment plants may be potential sources or contributing causes of fire and/or explosive conditions. Hydrocarbon liquids, such as gasoline, kerosene, oils, and other solvents, either discharged to drains or used for various applications at wastewater treatment plants, may also provide fire and/or explosion hazards at certain locations.

Combustible Solids and Dusts

Solids, such as granulated or powdered activated carbon, and other combustible dust by-products produced by various wastewater treatment processes, may be combustible and cause potential fire and/or explosive conditions.

Construction Materials

Some construction materials used in wastewater treatment plants, such as plastic, fiberglass-reinforced plastics (FRP), paints and coatings, insulating materials, and furnishings, may either be combustible or limited combustible under certain conditions. Some of these materials present a considerable fuel load, if ignited.

Ignition Sources

In addition to a combustible or flammable fuel source, there must also be an ignition source to cause a fire or explosion. Certain fundamental conditions limit the potential ignition of flammable gases, liquids, and solids (including dusts) found at a wastewater treatment plant. Gases and generated vapors must mix with sufficient air or oxygen to form a flammable mixture and be provided with heat of sufficient intensity for ignition. Ignition may result from one or more of these causes: (1) open flames and hot surfaces, (2) electrical arcs and sparks, or (3) chemical reactions.

Open Flames and Hot Surfaces. These potential means of ignition may be encountered during operations and repairs or with malfunctioning equipment and appliances. Ignition sources can include welding equipment, boilers, incinerators, kerosene-type lanterns, internal combustion engines, and smoking by humans.

Electrical Arcs and Sparks. Sustained arcing faults can extensively damage electrical switchgear and motor control centers. This can provide sufficient heat to ignite flammable gases or vapors present or generated as a result of the arc (e.g., pyrolysis of insulating material).

Sparks generated by defective/worn electrical and mechanical equipment, activities performed by personnel, and static electricity may be ignition sources for gases or flammable vapors.

Chemical Reaction. Fire and explosion may result from the chemical reaction of substances that are (1) introduced by the wastewater treatment plant influent, (2) used for laboratory analyses, (3) required in various unit processes, and (4) produced as by-products. Chemical reactions can cause hazardous conditions ranging in severity from the generation of flames (e.g., spontaneous combustion) to explosions.

PROCESS-RELATED HAZARDS

Many collection systems collect not only wastewater but various hazardous materials and chemicals. Materials and chemicals entering the collection system are the most numerous type of in-plant hazards and the least controllable, and, therefore, probably present the greatest risk of fire and explosion.

Some industries discharge combustible or explosive products, such as alcohol, industrial solvents, hexane, and other liquids and gases. Sewers also collect natural gas or gasoline from leaking pipelines or underground storage tanks. Combined sewers are particularly dangerous because they collect hazardous liquids and gases from highway spills, and fire departments sometimes inadvertently wash flammable hydrocarbons from traffic accidents into the combined sewer. In addition, illegal discharge of explosive or flammable material into the sewer system is always possible. Today utility managers must also be concerned about attempts by terrorists to introduce combustible, flammable, or explosive materials into the collection system in

an attempt to destroy the underground pipes, pumping stations, or the treatment facility.

Pumping stations that handle raw wastewater are subject to the same hazards as the collection system. When confined in a wet well, many hydrocarbons float on the surface of the wastewater. Gases that are lighter than air diffuse rapidly through the structure. Other liquid treatment processes, such as screening equipment and grit chambers that are housed in buildings or in below-grade pits, may be subject to the same fire and explosion hazards as the pumping station wet well. Unit processes, such as primary sedimentation, are generally open and allow lighter gases to escape but may collect and concentrate floating flammable liquids. Secondary and tertiary sedimentation tanks and aeration tanks not preceded by primary sedimentation may also collect and concentrate floating flammable liquids.

Liquid treatment processes are not only subject to the hazardous materials and chemicals in the incoming wastewater. They are also subject to a variety of chemicals used as additives in treating wastewater. Some of these materials are flammable or explosive, some are nonflammable but accelerate combustion, and some are not hazardous by themselves but react with other materials or chemicals. Gases commonly used in wastewater treatment and their physical properties are shown in Table 9.11.1. Their uses (from NFPA 820, *Standard for Fire Protection in Wastewater Treatment and Collection Facilities*) are described below.

Natural gas and gasoline are used as vehicle fuels, to heat buildings and unit processes, to provide hot water for personnel and cleaning operations, and for engine-driven pumps or generators. Figure 9.11.20 shows a typical vehicle fueling station.

TABLE 9.11.1 Gases Commonly Found in Wastewater Treatment Plants

Name (chemical formula)	Explosive Limits (% vol.) *LEL*	*UEL*	*Density*[a] *Heavier/Lighter Than Air*	*Sources*
Ammonia (NH_3)	16	25	L	Storage tank leaks
Chlorine[b] (Cl_2)	Nonflammable		H	Disinfection processes Storage tanks
Gasoline (C_3H_{12}—C_9H_{20})	1.3	7.1	H	Storage tanks Tank truck spills
Hydrogen chloride (HCl)	Nonflammable		H	Storage tank leaks Ceramic diffuser cleaning
Hydrogen sulfide[c] (H_2S)	4.0	44	H	Sewer gas Sludge gas
Natural gas	3.8–6.5	13–17	L	Gas piping leaks
Nitrogen (N_2)	Nonflammable		L	Storage tanks Oxygen generation processes Denitrification processes
Oxygen[b] (O_2)	Nonflammable		H	Generation of oxygen on-site Activated sludge processes Storage tanks Sludge processes
Ozone[b] (O_3)	Nonflammable		H	Disinfection processes On-site generation processes
Sewer gas[d]	5.3	19.3	H	Sewer systems
Sludge gas[e]	5	15	L	Sludge digestion processes
Sulfur dioxide (SO_2)	Nonflammable		H	Dechlorination processes Storage tanks

[a]The table lists the physical properties at standard temperature and pressure. In actual field conditions, these gases might disperse and might be present throughout the structure.
[b]These gases accelerate combustion.
[c]Rarely reaches explosive concentration in wastewater treatment plants.
[d]Contains approximately 70 percent carbon dioxide, 5 percent methane, and 25 percent other gases (Source: United States Environmental Protection Agency).
[e]Contains approximately 65 percent methane, 30 percent carbon dioxide, and 5 percent other gases (Source: United States Environmental Protection Agency).

Source: Data for ammonia, gasoline, hydrogen sulfide, and natural gas from NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids.*

FIGURE 9.11.20 Typical Vehicle Fueling Station

Methanol is used as a carbon source in denitrification processes. (Dentrification is a biological process by which nitrogen is removed from the wastewater.) Oxygen is used in certain types of biological processes, such as oxygen-activated sludge. Chlorine and ozone are used for disinfection, and sulfur dioxide is used in dechlorination processes. Lime, alum, ferric chloride, and polymers are used in sedimentation processes; and granulated and powdered carbon are used in some activated sludge processes or in carbon columns to remove organic compounds.

Solids treatment processes not only use gases and chemicals, but some processes also produce explosive or flammable materials or gases. Although several anaerobic processes produce sludge gas, the principal gas-producing unit process is anaerobic digestion. When organic matter decomposes in the absence of oxygen, sludge gas is produced. This sludge gas is approximately 65 percent methane. Large plants may use this gas as a fuel source. Sludge decomposing in sewers, wet wells, pits, or other tanks can produce a form of sludge gas sometimes called sewer gas. Although never used as a fuel source, sewer gas can contain up to 5 percent methane and can reach explosive limits if confined in inadequately ventilated spaces.[4]

As with liquid treatment processes, natural gas is used to heat solid treatment unit processes, such as anaerobic digesters and other heat treatment processes. Natural gas is also used as a fuel in sludge incinerators. Ammonia is used as a nutrient in some activated sludge processes and is a by-product of air-stripping processes and some composting and sludge dewatering processes. Chlorine and ozone are used in sludge stabilization processes. Hydrogen sulfide, found in sewer gas and sludge gas, is a by-product of some sludge stabilization and dewatering processes. Nitrogen, used as a medium to transport very dry organic material in certain sludge dehydration processes, is a by-product of on-site oxygen generation processes. Some sludge stabilization processes and reaeration processes use oxygen.

Of course, many other chemicals, fuels, and materials used in or around the wastewater treatment plant might present a fire or explosion hazard, if not handled properly. These chemicals and gases include solvents, oxidizing materials, hydrogen, acetylene, kerosene, oils, and various specialty gases used in laboratory analyses and instrumentation calibration. The handling of these gases and chemicals is beyond this chapter's scope, but it is covered in other NFPA documents.

FIRE AND EXPLOSION MITIGATION

General Practice

Control procedures used to minimize potential fire and explosion incidents at wastewater treatment plants include (1) hazard evaluation, (2) risk evaluation, (3) control of fire and explosions, (4) ventilation, (5) construction materials, and (6) education. These control procedures also include proper electrical classification of hazardous locations and proper selection, installation, and operation of electrical equipment, motors, and devices that are suitable for these locations. Effective control procedures cannot be implemented and enforced without the complete cooperation of the public, private, and government sectors, and plant management and personnel, in comprehensive safety programs.

Hazard Evaluation

Hazard evaluation should be initiated early in the design process and hazard prevention and protection recommendations integrated into plant process specification or design considerations. The evaluation should be reviewed and updated periodically as conditions at the plant change. All wastewater processes should be given some kind of hazard evaluation before plants are built and whenever significant changes are made. Some evaluations can be quite informal, whereas others are highly structured with complete documentation and attempts to quantify hazards inherent in the operation.

The first and most important consideration is the identification of potential hazards. The potential hazard associated with raw wastewater entering the plant, materials used in the treatment processes, and materials produced by the treatment processes must be completely understood and evaluated. Effects of temperature and pressure outside of normal ranges must be studied. The possibility of creating a hazardous by-product and gradually increasing its concentration in a closed system must be considered. In other words, there must be complete hazard identification for all aspects of the treatment. With this information, potential severity of the process hazards can be determined. Then the means to control the anticipated hazards can be identified. Hazard analysis begins with complete, comprehensive hazard recognition.[5]

Risk Evaluation

Risk evaluation takes into account the likelihood of the hazard resulting in a fire or explosion. Numerical quantification of the risk requires estimating failure rates of equipment and people. A judgment must be made about the necessary degree of maintenance of all important equipment and instruments, as well as the degree of training and judgment required of operators.

Risk control demands that wastewater treatment processes and equipment be well designed and well maintained to minimize potential for leaking and spilling. Redundant instrumentation, emergency controls, and fail-safe design are some risk-control tools. Venting and pressure-relief systems are essential for preserving process equipment. Damage-limiting construction should be used where processes are housed in a structure. Equipment and piping should be well supported to prevent vibrations that could cause leaks.

Control of Fire and Explosions

The three basic ways to control explosions and fire are (1) remove the fuel or explosive material, (2) remove oxygen required for combustion, or (3) remove the ignition source. In most wastewater treatment plants, controlling fuel or oxygen sources is difficult; therefore, controlling the ignition source is more practical. Each part of the system—collection, liquid treatment, solids treatment, or fuel and chemical handling—has different potential sources of ignition to be considered. In general, the potential for ignition within the collection system is restricted to sites where personnel entry is possible. Therefore, manholes and pumping stations are likely to present the greatest concern. The introduction of ignition sources at these sites must be limited to those occasions following life safety procedural mandates and always with adequate ventilation. In the event that a foreign combustible material enters the sewer system, removal by vacuum or coverage with foam may be necessary.

Potential for ignition within the liquid stream of a treatment plant is restricted to flammable materials entering the early stages of treatment and to flammable gases generated as by-products of wastewater decomposition in nonflowing or septic portions of the liquid stream. Introduction of ignition sources into these areas should be limited, and adequate ventilation should always be provided.

Conditions in the solids treatment stream are often similar to liquid treatment processes. Potential for ignition within the solids treatment process is restricted to floating flammable materials skimmed from tanks and to flammable gases generated as by-products of anaerobic decomposition of sewage solids. Introduction of ignition sources into these areas should be limited, and adequate ventilation should always be provided.

Fuel and chemical handling and storage areas, including laboratories, require special consideration. In general, potential for ignition is restricted to reactive or flammable chemicals, liquid fuels, flammable natural fuel gases, and fuels generated as by-products for use in various unit processes. Introduction of ignition sources into these areas should be limited, and adequate ventilation should always be provided. Chemicals and fuels should always be stored in accordance with safety codes and the manufacturer's instructions. Reactive chemicals should always be stored separately.

Ventilation

Mitigation of explosions and fire hazards is best achieved by copious flushing with fresh air (i.e., ventilation). Ventilation rates for enclosed spaces containing wastewater exposed to the atmosphere should be based on the calculated vaporization rate of the most volatile liquid anticipated to be present in the wastewater. In considering ventilation requirements, the designer should base calculations on the surface area of channels, tanks, or other vessels containing wastewater exposed to the atmosphere; the temperature of the wastewater; the ambient air temperature; and the volatilization rate of the volatile liquid. Allowances should be made for vaporization rate of the liquid from the free water surface in connecting sewers within a reasonable distance from the structure, turbulence that may accelerate vaporization of the volatile liquid, inefficiency of the ventilation system in purging the enclosures, and any other factors that the designer could reasonably expect to affect the release rate of the flammable vapor to the structure. Table 9.11.2 presents typical ventilation rates for various areas in wastewater treatment plants. Ventilation rates should conform to Table 9.11.2 or be based on actual calculations, whichever is greater.

Construction Materials

Construction materials can be divided into three basic categories: (1) combustible, (2) noncombustible, and (3) limited combustible. NFPA 220, *Standard on Types of Building Construction,* defines these terms. Construction materials for wastewater treatment plants should be selected based on the fire hazard and fire risk evaluation. Proper application of construction materials will not prevent explosion or fire hazards. Proper application may, however, reduce or eliminate effects of fire or explosion by maintaining structural integrity, controlling flame spread and smoke generation, preventing the release of toxic products of combustion, and maintaining the facility's serviceability and operation.

Construction materials meeting the definition of noncombustible should be used in all building or unit processes considered *critical* to the integrity of the treatment plant (e.g., raw wastewater pumping station), and, if out of service for even a few hours, could permanently or unacceptably damage the environment or endanger public health by allowing the release of raw wastewater or sludge. All buildings should be constructed in accordance with national and local fire and building codes.

Construction materials meeting the definition of noncombustible or limited combustible should be used in building or unit processes that are considered *important* to the integrity of the treatment plant (e.g., biological treatment), and, if out of service for short periods of time, would not permanently or unacceptably damage the environment or endanger public health, but would become critical if out of service for several days.

Any appropriate construction materials can be used in other areas of the treatment plant, where being out of service for a week or more would not permanently or unacceptably damage the environment or endanger public health.

For separate sanitary sewers serving residential areas, where there is limited possibility that significant quantities of flammable or hazardous materials will enter the system, all appropriate material may be considered. For separate sanitary sewers that may handle flammable or hazardous materials and for all combined sewers, only materials meeting the definition of noncombustible or limited combustible should be used.

TABLE 9.11.2 Minimum Ventilation Rates

Description	Ventilation Rate, Air Changes per Hour, or Velocity as Noted		
	Class I, Div. 1	*Class I, Div. 2*	*Unclassified*
1. Wet wells, screen rooms, and other enclosed spaces with wastewater exposed to the room atmosphere	<12 air changes/hr	≥12 air changes/hr	
2. Below-grade spaces (such as dry wells, equipment rooms, tunnels, or galleries)			
(a) With equipment using or processing flammable gas	<12 air changes/hr <74 ft/min (22.2 m/min) velocity in tunnels or galleries	≥12 air changes/hr ≥74 ft/min (22.2 m/min) velocity in tunnels or galleries	
(b) With gas piping		<6 air changes/hr <37 ft/min (11 m/min) velocity in tunnels or galleries	≥6 air changes/hr ≥37 ft/min (11 m/min) velocity in tunnels or galleries
(c) Without gas piping		<6 air changes/hr for dry wells NR for tunnels and galleries	≥6 air changes/hr for dry wells
3. Above-grade spaces (such as equipment rooms and galleries)			
(a) With equipment using or processing flammable gas	<12 air changes/hr <74 ft/min (22.2 m/min) velocity for galleries	≥12 air changes/hr ≥74 ft/min (22.2 m/min) velocity in galleries	
(b) With gas piping		<6 air changes/hr <37 ft/min (11 m/min) velocity in galleries	≥6 air changes/hr ≥37 ft/min (11 m/min) velocity in galleries
(c) Without gas piping		NR for galleries	

Note: NR = no requirement.

Structures entered by personnel who handle raw or partially treated wastewater should be constructed only of materials meeting the definition of noncombustible or limited combustible. When combustible materials and coatings are used, consideration should be given to flame spread rates, smoke generation, and release of toxins during fires.

Noncombustible materials should be used for air-supply and exhaust systems. However, when combustible or limited combustible materials are used to control corrosion, approved smoke dampers and fire dampers should be installed. Separate smoke ventilation systems are preferred; however, smoke venting can be integrated into normal ventilation systems using automatic or manually positioned dampers and motor speed control.

Cellular or foamed plastic material should not be used as interior finish. Roof coverings should be Class A when tested in accordance with NFPA 256, *Standard Methods of Fire Tests of Roof Coverings.* Construction materials and interior finishes should provide a maximum degree of fire resistance, with a minimum flame spread rate and smoke generation for a particular application.

Plastic or fiberglass-reinforced plastic products are often used as construction materials in unit processes, such as rotating biological contactors (RBCs), biotowers, trickling filter media, inclined plate (tube) settlers, ventilation ducts, and other equipment that may be subject to corrosion. Under normal operating conditions, these plastic or fiberglass-reinforced plastic materials may be submerged; however, they may become exposed during maintenance and repair. Extreme care should be taken with open flame, such as repair cutting torches, during any maintenance or repair operation, because exposed plastic or fiberglass-reinforced plastic materials present a considerable fuel load, if ignited.

Education

Another important and often overlooked mitigation measure is education. In-house training programs, such as plant emergency organizations (PEOs), housekeeping, and maintenance, should be established so all employees understand and can identify, prevent, and handle hazardous sources or situations relating to potential fire, explosion, and toxicity. Close liaison should

be implemented between the local fire department (including other authorized emergency personnel) and wastewater treatment plant safety personnel, so that mutually approved emergency procedures (including familiarity of the plant) can be established.

FIRE PROTECTION MEASURES

Wastewater treatment plants receive flammable and combustible liquids and gases in three ways: (1) through the collection system, (2) through introduction into the treatment processes, or (3) as by-products of the processes. In spite of considerable care taken in design and operation, fires and explosions do occur, and fire protection and suppression equipment are necessary. Generally, fire protection and suppression measures used in the wastewater treatment industry include (1) automatic sprinkler systems, (2) chemical suppression systems, (3) standpipes and hydrants, (4) portable fire extinguishers, and (5) special fire protection measures.

Automatic Sprinkler Systems

Automatic sprinkler systems in accordance with NFPA 13, *Standard for the Installation of Sprinkler Systems,* should be installed where appropriate in buildings or structures located at a wastewater treatment plant. The fire hazard evaluation should include detailed hazard classifications, with system density and application rates sufficient to suppress any anticipated fire. In certain areas of the wastewater treatment plant, such as chemical storage areas, underground tunnels or structures, or areas where electrical hazard is the principal concern, the use of other appropriate fire protection measures should be carefully considered and evaluated.

Chemical Suppression Systems

Foam, halon and other clean agents, and dry chemical systems should be installed or used where appropriate in buildings or structures located at a wastewater treatment plant. Foam systems are most effective for wet wells, grit and screening processes, primary clarifiers, and pits and tanks where floating flammable liquid may collect on the surface. Halon and other clean-agent systems are generally used where computer equipment is located. Dry chemical extinguishing systems should be considered in chemical storage areas, underground tunnels or structures, or where electrical hazard is the principal concern and water damage would seriously impair the treatment plant's integrity.

Standpipes and Hydrants

Standpipes, hose streams, and hydrants should be provided where appropriate in buildings or structures located at a wastewater treatment plant. Water supplies should be capable of delivering the total demand of sprinklers, hose streams, and foam systems. In areas with no public water supply or an inadequate public water supply, treatment plant effluent can be used for fire protection if all contaminents have been eliminated. In treatment plants with both a public water supply and a plant water system, the plant water system can be used as the principal water source for the fire protection system or as a backup to the public water supply system.

When the plant water system is the principal source for fire protection, the system must be capable of providing an adequate quantity and pressure and have sufficient standby capacity to meet all fire waterflow requirements. If the plant water system is used as a backup to the public water supply, the system should provide easy access and connection for pumper equipment. Where dual-hydrant systems are used, cross connections (where allowed) between the public water supply and the plant water system must be installed in accordance with local requirements. When fire pumps are the sole source of supply used in the plant water system, multiple pumps with sufficient capacity to meet fire flow requirements with the largest pump out of service should be provided. Pumps should be automatic starting with manual shutdown and should not be subject to common failure of either electrical or mechanical equipment.

Portable Fire Extinguishers

Portable fire extinguishers should be provided in buildings where appropriate in accordance with NFPA 10, *Standard for Portable Fire Extinguishers.* In some areas of the treatment plant, such as basements, underground pipe galleries connecting buildings, and other areas not continuously occupied, existing codes and standards may be inappropriate. In these cases, the authority having jurisdiction should consider local optional requirements for portable fire extinguishers, depending on frequency of occupancy, intended use, equipment contained in the space, and hazard potential for fire and/or explosion.

Special Fire Protection Measures

Some wastewater treatment plants and processes have unique problems that require special fire protection considerations. For example, fire protection measures during construction at both new and existing wastewater facilities should consider life safety, property protection, and potential construction delays, as well as plant or unit process startup. Lightning protection should be provided for those structures with a risk index (R) of 4 or greater, according to NFPA 780, *Standard for the Installation of Lightning Protection Systems.* In addition, arrangements should be made to permit the municipal fire department, police department, or other authorized personnel rapid entry in case of fire or other emergency. The plant emergency organization (PEO), if present, should be properly instructed and trained in the use of all fire protection equipment located at the treatment plant.

Early detection and reporting of fires and explosions is also important in protecting the integrity of the buildings and unit processes. Protective measures that detect flame, heat, or smoke should be selected and installed where needed. The location of proper types of detection equipment (e.g., smoke, heat, flame, etc.) is a function of the hazard severity or electrical classification. Where appropriate, central station, auxiliary, remote station, or proprietary sprinkler waterflow alarm system

monitoring in accordance with *NFPA 72®*, *National Fire Alarm Code,®* should be provided.

SUMMARY

Wastewater treatment processes fall into three categories: collection and pumping, liquid treatment systems, and solid treatment systems. The highest risks of fire and explosion are associated with collection and pumping operations and the early stages of liquid and solids processing. Fire hazards common in the wastewater treatment industry are fuel gases, sewer and sludge gases, specialty gases, liquids, solids, dusts, and construction materials. Fire protection and suppression measures include automatic sprinkler systems, chemical suppression systems, standpipes and hydrants, portable fire extinguishers, and early detection systems.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the protection of wastewater treatment plants. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™*
NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 22, *Standard for Water Tanks for Private Fire Protection*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 31, *Standard for the Installation of Oil-Burning Equipment*
NFPA 37, *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines*
NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals*
NFPA 51, *Standard for the Design and Installation of Oxygen–Fuel Gas Systems for Welding, Cutting, and Allied Processes*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres*
NFPA 54, *National Fuel Gas Code*
NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 59A, *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*
NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 70B, *Recommended Practice for Electrical Equipment Maintenance*
NFPA 70E, *Standard for Electrical Safety in the Workplace*
NFPA 72®, *National Fire Alarm Code®*
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA 82, *Standard on Incinerators and Waste and Linen Handling Systems and Equipment*
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA *101®*, *Life Safety Code®*
NFPA 204, *Standard for Smoke and Heat Venting*
NFPA 220, *Standard on Types of Building Construction*
NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations*
NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 256, *Standard Methods of Fire Tests of Roof Coverings*
NFPA 259, *Standard Test Method for Potential Heat of Building Materials*
NFPA 326, *Standard for the Safeguarding of Tanks and Containers for Entry, Cleaning, or Repair*
NFPA 329, *Recommended Practice for Handling Releases of Flammable and Combustible Liquids and Gases*
NFPA 430, *Code for the Storage of Liquid and Solid Oxidizers*
NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 601, *Standard for Security Services in Fire Loss Prevention*
NFPA 780, *Standard for the Installation of Lightning Protection Systems*
NFPA 820, *Standard for Fire Protection in Wastewater Treatment and Collection Facilities*
NFPA 1142, *Standard on Water Supplies for Suburban and Rural Fire Fighting*

Chapter 12

Fire Protection of Laboratories Using Chemicals

Revised by
Richard R. Anderson

Chapter Contents

Laboratory Design
Protection Strategies
Risk Reduction
Ventilation and Laboratory Hoods
Prevention and Emergency Planning

Key Terms

combustible liquid, compressed gas, cryogenic fluid, duct, evacuation, exhaust system, flammable liquid, hazard identification, hazardous chemical, hood, laboratory, liquefied gas, risk reduction, ventilation system

The fire protection considerations discussed herein focus on the design and operation of laboratories using chemicals to ensure the personal safety of laboratory workers, other building occupants, and emergency response personnel. Laboratories are defined in NFPA 45*, Standard on Fire Protection for Laboratories Using Chemicals,* as facilities where the containers used for reactions, transfers, and other handling of chemicals are designed to be easily and safely manipulated by one person. Other operations that often involve larger containers or quantities involved in producing or synthesizing chemicals are considered to be manufacturing or pilot plants and not laboratories within the scope of NFPA 45.

Laboratories and their buildings can present a mix of people and materials that combine aspects of hazards and population density found in office buildings and industrial sites. To elaborate, the population density of a laboratory is similar to that of an office building, and the hazards of a laboratory can resemble those found in an industrial site that uses flammable liquids and hazardous operations. Only through an adequate understanding of both the hazards and the operations conducted in the laboratory can an effective protection strategy be developed to allow for the two to safely coexist. This chapter details the components of an effective fire protection strategy for laboratories and encompasses passive and active protection strategies. These strategies are based on conducting a risk assessment, including hazard classification; using procedures to prevent fires and other incidents that may lead to a fire; and designing a laboratory that employs fire separation, fire protection equipment and systems, ventilation, and explosion hazard protection. The strategies also include the safe storage and handling of chemicals, chemical waste, and compressed and liquefied gases to prevent or minimize the consequences of a fire event.

For related topics, see Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 8, Chapter 2, "Chemical Processing Equipment"; Section 12, Chapter 9, "Fire and Emergency Services Protective Clothing and Protective Equipment"; and Section 13, Chapter 8, "Managing the Response to Hazardous Material Incidents."

LABORATORY DESIGN

The design criteria for laboratories found in most model building codes consider many elements, including the size of the fire compartment, type of construction, occupant capacity, fire loading, and provision or lack of sprinkler or other suppression protection. The hazardous chemicals to be contained will be classified,[1] and protections specified accordingly. The codes address size and height limitations and required compartmentalization.

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The design of the laboratory and operations within the laboratory should minimize the risk to the laboratory worker. The laboratory layout is important, and designers must view the entire laboratory unit, its furniture, access to means of egress, access for deliveries and pedestrian flow, flammable storage cabinets, spill containment design, and the locations of laboratory hoods, emergency showers and eyewash stations (Figure 9.12.1). The design team should include mechanical and electrical specialists, the persons responsible for the operation and maintenance of the laboratory, and safety and fire protection specialists familiar with laboratory hazards. The design of the laboratory depends primarily on the current and future use of the laboratory.

Laboratory Classification

Laboratory units are classified as Class A (high fire hazard), Class B (moderate fire hazard), Class C (low fire hazard), or Class D (minimal fire hazard). The greatest quantity of flammable and combustible liquids and liquefied flammable gases are permitted in Class A laboratory units, and the smallest quantity in Class D laboratory units. There are requirements in place to account for increases in hazards. As the hazard increases, limitations are enacted on the maximum area of the most hazardous (Class A and B) laboratory units and greater fire separation for Class A and Class B laboratories, and size restrictions for the highest hazard laboratories (Classes A and B).

Instructional laboratory units are classified as Class C or Class D laboratory units. Educational laboratory units are classified as Class D or are limited to 50 percent of the flammable and combustible liquids quantity for Class C laboratory units.

Life Safety in Laboratories

Means of Egress. Main aisles used for emergency egress should have a clearance width of at least 36 in. (0.9144 m) to expedite egress in the event of an emergency. The clearance should always be maintained even in the presence of laboratory stools. The space between adjacent workstations and laboratory benches should be 5 ft or greater to provide ease of access. In a teaching laboratory, the desired spacing is 6 ft. Bench spacing shall be considered and included in specifications and plans. Corridors and public spaces cannot be designated or used for storage, especially of any hazardous materials.

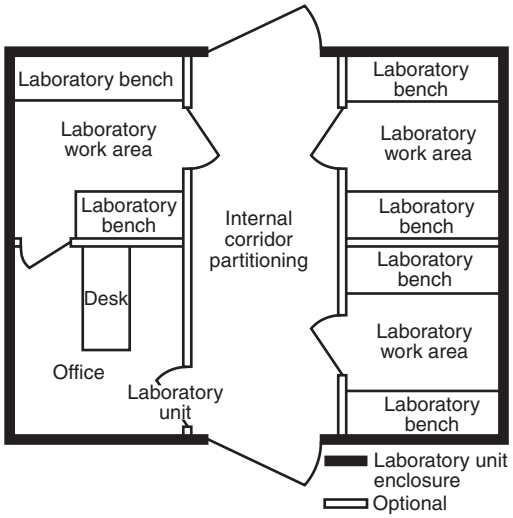

FIGURE 9.12.1 Laboratory Unit

NFPA *101*®, *Life Safety Code*®, when properly implemented, addresses all the life safety issues within a laboratory space, including egress, fire detection and alarms, and the protection of building services. These requirements for notification to the occupants and emergency forces are essential to safe evacuation of the occupants. When flammable liquids or gases are used or stored in laboratories, fires can intensify quickly, and any delay or impediment to egress cannot be tolerated. Based on the use of flammable or hazardous materials utilized in the laboratory, they are typically classified "industrial" by NFPA *101*. NFPA 45 requires laboratories to have a second means of access from the laboratory unit to a means of egress in the following six different situations:

1. An explosion hazard is located in such a manner that an incident would block access to or egress from the laboratory.
2. A laboratory work area within a Class A laboratory unit exceeds 500 ft^2 (46.5 m^2).
3. A laboratory work area within a Class B, Class C, or Class D laboratory unit exceeds 1000 ft^2 (93 m^2).
4. A laboratory hood is located adjacent to the primary means of egress.
5. A compressed gas cylinder is in use that may be larger than a standard lecture bottle and contains a gas that is either flammable or has a health hazard rating of 3 or 4 (see NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*), or prevents the safe egress in the event of an unintentional release.
6. A cryogenic container is in use that contains a gas that is flammable or has a health hazard rating of 3 or 4 or prevents safe egress in the event of an accidental release.

Laboratory Doors. NFPA 45 also prescribes that the door swing of exit access doors from a laboratory unit be in the direction of travel with a hazard classification of Class A (High) or B (Moderate). The laboratory doors should be automatically self-closing to maintain the compartmentalization and required HVAC balance. The doors must be able to be opened with a minimum of effort to allow access and egress for physically challenged individuals.

It is important to address the situation that can occur if recirculated air to the laboratory ceases while the fume hood ventilation continues to operate, creating an extreme negative pressure in the laboratory, and thereby making it extremely hard to open the door and exit the laboratory. Furniture, casework, and equipment must also be arranged so as not to impede the path of travel to the access doors from the laboratory unit. This should include minimum aisle clearance of at least 24 in. (0.6096 m).

PROTECTION STRATEGIES

Both passive and active protection strategies are important aspects of laboratory design. Therefore, during the design phase

of a laboratory, both strategies should be considered to meet code requirements and to satisfy the designer's and owner's functional objectives.

Passive Protection Strategy

Fire Separation Requirements. NFPA 45 establishes criteria for fire separation requirements, including door and window assemblies, based on the amount of flammable and combustible liquids or flammable compressed gases, including hazardous waste, that will be in use or stored within a laboratory building or any laboratory work unit. The following approach can help determine an appropriate laboratory design and construction criteria as specified in NFPA 45:

- Determine the intended use of each laboratory.
- Determine the likely chemical inventory required for this use.
- Determine likely in-use needs and what must be on hand in storage.
- Determine waste generation and removal to quantify temporary waste storage.
- Calculate total likely in-use flammable and hazardous materials and storage, including hazardous waste.
- Determine the laboratory unit fire hazard class.
- Determine the allowable area and construction requirements specified in NFPA 45.

Laboratories built to a lower standard or classification may not be used for a higher risk operation, even on a temporary basis. Therefore, the quantity of flammable liquid to be stored in a laboratory and the location within the laboratory are important considerations.

Hazard Management. Design details contribute to safe and efficient laboratory operation when they take the following safety measures into account:

- Prevention and containment of spills
- Sufficient storage
- Access to circuit breakers
- Adequate lighting during emergency shutdowns
- Ventilation
- Countertop material
- Nonslip flooring
- Proper traps in floor drains
- Work counter heights
- Adequate workspace

Solvent storage should not be located under the laboratory fume hood, as this is a location where fires are most likely to occur in laboratories. All laboratories should be designed to conveniently and safely accommodate the temporary storage of biological, radiological, and chemical materials (nonwaste and waste) based on laboratory use projections. Laboratory benches should be constructed of noncombustible and nonporous materials. Laboratory operations can involve concurrent use of chemical solvents such as formaldehyde, phenol, and ethanol, as well as corrosives. The laboratory bench must be resistant to the chemical actions of these substances and disinfectants. Wood is porous and combustible. Fiberglass can degrade when strong disinfectants are used and can release toxic smoke when ignited.

Electrical Equipment and Appliances. All electrical installations, including wiring, apparatus, appurtenances, lighting, grounding, signal devices, and alarm systems, must comply with NFPA 70, *National Electrical Code®*. Electrical equipment and appliances used within a laboratory should display a listing of intended use that is approved by a recognized testing laboratory, unless no test standards have been established for the devices. The electrical system must be carefully designed to locate receptacles, switches, controls, and other arcing devices away from areas where spills might occur. It is equally important to provide the proper number and spacing of receptacles to eliminate the need for extension cords. Uninterrupted power supplies or emergency power may be required for some critical analytical test equipment or chemical fume hoods when ventilation is critical during hazardous operations.

In general, laboratory work areas, laboratory units, and chemical fume hood interiors should be considered as unclassified electrically, with respect to Article 500 of *NEC*. Typical laboratory operations prevent an ignitable vapor from being present in the laboratory. However, if a hazard analysis reveals the potential for a likely scenario that would produce an ignitable vapor, the laboratory work area, or a part thereof, should be classified as a hazardous location. Compliance with the requirement to mitigate a spill scenario of 5 gal (0.1892 m) or more can ensure that an ignitable vapor is unlikely to occur in the laboratory.

Electrical Classification of Hoods. Rationale and calculations are provided in the informational section of NFPA 45 to explain the electrical classification of hoods. In general, the classification of chemical fume hoods as general purpose is appropriate. This is because, in general use, the combination of the airflow rate and flammable vapor concentration will not permit a stoichiometric vapor-air mixture, which could result in an explosion, given specific quantities of flammable liquids. If quantities beyond the specific amounts are present in the hood, a scenario can exist where an ignitable vapor could become present and a fire or explosion result.

The electrical classification of the hoods depends on the ventilation rate, the quantity of flammable materials, and the type of chemical process or activity.[2] The challenge is to determine how flammable vapors or gases can be safely used in a hood with unclassified electrical equipment and heated surfaces. When the quantity of flammable vapor is minimized and ventilation rates are maximized, a determination of the volume of vapor generated by the vaporization of flammable liquid can help to approximate the maximum quantity of liquid that can be used to operate below the lower flammable limit (LFL), assuming liquid vaporization in 1 minute with perfect mixing. The exhaust air volume is a critical parameter necessary to calculate the maximum quantity that can be vaporized in 1 minute before reaching LFL. Under these ventilation rates and controlled quantities of flammable liquids, the hood is considered to be electrically unclassified, since the LFL of the specific vapor will not be reached. Ventilation is assumed to be constant, and ventilation failure that occurs simultaneously with an

unexpected development of flammable vapors above the LFL is highly unlikely.

Active Protection Strategy

As stated at the start of this section, both passive and active protection strategies are important aspects of laboratory design. During the laboratory design phase, it is essential to specify the type of suppression, detection, and alarm systems that are necessary to both meet code requirements and meet the functional objectives of the designer and owners.

Detection and Alarms. In laboratories where a risk assessment, hazard classifications, or code requirements warrant a fire alarm system, it must be installed in accordance with *NFPA 72®, National Fire Alarm Code®,* and designed to alert all those who may be affected by the emergency. This could require 100 percent testing during installation to ensure notification is achieved in all occupiable spaces in the laboratory building. Notification schemes should also be considered for storage spaces where employees may work temporarily.

Automatic Fire Protection. In the 2004 edition of NFPA 45, a requirement was added to require all new laboratories to have automatic fire-extinguishing systems. For laboratories built before 2004, where a risk assessment, hazard classification, or code requirement warrants an automatic fire-extinguishing system, it must be installed in accordance with NFPA 13*, Standard for the Installation of Sprinkler Systems.* Laboratories with a Class A or B (High-Moderate) hazard classification should be protected as ordinary hazard (Group 2); Hazard Class C and D (Low) laboratories should be protected as ordinary hazard (Group 1). A study conducted by National Institute of Standards and Technology[3] demonstrated that quick-response sprinklers controlled flammable liquid test fires that were conducted in laboratories more quickly than standard-response sprinklers. Where required or used in place of automatic sprinkler systems, special hazard extinguishing systems and nonwater automatic extinguishing systems are also acceptable.

Although new laboratories are required to have automatic fire protection systems, automatic fire protection systems are not required to be extended to chemical fume hoods or exhaust systems except in the following cases:

- Existing hoods in which flammable liquids are handled have interiors with a flame spread index greater than 25.
- A hazard assessment shows that an automatic extinguishing system is required for the chemical fume hood.

Should the decision be made to extend the protection to the hoods, consideration should be given to the fact that whereas alternative extinguishing agents can control or suppress a flammable liquid fire in a chemical fume hood, tests[4] have demonstrated that the installation of automatic sprinklers with water mist nozzles in the chemical fume hood is the most effective fire protection strategy where nonthermal damage (from the extinguishing agent) outside of the chemical fume hood is a concern. Where water-reactive materials are utilized in the hood, special precautions must be taken to avoid an inadvertent discharge, regardless of the type of extinguishing system. Although water reacts with water-reactive chemicals, when the chemical fume hood is aflame with a flammable liquid fire, the resultant reaction (even with a sodium metal) is not so significant as to eliminate water as a safe and effective fire protection strategy. Of course this assumes that the chemical fume hood is not being used for significant out-of-container storage.

The other concern typically expressed by laboratory owners is about an inadvertent discharge of an automatic sprinkler system and the resultant damage to sensitive and expensive electronic equipment that may be utilized in the laboratory. Accidental discharges from mechanical means can be eliminated by concealing sprinkler heads. Accidental discharge from other than mechanical damage or microbiologically induced corrosion issues are almost nonexistent and do not typically warrant the elimination of the significant benefits of automatic sprinkler protection or the additional cost of a preaction sprinkler system.

Fire tests[5] conducted in the UK have demonstrated that clean agents break down and evolve significant toxic by-products when they come in contact with flaming combustion. In addition, in order for clean agents to work, chemical fume hoods must be shut down. The activation of any automatic fire protection system should send an activation signal to a constantly monitored station in accordance with *NFPA 72*. Alternative systems should be installed according to the applicable standards.

Inspection, testing, and maintenance of any fire protection system should be performed in accordance with the appropriate NFPA standard. Laboratory personnel should be educated on the specific function of these suppressions systems and know who should be called to report problems. Laboratory occupants should exercise care and not block or hang anything from sprinklers or sprinkler piping. Storage and equipment must not obstruct the sprinkler discharge.

Standpipe and Hose Systems. Laboratory buildings that are two or more stories above or below ground level must have an approved standpipe system installed in accordance with NFPA 14, *Standard for the Installation of Standpipe and Hose Systems.* The standpipe system must be regularly inspected, tested, and maintained in accordance with NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems.*

Portable Fire Extinguishers. Portable fire extinguishers can be a valuable tool to control a small fire in the incipient stage. However, the extinguishment of a flammable liquid fire or fire involving other chemicals can present a significant danger to an inexperienced operator who has not had actual hands-on training with a fire extinguisher. In addition, it is essential that personnel who are designated to use a fire extinguisher receive risk management training to help them evaluate go or no-go situations. Although extinguishing a fire in the incipient stage can prevent significant damage, laboratory designers should carefully evaluate whether incipient stage extinguishment presents the potential for significant injury or death. The proper type, placement, and maintenance of extinguishers are essential. NFPA 10*, Standard for Portable Fire Extinguishers,* regulates these appliances.

Explosion Hazard Protection. If the hazard assessment determines that an explosion hazard exists, appropriate protection must be provided for the occupants. The explosion hazard could be a rupture of apparatus, an overpressurized system, or implosion due to vacuum. Explosion hazard may be mitigated by explosion venting, special protected enclosures for vacuum and distillation columns, or by isolating the high-risk operations away from the other risks in specially designed buildings. Annual inspections should be required and include all safety features that have been designed for the space. This includes system components and construction features.

RISK REDUCTION

Laboratory Hazards

Laboratory operations using chemicals can include toxins, corrosives, ionizing and nonionizing radioactive materials, flammable liquids, and gases. Laboratory operations involving these chemicals may include distillations, which involve heating flammable liquids to above their boiling point, either under pressure or under vacuum. In addition, some high-pressure reactions involve hydrogen or other flammable gas. Accidents involving these operations can include rapidly spreading flammable liquid fires, explosions, and exposure to highly toxic and hazardous materials.

Risk-Reduction Strategies

The laboratory has many inherent risks, and some represent a higher risk factor than others. A risk assessment will identify the critical areas that need special consideration. High risk operations include the use of flammable liquids and flammable gases, reactions, and distillations. It is not uncommon or unsafe to perform distillation of a flammable liquid in a 5 gal (20 L) glass vessel. Once the risk is identified, strategies can be put into place that will prevent an incident or eliminate or reduce the impact. Standard risk-reduction strategies include the following approaches: inherent, passive, active, and procedural.

Inherent Risk Reduction. The inherent safety approach is the most reliable and a true prevention strategy. The procedural risk reduction strategy discussed below can also be considered a prevention strategy. In contrast, the passive risk reduction and active risk reduction strategies (also discussed below) are risk-reduction and consequence-minimization strategies. An example of an inherent safety strategy is the substitution of a nonflammable solvent for a flammable solvent—for example, using supercritical carbon dioxide in place of hexane for extraction.

Passive Risk Reduction. The single most favorable aspect of a passive approach is its performance reliability, which is a consequence of the fact that a passive strategy requires no mechanical device or system to actively function. For example, with a reactor system, instead of relying on an active system such as a safety relief valve to protect the reactor in the event of a runaway, a passive approach would be to design the reactor to contain the maximum expected overpressure. Another example of a passive approach is a fire-rated wall that confines a fire to the room of origin. Again, the prevention element here is solely the prevention of fire spread, not the prevention of the initiating event.

Active Risk Reduction. The next preferred risk-reduction strategy is the active approach. An active approach strategy is one that requires a mechanical device or protective system to actively prevent, detect, limit, or respond to the event. An active system must be reliably designed to work when intended, installed according to strict installation rules, and maintained and tested over its entire life. An automatic suppression system, such as an automatic sprinkler system, is a good example of an active approach.

Procedural Risk Reduction. The final approach and one that can also be preventive is the procedural approach. By following proper procedures and prudent practices, spills, fires, and explosions can be prevented. Emergency response is also recognized as a procedural approach to minimizing the consequence of a spill, fire, explosion, or other incident in the laboratory. Procedures should address the handling and storage of chemicals and flammable and combustible liquids and gases, use of open flames such as Bunsen burners, and use of portable electric cords. In addition, maintenance procedures should be in place that include periodic preventive maintenance and, where appropriate, predictive testing for equipment used in hazards operations, such as reactions and distillations.

VENTILATION AND LABORATORY HOODS

Purposes of Hoods and Cabinets

Ventilation systems and laboratory hoods provide important safety features. Laboratory hoods and other local exhaust systems provide important features that are not duplicated by other types of exhausting systems designed for vastly different purposes. For example, canopy hoods, biological cabinets, and laminar flow cabinets cannot be used in lieu of laboratory hoods. The main purpose of a canopy hood is to exhaust heat, water vapor, odors, and other nonhazardous materials. The purpose of a laminar flow cabinet is to provide filtered airflow over the work surface. A biological cabinet is used for storage to protect personnel, product, and the environment during storage.

Ventilation for Safe Operations

Where toxic or flammable chemicals are handled or stored, using proper systems to ensure the effective ventilation of laboratory work areas is critical to safe operations for two important reasons.

First, to prevent personnel exposure to toxic or odiferous materials during the course of conducting normal laboratory activities, the resulting vapors or gases are usually exhausted with nonrecirculated, conditioned air through hoods and local exhaust arrangements. This is one reason why it is very important to ensure that laboratory ventilation systems operate properly while activities are being carried out in the work area. Depending on

the nature of the chemicals and the type of operations, it might be possible to reduce ventilation rates during off hours when work areas are unoccupied.

Second, when activities involve the use of toxic or flammable materials in quantities that cannot be safely handled in work areas, the activity should be carried out in a hood. Typical modern hoods operate under negative pressure compared to the work area, with hood-face velocities that range from 80 to 120 linear ft/min (0.41 to 0.61 m/sec), with 100 linear ft/min (0.5 m/sec) being the most common. These ventilation rates mix, dilute, and exhaust toxic or flammable materials to a safe location.

Ventilation System Requirements

As is the case with the other safety features designed within the laboratory, these systems must be inspected, maintained, and tested. A basic design principle is to keep the laboratory at negative pressure with respect to the other nonlaboratory areas of the building, although some exceptions apply.

Laboratories must be continuously ventilated. Supply air for laboratories must be designed to prevent toxic and flammable vapors from being recirculated back into the laboratory. This requires the fresh air intakes to be located remotely from the exhaust discharge. The disposition of room air in a laboratory is governed by NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems.*

Requirements for Hoods and Exhaust Systems

Air ducts of hoods and local exhaust systems must be constructed of noncombustible material and must be designed to maintain a negative pressure with respect to the area outside the duct. Combustible duct linings must have a flame-spread index of 25 or less when tested in accordance with NFPA 255*, Standard Method of Test of Surface Burning Characteristics of Building Materials.* When the chemical fume hood is used properly, there are no "hazardous vapors," as defined by the model building codes, and hoods are therefore exempt from the requirements of automatic fire protection systems. NFPA 45 does not require hoods to have automatic fire protection systems unless a hazard analysis deems it necessary, or if the hood interior flame-spread index is not achieved.

Air exhausted from a laboratory hood and from special systems must be discharged above the roof at a sufficient velocity and height to prevent reentry. A proper lockout procedure is also needed for laboratory hoods to properly identify if a hood is out of service. Proper signs must be located at the hood to notify the user. Fan units for laboratory hoods should be selected to meet the specific design requirements, such as corrosion resistance or nonferrous rotating elements. Individual fans should be labeled and should identify which laboratories they serve. An airflow-measuring device should be installed on each hood to indicate inadequate or unsafe airflow. Hoods must also be designed to contain minor spills.

Design of Hoods and Ducts

Automatic fire dampers should not be located in laboratory hood exhaust ducts. The building fire alarm system should not be interlocked to shut down laboratory hood exhaust systems because it could cause a dangerous build-up of flammable or toxic vapors. The design and installation of duct systems for laboratory hoods must be in accordance with NFPA 91*, Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids.*

Care must be exercised when using energy conservation devices on laboratory hoods. A user-accessible device must be available that will immediately attain maximum exhaust hood airflow. This will ensure the removal of the contaminant and potentially harmful products regardless of the sash position should an emergency occur.

Inspection of Hoods

All laboratory hoods should be inventoried and the basic operational information maintained and updated. Details should list the last inspection date, the inspection interval, average face velocity, and location of exhaust fan and its controls. This information should be available to the user and maintenance personnel. Laboratory hoods should be tested and inspected following modification, after installation, or at least annually. Laboratory staff should be trained to recognize unsafe conditions and how to arrange for correction work.

Perchloric Acid Hoods

The use of specialized local exhaust and dedicated hoods for perchloric acid are control methods that minimize the fire risk. The use of perchloric acid creates unique hazards, and care must be extended to these operations. Laboratory hoods used for perchloric operations must be designed and identified for this purpose. A water spray system must be provided for these hoods along with a method to collect the wash-down water. If a perchloric hood is to be used for any other purpose, it must be tested to ensure that it is free of residual perchlorates.

PREVENTION AND EMERGENCY PLANNING

Unusual nonfire hazards that emergency response personnel might encounter in responding to a fire in a chemical laboratory include poisons, corrosives and irritants, radioactivity, nonionizing radiation, and biological hazards. Laboratories using radioactive materials must be identified in the facility emergency plan. NFPA 801*, Standard for Fire Protection for Facilities Handling Radioactive Materials,* provides further discussion on this subject. Laboratory management should train emergency response personnel in detailed emergency response plans that address these special hazards. Preplanning for emergencies should identify significant and unique hazards in all laboratories. Emergency response personnel will need to take additional care and be familiar with the hazards and proper response and decontamination techniques. Laboratory management should also encourage the public fire department to become familiar with these hazards through in-service inspections, joint emergency plan development, and coordinated emergency response drills.

Evacuation Plans

The management of each laboratory work area should be responsible for developing and distributing an evacuation plan for the facility. The plan should contain diagrams and should be distributed to each supervisor and posted in appropriate locations for all employees to read and study. In addition to fires and explosions, the evacuation plan should also consider hazardous incidents, such as spills, leaks, or releases of flammable, toxic, or radioactive materials, and seismic events and other acts of nature, such as tornadoes, hurricanes, and floods. The evacuation plan should include, but not be limited to, the following:

- Conditions under which evacuation will be necessary
- Method of alarm transmission
- Action to be taken in addition to evacuation by personnel upon receiving an alarm (e.g., turning off flames and other ignition sources)
- Primary and secondary routes to horizontal and vertical exits leading either to the exterior of the building or to safe refuge zones within the building, as might be permitted if total evacuation is not necessary and the alarm system is appropriately zoned
- Accountability for determining if everyone has left the facility
- Methods of notifying personnel as to when it is safe to reenter the facility

Laboratory management should conduct fire exit drills at least once a year to test the evacuation procedures by familiarizing personnel with exits, especially emergency exits not normally used, and the safe and efficient use of the exits. For required frequency of fire exit drills in educational occupancies and health care occupancies, see NFPA *101*. Fire exit drills differ from fire drills in that the latter are held for purposes of fire-fighting practice by the fire brigade or other emergency organizations. No one should be excused from participating in a fire exit drill.

Hazard Identification

NFPA 45 does not exclusively endorse any particular convention for communicating unusual hazards to emergency response personnel, recognizing that professional judgments need to be made on a facility-by-facility basis. However, entrances to laboratory units, laboratory work areas, storage areas, and associated facilities should be identified by signs to warn emergency response personnel of unusual or severe hazards such as poisons and radioactivity.

Procedures and Practices

Chemical storage shelves should not be placed above laboratory sinks. All shelves must have a passive restraining system such as seismic shelf lips (¾ in. [19.05 mm] or greater). The shelves themselves must be firmly fixed so they cannot be vibrated out of place and allow shelf contents to fall.

Laboratories should have an inventory management system in place to track new and waste products entering and leaving the laboratory. Product containers should be date stamped to manage date-sensitive chemicals. Hazardous products must only be used in laboratories designed and constructed for this intended use.

Flammable and Combustible Liquids

Proper storage and handling procedures for flammable and combustible products are critical to the safe operation of a laboratory. Many restrictions are identified in NFPA 45. The maximum allowable quantities are based on laboratory class, and allotments are made for every 100 ft^2 (9.3 m^2) of laboratory area, as shown in Table 9.12.1. Quantities are increased if the liquids are in storage cabinets or safety cans. The maximum quantity for any laboratory unit (regardless of size) is also specified. In addition to maximum overall quantities in a lab, NFPA 45 sets forth maximum allowable container capacities. Educational and instructional laboratories have additional caveats on the container size for lower flashpoint liquids. The classification of flammable and combustible liquids is the same as that used in NFPA 30, *Flammable and Combustible Liquids Code,* and is essentially the same system used by OSHA. The classes are summarized in the sections that follow.

Flammable Liquids. A liquid is considered to be flammable if it has a closed-cup flashpoint below 100°F (37.8°C) and is classified as Class I. A Class I liquid is any liquid that has a closed-cup flashpoint below 100°F (37.8°C) and a Reid vapor pressure not exceeding 40 psia (2068.6 mm Hg) at 100°F (37.8°C), as determined by ASTM D 323, *Standard Method of Test for Vapor Pressure of Petroleum Products (Reid Method).* Class I liquids are further classified as follows:

- Class IA liquids—those liquids that have flashpoints below 73°F (22.8°C) and boiling points below 100°F (37.8°C)
- Class IB liquids—those liquids that have flashpoints below 73°F (22.8°C) and boiling points at or above 100°F (37.8°C)
- Class IC liquids—those liquids that have flashpoints at or above 73°F (22.8°C) but below 100°F (37.8°C)

Combustible Liquids. A liquid is considered to be combustible if it has a closed-cup flashpoint at or above 100°F (37.8°C) and is classified as Class II or Class III as follows:

- Class II Liquid—any liquid that has a flashpoint at or above 100°F (37.8°C) and below 140°F (60°C)
- Class IIIA—any liquid that has a flashpoint at or above 140°F (60°C) but below 200°F (93°C)
- Class IIIB—any liquid that has a flashpoint at or above 200°F (93°C)

Class I liquids have more restrictions than Classes II and III, including container size and total volume permitted. Container type and size should be carefully monitored for compliance, and all flammable liquids should be stored in approved containers within storage cabinets. It is not mandatory to vent these cabinets. Neither NFPA 30 nor NFPA 45 requires that the storage cabinet be vented, but both documents allow this to be done where it is deemed necessary or desirable.

Laboratory Unit Storage

Storage cabinets help to prevent a laboratory fire from spreading to those products stored within these cabinets. Products stored in cabinets must be compatible. If a product requires refrigeration,

TABLE 9.12.1 Maximum Quantities of Flammable and Combustible Liquids and Liquefied Flammable Gases in Sprinklered Laboratory Units Outside of Inside Liquid Storage Areas

		Excluding Quantities in Storage Cabinets or Safety Cans				Including Quantities in Storage Cabinets or Safety Cans			
Laboratory Unit Fire Hazard Class	*Flammable and Combustible Liquid Class*[a]	Maximum Quantity[b] per 9.3 m^2 (100 ft^2) of Laboratory Unit[c]		Maximum Quantity[b] per Laboratory Unit		Maximum Quantity[b] per 9.3 m^2 (100 ft^2) of Laboratory Unit[c]		Maximum Quantity[b] per Laboratory Unit	
		L	*gal*	*L*	*gal*	*L*	*gal*	*L*	*gal*
A (high fire hazard)	I[d]	38	10	2270	600	76	20	4540	1200
	I[d], II, and IIIA	76	20	3028	800	150	40	6060	1600
B (moderate fire hazard)	I[d]	20	5	1136	300	38	10	2270	600
	I[d], II, and IIIA	38	10	1515	400	76	20	3028	800
C (low fire hazard)	I[d]	7.5	2	570	150	15	4	1136	300
	I[d], II, and IIIA	15	4	757	200	30	8	1515	400
D (minimal fire hazard)	I[d]	4	1	284	75	7.5	2	570	150
	I[d], II, and IIIA	4	1	284	75	7.5	2	570	150

Note: For maximum container sizes, see Table 10.1.4 of NFPA 45.
[a]See 4.2.1.3 and 11.1.6.5 of NFPA 45.
[b]See 4.2.2 of NFPA 45 for additional requirements for instructional and educational laboratories.
[c]The quantities per 9.3 m^2 (100 ft^2) do not imply the quantities must be within that 9.3 m^2 (100 ft^2) area; the quantities per 9.3 m^2 (100 ft^2) are for calculation purposes to determine the total quantity allowed.
[d]This category includes Class I flammable liquids and liquefied flammable gases.
Source: NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals,* Table 10.1.1, 2004, p. 45-17.

the appliance must be approved for its intended purpose and hazard rating.

In general, any "storage" within the laboratory unit is for the chemicals in use and is subject to same requirements as the rest of the laboratory as far as quantities, construction, and so on. If additional quantities are necessary, the storage can be defined outside the laboratory unit and can be classified as a flammable or a combustible liquids storage area, subject to the requirements of NFPA 30. Rooms specifically designed to the requirements outlined in NFPA 30 should be available for the following:

- Bulk storage of product
- Containers that measure above the quantities allowed in NFPA 45
- Containers that are larger than those allowed in NFPA 45

For all storage, incompatible materials must be segregated.

Dispensing Flammable Liquids

Dispensing of Class I liquids to or from containers less than or equal to 5 gal (20 L) in capacity should be performed in one of the following locations:

- In a chemical fume hood
- In an area provided with ventilation adequate to prevent accumulations of flammable vapor/air mixtures from exceeding 25 percent of the lower flammable limit
- Inside liquid storage areas specifically designed and protected for dispensing Class I flammable liquids that meet the requirements of NFPA 30

A pressurized liquid dispensing container that meets the requirements of NFPA 45, however, does not have to be used in the three areas listed above. Class I liquids should not be transferred between conductive containers of greater than 1 gal (4 L) capacity unless the containers are electrically interconnected by direct bonding or by indirect bonding through a common grounding system. When dispensing Class I liquids involves nonconductive containers larger than 1 gal (4 L), which can be difficult to bond or ground, special dispensing procedures commensurate with the electrical characteristics of the liquid shall be developed and implemented.

Allowable Quantities of Flammable Liquids

NFPA 45 provides quantity limitations for flammable and combustible liquids based on laboratory class, class of chemical, and size of laboratory unit, as shown in Table 9.12.1. The quantities are lower for Class A laboratories when compared to Class D laboratories; the quantities of Class I flammable liquids are more restricted than the Class III liquids; and the quantities are increased incrementally for each 100 ft^2 (9.3 m^2) of laboratory unit area, with a maximum overall quantity regardless of size. There are no density requirements in the laboratory unit such

that the chemicals must be distributed evenly throughout the lab. Part of the reason for this is that in many cases the chemicals are in a storage cabinet, which is not prohibited from containing more than the quantity allowed for a 100 ft^2 (9.3 m^2) area. Additionally, the committee reasoned that if there were density requirements per every 100 ft^2 (9.3 m^2), it is likely that there would be some unusual schemes to "split" up the square footage. However, good engineering practices should also be exercised; note that NFPA standards and codes are minimum requirements and are not always considered "best practices."

Pressurized Liquid Dispensing Containers (PLDCs)

In the 2004 edition, NFPA 45 recognized and defined a container called a pressurized liquid dispensing container (PLDC). The need for a large feedstock of solvent with high purity for modern laboratory sampling and testing equipment was satisfied by the PLDC. As defined in NFPA 45, PLDCs that are used for flammable and combustible liquids should be listed or labeled for their intended use by a nationally recognized testing laboratory. These containers have undergone exposure to fire tests and have demonstrated satisfactory venting properties.

The relief devices on PLDCs should discharge to a safe location, in accordance with the manufacturer's recommendation. The piping/hose between the container and the use point should be rated for the pressure, compatible with the materials being transferred and not subject to mechanical damage. A readily accessible means to stop the flow of liquid from the container should be provided. Containers should only be pressurized with nitrogen or inert gas. These containers are also subjected to the NFPA 45 maximum spill criteria of 5 gal (20 L). It is critical to design the system to prevent the entire 60 gal (227 L) of flammable liquid in a PLDC from being leaked out of the container into the laboratory.

Hazardous Chemicals

Hazardous chemicals must not be brought into a laboratory space unless the design, construction, and fire protection systems are appropriate for the quantities and the hazard involved. These hazardous products include, but are not limited to, flammable solids, oxidizers, and organic peroxides. Quantities of hazardous chemicals should be restricted to the minimum amounts necessary to perform the work. Only trained staff should undertake these activities, and the handling and storage of these materials must conform to the manufacturer's recommendations. Special storage facilities are needed for materials having unique physical or hazardous properties, such as temperature sensitivity, water reactivity, or explosive characteristics. Disposal of these products requires special consideration, and, again, should be carried out by qualified personnel only.

Compressed and Liquefied Gas Cylinders

The use of compressed and liquefied gases within a laboratory presents another unique hazard. The volume of gas cylinders within a laboratory should be kept to a minimum. Cylinders stored outside the laboratory must conform to NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks.* Cylinders or containers with a gauge pressure over 15 psi (103 kPa) should be fabricated as specified or authorized by the U.S. Department of Transport, Transport Canada, or Section VIII of the ASME Boiler and Pressure Vessel Code. Special continuously mechanically ventilated enclosures are required for lecture bottle-size cylinders that contain pyrophoric gases, gases with health-hazard ratings of 3 or 4, and gases with health-hazard rating of 2, and having no physiological warning properties. Cylinders other than lecture bottle-size having similar hazardous properties require storage within approved continuously mechanically ventilated gas cabinets and in the case of pyrophoric gases require sprinkler protection within the cabinet. Additionally, compliance with NFPA 55 is required. Cylinders should be handled and stored in accordance with procedures developed by the Compressed Gas Association.

Cryogenic Fluids

All system components used for cryogenic fluids must be designed for such use. Systems or apparatus handling cryogenic fluids that cause freezing or liquefaction of the surrounding atmosphere must be designed to prevent contact with the condensed air and organic materials. Location spaces for cryogenic systems must be ventilated commensurate with the properties of the specific fluid.

SUMMARY

Laboratory design must take into account the laboratory's layout, including its furniture, access to means of egress, access for deliveries and pedestrian flow, and the locations of laboratory hoods, flammable storage cabinets, emergency showers, and eyewash stations, as well as spill containment design. The fire protection strategy is critical in the design and operation of laboratories using chemicals in order to safeguard laboratory workers, other building occupants, and emergency response personnel. Fire protection considerations in construction include type of building material, electrical installations, and sprinkler protection. In addition to automatic sprinklers, fire protection systems include standpipes and portable fire extinguishers. Explosion hazard protection measures, the ventilation system, and laboratory hoods are all important pieces of the overall strategy. Proper procedures must be followed in chemical storage and waste disposal, compressed or liquefied gas handling, and other hazardous operations. A comprehensive safety management system includes prevention and emergency planning, hazard assessment, procedures and protocols, and training.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire protection of laboratories with chemicals discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protec*tion
NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
NFPA 17A, *Standard for Wet Chemical Extinguishing Systems*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals*
NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 72®, *National Fire Alarm Code®*
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA 99, *Standard for Health Care Facilities*
NFPA *101®*, *Life Safety Code®*
NFPA 220, *Standard on Types of Building Construction*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 259, *Standard Test Method for Potential Heat of Building Materials*
NFPA 285, *Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components*
NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment*
NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*
NFPA 750, *Standard on Water Mist Fire Protection Systems*
NFPA 801, *Standard for Fire Protection for Facilities Handling Radioactive Materials*
NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*

Chapter 13

Fire Protection of Telecommunications Facilities

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Chapter Contents

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Key Terms

central office (CO), performance-based design, private branch exchange (PBX), telecommunications, telecommunications equipment, telecommunications facility, telephone exchange

This chapter discusses protection against fire of the telecommunications network in the United States and Canada. To do so, it presents the basic layout and function of the U.S. telecommunications network, its evolution, and current trends. It describes the network's components and contains guidance for providing fire protection of the network against fire hazards to those components. It also provides recommendations for fire department response to telecommunications industry fires and for code compliance issues. It discusses both the public telecommunications network and private telecommunications equipment.

Driven by both technological advances and regulatory changes that have nothing at all to do with fire safety, dramatic changes are occurring in the North American telecommunications network. The impact of these changes on society and on fire risk is currently developing. This chapter describes many of these changes, their potential impact on fire risk, and methods to assess fire risk and determine appropriate fire protection programs.

Since Alexander Graham Bell made the first phone call on March 10, 1876, telephones have played an increasingly important role in people's lives. Once an oddity, then a convenience, the telephone is now a necessity of modern life. After some large loss fires affected the U.S. telecommunications industry in the 1960s and 1970s, the industry developed standards that include requirements to limit fire growth in equipment, wire, and cable used within central offices. This practice has been successful in limiting the size of fires that have occurred since.

Telecommunications, which touch almost every facet of daily life, include emergency 9-1-1 service, the Internet, automatic bank teller machines, point of sale transaction processing terminals, electronic funds transfer functions, fax machines, teleconferencing and videoconferencing, video services, cable TV, and standard and wireless telephone services.

Continuing evolution in the uses of telecommunications services has driven technologies that provide service to ever-increasing levels of sophistication. The following four important developments in the industry have resulted:

1. Long-distance transmission of signals between points in the network has been converted from analog signaling, which transmits a continually variable electrical signal, to digital signaling, which transmits on-and-off pulses of electricity or light.

2. Transmission routes have been extensively converted to fiber optics. This technology has found its way into local service, data and video services, and other wide bandwidth transmission facilities in many communities. Broadband connections to homes and to businesses are growing dramatically. Indeed, data communications volume is expected to exceed voice communications in the years ahead.

3. The development of wireless telephones has advanced throughout North America, and other major markets, permitting pocket-sized telephones and wireless data technologies to supplement or replace traditional land-based telecommunications facilities.

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4. Unrestrained competition has radically changed the telecommunications industry. Artificial barriers between long-distance service providers and local service providers have been removed. Services are now provided by traditional telecommunications service providers and new entrants, such as voice over the Internet, cable television companies, and others. However, concern is raised over the service levels provided by new entrants in this highly competitive business.

NFPA 76, *Standard for the Fire Protection of Telecommunications Facilities,* captures the best practices of the U.S. and Canadian telecommunications network providers to set a performance level for fire protection of the public network. It contains performance-based and prescriptive alternative approaches to achieve the level of network reliability against the threat of fire that the user public expects and that has been provided by the traditional telecommunication services. The performance-based method can be used for all future technology developments as the network equipment and facilities continue to evolve.

For related topics, see Section 8, Chapter 6, "Protection of Electronic Equipment"; and Section 9, Chapter 8, "Protection of Records."

U.S. TELECOMMUNICATIONS NETWORK

Many service companies provide telecommunication services in the United States and Canada. These companies operate networks ranging in size from small rural communities to large worldwide networks serving millions. Many types of facilities have emerged to provide the breadth and flexibility required in differing segments of the network. Buildings called central offices (COs) or telephone exchanges house primary control functions for the traditional network. Nearly 25,000 other smaller structures are required to operate the U.S. telecommunications network. Some of the larger buildings also include administrative office areas.

Between 1984 and the signing of the 1996 Telecommunications Reform Act passed by the U.S. Congress, the U.S. telecommunications network had two segments: (1) the portion local exchange carriers (LECs) or local phone companies provided, and (2) the portion interexchange carriers (IECs) or long-distance phone companies provided. The concept of the local access and transport area (LATA), established at the court-ordered divestiture of the Bell System in 1984, distinguished these two types of phone companies. The enactment of the 1996 Telecommunications Reform Act blurred the distinction between them, as has the entry of other communications media, such as cable TV and the Internet, into telecommunications service.

Figure 9.13.1 is a simplified schematic of a local network provided by an LEC. Each customer telephone connects to one, and only one, central office or exchange. Failure in any CO or the cables linking COs isolates all customers or services on one side of the failure from those on the other.

Although lacking redundancy at the local subscriber level, this design is made in compliance with the overall network design criteria in the United States as directed by the Federal Communications Commission (FCC). The criteria are intended to provide universal service at a low price, not uninterrupted service. However, well-established telecommunications companies do provide redundancies in certain high-traffic routes, such as links between hub COs. Many customers also have the option of purchasing redundant local services.

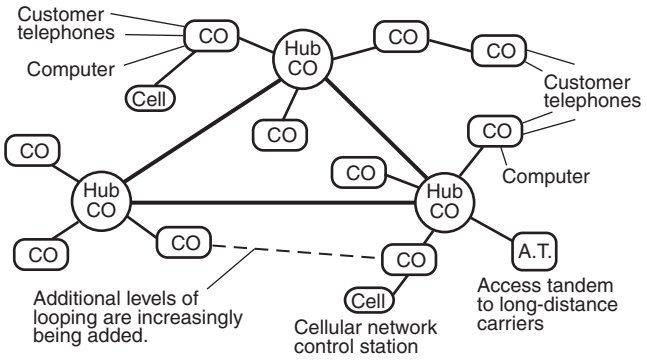

FIGURE 9.13.1 Typical Configuration of a Local Telecommunications Network

Paths between the end user, or customer, and the CO are generally composed of twisted-pair copper wires bundled into cables or from a cellular wireless network. In some cases, radio, coaxial copper, or fiber optic cable may be provided for groups of customers or certain large customers. Paths connecting various COs to one another may be composed of copper or fiber optic cables, or of microwave radio, depending on local conditions and terrain.

Figure 9.13.2 is a simplified diagram of a typical IEC network configuration. Some important differences exist between this diagram and Figure 9.13.1. Multiple paths between switching centers provide for redundant paths between points in the network in the event of a failure. The number and diversity of these paths are two key factors that predict reliability of a carrier's service. (Note that this discussion does not directly apply to "resellers" of either long-distance or local telecommunications

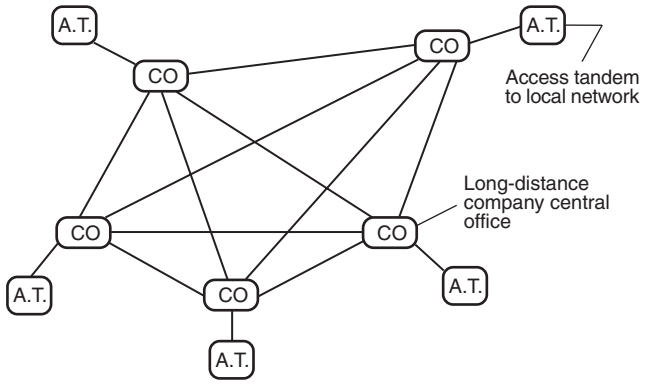

FIGURE 9.13.2 Architecture of a Typical Long-Distance Telephone Network

TABLE 9.13.1 U.S. Structure Fires in Telephone Exchanges or Central Offices

Year	*Total Fires*	*Fires with Telephone or Other Electronic Equipment as Equipment Involved in Ignition*	*Total Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
1980	132	5	0	0.40
1981	138	0	0	0.73
1982	117	4	8	0.75
1983	138	11	0	0.58
1984	79	5	10	0.07
1985	88	0	4	0.12
1986	86	3	0	0.19
1987	41	2	15	0.03
1988	73	7	2	0.78
1989	50	0	0	0.65
1990	58	5	2	0.37
1991	56	2	0	1.34
1992	75	9	0	0.32
1993	55	4	2	0.30
1994	44	0	0	0.35
1995	52	6	3	0.72
1996	37	4	0	0.40
1997	58	6	0	2.55
1998	37	0	0	0.05

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires and civilian injuries are rounded to the nearest one, and direct property damage is rounded to the nearest ten thousand dollars. Damage has not been adjusted for inflation.

Source: National estimates based on National Fire Incident Reporting System and NFPA survey.

service. These companies purchase large blocks of time on the networks of telecommunications companies that own physical networks.)

Paths connecting the COs in Figure 9.13.2 are composed of various transmission technologies, depending on traffic loads, topography, prevailing weather, and redundancy requirements. They may include one or more of the following:

- Copper cable
- Fiber optic cable
- Microwave radio
- Satellite radio

Along each path, as well as those in the LEC networks, a number of repeater or regeneration stations amplify and retransmit signals. These stations compensate for signals' deterioration over distance.

FIRE RECORD

Structure fires reported to U.S. local fire departments in telephone exchanges and central offices have declined over the past several decades. In the mid- to late-1990s, the latest available study, about 40 to 50 incidents per year were reported (Table 9.13.1). Only a small fraction of these fires originate within the specialized telecommunication equipment. Most reported fires are very small in physical size and typically develop very slowly. The average direct property loss per fire tends to be lower than for most other industrial and business occupancies. This is due to the industry's practice of using fire-resistive equipment, wire, and cable that meet standards of the telecommunications industry. Table 9.13.2 summarizes the notable telecommunications fires from 1975 to 2006 and illustrates that they are few in number, considering the size and scope of the industry, and no loss of life has occurred in any

TABLE 9.13.2 Notable Central Office Fires in North America, 1975 to 2006

Incident	*Extent of Service Interruption*	*Area of Fire Origin*	*Occupant or Fire Fighter Loss of Life*
New York City, 1975	170,000 customers, several weeks	Cable vault	None
Brooklyn, NY, 1987	41,000 customers, service was restored to more than half within 10 days and the remainder within 16 days	Main distribution frame on first floor, smoke spread to fourth floor.	None
Hinsdale, IL, 1988	38,000 customers, about one third restored in 3 days, most service restored in 12 days	Cable tray containing ac and dc cables	None
Los Angeles, CA, 1994	9-1-1 service for 12 hours, normal service for 16 hours	Battery plant undergoing reconfiguration	None
Orangeburg, NY, 1994	14,000 customers, partial service restored in 26 hours	Obsolete transmission equipment	None
Idabel, OK, 1995	5000 lines, restored in 13 hours	dc power cable	None
Portland, OR, 1996	88,900 lines, 9-1-1 rerouted quickly, critical service restored in 9 hours, all service restored in 15 hours	Cables fire, loss of power to transmission equipment	None
Toronto, Ontario, 1999	113,000 lines for less than one day, reduction in available 9-1-1 lines	ac electrical switch gear undergoing reconfiguration	None

Source: Compiled from public sources, including news reports and *NFPA Journal* reports.

of them. The telecommunications industry in the United States has never recorded a loss of life due to fire. However, because the density of valuable, vulnerable property and the services provided are unusually high in such facilities, many of the facilities are considered to be critical by the service providers on the basis of customers served or the commercial value of the services provided.

A special study on the fire history of the telecommunications industry was done for the FCC in 1992 and 1993.[1] This study surveyed local exchange and interexchange service providers in the United States, major telecommunications equipment manufacturers, and many other sources, representing more than 93 percent of the telephone lines in the nation. The study covered the fire record for the years 1988 to 1992.

During the study period, a total of 189 fire events were reported by responders to telecommunications facilities. On average, there were 38 incidents per year; only 8 affected service. Effects on service ranged from several minutes to one instance of several weeks of service outage. The study included an exhaustive root cause analysis and made recommendations to prevent recurrence.

Considering the millions of square feet of space included in telecommunications facilities, the cited studies demonstrate an exceptionally good fire record due, in large part, to exhaustive fire prevention efforts by the industry. The studies do not show one significant fact: even "large" telecommunications fires are rather small in comparison to large fires in most other industries. Quantities of materials burned, area of burn damage, and so on have been very small. Even the most significant telecommunications fire in recent history, the Hinsdale, Illinois, fire of May 1988, which burned for over 3 hours, was confined to cable trays in a 30 ft by 40 ft (9 m by 12 m) area.[2] Although small by most measures, the impact of these fires on the community can be quite large.

CENTRAL OFFICE

The nodes in each of the networks illustrated in Figures 9.13.1 and 9.13.2 are telephone exchanges located in buildings called central offices (COs) or smaller enclosures not classified as buildings. Designed and sized to meet customers' service needs, COs range in size from small, single-story buildings to large multistory buildings in large cities. Despite size differences, the equipment layout and function are similar. Figure 9.13.3 shows typical components of a CO. In smaller buildings, all these components may be in a single room. In large COs, each component may use one or more floors of a building.

Most major metropolitan central office buildings are constructed of reinforced concrete with rather massive structural elements. Older (pre-1980) suburban and rural central offices are generally of fire-resistive construction. In addition to loss prevention incentives for this type of construction, the buildings need to be strong enough to support the large masses of heavy copper cable the network requires. Although changes in equipment technology somewhat diminish cabling needs, the massive structural elements remain in older buildings. Central offices and other telecommunications facilities constructed since the advent of competition in the telecommunications industry have generally been constructed in accordance with applicable building codes, and may not be in excess of those codes, as had been prior industry practice.

Ceilings in traditional COs are generally much higher than those in commercial buildings. Typical slab-to-slab heights in

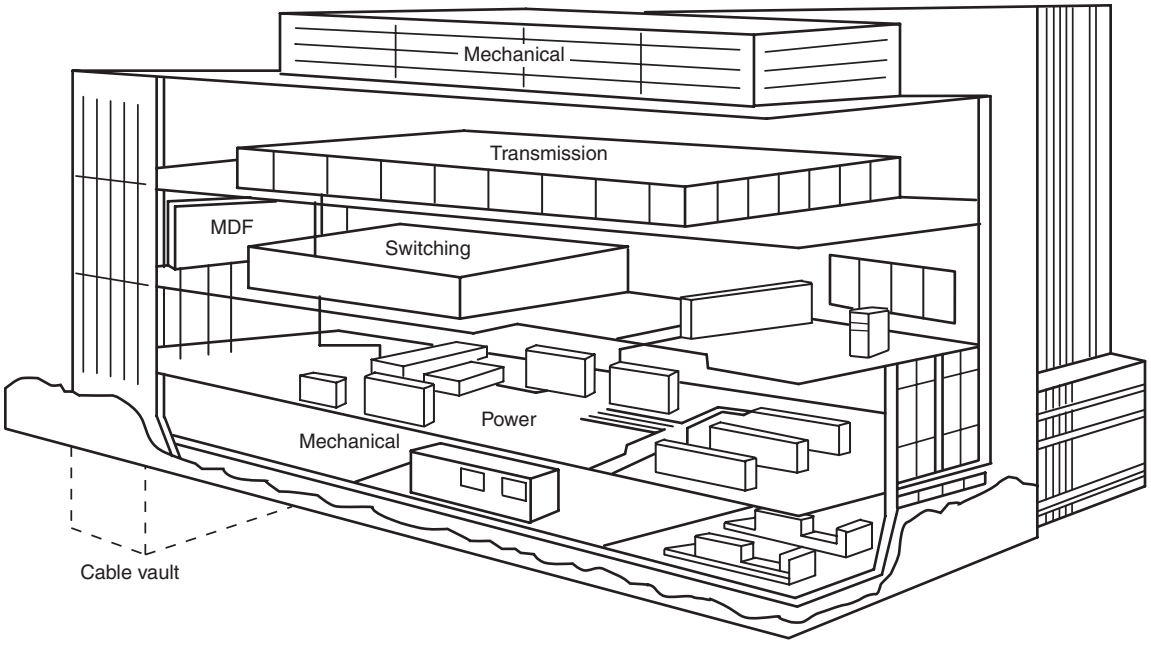

FIGURE 9.13.3 Typical Central Office Components

central offices are 14 to 16 ft (4.3 to 4.9 m). Few ceilings are dropped or suspended in the equipment areas so vertical space remains unobstructed. Clear space was necessary to accommodate 11 ft (3.5 m) equipment frames commonly used when the buildings were constructed, together with required cable racks, air-conditioning ducts, and other service equipment located above them.

CO buildings and other enclosures built more recently may have lower ceiling heights because more recently designed telecommunications equipment requires less vertical space. Newer facilities, or updated equipment areas of older facilities, may also use raised floors for cable connections between equipment cabinets. In general, telecommunications switch areas with raised floors contain less cable than do traditional switch areas due to the uses of fiber optics and newer data compression transmission techniques.

Cables enter and leave most COs through the cable vault, where they split into smaller, more fire-resistant cables for distribution in the building. Cables then rise through the building to the main distributing frame (MDF) where they break into individual pairs of wire for each circuit and cross connect to cables leading to the switching systems. After switching, signals pass to the transmission systems, which multiplex and boost the signals. After this is accomplished, the signal travels back out of the building through the cable vault on other cables. In some network switching facilities, the incoming and outgoing paths are solely fiber optic cables or wireless links, but the switching function is performed as for the copper cable COs.

In addition to standby generators, battery systems, and associated power control and distribution equipment, a variety of standard mechanical and building service systems support the telecommunications equipment (Figure 9.13.4).

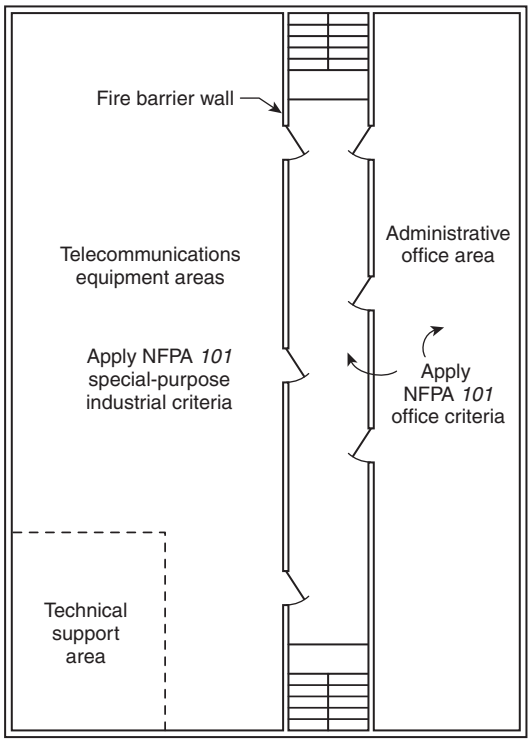

FIGURE 9.13.4 Example of the Application of NFPA *101*® to Telecommunications Equipment Areas and an Administrative Office Area (Source: NFPA 76, *Standard for the Fire Protection of Telecommunications Facilities,* Figure A.5.3.1, 2005, p. 76-28)

TELECOMMUNICATIONS EQUIPMENT

Description

Telecommunications equipment is fairly standardized in both function and appearance. It is arranged in parallel rows, or "lineups," 19 to 26 in. (48 to 66 cm) wide. The latest generations of digital electronic equipment generally range from 6 to 7 ft (1.83 to 2.14 m) in height.

Earlier generations of equipment were mounted in open frames without enclosures. This setup allowed easy access for maintenance and permitted heat dissipation by natural convection. Modern equipment is often enclosed in metal cabinets and looks much like ordinary computers. This arrangement, combined with miniaturization of equipment and attendant higher energy densities, requires forced ventilation (internal fans and extensive room air-conditioning systems) to dissipate heat generated during operation.

Providing for heat dissipation is important because the equipment is sensitive to temperature and humidity changes in the operating environment. Although absolute operating limits are rather wide, rapid changes of either a few degrees of temperature or a few percentage points of humidity can cause serious problems. Consequently, extensive environmental controls are used to ensure that ambient conditions remain within required limits.

Differences from Standard Computers

On first examination, modern digital telecommunications equipment resembles modern computers or data processing equipment. Although there are similarities, a number of important differences exist. Some were deliberately created to reduce the incidence, or effect, of potential loss-causing events. Other differences, necessitated by various technical requirements, have the opposite effect. Some of these differences present challenges that most traditional commercial loss prevention measures cannot adequately mitigate. As a result, telecommunications facilities must be analyzed on their own merits and characteristics.

One of the most significant differences is the type of information processing performed. Telecommunications systems are on-line information exchange systems. The telecommunications system does not store or process customer data; it merely transfers data from point A to point B. In a disruption, all information in transit is lost, and the ability to transmit information ceases. Data cannot be reloaded as long as the disruption continues, and missed opportunities cannot be made up. It is this ability to transmit information in real time that makes telecommunications so important. Many transactions routinely conducted over the network simply cannot wait until later.

In contrast, data processing systems generally process information stored in the system's memory subsystems. In a disruption, current memory may be lost, along with any calculation

results that have not been placed in permanent memory. However, all stored information remains in storage media. Interrupted, lost, or incomplete calculations can usually be reproduced after correcting the cause of disruption.

Another important difference between telecommunications equipment and data processing equipment is their power supplies. Data processing equipment is supplied with ac power to the cabinet. The ac to dc conversion takes place within the equipment, which generally operates at 5 to 10 V dc. On the other hand, dc power supplies telecommunications equipment. Conversion from commercial ac power to dc power takes place outside the equipment, often in a different building compartment. The power plant supplies the equipment with 12, 24, 48, or 130 V dc, depending on system requirements. Whereas emergency power off (EPO) switches may be appropriate for certain configurations of electronic data processing systems, such readily available means to kill power to telecommunications equipment would cause an abrupt end to 9-1-1 and other critical community-oriented emergency services. Therefore, the telecommunications industry avoids the use of EPO switches and NFPA 76, *Standard for the Fire Protection of Telecommunications Facilities,* provides an alternative condition-decision-based approach to use normal electrical disconnect means (Figure 9.13.5).

Another important difference lies in the redundancies usually provided for telecommunications equipment. In most networks, for instance, equipment operating in a duplex configuration performs all switching and call routing functions. This means that two separate processors simultaneously handle each call. In the unlikely event that one processor fails, the other continues to process the call, without interrupting the customer. In fact, the customer is unaware that the event occurred.

The final difference, which significantly impacts loss prevention, is the control programs' size. Programs that control various networks are among the largest and most complex. Programs involving millions of lines of program code are not uncommon. Their size naturally requires much more time to reload and initialize in the event of a disruption than common data processing programs. This requirement is one reason why it can take many hours to restart an electronic switching system in the event of a power loss. The thermal shock created by suddenly restoring power to the entire system is another.

Telecommunications equipment provided for use on a customer's premises, known as private branch exchange (PBX) equipment, differs in many respects from equipment used in COs. Major differences that impact a loss prevention program are discussed later in this chapter.

FIRE PROTECTION FOR THE PUBLIC NETWORK

Performance-Based and Prescriptive Solutions

NFPA 76 contains both a performance-based facility design method and a prescriptive method for protection of the network and life safety. NFPA 76 provides reasonable levels of fire protection for safety to life and to protect telecommunications equipment and service continuity. (See the Purpose section in NFPA 76.)

The Society of Fire Protection Engineers (SFPE) has developed *Engineering Guide to Performance-Based Fire Protection Analysis and Design.* NFPA 76 follows the SFPE format in its performance-based method.

The reasons for choosing a performance-based document type included the following:

- Many telecommunications service providers had previously existing company standards for fire safety, and the performance-based approach permits facility operators and designers to reconcile previously existing standards to the objectives and requirements of NFPA 76.
- Potentially more important, the performance-based approach can respond to the dynamic state of change currently occurring in the design of telecommunications switching and transport equipment and media, and the buildings and other structures that shelter and support that equipment.

On one hand, the prescriptive requirements found in NFPA 76 are a compilation of best practices of the industry for traditional telecommunications facilities and are directly applicable to many configurations of new telecommunications facilities. On the other hand, the performance-based objectives and guidance apply to all currently conceived telecommunications media and facilities. With new facility configurations and equipment types evolving rapidly, the performance-based approach may be more applicable to the new facility types that continue to emerge.

Traditional telecommunications industry practices for fire safety have been largely based on a chain of necessary actions and elements. Any missing action or element breaks the chain and increases the fire risk. The successful chain includes the following:

- Excellent fire prevention practices
- Noncombustible construction
- Compartmentalization
- Fire resistance–rated equipment
- Fire resistance–rated cable
- Very early warning fire detection
- Rigorous alarm processing and notification
- Rapid response by knowledgeable personnel
- Fire suppression, when needed
- Power interruption, when needed
- Smoke ventilation, when needed

The prescriptive solutions found in NFPA 76 are based on maintaining this chain unbroken for the life of a telecommunications facility. The prescriptive solutions are based on the widespread use of fire resistance–rated telecommunications equipment and cables.

For electronic equipment areas in which the predominant equipment and cable is not fire resistance rated, the chain is broken. An alternative strategy is required, generally including automatic suppression systems. Much of the industry relies on automatic suppression systems as part of its network fire protection practices.

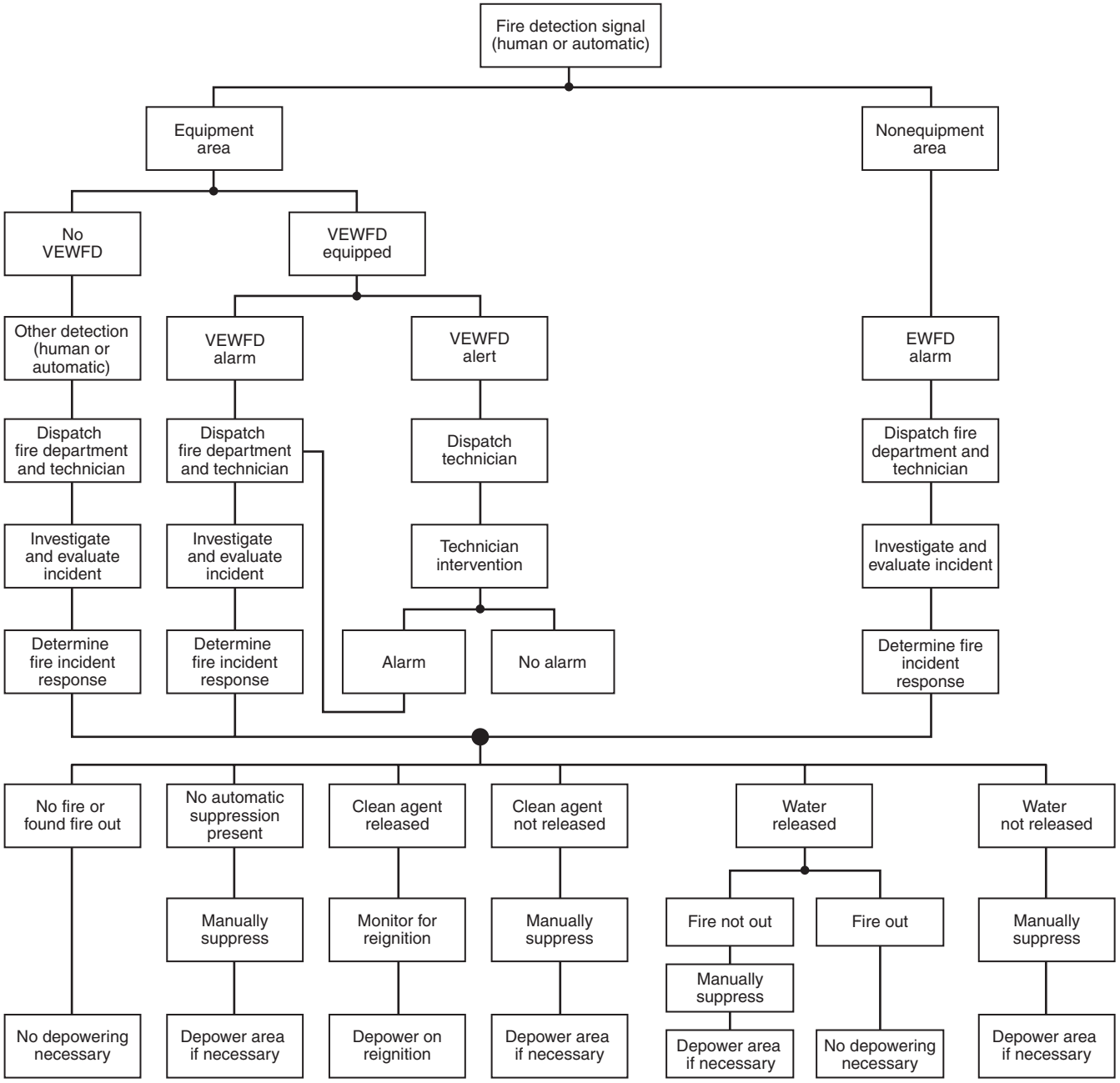

FIGURE 9.13.5 Depowering Decision Tree (Source: NFPA 76, *Standard for the Fire Protection of Telecommunications Facilities,* Figure A.6.5.1, 2005, p. 76-34)

Fire Risk Factors

Risk refers to the *probability* and *severity* of harmful events. Risk factors to consider when developing a fire safety program for telecommunications facilities include the following:

- Community served
- Public safety services
- Life safety of occupants and fire fighters
- Continuity of service
- Types of services provided
- Redundancy of facilities or services
- Property protection

Service providers make decisions on protection levels of facilities based on these risk factors, which are motivated by societal and commercial assessments of the criticality of various facilities. For instance, a switching facility that serves a major medical complex may be considered to be more critical than one that serves a small town. Although decisions of criticality are commercial and societal in nature, those decisions of criticality result in subsequent decisions on the extent to

which network redundancies and protective measures may be applied.

The goal of minimizing service interruption in emergency communications, national security information, commercial data, and voice telecommunications is the same regardless of the approach or solution chosen. Criticality is the only valid modifier.

For its prescriptive solutions, NFPA 76 approximates criticality by facility size—an imperfect approximation. The presumption is that the telecommunications flow rate is greater in larger facilities and, therefore, is more likely to contain critical data or voice communications. So the recommended fire protection measures are greater for large facilities than for small facilities.

Large facilities are defined as those having greater than 2500 ft^2 (232 m^2) of enclosed network equipment area. Small facilities are defined as those having less than 2500 ft^2 (232 m^2) of enclosed network equipment area.

When taking the performance-based approach to protecting the telecommunications network from fire, measures of criticality other than size of equipment area are more appropriate. For any given facility, or portion of a larger facility, these measures include knowledge of the community served, services provided, network redundancy, likely recovery time in the event of fire, available methods of recovery, business interruption costs, and any other factors that may determine the criticality of the facility.

The miniaturization that is occurring in telecommunications switching equipment and the differing network configurations that are emerging dictate that performance-based solutions consider all risk factors. Size of facility is not important in a performance-based analysis. It is the characteristics of the network and services provided that matter.

When the performance-based approach is applied rigorously to network facilities, one may expect a superior result compared to a prescriptive solution that is determined by facility size.

Hazard Areas

Telecommunications facilities, within buildings or other enclosures, can be categorized into one or more of eight types of areas, each with its own fire hazard characteristics (Table 9.13.3). The hazard types are the same whether a performance-based or prescriptive solution is chosen to determine a fire safety program.

Where an area combines more than one hazard area type in a single compartment or enclosure, the entire combined area should be treated as the most demanding of its subareas for protection of the network, occupants, and fire fighters.

PRIVATE TELECOMMUNICATIONS EQUIPMENT

Equipment provided by public telecommunications companies terminates at a network interface on the customer's property. The customer is responsible for providing all on-site telephone equipment and wiring. Customers accomplish this in a variety of ways. Commonly, they purchase and maintain their own telecommunications system, lease the equipment from either a telephone company or a third-party vendor, or contract with the local telephone company for a central office based service. Numerous other possibilities exist.

Large commercial or business occupancies typically have large telecommunications systems; some are more complex than those provided for whole towns. These systems can provide a wide array of voice, data, and video information to their users. Usually, they are controlled by private branch exchange (PBX) equipment located in the building or complex.

At first glance, modern PBX equipment appears to be very similar in design to modern central office equipment. PBX equipment performs many functions that CO equipment does but only for the building or complex it serves.

From a fire protection viewpoint, three significant differences exist between CO and PBX equipment:

1. The most important difference is that PBX equipment does not have to conform to the very rigorous fire resistance rating standards that apply to CO equipment. Listed by independent agencies, PBX equipment does meet a variety of other tests, including flammability tests, required to achieve that listing. The implications of this are discussed below.
2. Replacement PBX equipment is more readily available than replacement CO equipment. This allows more flexibility in making risk management decision in some instances.
3. PBX systems are usually easier to turn off than CO equipment. PBX power supplies often have redundancies similar to those of the CO, but the systems are smaller and less complex. In some cases, a switch or circuit breaker can be used to power down the equipment in the event of an emergency.

Protection Fundamentals for PBX Equipment

Most protection measures indicated for central offices are appropriate for PBX equipment as well. In general, the PBX should be protected in the same fashion as an important computer room. Several elements, as follow, are worthy of special note:

1. The equipment should be located in a room separated from the rest of the building by at least a 1 hour rated fire barrier.
2. Access to the room should be limited to authorized persons.
3. Good fire prevention and housekeeping measures should be in place at all times. Storage of combustible materials in the room should be strictly prohibited.
4. The room should be equipped with a smoke detection system that alarms at a constantly attended location.
5. Power shutdown procedures should be developed and made available for responding fire fighters to use.

Automatic Suppression

Exceptions found in most building codes that allow a central office to omit automatic suppression systems in equipment areas do not apply to PBX equipment or to telephone closets in commercial buildings. Those exemptions are based in part on fire

TABLE 9.13.3 Range of Hazard Areas in Telecommunications Facilities

Area	*Contents*	*Fire Scenarios*	*Assumptions*
Signal processing equipment area	Electronic equipment in racks or cabinets with cables in racks or under a raised floor	Slowly developing smoky fire producing corrosive vapors with heat release rates of typically 5 to 15 kW that do not exceed 150 kW for a fully involved cabinet or rack	Electronic equipment and cable meet U.S. or Canadian standards of the industry for fire resistance rating.
Cable entrance facility—separated by construction from other areas	Cables having no fire resistance rating entering the building from outside; spliced to rated cables	High or low heat release rate fires. Corrosivity of the products of combustion can affect electronic equipment if the products spread to those areas.	Cables that extend to other parts of the building are fire resistance–rated cables.
Power areas	Batteries on racks, rectifiers, switchgear, buss bars, and cables	Low heat release rate fire. Some may produce corrosive vapors. Some may result in acid spill.	Thermal effects of fire are limited to the items involved.
Main distribution frame area	Large amounts of low voltage communications wire	Low to medium heat release rate smoky fires. Corrosivity of the products of combustion can affect electronic equipment if the products spread to those areas.	The frame contains no inherent ignition sources. Other ignition sources are strictly controlled.
Standby engine area—separated by construction from other areas	Generator powered by an internal combustion engine with fuel day tank and starting batteries	Fire history of these areas indicates more electrical fires than fuel fires, but either is possible.	Major fuel storage is not in the same enclosed space. Means of fuel shutoff is available.
Technical support areas—contained within the tele-communications equipment areas	Metal desks, cabinets, tools, and equipment used by technicians in direct support of technical operations	Combustibles are present in small quantities and are stored in metal containers. Fires are typical of the telecommunications equipment areas. Exceptions may be when staging new equipment installations increases risk.	Technical support areas do not contain the quantity of combustible material typical of an administrative office area.
Administrative area	Normal commercial office furniture and equipment	Fires typical of commercial offices	Meets building code requirements for a business occupancy
Building services and support areas	Mechanical and maintenance equipment and storage as required for building operations	Fires typical of well-maintained commercial office building support areas	Combustibles are stored and handled subject to accepted fire prevention practices. Meets building code

prevention practices described earlier in this chapter and are not fully used in PBX equipment.

If code requires a building to be equipped with an automatic suppression system, the system should be provided in the PBX room. An appropriate system should be selected with a clear understanding of risks involved and advantages that each candidate system offers. The system may be omitted if the local authority having jurisdiction (AHJ) grants a variance or exemption. The system's owners may decide to install additional fire protection features to enhance the reliability of their system, because building code requirements do not address business interruption concerns. Such additional features might include very early fire warning detection systems or gaseous agent suppression systems.

A GLIMPSE OF THE FUTURE

A summary of current technology cannot be complete without drawing the separation of quite different segments of the emerging successors to the more traditional telecommunications network.

Consider three separate uses of computer-based equipment used to support today's electronic information systems. For simplicity, they can be described as the following:

- Telecommunications switching and transport equipment
- Internet server and router equipment
- Data processing computers

This chapter does not cover data processing computers.

We cannot predict the future, but we can observe current developments and trends. In electronic information distribution, the traditional telecommunications methods of switching and transport are being supplemented by new server and router configurations that may not be equivalent in equipment fire resistance or network redundancy and may be housed in buildings of less traditional design.

Trends are apparent that may change the fire risk and, therefore, the fire protection methods needed for telecommunications facilities that are affected by these changes.

Internet service providers rely on the telecommunications network for data transport. In addition, Internet switching and transport services are also provided by new types of facilities that may be small, large, or very large and may be very different from traditional telecommunications facilities. The operating equipment and cable that support these services may not have the fire resistance ratings of equipment used in traditional telecommunications services, and installation and maintenance standards may not be equivalent. Although the data communications services provided may also be quite different, mergers of these two forms of electronic data communications are taking place. Fire protection decisions for newer facility types should be based on assessments of criticality, similar to more traditional telecommunications facilities, and also on an assessment of the hazards present, construction of the facility, configuration of the building contents, and differences from the types of facilities that have proven successful in the past.

It may be anticipated that some buyers of Internet servers and routers will require that the equipment be designed and manufactured in accordance with the same fire-resistive rating standards as telephone switching equipment and they may install fire resistance–rated cables. This reinforces the need to become familiar with the contents of equipment areas as a necessary part of assessing the fire risk and determining fire protection methods for the hazard areas.

It is advantageous to locate Internet and private intranet servers and routers in close proximity to standard telecommunications switching equipment for direct access to the telecommunications network. The result is that Internet and private intranet equipment may be collocated in the same buildings as telecommunications network equipment. Where this occurs, the fire risk assessment should consider both types of equipment, separations between them, and fire resistance ratings of the equipment types.

Two current examples that can be cited of such combinations of equipment arranged to meet the requirements of NFPA 76. In one, the Internet server and router equipment and cables are required to meet the same fire resistance ratings as the telecommunications equipment and cables. In the other example, nonfire resistance–rated equipment is located in separate fire-resistive compartments within the building and those compartments are protected by automatic suppression systems.

FIRE DEPARTMENT CONCERNS

Despite the prevention measures many telecommunications companies take, fires still occur. Although these fires have historically been small in relation to fires in other industries, fire fighters face some clear differences when responding to such a fire.

Smoke Control

Fires in telecommunications equipment can produce very large quantities of dense, corrosive smoke. Visibility may become nearly impossible, even with handheld lamps. When combined with unfamiliar building configurations, the prospect for disorientation is clear. Appropriate precautions must be planned in advance. Fire departments should consider requesting that the owner install manual smoke exhaust systems, which differ from smoke control systems, to assist in fire control efforts. The portable smoke extractors or smoke fans that fire departments carry are inadequate to handle the large quantities of smoke the fires can generate. Even 10 to 12 smoke fans may be inadequate. Smoke exhaust systems have been proven highly effective in at least one actual telecommunications fire incident.[3–5]

Power Cables

A fire involving cables may involve power cables. It is critical that responding fire fighters be familiar with the power disconnect procedures established by the owner. If the owner does not provide such a plan, fire departments should demand one. The state of Illinois, site of the Hinsdale fire in 1988, requires a power shutdown plan for every telecommunications facility. This requirement is not something new, and there are established procedures for developing these plans. NFPA 76 recommends that a means to disconnect power from equipment be developed for every facility. The means is not intended to be automatic nor readily available. It is intended to be used by knowledgeable telecommunications provider personnel or fire service personnel and may require operation of electrical switchgear or overcurrent protective equipment.

Batteries and Electrical Power

Two physical hazards are present in telecommunications facilities that are not present in the same degree extent in other occupancies: large batteries and electrical power. Both are generally well engineered and maintained; neither presents extraordinary dangers in comparison to other dangers fire fighters commonly encounter. Responding personnel must be aware of these hazards and must be familiar with appropriate safety precautions before entering a smoke-filled telecommunications facility.

These issues are not insurmountable. Most telecommunications companies are happy to provide tours to familiarize fire departments with their facilities. It is important that these be done, if for no other reason than fire fighter safety.

APPLICATION BEYOND THE UNITED STATES AND CANADA

The information and guidance contained in this chapter is based on the fire experience and "best practices" for fire protection for the telecommunications industry in the United States and Canada. The recommendations of NFPA 76 are based on the same experience and practices.

Users who may be considering using this chapter or NFPA 76 to protect network equipment or facilities outside of the United States or Canada or for protection of equipment other than telecommunications equipment should first assess the fire-related characteristics of the equipment and facility to be protected.

Fire protection for equipment and facilities that do not include the equipment and cable fire resistance, the facility fire prevention practices, or fast response to fire detection signals would be more challenging. Additional measures beyond the prescriptive recommendations of NFPA 76 would be required for network protection. A performance-based analysis would be required.

SUMMARY

Methods and precautions discussed in this chapter and NFPA 76 provide a sound, proven basis for fire risk management for telecommunications equipment and services. Like any loss prevention program, the fire risk management program for telecommunications networks and equipment must be ongoing. There will be many changes both in the technology employed in the equipment and in the uses of telecommunications services as the future unfolds.

Many changes envisioned today will serve to increase redundancy in networks, thereby decreasing overall risk to network service continuity. Other changes may increase the net level of risk and present unique new challenges for risk managers. Risks must be evaluated systematically, so that effective risk reduction measures that truly reduce overall fire and network failure risk levels can be implemented.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire protection of telecommunications facilities as discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 75, *Standard for the Protection of Information Technology Equipment*
NFPA 76, *Standard for the Fire Protection of Telecommunications Facilities*
NFPA 220, *Standard on Types of Building Construction*
NFPA 262, *Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces*
NFPA 550, *Guide to the Fire Safety Concepts Tree*

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Chapter 14

Electric Generating Plants

Revised by
Daniel J. Sheridan

Chapter Contents

General Industry Overview
Management Policy and Direction
General Plant Design
Life Safety
Wind Energy

Key Terms

boiler, coal fuel, conveyor, electric generating plant, electrical cable, flue, Powder River Basin (PRB) coal, transformer, turbine, water supply, wind energy

The purpose of this chapter is to help the reader achieve a well-developed fire safety program tailored to the needs of an electric generating plant. This chapter offers guidance on how to develop a program that addresses life safety, continuity of operations, and property protection for individuals who are responsible for the design, construction, operation, and protection of electric generating plants that are fueled by fossil fuels, alternative fuels, and hydroelectric plants.

The process of producing and delivering electrical energy to customers includes three distinctive elements: generation, transmission, and distribution. This chapter addresses fire protection for generation of electricity from a variety of fuels. One section discusses high-voltage direct current converter stations. Section 9, Chapter 15, "Nuclear Facilities," discusses some unique fire protection challenges of nuclear fueled generation. Note that many hazards and fire protection concepts discussed in this chapter may apply to all means of electric generation, including nuclear. Other methods of generating electrical energy are described in Section 8, Chapter 10, "Stationary Combustion Engines and Fuel Cells."

For related topics see Section 7, Chapter 1, "Storage and Handling of Solid Fuels"; Section 8, Chapter 10, "Stationary Combustion Engines and Fuel Cells"; Section 9, Chapter 15, "Nuclear Facilities"; and Section 10, Chapter 6, "Boiler Furnaces."

GENERAL INDUSTRY OVERVIEW

Today's society increasingly relies on the socioeconomic benefits of electric energy for residential, commercial, and industrial applications. Over the years, in our everyday lives our dependence on electrically powered labor-saving devices has escalated. In 1999, the average annual U.S. consumption was about 13,833 kWh per person. By 2004 consumption rose to 26,068 kWh per person.[1] According to the Energy Information Administration, electricity demand is expected to increase by 2.5 percent in 2006 and 1.9 percent in 2007.[1] In the future, consumption is expected to continue to rise. Industry has turned toward electrification in new ways to increase efficiency and control costs in a highly competitive global marketplace. Electrification of developing countries is an important goal in improving the standard of living and attracting investment in these countries.

The availability and reliability of the electrical supply impacts our lives in many ways. These include safety, security, and the creation of employment opportunities. Certainly, today's information-hungry, service-oriented, and computer-oriented society could not function without an adequate and reliable electrical supply.

Over 16,000 electric generating units operate in the United States.[2] Over the years the generation industry has scaled up. In the 1920s units had a capacity of about 20 MW; plants designed in the last two decades have capacities over 1000 MW. Capacity expanded most rapidly in the 1950s and 1960s as technological advancements enabled production of larger and more efficient turbines, generators, boilers, transformers, and so on, with accompanying lower capital, operating,

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and maintenance costs per megawatt. An electric generating plant is capital intensive, with the cost spread over its 40 to 50 year life.

The increase in energy prices in the early 1970s changed the economic structure of the utility industry. Driven by inflation, regulation, and environmental concern, the cost of building electric generating units began to escalate rapidly. Rising costs undermined traditional economies of scale, requiring optimization of plant size and configuration to control costs. Therefore, many recently constructed electric generating plants are smaller than those constructed from the 1960s to the 1980s.

The U.S. electric utility industry is changing profoundly as it heads toward deregulation. Changes began with the passage of the Public Utility Regulatory Policies Act of 1978 (PURPA), which created a new class of preferred power producers. The act intended to encourage alternative sources of electric generation. As a result, a host of newly formed entrepreneurial enterprises erected electric generating plants to compete with traditional utilities that were required to purchase their electrical output. These new nonutility generators became known as independent power producers. In 1979 independent power producers generated 3 percent of U.S. power, increasing to 34 percent in 2005.[2] In the future, independent power producers will construct a considerable portion of the new capacity; traditional utilities will construct the balance.

Increasing competition among electric producers in future years will elevate reliability issues in the eyes of stakeholders. Avoiding forced outages will become more important in a deregulated environment. Good fire protection practice for electric generating plants will contribute to reliability, operator safety, and protection of physical assets.

In its most basic form, a fossil fuel electric generating plant converts fuel to produce steam that spins a generator to produce electrical energy. A hydroelectric plant uses kinetic energy to spin a generator for similar purposes. In 2005 the means used to produce electric energy in the United States were coal (49.7 percent), natural gas (18.7 percent), nuclear (19.3 percent), hydro (6.5 percent), and other fuels (5.8 percent) including petroleum, geothermal, wood, waste, wind, and solar.[3] This chapter addresses the fire-related hazards for each fuel, as well as hazards unique to electric generating plants.

MANAGEMENT POLICY AND DIRECTION

Best practice guidance is available in NFPA 850, *Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations,* and NFPA 851, *Recommended Practice for Fire Protection for Hydroelectric Generating Plants.* These documents provide information on the design, construction, operation, and protection of various types of electric generating plants. In addition, NFPA 853, *Standard for the Installation of Stationary Fuel Cell Power Systems,* first issued in 2000, covers stationary fuel cell installations of all sizes.

A key element in a well-protected plant is for management to establish a policy and follow through on a program to protect lives, conserve property, and ensure continuity of operations. For an operating electric generating plant this includes a written plant fire prevention program (i.e., control of combustibles, housekeeping, hot work controls, etc.); a fire emergency plan; testing, inspection, and maintenance programs; and related policies and procedures. When an electric generating plant is being designed or is undergoing changes, a fire risk evaluation should be initiated to ensure that all fire hazards are identified and appropriate strategies are established to cope with these hazards. The fire risk evaluation should address the fire prevention and fire protection concepts offered in NFPA 850 and NFPA 851.

Management's decision on the establishment of a plant fire brigade should be made after considering a number of variables, including requirements specified by the U.S. Occupational Safety and Health Administration (OSHA) in 29 CFR 1910.156. Some electric generating plants are located in areas remote from immediately available professional or volunteer fire departments. For these plants the establishment of a fire brigade may be necessary. The trend in the generating industry today is to reduce the size of the plant operating staff, which obviously affects the pool of qualified personnel who can perform fire brigade duties. Some smaller plants even operate unmanned or with as few as three people on a shift. (See NFPA 600, *Standard on Industrial Fire Brigades.*)

In all cases, a workable fire emergency plan needs to be developed. Fire fighters (plant fire brigade or local fire department) who are expected to respond to electric generating plant fires should be trained in the unique hazards that they could face.

GENERAL PLANT DESIGN

The "power block" typically houses the steam generator (boiler-furnace), turbine-generator, and auxiliary equipment. Electric generating plants are usually large open structures, perhaps several stories high (Figure 9.14.1). Building construction is typically of heavy structural steel frame with insulated metal panel walls in cold climates. In warm climates the structure may be open, including the turbine-generator operating floor. The power block for a combined cycle plant typically houses one

FIGURE 9.14.1 Typical Fossil-Fuel Electric Generating Units (Sherco, Courtesy of Xcel Energy)

or more combustion turbines, one or more heat recovery steam generators (HRSGs), a turbine-generator, and auxiliary equipment (Figure 9.14.2).

Some hydroelectric and pumped storage plants may be located the equivalent of several stories below grade in reinforced concrete and unprotected steel structures. Generators may be housed in a single undivided building or structure (Figure 9.14.3). As one might expect, newer technologies such as wind turbine-generators (Figure 9.14.4) and stationary fuel cell power plants have relatively smaller power blocks.

LIFE SAFETY

Life safety design is a critical component of the overall design of a new electric generating plant. In general, locally adopted codes govern life safety design for new construction; however, at a minimum the design should meet the requirements of NFPA *101*®, *Life Safety Code*®. NFPA 850 provides guidance for applying NFPA *101* requirements to specific areas of electric generating plants. Other standards impacting the design of new domestic electric generating plants are OSHA and the Americans with Disabilities Act (ADA). All design criteria should be approved by the authority having jurisdiction (AHJ), including identification of ADA "accessible" areas. These areas typically include administration and office areas not associated with plant operations.

Electric generating plants are unique structures due to the equipment arrangement required for their operation and maintenance. These equipment requirements often present challenges in designing for life safety and egress. Large enclosed boiler buildings can be up to 250 ft (76 m) high and typically consist of multiple grating levels providing access to equipment for maintenance, inspection, testing, and repairs. This arrangement requires a continuous vertical opening up the boiler and, in the event of fire, presents a potential smoke hazard to any personnel performing these operations.

In emergency situations, performance of emergency shutdown procedures often delays egress of control room personnel. Therefore, control facilities should have a means of egress separate from other plant areas. At many existing plants the control

FIGURE 9.14.2 Greater Des Moines Energy Center (Courtesy Bibb & Associates, Inc.)

FIGURE 9.14.3 Typical Generator Floor at a Hydroelectric Plant (Courtesy Sheridan Engineering, Inc.)

FIGURE 9.14.4 Wind Power Units (Courtesy Mike McPheeters Photography)

room's location is such that there is a heightened risk of exposure to smoke, heat, and fire, because it is too close to likely areas of fire origin, such as the turbine-generator. Adequate fire barriers and egress facilities are required. Fire can trap control room personnel, with lethal consequences, or block them so that escape is achieved only with difficulty.

NFPA 850 recommends special hazards protection in turbine-generator buildings and boiler buildings in lieu of a more restrictive philosophy of complete automatic sprinkler protection. In general, this philosophy is accepted as an equivalent to complete sprinkler protection, allowing extended travel distance, common path of travel, and dead-end limits in accordance with NFPA *101*. The AHJ should review and approve this interpretation before designing for life safety and egress.

Water Supplies

An adequate and reliable water supply should be provided. For many electric generating plants this is typically two independent supplies, each sized to meet the simultaneous demands of the hydraulically most demanding sprinkler system and 500 gal/min (1900 L/min) for hose streams for 2 hours. Older plants have combination service water-fire protection systems, while newer plants have dedicated fire protection water supplies and underground fire water delivery systems.

Site conditions dictate the supply source. Rivers, lakes, cooling tower basins, cooling lakes and ponds, suction tanks, and municipal water supplies have all been used successfully to meet fire protection needs. Open reservoir fresh (raw) water bodies may permit biological infestation and contribute to microbiological corrosion.

Fuel Hazards

Fuels used at an electric generating plant have unique hazards that the fire risk evaluation should address.

Coal. Today's coal-fired plants in the United States typically consume bituminous coal, sometimes called Eastern coal, and subbituminous coal, sometimes called Western coal or Powder River Basin (PRB) coal. Lignite is another type of coal available in certain geographic areas. For environmental reasons many electric generating plants burn lower sulfur coals. The need for compliance with more stringent emissions standards, the rising cost of natural gas, and enhanced rail system routes have made low sulfur PRB coal a viable alternative for more and more Eastern plants. Coal's principal hazards are combustibility, spontaneous ignition, and propensity to create fugitive dust. These hazards are more prevalent in the low-sulfur, low-rack coals such as PRB and lignite. All should be carefully considered at the outset of any new project or coal conversion project.

Coal is transported by a variety of means and stored or "stacked out" in open coal yards. For economic reasons the trend is to limit storage to a 30 to 45 day supply, whereas in the past storage of over a 90 day or greater supply was common. Coal stored in open piles should be compacted to prevent spontaneous heating (Figure 9.14.5). Additional information on coal can be found in Section 7, Chapter 1, "Storage and Handling of Solid Fuels."

FIGURE 9.14.5 Spontaneous Heating in a PRB Coal Pile (Courtesy Sheridan Engineering, Inc.)

A coal-handling system moves the coal from the storage pile to the boiler-furnace where it is consumed to produce steam (Figure 9.14.6). The typical coal conveyor belt is combustible and can ignite from friction between the conveyor belt and the roller, belt slippage, or static electricity. Uncontrolled hot work can also cause fires in coal handling areas. Housekeeping and dust control are vitally important, especially with PRB coal where spontaneous heating of spillage and dust is more common. An automatic sprinkler system or water spray system is needed to protect areas above and below the conveyor belt (Figure 9.14.7). Fire-retardant conveyor belts are recommended, but they burn under certain circumstances and therefore cannot substitute for automatic sprinkler or water spray protection.

Electrical equipment in coal handling areas should meet NFPA 70, *National Electrical Code*®, criteria for Class II, Division 1 or 2, Group F occupancies. A postevent investigation attributed a severe explosion and fire to an improperly closed electrical panel at an electric generating plant in 1998. The re-

FIGURE 9.14.6 Coal-Handling System

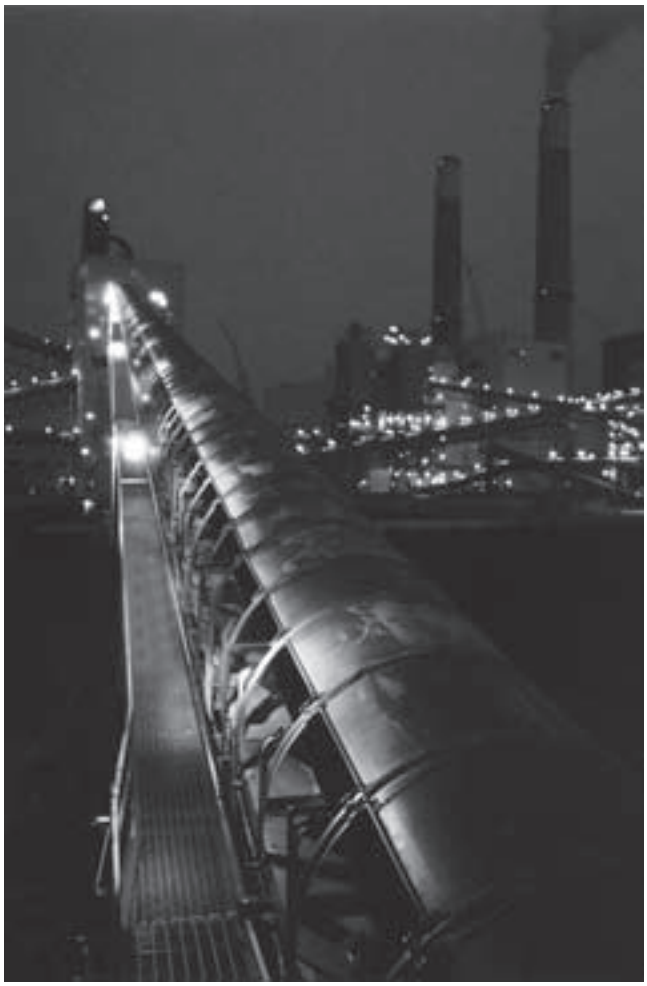

FIGURE 9.14.7 Coal Conveyor Protected with a Deluge Water Spray System (Courtesy F. E. Moran, Inc. Special Hazard Systems)

sult was 16 injuries, a 6 month plant outage, and $64.85 million in property damage (amount adjusted to 2007 U.S. dollars).[4] Crusher buildings, transfer buildings, and tripper areas (galleries) are all considered parts of the coal-handling system that require automatic sprinkler or water spray protection.

One of the largest coal-handling fires in the United States, identified in a 30 year study of large-loss fires, occurred in a crusher building because of a serious dust condition. An unknown ignition source caused an explosion that engulfed the unoccupied crusher house. The ensuing fire burned several thousand feet of conveyor belt, causing widespread damage. The result was several injuries, $35.42 million in property damage (amount adjusted to 2007 U.S. dollars), and a 4 month outage. There were no fixed automatic fire suppression systems.[4]

In-plant coal storage may be in silos (600 to 1000 tons [544.3 to 907.1 metric tonnes]) or bunkers (up to 5000 tons [4535.9 tonnes]). During plant outages the coal should be emptied to preclude spontaneous ignition. Coal fires can lead to explosions and injuries and are difficult to extinguish. These fires can last for several days or even weeks. NFPA 850 discusses various strategies to deal with these fires.

It is important to note that safe application of micelle encapsulating agents or other fire-fighting additives to burning coal requires proper planning, emergency procedures, and training. Baseline guides and procedures for preplanning and applying such agents to these fires are available from industry groups such as the PRB Coal Users' Group (http://www.prbcoals.com). These guides and procedures can be used as a *starting point* by the owner's structural fire brigade and local fire department to customize the approach for the specific facility. These fire-fighting activities are inherently dangerous and should not be performed by incipient fire brigades or other personnel. One newer strategy for extinguishment of PRB coal fires in silos and bunkers involves the use of thermal imaging cameras to locate the fire or hot spot and application of micelle encapsulator solutions via a piercing rod (Figures 9.14.8).

A pulverized coal system has significant explosion potential. See Electric Power Research Institute Project 1883-1, February 1987, *Prevention, Detection, and Control of Coal Pulverizer Fires and Explosions.* The fire protection features of these systems should be reviewed in detail if a plant desires to convert to a different type of coal. Pulverizers originally designed for eastern coal may not have OEM fire protection systems. The need for retrofit fire protection systems should be carefully considered in such cases. In an effort to lower emissions from levels associated with standard pulverized coal plants, the industry is exploring integrated gasification combined cycle (IGCC) plant designs. These plants use a gasifier to convert coal or other solid fuel to a cleaner-burning gaseous fuel. The main hazards are similar to those found in the fuel-handling areas of standard pulverized coal plants. The next edition of NFPA 850 will include recommendations for this emerging technology.

Natural Gas. Beginning in the 1980s and continuing through the early years of the new millennium, natural gas has become

FIGURE 9.14.8 Piercing Rod Components (Courtesy Hazard Control Technologies, Inc.)

the fuel of choice for much of the electric generating capacity that has or will come online. This is particularly true for combustion turbines operating in either simple-cycle or combined-cycle configurations. The gas supply piping system should be designed, installed, and maintained in accordance with NFPA 54, *National Fuel Gas Code,* and NFPA 58, *Liquefied Petroleum Gas Code.*

Oil. Very little oil-fired capacity is being added to the U.S. generation mix for economic reasons. A number of areas in the United States continue to depend on oil-fired capacity—particularly on the West and East coasts. Also note that many coal-fired plants use oil for ignition. NFPA 30, *Flammable and Combustible Liquids Code,* and NFPA 31, *Standard for the Installation of Oil-Burning Equipment,* should be followed.

Fuel oil is often heated before it is pumped to the boiler burner tip. Heating equipment may be installed inside the power block. Pipe failure and human error can result in fires involving pumping and heating equipment that expose vital equipment. NFPA 850 calls for automatic fire suppression systems to protect the hazard and a minimum 2 hour fire barrier to isolate it.

Alternative Fuels. NFPA 850 defines alternative fuels as refuse-derived fuel, municipal solid waste, and biomass. The latter includes wood chips, wood waste, rice hulls, and sugar cane stalks, among others. Each fuel presents a unique hazard and needs to be addressed as part of the fire risk evaluation. For additional information refer to Section 7, Chapter 1, "Storage and Handling of Solid Fuels."

Stationary Fuel Cell Plants. NFPA 853 addresses the unique hazards associated with fuel cells. Gas, oil, or other fuels can be used depending on the design (Figure 9.14.9).

Boiler-Furnaces

The steam generator or boiler-furnace presents a major exposure due to the potential for a firebox explosion. At the burner, an uneven or low fuel flow can result in loss of flame in a portion of the boiler. Continued introduction of fuel can result in accumulated raw fuel that another burner or hot surface can ignite. A database assembled by Marsh Risk Consulting indicates that these rare events can be very destructive. Between 1977 and 1996, eight explosions alone resulted in an average of $53.75 million in property damage per fire (amount adjusted to 2007 U.S. dollars), with forced outages at a rate of about one per year.[4] More recent explosions in the late 1990s may significantly increase the average property damage amount once cause and origin details are made available. Undoubtedly, there have been numerous "puffs" or explosions with relatively minor damage. The NFPA Technical Committee on Boiler Combustion System Hazards develops guidance on preventing explosions and implosions through properly controlling boiler operations. See NFPA 85, *Boiler and Combustion Systems Hazard Code.*

Burner front fires are a significant fire hazard associated with boiler-furnaces. These occur when oil inadvertently released from the fuel system or ignition system ignites on the hot surface of the boiler's exterior face. The oil pumping system feeds the fire, which may extend several stories on the boiler's entire vertical face. NFPA 850 recommends fire suppression systems to protect the fuel and ignition piping, and igniter and burner areas within a 20 ft (6.1 m) horizontal distance from the boiler face on all firing levels.

Flue Gas Treatment

Environmental requirements have become more stringent in an effort to control the release of sulfur dioxide, nitrogen oxide,

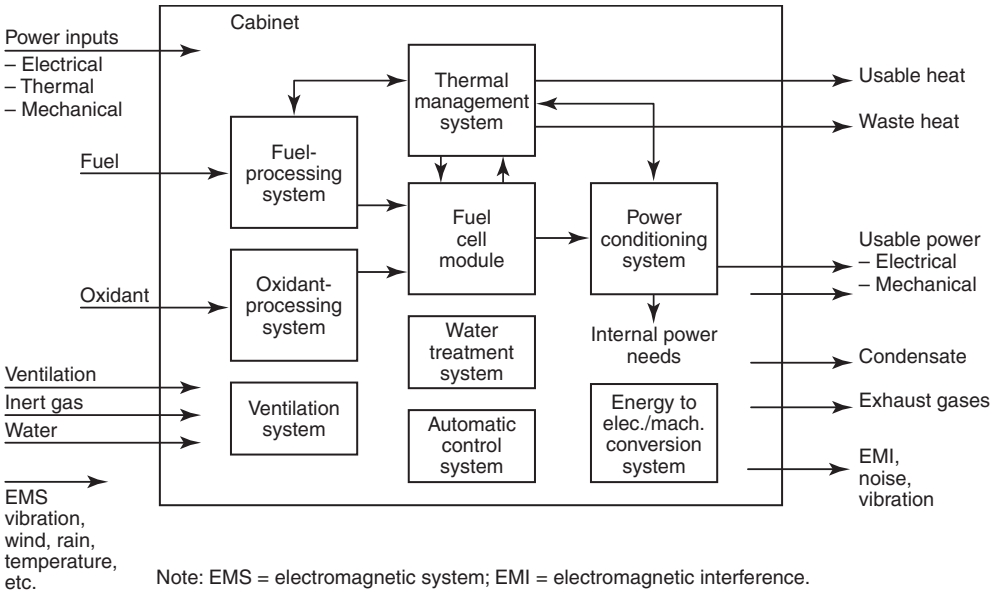

FIGURE 9.14.9 Typical Fuel Cell Power System (Source: NFPA 853, *Standard for the Installation of Stationary Fuel Cell Power Systems,* Figure B.1, 2007, p. 853-12)

and particulate matter—particularly from coal-fired plants. To deal with this challenge, the flue gas stream is erected with equipment that meets environmental requirements. This equipment includes flue gas desulfurization (FGD) systems (scrubbers), electrostatic precipitators, fabric filters (baghouses), and chimneys to release the off-gases. All have unique fire hazards that are addressed in NFPA 850.

Of particular concern is the flue gas desulfurization system, which may contain large quantities of plastics and other combustibles, particularly duct linings for corrosion control purposes. Some chimneys erected with combustible materials have presented challenging fire situations. The FGD scrubber absorbers require an emergency water quench system to cool hot flue gases which may be elevated during an abnormal event such as an air heater fire. These quench systems require large waterflow rates, which need to be available during a station blackout. They should have dedicated water supplies such that the quench water demand does not impair the fire protection system.

Steam Turbine-Generators

A study of 20 significant turbine-generator fires that occurred worldwide over 10 years at both fossil and nuclear power plants found four fatalities, several injuries, and an average of $47 million in property damage per fire with an average forced outage of 200 days. Two fires led to the permanent decommissioning of plants. Extensive vibration, overspeed, instrumentation failure, human error, blade failure, and filtration failure caused these fires.[5]

The heart of the fire challenge is the pressurized lubrication oil system (in the range of a gauge pressure of 150 to 250 psi [1035 to 1725 kPa]) that uses a Class III B combustible liquid with a flashpoint ranging from 400 to 500°F (204 to 260°C) and an autoignition temperature of 700°F (371°C). Lubrication oil is released if the lubrication oil piping system is breached. Ignition may occur due to a hot surface, which can cause a spray fire, three-dimensional fire, pool fire, or a combination of all three, producing large quantities of smoke and heat. Turbine-generators can take from 20 to 40 minutes to coast down. Turbine shaft-driven pumps shut down at 90 to 95 percent of rated speed. However, motor-driven backup pumps are designed to continue to supply lubricating oil while the shaft rotates and therefore they could feed oil to a fire.

Strategies to deal with a turbine-generator fire are outlined in NFPA 850 and Electric Power Research Institute Project 1843-2, July 1985, *Turbine-Generator Fire Protection by Sprinkler System.* Automatic sprinklers and heat detectors should be provided over all bearings. All lubrication oil piping, including instrumentation lines above the turbine operating floor and its lagging or skirt area, should be protected by automatic sprinklers. Protecting areas where oil can spread beneath the turbine-generator with automatic sprinklers is vitally important. The extent of coverage is critical and should include areas beneath the mezzanine and in condenser pit areas.

Fire suppression is also recommended for the oil storage reservoir and filtration equipment. Ideally, this equipment should be installed in a room with a minimum fire barrier rating of 2 hours.

Turbine-generator fires can also expose the turbine hall roof to excessive heat exposure and possible structural failure. There is no requirement for automatic sprinklers throughout the roof area of a large turbine hall, but roof level automatic sprinklers may be critical for newer, more compact plants without solid turbine operating floors. Smoke and heat venting is important in preventing structural roof failures.

Another potential hazard is the hydraulic control system if it is common with the lubrication oil discussed above. These systems operate at high pressures (up to 1600 psi [11,032 kPa]) and, therefore, can result in spray oil fires. Newer units, particularly those built after the early 1970s, use a separate electro-hydraulic control system that has nearly eliminated this hazard by using a less flammable synthetic fluid such as a phosphate ester.

Concentric or guarded piping for lubrication oil systems is recognized as good design practice. It does not, however, completely replace the automatic sprinkler systems discussed earlier. Fire experience shows that smaller lines that cannot be practically placed in concentric piping have been known to fail. In one case, an instrumentation line failure caused $24.43 million in damage (amount adjusted to 2007 U.S. dollars). In another case, oil escaped from a concentric pipe, resulting in a $19.54 million fire, and in yet another case, human error caused oil to be released from a filter system, resulting in a $65.96 million fire (both amounts adjusted to 2007 U.S. dollars).[4]

The vast majority of generators are hydrogen cooled. In North America, hydrogen is received in bulk and may be located on tube trailers or in high-pressure cylinders. Some foreign plants produce hydrogen on site. Hydrogen can contribute to turbine-generator fires and cause explosion damage, expected to be minor in comparison to the more severe fire damage associated with turbine lubrication oil. Hydrogen explosions inside the generator are considered unlikely as hydrogen is typically 100 percent pure and therefore there is insufficient oxygen to support combustion. Rugged generator casings have minimized the amount of damage.

Historically, one reason for not providing fire protection for turbine-generators was the belief that water released from the fire protection system would cause thermal shock to turbine components and auxiliary equipment. The previously mentioned Electric Power Research Institute (EPRI) report studied this subject.[6] The study focused on utility experience with respect to the application of water around hot turbine parts, including both intended and inadvertent fire protection system activation. Of the 24 events studied, the application of water caused no significant damage. No cases of thermal shock have been reported since the EPRI report's release. A dissertation also examined this issue; it corroborated the EPRI report and found that fire risk far exceeds any damage that a fire protection system causes.[7]

Combustion Turbines

Traditionally, combustion turbines or gas turbines were used in peaking applications during high demand periods, usually in the summer. The bulk of the peaking capacity was installed during the decade following the 1965 Northeast blackout. These machines are typically in the 10 to 40 MW range. Today, in

areas with low electric reserve margins it is not uncommon to operate these peaking units around the clock. The availability of natural gas, advances in gas turbine technology, and the advent of nonutility generators has resulted in a significant increase in the number of gas turbines in the United States and in the world. In 1999 in the United States there were 2366 units in operation, which is a 17 percent increase over 1998.[8] Since the late 1990s, natural gas has been the fuel of choice for the majority of new generating units, resulting in a nearly 81 percent increase in gas-fired capacity since 1999. The construction of natural gas plants began increasing in 1999, peaked during 2002 and 2003, and since then has declined considerably.[2]

Combustion turbines are typically purchased as a package, and the seller, not the buyer, usually determines the type of fire suppression system. Initially, the overwhelming majority has been protected with carbon dioxide or halon systems. More recently, FM-200 has been used to protect new installations. Fear of thermal shock is the chief reason for avoiding water-based systems. Currently, there is interest in protecting these machines with water mist technology and systems specifically approved for large combustion turbines.

Gas turbines are frequently installed in combined-cycle facilities utilizing heat recovery steam generators (HRSG). Steam produced by an HRSG drives a steam turbine with the same fire hazards as described earlier. The NFPA Technical Committee on Boiler Combustion System Hazards has produced NFPA 85, which addresses these hazards.

Hydroelectric Plants

Unique Fire Protection Challenges. Hydroelectric plants (Figure 9.14.10) are addressed in NFPA 851. Hydroelectric plants lack many fire hazards addressed above with respect to combustible fuels and large pressurized lubrication oil systems that operate under high pressure. Nevertheless, hydroelectric plants present unique fire protection challenges. Among them are life safety (particularly when facilities are several hundred feet below grade), use of oil-filled cable and grouped electrical cable, minimal staffing or unattended operations (even in plants as large as 1300 MW), transformer exposure, use of hydraulic control and lubrication oil systems for penstock or wicket gates, and use of generator windings.[9]

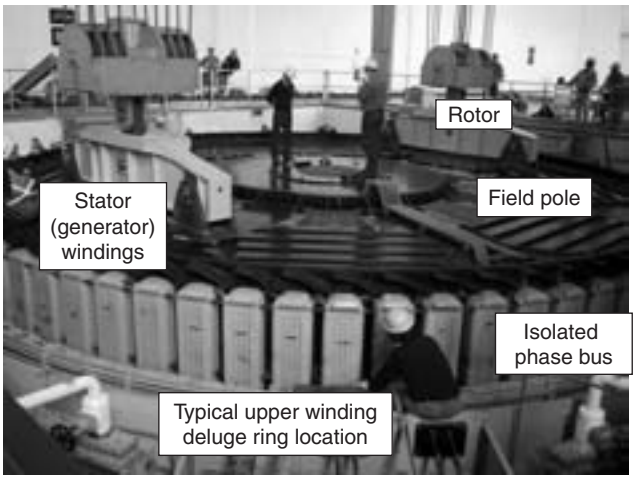

FIGURE 9.14.10 Rotor Lift at Large Hydro Unit (Courtesy Manitoba Hydro)

Generator Windings. If the phases of the generator (A, B, C, Neutral) are not totally balanced, these components can overheat or short. Such electrical faults represent a very high energy ignition source and can easily develop into a large fire considering the quantity of combustible components in the generators. The magnitude of the generator fire hazard depends on the materials used. Thermoplastic materials such as asphalt are more common on older units. Thermoplastic materials such as asphalt are highly combustible and tend to break down over time, presenting a higher risk of electrical fault. Thermoset materials such as fiberglass epoxy resins are more common on new units. Thermoset materials tend to be self-extinguishing when de-energized.

Rewinding the generator with thermoset insulation does not entirely eliminate the hazard. Other combustible components typically remain, such as current transformers, potential transformers, grounding transformers, grounding resistors, thermoplastic end-turn windings and isophase bus ducts. Protection should be provided. Fire stops should be considered for isophase ducts.

One of the largest hydroelectric plant fires occurred in 1981. A fault in an oil-filled cable led to a hot smoky fire, complicated by difficult access into the cable tunnel. An inadequate water supply hampered fire fighters. Property damage was $39.09 million (amount adjusted to 2007 U.S. dollars), and the 700 MW unit was out of service for one year.[4]

Use of Carbon Dioxide Systems. Historically, carbon dioxide fire protection systems have been commonly used to protect hydroelectric generators. NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems,* specifically addresses the design of carbon dioxide systems for protection of rotating electrical equipment. However, there are widespread efforts in the international hydroelectric industry to replace these systems. In the United States, the trend is to replace aging high-pressure carbon dioxide systems with new bulk storage low-pressure carbon dioxide systems. This addresses the need to lower maintenance costs associated with the cylinders and addresses difficulties obtaining spare parts for the old systems, some of which are over 50 years old. The low-pressure systems are also designed in accordance with NFPA 12.

In Canada, the trend is to replace carbon dioxide systems with deluge water spray. This addresses a grass-roots life safety concern with the use of carbon dioxide in below-grade areas and addresses a nationwide effort to reduce greenhouse gas emissions in accordance with the Kyoto Protocol. The water spray system designs vary. Generally a "water ring" header is installed above and below the rotor, with nozzles or orifices directing water towards the stator windings. Flow rates depend on the diameter. Sophisticated interlocks and protective relays ensure that all fields in the generator are de-energized prior to waterflow. Windage inside the rotating generator helps convert the

spray to a fine mist to penetrate deep-seated insulation fires. On extinguishment, the wicket gates are immediately opened to rotate the de-energized machine until completely dry.[10]

In New Zealand and Australia, the trend is to eliminate thermoplastic windings whenever possible. Otherwise, the trend is to replace carbon dioxide with FM-200 or Inergen. This addresses a life safety concern with the use of carbon dioxide which could migrate to potentially occupied spaces. There is also an interest in water mist technologies; however implementation in the future depends on the availability of funding for fire tests to determine a viable design basis.[11,12]

WIND ENERGY

Wind turbine generator technology is evolving rapidly and individual units are now available in the 2 to 3 MW range for use onshore. Offshore units can be as large as 6 MW. Europe has led the way with over 40,000 MW of wind energy capacity as of 2005. An additional 8000 MW were expected by the end of 2006.[13] Total capacity in the United States from wind began with 10 MW in 1981 and has risen to over 9000 MW in 2005. Preliminary data indicates that another 2500 MW were added in 2006.[14] The next edition of NFPA 850 will provide fire protection recommendations for this new technology.

Electrical Cable

Electric generating plants use insulated, jacketed cable for power, instrumentation, and control. Cables are typically routed in open cable trays throughout the power block. Plants built in the 1960s through the 1990s used significant quantities of cable. Future electric generating plants may use less cable due to computer advances and changes in technology, including the use of fiber optic cable.

Many electric generating plants are traditionally arranged to concentrate cable in areas immediately below the control room. The arrangement may typically include a control room at the top level with a cable spreading room below and a burner management room below that, with motor control centers and relay rooms on lower elevations. All these areas should be erected within walls and floor/ceiling assemblies of 2 hour fire resistance and with suitably protected openings.

Grouped electrical cables constructed of organic materials present fire hazards of various magnitudes. A few very severe fires involved PVC jacketed cable, including the 1975 fire in the cable spreading room at the Browns Ferry nuclear power plant. Electricians used an open candle flame to check a cable penetration seal made of polyurethane. The flame accidentally ignited the sealant material in the wall between the cable spreading room and reactor building. Fire then spread to the grouped electrical cable system. No serious injuries resulted, but the fire caused $302.93 million in property damage (amount adjusted to 2007 U.S. dollars), a 1½ year outage for the two 1065 MW units, and worldwide reappraisal of fire protection for nuclear power plants.[4]

At a foreign fossil-fuel plant, an electrical fault ignited the cables, consuming 5 tons of PVC in 10 hours and causing $45.19 million in property damage (amount adjusted to 2007 U.S. dollars). The plant was out of service for nearly one year.[4]

NFPA 850 recommends installation of cable that passes the flame propagation test of IEEE 383. The insulation and/or jacketing of many newer cables are of materials that are difficult to ignite. However, under certain circumstances even this cable burns. A fire risk evaluation should be performed to determine the need for automatic fire sprinkler systems in areas with significant amounts of grouped electrical cable.

Transformers

Electric generating plants use both indoor and outdoor transformers. Usually indoor transformers are relatively small, air insulated, and used for individual plant service. Larger, oil-cooled transformers used for main generator voltage step up and for station service are located outdoors. These transformers are usually grouped in an area close to the generator to minimize the length of the isolated-phase bus duct from the generator leads to the main power transformer. The amount of cooling oil can range from 20,000 to 25,000 gal (75,000 to 94,750 L). Internal high energy faults can be violent, expending tremendous power, rupturing the transformer casing, releasing oil (and possibly missiles), and subsequently igniting.[15] There have been cases of a transformer fire propagating to the generator, or from the generator to the transformer, resulting in the challenge of combating two fires simultaneously.

NFPA 850 provides guidance on transformer, spatial separation, and fire walls. For example, transformers with an oil capacity of 500 to 5000 gal (1,895 to 18,950 L) should be separated from adjacent transformers and from buildings by a minimum distance of 25 ft (7.6 m) or by a fire wall. NFPA 850 also provides criteria for the fire resistance and height of fire walls. For best practice, installation should include lightning protection, a drainage system, fire barriers, and automatic water spray systems (Figure 9.14.11). The latter should be designed according to NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection.*

FIGURE 9.14.11 Water Spray System Protecting a Transformer (Courtesy McDaniel Fire Systems, Inc.)

The purpose of an automatic water spray system is exposure protection. The benefit of such systems under catastrophic conditions has been debated. Some contend that the violent nature of a transformer failure renders automatic water spray systems useless. Although this may have occurred, in many cases the automatic water spray systems did survive explosions and were credited with controlling fire, limiting damage, and minimizing plant downtime.

Alternative fire suppression technologies are being developed. One such system being considered for acceptance testing relieves pressure buildup from a transformer excursion and conducts the escaping transformer oil to a holding tank. The transformer shell is protected against overpressurization and the oil does not come in contact with oxygen, so there is no spill or fire to extinguish. Nitrogen is bubbled up through the core of the transformer to aid in cooling.

High-Voltage Direct Current Converter Stations

A high-voltage direct current converter station with transmission line effectively controls electrical power systems that may not be synchronized, such as those between the United States and Canada. High-voltage direct current transmission links also transmit large blocks of power more efficiently over long distances. At one end of the line, the converter station converts alternating current, and at the other end, the converter station functions as an inverter, changing power back to alternating current for consumption by the local grid.

A 30 year study of the approximately 75 converter stations in the world identified about 30 minor fires and 3 major fires between 1989 and 1993.[4] The major fires caused property damage of $31.76 million, $34.20 million, and $41.53 million, respectively (amounts adjusted to 2007 U.S. dollars). First utilized in these facilities, mercury arc technology has now been replaced by thyristor technology. All three major fires have been in thyristor valves. The valves are stacked in an array of energized electrical components with combustible dielectric fluids and plastics. The stacks can be suspended from the ceiling or mounted on the floor.

This technology presents a unique fire problem. Under normal shutdown conditions, isolating and properly grounding the equipment may take up to an hour. Under emergency conditions this can be done more rapidly, but a delay can be expected in manual fire-fighting operations. High temperatures at the ceiling or thermal shock from fire water may cause the valve stack supports to fail. Major damage can then be expected from smoke and contamination of sensitive electronic equipment.

Air sampling smoke detection systems should be considered as a means to detect smoke in a fire's incipient stage. The use of automatic sprinklers is expected to be limited. There is a need for early warning fire detection and a preplanned fire fighting strategy.

SUMMARY

This chapter addresses conventional means of producing electrical energy from fossil fuels, biomass, and hydro sources. Other technologies, such as geothermal, solar, wind, and fuel cells, also exist. A variety of economic and technological reasons limit their contribution to the total electric production mix. It is highly likely that technological advances will bring forth new and unknown electric production technologies.

As the demand for electricity increases, there will be a need to build new electric generating plants, to renovate older plants, and to retire and replace plants that have outlived their usefulness. The trend is to deregulate the electric utility industry in the United States and to privatize in many foreign countries. All these issues increase the importance of fire protection for electric generation plants globally.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on electric generating plants discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 18, *Standard on Wetting Agents*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 31, *Standard for the Installation of Oil-Burning Equipment*
NFPA 54, *National Fuel Gas Code*
NFPA 58, *Liquefied Petroleum Gas Code*

NFPA 70, *National Electrical Code®*
NFPA 85, *Boiler and Combustion Systems Hazards Code*
NFPA *101®*, *Life Safety Code®*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 850, *Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations*
NFPA 851, *Recommended Practice for Fire Protection for Hydroelectric Generating Plants*
NFPA 853, *Standard for the Installation of Stationary Fuel Cell Power Systems*

References

References to various good practice reports developed by the Edison Electric Institute (EEI), Washington, DC, Fire Protection Committee, will provide further information on electric generating plants discussed in this chapter.

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"Combustion Turbine Fire Prevention and Protection," 1993.
"Fire Brigades and Training for Electric Utilities," 1985.
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"Fire Prevention and Protection in Hydrogen Systems for Generating Cooling," 1986.
"Fire Protection and Prevention in Baghouse Dust Collectors," 1983.
"Fire Protection and Prevention in Coal Handling Systems," 1981.
"Fire Protection Systems for Conveyors," 1989.
"Fossil Generating Station Administrative Controls for Fire Prevention and Fire Protection," 1989.
"Hazard Protection Identification Report," 1994.
"Steam Generator (Boiler) Area Fire Prevention and Protection," 1983.
"Suggested Guidelines for Completing a Fire Hazards Analysis," 1981.
"Transformer Fire Protection," 2001.
'Turbine Building Fire Protection," 1996.
"Use, Handling, and Storage of Liquid Fuels in Electric Utility Generating Plants," 1980.
"Water Distribution Systems for Fire Protection," 1986.

PRB Coal Users Group

Good practice reports developed by the Powder River Basin (PRB) Coal Users Group, Houston, Texas, provide further information on coal-fired electric generating plants discussed in this chapter, which can be used as a starting point for developing practices for specific plants.

"Coal Bunker, Hopper & Silo Fire Protection Guidelines," Jan. 1, 2003.

Chapter 15

Nuclear Facilities

Wayne D. Holmes

Chapter Contents

Nuclear Reactors
Radiation Machines
Facilities Handling Radioactive Materials
Radiation Exposure
Fire Protection

Key Terms

glove box, hot cell, nuclear reactor, nuclear safety, particle accelerator, performance-based approach, radiation exposure, radioactive material

Since the 1950s, the use of nuclear materials has continued to increase worldwide. In addition to nuclear fuels used for the production of electric power, nuclear materials are widely used for medical purposes, industrial controls, household uses (e.g., ionization smoke detectors), basic research, and weapons operations. Global use of nuclear materials continues to expand.

The use and storage of nuclear materials present special fire protection concerns. Although the general fire hazard in facilities that use or store nuclear materials are the same as those of similar facilities that do not include nuclear materials, fires in nuclear facilities may have more significant consequences. Employees and emergency response personnel must be protected against direct exposure to nuclear radiation and contamination. The environment and general public should not be unnecessarily exposed to radiation hazards. Unintentional nuclear criticality (self-sustaining nuclear fission reactions) must be avoided. In addition, fires and explosions may compromise circuits, mechanical systems, and equipment necessary to safely contain and confine nuclear materials and radiation.

This chapter discusses some special practices and hazards associated with facilities handling and using nuclear materials. Among the special occupancies this chapter addresses are nuclear reactors, radiation machines, and other facilities handling nuclear materials. This chapter also discusses hazards associated with radiation exposure and special fire protection procedures for nuclear facilities. Other chapters of this handbook discuss general fire hazards, construction practices, and fire control practices not unique to nuclear facilities, but common to all facilities.

For related topics, see Section 1, Chapter 6, "Premises Security"; Section 1, Chapter 7, "Protecting Against Extreme Events"; Section 5, Chapter 3, "Disaster Preparedness Education"; Section 7, Chapter 5, "Hazardous Waste Control"; Section 9, Chapter 14, "Electric Generating Plants"; and Section 12, Chapter 12, "Disaster Planning and Response Services."

NUCLEAR REACTORS

Whereas nuclear power accounts for less than 20 percent of electric power production in the United States, nuclear power is more prominent in the fuel mix for electric power in other countries. For example, in 2005 nuclear power accounted for over half of the electric power produced in France (78 percent), Lithuania (72 percent), Belgium (55 percent), Slovakia (55 percent), Sweden (52 percent), and the Ukraine (51 percent).[1]

Of 443 nuclear power reactors operating in 31 countries in 2005, 339 are located outside the United States. Another 23 nuclear power reactors are under construction, and an additional 48 reactors are on order or planned outside the United States. Nuclear power will continue to be an important source of energy worldwide.

An international collaboration known as the Generation IV International Forum (GIF) is working on the development of the next-generation nuclear energy systems known as "Generation IV." Argentina, Brazil, Canada, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States, along with the European Agency Euratom, are working to develop and demonstrate advanced nuclear energy systems. These systems will meet future needs for safe, sustainable, environmentally responsible, economical, proliferation-resistant,

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and physically secure energy. Generation IV reactors, which might include Very High Temperature Reactors, Supercritical Water Cooled Reactors, Molten Salt Reactors, Gas-Cooled Fast Reactors, Sodium-Cooled Fast Reactors, or Lead-Cooled Fast Reactors, are expected to be available for global construction by about 2030.

In the meantime, there are indications of a future revival of nuclear power in the United States. Three utilities have filed early site permit applications for nuclear power plants. Three advanced reactor designs have been certified. Several construction and operating license applications are expected to be submitted in 2008. The nuclear energy industry's Vision *2020* is that an additional 50,000 megawatts of nuclear electric power will be available in the United States by the year 2020.

By any available measure of frequency of acute incidents, the nuclear power industry has had a good safety record. However, the costliest U.S. fire ever involving the electric power industry occurred at an Alabama nuclear power facility, and the global effects of the Chernobyl station incident have shaped perceptions of safety in many people's minds. Because of the high consequence potential, the industry has reason to seek out and adopt improvements in safety, notwithstanding the low incident frequency.

A nuclear reactor is a device or assembly for initiating and maintaining a controlled nuclear chain reaction in a fissionable fuel (uranium or plutonium). Nuclear reactors are used to produce energy, to study the fission process, or to produce radioactive materials within the reactor or in a material exposed by the reactor's radiation or radioactive particles. Basically, nuclear reactors may be divided into two categories: (1) large nuclear power reactors, up to 3500 MW (megawatts thermal) or 1100 MW(e) (megawatts electrical), and (2) research reactors that operate at power levels from a few watts to many megawatts.

Nuclear reactors that include a containment vessel, generating equipment, and heat-removal equipment can be as large as the largest fossil-fueled electrical generating plants. Most research reactors, however, are so small that they may occupy only one small corner of a room in a typical laboratory building at a research facility or college campus. Therefore, the magnitude of hazard each kind of reactor presents varies considerably.

Various national and international groups have addressed the need for fire protection requirements for nuclear power reactors and research reactors. These groups include the National Fire Protection Association (NFPA), the American Nuclear Society, the United States Nuclear Regulatory Commission (NRC), the American Nuclear Insurers, Nuclear Energy Institute (NEI), Nuclear Electric Insurance Limited, and the International Atomic Energy Agency (IAEA). (See Bibliography at the end of this chapter.)

Objectives for achieving and maintaining adequate nuclear reactor safety include the following:

- Provide means to safely shutdown the reactor and maintain it in safe shutdown condition during and after accident conditions.
- Provide means to remove residual heat from the reactor core after reactor shutdown, including during and after accident conditions.
- Provide means to reduce the potential for radioactive releases within acceptable limits.

To meet these safety objectives, different reactor designs provide redundant safety systems so that initiating events, such as fires, do not prevent safety systems from performing their required functions. Advanced reactor designs include a high degree of safety system redundancy. Earlier designs of reactors include less redundancy. As redundancy decreases, the need to protect each system from the effects of fire and explosion increases. Improved passive fire protection, increased physical separation, and greater use of fire detection and suppression systems often provide this protection.

A high degree of fire protection is necessary to ensure that fires will not significantly degrade the level of nuclear safety. The "defense-in-depth" concept can achieve this safety. It includes three principle objectives:

1. Preventing fires from occurring
2. Detecting and quickly extinguishing those fires that do start, thus limiting fire damage
3. Preventing the spread of those fires that have not been extinguished, thus minimizing their effect on essential plant functions

The first objective requires that plant design and operation be such that the probability of a fire is minimized. The second objective concerns early detection and extinguishing of fires by a combination of automatic and/or manual fire-fighting techniques and relies on active fire protection measures. The third objective places particular emphasis on passive fire barriers and physical separation. This is the last line of defense if the first two objectives are not met. For the defense-in-depth concept to be effective, fire safety design and procedures must include all three objectives and implement them simultaneously.

Heat Removal

All nuclear reactors, even very low power training or research reactors, produce heat while operating. This heat either must be dissipated or used, depending on the amount produced and the reactor's intended purpose.

Reactor Control

Reactor control systems and safety systems are of utmost importance. The control system design is fitted to the technical characteristics of the reactor and is capable of producing power changes at acceptable rates. The control system design also makes it possible to produce and maintain the desired power level within the reactor so that excessive temperatures are avoided. The safety system, an addition to the control system, is adapted to the characteristics of the reactor in the instrument and control system. The safety system automatically operates in response to signals from the instruments to prevent operational variables from exceeding safe limits. On appropriate signals, the safety system warns of incipient performance changes and, if necessary, shuts down the reactor.

A reactor becomes "critical" when the total rate of production of neutrons, under control conditions, is such that self-sustaining reactions occur. Control methods must be rapid, sensitive, and protected from fire. Since the control system is vital to the reactor's adequate functioning and safe operation, protection of the control room, cableways, emergency power supply, and electrically or hydraulically operated equipment is of prime importance. Protection for these areas should be fully consistent with that used in computer rooms containing vital records.

Power Reactors

Nuclear power reactors have many of the common and special fire protection hazards that are frequently encountered at large industrial facilities. Other chapters in this handbook and numerous NFPA standards can be consulted for recommendations on appropriate means of managing such hazards. Unique to nuclear power plants are fire consequences that could result in loss of ability to adequately cool the nuclear reactor or that could result in release of radioactive materials. Special attention must be paid to controlling fire hazards in nuclear power plants so that the nuclear safety risks are successfully managed.

History of Relevant NFPA Standards. NFPA has provided fire safety standards for nuclear facilities for over 50 years with the publication in 1955 of NFPA 801, *Standard for Fire Protection for Facilities Handling Radioactive Materials,* as the first NFPA nuclear fire protection standard. The first NFPA recommended practice for nuclear reactors, NFPA 802, *Fire Protection for Nuclear Research and Production Reactors,* was initially published in 1958. This was followed by NFPA 803, *Standard for Fire Protection for Light Water Nuclear Power Plants,* adopted by NFPA in 1978. However, NFPA 802 and 803 are no longer current. NFPA 803 was replaced by a performance-based standard as described in the following section. The NFPA documents on nuclear fire protection address the unique exposures of nuclear materials and operations as well as common fire protection hazards in nuclear facilities.

Performance-Based Standards. In the mid-1990s, NFPA recognized the need to develop performance-based standards for general fire safety. A white paper, *NFPA's Future in Performance-Based Codes and Standards,* was published in July 1995. This was followed by five NFPA primers on performance-based methods developed by the NFPA staff performance-based support team. In the late 1990s, the NFPA Technical Committee on Fire Protection for Nuclear Facilities was the first NFPA technical committee to begin work on a proposed performance-based standard. This standard, NFPA 805, *Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants,* was proposed to replace the existing prescriptive standard, NFPA 803. To meet the requirements of Public Law 104-113 to support consensus standards rather than develop federal standards, the U.S. Nuclear Regulatory Commission (USNRC) encouraged, supported, and participated in the development of NFPA 805.

As described by NFPA, performance-based codes and standards specifically state their safety goals and reference approved methods that can be used to demonstrate compliance with their requirements. A performance-based code or standard may be phrased as a method for quantifying equivalencies to an existing prescriptive-based code or standard, or it may identify one or more prescriptive codes or standards as approved solutions. Either way, the document allows the use of any solution that demonstrates compliance.

Nuclear Safety. NFPA 805 was created on the foundation of NFPA 803 and accepted fire protection practices but added numerous new features in an NFPA standard. For the first time, nuclear safety was addressed in an NFPA standard. Previously, NFPA 803 and other NFPA nuclear standards addressed property protection, business interruption, and life safety but not nuclear safety. Fire protection approaches to nuclear power safety are discussed in the paragraphs that follow.

Safety performance goals, objectives, and criteria can be used to implement an effective fire protection program for nuclear power plants. These performance elements are important in establishing benchmarks to measure safety performance. Performance-based or deterministic approaches for nuclear safety can be used to meet performance criteria. The performance elements are summarized in Tables 9.15.1 through 9.15.4.

Certain minimum and fundamental fire protection requirements are specified prescriptively in NFPA 805. Common fire

TABLE 9.15.1 Performance-Based Approach to Maintaining Nuclear Safety

Goal	*Objectives*	*Criteria*
Maintain fuel in safe and stable condition	• Achieve and maintain subcritical conditions • Achieve and maintain decay heat removal and inventory control functions • Prevent fuel clad damage	• Prompt negative reactivity insertion to subcritical condition • Maintain coolant level to prevent fuel clad damage • Maintain sufficient decay heat removal to keep fuel safe and stable • Maintain vital auxiliary support for nuclear safety criteria functions • Maintain process monitoring for nuclear safety criteria functions

TABLE 9.15.2 Performance-Based Approach to Preventing Radioactive Release

Goal	*Objectives*	*Criteria*
Reasonably prevent radiological release that adversely affects the public, plant personnel, or the environment	• Maintain containment integrity *–OR–* • Limit source term	Radiological release as low as reasonably achievable and less than regulatory limits

TABLE 9.15.3 Performance-Based Approach to Providing Life Safety

Goal	*Objectives*	*Criteria*
Reasonably prevent loss of life of plant occupants due to fire	• Protect occupants not intimate with fire from loss of life and improve survivability of those intimate with fire *–AND–* • Provide adequate protection for essential and emergency personnel	• Provide safe egress or area of refuge for occupants other than essential personnel • Provide adequate protection and lighting for essential personnel to perform necessary functions • Provide adequate protection for essential personnel providing necessary emergency services

TABLE 9.15.4 Performance-Based Approach to Limiting Plant Damage and Business Interruption

Goal	*Objectives*	*Criteria*
Assure acceptable risk of economic consequences	• Limit property damage to levels acceptable to the owner/operator • Limit business interruption (plant downtime) to levels acceptable to the owner/operator	• Limit the probable maximum loss (PML) to levels acceptable to the owner/operator • Limit the business interruption due to probable maximum loss (PML) fire to levels acceptable to the owner/operator

protection requirements might not be subject to performance-based methods. These include the following:

- Minimum and fundamental fire protection elements, such as fire protection programs, plans, and procedures
- Minimum protection requirements for manual and automatic fire protection
- Compliance with applicable NFPA standards for equipment, systems, or features that are credited with providing protection

The flowchart in Figure 9.15.1, derived from NFPA 805, illustrates deterministic or performance-based methods which can be used to demonstrate attainment of safety goals. The standard allows for the performance-based approach to be implemented either by fire modeling or by risk evaluation methods.

A standard framework by which risk-informed, performance-based fire protection can be implemented in a nuclear power plant is further described in NFPA 805. The methods provide nuclear power plant operators with flexibility in meeting safety objectives, while maintaining existing prescribed levels of safety. The performance-based approach to nuclear power plant fire protection allows for innovative solutions that may be more risk-specific and risk-effective than solutions developed through other approaches. Implementation of the performance-based nuclear fire protection methods provides the potential to reduce regulatory burden by providing relief from prescriptive requirements. In June 2004, the USNRC revised Title 10 Code of Federal Regulations 50.48 and endorsed NFPA 805-2001 as a voluntary alternative for licensing. Several nuclear power plant operators are considering the use of NFPA 805 as a licensing alternative.

At the urging of the USNRC and with participation by the USNRC and other nuclear stakeholders, the NFPA Technical Committee is developing a proposed NFPA 806, *Performance-Based Standard for Fire Protection for Advanced Nuclear Reactor Electric Generating Plants.* NFPA 806, which will apply to future reactor designs, is proposed for adoption as a 2008 edition.

Beyond the effects that fire might have on nuclear safety functions, the fire hazards in nuclear electric-generating stations include large volumes of combustible lubricating oils, concentrations of combustible cables, oil insulated transformers, and similar hazards that are common to all types of electric generating plants. See Section 9, Chapter 14, "Electric Generating Plants," of this handbook for further information about fire protection for electric generating plants.

Research and Production Reactors

In general, research and production reactors may present particular problems due to their location in existing buildings (which are sometimes of combustible construction), and the use of much combustible loading in the form of paraffin shielding, boronated polyethylene, wall finishes, and instrumentation. Combustibles should be eliminated wherever possible. For example, water can be used in place of paraffin. Where combustibles cannot be eliminated, automatic sprinkler protection can be very effective in controlling potential fire exposure. Supervi-

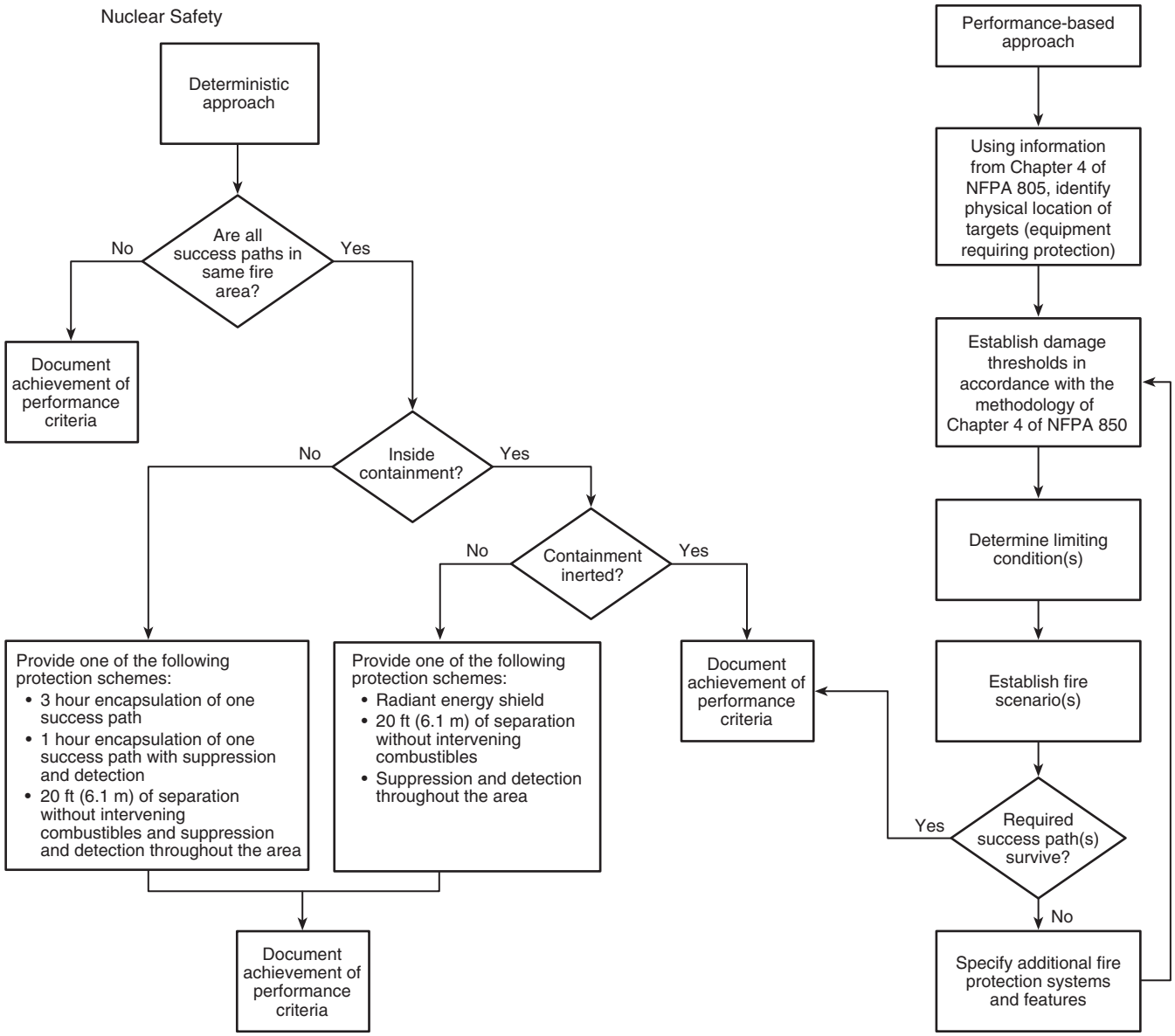

FIGURE 9.15.1 Nuclear Safety Capability Flowchart (Source: NFPA 805, *Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants,* Figure 6.2.2.1, 2006, p. 805-21)

sion of construction/operating personnel is especially important because a number of different operating groups may be involved with a single reactor.

A general lack of containment for research and production reactors further increases the need for effective fire protection design and procedures. Large power reactors often include passive containment systems and structures, typically of massive concrete and steel construction, to contain nuclear materials; research and production reactors may lack such containment structures. In these cases, confinement systems control and limit the undesirable release of nuclear contaminants. Ventilation systems become a key component in preventing nuclear releases. Special precautions must be taken to ensure that fires will not directly damage ventilation and confinement systems necessary to prevent the release of nuclear contaminants. Further, dynamic pressures created by fires and explosions must be considered and protected against to prevent air flow reversals that might significantly impact the spread of nuclear contamination.

RADIATION MACHINES

Radiation machines include mechanical and electrical devices that produce or use subatomic particles or electromagnetic radiation, or both. X-ray machines are used in radiography, therapeutic treatment, and studies of the behavior of radiation and its effect on materials. Particle accelerators, although they are radiation sources, are primarily devices for imparting extremely

high energies to subatomic particles that enter and alter atomic nuclei, thereby providing the means for developing basic information concerning the structure and behavior of matter. Gamma ray sources in the form of radioactive isotopes are employed in radiography equipment. This equipment may produce intense radiation. The use of isotopes as a source of radiation is not discussed in this chapter.

X-Ray Machines

Except for the radiation hazard while in use, X-ray machine hazards are mainly hazards of high-potential and high-energy electrical equipment. When shut down, there is seldom any appreciable residual radiation to interfere with fire-fighting or salvage operations. Although no flammable gases or hazardous amounts of flammable liquids are ordinarily needed to operate X-ray machines, they are frequently encountered in studies of the effects of radiation on a wide variety of substances.

Particle Accelerators

Particle accelerators include Van de Graaff generators, linear accelerators, cyclotrons, synchrotrons, betatrons, or bevatrons. The machines are used, as their names imply, to accelerate various charged atomic particles to tremendous speeds and, consequently, to high-energy levels. Particle accelerators furnish scientists with atomic particles, in the form of a beam, which may be used for fundamental studies of atomic structure. In addition, accelerators furnish high-energy radiation, which may be used for radiography, therapy, or chemical processing. Particle accelerators emit appreciable radiation only while operating. Attempts to extinguish a fire in the immediate vicinity of the machine should be delayed until the machine's power supply can be disconnected.

Certain "target" materials become radioactive when bombarded by atomic particles, and for this reason monitoring equipment should be used during fire-fighting operations to estimate the radiation hazard. The usual hazard presented by particle accelerators is largely that of electrical equipment. There are, however, some important exceptions. Some installations use such hazardous materials as liquid hydrogen or other flammable materials in considerable quantities. The large amounts of paraffin used in the past for neutron shielding have been replaced, in many cases, by boronated polyethylene. In fires, polyethylene materials have a very high heat release rate, which can further increase the fire hazard. In some cases, fire-retardant chemicals added to polyethylene decrease its ignition potential. Once ignited, however, even "fire-retardant" polyethylene may burn intensely when exposed by other burning materials. Limited, small-scale fire testing of combustible moderator and shielding materials does not ensure that these materials will not burn in the configurations in which they are used. Another factor is the possible presence of combustible oils used for insulating and cooling.

Industrial applications for particle accelerators include chemical activation, acceleration of polymerization in plastics production, and the sterilization and preservation of packaged drugs and sutures. The general fire protection and prevention measures for these machines should include the use of noncombustible or limited combustible (Type I or Type II) construction housing, noncombustible or slow-burning wiring and interior finishing, and the elimination of as much other combustible material as possible. (See NFPA 220, *Standard on Types of Building Construction.*) Automatic sprinkler protection should be provided in areas containing hazardous amounts of combustible material or equipment. Special fire protection should be provided for high-voltage electrical equipment.

FACILITIES HANDLING RADIOACTIVE MATERIALS

The type of equipment used to process radioactive materials depends not only on the work to be performed but also on the degree of hazard associated with the material and the process it is to undergo. Materials with low levels of radioactivity and with little or no inherent fire or explosion hazards require less protective equipment than others. To protect personnel, the amount and kind of shielding required will depend on the types of radiation emitted, as well as the activity involved. In addition, the chemical and physical nature of the radioactive materials will dictate the degree of containment necessary, as well as the construction materials necessary in the containment system. All equipment used for handling and processing radioactive materials should be designed to minimize fire and explosion potentials, as well as to protect personnel against harmful radiation exposure and prevent damage to property by contamination.

NFPA 801 provides requirements for personnel responsible for the design or operation of facilities that involve the storage, handling, or use of radioactive materials. The requirements in NFPA 801 apply to all locations, except power plants, where radioactive materials are stored, handled, or used in quantities and conditions that require government oversight license (e.g., U.S. Nuclear Regulatory Commission or U.S. Department of Energy) to possess or use these materials and to all other locations with equal quantities or conditions.

Many types of equipment and systems handle radioactive materials; most can be classified as benches, hoods, glove boxes, or hot cells.

Benches

Benches are used generally for handling relatively small amounts of alpha- or beta-emitting materials requiring little or no shielding when handled with gloved hands or tongs. No special ventilation for the bench is provided in most instances, and its use is thereby restricted to materials that will not easily become airborne.

Benches should be of noncombustible construction with a nonporous continuous working surface that can be decontaminated easily. Usually, one or two layers of blotting paper on the bench top to absorb small spills will not materially increase the fire hazard.

Hoods

Hoods, sometimes referred to as *fume hoods,* are similar to benches except for an enclosure and exhaust system added to re-

move vapors. The nature of the operations conducted within the hood may require a filter system to prevent the spread of radioactive materials. Filters with a low degree of combustibility are desirable. Fire protection and ventilation requirements for hoods are similar to those described for glove boxes. For requirements for laboratory exhaust hoods, see NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals.*

Glove Boxes

The term *glove box* refers to a system designed to contain materials, generally alpha-radiation emitters, that present little or no external radiation hazard but that can present a serious problem if they become airborne. Glove boxes may be large and are used in a wide variety of operations involving flammable liquids and gases, combustible solids, and toxic materials. The sides are fitted with long rubber-like gloves that permit manual operations to be conducted without personal contact with the hazardous materials. Figure 9.15.2 shows a typical glove box with gloves extending from the ports in the viewing window on the left. Note the portable fire extinguisher adapted for discharge into the box through a fixed piping arrangement.

Confinement of radioactive materials that may be contained in hoods and glove boxes greatly depends on the enclosure materials and the ventilation systems. Therefore, fire hazards, fire protection, construction materials, and ventilation must receive special attention to prevent a breach of the confinement system.

Burning of combustible materials that may be present in the hood or glove box could produce dynamic pressures that might overpressurize the enclosure or cause direct fire damage to the enclosure. Where combustible material must be used inside the hood or glove box, special extinguishing agents, such as dry powders, clean fire suppression agents, or automatic sprinklers, may be necessary to prevent internal fires from breaching the containment enclosure. This could lead to release of nuclear materials. Additionally, extreme care must be exercised to assure that introducing the fire suppression agent will not overpressurize the enclosure or increase the potential for accidental nuclear criticality where fissile materials may be present. The design of ventilation systems—whose purpose is to maintain a negative pressure in the hood or glove box or to maintain a specific airflow pattern—should anticipate and control pressure and airflow changes due to fires or fire suppression systems.

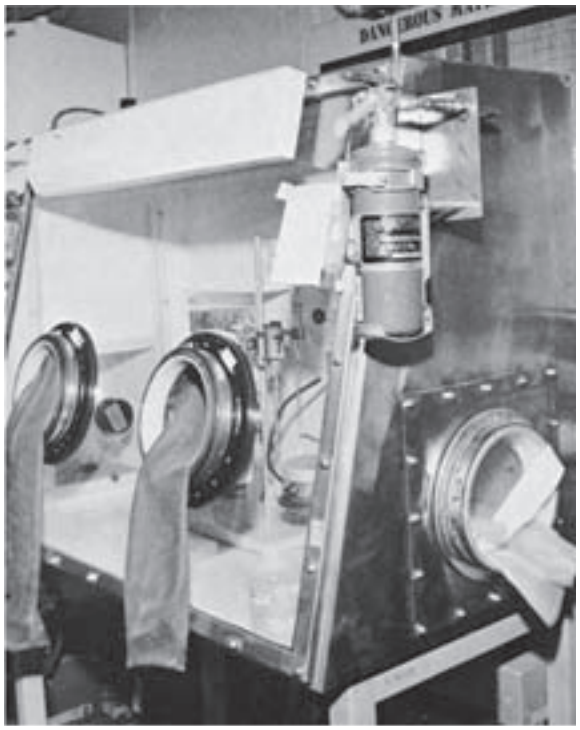

FIGURE 9.15.2 Typical Glove Box

Hot Cells

A hot cell is a heavily shielded enclosure in which gamma-emitting radioactive materials can be handled by persons using remote manipulators while viewing the operation through shielded windows or periscopes. Hot cells are preferably constructed of noncombustible materials and contain the minimum amount of combustibles consistent with operational requirements.

The high gamma radiation hazard associated with hot cells may be further complicated by the need to handle combustible materials in the hot cells, the use of combustible moderators and shielding materials, combustible oils in shielded viewing windows, and the lack of internal accessibility within the cell. Fire protection and ventilation concerns for hot cells are similar to those described for hoods and glove boxes.

In addition to all the fire and explosion hazards of glove boxes, hot cells also present increased damage potential due to the nature of the high gamma ray producing materials used. Where gamma radiation levels are very high, the possible failure of containers as a result of radiation damage must also be considered.

RADIATION EXPOSURE

Radiation Injury

The amount of injury to a person from radiation varies with the type of radiation, how much of the body has been exposed, and whether it is a one-time exposure or an accumulation of exposures to small amounts of radiation. Injuries from excessive exposures may not become apparent for days, weeks, months, or years.

Radiation experts report that, similar to many potentially hazardous materials, any exposure to radiation, either external or internal, has some element of risk, which may be too low to be measurable. Certain exposures are believed to be of reasonable risk balanced against the benefits from any activity using radiation exposure, such as medical and dental uses of radiation. Since the human race has evolved on a planet that has always been radioactive from naturally occurring radioisotopes in the air, soil, and water, it is probable that a low "background" radiation is tolerable. The controversy on radiation exposure

concerns the additional amounts that humans can tolerate. Standards have been set with the objective of lowering risks to the best practicable levels.

Occupational Exposure from Radiation in Air and Water

Radiological authorities having jurisdiction (AHJs) have set extremely low limits on concentrations of radioisotopes in air and water, based on quantities that may be inhaled or ingested. Complete treatment of the subject would require consideration of maximum permissible concentrations in both air and water. The problem of airborne concentrations is of particular concern in fires, as fire fighters and other emergency personnel may be confronted with such material in the fumes, dust, smoke, and gases liberated by a fire involving radioactive materials.

A hard-and-fast rule should be mandated that self-contained breathing apparatus (SCBA) are to be used whenever exposure to airborne radiation is a possibility. Maximum permissible concentrations (MPCs) of various radioisotopes in air and water are commonly stated as limits intended to apply to persons who are continuously exposed to the concentrations named. Consequently, the concentrations are far below the exposures that could be tolerated for infrequent exposure, as would most often be the case with fire fighters or emergency workers. Apparatus is available for sampling an atmosphere. The number of radioactive emissions in the air can be counted with an appropriate counting instrument. From these counts, the extent to which the particular atmosphere is contaminated can be determined. Figure 9.15.3 illustrates portable instruments developed at Oak Ridge National Laboratory for measuring radioactive emissions. The meters are for fast neutrons (shown bottom row at left), thermal neutrons (shown bottom row at right), beta-gamma (shown top row at left), and for alpha particles (shown top row at right), with an alpha scintillation detector at the top of the picture.

Any space normally occupied by persons not primarily engaged in radiation work should not be subjected to unreasonable radiation levels. Also, a person outside the installation should not be subjected to excessive radiation level exposure through contact with radioactive waste or by other means. Air should be monitored continuously for the presence of radiation from fixed sources or from airborne radioactive matter. In emergencies, alarms should sound and radiation levels be recorded by available commercial instruments.

Fire Department Radiation Exposures

Emergency exposures are usually allowed to exceed those tolerable to persons who work continuously with radioactive materials. In an emergency, such as a necessary rescue operation, raising the exposure, within limits, for single doses is considered acceptable. The National Council on Radiation Protection and Measurement has recommended that in a life-saving action, such as search for and removal of injured persons or for entry to prevent conditions that would injure or kill numerous persons, the planned dose to the whole body should not exceed 100 rems.[2] During less stressful circumstances, where it is still desirable to enter a hazardous area to protect facilities, eliminate further escape of effluents, or control fires, the recommended planned dose to the whole body should not exceed 25 rems.[2] These rules may be applied to the fire fighter for a single emergency; further exposure is not recommended. Internal radiation exposure may be guarded against by adequate respiratory equipment.

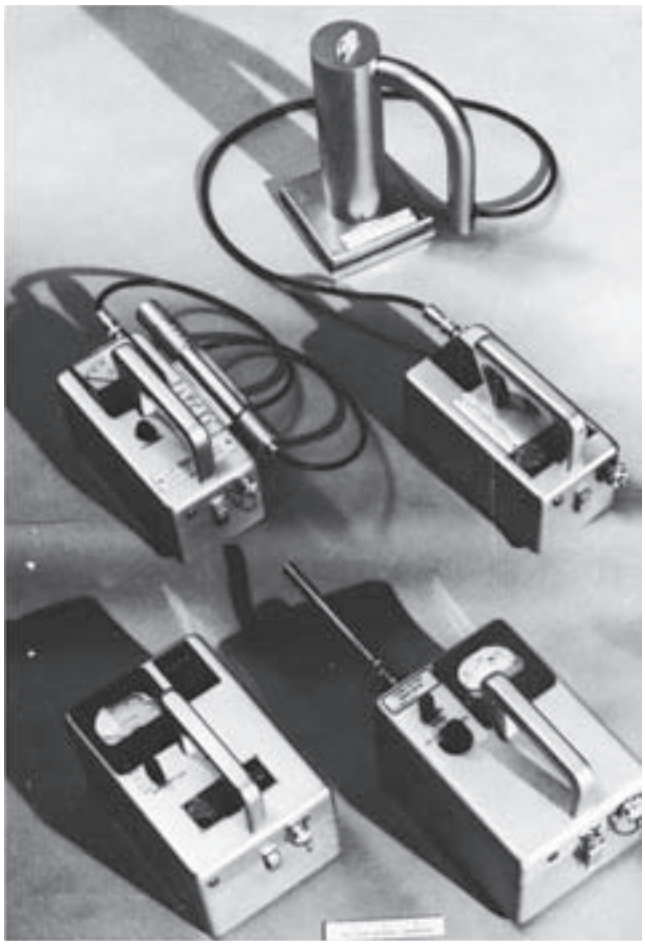

FIGURE 9.15.3 Portable Instruments for Measuring Radioactive Emissions

External exposure at the time of a single fire emergency can be judged by the use of commercial radiation survey meters, which measure radiation in roentgens or by counted disintegration rates, or by the close observation of the dosimeter indicators individuals carry. Pocket-sized dose rate alarms, which can be carried on the person, are also available. These give an audible signal dependent on radiation intensity. Film badges do not provide immediate information.

A rescue procedure that would combine external and internal radiation exposure is usually not attempted. SCBA should be used when instruments indicate the presence of airborne radiation.

Property Contamination

Entire buildings, land, and important equipment can be rendered unusable for long time periods because of severe radioac-

tive contamination from the inadvertent escape of radioactive substances. Radiological contamination may not stay in one area—it can sift through openings or ventilating systems in the form of dust or vapor and spread throughout a structure. Careless movement of persons through a contaminated area could also spread contamination to an uncontaminated area. Once a surface has become contaminated, a decision must be made as to how to remove the particular contaminating material, if this is possible. Vacuum cleaning can sometimes remove radioactive dust from building surfaces. If vacuum cleaning is used, however, highly efficient particulate filters must be used on the exhaust. Some surfaces can be hosed with water. Cleaning with soap and detergents is often a hand operation. The amount of exposure that persons doing the cleaning may tolerate must be continuously checked. Sand or vacuum blasting can be used on some surfaces, and paint may cover alpha contamination.

FIRE PROTECTION

As noted previously, substances and operations involving radioactive substances or devices presenting radiation hazards have the same fire and explosion features as those of similar materials and operations without radiation hazards. The presence of radiation or of radioactive substances affects the loss caused by fire, explosion, and accident in the following ways:

- Possible interference with manual fire fighting due to the presence of harmful radiation or possible criticality of radiation levels
- Possible increased delay in salvage and in normal resumption of operations due to the necessity of decontaminating of buildings, equipment, or materials

In properties where atomic energy is a factor, an in-plant fire protection force is recommended. In nuclear reactors, and many other such plants, 24-hour/day routines must be maintained for handling fires and emergencies. (See NFPA 600, *Standard on Industrial Fire Brigades.*)

Plan for Handling Fires

In plants involving a nuclear reactor, radiation machines, and in other facilities handling radioactive materials, the problems affecting decisions on how best to deal with a fire or other emergency are not those types of problems that can be solved by simply calling the public fire department. As many decisions as possible must be made with respect to the types of fire or emergency to be expected—and these decisions must be made well in advance. The particular fire-fighting and personnel safety measures to be taken may involve shutting down or isolating parts of the plant or individual equipment items. The areas where special procedures are necessary must be identified, and the procedures for these special areas thoroughly understood by all plant/facility personnel.

Fire emergency arrangements should include provisions for prompt notification of the plant emergency organization and public fire department, usually through a public fire alarm signal box. However, the plant fire protection department must preplan fire-fighting operations with the local fire department so that the local department will be properly coordinated with the plant's own emergency plans. Emergency planning should include measures to prevent the spread of contamination and to promptly decontaminate the area in case of accidental release of radioactive substances.

Fire fighters and other emergency personnel operating in areas where radiation exposure is a danger must be fully trained and be provided with suitable protective clothing. Respiratory protective equipment is a must, and competent radiological advisors, equipped with instruments for measuring area and local exposure, are necessary to guide emergency personnel. Dosimeters or other instruments for recording each individual's accumulated radiation exposure are helpful.

A nuclear reactor site must have a generous water supply to facilitate fire control and decontamination operations. Facilities must also be prearranged for safe disposal or storage of water that may be contaminated. The use of noncombustible materials for reactor buildings and equipment will help to avoid complications of fire hazards. For example, all finish materials used for decorative, acoustical, or insulation purposes should be both noncombustible and easy to decontaminate.

The hazard of a reactor structure exposing other buildings to radiation is prevented by appropriate distance separation or fire barriers. To prevent exposure to the reactor, it is always appropriate to separate shops and service spaces from the reactor equipment and structure itself. Wiring ducts in floors introduce an opportunity for fire or contaminated liquid or gas to spread from one space to another. Good duct seals separate one space from another. Subassembly or other operations in the preparation of fuel elements for reactors is carried on in work areas separated from the reactor so that fire cannot reach the reactor space.

Equipment for Fighting Fires

Automatic sprinkler systems or specially designed piped water spray systems are the first choice for fire protection in any location where fires may occur in nuclear reactor plants, properties housing radiation machines, and facilities handling radioactive materials. Sprinklers can operate with full effectiveness under radiation or contamination conditions that would make approach by fire fighters impossible.

In spaces where water used in fire fighting is subject to possible contamination, the collection and disposal of this water must be provided for in the local facilities; this means the facilities should have waterproofed floors and controlled floor drainage. Substantial capacity of such drainage systems would be required if hose streams and manual fire fighting were necessary. By contrast, sprinklers or a specially designed spray system would require relatively modest amounts of water for fire fighting.

If a fire occurs in a containment vessel during construction, the difficulties of access and visibility warrant the provision of temporary fixed automatic extinguishing systems when combustibles cannot be effectively controlled. Temporary interior hose stations and an ample supply of portable extinguishing equipment should be within easy reach in all portions of the vessel. Because of the smoke confinement potential, only very fast

manual response may be effective; hence, the available manual fire-fighting equipment should be in excess of normal construction practice to ensure the earliest response.

Incompatible Materials

Careful design analysis is required to reduce the fire protection problems inherent in the use of materials that are incompatible in fire situations. For example, the contemplated use of liquid metal as a reactor coolant/moderator requires special extinguishing systems not compatible with water; in fact, the possibility of a water-liquid metal reaction may justify the exclusion of water systems from the area. Such a decision, however, imposes severe limitations on the presence of flammable oils, plastics, foam insulations, and other materials that generally require copious quantities of water for fire extinguishment. Where such mixed hazards exist, careful consideration must be given to the potentials for a failure in one system to cause a failure in the incompatible system. In such cases, either protection systems must be provided that can ensure the extinguishment of fire in either system before it can rupture the other system, or a single protection system (such as inerting) must be developed that is adequate for either hazard. The difficulties inherent in such problems warrant the most thorough hazards analysis at the earliest design stages.

Water is a preferred fire suppression agent in many cases due to its high effectiveness in suppressing fires, its low cost, and its general availability. Water from sprinkler systems, water spray systems, and hose streams can be used effectively in nuclear facilities to reduce the nuclear safety impact of fires. However, the positive fire control contribution of water as a suppression agent in nuclear facilities must be balanced against the detrimental effects of water if used indiscriminately in nuclear facilities. Because of the very positive fire suppression capabilities of water and the potentially highly detrimental effects of uncontrolled fires in nuclear facilities, the use of water should not be dismissed just because its use may have some undesirable effects.

The use of water as a fire suppression agent introduces the potential for spread of water-borne contamination. Means of confining potentially contaminated fire-fighting water must be provided. In addition to providing for confinement of potentially contaminated water, radwaste processing systems should have sufficient capacity to process the amounts of water that may be discharged for fire fighting. Automatic sprinkler systems provide the advantage of discharging only limited amounts of water and only in locations where fires are actually burning, thus limiting the total amount of water that may become contaminated. Further, automatic sprinklers have high effectiveness in controlling fires and a very low frequency of inadvertent water discharge.

Where combustible and fissile materials may be present, it may be desirable to eliminate water suppression systems due to the concern for the neutron moderating and reflecting effects of the water and the potential for unintentional nuclear criticality (i.e., accidental, self-sustaining nuclear fission reactions). Some nuclear criticality specialists are reluctant to allow the use of water to control fires where fissile materials are present, even when the degree of fire hazard dictates that providing automatic sprinklers would be prudent. Such reluctance is certainly understandable, but not necessarily justifiable in all cases. In many, if not most, situations where both combustible and fissile materials are present, water spray or sprinkler protection can and should be provided. Nuclear criticality safety analyses can predict and include the neutron moderating effects of sprinklers. A safety system that simultaneously maintains fire safety and criticality safety at acceptable levels can include automatic sprinkler protection.

SUMMARY

Fires in facilities that store or use nuclear material are especially dangerous, because of the hazards of nuclear radiation and contamination. In nuclear reactors, a high degree of fire protection is necessary to ensure that fires will not significantly degrade the level of nuclear safety. The primary goals of fire protection are preventing fires from occurring; detecting and quickly extinguishing those fires that do start; and preventing the spread of those fires that have not been extinguished. These goals can be achieved by plant construction design, a combination of automatic and/or manual fire-fighting techniques, and passive fire barriers and physical separation. For radiation machines, general fire protection and prevention measures should include the use of noncombustible or limited-combustible construction housing, noncombustible or slow-burning wiring and interior finishing, and the elimination of as much other combustible material as possible. All equipment used for handling and processing radioactive materials should be designed to minimize fire and explosion potentials, as well as to protect personnel against harmful radiation exposure and prevent damage to property by contamination. In any facility handling radioactive materials, emergency planning and coordination with the local fire department are essential, including provisions for alarm systems, fire suppression systems, personal safety equipment, radiation measuring, and procedures that minimize the spread of contamination.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for nuclear facilities discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals*
NFPA 72®, National Fire Alarm Code®
NFPA 220, *Standard on Types of Building Construction*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*

NFPA 259, *Standard Test Method for Potential Heat of Building Materials*
NFPA 484, *Standard for Combustible Metals*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 801, *Standard for Fire Protection for Facilities Handling Radioactive Materials*
NFPA 804, *Standard for Fire Protection for Advanced Light Water Reactor Electric Generating Plants*
NFPA 805, *Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants*

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Chapter 16

Mining and Mineral Processing

Larry J. Moore

Chapter Contents

Surface Mining Methods
Underground Mining Methods
Mineral and Coal Processing Methods
Fire and Explosion Hazards
Fire and Explosion Safeguards

Key Terms

coal fuel, coal mining, coal preparation plant, explosion, methane, mine safety, mineral processing, mining (contour), mining (metal and nonmetal), mining (open pit), mining (strip), mining (surface), mining (underground), ore mining, smelting

This chapter describes typical mining methods, the excavation and distribution equipment used in mining, and the various and typical mineral concentration or coal preparation processes used to convert mined materials into intermediate or final consumer products. Fire and explosion hazards presented by the mining and processing of coal, metal and nonmetal ores, structural and construction materials are the focus.

Examples of coal are bituminous, anthracite, and lignite grades. Examples of metal ores are those of gold, silver, lead, copper, nickel, iron, aluminum, and zinc. Nonmetal minerals are materials such as fertilizers (e.g., potash, soda ash, and phosphate), gemstones (e.g., diamonds), salt, and sulfur. Nonmetal structural materials include limestone (used in cement), sand, gravel aggregates, and quarried materials such as marble, granite, and sandstone.

Mining is defined as the process of gaining access to and extraction of minerals, materials, or coal from the earth. The goal of mining is to economically remove desirable raw mineralized ore or materials and transport these raw materials to the next point of use or processing (Figure 9.16.1).

Mining can be done underground, on the earth's surface, or on or under bodies of water. Underground and surface mining is prevalent, with surface strip or open pit mining being the preferable and most common form of mineral or coal extraction due to economics.

Surface mining involves removing all overlying layers of dirt and rock strata—called overburden—before excavating desired materials. Underground mining is used where the overlying strata are so thick that it is uneconomical to reach the desired ore or mineral from the surface. In some cases, an open pit surface mine reaches a practical and safe limit of depth, often defined by pit wall slope stability or other geotechnical factors, and underground mining commences from the bottom of the pit. Desirable minerals located under shallow bodies of water are usually mined using a dredge, which is a floating excavation and processing plant.

Following extraction, the mined ore or coal and waste rock are removed from the mine and transported or distributed to the next point of use, a processing mill (concentrator facility) or coal preparation plant. The process of ore and mineral distribution and transportation, whether using large haul trucks, hoist systems, rubber belt conveyors, and/or large reclaim equipment, presents many fire hazards.

The goal of mineral processing or coal preparation is to convert the mined material into a more concentrated or consumer usable form. Processing of ores, coal, and nonmetal materials takes many forms and includes sizing (crushing, grinding, and milling), cleaning, separation of desirable ores or materials from undesirable waste, chemical treatment, and often electrical or heat refining. In the case of coal, preparation usually takes the form of simply sizing, cleaning, and drying the coal for shipment to a power plant. In the case of metal ores, many complex processes—such as flotation, leaching, or solvent extraction using combustible or flammable reagents—are often needed to remove the desired metal from undesired elements (such as sulfides and pyrites). Mineral processing plants (called concentrators or mills) and coal preparation facilities are usually on the mine site or nearby the mine.

Larry J. Moore, P.E., is the past chairman of the NFPA Mining Facilities Committee and has been with FM Global his entire career in a variety of engineering and management positions. He is currently the corporate principal engineer for mining and metallurgical refining and has a professional engineer's license in fire protection engineering.

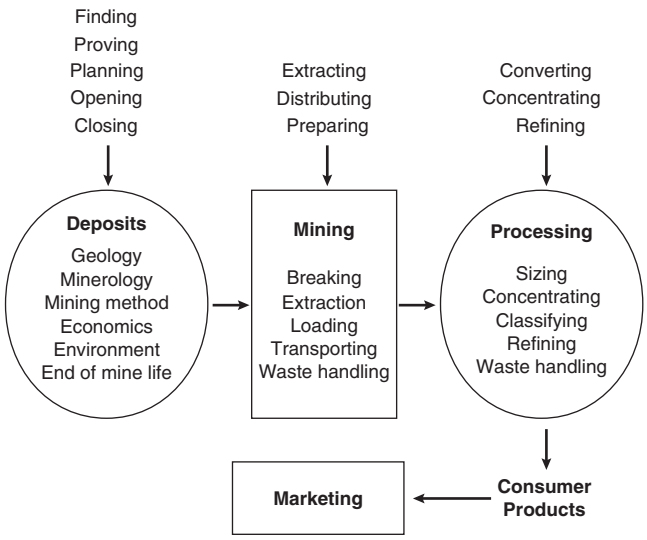

FIGURE 9.16.1 Mine Development and Life Matrix (Source: Property Loss Prevention Data Sheet 7-12, "Mining and Ore Processing Facilities"; © 2006 Factory Mutual Insurance Company. Reprinted with permission. All rights reserved.)

Large pyro- or electrometallurgical smelters and blast furnaces or hydrometallurgical chemical plants are often used to produce final metallic products such as aluminum, gold, copper, zinc, cobalt, nickel, steel, and lead from concentrated ores produced in mineral processing facilities. These facilities are usually remote from actual mining sites and are not applicable to this chapter.

The following chapters contain additional information relevant to mining and ore processing hazards: Section 2, Chapter 8, "Explosions"; Section 6, Chapter 8, "Dusts"; Section 6, Chapter 15, "Explosives and Blasting Agents"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 8, Chapter 11, "Fluid Power Systems"; and Section 14, Chapter 8, "Gas and Vapor Detection Systems and Monitors."

SURFACE MINING METHODS

Numerous surface mining methods have evolved in response to varying surface and subsurface geological conditions and to continual improvement in mining equipment technology. Methods of surface coal mining, or strip mining, include area strip mining and various forms of contour mining.[1,2]

Crushed stone and dimension stone are mined from rock quarries. Stone for crushed aggregate generally is mined by conventional open pit methods. Dimension stone is removed in large blocks using wire saws, channeling machines, or similar means.

Other than maintenance facilities, the surface mining process involves few fixed structures. Rather, surface mining is performed outdoors by specialized mobile and portable mining equipment. Major equipment types and their primary functions include blasthole drills to drill holes for explosives (used in both overburden and coal or ore); stripping machines, such as draglines, stripping shovels, and bucketwheel excavators, for overburden removal; equipment, such as shovels, wheeled loaders, and hydraulic excavators, for loading overburden, coal, or ore at the working face; and haulage trucks, trains, or conveyors to transport materials from the working face to storage or processing facilities.[3]

The mining process requires support from a wide variety of miscellaneous equipment. This equipment includes scrapers, explosives haulers, dozers, graders, water trucks, pumps, power substations, generators, crushers, cranes, backhoes, and maintenance and utility vehicles.

Area Strip Mining

Area strip mining is practiced where terrain is relatively flat, mineral seams are moderately thick (3 to 30 ft [0.9 to 9 m]) and overburden seams are relatively shallow. Strip mining is most often used for coal. Most surface coal mining in the midwestern states and the less mountainous areas in the eastern and western coal fields employs the area strip mining method. It begins with removal of overburden from above the coal seam in a roughly linear strip usually 100 to 170 ft (30 to 52 m) wide and several miles long. Overburden depths of 60 to 120 ft (18 to 37 m) are common. Uncovered coal is loaded into trucks and hauled to storage or processing facilities. When an entire strip has been mined, the process is repeated, with the overburden above the adjoining strip of coal cast onto spoil piles in the cut previously mined (Figure 9.16.2). Stripped areas are recontoured and reclaimed.

Contour Mining

Contour strip mining is most common where flat-lying coal seams occur in rolling or mountainous terrain, typical in many parts of the Appalachian coal field. In contour mining, an initial cut is established along a hillside at the point where the coal seam outcrops or is exposed. Successive cuts then are made into the hillside until an economic stripping limit is reached. Mining proceeds laterally along the hillside, following the outcrop. Contour mining follows the same overburden removal/coal loading cycle as area strip mining but generally employs much smaller equipment.

Open Pit Mining

Most surface metal and nonmetal mining is by the open pit or open cast method.[4] The overburden is first stripped to expose the top of the ore body; stripping and mining then proceed concurrently. The pit expands in depth and area until an economic pit limit is reached (Figure 9.16.3). Pit geometries vary, owing to ore bodies' irregular shape and orientation, but dimensions of 0.5 mi (0.8 km) to several miles across and 100 to over 1000 ft (30 to 305 m) deep are common.

Specialized Mining Systems

Specialized mining systems resembling metal and nonmetal open pit methods have been developed for multiple, steeply pitched, and/or thick seams. Some of the largest and most pro-

FIGURE 9.16.2 Area Strip Mining

FIGURE 9.16.3 Open Pit Mine

ductive surface coal mines in the world are located in Wyoming and Montana, where these methods are used to mine coal seams 200 ft (61 m) thick or more.

Specialized mining systems are used for certain metal and nonmetal ore deposits. Examples include dragline stripping and hydraulic removal of phosphates, placer mining, and dredging of alluvial beach sands, gold, and tin. Sand and gravel generally are mined from shallow pits and small surface excavations or with draglines and dredges from natural or artificial ponds.

UNDERGROUND MINING METHODS

Access to underground mine workings from the surface is by shaft, slope, adit, or entry. A shaft is a vertical or nearly vertical opening, usually equipped with hoisting facilities for transporting personnel, supplies, and mined products. A slope—also called an incline or decline—is an inclined opening that may be designed to accommodate a belt conveyor for materials haulage, a hoist for personnel and supplies, or diesel trackless haulage. An adit mine, or drift mine, is entered through a horizontal opening in a hillside. The term *adit* is used for metal and nonmetal mines and the term *entry* is used for coal mines. An individual mine may employ any or all of these access means, depending on the depth and orientation of its coal seam or ore body and the requirements of its production and materials-handling systems.

Where a single, uniform, relatively flat-lying coal seam or ore body is worked, the entire mine is generally confined to a single working level. Where multiple, irregularly shaped, and/or steeply inclined coal seams or ore bodies are worked, mining may be spread over many levels. Large mines may comprise miles of drifts or entries, which are horizontal openings in metal or coal mines, respectively, on many levels and interconnected with shafts, slopes, raises (vertical openings between levels), and ramps (inclined openings between levels).

The predominant constraint influencing the underground mining method selected is the amount of support required to prevent failure of the roof and/or walls. Factors related to this constraint are the physical character, size, shape, orientation, and depth of the coal seam or ore body, and the characteristics of the surrounding and overlying strata. In addition, planned production capacity and the presence of water, methane, high-rock temperatures, radon, or other environmental factors may be important considerations in selecting a mining method.

Mine designs and operating practices vary widely, since nearly infinite variability exists among these factors from deposit to deposit and even within a single mine. However, the broad spectrum of underground mining methods can be subdivided into three generic classifications:

1. Methods that produce openings that are naturally supporting or that require minimal artificial support
2. Methods that provide for substantial artificial roof support
3. Caving methods, where roof failure is integral to the mining process

With few exceptions, coal mining systems differ from non-coal mining systems, and this chapter treats them separately. Similarities that do exist are limited to softer, bedded nonmetallics, such as potash, salt, and trona, which are often amenable to coal mining systems and equipment.

Underground Coal Mining

The two basic coal mining methods are (1) room-and-pillar, which produces naturally supportive openings, and (2) longwall, which requires substantial artificial support.[1] As its name implies, room-and-pillar mining involves extracting coal in a regular pattern of rooms separated by pillars of in-place coal to support the roof (Figure 9.16.4).

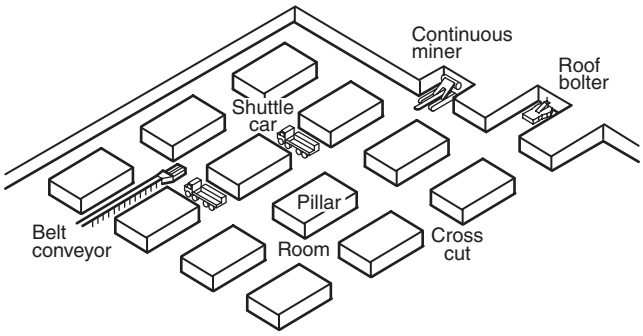

FIGURE 9.16.4 Room-and-Pillar Coal Mining

Room-and-Pillar Method. Two systems are used for room-and-pillar coal mining: (1) conventional and (2) continuous. Of the two methods, continuous mining is much more common in the United States. In conventional mining, coal is extracted in a sequence of operations, and executing each step requires specialized equipment. A cutting machine resembling a large chain saw cuts a slot into the coal face across the entire width of the room along the floor, center, or roof line. Next, a drill bores holes for explosives in the coal face. A loading machine gathers coal broken by the explosives. The machine either feeds a self-propelled shuttle car or may be loaded and hauled by a self-propelled diesel or electric scoop. In either case, coal is discharged onto a conveyor belt or into rail cars for transport to the surface or to hoisting facilities.

In continuous mining, a single machine called a "continuous miner" mechanically cuts coal from the face using a rotating drum fitted with dozens of cutting picks. The continuous miner also has a means for gathering broken coal and loading it into a shuttle car or self-propelled scoop. After each drill-blast-load cycle in conventional mining, or each machine advance in continuous mining, the mining equipment is withdrawn, and a machine called a "roof bolter" secures the roof. Holes are drilled into the roof, and long bolts are inserted and anchored to strengthen the roof span and prevent roof failure.

Longwall Mining Method. Longwall mining involves extracting coal (and occasionally soft deposits like Trona, which is the mineral form of sodium sesquicarbonate) in a nearly continuous operation using a specialized, integrated mining and roof support system (Figure 9.16.5). Using standard room-and-pillar techniques, blocks of unmined coal called longwall panels are prepared. These blocks are typically 300 to 1000 ft (90 to 305 m) by 3000 to 6000 ft (915 to 1830 m); however, "super longwalls" with lengths of 20,000 ft (6100 m) or more are possible. Each longwall panel is mined in linear slices at full seam height by a mechanical cutting machine or plow drawn back and forth across the short face. Cut coal is forced onto a chain conveyor that extends the face's entire length. Large, self-advancing hydraulic jack units called longwall shields support the roof immediately adjacent to the face. As the roof support line advances with the coal face, the roof behind it is permitted to cave. Longwall mining is more productive and generally considered safer than conventional or continuous mining.

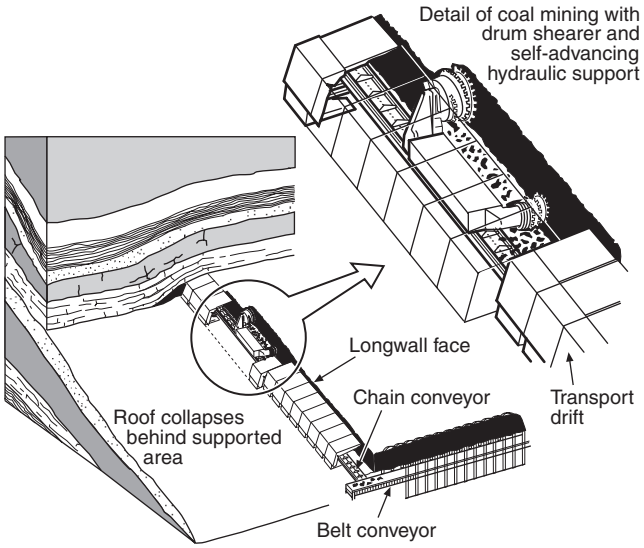

FIGURE 9.16.5 Longwall Coal Mining (Source: Courtesy of Atlas Copco)

It accounts for about 35 percent of U.S. underground coal mine production.

Coal Mining Equipment

Most coal mining equipment is electrically powered. Electrically powered mobile equipment, such as undercutting machines, drills, loading machines, continuous miners, shuttle cars, scoops, and roof bolters, generally receive power through a trailing cable. Belt conveyors, pumps, and trolley haulage systems are generally wired directly to a permanent or semi-permanent power center. Battery-powered scoops, personnel transports, and utility vehicles are also common. Some mobile haulage equipment, notably scoops, load-haul-dump (LHD) vehicles (low-profile front-end loaders, also called *scoop trams*), and rail locomotives, can also be diesel powered. Although significant and growing, diesel-powered equipment is not as extensively used as electrically powered equipment in underground coal mining.

Ancillary Operations

Numerous ancillary operations must be coordinated with the mining process. The main haulage network, whether rail or belt, must function smoothly to prevent materials-handling bottlenecks from interfering with production. The roof in active areas is constantly monitored for failures or signs of impending failure. In heavily traveled areas, such as main haulageways and important ventilation routes, heavy timbers or steel arches or beams are often installed to help support the roof. Water supply, power distribution, and ventilation systems require periodic attention; equipment and facilities inspection, maintenance, and repair are continuous. Dust control also receives high priority, both to protect miners' health and to prevent explosive conditions.

Underground Metal and Nonmetal Mining

Underground metal and nonmetal mining methods are more diverse than underground coal mining methods, because the physical character, size, shape, and orientation of these ore bodies vary more greatly than most coal seams.[5] The following paragraphs describe six standard mining methods. In actual practice, great variability, combination, and adaptation of standard methods are required to suit local conditions.[6] Room-and-pillar and sublevel stoping methods are used in extraction areas that require minimal artificial roof support. Shrinkage stoping and cut-and-fill are used in extraction areas that require substantial roof and wall support. The two most common caving methods are sublevel caving and block caving.

Room-and-Pillar Method. The room-and-pillar method (Figure 9.16.6) is used for relatively flat-lying deposits of moderate thickness with a competent roof. With the exception of the softer, bedded nonmetallics, metal and nonmetal mine openings are generally larger than those in typical room-and-pillar coal operations, permitting the use of larger, more productive mining equipment.

Sublevel Stoping Method. Sublevel stoping, used in vertical or nearly vertical ore bodies of highly competent rock, requires considerable premine development to prepare the ore body for production mining. Sublevel drifts along the longitudinal centerline of the ore body are driven in a vertical column between the mine's main levels (Figure 9.16.7). On the main haulage levels, drawpoints perpendicular to the sublevel drifts are driven into the ore body. A complete radial pattern of blastholes, or parallel rows of vertical blastholes, is then drilled at regular intervals along the entire length of each sublevel drift. Each ring or row of holes is loaded individually with explosives and blasted. Every blast vertically slices ore, which falls to the bottom of the open cavity, or stope, where it is loaded out through the drawpoints.

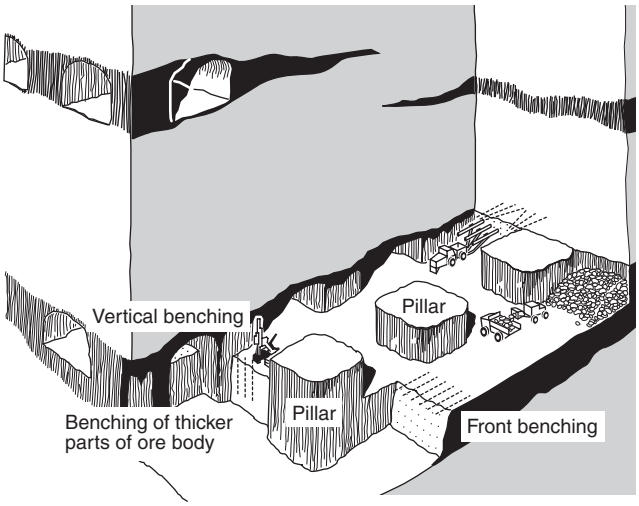

FIGURE 9.16.6 Room-and-Pillar Metal and Nonmetal Mining (Source: Courtesy of Atlas Copco)

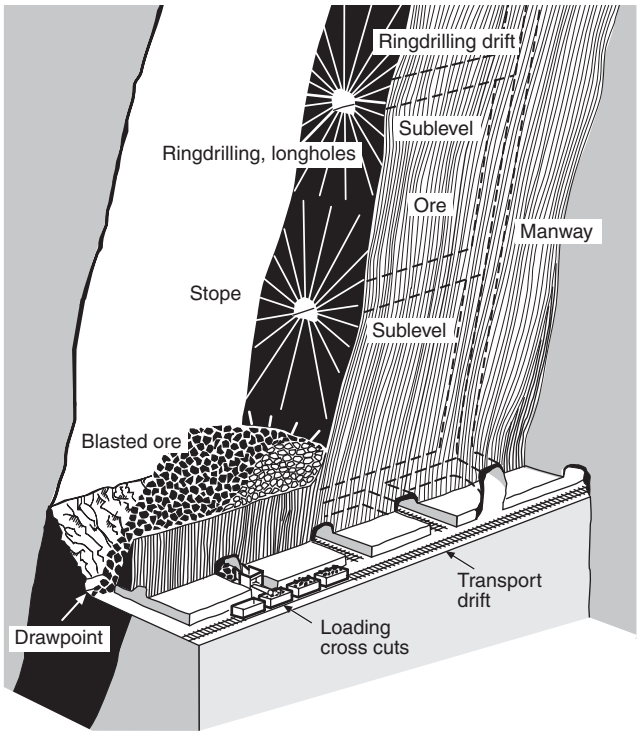

FIGURE 9.16.7 Sublevel Stoping (Source: Courtesy of Atlas Copco)

Shrinkage Stoping Method. If the ore or surrounding rock is too weak or the rock pressures too great, open stopes are not feasible. Such ore bodies require artificial support of the stopes during mining. Shrinkage stoping and cut-and-fill stoping are most commonly employed to extract such ore bodies. Shrinkage stoping requires very little preproduction development. Drawpoints are driven into the ore body at regular intervals along the main levels, and raises are driven into the ore between levels (Figure 9.16.8). The ore is extracted in horizontal slices, starting at the bottom of the stope and advancing upward by drilling and blasting the roof. Just enough broken ore is removed from the stope to provide a work platform for miners. Ore remaining in the stope supports the walls and prevents adjoining rock from breaking loose and contaminating and diluting the ore. The process of mining horizontal slices repeats until the upper limit of the stope is reached. The stope is then emptied of ore.

Cut-and-Fill Method. Preproduction development for cut-and-fill mining is similar to that for shrinkage stoping, except it requires only one or two drawpoints (Figure 9.16.9). Mining is similar as well, with the ore body mined in horizontal slices from bottom to top. However, the stope is emptied of broken ore after each slice, or cut, and the stope is filled with waste material before mining resumes. The fill provides a work platform for miners and supports the stope walls. Ore is removed from the stope through timber or steel ore chutes embedded in the fill.

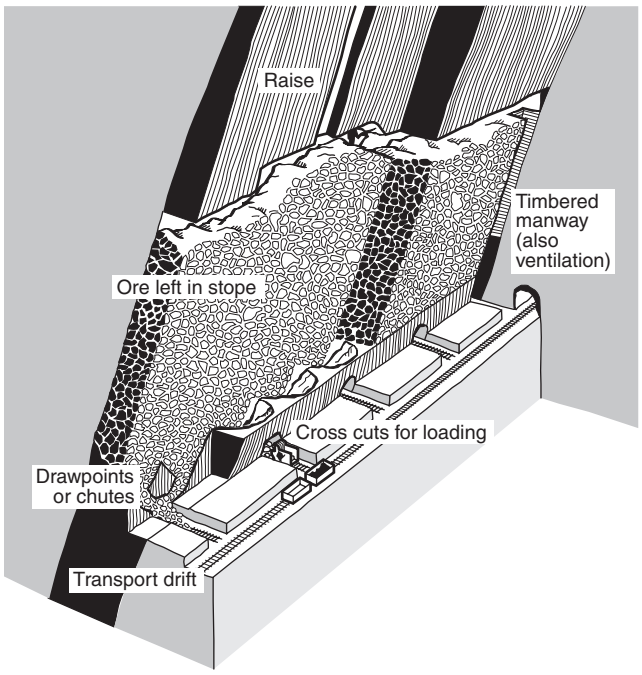

FIGURE 9.16.8 Shrinkage Stoping (Source: Courtesy of Atlas Copco)

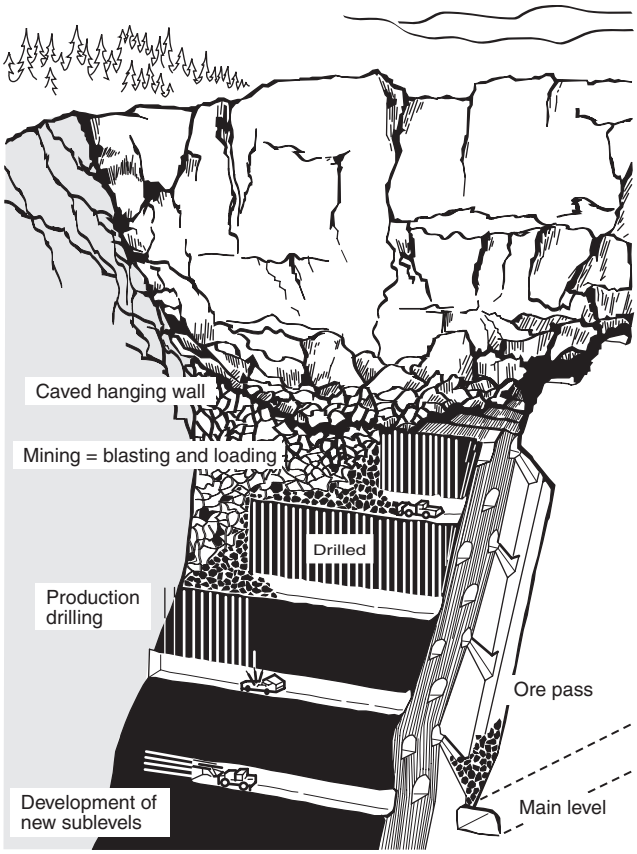

FIGURE 9.16.10 Sublevel Caving (Source: Courtesy of Atlas Copco)

Sublevel Caving Method. A high degree of mechanization, high production capacity, and low production costs characterize caving systems. In sublevel caving, preproduction development is similar to sublevel stoping, with sublevel drifts driven into the ore at 30 to 50 ft (9 to 15 m) intervals (Figure 9.16.10). Drawpoints on the main levels are not required, how-

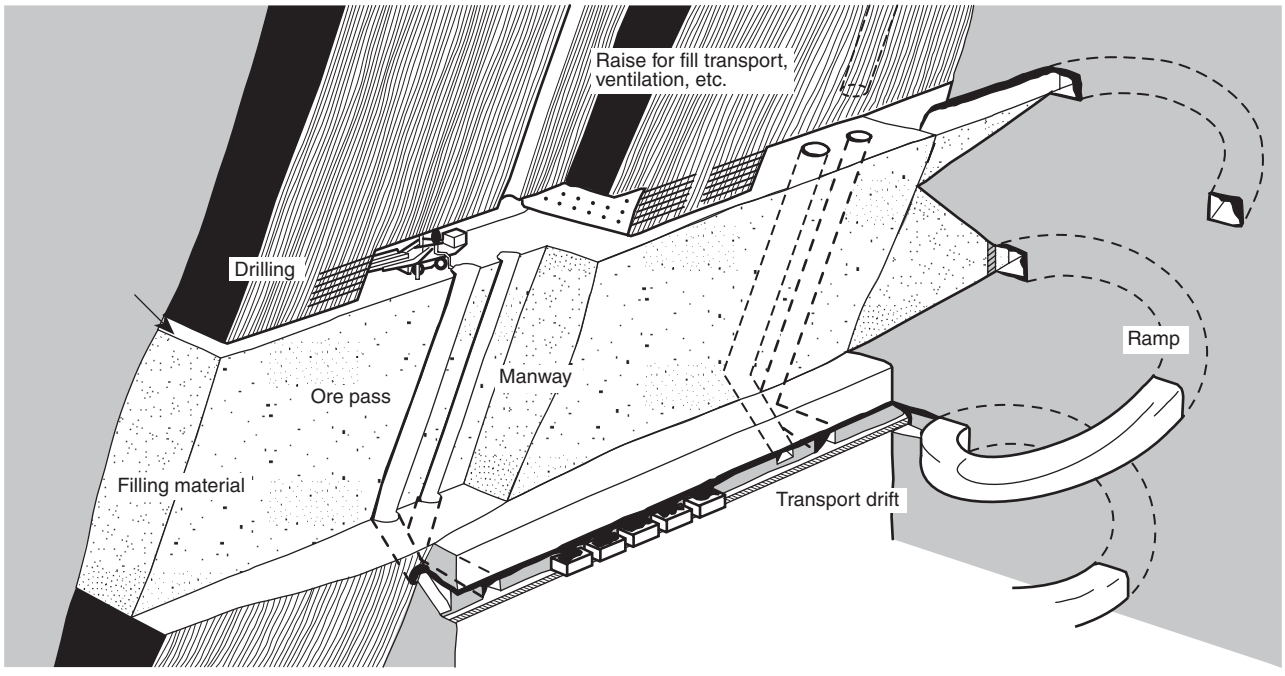

FIGURE 9.16.9 Cut-and-Fill Mining (Source: Courtesy of Atlas Copco)

ever, because the ore is retrieved through the sublevel drifts. Fan-shaped blasthole patterns are drilled upward at regular intervals along the entire length of each sublevel drift. Drill fans are blasted individually, with broken ore caving into the sublevel drifts. LHDs load the ore and transport it to an ore pass system.

Block Caving Method. The principle of block-cave mining is the natural fracturing and caving of ore that has been undercut over a large area. The ore extraction phase requires minimal drilling and blasting, because the ore fractures itself as gravity acts on the undercut rock masses.

Preproduction development is undertaken in four steps (Figure 9.16.11). First, a network of haulageways is developed beneath the ore horizon. Next, finger raises are driven up to a set of grizzly drifts. From the grizzly drifts, a second set of finger raises is driven, gradually widening to form funnels at the undercut level. Finally, the entire ore block is undercut.

The weight of overlying ore and overburden creates enormous stresses on the ore at the bottom of the block, causing it to fracture and cave into the funnels.

Equipment

A wide variety of equipment is used in underground metal and nonmetal mining. Where space permits, drilling is performed with mobile "drill jumbos" fitted with two or more rock drills. Diesel-powered LHDs are used to load and haul broken ore from the drawpoint or working face. Where space is limited, small, portable, manually operated rock drills perform drilling. Broken ore is loaded out by small pneumatic loading machines or by a scraper blade suspended on a cable between a hoist and a pulley, which gathers ore as it is dragged over a pile. Main haulage usually is accomplished with belt conveyors, rail cars, or haulage trucks.

As with underground coal mining, a vast array of ancillary operations supports the ore extraction process. Primary among these are the inspection, maintenance, and repair of mine equipment, which is performed at most mines in large underground shops. Mines relying on diesel equipment also must have facilities in which to store and/or transfer diesel fuel. In addition, power distribution, ventilation, hoisting, roof control, and dewatering are important ancillary operations.

With the dual goals of increasing productivity and removing miners from hazardous workplaces, emerging mining technologies in the coal and metal and nonmetal sectors employ modern automation and robotics technology. In the coal sector, significant research is aimed at both fully automated and teleoperated remotely controlled extraction and haulage systems. The metal and nonmetal sector has developed and deployed fully automated haulage systems based on both rail and trackless equipment.

MINERAL AND COAL PROCESSING METHODS

After extraction by one of the aforementioned mining methods, the mineral, structural material, or coal is transported to a processing facility or, in the case of coal, to a preparation plant

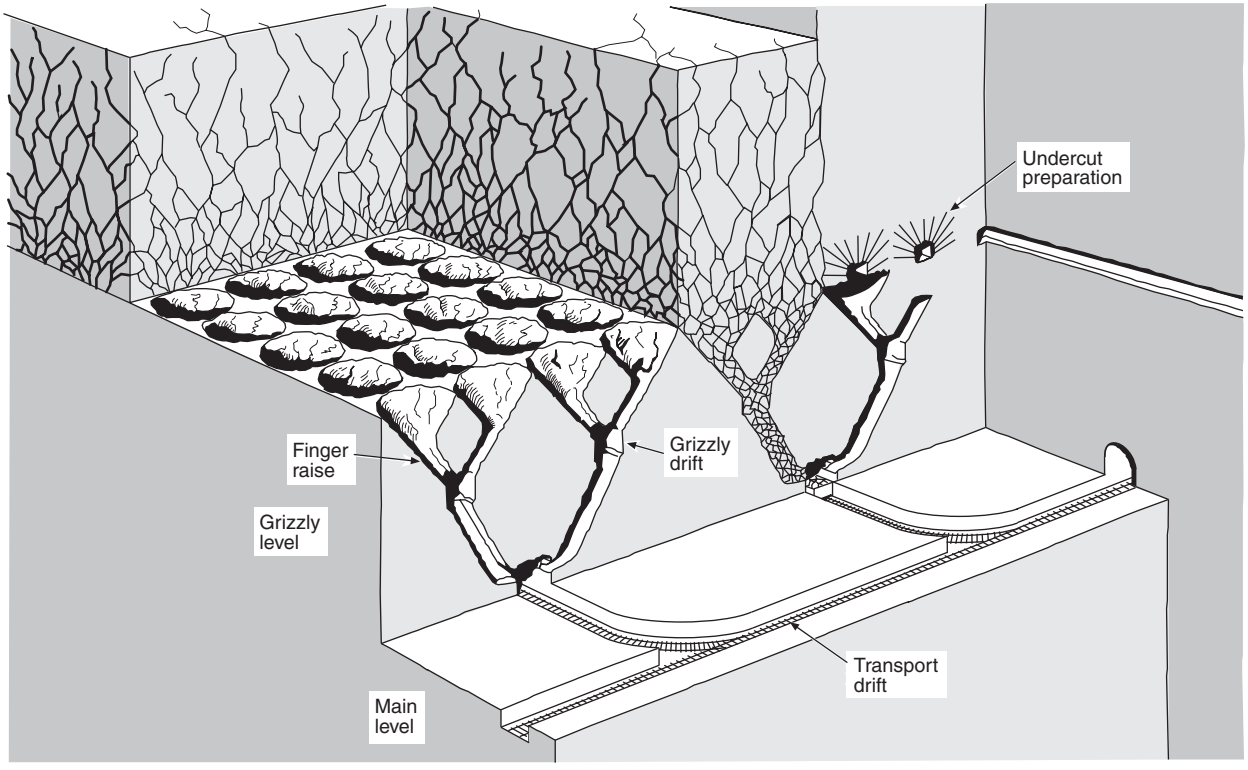

FIGURE 9.16.11 Block Caving (Source: Courtesy of Atlas Copco)

for conversion to intermediate or final consumer products. The processing facility is commonly located on or near the mining site due to the poor economics of transporting low-grade or run of mine (ROM) ores or coal over long distances. Waste rock or overburden from the mine may be used for road building or might be sent back to the mine for fill or for environmental remediation.

The purpose of the processing or preparation plant is to size, dry, clean, chemically convert, and/or concentrate the ore or coal (Figure 9.16.12). It also allows for removal and disposal of waste materials.

Prior to processing, the ore, structural material, or coal is transported from the mine by rubber belt conveyor, haul truck, tramway, sluice, pipeline, or other conveyance. The preprocessed ore or coal is usually stored in open stockpiles, silos, or inside buildings if susceptible to damage from the elements (such as water-soluble fertilizers like potash).

Structural materials such as granite and sandstone are cut to size, polished, stored, and shipped with little further processing or finishing. Aggregates such as sand and gravel are sized and washed also with little further processing. Limestone is often heat calcined in horizontal or vertical fuel-fired kilns or roasters and mixed on site with sand or gravel to produce cement or concrete.

Metal ores are subjected to many processing steps depending on the material. The most common processing facility is known as an ore concentrating or dressing mill. The first step is rough sizing whereby ore is crushed in large crushers and screened. Primary crushers may be located inside open pits or underground. Secondary crushers are usually located closer to the mill. Each crushing step further reduces the mineralized rock in size (Figure 9.16.13).

The crushed ore may be stored in intermediate stockpiles. Large semimobile or rail-mounted equipment and conveyors may be used to reclaim the ore for transport to further downstream processing.

FIGURE 9.16.12 Ore Concentrating Plant (Source: Property Loss Prevention Data Sheet 7-12, "Mining and Ore Processing Facilities"; © 2006 Factory Mutual Insurance Company. Reprinted with permission. All rights reserved.)

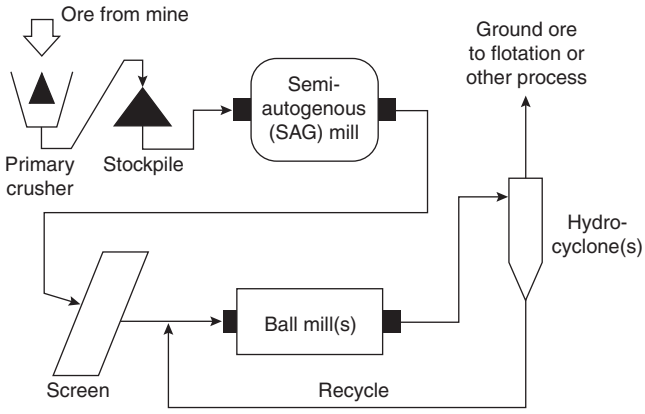

FIGURE 9.16.13 Typical Metal Ore Grinding Circuit (Source: Property Loss Prevention Data Sheet 7-12, "Mining and Ore Processing Facilities"; © 2006 Factory Mutual Insurance Company. Reprinted with permission. All rights reserved.)

After crushing, the rock is wet milled with water or low-grade acid solutions using ball or rod, semiautogenous grinding (SAG) mills, or fully autogenous grinding (FAG) mills. Wet mills reduce the rock to a fine, talc-like powder. These mills are large rotating machines that use steel balls, steel rods (less common), or ore-to-ore contact to reduce the particle size. World-class-size SAG mills are 35 ft (10.7 m) in diameter and may be driven by 10,000 hp electric motors (Figure 9.16.14).

Following fine grinding, the powdered ore is usually in a liquid slurry (or pulp) form and can be piped throughout the facility. Desired metal minerals are separated from undesired waste materials (called gangue) by separation processes such as flotation, spirals, thickening, gravity, shaker tables, or mag-

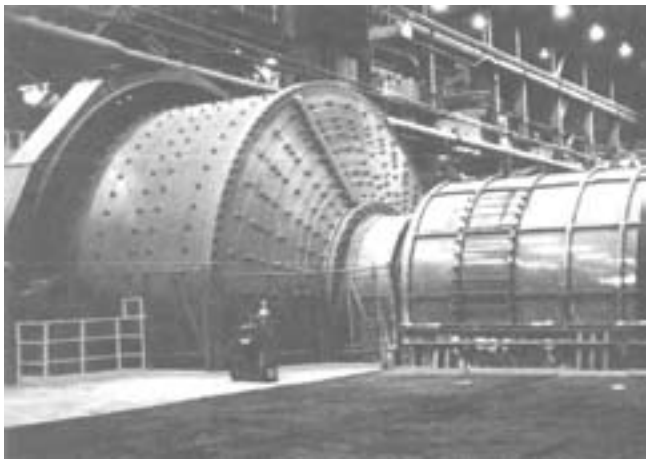

FIGURE 9.16.14 Semiautogenous Grinding (SAG) Mill (Source: Property Loss Prevention Data Sheet 7-12, "Mining and Ore Processing Facilities"; © 2006 Factory Mutual Insurance Company. Reprinted with permission. All rights reserved.)

nets. Mill circuits feature extensive rubber-lined equipment; plastic screens; rubber belt conveyors; grouped electric cables with combustible plastic insulation; large hydraulic, thermal, and lubrication oil systems; and combustible or toxic flotation reagents. In cold climates, concentration processes are located inside large industrial buildings. Plastic materials are often used in construction.

Some highly oxidized and low sulfide ores (notably copper and gold) can be directly processed by heap pad leaching. In this process, pyramidal-shaped mountains of ore are layered onto impervious layers such as clay or rubber liners by large earthmoving equipment, haul trucks, and conveyors. These man-made mountains of ore can be over 400 ft (150 m) high and thousands of feet (hundreds of meters) long and wide and can fill entire valleys. A water-based solution of weak cyanide (for gold) and/or sulfuric acid (for copper) is sprayed or irrigated onto the pile. The solution selectively dissolves the desired metals and is captured onto the impervious layer under the pile. The metal-rich pregnant solution is gravity-flowed or pumped to collection ponds from which it is sent to downstream processing. The pregnant solution, in the case of copper, is then processed by solvent extraction (SX) featuring flammable or combustible organic solutions and sent to an electrowinning plant for metal recovery. In the case of gold or other ores, there is a wide variety of alternate processes.

Waste materials from concentrating processes are pumped to a tailings disposal facility, where solids and liquids are separated and toxic or waste solids are permanently stored and environmentally monitored and controlled.

The desired product from an ore-processing mill is a moderately concentrated form of the metal ore. It is dried and filtered and then stored for further processing. Concentrates up to approximately 30 percent metal value can be obtained from this process.

Following concentration, the concentrate is further processed to remove remaining undesirable materials, notably common sulfides (pyrites) and iron-based compounds. These downstream steps are categorized as hydrometallurgical, electrometallurgical, pyrometallurgical, or chemical processes.

A typical pyrometallurgical process is one in which the concentrate is sintered, calcined, roasted, or smelted at high temperatures in the presence of oxygen or enriched air (Figure 9.16.15). This is typical for zinc, gold, copper, and lead. This process usually removes sulfides (which are often converted to sulfuric acid in emission control acid plants) and trace, undesirable iron compounds, which are disposed of as slag.

Examples of hydrometallurgical processes are pressure oxidation leaching of gold using high-pressure chemical reactors (called autoclaves in the industry), zinc lixiviation using acids, and solvent extraction of copper or uranium using flammable or combustible organic liquids.

Examples of electrometallurgical processes are electrowinning (Figure 9.16.16), often used for gold and copper, and electrorefining, often used for aluminum and zinc. Highly specialized electrical and chemical processes are used to recover titanium, zirconium, and magnesium. Chemical reduction reactions using hydrogen or hydrogen sulfide gases are used for nickel, cobalt, and direct reduction iron. All these specialized processes present unique and often challenging fire and explosion exposures.

FIGURE 9.16.15 Large Copper Smelting Facility (Source: Property Loss Prevention Data Sheet 7-12, "Mining and Ore Processing Facilities"; © 2006 Factory Mutual Insurance Company. Reprinted with permission. All rights reserved.)

FIGURE 9.16.16 Electrowinning Plant for Copper (Source: Property Loss Prevention Data Sheet 7-12, "Mining and Ore Processing Facilities"; © 2006 Factory Mutual Insurance Company. Reprinted with permission. All rights reserved.)

Diamond-bearing ores are initially processed similar to metal ores (crushing, screening, etc.) but do not use flotation with reagents. Processes such as Dense (or Heavy) Media Separation are used instead.

Coal processing—usually called preparation—is used to clean (remove impurities), wash, dry, and size the coal prior to further downstream use. Most downstream use of coal is for power plants or for producing steel. Many of the coal preparation processes and hazards are similar to those of metal ore concentrating plants, including sizing, grinding (or pulverizing), flotation, and filtering. Large thermal coal dryers using

combustible fuels or thermal oils may be used. A coal preparation plant also has unique hazards of dust and methane gas explosions and the potential for spontaneous heating inside coal piles or silos. Waste from preparation processes is pumped to a coal impoundment facility, where solids and liquids are separated and toxic or waste solids are permanently stored and environmentally monitored and controlled.

FIRE AND EXPLOSION HAZARDS

Mining and mineral processing facilities represent significant fire and explosion exposures to both personnel and production equipment and buildings.

From a personnel safety standpoint, underground mining has been by far the global loss leader in fatalities and injuries for all industries. In the 100 year period from 1900 to 1999, over 100,000 miners died from all unintentional-injury causes, including fire and explosions, in U.S. coal mine incidents alone, an average of 1040 per year. In the 10 year period from 1990 to 1999, this figure had been reduced to 450 fatalities, or an average of 45 per year. Approximately 10 to 15 percent can be attributed directly to fires and explosions.[7]

Life threatening incidents, though more common in coal mines, have also occurred in the noncoal (metal and nonmetal) mining industry. In the same 100 year period ending 1999, approximately 23,000 miners died in various incidents in noncoal mines, including fire and explosions. To put this in recent perspective, on May 2, 1972, a fire in the underground workings of the Sunshine silver mine in Kellogg, Idaho, claimed 91 lives.[8]

In the most recent 5 year analysis period (2000 to 2004) 116 fatalities have occurred in all types of mining, of which 83 occurred in underground coal mining and 16 in underground metal mines.[9]

Early in 2006 several major underground mine incidents occurred resulting in multiple fatalities and extended emergency rescue operations. At the Sago Coal Mine (West Virginia, January 2006), 11 miners died after suspected surface lightning ignited underground gases causing an explosion. Later that same month a rubber belt conveyor fire in the underground Alma coal mine (also in West Virginia) caused two fatalities and forced rescue of many others. In February 2006, a coal mine fire in Mexico caused 65 fatalities. Topping this off are an estimated 10,000 fatalities a year in Chinese coal mines.

In January 2006, heavy smoke from an incidental fire involving plastic piping in a Canadian potash (nonmetal) mine trapped 72 miners underground. All were rescued. Many additional fires occur in underground metal mines that go unreported or do not involve personnel injury.

Table 9.16.1 shows mine disasters since the early 1880s, for both coal and noncoal mines.[7] This is for all incidents, but fires and explosions, followed by collapse, represent the vast majority of multifatality disasters. Tables 9.16.2 and 9.16.3 show a listing of selected historic mine disasters.[7] Table 9.16.4 shows ignition sources of underground mine fires.

These and additional statistical information for U.S. mining can be found on the Mine Safety and Health Administration

TABLE 9.16.1 Number of Documented Mine Disasters (5 or More Deaths)

Historic Period	*Coal Mines*	*Metal and Nonmetal Mines*	*Total*
Through 1875	19	4	23
1876–1900	101	17	118
1901–1925	305	51	356
1926–1950	147	23	170
1951–1975	35	9	44
1976–present	13	1	14

TABLE 9.16.2 Five Worst Coal Mine Disasters, Since 1940

Year	*Day*	*Mine*	*Location*	*Type*	*Deaths*
1951	12/21	Orient No. 2	West Frankfort, Illinois	Explosion	119
1947	03/25	Centralia No. 5	Centralia, Illinois	Explosion	111
1940	01/10	Pond Creek No. 1	Bartley, West Virginia	Explosion	91
1968	11/20	Consol No. 9	Farmington, West Virginia	Explosion	78
1940	03/16	Willow Grove No. 10	St. Clairsville, Ohio	Explosion	72

TABLE 9.16.3 Five Worst Metal and Nonmetal Mine Disasters, Since 1940

Year	*Day*	*Mine*	*Location*	*Type*	*Deaths*
1972	05/02	Sunshine Mine (silver)	Kellogg, Idaho	Fire	91
1942	03/26	Sandts Eddy Quarry (limestone)	Allentown, Pennsylvania	Explosion (surface)	31
1968	03/06	Belle Isle Mine (salt)	Franklin, Louisiana	Fire	21
1963	08/28	Cane Creek Mine (potash)	Moab, Utah	Explosion	18
1943	01/05	Boyd Mine (copper)	Ducktown, Tennessee	Explosion	9

TABLE 9.16.4 Categories of Underground Mine Fires (1991–2000)

Ignition Source Type	*Percentage of Coal Fires*	*Percentage of Metal/Nonmetal Fires*
Cutting and welding	14	16
Electrical	14	10
Friction	24	5
Mobile equipment	15	46
Spontaneous combustion	12	2
Other	21	21
Total	100	100

Source: MSHA, Mine Safety and Health Administration, http://www.msha.gov.

(MSHA) website at http://www.msha.gov or at the National Institute for Health and Safety website at http://cdc.gov/niosh/mining. Recent advances in mining and safety technology and the promulgation of more stringent government regulations have reduced fatalities from underground mine fires and explosions but have not yet reached acceptable rates.

Surface mining and processing plant personnel safety exposures are not significantly different from those of other heavy industries. An exception might be in on-site explosive emulsions mixing facilities where loss of life has occurred.

Fires and explosions in mines and mineral processing plants also cause major loss of property, production equipment, buildings, and business interruption. From 1994 to 1998, mines and quarries of all types averaged $12.3 million a year in direct damage in fires reported to U.S. local fire departments.[10] In the same period, nonmetallic mineral processing and product manufacturing facilities averaged $16.1 million a year in direct damage in fires reported to U.S. local fire departments.[10] More recent statistics are not available.

The following sections further discuss important fire and explosion hazards in mining and mineral and coal processing facilities.

In noncoal underground mines, most mobile equipment is diesel powered, and so fires can result from broken or leaking hydraulic fluid, fuel, or lubricating oil lines, which spray combustible liquid mist onto a hot surface, such as an engine manifold. In recent years, diesel equipment usage has grown rapidly in underground coal mining, especially in the western states. In coal mines, the presence of coal, coal dust, and methane compounds fire hazards normally associated with diesel operations.[11]

Because prototype and first generation commercial mining systems contain both fuel sources (diesel fuel, hydraulics, hose, wiring, tires, etc.) and ignition sources (diesel engines, electrical equipment, conveyors, brakes, etc.), risks exist for onboard fires. Because these systems may be unattended, risks are compounded by the absence of an operator who could quickly detect and suppress a fire while it is still small. In a mine operated largely with automated equipment, the underground workforce would likely be quite small. In the event of a large fire, quickly marshaling a sufficient number of fire brigade members could be problematic.

Like fires on underground diesel equipment, fires on diesel-powered surface mining equipment can occur when leaking high-pressure hydraulic lines spray hot, highly combustible liquid mist onto an ignition source, such as a hot exhaust manifold or turbocharger. Fire can grow so quickly on this equipment that the operator's cab can become engulfed in flame before the driver is even aware of a fire. On large power shovels, blasthole drills, and draglines, faults in electrical equipment are a major fire hazard.

Welding and cutting operations are an important potential cause of shaft fires in both coal and noncoal underground mines. The potential seriousness of shaft fires cannot be overemphasized, because a fire in a shaft may contaminate the mine's intake air supply and/or block a critical escape route from the mine.

Exothermic oxidation reactions occur in both coal and metal sulfide ores.[12,13] When the heat these reactions generate is not dissipated, the temperature of the rock mass or pile increases. If temperatures become high enough, rapid combustion of coal, sulfide minerals, and other combustibles can result.[14] Spontaneous ignition fires can be disruptive to mine operations and difficult to extinguish, particularly if they occur in remote, abandoned mine sectors where fire-fighting access is difficult.

Heat generated by friction between a conveyor belt and a drive roller or idler can cause fires in underground mines. Despite improvements due to sequence and slippage switches, this hazard has become of renewed concern, as conveyor belt haulage has replaced rail haulage systems in older mines. Other frictional heat sources include overheated rubber tires and parking brakes on mobile equipment that are engaged during vehicle operation.

For many years, timber most commonly provided both temporary and permanent roof support for underground openings. This timber construction posed a major fire hazard. In recent years, the use of roof bolts has significantly reduced the use of timber underground. But older mines still contain large amounts of timber, and timber still supplements other means of roof support in most mines. Only about 10 percent of underground fires involve wood.[7] Timber fires tend to constitute a greater overall hazard than their frequency indicates, because timber fires can spread more rapidly, can burn longer, and can be more difficult to extinguish than fires involving most other extraneous combustible material.

The ultimate objective of underground coal mine fire protection efforts is preventing ignition of the coal. The amount of combustible material present generally limits equipment fires. Once coal ignites, however, the entire mine represents the available fuel supply. Over one-third of fires involving burning coal last longer than 24 hours, with an average duration of 6 days. Failure to extinguish a developing fire results in a 50 percent chance that more than 8 hours will be required to bring it under control and a 5 percent chance that part or all of the mine will be sealed.[15,16]

The storage, handling, and use of flammable and combustible liquids pose fire hazards for all sectors of the mining

industry. More fires in surface mines involve flammable and combustible liquids than any other combustible material. Most occur in mobile equipment. Hydraulic fluid at elevated temperature and pressure is a primary hazard.[17]

In underground mines, the storage of flammable and combustible liquids is an especially important concern. These materials ignite more easily and propagate more rapidly than ordinary combustibles involved in fires. Both flammable and combustible liquids are stored underground in most noncoal mines. In some mines, the main storage facility for diesel fuel, lubricating oil and grease, and hydraulic fluid is underground, with storage facility capacities reaching 30,000 gal (11.4 m^3). The potential seriousness of a fire in an underground flammable and combustible liquid storage area prompted extreme care in storage areas' design, plus the implementation and strict enforcement of safe operating procedures. As a result, few fires have been reported in such storage areas.[17]

Mine Explosion Hazards

Practically all underground coal and many noncoal mine explosions start with methane ignition. Methane is a colorless, odorless gas usually present in coal seams and sometimes in the rock strata above and below coal seams.[18] It is also found in some noncoal mines. During mining, methane escapes into the mine and is transported by the mine's ventilation airflows. In a properly designed and operated ventilation system, the airflows dilute the methane, render it harmless, and carry it away. However, if ventilation is inadequate, or if a large amount of methane releases suddenly (in a methane outburst, for example), dangerous and explosive methane-air mixtures can form. Even when the average methane concentration is below dangerous levels, explosive mixtures may form in pockets or layers.

The high number of explosions can be attributed to the small amount of methane necessary to produce an explosive mixture in air and to the low energy required to ignite a methane-air mixture. The lower explosive limit (LEL) for methane in air is 5 percent. As little as 0.3 mJ of electrical energy can ignite methane under proper conditions. This charge is equivalent to 1/50 of the static electricity the average person accumulates walking across a carpeted floor on a dry day.[19]

If an explosion propagates more than a few hundred feet, coal dust, swept off the floor, roof, and side walls of the mine entry, becomes the most important fuel source. The LEL for a suspension of high-volatile bituminous coal dust in air is 0.05 oz/ft^3 (28 g/m^3). Methane's presence in the atmosphere increases the hazard by producing a linear reduction in the LEL for coal dust. In the absence of methane, electrical or frictional sparks or explosives can ignite coal dust. Much more energy is required for ignition if methane is not present. Methane ignitions generally are the trigger for secondary coal dust explosions. The flame provides the necessary ignition source, and the shock wave causes settled coal dust to become airborne.[20]

The destructive potential of ignitions and explosions results from the high-temperature flame fronts and the static and dynamic pressures produced. Flame temperatures of 3600°F (1982°C) and static pressures in excess of 50 psig (345 kPa) are possible. Dynamic, or "wind," pressure is directional and depends on the air velocity the explosion produces, which, in turn, depends on the static pressure.

Table 9.16.4 shows ignition sources of recent mine explosions and methane ignitions. Frictional sparking between rock surfaces and cutting bits, continuous miners, roof bolters, cutting machines (undercutters), face drills, and longwall equipment caused over 85 percent of these ignitions and explosions in underground coal mines. Other possible sources of frictional sparking are drill steel striking machine frames, sandstone hitting sandstone or other hard rock during a roof failure, and mobile vehicle brake linings.

Welding and cutting operations are another leading cause of mine explosions and ignitions. In underground coal mines, the trend since 1970 has been increasing numbers of explosions and ignitions caused by welding and cutting operations.[21,22]

About 2.5 percent of underground coal mine ignitions and explosions result from electric arcs. This figure is surprisingly low, considering the extensive use of electrical equipment in underground coal mine face areas and the low electrical energies required to ignite methane.[22]

One cause of explosions in metal mines is sulfide dust ignition during a blast.[23] As noted earlier, ore minerals in many metal mines are metallic sulfides and are combustible under certain conditions. In some cases, the blast may create a combustible dust that the flame produced from the explosive or blasting agent can ignite.

Mineral Processing and Coal Preparation Facility Fire and Explosion Hazards

The principal fire exposures in mineral and coal processing plants include those from polymeric (plastic or rubber-based) construction and process materials and flammable or combustible fluids, reagents, solvents, and fuels.

Polymeric materials include rubber or plastic linings inside of vessels, piping, pumps, and cyclones in concentrator mills. Rubber linings are used for acid and abrasion resistance and are very common, widespread, and create high "hidden" combustible loading in an often otherwise noncombustible facility. Piping, vessels, and emission control systems may feature glass fiber reinforced plastic (FRP) or other plastic construction materials, as might the wall or roof systems, especially where corrosion is a concern. Electrolytic and leaching processing buildings using acid-based solutions are commonly constructed of plastic, or if older, of wood.

A typical concentrator mill or coal preparation plant will have rubber belt conveyors; plastic-insulated electric cables in vaults, tunnels, or under floors of control rooms; and rubber-lined equipment, as depicted in Figure 9.16.17. If plastic or other combustible construction is present, a high combustible loading can exist. Rubber liner fires can be particularly insidious as they cannot be easily accessed for manual fire fighting, fixed automatic protection like sprinklers can rarely be installed so as to be effective on fires in these relatively inaccessible products, and the fire can spread internally with liberation of dense black smoke, hampering fire fighting.

Oils, fuels, reagents, and lubricants are also common but often scattered or concentrated in dedicated rooms or areas.

FIGURE 9.16.17 Rubber-Lined Tank with Fire Warning Label (Source: Property Loss Prevention Data Sheet 7-12, "Mining and Ore Processing Facilities"; © 2006 Factory Mutual Insurance Company. Reprinted with permission. All rights reserved.)

FIGURE 9.16.18 Large Haul Truck in Equipment Maintenance Garage (Source: © 2006 Factory Mutual Insurance Company. Reprinted with permission. All rights reserved.)

Large rotating mills require both hydraulic fluids under high pressure as well as lubricating fluids. Flotation processes use combustible (often alcohol-based) or diesel fuel-like reagents to separate ores and undesirable materials. Toxic reagents such as sodium cyanide, though noncombustible, can hinder manual fire-fighting response. Transformers, commonly in indoor vaults or outdoors in power distribution yards, have large quantities of combustible cooling and dielectric oil.

Combustible or flammable fuels are used for heating and processing. Dryers using hot thermal oil are common for coal and molybdenum processing. Thermal oil fires create high heat of combustion, and an atomized spray of hot oil might cause an explosion in a small confined room. Diesel fuel and natural gas are commonly piped into processing plants and, if released, can cause serious fire damage to property.

Mine sites, especially surface mines, typically have very large, high bay mobile equipment garages, which can house multiple haul trucks or other large vehicles for maintenance, as depicted in Figure 9.16.18. These buildings can be several hundred feet long and have roofs up to 75 ft (25 m) high. Significant combustible loading exists from rubber tires, fuel, and hydraulic and lubrication oil systems. Trucks are often parked side by side with fueling and/or lubrication bays located between trucks. A fire originating in one truck—caused by overheated tires or a fuel spill—could spread throughout the entire facility if not properly protected and arranged.

Coal preparation plants present special fire hazards in addition to those described for ore processing plants. A particularly important special hazard is the combustibility and hazard characteristics of the coal itself. Coal can spontaneously heat in piles or in bins and silos without external ignition sources. Methane gas can be given off, causing localized fires or igniting dusts. Uncontrolled coal spillage inside buildings can contribute to combustible loading. Fires in rubber belt conveyors pose a particular risk in coal preparation plants, as ease of ignition is significantly reduced by the presence of the combustible material being conveyed.

A major fire hazard in ore processing and coal preparation facilities is cutting and welding. Hot work on dry rubber-lined piping or tanks can ignite the internal lining causing unrestricted fire spread. Hot work over open rubber-lined tanks can allow hot slag to fall into tanks igniting the liners. Fire can spread to adjacent vessels via lined pipes. Severe damage to production equipment and buildings can result.

Hot work operations can also ignite combustible reagents, plastic construction, lubricants, and rubber conveyor belts. Rubber conveyor belts, especially in coal handling facilities, continue to be a major cause of fire loss in the mining industry (Table 9.16.5). Other possible ignition sources are transformer or electrical cable arcing and spontaneous heating of coal or sulfide ores.

Explosion hazards in mineral processing facilities include those from gaseous or liquid fuel-fired process heaters, boilers, roasters and dryers, low-flashpoint solvents, flammable gas vapors in closed vessels, and high-pressure vessels. For example, by-product waste hydrogen gas is generated in leaching vessels

TABLE 9.16.5 Coal Industry Conveyor Belt Fires, 1978–1999

Probable Cause	*Number of Losses*	*Percentage of Number*
Open flame	6	25
Spontaneous ignition	5	21
Friction	5	21
Hot surface/radiant heat	2	8
Overheating	2	8
Unknown	4	17
Total	24	100

Source: FM Global Loss Prevention Data Sheet 7-12, *Mining and Ore Processing Facilities.*

where zinc is reacted with acids and in some electrolytic cell processes.

Pressure oxidation, acid or caustic leaching reactors, digesters or their associated flash tanks (common on gold, nickel, and bauxite plants) may fail catastrophically under pressure due to corrosion, causing severe pressure-volume (PV) rupture events, which can destroy equipment and buildings for many hundreds of feet. In July 1999, a digester-flash tank pressure vessel explosion occurred at an alumina processing facility in Louisiana, injuring seven and destroying most of the plant.[7]

Blasting emulsion-mixing facilities can detonate, causing widespread damage if not well separated from processing plants.

Combustible dusts, prevalent in coal handling facilities, can also be present in metal ore plants. For example, highly explosive, fine zinc powder is intentionally produced for seed material in zinc processing facilities.

Downstream metal refining processes may also have molten metal-water reaction explosion hazards. In contact with water high-energy rapid-phase transition explosions can occur.

Coal preparation plants have serious explosion exposures from fugitive coal dusts and methane gas, as well as aforementioned hazards typical to all processing plants. Cement plants often use coal for firing kilns and this procedure has led to coal dust explosions in these facilities.[7]

Ignition sources for explosions include poorly rated electrical equipment, compounded by poor housekeeping and poor ventilation. Lack of fuel burner management controls on fired heaters, dryers, roasters, and boilers has contributed to internal explosions.

FIRE AND EXPLOSION SAFEGUARDS

Fire and explosion safety in the mining and mineral processing industries is based on the same general principles of restricting or limiting combustible loading, ignition source prevention, early warning and detection, fixed protection (suppression), and emergency response capability as those that apply to all industrial facilities. However, due to inaccessibility, special requirements are needed for underground mines that are not needed in normal industrial plants.

The following sections, broken down separately by mining and mineral processing operations, are intended to provide only a general flavor of the different approaches to fire and explosion safety in this industry. They are not intended to represent a comprehensive list of solutions or mandatory requirements.

Many federal and state regulatory laws cover fire safety for both mining and processing occupancies. The MSHA is the principal federal mine regulatory organization in the United States. The MSHA may also regulate surface mineral processing plants if on or near the mine site, but the U.S. Department of Labor, Occupational Safety and Health Administration (OSHA) may regulate the same facility if located remote from the mine. NFPA codes are available for underground mining, underground mobile equipment, and surface coal preparation plants. NFPA 120, *Standard for Fire Prevention and Control in Coal Mines,* contains fire protection requirements for underground coal mines. NFPA 122, *Standard for Fire Prevention and Control in Metal/Nonmetal Mining and Metal Mineral Processing Facilities,* covers requirements for underground metal and nonmetal mines.

There are no public domain standards or codes that provide specific fire protection guidelines for mineral, coal, and metallurgical processing plants other than general NFPA industrial codes. FM Global publishes a comprehensive Loss Prevention Data Sheet, DS 7-12, *Mining and Ore Processing Facilities,* which covers property loss prevention and protection for these occupancies.[21] Various publications and books on mine safety and technology also are available from the Society of Mining and Exploration (SME) located in Littleton, Colorado.

Fire Prevention

Where fires involving certain combustible materials are of sufficient frequency and/or severity, and where suitable and less hazardous substitutes for those materials are available, using less hazardous materials is preferred or, in some cases, mandated by law. Examples of less hazardous materials include fire resistive hydraulic fluids, conveyor belting, hydraulic hoses, and ventilation tubing; all are required in underground mines under certain conditions.[24–26] In some cases, highly toxic products of combustion resulting from the burning of certain materials may prompt substitution with less hazardous materials. For example, many countries have banned polyurethane foam, once widely used in underground mines for ventilation seals. Even more basic is good housekeeping to prevent unsafe accumulations of trash, oily rags, coal dust, and other combustible materials.

Combustible loading and continuity of combustibles in mineral and coal processing buildings should be limited as far as practical. When possible, plastic and wood construction materials are to be avoided for both buildings and equipment. If the use of plastic cannot be avoided, an effort should be made to use fire-resistive or fire-retardant materials or materials that have been listed with low flame spread characteristics.

Rubber liners for equipment and vessels are common and cannot always be eliminated. Ceramic and special metal alloys, though more costly, can be substituted for rubber if done early in the design stage.

Similar to underground mines, the use of less hazardous hydraulic fluids and fire-retardant conveyor belting is preferred in processing buildings. Whether on the surface or underground, combustible fuels and reagents need to be properly arranged with catch pans or dikes where appropriate, located in dedicated rooms, and fitted with safety shutoff valves.

Fire sources nonessential to the mining process can be banned altogether. Examples are prohibitions on open fires and smoking. Means to prevent unwanted heat buildup, such as slippage and sequence switches on conveyors and thermal cutouts on electric motors, are also common.

Many combustible materials and potential ignition sources are essential to mining and processing operations. Fire safety depends on preventing contact between the ignition source and the fuel source. For example, precautions are taken during welding and cutting operations. When welding cannot be performed in fire-safe enclosures, areas are wet down and, if practical,

nearby combustibles are covered with fire-resistive materials or relocated. Fire extinguishers must be readily available and a fire watch posted for as long as necessary to guard against smoldering fires. This is particularly important for rubber-lined equipment in processing plants. On mobile equipment, hydraulic fluid, fuel, and lubricant lines can be rerouted away from hot surfaces, electrical equipment, and other possible ignition sources. Spray shields also can be installed to deflect sprays of combustible liquid from a broken fluid line away from a potential ignition source. Areas with a high loading of combustible materials, both underground and surface, such as timber storage areas, explosives magazines, flammable and combustible liquid storage areas, and shops, can be designed to minimize possible ignition sources. Potential sources of ignition, such as power substations, battery chargers, and electric motors, can be kept clear of extraneous combustible material.

Within the past 5 years a number of very serious fires have occurred in mineral solvent extraction plants. These fires, although not causing fatalities, produced in excess of $500 million in financial property and business interruption damage. Improper plant layout, spacing, drainage, protection, and use of combustible or frangible pipe and vessel construction materials were all major factors in the loss severity in these incidents. Conventional fire protection systems were seriously challenged in many of these incidents due to poor layout and construction materials. In some cases the fire protection systems failed entirely to limit fire impact.[27–33]

Explosion Prevention

Mining. Coal dust and methane are the primary fuels involved in underground coal mine explosions. Methane also may be present in noncoal mines.[34] Although every attempt is made to minimize the generation of coal dust in mining processes, the tiny amount of dust sufficient to propagate a coal dust explosion is virtually unavoidable. Indeed, a layer of dust on the floor just 0.005 in. (0.012 mm) thick, if suspended in air, can propagate an explosion; less is necessary if methane is present. Bituminous coal dust properly mixed with an inert material, such as pulverized limestone, dolomite, or gypsum (rock dust), does not propagate an explosion.[7] Hence, regulations require that the incombustible content of dust in coal mines be frequently checked and followed by rock dusting if necessary to ensure incombustibility.

Methane is treated in two ways. More commonly, it is diluted by ventilation air and exhausted from the mine. However, "degassification" in advance of mining may be practiced where levels of methane are unusually high.[35,36]

Every effort is made to eliminate extraneous ignition sources from the environment. Smoking is prohibited in coal mines, and electrical equipment operating where methane may be present must be "permissible" or "intrinsically" safe. Permissible electrical equipment has been tested by the federal government and designed, constructed, and installed so that its operation will not cause a fire or explosion. Use of explosionproof enclosures, specially designed plugs and receptacles, automatic circuit-interrupting devices, and voltage limitations are typical. Intrinsically safe equipment has been tested by the federal government and determined to be incapable, under normal or abnormal conditions, of releasing sufficient electrical or thermal energy to ignite an explosive gas mixture. Some success has been achieved in reducing frictional sparking at the face by using slower bit rotation, novel bit designs and bit materials, and specially engineered water sprays.[29–33] In coal mines, explosives must be permissible and used in strict conformance with special blasting regulations. Where sulfide dust explosions are possible in metal mines, special anti-incendive blasting agents are available.[19] In both coal and noncoal mines where methane is present, diesel-powered equipment must also be permissible.

Because of geologic nonuniformity, varying mining rates, atmospheric pressure, and other factors, methane is not uniformly liberated into mine ventilation air from the workings. In addition, methane and ventilation air may not mix completely and may form explosive pockets or layers, even though the average methane concentration is below the LEL. Thus, diluting and draining methane cannot always be relied on to produce nonexplosive atmospheres. Great effort has been devoted to developing safer procedures for ventilating active coal mine working areas, both longwall and room-and-pillar, to minimize the occurrence of localized pockets of explosive methane-air mixtures.[37–39] Methane checks are made frequently with handheld and machine-mounted methanometers. If the methane levels reach or exceed a predetermined point, all electrical equipment is shut down.

Ore Processing and Coal Preparation Plants. Unique explosion hazards are also present in surface mineral processing plants, especially in coal preparation plants or in other facilities (for example, cement plants) where coal is commonly used as a fuel. Coal dusts are controlled by proper design, maintenance, and operation of coal pulverizers, collectors, and handling systems. Nitrogen inerting may be used to eliminate oxygen during transfer or storage. Where possible, coal dust handling equipment is located outdoors.

Frequent and dedicated housekeeping of fugitive dusts is paramount. Proper ventilation and detection is installed for areas where methane gas might be present, for instance, in coal conveyor tunnels or silos.

In buildings with combustible dusts or flammable gases, classified or intrinsically safe electrical equipment is installed similar to underground mines. Electrical switch rooms and control rooms are pressurized to prevent dust or gas entry. NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* and NFPA 69, *Standard on Explosion Prevention Systems,* cover dust and gas explosion hazards in detail for industrial facilities.

Early Fire Detection and Warning

The time elapsed between a fire's onset and its detection is critical, because fires tend to grow in size and intensity with time. Early fire detection and warning systems permit the initiation of an emergency plan (evacuation, fire fighting, etc.) while the fire is still small or, ideally, while it is still in the incipient stage. Advanced fire detection and warning systems using sensitive heat, flame, smoke, and gas analyzers provide the most rapid and reliable indication of fire.[40–44]

Thermal fire detection systems are commonly installed over conveyor belts, belt drives and takeups, and other unattended equipment. In localized, high-hazard areas, such as flammable and combustible liquids storage areas, refueling areas, and shops, faster-acting fire detection devices may be appropriate. Optical flame detectors, which sense either the ultraviolet or infrared radiation a fire emits, have been used successfully.

Smoke and/or gas detection is the most cost-effective approach to providing large area, or even whole mine, fire detection coverage[22,45–58] (Figure 9.16.19). Instruments sampling the mine ventilation airstreams can detect increases in particulates, or smoke, of less than 1 micrometer (1 mm) in size in concentrations as low as 1 mg/m^3 and of distinguishing diesel smoke from fire smoke.[51] Instrumentation also is available that can detect very small increases in combustion gases. For example, instruments intended for permanent underground installation can reliably detect carbon monoxide (CO) at levels as low as 2 ppm.

Products of combustion detection, such as smoke, thermal, or optical detectors, are usually provided in electrical rooms, control rooms, battery rooms, inaccessible tunnels, and concealed spaces housing cables or other electrical systems in surface processing plants.

After fire detection and notification of responsible mine officials, each miner must be warned. Telephones and messengers are sometimes used, but miners are often too remote from telephones and too widely scattered for these means to provide a timely warning. In coal mines, the most common means of fire warning are electric power shutdown and/or notification by telephone and messengers. In noncoal mines, electric power shutdown is generally ineffective because so little equipment is electrically powered. Stench warning is the most common method of emergency communication in noncoal underground mines.[59]

Wireless radio frequency communication systems have been used successfully in both coal and noncoal mines.[51] Ultrahigh-frequency systems use a "leaky feeder" transmission antenna that is installed wherever underground signal reception is desired. Miners use belt-held "walkie talkie" type or vehicle-mounted transceivers for two-way voice communication. Ultralow-frequency systems use antennae deployed on the surface that transmit signals through the earth to receivers built into miners' cap lamp battery cases or to dashboard-mounted receivers installed on mobile equipment. These systems enable one-way transmission of messages, which appear on LCD displays.[60–62]

FIGURE 9.16.19 Fire Detection Instruments in an Underground Mine

Fire Protection

The types of fire suppression equipment most commonly used in underground coal mines are portable hand extinguishers, generally multipurpose dry chemical; water hoselines and sprinkler systems; rock dust, applied manually or from a rock dusting machine; and foam generators. Fire suppression equipment in non-coal underground mines includes portable hand extinguishers and water hoselines. Fire suppression systems, manual or automatic, are becoming more common for mobile equipment, combustible liquids storage areas, conveyor belt drives, and electrical installations[17,51,59,63,64] (Figure 9.16.20). Automatic fire suppression is especially important for unattended, automated, or remote-control equipment where personnel are not present to detect a fire, activate a fire suppression system, or initiate fire-fighting operations.

NFPA 120 contains fire protection requirements for underground coal mines. NFPA 122 covers requirements for underground metal and nonmetal mines.

Where large areas of coal or timber are burning in an underground mine and fire fighting is complicated by extensive roof falls, ventilation uncertainties, and explosive gas accumulations, the only practical alternatives may be inerting with nitrogen, carbon dioxide, or the combustion products of an inert gas generator; flooding with water; and/or sealing all or parts of the mine.[65] All underground miners are trained to use basic fire-fighting equipment. However, only highly trained and specially equipped fire-fighting teams can fight advanced fires. To assist these teams in fighting advanced fires, research has investigated the technological feasibility of teleoperated, remote-controlled, fire-fighting vehicles capable of approaching fires at close range to apply fire-suppressing agents.

Mobile equipment is the primary fire hazard in surface mines. Consequently, most surface mining fire suppression equipment is specifically designed for maximum effectiveness on typical mobile equipment fires. Mobile equipment is commonly provided with one or more portable hand extinguishers. Manually or automatically actuated suppression systems may be installed for added protection.[66–71] NFPA 120 contains fire protection requirements for such mining equipment.

Mineral processing and coal preparation plants often need automatic sprinkler protection backed by an adequate and reliable industrial fire water system. Hydrants and monitor nozzles are needed for manual response. The need for protection is based on combustible loading, production importance, personnel safety, and economics and is determined by a risk study by a fire protection engineer.

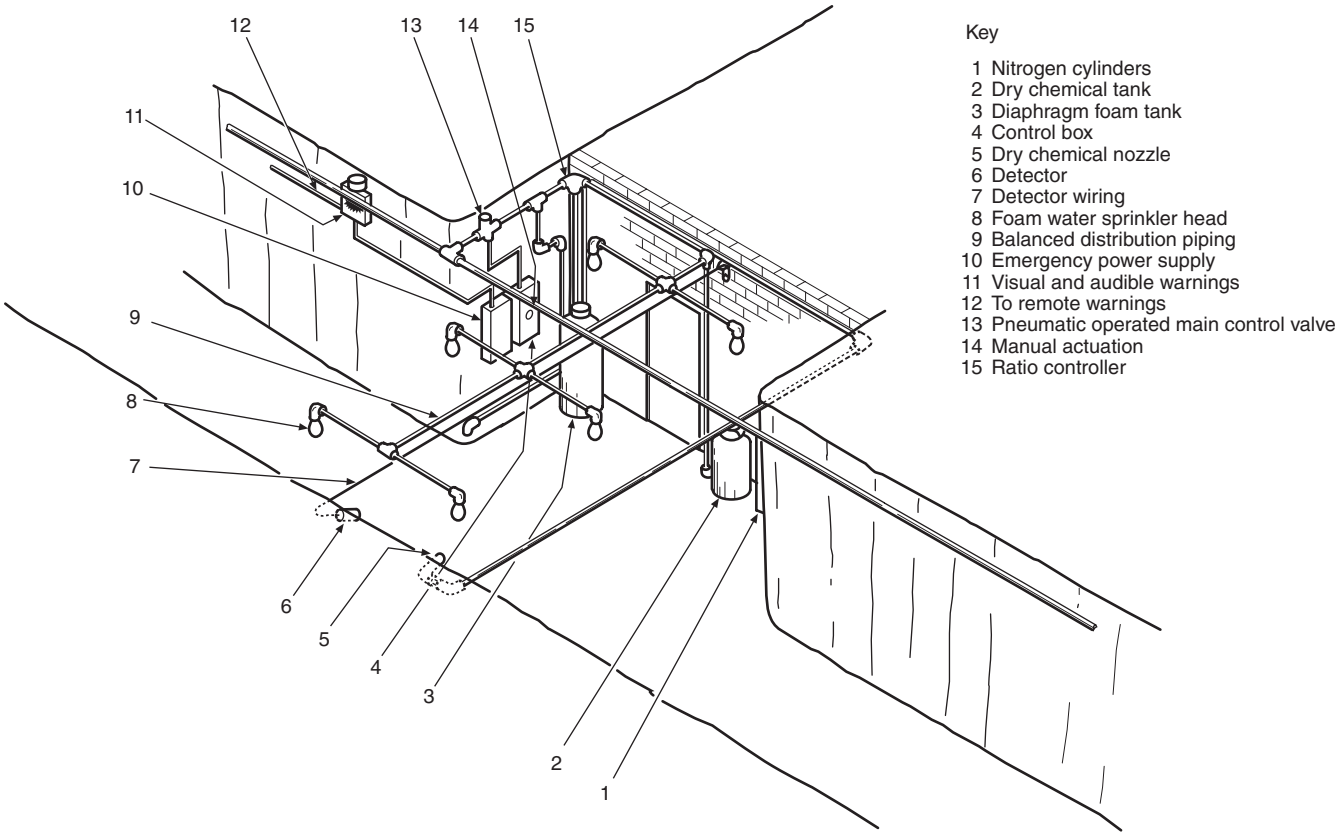

FIGURE 9.16.20 Fire Suppression System for Underground Diesel Refueling Area

Examples where automatic sprinkler protection is commonly installed in mineral processing sites are:

- Where construction is combustible and values or production reliance warrant (such as over rubber belt conveyor systems)
- Over hydraulic and lubrication oil systems for rotating equipment (such as crushers, mills, fans, and compressors)
- Over and/or inside FRP plastic equipment and exhaust duct systems
- In electrical cable spreading areas under floors, in tunnels, or in dedicated switchrooms. (An alternative to water suppression in these areas might be fire-resistive cable coatings, foam systems, or gaseous suppression systems.)
- Over important and high value transformers that use combustible insulating oil
- Over plastic electrowinning and electrorefining cells
- Over combustible or flammable reagents and fuel pumping systems for mineral solvent extraction plants
- Over power generation units that have combustible fuels or lubrication oils
- Inside combustible cooling towers for chemical processes
- Inside warehouses, mobile equipment garages, and important occupied support buildings

Foam water systems may be appropriate for certain special hazards such as reagents and fuel storage areas. NFPA 120 contains protection requirements for coal processing facilities including coal preparation plants. NFPA 122 covers requirements for surface metal and nonmetal processing facilities.

Explosion Protection

Mines. On a limited basis, some European coal mines use explosion suppression technology in the form of passive or triggered barriers. Passive barriers consist of rows of large tubs containing water or rock dust that are suspended from the roof of a mine entry. In an explosion, the pressure front that precedes the flame creates wind forces that dump the tubs' contents. The dispersed suppressants quench the flame as it passes through the entry protected by the barrier system. Triggered barriers utilize an electrically or pneumatically operated activation device that the heat, flame, or pressure of the explosion triggers to release suppressing agents stored in pressurized containers.[72–74]

Ignition suppression devices have also been developed for quenching methane ignition at its origin point, usually on a continuous mining machine or longwall shearer. These systems typically consist of a rapid-response optical detector. On sighting a fire ball of sufficient size and intensity, the detector triggers the release of a suppressing agent. The systems are designed to totally flood the area surrounding the cutting drum (roof to floor, full room width), the likely ignition source.

Surface Ore Processing and Coal Preparation Plants. To protect against damaging explosions from combustible dusts or flammable vapors, passive safety is the first step. Design of the dust handling system should address potential for dusts accumulations and release of fugitive dusts into the environment.

Examples of passive systems are using equipment strong enough to contain the forces of an explosion and using systems at negative pressure to prevent escape of dusts. Dusts carried at positive pressures inside enclosed systems can escape more easily at duct seams, joints, and broken collector bags.

Another passive system is use of nitrogen inerting to eliminate oxygen, which generally eliminates the need for other active protection systems. To supplement or replace passive systems, fixed active explosion protection can be installed to reduce the effects of an explosion or to suppress an explosion before it can cause damage.

Where possible, equipment and piping or duct systems handling dusts or vapors are located outdoors to minimize the potential for building damage or secondary explosions. Buildings or rooms that house equipment, deposits, or dusts are designed to minimize damage by the use of damage-limiting construction (DLC). DLC features a combination of wall strength and weak wall or panel emergency venting. Through proper design, based on testing of the dust or vapor to determine explosivity characteristics such as K_{st} and K_g, these wall-venting systems can effectively channel forces and limit structural damage.

Similarly, equipment, especially when located indoors, is designed using damage-limiting construction, combining vessel or pipe strength with special venting panels. When equipment that is located indoors needs to be vented, the vent system is channeled by strong ducts through exterior walls to safely discharge forces and burning material outside of the building.

When venting is impractical or a high frequency of explosions occurs (like in coal pulverizers) or when extremely high-value processes or equipment are exposed, explosion suppression systems are used. An explosion suppression system works by detecting light or developing pressure and rapidly injecting a powder or gas into the vessel. The incipient explosion is suppressed and damaging pressures are reduced. Blocking systems are also often used to prevent an explosion in one vessel from reaching another vessel via a pipe or duct. Chemical and mechanical blocking systems are available. Both work on light or pressure detection. A chemical system injects a gas or powder similar to a suppression system, blocking and suppressing the moving flame front. A mechanical system shuts the valve or gate to achieve the same end. Explosion suppression and blocking systems, as well as venting systems, are commonly installed in coal-handling systems, especially after the coal has been cleaned, dried, and pulverized.

Control of methane in coal-handling facilities is similar to methods for underground coal mines. Ventilation and detection are the primary means of protection against a buildup of gas that can cause damage if ignited. Damage-limiting construction is also used to protect against damaging methane gas explosions.

Other industrial explosion hazards, such as those that might occur inside a natural gas fueled process heater, kiln, roaster, or boiler are controlled by process controls, fuel burner management systems, and operator training. Fixed explosion protection is usually not installed on these types of equipment due to economics.

Some high-temperature roasters and zinc calciners in metallurgical refining plants have water-cooling jackets. An inadvertent release of water onto a hot sand or molten metal bed could cause a steam explosion inside the high-value production equipment, causing significant damage and production interruption. In addition to process controls and operator training, emergency explosion relief vent panels or doors are often installed on these vessels.

Many additional details on protection and design requirements for buildings and equipment handling flammable gases and combustible dusts are covered in NFPA 68 and NFPA 69. Protection requirements for explosives and blasting agents are covered in NFPA 495, *Explosive Materials Code.*

Limiting Fire Propagation

Means for confining or limiting the propagation rate of an underground mine fire can help ensure a safer mine evacuation and lessen fire-fighting hazards. In underground coal mines, oil and grease must be stored in closed, fire-resistant containers, and storage areas must be of fire-resistant construction. Transformer stations, battery-charging stations, air compressors, substations, shops, and other installations must be housed in fire-resistant areas or fireproof structures. Unattended electrical equipment must be mounted on a noncombustible surface and separated from the coal or protected by a fire suppression system. Materials for building bulkheads and seals, including wood, brattice cloth, saws, nails, hammers, plaster or cement, and rock dust, must be readily available to each working section. In underground noncoal mines, oil, grease, and diesel fuel must be stored in tightly sealed containers in fire-resistive areas at safe distances from explosives magazines, electrical installations, and shaft stations. Ventilation control stoppings and doors and fire doors are required in certain areas to prevent the spread of fire, smoke, and toxic gas.[75–77]

Providing for Miner Safety During a Fire Emergency

The primary concern during an underground fire is the safety of underground personnel. Because smoke and toxic fire gases represent the greatest threat, the mine ventilation system and its relationship to various working areas, potential fires, primary and secondary escape routes, refuge chambers, and so on are critically important. Detailed emergency planning must consider these factors. However, the complex behavior of mine fires, the flow of contaminated air through the ventilation system, and the interactions between a fire and a ventilation system that has been altered by fire-induced flow changes are normally far too complex to understand and control without specialized analytical methods. Using computer models that simulate mine ventilation systems can be very helpful in understanding these complex processes, developing and optimizing emergency plans, and

designating escape routes. Particularly valuable are advanced models that calculate ventilation changes due to a mine fire (heat-induced buoyant forces causing throttling, reversals, etc.) and can track contaminants' distribution and concentration.[51,78–80] To ensure smooth implementation of the emergency plan, miners are comprehensively trained and annually retrained in emergency procedures. Frequently performed fire drills, complete with the activation of the mine warning system, reinforce training and identify the plan's weaknesses.

Although every attempt is made to avoid such situations, evacuating miners must sometimes travel through areas contaminated by smoke and toxic fire gases. These combustion products present two hazards: (1) toxic atmospheres and (2) impaired visibility. Appropriate respiratory protection is required to safeguard miners from toxic combustion products. In coal mines, self-contained breathing apparatus, supplying a minimum of 1 hour of oxygen, must be provided.[81–83] In noncoal mines, 1-hour-rated self-rescue devices that convert carbon monoxide to carbon dioxide must be provided.

Toxic atmospheres are the principal cause of death in mine fires. However, recent research demonstrates that impaired visibility due to smoke accumulation in escapeways can become quite significant long before the concentration of combustion products becomes acutely toxic. As a result, miners lost in or disoriented by the smoke may succumb to the toxic atmosphere when they deplete their respiratory protection, even though they had adequate warning and time to escape. For this reason, smoke-free escapeways and frequent fire drills and evacuation training are especially important to familiarize miners with escape routes and evacuation procedures. To further combat the visibility problem smoke buildup causes, some mines have installed rope lifelines in escapeways. They enable miners to feel their way to safety through smoke-filled entries.

Emergency Response for Surface Processing and Coal Preparation Plants

Mineral processing sites are usually remote and will rarely have timely emergency response support from local communities for fire or explosion incidents. Larger sites have dedicated emergency response teams and are provided with structural firefighting apparatus and equipment such as fire pumper trucks. Smaller sites may only have basic fire brigades or plant emergency organizations. Large mine water haul trucks are often fitted with monitor nozzles to use for elevated conveyor fires, brushfires, and remote equipment incidents.

SUMMARY

Mining can be grouped into two broad categories: surface mining and underground mining. Surface mining methods include area strip mining, contour mining, contour pit mining, and open pit mining. Underground coal mining methods include room-and-pillar, which involves extracting coal in a regular pattern of rooms separated by pillars of in-place coal to support the roof, and longwall mining, which requires substantial artificial support. The underground mining of metals and nonmetals involves more diverse methods, including room-and-pillar, sublevel stoping, shrinkage stoping, cut-and-fill, sublevel caving, and block caving. A wide variety of ancillary operations support both underground coal mining and underground metal and nonmetal mining. These ancillary operations include inspection, maintenance, and repair of mine equipment; power distribution; ventilation; hoisting; roof control; and dewatering.

After extraction by one of the aforementioned mining methods, the mineral, structural material, or coal is transported to a processing facility, or in the case of coal, a preparation plant, for conversion to intermediate or final consumer products. The purpose of the processing or preparation plant is to size, dry, clean, chemically convert, and/or concentrate the ore or coal.

Mining and mineral processing facilities represent significant fire and explosion exposures to both personnel and production equipment and buildings. The principal fire exposures in mineral and coal processing plants include those from polymeric (plastic or rubber-based) construction and process materials and flammable or combustible fluids, reagents, solvents, and fuels. Hot work is a major fire hazard in ore processing and coal preparation facilities.

Fire and explosion safety in the mining and mineral processing industries is based on restricting or limiting combustible loading, ignition source prevention, early warning and detection, fixed protection (suppression), and emergency response capability.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on mining and mineral processing discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 51, *Standard for the Design and Installation of Oxygen–Fuel Gas Systems for Welding, Cutting, and Allied Processes*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 70, *National Electrical Code®*
NFPA 120, *Standard for Fire Prevention and Control in Coal Mines*
NFPA 122, *Standard for Fire Prevention and Control in Metal/Nonmetal Mining and Metal Mineral Processing Facilities*
NFPA 495, *Explosive Materials Code*

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Chapter 17

Oxygen-Enriched Atmospheres

Revised by
Keisa Rosales ❑ Joel M. Stoltzfus

Chapter Contents

Fire Hazards
Ignition and Combustion of Materials
Design of Systems for Oxygen-Enriched Atmospheres
Fire Extinguishment in Oxygen-Enriched Atmospheres

Key Terms

activation energy, autoignition temperature, flashpoint, lower flammable limit, minimum ignition energy (MIE), oxygen compatibility assessment, oxygen-enriched atmosphere (OEA), spontaneous ignition temperature, upper flammable limit

Oxygen is a clear, odorless, tasteless, colorless element. It is most commonly found in the gaseous state and comprises approximately 21 percent of the atmosphere. As the most common oxidizing agent in the atmosphere, oxygen can react with many materials in highly exothermic reactions. An oxygen-enriched atmosphere (OEA) is defined as an atmosphere in which the concentration exceeds 21 percent by volume, or the partial pressure of oxygen exceeds 160 torr (21.3 kPa), or both (Table 9.17.1).

Oxygen supports combustion and is necessary for plant and animal life. The concentration of oxygen available in the atmosphere is generally sufficient for human needs during normal conditions of health and for most combustion applications. Further, it has many uses under different circumstances. Oxygen-enriched atmospheres are commonly used in medical applications, industrial processes, underwater tunneling and caisson work, deep-sea exploration, spaceflight operations, and commercial and military aviation. Oxygen-enriched atmospheres can develop inadvertently at any time when oxygen or compressed air is transported, stored, or utilized.

The preparation of oxygen conventionally involves the compression of air, followed by cooling and reexpansion, which is repeated until the temperature of the air falls below the critical pressure of oxygen and causes it to liquefy. Fractional distillation of the liquid air then separates its various gaseous components. The oxygen is then collected and may be stored as a compressed gas or a liquid. Oxygen is also separated from air by absorption and membrane systems and by electrolysis. Because it is necessary to use oxygen for various applications, it is vital to consider the hazards involved in building oxygen systems.

This chapter discusses the fire hazards that may be associated with oxygen-enriched atmospheres. Methods that can reduce and protect against fire hazards are also discussed. When working in oxygen-enriched environments or introducing components to oxygen systems, the risks need to be understood and managed fully. Proper management of fire hazards requires a systematic analytical approach, such as an oxygen compatibility assessment.

Further information concerning oxygen-enriched atmospheres can be found in the following chapters: Section 6, Chapter 1, "Fire Hazards of Materials"; Section 6, Chapter 10, "Gases"; Section 6, Chapter 11, "Medical Gases"; Section 6, Chapter 12, "Flammable and Combustible Liquids"; Section 8, Chapter 11, "Fluid Power Systems"; Section 9, Chapter 12, "Fire Protection of Laboratories Using Chemicals"; and Section 20, Chapter 15, "Health Care Occupancies." See also Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems."

FIRE HAZARDS

The phenomenon known as *fire* is a chemical reaction between a fuel and oxygen. The initiation and rate of the reaction is subject to the laws of chemical kinetics. The degree of fire hazard

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TABLE 9.17.1 Partial Pressure of Oxygen in a Rarefied or Compressed-Air Atmosphere

Total Absolute Pressure				Altitude Above or Depth Below Sea Level (Air or Sea Water)		Partial Pressure of Oxygen if Atmosphere Is Air (torr[a])	Concentration of Oxygen if Partial Pressure of Oxygen Is 160 torr (% by Volume)
Atmospheres	*torr*	*psia*	*kPa*	*m*	*ft*		
1/5	152	2.9	20.0	11,735	38,500	32	100.0[b]
1/3	253	4.9	33.8	8,832	27,500	53	62.7[b]
1/2	380	7.3	50.3	5,486	18,000	80	42.8[b]
2/3	506	9.8	67.6	3,353	11,000	106	31.3[b]
1	760	14.7	101.4	Sea level	—	160	20.9
2	1,520	29.4	202.7	–10	–33	320[b]	10.5
3	2,280	44.1	304.1	–20	–66	480[b]	6.9
4	3,040	58.8	405.4	–30	–99	640[b]	5.2
5	3,800	73.5	506.8	–40	–132	800[b]	4.2

[a]This column shows the increased available oxygen in compressed-air atmospheres.
[b]Oxygen-enriched atmosphere.
Source: NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres,* Table C.1.2.1, 2004, p. 53-15.

varies with the concentration of oxygen present, the diluent gas, and the total pressure. In most commonly encountered oxygen-enriched atmospheres, an increased fire hazard is produced by the increased partial pressure of oxygen (e.g., in an atmosphere of compressed air). However, an oxygen-enriched atmosphere does not necessarily produce an increased fire hazard. Certain oxygen-enriched atmospheres can exhibit combustion-supporting properties similar to ambient air, whereas others are incapable of supporting the combustion of normally flammable materials. For example, a 4 percent oxygen mixture in nitrogen or helium with a total pressure of 12 atm (1216 kPa) will not support the combustion of paper, even though the partial pressure of oxygen is 365 torr (48.7 kPa). However, different concentrations and pressures may accelerate the combustion of materials, facilitate ignition, and, in general, increase fire hazard. Most commonly encountered oxygen-enriched atmospheres fall into this last category (see Table 9.17.1).

Fires and explosions can occur in many diverse circumstances involving intentional and unintentional oxygen-enriched atmospheres. Among them are the following:

1. Transport, transfer, and production of oxygen, including truck delivery of liquid oxygen, leakage or venting from storage or dispensing equipment, and recharging of containers
2. Medical applications involving inhalation therapy, life-support systems, resuscitation procedures, hyperbaric chambers, and anesthesia
3. Industrial applications in petrochemical processing, steel manufacturing, mining, secondary treatment of municipal and industrial wastewaters, manufacturing microchips, paper and pulp bleaching procedures, fire flooding in tertiary oil recovery, and caisson work and underwater tunneling
4. Aerospace activities that involve the use of liquid oxygen in liquid-fueled rockets and aviator breathing systems. Gaseous oxygen is used in the NASA space shuttle orbiter at concentrations as high as 25.9 percent oxygen under normal conditions, and the space station is designed to use a 10.2 psia (70.3 kPa) 30 percent oxygen atmosphere.
5. Test systems, ground support equipment, laboratory piping systems, and acteylene/oxygen torches using oxygen-enriched and high-pressure oxygen environments
6. Inadvertent oxygen-enriched atmospheres that may result from improper design, malfunction, or improper use of oxygen storage or dispensing equipment. Oxygen is more soluble in aircraft fuel than nitrogen and, if such fuel is exposed to air for a significant period of time, enough oxygen may dissolve in the fuel and release during flight because of the decreased atmospheric pressure to create a hazardous oxygen-enriched atmosphere.
7. Inadvertent substitution of oxygen for air or nitrogen
8. Organic, inorganic, or particulate contamination. Contamination control in oxygen systems and components is imperative to minimize hazards and component failures in oxygen systems. Contamination must also be controlled to ensure an acceptable product. The level of cleanliness required is a function of the system design and operational conditions. Ideally, the systems and components should be dismantled and the parts cleaned as individual items. This choice is often not viable, and the best that may be done is to remove the functional components, clean those separately at the piece-part level, and flush the piping system in place. Before developing or introducing a component to an oxygen system, the material should be assessed for risks. The oxygen compatibility assessment discussed in this chapter provides a process for identifying hazards and managing risks.

Further, an oxygen-enriched atmosphere may develop in situations where nitrous oxide is employed. Two common nitrous oxide applications are (1) medical, for example, as a mild

anesthetic agent and (2) industrial, as a propellant in aerosol products. The use of other oxidants, for example, chlorine, chlorates, nitric oxide, and ozone, may result in enhanced combustion. Appropriate safety literature, such as materials safety data sheets (MSDSs), should be consulted.

IGNITION AND COMBUSTION OF MATERIALS

Hazards are always present when using oxygen. Most materials will ignite at considerably lower temperatures in oxygen-enriched environments than in air, and once ignited, combustion rates are greater in oxygen-enriched environments. However, these hazards do not preclude the use of oxygen.

Activation Energy and Ignition Mechanism

Flames involve strongly exothermic reactions between oxidants and fuels, producing combustion products at high temperatures. In general, for a fuel molecule and an oxygen molecule to interact chemically, sufficient energy has to be imparted to these molecules to enable a collision between the two to result in a chemical transformation. The minimum energy for the molecules to react is referred to as the *activation energy.* If the energy released by this reaction is imparted to adjacent molecules in the form of heat, the temperature of the gas will increase. An increase in gas temperature increases the number of molecules with energy equal to the activation energy and increases the reaction rate. As the temperature further increases, enough fuel and oxygen molecules react with enough additional energy released to enable the reaction to become self-sustaining until one or both of the reactants have been consumed and the combustion ceases.

The minimum ignition energy for combustion will vary with the type of ignition source, the specific chemical nature and physical character of the fuel, and the composition and pressure of the atmosphere. Though combustion is typically accompanied by a gas- or vapor-phase combustion reaction, certain materials, for example, metals, can burn in liquid or solid phase; that is, a condensed-phase reaction.[1–5] If the reaction is to continue in the vapor phase, as in the case of solids or liquids, sufficient thermal energy first needs to be supplied to convert a part of the fuel to vapor. In all cases, for the combustion to proceed, the ignition source has to impart energy to the fuel at a faster rate than the fuel loses energy. A source of heat sufficient to ignite the materials of construction or contaminants in a system is referred to as an *ignition mechanism*.

The ignition mechanisms of principal concern for oxygen-enriched atmosphere application can be categorized into two types: ignition caused by internal heating (self-heating) or external heating. The physical and chemical mechanisms involved in ignitions caused by external heating and those caused by self-heating are different. There are situations that overlap, but this division proves convenient both in the scientific world and in practice. Most ignitions encountered are due to external heating. For example, if a match ignites paper, or a halogen lamp ignites a curtain, the source is external. When a pile of linseed oil–soaked cloths bursts into flame, the cause is internal heating. Internal heating is more complicated than external heating, because factors such as airflow or exact details of the oxidation chemistry, which are of minor importance in external ignitions, become of major concern. Table 9.17.2 provides a list of ignition mechanisms.

TABLE 9.17.2 Ignition Mechanisms

Internal Heat Source	*External Heat Source*
Particle impact	Thermal ignition
Rapid pressurization	Lightning
Flow friction	Explosive charges
Resonance	Personnel smoking and open flames
Mechanical impact	Fragments from bursting vessels
Galling and friction	Welding
Fresh metal exposure	Thermal combustion engine exhaust
Static discharge	Mechanical impact
Electrical arc	
Chemical reaction	
Thermal runaway	

In general, the greater the oxygen concentration, the lower the energy required for ignition and the faster the flame spread rate. Figure 9.17.1 depicts, in an oversimplified manner, the effects of variations in oxygen concentration and environmental pressure. For a fixed-volume percent of oxygen, the minimum ignition varies inversely with the square of the pressure. There exists a minimum pressure below which ignition will not occur. As the temperature of a given system increases, less and less

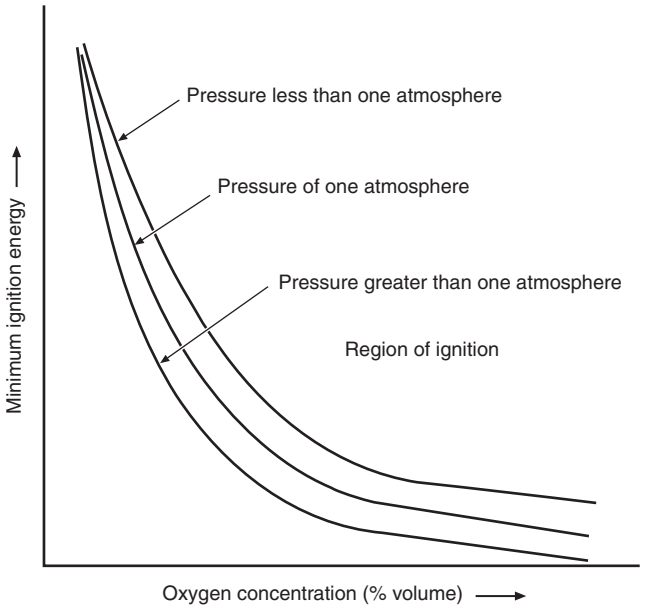

FIGURE 9.17.1 Effects of Variations in Oxygen Concentration and Environmental Pressure on the Minimum Ignition Energy

energy is required to ignite the mixture until it reaches a sufficiently high temperature to ignite spontaneously. This minimum temperature is known as the autoignition or spontaneous ignition temperature.

The likelihood of ignition and the rate of flame propagation of a combustible are primarily influenced by the oxygen content in the environment. Thus, a minimum amount of oxygen must be present for a flame to propagate, regardless of the ratio of the fuels to inert gases present. Effects on ignition energy requirements by typical ignition sources will vary with the particular inert gas present and are a function of the heat capacity and thermal conductivity of these gases in the atmosphere.

Combustion is a complex sequence of chemical reactions between a fuel and an oxidant, accompanied by the evolution of heat and, usually, by the emission of light. The rate of combustion process depends on the chemical nature of the fuel and oxidant, their relative concentrations, environmental pressure and temperature, and other physical parameters, for example, geometry and ventilation.

Combustible Gases, Vapors, and Liquids

Once ignition occurs, the propagation of combustion requires a continued supply of fuel and oxidant. The limits of flammability represent the extreme concentration limits of a combustible in an oxidant through which a flame, once initiated, will continue to propagate at the specified pressure and temperature. In the case of combustible gases, vapors, and liquids, two types of mixtures, homogeneous or heterogeneous, can exist within the atmosphere. A homogeneous mixture is one in which the components are intimately and uniformly mixed so that any small volume is representative of the whole. If the mixture is not homogeneous, it is necessarily heterogeneous.

Figure 9.17.2 shows that, for liquid fuels in equilibrium with their vapors in air (or in oxygen), a minimum temperature exists for each fuel above which sufficient vapor is released to form a flammable vapor-air (or vapor-oxygen) mixture. The experimentally determined value of this minimum temperature is commonly referred to as the *flashpoint.*

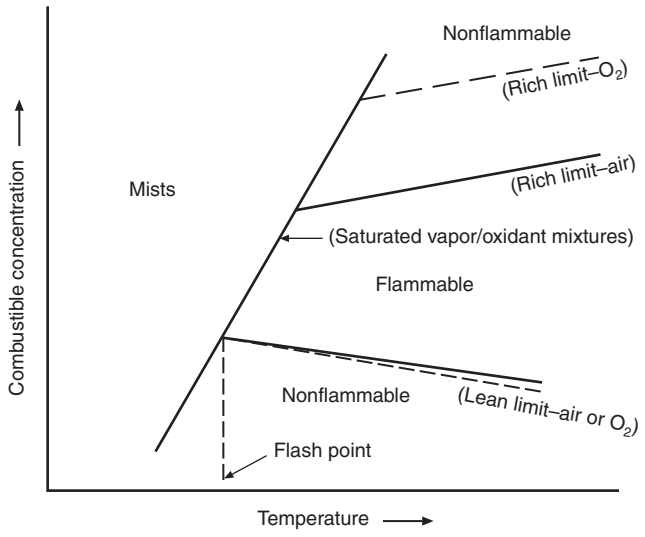

FIGURE 9.17.2 Minimum Temperature for Flammable Vapor Mixtures

The total environmental pressure also has an effect on the limits of flammability (Figure 9.17.3). For a given atmospheric composition, an increase in pressure generally broadens the flammability range. The low-pressure limit is dependent on the particular fuel and oxidant, as well as the temperature, size, geometry, and physical orientation of the confining vessel. The quenching or low-pressure limits are represented in Figure 9.17.3 by broken lines to indicate their dependency on surroundings.

The lower limit of flammability is of great interest, because it defines the minimum combustible concentration required for the propagation of flame throughout the particular mixture. The minimum temperature at which a lower limit concentration can exist depends on the volatility of the combustible and corresponds roughly to the flashpoint of the combustible. Flammable liquids have flashpoints in air of less than 100°F (38°C) (Table 9.17.3). Also, fuel-air mixtures formed at or above their flashpoint temperature will propagate flame if ignited. In oxygen, flashpoints of combustibles are slightly lower than those in air. Where fuel mists or foams are formed, the mixtures may propagate flame at temperatures far below the flashpoints of the fuels.

Typically, the lower flammability limits for most hydrocarbon fuels, anesthetics, and solvents are between 1 and 5 percent by volume in air or oxygen at 1 atm pressure. In comparison, the values for most lubricants are less than 1 percent by volume because of the higher molecular weights of such fluids. Further, lubricants need much higher temperatures, for example, 200 to 700°F (93 to 371°C), to form lower-limit flammable mixtures than do paraffins or other hydrocarbons.[6] Although most lower flammable limits in oxygen do not differ greatly from those in

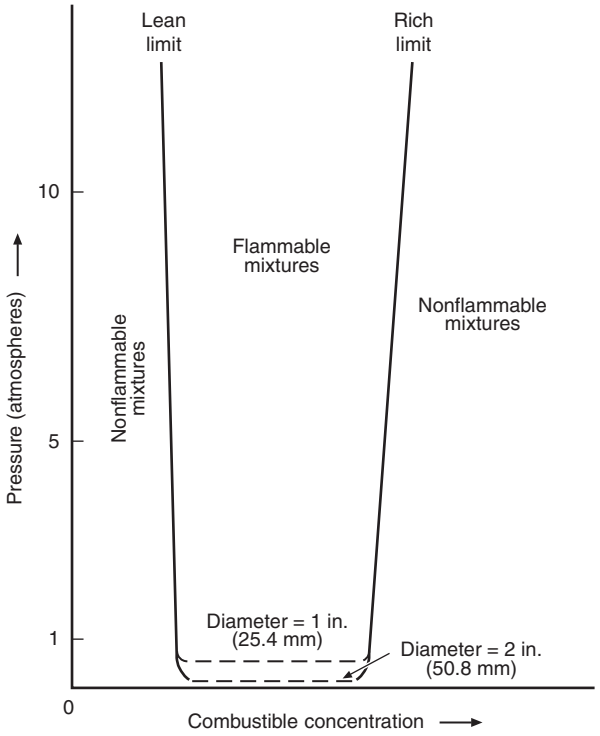

FIGURE 9.17.3 Effects of Pressure on Limits of Flammability

TABLE 9.17.3 Ignition and Flammability Properties of Combustible Liquids and Gases in Air and Oxygen at Atmospheric Pressure

	Flashpoint[a]		Minimum Ignition Temperature				Minimum Ignition Energy		Flammability Limits Vol. Percentage			
	Air		Air		Oxygen		Air	Oxygen	Air		Oxygen	
Combustible	*°C*	*°F*	*°C*	*°F*	*°C*	*°F*	*mJ*	*mJ*	*LFL*	*UFL*	*LFL*	*UFL*
Hydrocarbon Fuels												
Methane	Gas		630	1166	—		0.300	0.0030	5.0	15.0	5.1	61.0
Ethane	Gas		515	959	506	943	0.250	0.0020	3.0	12.4	3.0	66.0
n-Butane	–60.0	–76	288	550	278	532	0.250	0.0090	1.8	8.4	1.8	49.0
n-Hexane	–3.9	25	225	437	218	424	0.288	0.0060	1.2	7.4	1.2	52.0[b]
n-Octane	13.3	56	220	428	208	406	—	—	0.8	6.5	≤0.8	—
Ethylene	Gas		490	914	485	905	0.070	0.0010	2.7	36.0	2.9	80.0
Propylene	Gas		458	856	423	793	0.280	—	2.4	11.0	2.1	53.0
Acetylene	Gas		305	581	296	565	0.017	0.0002	2.5	100.0	≤2.5	100.0
Gasoline (100/130)	–45.5	–50	440	824	316	600	—	—	1.3	7.1	≤1.3	—
Kerosene	37.8	100	227	440	216	420	—	—	0.7	5.0	0.7	—
Anesthetic Agents												
Cyclopropane	Gas		500	932	454	849	0.180	0.0010	2.4	10.4	2.5	60.0
Ethyl ether	–28.9	–20	193	380	182	360	0.200	0.0013	1.9	36.0	2.0	82.0
Vinyl ether	–30.0	<–22	360	680	166	331	—	—	1.7	27.0	1.8	85.0
Ethylene	Gas		490	914	485	905	0.070	0.0010	2.7	36.0	2.9	80.0
Ethyl chloride	–50.0	–58	516	961	468	874	—	—	4.0	14.8	4.0	67.0
Chloroform	Nonflammable											
Enflurane	>200.0	93	NA		NA		NA	NA	NA	NA	9.8	NA
Isoflurane	>200.0	93	NA		NA		NA	NA	NA	NA	8.8	NF
Desflurane	NF		NA		NA		NA	NA	NA	NA	17.2	20.8
Nitrous oxide	Nonflammable											
Solvents												
Methyl alcohol	12.2	54	385	725	—		0.140	—	6.7	36.0	≤6.7	93.0
Ethyl alcohol	12.8	55	365	689	—		—	—	3.3	19.0	≤3.3	—
n-Propyl alcohol	15.0	59	440	824	328	622	—	—	2.2	14.0	≤2.2	—
Glycol	111.0	232	400	752	—		—	—	3.5[b]	—	≤3.5	—
Glycerol	160.0	320	370	698	320	608	—	—	—	—	—	—
Ethyl acetate	–4.4	24	427	800	—		0.480	—	2.2	11.0	≤2.2	—
n-Amyl acetate	24.4	76	360	680	234	453	—	—	1.0	7.1	≤1.0	—
Acetone	–17.8	0	465	869	—		1.150	0.0024	2.6	13.0	≤2.6	60.0[b]
Benzene	–11.1	12	560	1040	—		0.220	—	1.3	7.9	≤1.3	30.0
Naphtha (Stoddard)	37.8	~100	232	~450	216	~420	—	—	1.0	6.0	≤1.0	—
Toluene	4.4	40	480	896	—		2.500	—	1.2	7.1	≤1.2	—
Butyl chloride	–6.7	20	240	464	235	455	0.332	0.0070[b]	1.8	10.0	1.7	52.0[b]
Methylene chloride	—		615	1139	606	1123	—	0.1370	15.9[b]	19.1[b]	11.7[b]	68.0
Ethylene chloride	13.3	56	476	889	470	878	2.370	0.0110[b]	6.2	16.0	4.0	67.5
Trichloroethane	—		458	856	418	784	—	0.0920	6.3[b]	13.0[b]	5.5[b]	57.0[b]
Trichloroethylene	32.2	90	420	788	396	745	—	18.0000[b]	10.5[b]	41.0[b]	7.5	91.0[b]
Carbon tetrachloride	Nonflammable											
Miscellaneous Combustible												
Acetaldehyde	–27.2	–17	175	347	159	318	0.380	—	4.0	60.0	4.0	93.0
Acetic acid	40.0	104	465	869	—		—	—	5.4[b]	—	≤5.4	—

(continued)

TABLE 9.17.3 Continued

	Flashpoint[a]		Minimum Ignition Temperature				Minimum Ignition Energy		Flammability Limits Vol. Percentage			
	Air		Air		Oxygen		Air	Oxygen	Air		Oxygen	
Combustible	*°C*	*°F*	*°C*	*°F*	*°C*	*°F*	*mJ*	*mJ*	*LFL*	*UFL*	*LFL*	*UFL*
Miscellaneous Combustible *(continued)*												
Ammonia	Gas		651	1204	—		>1000.000	—	15.0	28.0	15.0	79.0
Aniline	75.6	168	615	1139	—		—	—	1.2[b]	8.3	≤1.2	—
Carbon monoxide	Gas		609	1128	588	1090	—	—	12.5	74.0	≤12.5	94.0
Carbon disulfide	–30.0	–22	90	194	—		0.015	—	1.3	50.0	≤1.3	—
Ethylene oxide	–17.8	<0	429	804	—		0.062	—	3.6	100.0	≤3.6	100.0
Propylene oxide	–37.2	–35	—		400	—	0.140	—	2.8	37.0	≤2.8	—
Hydrogen	Gas		520	968	400	752	0.017	0.0012	4.0	75.0	4.0	95.0
Hydrogen sulfide	Gas		260	500	220	428	0.077	—	4.0	44.0	≤4.0	—
Bromochloro-methane	—		450	842	368	694	—	—	NF[c]	NF	10.0	85.0
Bromotrifluoro-methane	Gas		>593	>1100	657	1215	—	—	NF	NF	NF	NF
Dibromodifluoro-methane	Gas		499	930	453	847	—	—	NF	NF	29.0	80.0

[a]Open-cup method.
[b]Data at 93°C (200°F).
[c]NF = No flammable mixtures found.

Source: NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres,* Table F.2.1, 2004, pp. 53-32 and 53-33.

air, the upper flammable limits usually require much higher oxygen concentration, which tends to be about 50 percent for many materials (see Table 9.17.3).

Combustible Solids—Nonmetals

The burning of solid combustibles requires the consideration of only heterogeneous fuel-oxidant systems. As in the case of flammable liquids and gases, the flame reaction occurs in the gas phase. Once a particular solid combustible has been ignited, flame propagation requires that a portion of the heat of combustion be fed back to the solid fuel to cause its vaporization or pyrolysis, or both, thereby making additional gaseous fuel available to mix with the oxidant. The flame process is of the diffusion type.

The fire resistance of a material is an important selection property when designing an oxygen component or system. Nonmetals are especially sensitive to stresses, such as temperature, time, pressure, abrasion, light, particle impact, tensile or compression forces, or any other force that may cause aging. After a period of time, the material can *metamorphosize* into something other than its initial condition. Some changes due to aging or oxidation may be the loss of mechanical properties and temperature resistance, changes in ignition and propagation properties, and particle generation. Metals can form oxide layers, which generate particles, cause loss of strength, enhance surface roughness that results in leak paths, and decrease service life.

Figure 9.17.4 depicts the effects of oxygen content and pressure on the flame spread rate. Note that increasing the partial pressure of oxygen at a constant environmental pressure may change the classification of a material from the nonflammable to the flammable category. For materials already in the flammable category based on 21 percent oxygen, further increases in the oxygen partial pressure result in higher flame spread rates.

Organic materials in the form of finely dispersed dust clouds are extremely susceptible to combustion. Typically, spark ignition energies are less than 0.1 J. Single fibers of organic materials (e.g., lint, cotton tufts, and fluffy fabrics) may be ignited by a 0.02 J static spark in 100 percent oxygen but not in 64 percent oxygen.[7] Textile fabrics (cotton and wool used in clothing) can be ignited with a spark energy as low as 2.3 J in 100 percent oxygen, whereas, in normal air, a spark energy of at least 193 J is required.[8]

Combustible materials, when heated, may self-ignite at relatively low temperatures that approach the spontaneous or autogenous ignition temperatures ([SIT] or [AIT], respectively) obtained under ideal test conditions. As shown in Figure 9.17.5, the AIT rapidly decreases with increasing pressure up to approximately 1000 psi (7 MPa), after which the AIT remains essentially constant (Table 9.17.4).

The majority of the materials commonly used in the home and workplace are flammable in air. Chemical additives to plastics and textile fabrics, such as halogens, borax, phosphates, and various metal oxides, are effective in reducing both ignitability and flammability and have been found to be effective for many materials in atmospheres containing up to 30 to 35 percent oxygen. However, it should be mentioned that materials treated with some fire retardants will burn differently than nontreated materials and may generate corrosive or toxic vapors during the combustion process. The hot plate ignition temperatures and the flame resistance of several materials are shown in Tables 9.17.5 and 9.17.6.

TABLE 9.17.4 Autoignition Temperatures for Selected Materials: Polymers and Lubricants

Materials	*Description*	*AIT °C*	*Notes*
	Plastics		
ABS	Copolymer of acrylonitrile, butadiene, and styrene	243	a
ACLAR 22	Polychlorotrifluoroethylene (PCTFE)	390	a
Delrin	Polymethylene oxide	178	a
Halar	Copolymer of ethylene and chlorotrifluoroethylene	171	a
Kel-F 81	Polychlorotrifluoroethylene (PCTFE)	388	a
Kynar	Polyvinylidene fluoride	268	a
Mylar	Polyethylene terephthalate	181	a
Noryl	Polyphenylene oxide blended with polystyrene	348	a
PEEK	Polyetherether ketone	305	a
PE	Polyethylene	176	a
PES	Polyethersulfone	373	a
PPS	Polyphenylene sulfide	285	a
PVC	Polyvinyl chloride	239	a
Rulon E	Glass-filled fluorocarbon (PTFE)	427+	a
Tedlar	Polyvinyl fluoride	222	a
Teflon A	Polytetrafluoroethylene (PTFE)	434	a
Teflon FEP	Copolymer of tetrafluoroethylene and perfluoro (propyl vinyl ether)	378	a
Teflon PFA	Perfluoroalkoxytetrafluoroethylene	424	a
Tefzel	Copolymer of tetrafluoroethylene and ethylene	243	a
Tetratemp 900	Polyimide	399	a
Ultem	Polyetherimide	385	a
Vespel SP-21	Polyimide with 15 wt % graphite	343	a
Zytel	Polyamide (nylon 6/6)	259	a
Epoxy/fiberglass		258	b
	Elastomers		
Aflas	Copolymer of tetrafluoroethylene and propylene + cure site monomer	254	a
Butyl rubber	Copolymer of isobutylene and small quantities of isoprene	208	a
EPDM	Copolymer of ethylene, propylene, and a diene monomer	159	a
Fluorel	Copolymer of vinylidene fluoride and hexafluoropropylene	302	a
Kalrez	Copolymer of tetrafluoroethylene and perfluoro (methyl vinyl ether + cure site monomer)	355	a
Neoprene	Polychloroethylene	258	a
Nitrile	Copolymer of butadiene and acrylonitrile	173	a
Polyurethane rubber	Polyurethane	181	a
Silicone rubber	Polysiloxane	262	a
Viton A	Copolymer of vinylidene fluoride and hexafluoropropylene	268 to 322	a, c
	Lubricants		
Brayco 600	Perfluoroalkyl polyether oil	427	d
Brayco Micronic 631A	Perfluoroalkyl polyether grease	421	d
DC 55M	Silicone grease	216	d
Everlube 811	MoS2 in sodium silicate	271	d
Fluorolube FS-2	PCFTE oil	399	d
Fluorolube GR362	PCTFE grease	427	d
Fomblin RT-15	Perfluoroalkyl polyether grease	427+	d
Fomblin Y-02	Perfluoroalkyl polyether oil	427+	d
FS 3452	Fluorosilicone grease	249	d
Halocarbon 10-25	PCTFE oil	399	d
Halocarbon 25-20M	PCTFE grease	427+	d
Krytox 143AC	Perfluoroalkyl polyether oil	427	d
Krytox 240AC	Perfluoroalkyl polyether grease	427+	d

Notes:

[a]Tests conducted per ASTM Test Method G 72 at 10.3 MPa in 100% oxygen. Source: Hshieh, F. Y., Stoltzfus, J. M., and Beeson, H. D., "Autoignition Temperature of Selected Polymers at Elevated Oxygen Pressure and Their Heat of Combustion," *Fire and Materials,* Vol. 20, 1996, pp. 301–303.

[b]Tests conducted per ASTM Test Method G 72 at 10.3 MPa in 100% oxygen. Source: Beeson, H. D., Hshieh, F. Y., and Hirsch, D. B., "Ignitability of Advanced Composites in Liquid and Gaseous Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres,* ASTM STP1319, 1997.

[c]The AIT depends on the carbon black content in rubbers.

[d]Tests conducted per ASTM Test Method G 72 at 10.3 MPa in 100% oxygen. Source: David W. Taylor, Naval Ship Research and Development Center.

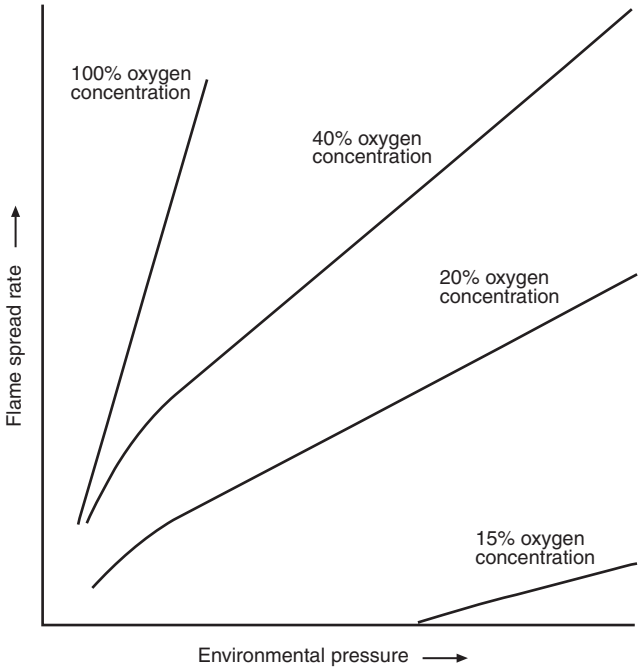

FIGURE 9.17.4 Effects of Oxygen Content and Pressure on Flame Spread Rate

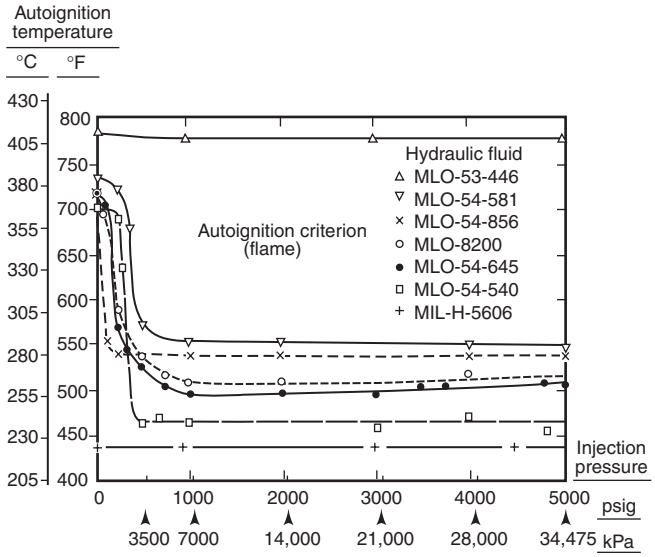

FIGURE 9.17.5 Effect of Pressure on Autogenous Ignition Temperature

TABLE 9.17.5 Minimum Hot Plate Ignition Temperatures (°C) of Six Combustible Materials in Oxygen-Nitrogen Mixtures at Various Total Pressures

		Ignition Temperature (°C)			
		Total Pressure (atm)			
Material	*Oxidant*	*1*	*2*	*3*	*4*
Cotton sheeting	Air	465	440 (425)[a]	385	365
	42% O_2, 58% N_2	390	370	355	340
	100% O_2	360	345	340	325
Cotton sheeting, treated[b]	Air	575	520 (510)[a]	485 (350)[a]	370 (325)[a]
	42% O_2, 58% N_2	390 (350)[a]	335	315	295
	100% O_2	310	—	300	285
Conductive rubber sheeting	Air	480	395	370	375
	42% O_2, 58% N_2	430	365	350	350
	100% O_2	360	—	345	345
Paper drapes	Air	470	455	425	405
	42% O_2, 58% N_2	430	—	400	370
	100% O_2	410	—	365	340
Nomex fabric	Air	>600	>600	>600	560
	42% O_2, 58% N_2	550	540	510	495
	100% O_2	520	505	490	470
Polyvinyl chloride sheet	Air	>600	—	495	490
	42% O_2, 58% N_2	575	—	370	350
	100% O_2	390	—	350	325

[a]Values in parentheses indicate the temperature at which material glowed.
[b]Cotton sheeting treated with DuPont® X-12 fire retardant; amount of retardant equal to 12 percent of cotton specimen weight.

Source: NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres,* Table F.3.2.8, 2004, p. 53-39.

TABLE 9.17.6 Flame Resistance of Materials Held Vertically at One Atmosphere Pressure in O_2/N_2 Mixtures

NRL Sample Number	*Material*	Combustion in O_2/N_2 Mixtures		
		21% O_2	*31% O_2*	*41% O_2*
FM-1	Rosin-impregnated paper	Burned		
FM-3	Cotton terry cloth	Burned		
FM-28	Cotton cloth, white duck	Burned		
FM-4	Cotton terry cloth, roxel-treated	No	No	Burned
FM-5	Fleece-backed cotton cloth, roxel-treated	Surface only	Burned	Burned
FM-14	Cotton O.D. Sateen, roxel-treated	No	Burned	—
FM-15	Cotton green whipcord, roxel-treated	No	Burned	—
FM-16	Cotton white duck, roxel-treated	No	Burned	—
FM-17	Cotton King Kord, roxel-treated	No	Burned	—
FM-29	Cotton white duck, treated with 30% boric acid, 70% borax	No	Burned	Burned
FM-30	Cotton terry cloth, treated with 30% boric acid, 70% borax	No	Burned	Burned
FM-6	Fire-resistant cotton ticking	No	Burned	—
FM-7	Fire-resistant foam rubber	No	No	Burned
FM-9	Nomex temperature-resistant nylon	No	Burned	—
FM-10	Teflon fabric	No	No	No
FM-11	Teflon fabric	No	No	No
FM-12	Teflon fabric	No	No	No
FM-13	Teflon fabric	No	No	No
FM-19	Verel fabric	No	Burned	Burned
FM-22	Vinyl-backed fabric	No	Burned	Burned
FM-23	Omnicoated DuPont® high-temperature fabric	No	Burned[a]	Burned
FM-24	Omnicoated glass fabric	No	No	Burned[a]
FM-20	Glass fabric, fine weave	No	No	No
FM-21	Glass fabric, knit weave	No	No	No
FM-25	Glass fabric, coarse weave	No	No	No
FM-26	Glass fabric, coarse weave	No	No	No
FM-27	Aluminized asbestos fabric	No	No	Burned
FM-32	Rubber from aviator oxygen mask	Burned	Burned	Burned
FM-33	Fluorolube grade 362	No	No	No[b]
FM-34	Belco no-flame grease	No	No	No[b]

[a]Burned only over igniter.
[b]White smoke only.

Source: NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres,* Table F.3.3.1, 2004, p. 53-40.

The oxygen index test is commonly used to evaluate the ignition and propagation properties of materials in oxygen-enriched atmospheres. Many commonly used materials will ignite and burn in as little as 16 percent oxygen; however, fluorocarbon plastics did not propagate flames in 100 percent oxygen. The oxygen index values for a number of materials are shown in Table 9.17.7.

Electrical wiring insulation is a critical application of polymeric materials. Commonly used polymers are Teflon (PTFE), Nomex, Kapton, Kynar, silicone, polyolefin, and

TABLE 9.17.7 Oxygen Index for Selected Materials

Material	*Description*	*OI*[a]
Polyacetal		16
Loctite pipe sealant		
Nuclear grade PST®	Anaerobic sealant (cured), cup test[b]	17
Type PS/T	Anaerobic sealant (cured), cup test[b]	20
Poly(methylmethacrylate)		
Plexiglas		18.5 ± 0.5
ECO/Rubber	Epichlorohydrin rubber	18.5
Silicone rubber		
RTV 102		23
Silastic@ 732		25
SMS 2454		25
RTV 60		28.5
RTV 560		29
RTV 560 mixture	User-added 50% glass	36
Silicone grease	Cup test[b]	26 ± 1
Rectorseal® #15 thread sealant		<30.0
Durabla gasket		28.0 ± 0.5
Fluorosilicone grease #822	Cup test[b]	30
Blue Gard® gaskets		
Blue Gard 3000	Nonasbestos gasket	30.5 ± 0.5
Blue Gard 3200	Nonasbestos gasket	31
Blue Gard 3400	Nonasbestos gasket	52
Blue Gard 3200	Nonasbestos gasket	60
Blue Gard 3000	Nonasbestos gasket	62
Blue Gard 3300	Nonasbestos gasket	68
Nylon		
Nylon 66		30.5
Nylon 66 (glass-filled)		23.5
CYL-SEAL thread sealant		38
Polyvinylidene fluoride		
Kynar®		39
Fluorocarbon rubber		
Viton®	Brown O-ring	40.5 ± 0.5
Viton, green	Green O-ring	42
Viton A		57
Viton A		57.5
Viton E-60C		60.5
Viton B®, #V494-70		DNP
Balston® filters		
Type—Epoxy	Cut from cylinder	42.5
Type Q-fluorocarbon	Cut from cylinder	47 ± 1
Type H-Inorganic	Cut from cylinder	DNI
Molykote® Z powder	MOS_2 cup test[b]	45
Bel-Ray greases	Cup test[b]	57
FC1260	Cup test[b]	DNP
FC1245	Halocarbon oil/graphite	
Key Abso-Lute®	Cup test[b]	67
CTFE lubricants		
Fluorolube GR362 grease	Cup test[b]	67 ± 4
Halocarbon 25-20 oil	Cup test[b]	75
Halocarbon 11-14S oil	Cup test[b]	DNP
Fluorocarbon FEP	Tubing	77
Fluorocarbon PFA		100
Fluorocarbon TFE		DNP

TABLE 9.17.7 (Continued)

Material	*Description*	*OI*[a]
PFPE grease		
Fomblin RT15	Cup test[b]	DNP
Krytox 283AC®	Cup test[b]	DNP
Krytox GPL 225	Cup test[b]	DNP
Krytox GPL 205	Cup test[b]	DNI
Tribolube 13C	Cup test[b]	DNP
PFPE fluid		
Fomblin Y25	Cup test[b]	DNI
Krytox GPL 105	Cup test[b]	DNP
CTFE plastic		
Kel-F 81®	15% glass-filled	DNP
Kel-F 81	Nonplasticized	DNP
Perfluoroelastomer		
Kalrez® 1045	O-ring	DNP
Kalrez 1050	O-ring	DNP
Kalrez 4079	O-ring	DNP
Silica gel	Cup test[b]	DNI
Blue drierite	Cup test[b]	DNI
Kaowool insulation	Alumina-silica	DNI
Cerawool paper		DNI
Fiberglass/cement board		DNI
Kwik Flux #54®	Cup test[b]	DNI
Asbestos cement board		
Transite®		DNI
Sindanyo CS51®		DNI
Turnalite TI 150®		DNI
Asbestos paper	32 lb/100 ft^2	DNI

[a]DNP = Did not propagate. DNI = Did not ignite.
[b]Cup test performed as described by Nelson, G. L., and Webb, J. L. "Oxygen Index of Liquids, Techniques and Application." *Journal of Fire and Flammability*, Vol. 4, July 1973, pp. 210–226.

Source: NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres,* Table F.3.3.4, 2004, pp. 53-42 and 53-43.

polyvinylchloride. Of these, Teflon (PTFE) is the most ignition and flame resistant in oxygen-enriched atmospheres. Kapton is resistant to ignition in oxygen-enriched atmospheres, but is susceptible to arc tracking. Potting compounds, circuit boards, and other components of the electrical system can also contribute to the fuel supply.[9,10]

The rate at which flame spreads under a given set of conditions in an oxygen-enriched atmosphere is the single most important property to fire hazard development in such an atmosphere. The rate of flame spread over the surface of a given combustible material provides an indication of the speed at which a fire involving the combustible will develop (Table 9.17.8). Flame spread rates are much greater in an upward direction, due to the buoyant convection, than in the horizontal and downward directions. The rate of flame spread increases with (1) an increase in the oxygen concentration at constant pressure or (2) an increase in total pressure at a constant percentage of oxygen. Table 9.17.9 shows typical data for the burning of filter paper over a wide range of pressure and atmospheric conditions.

Several test methods for determining flame spread rate include the following:

1. NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
2. ASTM E162, *Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source*
3. ASTM D568, *Standard Test Method for Flammability of Flexible Plastic*
4. ASTM D1230, *Standard Test Method for Flammability of Apparel Textiles*
5. ASTM D2863, *Standard Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-like Combustion of Plastics (Oxygen Index)*
6. ASTM G125, *Standard Test Method for Measuring Liquid and Solid Material Fire Limits in Gaseous Oxidants*
7. ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials*

For each method, selected materials are tested under conditions of intended use prior to use in oxygen-enriched atmospheres.

TABLE 9.17.8 Effect of Oxygen on Flame Spread Rates over Various Materials (Edges Not Inhibited)

Material	Flame Spread Rate (mm/sec) In Air	Flame Spread Rate (mm/sec) In 258 mm Hg Oxygen
Aluminized Mylar® tape	—	49.53
Aluminized vinyl tape	NI	78.74 ± 10.16
Asbestos insulating tape	NI	2.03
Butyl rubber	0.152	0.40 ± 0.04
Canvas duck	NP	6.35
Cellulose acetate	0.305	7.1
Chapstick	NI	46.23
Cotton shirt fabric	NP	38.1 ± 1.27
Electrical insulating resin	NI	6.86
Electrical terminal board	NI	1.524 ± 0.254
Fiberglass insulating tape	NI	106.68 ± 15.24
Foam cushion material	4.830	314.96
Foamed insulation	0.051	55.88 ± 5.08
Food packet, aluminized paper	NI	7.112 ± 1.27
Food packet, brown aluminum	NI	17.78 ± 7.62
Food packet, plastic	8.380	13.97
Glass wool	NI	NI
Kel-F	NI	NI
Masking tape	4.320	46.228
Natural rubber	0.254	15.49
Neoprene rubber	NI	(8.13 ± 1.0)
Nylon 101	NI	(4.83 ± 1.27)
Paint, Capon, ivory	NI	9.652 ± 1.016
Paint, Pratt & Lambert, grey	NI	15.24 ± 5.08
Plexiglas®	0.127	(8.89 ± 0.25)
Polyethylene	0.356	(6.35 ± 1.27)
Polypropylene	0.254	(8.89 ± 0.25)
Polystyrene	0.813	(20.32 ± 5.08)
Polyvinyl chloride	NI	(2.54 ± 0.25)
Pump oil	NI	122.606
Refrigeration oil	NI	20.828 ± 1.778
Rubber tubing	0.760	6.096
Silicone grease	NI	23.368
Solder, rosin core	NI	4.572
Sponge, washing	1.780	205.74 ± 2.54
Teflon pipe-sealing tape	NI	NI
Teflon tubing	NI	NI
Tygon tubing	4.570	12.7 ± 1.27
Viton A®	NI	(0.076 ± 0.051)
Wire, Mil W76B, blue	NI	—
Wire, Mil W76B, orange	NI	14.478 ± 1.27
Wire, Mil W76B, yellow	NI	—
Wire, Mil W16878, black	NI	NI
Wire, Mil W16878, green	NI	NI
Wire, Mil W16878, yellow	NI	NI
Wire, Mil 16878, white	NI	NI
Wire, misc., black, $^{3}/_{16}$	NI	—
Wire, misc., brown, $^{7}/_{32}$	NI	12.954 ± 1.27
Wire, misc., white, $^{3}/_{32}$	NI	8.382
Wire, misc., yellow $^{7}/_{64}$	NI	22.606
Wire, misc., yellow, $^{5}/_{32}$	NI	10.414

Note: NP = No sustained propagation of flame. NI = No ignition of material.

Source: NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres,* Table F.3.3.4, 2004, p. 53-41.

Combustible Solids—Metals

The burning of metals can occur either in the vapor phase or in a condensed-phase reaction and, therefore, can require the consideration of both homogeneous and heterogeneous fuel-oxidant systems. Once a particular metallic combustible has been ignited, propagation of the combustion, whether burning in the vapor phase or condensed phase, requires that a portion of the heat of combustion (assuming the ignition source has been removed) be fed back to the solid fuel to cause it to heat past the ignition point.

All metals, with the possible exception of the noble metals—gold and platinum—can be expected to ignite in oxygen at some elevated temperature and pressure. Metals most subject to ignition hazards are those configured with high surface-to-volume ratios, such as dusts, thin sheets, wires, and wire meshes. When the structural elements of systems containing pressurized oxygen ignite and burn, the results are often catastrophic, due to the explosion-like release of high-pressure gases and ejection of burning debris. Ignition mechanisms include mechanical impact, particle impact, friction, electrical arc and spark, resonance, rupture, exposure of fresh metal surfaces, and promoted ignition. The most ignitable common metals are titanium, magnesium, and lithium; the least ignitable are nickel, copper, and cobalt. Increase in oxygen pressure and concentration promotes the ignition of metals at lower temperatures.[11]

As with nonmetals, the extent of combustion and flame propagation for metals depends on a number of factors, including the absolute pressure, ambient temperature, fuel and oxidizer composition, geometric shape and temperature of the fuel sample, and direction of combustion front. Depending on these factors, the combustion front in metals can propagate at greatly varying rates. For example, a 0.13 in. (3.3 mm) diameter 316 stainless steel rod burning upward in 1000 psi (7 MPa) oxygen will propagate at about 0.43 in./sec (11 mm/sec), whereas a 0.13 in. (3.3 mm) diameter 6061 aluminum rod will burn at 2.5 in./sec (64 mm/sec).[12] In general, the combustion front propagation rate increases with increasing ambient pressure, oxidizer concentration, ambient temperature, and decreasing sample dimensions.[13,14]

Flammability limits per se do not exist for most structural metal alloys, because they burn mostly in the liquid rather than the vapor phase. However, two measures of the relative flammability of metals exist that are of practical value: (1) the minimum

TABLE 9.17.9 Typical Measured Burning Rates for Strips of Filter Paper at 45° Angle

Total Pressure Gas Composition (dry basis)			Burn Rate, cm/sec					
		atm abs ft of Seawater	*0.21 atm*	*0.53 atm*	*1.00 atm*	*4.03 atm*	*7.06 atm*	*10.09 atm*
			—	—	*0 ft*	*100 ft*	*200 ft*	*300 ft*
% O_2	*% N_2*[a]	*% He*						
99.60	0.40	0.0	2.32	3.13	4.19	[d]	[d]	[d]
50.30	49.70	0.0	1.13	1.44	2.36	3.72	5.10	6.34
			1.17			3.77	4.06	
20.95[b]	79.05	0.0	[c]	0.80	1.17	1.82	2.80	3.13
					1.17	1.78	2.28	3.25
					1.10			
49.50	0.00	50.5	1.24	1.87	2.96	4.06	4.90	[d]
				1.90	2.89		4.82	
					2.89			
20.30	0.00	79.7	[c]	[c]	[c]	2.23	2.61	2.49
47.00	24.60	28.4	[d]	[d]	2.74	3.66	4.41	5.53
					2.68		4.64	6.78
20.90	39.60	39.5	[d]	[d]	1.38	2.28	2.71	3.72
					1.38	2.28	2.83	3.13
					1.35	1.97	2.74	3.56
					1.27	2.28		3.33
						1.81		3.00
						1.72		

[a]Includes any argon that was present.
[b]Compressed air.
[c]Sample would not burn, even with brightly glowing igniter grid.
[d]No run was made under these conditions.

Source: NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres,* Table F.3.3.5, 2004, p. 53-42.

oxygen pressure required to support combustion of a standard sample (threshold pressure) and (2) the minimum oxygen concentration required to support combustion of a standard sample at a given pressure (oxygen index). Data on the threshold pressures and oxygen indices of several metals and alloys are provided in Table 9.17.10 and Figure 9.17.6, respectively.

DESIGN OF SYSTEMS FOR OXYGEN-ENRICHED ATMOSPHERES

A systematic approach should be used to minimize the risk of fire and the potential effect of a fire on personal safety and the safety of the system before designing systems associated with oxygen-enriched atmospheres, such as the following: gas and compressed air supplies, welding applications, spacecraft propulsion and ground support equipment, self-contained underwater breathing apparatus (SCUBA), and medical applications (including home assisted-breathing apparatus).

Oxygen Compatibility Assessment

The oxygen compatibility assessment process provides a tool for identifying and addressing the fire hazards in an oxygen system with the primary goal of determining the likelihood of a fire occurring in an oxygen system.[15,16] The oxygen compatibility assessment process may be used as both a design guide and an approval process for components and systems. Figures 9.17.7 and 9.17.8 provide an example of an oxygen compatibility assessment and show the complete analysis of a single component. The suggested oxygen compatibility assessment procedure is as follows:

1. Determine the most severe operating conditions.
2. Assess the flammability of the system materials.
3. Evaluate presence and probability of ignition mechanisms.
4. Determine the kindling chain, which is the potential for a fire to breach the system.
5. Determine the reaction effect, which is the potential loss of life, mission, and system functionality as the result of a fire.
6. Record the results of the analysis.
7. Review the results to obtain consensus from others involved in the process.
8. Finalize, archive, and transmit assessment.

Worst-Case Operating Conditions. To ascertain the ignition and flammability risks for a component or system, one must first understand the worst-case operating environment for the application. Increased oxygen concentration, temperatures, pressures,

TABLE 9.17.10 Minimum Oxygen Pressure Required to Support Self-Sustained Combustion of Approximately 6 in. (15 cm) Long, 0.125 in. (0.32 cm) Diameter Rods Ignited at the Bottom

Material	Threshold Absolute Pressure		*Next Lower Absolute Pressure Tested, psi*
	MPa	*psi*	
Silver (commercially pure)	>68.9[a]	>10,000	—
Monel K-500	>68.9	>10,000	—
Inconel MA754	>68.9	>10,000	—
Monel 400	>68.9	>10,000	—
Brass 360 CDA	>68.9	>10,000	—
Copper beryllium	>68.9	>10,000	—
Nickel 200	>55.2	>8000	—
Copper 102	>55.2	>8000	—
Red brass	>48.3	>7000	—
Tin bronze	>48.3	>7000	—
Yellow brass	>48.3	>7000	—
Haynes 188	34.5	5000	3000
Haynes 242	34.5	5000	3000
Hastelloy C22	34.5	5000	1000
Hastelloy C276	20.7	3000	1000
Inconel 600	20.7	2500	1000
Stellite 6	20.7	2500	1000
Inconel 625	20.7	2500	1000
440C Stainless steel	17.2	2500	1000
MP 35N	13.8	2000	1500
Elgiloy	13.8	2000	1500
Udimet 700	6.9	1000	500
Haynes G3	6.9	1000	500
Inconel 718	6.9	1000	750
Waspaloy	6.9	1000	500
Invar 36	≤6.9[b]	≤1000	none
304 Stainless steel	6.9	1000	500
Colmonoy	6.9	1000	500
17-4 PH	6.9	1000	500
303 Stainless steel	≤6.9	≤1000	none
321 Stainless steel	6.9	1000	500
Lead (commercially pure)	≤5.2[b]	≤750	none
Beryllium (commercially pure)	4.1	600	500
316 Stainless steel	3.5	250	100
Carbon steel A302B	≤3.5	≤500	none
Ductile cast iron	≤3.5	≤500	none
Nitronic 60	≤3.5	≤500	none
9% Nickel steel	≤3.5	≤500	none
Welda-lite 049-T851	2.1	300	250
Tin (commercially pure)	1.4	300	200
Aluminum-bronze	1.4	250	100
AMS 6278	1.4	200	100
Iron (commercially pure)	≤0.7	≤100	none
Aluminum 1100	≤0.7	≤100	none
AISI 9310	0.7	100	50
Aluminum 2219	0.2	25	20
Aluminum 5058	≤0.2	≤35	none
Aluminum (commercially pure)	≤0.17	≤50	none
Hafnium (commercially pure)	≤0.17	≤25	none
Zirconium	≤0.07	≤10	none
Titanium (commercially pure)	≤0.007	≤1	none
Ti-6A1-4V	≤0.007	≤1	none

[a]> Indicates that this was the highest pressure tested and the material did not support self-sustained combustion. The threshold pressure, if it exists, is greater than the stated value.

[b]≤ Indicates that no tests were conducted at lower pressures and, therefore, the threshold pressure is less than or equal to the stated value.

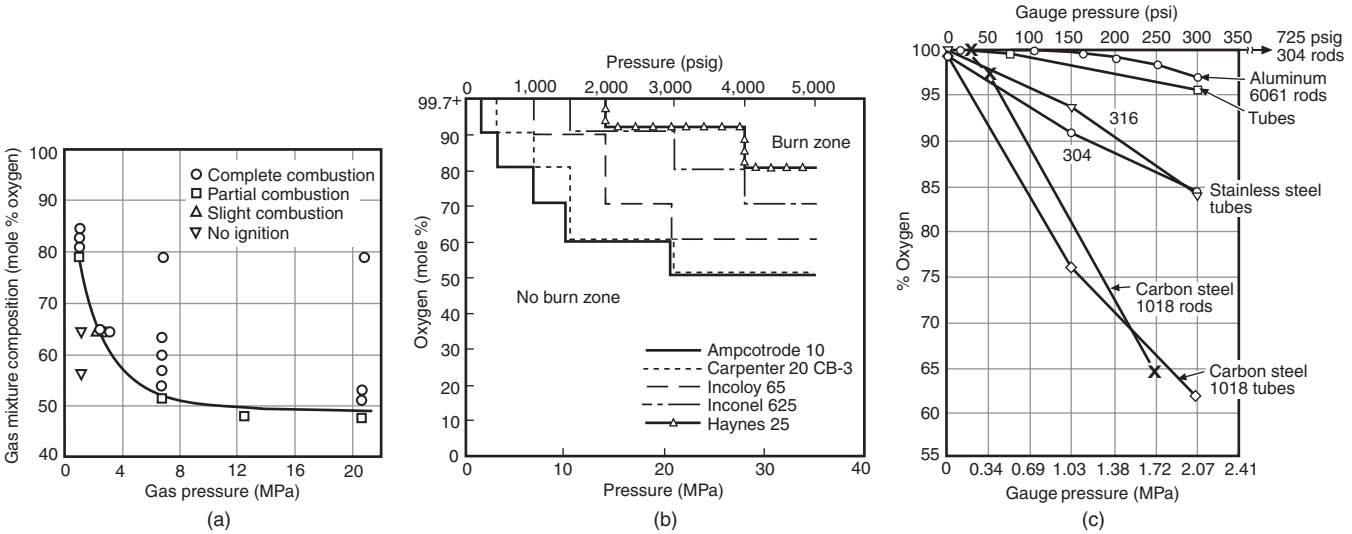

FIGURE 9.17.6 Oxygen Indices

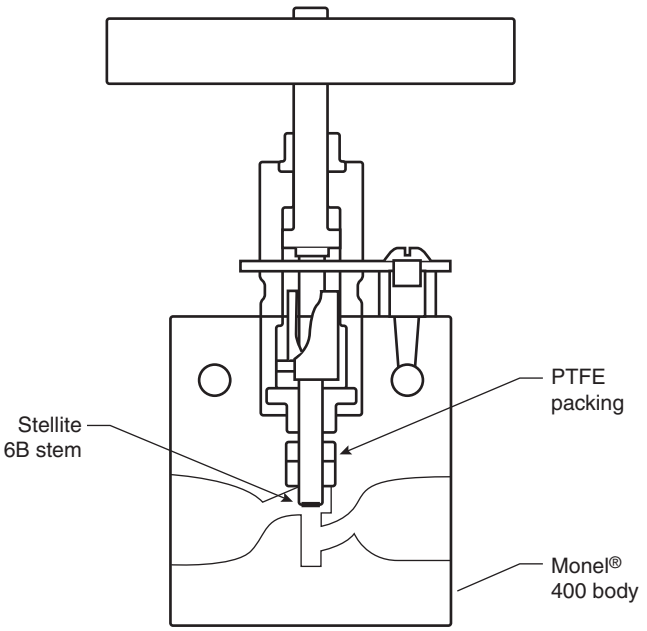

FIGURE 9.17.7 Oxygen Compatibility Assessment Example (Note: Monel® is a trademark of Special Metals Corporation)

flow rates, and contamination can contribute to the ignition and flammability risks for a system or component. Therefore, it is necessary to quantify each of these before analyzing a system or component.

Flammability Assessment. The configuration of a system or component significantly influences the ignitability and flammability of the materials of construction. Therefore, a cross-sectional diagram (e.g., machined cutaway) of the component and system flow schematic is important to reference when performing the oxygen compatibility assessment.

With few exceptions, materials become more flammable in oxygen as pressures increase. This includes metals, plastics, elastomers, lubricants, and contaminants. In fact, almost all polymer materials are flammable in 100 percent oxygen at atmospheric pressure. Several test methods have been developed to determine the relative flammability of materials. American Society for Testing and Materials (ASTM) Manual 36 and Standards G63 and G94 provide more information on determining the flammability of materials based on current data. Unfortunately, material flammability is affected by many factors and, therefore, absolute flammability thresholds are difficult to establish without testing the actual use configuration. As such, much of the oxygen compatibility assessment process focuses on the presence and probability of ignition mechanisms.

Ignition Mechanisms. The most effective way to analyze the ignition risks in a system is to methodically analyze the system for known ignition mechanisms. Ignition mechanisms occur inside and outside the oxygen-wetted portion of the component or system. For ignition mechanisms to be effective, certain elements must be present. These characteristic elements are unique for each ignition mechanism and each element is necessary for an ignition to occur. If any one characteristic is not present, the ignition mechanism will not occur. Conversely, if all the characteristic elements are present, ignition is possible.

Kindling Chain. The ability of a fire to propagate and burn through a component is called kindling chain. Kindling chain begins when a material is ignited, and the material's heat of combustion is sufficient to heat and ignite the surrounding materials leading to a burnthrough of the component. A burnthrough is considered unlikely when the materials are nonflammable or an unfavorable configuration is present. A burnthrough is considered likely when most materials (including the body) are flammable and a configuration favorable for burn propagation is present.

Component Information		Environment Information	
Component Type:	Manual Valve	**Max Pressure:**	2450 psig
Source:		**Max Temperature:**	115°F
Description:		**Cleanliness Spec:**	NASA JPR 5322.1
Model:		**Particulate Level:**	100
		NVR Level:	A

Schematic Reference(s)	Chemical	State	Percent
HV-7AO2-23	O2	Gas	100

Notes/Recommendations: Notes/Recommendations:

Material Flammability

Part	Category	Material	Flammability	Notes/Recommendations
Stem	Metal	Haynes 6B Stellite	F	Stellite 6B is flammable as a ⅛ in. rod in 100% oxygen at pressures above 2500 psia (ASTM STP 986, pp. 28–53). Note: the threshold pressure has not been found but is known to be between 1000 and 2500 psia.
Trim	Metal	Monel® 400	F	Thin cross sections of Monel® are flammable in 100% oxygen at ambient pressure (ASTM STP 1040, pp. 178–194).
Inner sleeve	Metal	Monel® 400	F	Thin cross sections of Monel® are flammable in 100% oxygen at ambient pressure (ASTM STP 1040, pp. 178–194).
Packing	Soft good	PTFE	F	PTFE is flammable in 100% oxygen at ambient pressure (ASTM STP 812, pp. 56–67).
Body	Metal	Monel® 400	N	Monel® is nonflammable as a ⅛ in. rod in 100% oxygen at pressures up to 10,000 psia (ASTM STP 1040, pp. 54–75).

Ignition Hazard

Hazard Type	Ignition Hazard	Notes/Recommendations
Flow friction	1	In this component, the seals are well-supported and unlikely to be damaged. However, the pressure is high. Therefore ignition by flow friction is considered remotely possible. It is recommended to promptly repair leaks or to replace components that persistently leak.
Frictional heating	0	Friction is present as the stem moves inside the housing. However, the frictional forces are low due to low side loads and the forces needed to produce ignition are not present. Therefore, ignition due to frictional heating is considered not possible.
Particle impact	0	High velocities will exist in this component at the stem/seat opening. The Monel® body is nonflammable; however, the Stellite stem is flammable in these conditions. This valve is located downstream of a 20 micron filter, which limits the size and amount of particles that may enter this valve. In addition, any impacts on the stem would be at oblique angles. Therefore, ignition due to particle impact is considered not possible.
Rapid pressurization	0	This valve has a metal-to-meal seat, the soft goods are well protected, and this component is not the only dead end.

Reaction Effect

Reaction Effect	Notes/Recommendations
A	There is a credible ignition mechanism present. However, there is no kindling chain present to cause component burnthrough since the body material is nonflammable. Therefore, reaction effect is considered negligible.

History of Use

History of Use	Notes/Recommendations
+	Similar components have a successful history of use at WSTF.

FIGURE 9.17.8 Oxygen Compatibility Assessment Example (Note: Monel® is a trademark of Special Metals Corporation)

Reaction Effect. As stated earlier, the effects of an oxygen system can be very severe. The effects of a fire on personnel, mission, and system objectives are assessed by determining the reaction effect. This value is primarily assigned based on a fire that breaches the pressure containment of a system.

History of Use. The history of use is determined by whether the component has experienced routine operation/cycling in similar or more severe conditions over an extended period of time. History of use is given as successful, negative, no known, or unknown.

Results. Documentation of the results of the compatibility assessment is recommended. An oxygen compatibility assessment report can facilitate the communication and dissemination of the results to interested parties and record the findings for future reference. The report should identify the components with the highest probability of fire. The oxygen compatibility assessment report may also recommend changes to design, materials, and procedures that mitigate the fire hazards identified.

Oxygen System Design

In addition to evaluating the fire safe characteristics of all materials involved in oxygen-enriched environments under the end-use performance conditions, oxygen service durability is evaluated by (1) accelerated time tests for deterioration and (2) high-energy tests for degradation. The acceptability of candidate materials for oxygen-enriched atmosphere systems applications is, in part, based on data developed by tests, such as:

1. ASTM G72, *Standard Test Method for Autogenous Ignition Temperature of Liquids and Solids in a High-Pressure Oxygen-Enriched Environment*
2. ASTM G74, *Standard Test Method for Ignition Sensitivity of Materials to Gaseous Fluid Impact*
3. ASTM G86, *Standard Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Ambient Liquid Oxygen and Pressurized Liquid and Gaseous Oxygen Environments*
4. ASTM G124, *Standard Test Method for Determining the Combustion Behavior of Metallic Materials in Oxygen-Enriched Atmospheres*
5. ASTM G125, *Standard Test Method for Measuring Liquid and Solid Material Fire Limits in Gaseous Oxidants*
6. ASTM G127, *Standard Guide for the Selection of Cleaning Agents for Oxygen Systems*

Other tests are available for the determination of flashpoints and fire points; upward/downward combustion propagation rates; calorific fuel values (heat of combustion); electrical wire insulation, coating, and accessory flammability; electrical overload and hot-wire ignition; odor; toxicity; and off-gassing.

Electrical equipment used in oxygen-enriched atmospheres is limited to that approved at the maximum anticipated oxygen pressure and concentration. Because most commonly used metals burn freely in oxygen-enriched atmospheres, electrical contacts that do not burn in normal atmospheres could burn away and initiate insulation fires in an oxygen-enriched atmosphere. Fire-resistive encapsulation, electrical mineral insulation, and noncombustible organometallic or ceramic (cermet) have been found to be effective for power cables.

The following firestopping design techniques can minimize ignition potential and fire spread for systems in oxygen-enriched atmospheres:

1. Avoid mass concentration of combustible materials near potential heat or ignition sources.
2. Use spatial separation and configuration to minimize or eliminate flame propagation paths.
3. Create "thermal damping" by judicious placement of fire-resistant heat-sink masses.
4. Install flashover barriers.
5. Create sealed packaging, for example, inerted compartmentations, fire-resistant encapsulation, and so on.
6. Install automatic fire monitoring, for example, infrared thermography, fire detectors, and so on.
7. Use hose line flashback arresters (consult Compressed Gas Association, Inc. [CGA], TB-3, *Hose Line Flashback Arresters*).

The design of systems that will be used in oxygen-enriched atmospheres should be undertaken only by experienced personnel. All materials that come into contact with oxygen-enriched atmospheres should be cleaned to remove all foreign material. To aid in the education of designers, ASTM Committee G4 has developed a standards technology training course, "Fire Hazards in Oxygen Systems," which is accompanied by a course textbook, *Fire Hazards in Oxygen Systems.* This course was developed by a committee whose members were from oxygen manufacturers, government, equipment suppliers, and users. The course is based on the experience of committee individuals and their respective organizations. Course content was derived from many of the following documents:

1. BS 4N 100-2, *Aerospace Series—"Specification for Aircraft Oxygen Systems and Equipment Part 2—Tests for the Compatibility of Materials in the Presence of Oxygen"—Autogenous Ignition Temperature Tests*
2. BS 4N 100-2, *Aerospace Series—"Specification for Aircraft Oxygen Systems and Equipment Part 2—Tests for the Compatibility of Materials in the Presence of Oxygen"—LOX Mechanical Impact*
3. CGA G-4.1, *Cleaning Equipment for Oxygen Service*
4. CGA G-4.4, *Industrial Practices for Gaseous Oxygen Transmission and Distribution Piping Systems*
5. CGA Video AV-8, "Characteristics and Safe Handling of Cryogenic Liquid Gaseous Oxygen"
6. CGA P-14, *Accident Prevention in Oxygen-Rich and Oxygen-Deficient Atmospheres*
7. CGA E-2, *Hose Line Check Valve Standards for Welding and Cutting*
8. DIN 51794, *Autogenous Ignition Temperature Tests*
9. European Industrial Gas Association 33/86/E, *Cleaning Equipment for Oxygen Service*
10. European Industrial Gas Association 5/75/E, *Code of Practice for Supply Equipment and Pipeline Distributing Non-Flammable Gases and Vacuum Services for Medical Purposes*

11. European Industrial Gas Association 6/77, *Oxygen-Fuel Gas Cutting Machine Safety*
12. European Industrial Gas Association 8/75/E, *Prevention of Accidents Arising from Enrichment or Deficiency of Oxygen in the Atmosphere*
13. European Industrial Gas Association 12/80/E, *Pipelines Distributing Gases and Vacuum Services to Medical Laboratories*
14. European Industrial Gas Association 10/81/E, *Reciprocating Compressors for Oxygen Service*
15. European Industrial Gas Association 27/82/E, *Turbo Compressors for Oxygen Service, Code of Practice*
16. EN 585, *Gas Welding Equipment—Pressure Regulators for Gas Cylinders Used in Welding, Cutting, and Allied Processes up to 200 Bar*
17. EN 849, *Transportable Gas Cylinders—Gas Cylinder Valves—Specification and Type Testing*
18. EN 961, *Gas Welding Equipment—Manifold Regulators Used in Welding, Cutting, and Allied Processes up to 200 Bar*
19. ISO 11114-3, *ISO Autogenous Ignition Test in Oxygen*
20. NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used*
21. NFPA 50, *Standard for Bulk Oxygen Systems at Consumer Sites*
22. NFPA 51, *Standard for the Design and Installation of Oxygen-Fuel Gas Systems for Welding, Cutting, and Allied Processes*
23. NFPA 99, *Standard for Health Care Facilities*
24. ASTM G63, *Standard Guide for Evaluating Nonmetallic Materials for Oxygen Service*
25. ASTM G88, *Standard Guide for Designing Systems for Oxygen Service*
26. ASTM G94, *Standard Guide for Evaluating Metals for Oxygen Service*
27. ASTM G128, *Guide for the Control of Hazards and Risks in Oxygen-Enriched Atmospheres*

FIRE EXTINGUISHMENT IN OXYGEN-ENRICHED ATMOSPHERES

Fire-extinguishing systems for use in oxygen-enriched atmospheres face many requirements in addition to those required for conventional systems because of ignition susceptibility, increased flame spread rate and burning intensity, and the flammability of normally flame-resistant materials. In general, these requirements cannot be satisfied by the simple extension of traditional extinguishment techniques. Special instruction and training of emergency personnel is required, as well as careful selection of extinguishing agents and systems.

Most common materials exhibit increased burning rates in oxygen-enriched atmospheres. To protect occupants and real property, fire extinguishants must (1) act rapidly to be effective, (2) be inherently nontoxic, and (3) not produce toxic or corrosive decomposition products.

Water has proved to be an effective extinguishant in oxygen-enriched atmospheres when applied in sufficient quantities. Water at a spray density of 1¼ gpm/ft^2 (50 L/min/m^2) applied for 2 minutes will extinguish cloth burning in 100 percent oxygen at atmospheric pressure. The application method of the water is all important. Water extinguishing systems must be carefully designed such that (1) all protected space is covered by the minimum spray density, and (2) water is distributed to a depth sufficient to extinguish stratified fires in nonhomogeneous materials, for example, layers of cloth in clothing.

The use of conventional halogenated extinguishants has been restricted by the Montreal Protocol, due to the ozone-depleting potential of the agents themselves as well as their decomposition products. Halon® 1301 (bromotrifluoromethane) has proved to be effective in extinguishing fires in oxygen-enriched atmospheres. See Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems."

Use of other extinguishants has been examined. Diluents, such as carbon dioxide and nitrogen, have been employed. Carbon dioxide systems have become widely used in unoccupied computer rooms. Note, however, their use must be restricted in occupied areas. No reliance should be placed on blankets made of Nomex®, wool, or fiberglass.

New technology in the use of high-expansion, water-based foams has resulted in improved extinguishing properties. However, the applicability of these agents to each particular candidate system must be carefully evaluated with regard to the available space, required time, and application methods. More data have become available on the use of low-expansion foam and dry chemical extinguishants in normal atmospheres, but their applicability in oxygen-enriched atmospheres is still unknown.

Rapid flame spread in oxygen-enriched atmospheres requires that fire-extinguishing systems be capable of fast automatic actuation by fire detectors, as well as by manual actuation. Fixed systems utilize an extinguishing agent acceptable for use on fires in oxygen-enriched atmospheres, and automatic actuation occurs in less than 1 second of the perception of detectable flame. In addition to the automatic fixed system in occupied areas, a manually operated water hose not less than ½ in. (13 mm) inside diameter, and with an effective nozzle pressure of not less than 50 psi (345 kPa) above the ambient pressure, is usually provided.

SUMMARY

Fire hazards that may be associated with oxygen-enriched atmospheres can be effectively reduced through understanding the risks and planning preventive measures. The degree of fire hazard varies with the concentration of oxygen present, the diluent gas, and the total pressure. An oxygen-enriched atmosphere may not necessarily produce an increased fire hazard. However, different concentrations and pressures may accelerate the combustion of materials, facilitate ignition, and in general increase the fire hazard. Oxygen system engineers and facility managers should consider the ignition and combustion of materials, design of systems for oxygen-enriched atmospheres, and fire extinguishment in oxygen-enriched atmospheres before designing oxygen systems or implementing new materials within an existing system. A systematic approach to evaluating the risks

was provided in this chapter. The oxygen compatibility assessment allows personnel to follow a step-by-step procedure that will determine areas of concern and, ultimately, prevent damages to a system or personal injuries. The intent of this chapter is to increase the reader's awareness of the special nature of oxygen-enriched atmospheres and to apply that awareness to the safe use and design of oxygen systems.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on oxygen-enriched atmospheres discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 51, *Standard for the Design and Installation of Oxygen–Fuel Gas Systems for Welding, Cutting, and Allied Processes*
NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres*
NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks*
NFPA 99, *Standard for Health Care Facilities*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids*
NFPA 491M, *Manual of Hazardous Chemical Reactions*

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SECTION 10

Building Services

L. Jeffrey Mattern

10.1 Emergency and Standby Power Supplies
10.2 Heating Systems and Appliances
10.3 Building Transportation Systems
10.4 Air-Conditioning and Ventilating Systems
10.5 Ventilation of Commercial Cooking Operations
10.6 Boiler Furnaces

All occupancy classes have at least some of the building services described in this section. With loss of these services, many operations would be forced to shut down. As a result, building services are critical to the continuity of the primary function of the business. The purpose of this section is to describe primary building services, highlight the hazards associated with a specific service, and provide a description of fire prevention and fire control concepts.

In some particularly critical operations, loss of power can cause significant damage to process equipment and in-process goods. Chapter 1, "Emergency and Standby Power Supplies," provides information on the components that, alone or in combination, form emergency and standby power systems.

Three chapters in the section cover equipment associated with heating and cooling systems. Chapter 2, "Heating Systems and Appliances," addresses topics such as fuel burners, ducts and pipes, chimneys and vents, chimney and vent connectors, and fireplaces and fireplace stoves. Chapter 4, "Air-Conditioning and Ventilating Systems," includes explanations of system types and operation, fresh air intakes, air filters and cleaners, fans and controls, and unit air conditioners, as well as techniques for restricting the spread of smoke and fire and energy conservation considerations. Chapter 6, "Boiler Furnaces," describes the combustion process, fuels, and oil- and gas-burning systems. It then discusses topics such as pulverized coal systems, fluidized bed combustion, boiler-furnace hazards, and small boilers.

Chapter 3, "Building Transportation Systems," examines the various building transportation systems—elevators, escalators, dumbwaiters, and moving walks—that transport people or materials vertically or horizontally in a building. The discussion is intended to complement NFPA *101®*, *Life Safety Code®*, and *NFPA 5000®*, *Building Construction and Safety Code®*, requirements that equipment for elevators and the like be installed in accordance with ASME A17.1, *Safety Code for Elevators and Escalators.*

Chapter 5, "Ventilation of Commercial Cooking Operations," discusses ventilation systems for commercial cooking equipment, particularly in the context of fire concerns with system operation design, system component design, and system maintenance.

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Chapter 1

Emergency and Standby Power Supplies

Revised by
Dan Chisholm, Sr.

Chapter Contents

Power Supply System Codes and Standards
Energy Sources
Engine-Driven Generator Power Systems
Other Considerations

Key Terms

alternate power supply, closed transition transfer switch, emergency power supply, prime mover, standby power supply, stored emergency power supply system, uninterrupted power supply, unit equipment

The Northeast blackout of 2003 and the hurricanes in 2005 dramatically demonstrate the need for a source of electric power independent of public electric utilities. Power interruptions occur due to natural or man-made causes. Natural causes include storms, floods, earthquakes, and the like; man-made causes are many, such as vehicles striking transformers or utility poles, equipment failure from one or more causes, and human operational error.

More generally, the electric utility industry's capacity margins have steadily declined in recent years, leaving less room to compensate for unexpected loads and events. Summer capacity margins shrank from one-fourth of capacity in the early 1980s to one-tenth in the late 1990s. Winter capacity margins shrank from one-third of capacity in the early 1980s to one-fourth in the late 1990s.[1]

The chapter provides information on the components that, alone or in combination, form emergency and standby power systems.

See Section 8, Chapter 10, "Stationary Combustion Engines and Fuel Cells," for details on safeguards for on-site fuels.

POWER SUPPLY SYSTEM CODES AND STANDARDS

NFPA 70, *National Electrical Code*®

NFPA 70, *National Electrical Code*® (NFPA 70 or *NEC*), recognizes two types of private power supply systems: emergency and standby. The latter is further subdivided into legally required standby systems and optional standby systems. Requirements for the proper installation of any of these systems are found in Articles 700, 701, and 702 of the *NEC*.

Emergency, or alternate, power systems are systems supplying power for illumination; elevators, critical heating, ventilation, and air conditioning (HVAC); fire pumps and alarms; public address systems; and other loads essential to the safety of life and property when public utility power is unavailable and where required by local, state, or federal codes (Figure 10.1.1).

Legally required standby systems are provided as an alternate source to the normal power source (e.g., a public utility), where an electric power interruption to a continuous industrial process, or institution, could endanger lives or hamper rescue or fire-fighting operations. These systems are also installed for heating, refrigeration, and ventilation systems, or to serve other electrical loads that are specified by municipal, state, federal, or other codes or by any governmental agency having jurisdiction.

Optional standby systems are intended to protect private business or property where life safety does not depend on the performance of the system. Some examples of loads that are connected to these systems are heating and cooling equipment, data processing, and communications systems.

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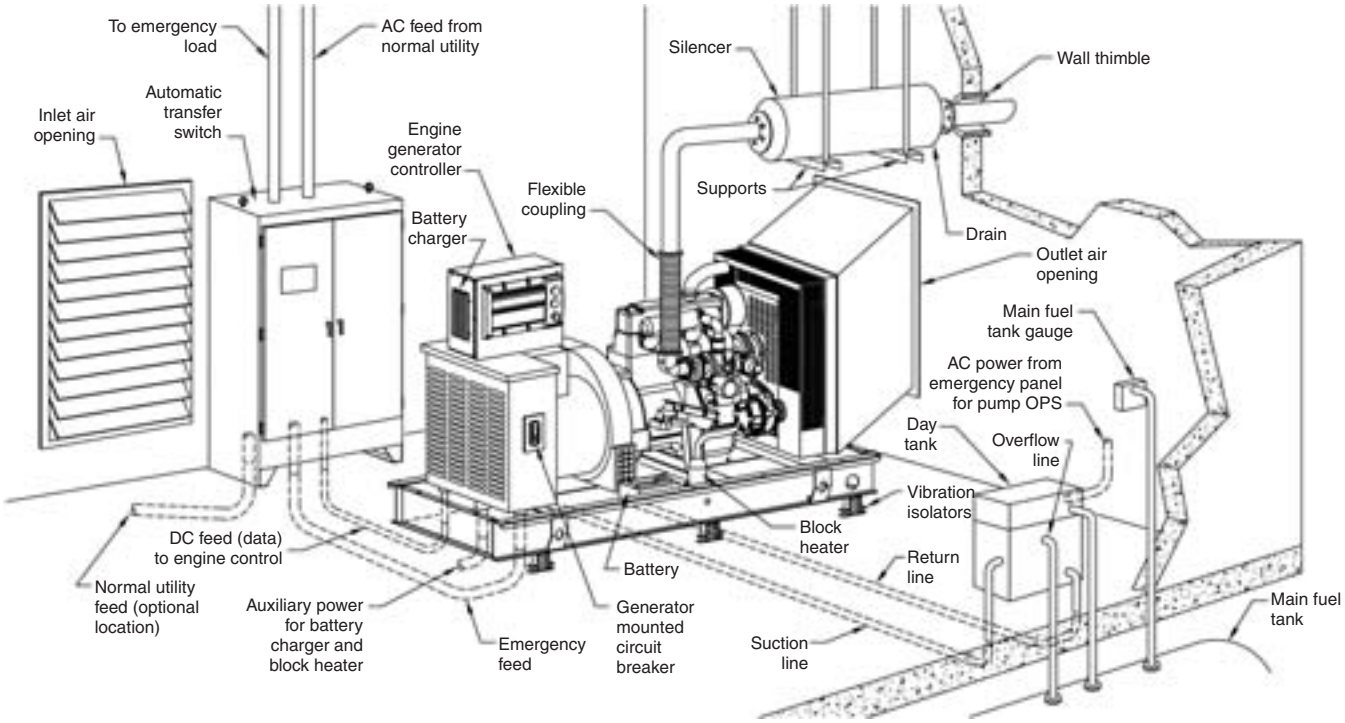

FIGURE 10.1.1 Typical Generator Installation Used to Supply Emergency Power (Source: Courtesy of Generac Power Systems)

Optional standby systems, selected by the owner, are also used on farms and in residences to supply loads during a power failure.

The loads to be served by the emergency or standby power system can be classified as critical and noncritical. Critical loads are loads that must be served within a relatively short time period after the power is needed in order to preserve life or property. Noncritical loads are all other loads that are permitted to be connected to the system.

In hospitals, alternate power source wiring and equipment are termed an Essential Electrical Distribution System. One or more on-site generators must be used to supply this system. The Essential Electrical Distribution System comprises an Emergency System and an Equipment System. The Emergency System is further divided into the Life Safety Branch and the Critical Branch. (See NFPA 99, *Standard for Health Care Facilities,* Chapter 4, "Electrical Systems.")

NFPA 110, *Standard for Emergency and Standby Power Systems*

Several terms overlap each other, for example, alternate power systems, standby power systems, legally required standby systems, alternate power sources, and so on. The terms power supply, power system, and power source are also used somewhat interchangeably. NFPA 110 places all such systems into categories defined in terms of type, class, and level, rather than using the aforementioned terms. *Type* defines the maximum allowable time that the load is without acceptable electrical power. *Class* defines the minimum allowable time that the alternate source has the capability of providing its rated load without being refueled. *Level* defines the equipment performance stringency requirements.

ENERGY SOURCES

NFPA 70 recognizes five electric sources for emergency power supplies:

1. Storage batteries
2. Generator set(s)
3. Uninterruptible power supplies
4. A separate service
5. Unit equipment

Item 4 is not recognized as an acceptable emergency power source for those occupancies covered by NFPA *101®, Life Safety Code®*. To cope with emergencies, a plaque or directory is required at each electric power source. Each sign must indicate where all other sources are located.

Energy sources for emergency and standby power supplies are generally one of the following: liquid petroleum products, liquefied petroleum gas, natural or synthetic combustible gas, or batteries. Other sources, for example, steam, rotating mass (flywheel), and compressed noncombustible gas, have limitations that restrict their use for these purposes.

On-site storage of the energy source to supply power for the duration of the need for emergency and standby power is an important consideration, especially in areas subject to severe environmental disturbances, such as storms, earthquakes, flood-

ing, and so on. As previously noted, Section 8, Chapter 10, "Stationary Combustion Engines and Fuel Cells," provides details on safeguards for on-site fuels.

Batteries

Batteries, in general, are the most dependable energy source for emergency and standby power and are primarily used for emergency lighting, either as a central battery system or as a self-contained lighting assembly defined as "unit equipment" in NFPA 70. They are also used with uninterrupted power supplies (UPS), a system that automatically provides power, without delay or transients, during a period when the normal power source is incapable of performing acceptably. A single battery or a group of batteries is limited in the amount of usable energy it is capable of delivering before becoming discharged; hence, backup to the battery source is often supplied in the form of other on-site emergency or standby power supplies.

Batteries used for this service must have sufficient capacity to supply the total emergency load for at least 1½ hours. During this time the voltage cannot drop below 87.5 percent of normal. They are usually either lead-acid or nickel-cadmium type. The lead-acid battery is less costly and requires less space for the same capacity; but the nickel-cadmium type has a longer life, more rugged construction, and requires less maintenance. Sealed batteries, that is, those not requiring periodic replacement of water, are favored for use with self-contained lighting assemblies.

After use, batteries must be recharged to have power available again when needed. A self-contained lighting assembly is normally provided with an automatic recharger and a sensing relay for determining normal power supply loss to the normal illuminating means. Consideration should be given to having the battery recharger connected to the emergency or standby power source (when such a source is installed) on loss of normal power where evacuation of the installation is not expected during a normal power outage or where a large number of people could be stranded in a high-rise building for a duration longer than the expected usual discharge time of the battery without recharging. Central battery systems and UPS systems are normally provided with more complex battery rechargers, such as dual-rate, regulated, and so on, to maximize battery life and minimize gassing.

Proper location of batteries with adequate ventilation and liquid electrolyte containment are important environmental considerations. The gaseous products of electrolysis (hydrogen and oxygen) can be a fire hazard.

Uninterrupted Power Supplies and Other Stored Energy Power Supplies

A true UPS system providing continuous and transient-free, single-phase or polyphase ac power is used to supply such critical load applications as sensitive electronic and computer equipment for data processing, life support, communications, and control equipment. Such a system, on loss of normal power, continues to supply power without waveform distortion, and the load is totally unaware of normal power loss.

There are applications where such purity is not required and either waveform distortion (transient or phase displacement of waveform) or a brief lapse of power to the load, or both, is acceptable. Economic considerations will bear upon the type of stored-energy power supply used.

Batteries, combined with rectifiers and solid-state inverters (converters of dc power to ac power), provide power to the majority of UPS systems in use. Such systems are known as static UPS systems. This system rectifies the incoming ac power to dc power, then inverts the dc power back to ac power for delivery to the load. A battery is permanently connected between the rectifier and inverter (on the dc bus) and takes over as the power source immediately upon loss of the incoming ac power. On return of the incoming ac power, the load is supplied by the incoming ac power and the batteries are recharged. The inverter serves to determine the characteristics of the ac power to the load, so that any voltage or frequency variations or transients on the incoming power are absent from the load. The rectifier is continuously sized to the capacity of the load, plus that required for battery recharging, while the inverter is continuously sized to the capacity of the load.

Other UPS systems are variations of a rotating generator driven by various drivers (engines, ac and dc motors), with or without a flywheel.

A Stored Emergency Power Supply System (SEPSS), similar to the UPS system, but economically more attractive, is one in which the normal ac power is fed through to the load with a static transfer switch transferring the load to an inverter supplied by a battery on loss of the normal ac power. The inverter receives a continuous synchronizing signal from the normal ac power, so that, on loss of this power, the inverter is still approximately in phase with the power just lost. This, coupled with a transfer time of a few milliseconds, permits the load to be without power for only a brief period and without serious transients occurring on application of inverter power. Note, however, that the inverter needs only to be sized intermittently for the load power and that the rectifier is sized only to accommodate the recharging power of the battery.

ENGINE-DRIVEN GENERATOR POWER SYSTEMS

An engine-driven generator power system usually consists of a prime mover, a governor, a generator coupled thereto (either direct or geared), transfer equipment, and distribution and protective equipment (Figure 10.1.2). Such a system is supplied for either standby or emergency service and is most common where such power is required for a considerable period of time.

Prime Mover

The prime mover can be a reciprocating engine fueled by gasoline, diesel fuel, or natural or synthetic gas. Gas turbines are also used, particularly for larger power outputs. Gasoline and natural and synthetic gas engines are less costly than diesel engines but have disadvantages that are considerable. For example, the gasoline engine and its fuel storage are more

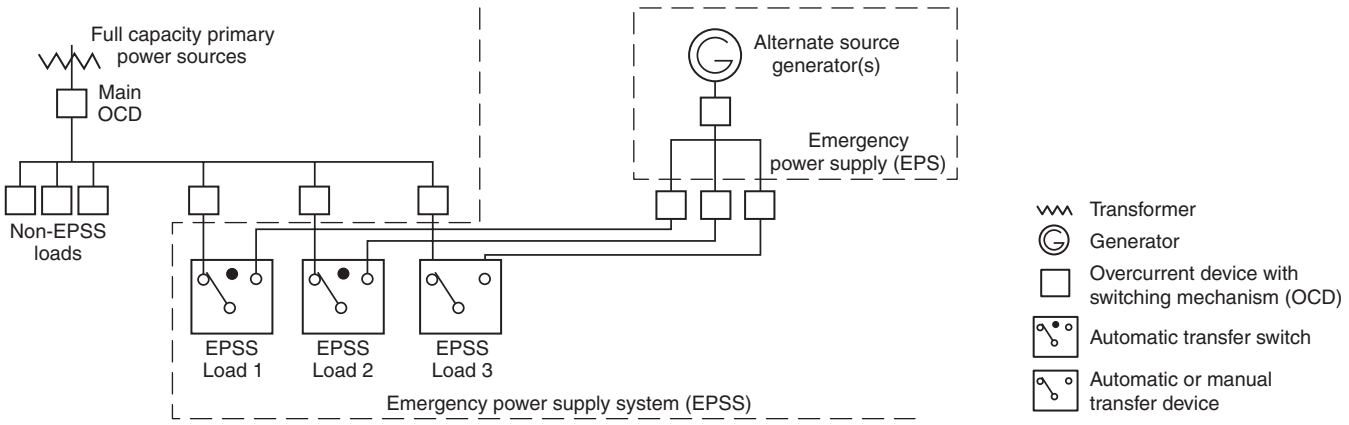

FIGURE 10.1.2 Typical Rotating Emergency Power Supply System (EPSS) (Source: NFPA 110, *Standard for Emergency and Standby Power Systems,* 2005, Figure B.1a)

susceptible to fire and explosion. Also, the natural gas engine usually obtains its energy supply from an off-site gas utility, a supply that might not be available at the same time that the normal power supply is unavailable (for this reason, an on-site fuel supply might be required by the authority having jurisdiction).

Gas turbines are much smaller than reciprocating engines of the same output and operate at much higher speeds. They require no cooling-water connection and burn natural gas, kerosene, diesel fuel, or fuel oil. They are, however, quite inefficient and are slow in coming up to full speed (more than 10 seconds).

The prime mover and its associated auxiliary equipment are required by the *NEC* to have the following characteristics for emergency service:

1. The prime mover must start automatically and come up to full speed and power capability within 10 seconds of demand.
2. A minimum on-site fuel supply permitting full engine-generator output for 2 hours or more must be available.
3. When water-cooled engines are used (generally above 50 kW), the municipal water supply cannot be used for cooling (i.e., municipal water supply input, waste to drain output).
4. When a battery is used for engine starting, the battery must have an automatic charging means independent of the prime mover.
5. When the prime mover requires more than 10 seconds to come up to full speed and power capability, an auxiliary power supply can supply the required power (within 10 seconds) to the load, provided it can continue to do so until the load is assumed by the prime mover.

Governor

A governor maintains an approximately constant speed of the prime mover throughout the full power output range by varying the fuel input to the prime mover. Governors can be mechanical, electrical, hydraulic, or a combination thereof.

Generator

Generators convert the mechanical shaft output of the prime mover into the electrical power for use by the loads connected thereto. The performance of the generator and its voltage regulator under varying load conditions must be considered in determining its suitability. The output voltage of a generator drops suddenly when a load is applied and rises suddenly when a load is removed. At present, generators larger than a few kilowatts in size have automatic voltage regulators that quickly bring the voltage back to the specified value. The initial voltage drop is important because if the drop is excessive, even for a few cycles, electromagnetic components—for example, relays and motor starters—might drop out and might or might not, depending on circuitry, reclose when the voltage is restored, or they might cycle open and closed repeatedly, causing equipment damage.

Voltage rise (overshoot) on load removal can cause damage to equipment remaining connected. The initial voltage drop is not usually of concern when the loads being connected are within the ratings of the generator. However, it is customary to exceed the rated current of the generator by two to three times during motor starting only. The initial voltage dip during these current overloads is, therefore, one of the limiting factors in sizing the generator. The performance of the generator when subjected to a short-circuit or heavy overload condition is also a matter of consideration. Under this condition, the generator current output decays with time, a characteristic inherent in the generator, so that, in a relatively short time, the current lessens to a magnitude of only several times its rating. If the decay rate is too rapid, it might not be possible to have selective tripping of overcurrent devices in the current loop.

Transfer Equipment

Electromechanical automatic transfer switches are normally used to transfer selected loads to the engine generator power supply when the normal source fails. The transfer switch senses normal power (usually all phases) and, on loss of normal power, automatically signals the prime mover to start. A brief time delay

is generally built into the transfer switch logic to delay the signal so that a momentary normal power interruption or flicker does not activate the prime mover (NFPA 110, 8.4.5(1)(a) requires a minimum 1-second delay for diesel engines). The transfer switch also senses the voltage and frequency of the generator output and, when these reach acceptable levels, either immediately thereafter or after a time delay (for selective load pickup), the switch transfers the load to the engine generator output. On restoration of the normal power supply to acceptable levels, the transfer switch might transfer the load automatically (usually after a time delay to allow for permanent normal power restoration—NFPA 110, 8.4.5(3) requires a minimum of 5 minutes) back to the normal source, or manual transfer of the load might be required, the choice having been originally made by the characteristics of the load. Transfer switches, in general, immediately retransfer the load back to the normal source (if available and at an acceptable level) should the emergency source fail. Maintenance of a transfer switch might require deactivation of loads connected to the switch while the maintenance is being performed. Some loads are so critical that such deactivation is unacceptable. In such cases, the transfer switch is furnished with an isolation bypass switch, making it possible for the load to be served by the normal or emergency source while the automatic transfer switch is being serviced.

Distribution and Protective Equipment

Distribution of the available auxiliary power (emergency or standby) concerns itself with the loads served, the order of priority, and the total loading of the engine generator set. Protection concerns itself primarily with equipment protection and with continued availability of power to unfaulted loads on a system electrical fault.

Engine generator set loading prioritizes the need for power and the magnitude of the various loads. Critical loads must be served first, followed by noncritical motor loads. A motor load produces large power and kVA load on first starting, which influences momentary voltage and frequency output of the generator, causing a decrease in each. Step loading of the engine generator set is accomplished by using multiple transfer switches, timed to operate in sequence in the order of priority. Other more complex arrangements with programmable controllers or computers are sometimes used.

Permissible loading of the engine generator set during periods of loss of normal power is governed by codes and standards. Generally, during such periods, it is permissible to use available power not being used for critical loads to power noncritical loads and to resort to load-shedding techniques to pick up the critical loads when needed.

Protection, although generally in accordance with established procedures for the normal power supply, must take into account the usual situation of limited power availability of the engine generator set versus the larger power availability of the normal source. As indicated earlier, generators, under short-circuit or heavy overload conditions, have collapsing outputs such that the sustained total current output of the generator drops to a magnitude comparable to its full-load value. Rapid clearing of the fault is essential (prior to the drop in current to its sustained value); otherwise the protective device will not see the short-circuit condition. Rapid fault clearing is also important to enable the generator to reestablish itself (voltage restoration) and continue to serve the loads still connected to it.

Closed Transition Transfer Switches (CTTS) are now being specified by design engineers to mitigate problems during scheduled testing of the EPSS, both during the split second of transferring to emergency power and the retransferring back to normal power. During a normal power outage, the CTTS cannot prevent the short duration of power loss while the generator is coming up to speed, but can prevent power "blips" on the return to normal power. Soft-load transfer switches can prevent frequency "sags" during the planned transfer of loads to the alternate or normal power sources.

OTHER CONSIDERATIONS

Peak Shaving

Multiple-engine generator sets are sometimes used to supply emergency and standby power. Such sets are usually operated in parallel, with load-shedding provisions incorporated should one of the sets fail. Because of the sizable monetary investment in an emergency or standby power system, some installations use the engine generator set in conjunction with the normal power supply for peak-shaving purposes. Peak shaving is the transfer of some loads from the normal power source to the auxiliary power source during periods of maximum loading of the normal power source. The economic benefit of peak shaving is a result of the utility rate structure. If a user can keep the ratio of maximum (or peak) power usage to average power usage low, then the utility charge is lessened. By transferring selected loads to the engine generator set during periods of peak power usage, the aforementioned ratio is lowered.

Motor-Starting Methods

Motor-starting methods for large motors are another significant consideration. Two matters of concern are the power required from the prime mover and the kVA required from the generator. Selection of the proper type of reduced voltage starting is equally important. Open-transition reduced voltage starting is not a recommended method, nor is primary resistance reduced voltage starting. Autotransformer starting and closed-transition wye-delta starting are generally preferred to other methods.

SUMMARY

Electrical power interruptions can occur from natural causes, such as storms, floods, and earthquakes, or from man-made causes, such as human operational errors or accidents to, or failure of, equipment. Such power interruptions as well as the rising threat of electrical power shortages and associated blackouts or brownouts point to the need for an independent source of power.

This chapter examined the components of emergency standby power systems, including batteries, uninterruptible power supplies and other stored energy power supplies, and

engine-driven generator power systems—the latter consisting of a prime mover, a governor, a generator, transfer equipment, and distribution and protective equipment. The chapter also discussed two other considerations—that is, peak shaving, whereby some loads from the normal power source are transferred to the auxiliary power source during periods of maximum loading of the former, and motor-starting methods.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on emergency and standby power supplies discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 37, *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines*
NFPA 70, *National Electrical Code®*
NFPA 99, *Standard for Health Care Facilities*
NFPA *101®*, *Life Safety Code®*
NFPA 110, *Standard for Emergency and Standby Power Systems*
NFPA 111, *Standard on Stored Electrical Energy Emergency and Standby Power Systems*

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"Maintenance and Testing of Emergency Power Supply Systems for Healthcare Facilities," MGI Systems, Winter Park, FL, 2007.

Chapter 2

Heating Systems and Appliances

Peter J. Gore Willse

Chapter Contents

Fuels and Methods of Firing
Controls for Fuel Burners
Heating Appliances and Their Applications
Distribution of Heat by Ducts and Pipes
Installation of Heating Appliances
Chimney and Vent Connectors
Vents
Chimneys
Fireplaces and Fireplace Stoves

Key Terms

appliance (fuel burning), appliance (heat producing), appliance (heating and cooking), chimney, coal fuel, creosote, fluidized bed, fuel, fuel gas, fuel oil, room heater, vents

Heat-producing appliances and associated equipment are among the most prevalent causes of fire because they operate at temperatures above the ignition temperature of many common materials. In addition, combustion-type appliances can sometimes involve the hazards of an accumulated combustible mixture, the discharge of unburned fuel, and possible exposure of fuel to ignition sources.

Additional information about heating systems and appliances can be found in Section 2, Chapter 1, "Physics and Chemistry of Fire"; Section 6, Chapter 10, "Gases"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 7, Chapter 3, "Storage of Gases"; Section 8, Chapter 8, "Industrial and Commercial Heat Utilization Equipment"; Section 8, Chapter 13, "Electrical Systems and Appliances"; Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems"; and Section 10, Chapter 6, "Boiler Furnaces."

For additional information on carbon monoxide, see Section 6, Chapter 2, "Combustion Products and Their Effects on Life Safety." Also see Section 14, Chapter 9, "Carbon Monoxide Detection in Residential Occupancies."

For additional information on CFBs, see Section 10, Chapter 6, "Boiler Furnaces."

FUELS AND METHODS OF FIRING

Combustion can be defined as a chemical reaction between a fuel and oxygen with evolution of heat and light. In a fuel-burning, heat-producing device, this reaction needs to be continuous so a balance will be established between the rate at which oxygen, or air, and fuel are supplied and the rate at which heat and the products of combustion are removed. Complete combustion (also known as stoichiometric combustion) takes place when all of the fuel is oxidized by the air supplied to it. Air left over after complete oxidation is called excess air. If only enough air is supplied for complete combustion, perfect combustion can theoretically result under suitable conditions. Because perfect combustion is impractical in most heat-producing appliances, the appliances operate with some excess air.

Air for combustion is supplied in two ways: (1) primary air is introduced through or with the fuel, and (2) secondary air is supplied to the combustion zone. In some cases, all of the air supplied is primary air, whereas in others only part is primary air and the balance is secondary air.

Incomplete combustion in a fuel-burning device can produce hazardous carbon monoxide. This condition indicates poor efficiency, because the fuel is not completely oxidized, and the total heating value of the fuel is not obtained. Incomplete combustion usually results from inadequate air supply, insufficient mixing of air and gases, or a temperature too low to produce or sustain combustion.

Solid Fuel—Coal

Coal is one of the principal solid fuels used in heat-producing appliances. There are a number of types of coal, each having widely different characteristics. In many cases, there is no distinct line

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of demarcation between them, and the qualities of one type can overlap those of another. Pulverized coal systems, however, require the use of coals having characteristics within the specific range of the coal-handling and coal-burning equipment.

The seven principal types of coal used in heat-producing appliances follow.

Anthracite. Anthracite is a clean, dense, hard coal. It burns with a minimum of smoke and has a minimum dust hazard during handling.

Semianthracite. Semianthracite coal has a higher volatile content than anthracite but not as hard.

Bituminous. This type includes many types of coal with different properties, depending on where they are mined. It gives off considerable smoke and soot if improperly fired. Bituminous coal can be subject to spontaneous heating under some storage conditions and has a dust hazard during handling.

Semibituminous. This dusty soft coal tends to break up. It can be subject to spontaneous heating under some storage conditions. It normally produces less smoke than bituminous coal.

Subbituminous. Subbituminous coal is subject to spontaneous heating under some storage conditions. It burns with very little smoke or soot.

Lignite. This coal has a woody structure and normally a high moisture content. It is subject to spontaneous heating under some storage conditions. It burns with little smoke or soot.

Coke. Coke is a product of the destructive distillation of coal. The type of coke produced is determined by the coal used and the temperatures and time of distillation. Petroleum coke is produced from the destructive distillation of oil.

Combustion of Coal

When coal is burned in a firebox, oxygen in the air passing through the grate (primary air) unites with the carbon in the lower portion of the fuel bed, called the oxidation zone, to form carbon dioxide. Some of this carbon dioxide is then reduced to carbon monoxide in the upper part of the fuel bed, called the reduction zone. Gases liberated from the fuel bed are carbon monoxide, carbon dioxide, nitrogen, and some oxygen. Oxygen from the air admitted over the fuel bed (secondary air) combines with some of the carbon monoxide to form carbon dioxide. When fresh coal is applied to the fire, moisture is driven off as steam and the hydrocarbon gases are distilled, combined with oxygen, and burned above the grate in what is called the distillation zone.

Methods of Firing Coal

Coal is fired either manually or automatically by stokers, pulverized fluidized bed coal burners, or in fluidized bed boilers.

Hand Firing. There are many acceptable hand-firing methods. With highly volatile coals, the objective is to leave a suitable bed of glowing fuel to ignite the gases as they are driven off from the fresh coal charge; otherwise the gas might accumulate and explode. Draft regulation is the only automatic feature of a hand-fired furnace. Draft can be controlled by a room thermostat, steam pressure, or water temperature. But, as with any hand-fired solid fuel, the fire is continuous, and overtemperature conditions are difficult to control unless the fire is continually attended.

Mechanical Stokers. Mechanical stokers are classified according to their coal burning capacities and range from those that handle 10 lb (4.5 kg) per hour to those handling over 1200 lb (540 kg) per hour. A stoker feeds fuel to the combustion chamber and usually supplies air for combustion under automatic control. There are four basic types of stokers: (1) underfed, (2) overfed, (3) traveling and chain grate, and (4) spreader, with fired grate or continuous ash discharge.

Underfed stokers move the coal by screw conveyor or rams (Figure 10.2.1). Overfed stokers feed the coal pneumatically or by rotors. Spreader stokers feed coal by rotors or paddles and discharge onto stationary or traveling grates. Stokers feed from hoppers or directly from bins. They are equipped with fueling controls that either change the firing rate or stop the fuel altogether. Some stokers are equipped with a control that will stop the feeding of fuel if the fire goes out.

Pulverized Coal Systems. Pulverized coal systems are of two general types: (1) the direct-fired, or unit, system, and (2) the storage, or bin, system. In the direct-fired system, raw coal is fed directly to a pulverizer where it is pulverized, mixed with air, and blown to the burners. In the storage system, coal is delivered to a raw fuel bin and then passed to a pulverizer where it is reduced to a powder and dried for storage in a pulverized fuel bin before delivery to the furnace.

Fluidized Bed. There are two major types of fluidized bed boilers—atmospheric and pressurized. In either case, fuel such as coal, wood, agricultural waste, industrial waste, or municipal waste, can be burned. In the case of coal, it is crushed into particles and injected inside the unit (Figure 10.2.2). It is suspended on upward-blowing jets of air much like a ping pong ball bobbing on top of the exhaust of a wood shop vacuum cleaner. The

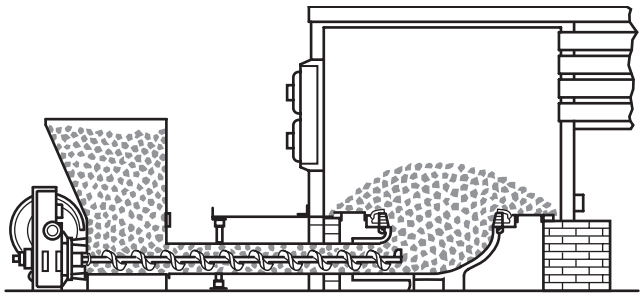


FIGURE 10.2.1 One Type of Underfed Coal Stoker

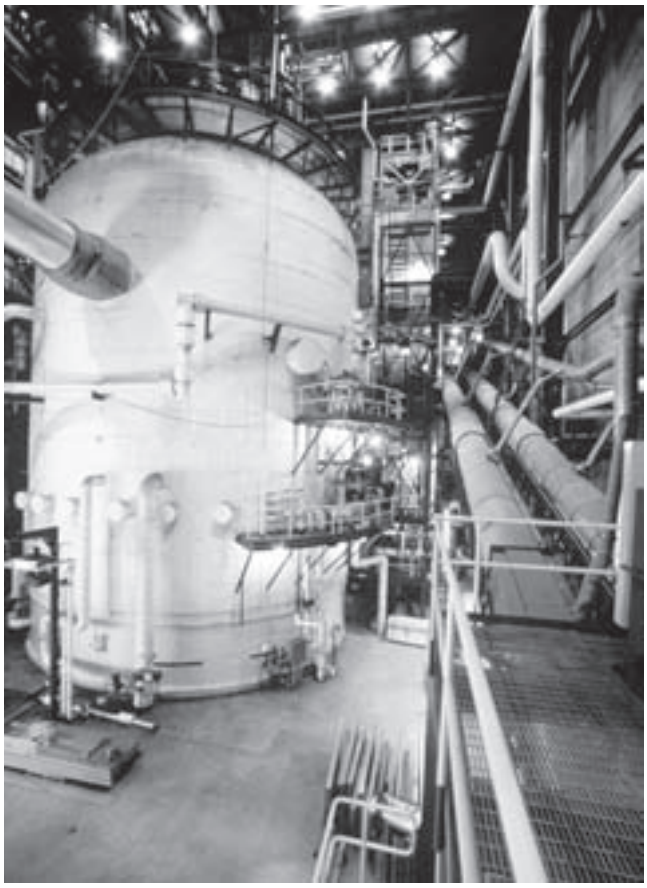


FIGURE 10.2.2 Fluidized Bed Boiler (Courtesy of the U.S. Department of Energy)

floating coal—called the "bed"—spreads out over the upward-blowing air and looks like it is bubbling.

First used in the early 1980s, today's units have become more efficient. The first units operated at temperature of approximately 3000°F (1645°C); units today operate at a temperature of approximately 1400°F (760°C). Fluidized bed boilers that fire coal have limestone injected with the coal. When the coal burns, it gives off sulfur. The limestone gas in the boiler absorbs the sulfur and a chemical reaction takes place to turn the sulfur and limestone gas into calcium sulfate, which solidifies into a powder that can be removed from the boiler. Calcium sulfate is used to produce wallboard for houses.

Solid Fuels—Miscellaneous

Miscellaneous solid fuels include wood, logs, scrap lumber, and wood waste from lumber and paper mills (sawdust, shavings, bark); hogged fuel (sawmill refuse run through a disintegrator or "hog" to form uniform chips or shreds); charcoal; briquets; peat; bagasse; sugar cane; and a host of other combustibles such as tanbark, wet bark, straw, city refuse, paper, and so on. The methods of firing these fuels vary considerably with the type of device and the nature of the particular fuel.

Since the mid-1970s, the most prevalent form of solid fuel usage has been in residential cordwood stoves, furnaces, and fireplaces. Concerns about price and availability of conventional residential energy sources sparked a surge in installation and use of such devices. Although the "crisis" attitude toward conventional energy has eased, solid fuel appliances remain a popular alternative source of supplemental heating.

The rise in installation of wood-burning appliances was accompanied by a dramatic increase in heating-related home fires, especially in the early 1980s. The severity of this problem has also decreased since then, due to decreased usage of installed appliances and better installation, use, and maintenance practices. The hazards associated with wood-burning devices are discussed in detail in a later section of this chapter.

An evolution from the wood-burning stove was the introduction of pellet fuel–burning appliances in the mid- to late 1980s. Processed solid fuels of various types have long been used in commercial and industrial operations. Pellet fuel–burning appliances are relatively small-capacity residential appliances. Pellet fuel is produced by milling wood waste to fine particles, then extruding under high pressure to form pellets about ¼ in. (6 mm) in diameter by ½ to 1 in. (12 to 25 mm) long. The fuel is placed in the hopper of a pellet fuel–burning appliance, from where it is metered to a burn pot, depending on heat demand. Pellet fuel–burning appliances thus bring a degree of automatic operation to residential solid fuel usage.

Combustion of wood takes place in three stages. Unless the wood has been purposely kiln-dried before use, the first stage is the driving-off of moisture. The second stage is destructive distillation such as that which occurs in a charcoal kiln, where the heat drives off combustible gases from the wood and leaves charcoal. The third stage involves burning of the gases in the air above the wood and burning of the charcoal combined with oxygen, forming an intensely hot and luminous bed of coals. The heat from both burning gases and charcoal distills more volatiles from the wood and increases the temperature and rate of combustion. The acceleration of combustion is limited only by the rate at which air can be brought into contact with the burning wood.

Liquid Fuel—Fuel Oils

Fuel oil, like other petroleum products, is composed of varying compounds of hydrocarbons. Even the same grade of fuel oil will vary as to its chemical composition, depending on such factors as the type of crude oil used and the refining process employed.

Types of Fuel Oil. Fuel oils obtained from present-day refining processes are known as "cracked" oils and practically all petroleum products on the market today are obtained by the cracking process. No. 1 and No. 2 fuel oils, as well as those fuels commonly known as kerosene, range oil, furnace oil, star oil, and diesel oil, are broadly classed as distillate and No. 4, No. 5, and No. 6 oils (as well as Bunker C) as residuals.

Oil burners are constructed (and subsequently tested and listed by testing laboratories) for a specific grade or grades of fuel oil. For example, burners listed by Underwriters Laboratories

Inc. (UL) have the grade or grades of fuel oil that can be used in each inscribed on the UL listing mark applied to the unit (Figures 10.2.3 and 10.2.4). It is important that only the proper grade or grades of oil be used in each burner for safety as well as efficiency. Note the grade of oil satisfactory for use in the device appears at the bottom of the markers. Specifications for fuel oil are outlined by the ASTM in ASTM D396, *Standard Specification for Fuel Oils,*[1] and in Canadian Government Specification 3-GP-28[2] (Table 10.2.1).

Methods of Firing Fuel Oil

Two methods, vaporization and atomization, are used to prepare fuel oil for combustion. Air for combustion is supplied by natural or mechanical draft. Ignition is by an electric ignition system, a gas pilot, an oil pilot, or manual means. Operation can be continuous, modulating with high-low flame, or intermittent. Although most burners operate from automatic temperature- or pressure-sensing controls, some simpler types are operated manually.

Oil burners are classified in several different ways: by application, by type of vaporizer or atomizer, by firing rates, and so on. They are divided into two major groups: (1) residential and (2) commercial-industrial. Vaporizing burners and atomizing burners having capacities of not more than about 6.5 gal/hr (25 L/hr) are considered residential types and are intended to be used with fuel oils not heavier than No. 2. Most residential-type burners are the pressure atomizing type, commonly referred to as the gun type.

Vaporizing Burners. These burners include the sleeve type, the pot type, and the vertical rotary wall flame type. Sleeve-type burners (Figure 10.2.5) are used in residential heating and cooking stoves. Perforated metal cylindrical sleeves are placed in the grooves so that the space between the inner two sleeves and the outer two sleeves becomes a combustion chamber. The space between the second and third sleeves is for the purpose of furnishing combustion air. Covers with annular openings are usually placed on top of the sleeves. Sleeve burners may or may not employ wicks in the annular spaces in the base, depending on the make and type of burner. Natural draft pot burners (Figure 10.2.6) have applications similar to sleeve-type burners, while forced-draft pot burners can be used in central heating furnaces. In a vaporizing pot-type burner, the oil is introduced into the bottom of the burner and is continually vaporized by the heat of the fire. The holes on the side permit primary and secondary air to enter the burner where they mix with the oil vapors for proper combustion. The primary air is mixed with oil vapors before combustion takes place, and the secondary air is supplied to complete the combustion process. At full fire, the velocity of the vapors and the amount of air required result in

FIGURE 10.2.3 Listing Mark Used on an Oil Burner Listed by Underwriters Laboratories Inc.

FIGURE 10.2.4 Listing Mark Used on an Oil-Fired Boiler Assembly Listed by Underwriters Laboratories Inc.

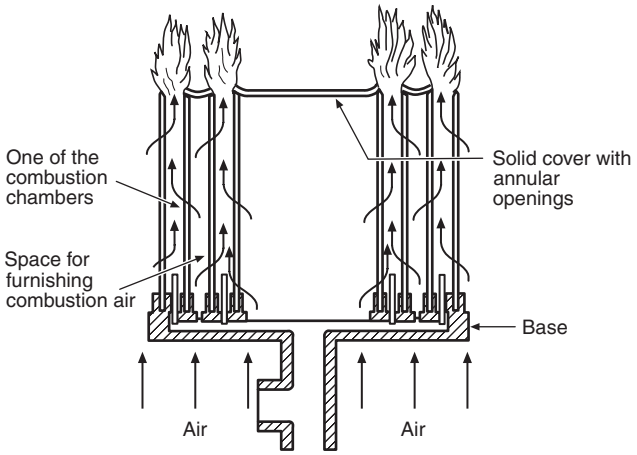


FIGURE 10.2.5 Sleeve-Type Burner That Consists Essentially of a Flat, Cast-Iron or Pressed Steel Base Having Two or More Interconnecting Grooves

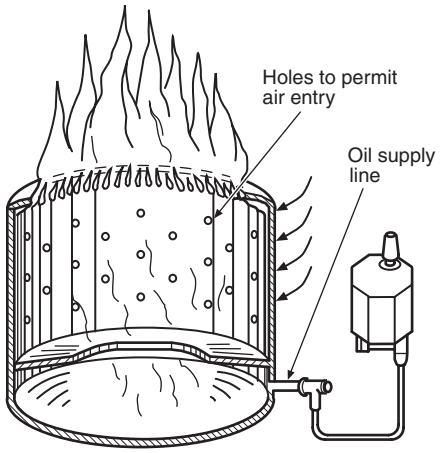


FIGURE 10.2.6 Vaporizing Pot-Type Burner

TABLE 10.2.1 Detailed Requirements for Fuel Oils[a,b]

Grade of Fuel Oil	Flash-point [°F (°C)]	Pour Point [°F (°C)]	Water and Sediment (Percent by Volume)	Carbon Residue on 10 Percent, Bottoms (Percent)	Ash (Percent by Weight)	Distillation Temperature [°F (°C)]			Saybolt Viscosity (s)				Kinematic Viscosity (centistokes)				Gravity (deg. API)	Copper Strip Corrosion	Sulfur (Percent)
						10 Percent Point	90 Percent Point		Universal at 100°F (38°C)		Furol at 122°F (50°C)		At 100°F (38°C)		At 122°F (50°C)				
	Min	Max	Max	Max	Max	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Max
No. 1: A distillate oil intended for vaporizing pot-type burners and other burners requiring this grade of fuel	100 or legal (38)	0[c]	trace	0.15	—	420 (215)	—	550 (288)	—	—	—	—	1.4	2.2	—	—	35	No. 3	0.5 or legal
No. 2: A distillate oil for general-purpose domestic heating for use in burners not requiring No. 1 fuel oil	100 or legal (38)	20[c] (–7)	0.05	0.35	—	—	540[c] (282)	640 (338)	(32.6)[d]	(37.93)	—	—	2.0[c]	3.6	—	—	30	—	0.5[c,e] or legal
No. 4: Preheating not usually required for handling or burning	130 or legal (55)	30 (–1)	0.50	—	0.10	—	—	—	45	125	—	—	(5.8)	(26.4)	—	—	—	—	—[f]
No. 5 (Heavy): Preheating may be required for burning and, in cold climates, may be required for handling	130 or legal (55)	—	1.00	—	0.10	—	—	—	150	300	—	—	(32)	(65)	—	—	—	—	—[f]
No. 5 (Light): Preheating may be required for burning and, in cold climates, may be required for handling	130 or legal (55)	—	1.00	—	0.10	—	—	—	350	750	(23)	(40)	(75)	(162)	(42)	(81)	—	—	—[f]
No. 6: Preheating required for burning and handling	150 (65)	—	2.00[g]	—	—	—	—	—	(900)	(9000)	45	300	—	—	(92)	(638)	—	—	—[f]

[a] It is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless, in fact, it meets all requirements of the lower grade.
[b] This table reprinted from ASTM D396. See complete specification ASTM D396.
[c] Lower or higher pour points may be specified whenver required by conditions of storage or use. When pour point less than 0°F (–18°C) is specified, the minimum viscosity must be 1.8cSt (32.0 s, Saybolt Universal) and the minimum 90 percent point must be waived.
[d] Viscosity values in parentheses are for information only and not necessarily limiting.
[e] Outside U.S., the sulfur limit for No. 2 must be 1.0 percent.
[f] The 10 percent distillation temperature point may be specified at 225°C maximum for use in other-than-atomizing burners.
[g] The amount of water by distillation plus the sediment by extraction must not exceed 2.00 percent. The amount of sediment by extraction must not exceed 0.50 percent. A deduction in quantity shall be made for all water and sediment in excess of 1.0 percent.

the flame burning only at the top of the burner. Vertical rotary wall flame vaporizing burners are used in residential boilers and furnaces for central heating. Although the gun-type burner is now the most common, many of the burners listed above are still in service.

Atomizing. These burners include high- and low-pressure types, horizontal rotary cup types, and air and steam atomizing types, the latter used primarily for commercial and industrial applications. High-pressure, gun-type burners consist of a motor, oil pump (with integral or separate pressure-regulating and shutoff valve), strainer, fan, ignition transformer, nozzle, and electrode assembly (Figure 10.2.7). The motor-driven pump draws oil from the supply tank and delivers it to the nozzle at pressures of from 100 to 300 psi (690 to 2700 kPa). The nozzle atomizes the oil into fine particles and swirls it into the combustion chamber as a cone-shaped spray where it mixes with air and is ignited. These burners are generally designed to burn No. 2 oil, although some of the larger sizes are made for No. 4 oil.

The industrial version of the high-pressure burner, known as the mechanical atomizing burner, is a high-capacity burner for use with large boilers and industrial furnaces. Figure 10.2.8 shows a typical piping arrangement for one or more burners supplied by separate pump sets.

The low-pressure gun burner is similar to the high-pressure gun burner, but differs from it in two ways. First, the burner includes an air pump to supply compressed air for atomization, and second, the oil and air are delivered to the nozzle at pressures of 15 psi (100 kPa) or less. The size ranges, ignition, and fuel used are as described for the high-pressure gun burner.

The horizontal rotary-cup oil burner atomizes the oil by spinning it in a thin film from a horizontal rotating cup and injecting high-velocity primary air into the oil film through an annular nozzle that surrounds the rim of the cup. Secondary air for combustion is supplied from a separate fan that forces air through the burner wind box. The introduction of secondary air by means of natural draft is not recommended. These burners are used for firing boilers and furnaces and can be used singly or as multiple units on a single appliance. No. 2 fuel can be used with some of the smaller sizes, but Nos. 4, 5, and 6 are generally used with the larger sizes (Figure 10.2.9).

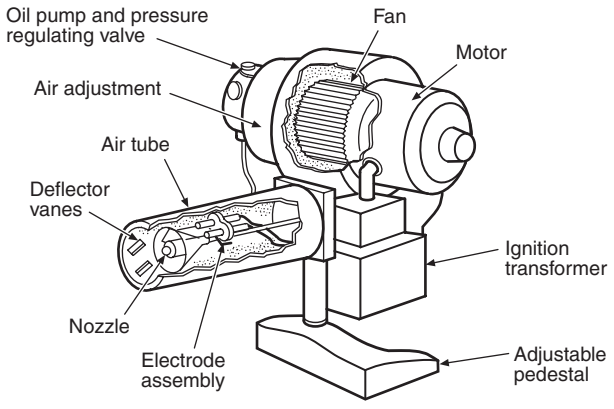


FIGURE 10.2.7 High-Pressure Atomizing Oil Burner

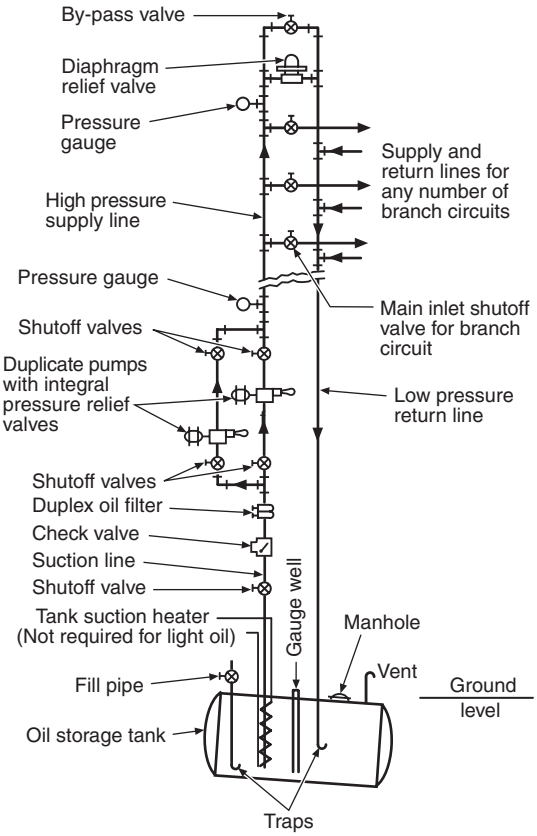


FIGURE 10.2.8 Typical Piping Arrangement for Burners Supplied by Separate Pump Sets

In the steam atomizing burner, atomization is accomplished by the impact and expansion of steam. Oil and steam flow in separate channels through the burner gun to the nozzle where the steam and oil mix before being discharged through an orifice into the combustion space. This type of burner is used mainly on large

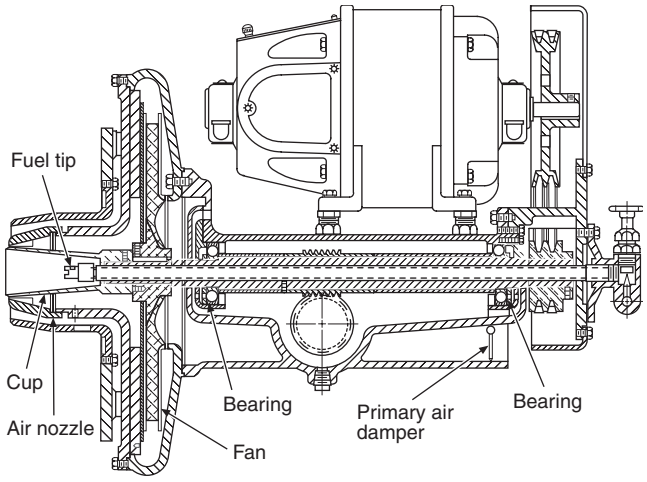


FIGURE 10.2.9 Horizontal Rotary-Cup Oil Burner

boilers generating steam at 100 psi (690 kPa) and higher and having capacities above 12,000,000 Btu per hour (3.5 MW) input.

Air-atomizing burners are designed to use compressed air at either high or low pressure for atomization. The high-pressure burner is nearly identical with the steam atomizing burner in design and application. Some burners operate well with either medium.

The low-pressure air atomizing burner uses comparatively large volumes of air at low pressure of 5 psi (35 kPa) or less. Air from the blower passes through the burner body and is discharged through annular slots between the body and the nozzle tip, where it meets the film of oil at an angle as it issues from the tip. The impact of the air stream upon the oil film produces a fine mist that is projected into the combustion space. These burners can be fired with either light or heavy oil and are most often used to fire industrial heating and processing furnaces (Figure 10.2.10).

Combination oil and gas burners, which combine the features of certain oil burners with provisions for burning gas, have been developed, permitting the operator to choose either fuel as circumstances dictate.

Fuel Oil Storage

Details on the installation of fuel oil tanks and related piping are described in NFPA 31, *Standard for the Installation of Oil-Burning Equipment.* NFPA 31 directly covers the installation of underground tanks, tanks inside buildings, and outside aboveground tanks that do not exceed 660 gal (2500 L). Larger outside aboveground tanks are covered by Chapter 4 of NFPA 30, *Flammable and Combustible Liquids Code.* The installation requirements of NFPA 31 differ somewhat from those in NFPA 30, which is more general in nature and covers liquids with a wider range of flashpoints used in a variety of locations and occupancies.

Corrosion of Tanks. Internal corrosion of fuel oil tanks caused by electrolytic action of water on steel can be a major problem. Corrosion and subsequent leakage are actually more of an environmental problem than a fire hazard. Fire can occur, however, when a burner is located in a pit in the basement of a building and oil from a leaking tank flows into the pit. Two generally accepted procedures are recommended to minimize corrosion. The first is to slope the tank toward one end and connect the burner supply line to the bottom of the tank at that end. In this way, water does not accumulate in the tank. The small quantity of water, which originates from condensation within the tank, is small enough to not affect operation of the burner. The second method is to add a small amount of an alkaline solution to the oil itself or directly to the tank at periodic intervals.

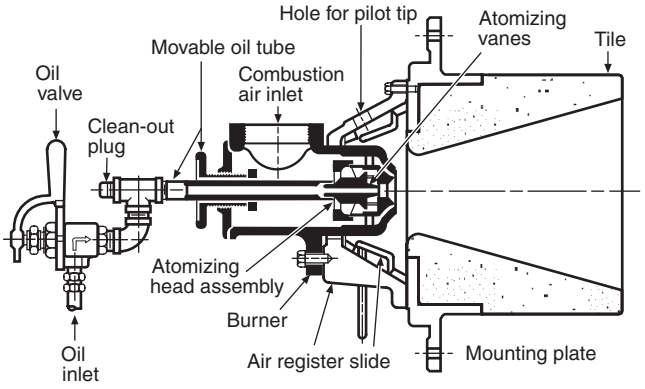


FIGURE 10.2.10 Low-Pressure Air Atomizing Oil Burner

Tanks in Buildings. NFPA 31 currently permits installation of tanks inside buildings as follows:

- On any floor, up to 60 gal (227 L) capacity
- On the lowest floor (basement, cellar, etc.), up to an individual capacity of 660 gal (2500 L)
- On a higher floor level (such as an attached garage of a split-level house) where there are no floors or spaces directly beneath and where all openings to the rest of the structure are provided with a means to prevent spread of spilled fuel into the structure, up to an individual capacity of 660 gal (2500 L)

In each case, the tank(s) are unenclosed, that is, are not in a dedicated room. The aggregate capacity of all tanks connected to any one burner or any one group of burners cannot exceed 660 gal (2500 L), and the total aggregate capacity of all such tanks, unenclosed, cannot exceed 1320 gal (5000 L). A distance of at least 5 ft (1.5 m) must be maintained between each tank and any fire or flame, either in or external to any fuel-burning appliance. Furthermore, such tanks must not obstruct quick and safe access to any utility service meter, switch panel, or shutoff valve.

Tanks larger than 660 gal (2500 L) can be installed in buildings, provided they are located in an enclosure constructed of walls, floor, and ceiling that provide a fire resistance rating of not less than 3 hours. The walls must be bonded to the floor to effect a liquid-tight seal. The ceiling and walls of the enclosure must be independent of the building, except that an exterior wall having a fire resistance rating of not less than 3 hours can serve as a wall. Any opening into the enclosure must have a noncombustible sill or ramp at least 6 in. (150 mm) high. Since such openings are Class A (horizontal) openings, they must be provided with self-closing fire doors. Enclosures of this type are found only in commercial or industrial buildings.

A recent change to NFPA 31 allows up to five 275 gal (1040 L) tanks to be installed unenclosed and cross-connected, so as to allow a single fill connection and single vent, but only if the fill and vent piping are pre-engineered so that all tanks are filled simultaneously at the same rate.

Outside Aboveground Tanks. Under the following conditions, tanks can be installed outside aboveground in built-up areas. Such tanks are allowed to be located immediately adjacent to buildings, without having to meet the separation distances of NFPA 30, but must be kept away from an adjacent property line. Not more than one or two tanks having an aggregate capacity of 660 gal (2500 L) are permitted to be connected to any one oil burner or any one group of oil burners.

Individual tanks exceeding the 660 gal (2500 L) limit can be installed, but must meet all relevant requirements of NFPA 30 for separation distance, spill control, emergency venting, and so on.

Underground Tanks. Tanks can be installed underground. Such tanks must conform to types recognized by NFPA 31 and must be installed in accordance with NFPA 30. Both documents impose requirements dealing with location of tanks in relation to building foundations or footings, separation to property lines, protection against traffic (i.e., vehicle movement over the tanks), and dislocation of tanks due to high ground water or flooding. See NFPA 30 for additional information on protecting fuel oil tanks in areas subject to flooding.

Centralized Oil Distribution System. A system of piping that supplies oil from a central tank or tanks to a number of buildings, manufactured homes, recreational vehicles, and so on, is allowed under certain conditions. For details covering such systems see NFPA 31.

Fill and Vent Pipes. Underground tanks, including tanks buried beneath buildings, must have fill and vent pipes that terminate outside the building. Vent openings and vent pipes must be large enough to prevent abnormal pressure within the tank during filling and, in any case, must not be smaller than 1¼ in. (30 mm) nominal pipe size for tanks up to 660 gal (2500 L) capacity. Larger tanks must have vent pipes of larger nominal size.

Tanks located inside buildings must have fill and vent pipes that terminate outside the building. Vent openings and vent pipes must be at least 1¼ in. (30 mm) nominal pipe size for tanks up to 660 gal (2500 L) capacity and correspondingly larger for tanks of greater capacity.

Outside aboveground tanks must have vent openings and vent pipes large enough to prevent abnormal pressure within the tank during filling and, in any case, must not be smaller than 1¼ in. (30 mm) nominal pipe size for tanks up to 660 gal (2500 L) capacity. Larger tanks must have vent pipes of larger nominal size.

Gauging devices are required, but on inside tanks they must not allow oil or vapor to be discharged into the building. Test wells are not allowed on inside tanks. Piping to the burner(s) and the required accessories are covered in NFPA 31.

Small-Capacity Tanks. There are several types of small tanks used with cooking appliances and room heaters. An auxiliary tank of not over 60 gal (227 L) capacity is allowed between the burner and the main fuel supply tank. An unenclosed supply tank of not more than 10 gal (38 L) capacity for an individual appliance is permitted, provided it is placed not less than 2 ft (0.6 m) from a source of heat either inside or outside the appliance being served, and provided that the temperature of the oil in the tank will not exceed 25°F (–4°C) above room temperature at the maximum firing rate.

Integral tanks are furnished by manufacturers as a component part of some oil-burning appliances, for example, kerosene and oil stoves. Stoves with integral tanks (not over 5 gal [20 L] capacity) operate on the gravity or barometric feed principle. The tank reservoir oil and the burner oil are at the same level. As the oil level drops due to burning, oil runs into the reservoir from the tank, either because a float drops and opens a valve (gravity feed) or because air enters the tank through the cap and allows oil to enter the reservoir until it covers the air opening (barometric feed).

NFPA 31 contains specific provisions on supply tanks for kerosene and oil stoves, portable kerosene heaters, and conversion range oil burners. The intent of these provisions is to prohibit contamination of storage containers with other types of fuel. Contamination can lead to explosion or flare-up in the equipment.

Liquid Fuels—Miscellaneous

Alcohol, gasoline, crankcase oils, and used oils are used for some heat-producing appliances and equipment to a limited extent. Alcohol stoves and torches and gasoline torches are examples. NFPA 31 gives additional basic requirements for safe storage practices for these fuels.

Gas Fuels

Generally, gas-fired, heat-producing devices and equipment use natural gas, LP-gas (liquified petroleum gas), an LP-gas/air mixture, or mixtures of these gases. Natural gas is the most commonly used gas fuel in the United States, because gas transmission pipeline systems supply most areas of the country. LP-gas-fired heating devices also are popular, particularly in sparsely settled areas and in recreational vehicles. A number of other flammable gases are used as fuel in many industrial processes for special purposes.

Natural gas consists principally of methane and some ethane, propane, butane, and small amounts of carbon dioxide and nitrogen. Fuel gases can be made in a variety of ways from coal or by the cracking of oils. Liquified petroleum gases are largely propane, propylene, butane, and butylene, or mixtures of these gases.

Typical calorific values of various gases as fuel are given in Section 6, Chapter 10, "Gases." Various procedures for sampling, analyzing, measuring, and testing gaseous fuels are outlined in 13 ASTM standards, which have been compiled in the publication ASTM *Standards on Gaseous Fuels.*[3]

Methods of Firing Fuel Gases

Air is either mixed with gas at the burner of a gas-fired appliance or premixed with gas. A wide variety of types and sizes of burners are used to mix the gases effectively under different conditions. Every burner is designed to transform the potential energy of the fuel gas into useful heat, which can be absorbed in the most effective manner.

Injection (Bunsen) Burners. Injection-type gas burners are popular in residential and commercial gas appliances and, to a lesser extent, in industrial gas-fired appliances. A jet of gas injects primary air for combustion into the burner and mixes it with the gas. This mixing occurs before the gas reaches the burner ports or point of ignition. Figure 10.2.11 shows a typical injection-type gas burner.

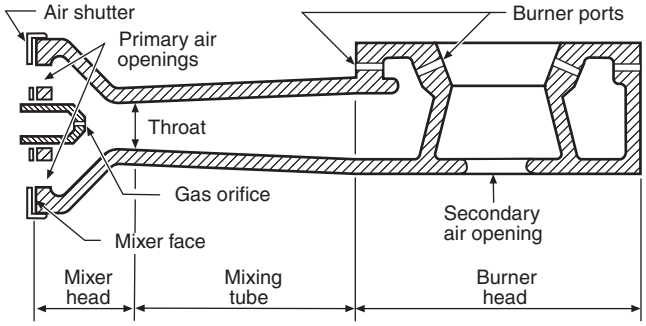


FIGURE 10.2.11 Typical Injection-Type Burner

Luminous or Yellow-Flame Burner. In the luminous or yellow-flame burner, only air externally supplied at the point of combustion is used for burning the gas. The flame is produced without premixing air with the gas.

Catalytic Burners. Another type of burner is the catalytic burner that permits combustion of the gas at temperatures well below the normal ignition temperature of fuel gas/air mixtures.

Power Burners. In a power burner, either gas or air or both are supplied at pressures exceeding the line pressure of the gas and atmospheric pressure of the air. The added pressure is applied at the burner. When air for combustion is supplied by a fan ahead of the appliance, the appliance is known as a forced-draft burner. A premixing burner is a power burner in which all or nearly all of the air for combustion is mixed with the gas as primary air (air that mixes with the gas before it reaches the burner port or ports). A pressure burner is supplied with an air/gas mixture under pressure (usually from 0.5 to 14 in. of water [0.1 to 3.5 kPa] and occasionally higher).

Figure 10.2.12 illustrates some of the types of industrial appliance gas burners.

Interchanging Gases. Changing from one kind of gas to another can cause serious problems unless the appliance is designed to accept the change. Appliance designs certified by CSA International (formerly the American Gas Association [AGA]) laboratories are tested for satisfactory performance with one or more gases as requested by the manufacturer. These include natural and mixed gases, as well as LP-gas and LP-gas/air mixtures. The specific gas or gases that can be used in an appliance are marked on the appliance. Although such appliances may be converted in the field to any one of the marked gases, the conversion can require some interchange of parts and involves some element of hazard unless carefully performed by experienced, qualified personnel.

Appliance and Piping Installation

Installation, alteration, and repair of gas appliances and gas piping should be done only by qualified agencies fully experienced in this work. Provisions outlined in NFPA 54, *National Fuel Gas Code,* provide the necessary guidance. Gas must be turned on *only after* the system has been thoroughly tested to be certain there is no leakage. All air in piping must be purged, as a remaining slug of air will extinguish the flame. When gas flows again, unburned gas will escape, resulting in a potentially hazardous condition.

The uncontrolled flow of unburned gas into any gas appliance could form an explosive gas/air mixture. Safeguards to prevent this are extremely important, particularly in industrial and other large gas-burning devices. Without such safeguards, unburned gas can accumulate in combustion chambers or ovens at the time of lighting or when the gas pressure fluctuates. If the pressure is reduced below a certain point, the flame might be extinguished. With a subsequent return of normal pressure, unburned gas might continue to flow. An increase in pressure might increase the velocity of flow through the burner in excess of the flame propagation rate. This will force the flame away from the burner. A number of automatic devices are available to safeguard against this hazard and are commonly found on the larger installations.

Electricity

Most electrical heating appliances for heating small rooms and for other small heating jobs involve resistor heating elements, which are usually one or more metal alloy wires, nonmetallic carbon rods, or printed circuits. Resistor heating is used in radiators, unit heaters, convectors, central hot water systems, central warm air heating systems, and panel-type radiant heat installations for walls, floors, and ceilings. Resistor heating is also used for household electrical appliances, such as stoves, irons, and toasters.

Controls. Automatic regulation of the electrical input (usually through proportional-type step controllers) allows heaters to be energized and de-energized in increments small enough to prevent excessive total operation of all heaters during temperature drops.

Method of Installation. Electric heating systems should be installed in accordance with NFPA 70, *National Electrical Code®*.

CONTROLS FOR FUEL BURNERS

The uncontrolled flow of unburned fuel into appliances and burners can lead to serious consequences. When fired with pulverized coal, gas, or oil, a combustible mixture could accumulate within the confines of the appliance or equipment. If ignited, it could result in an explosion. To guard against the discharge of unburned fuel or improper mixtures of fuel and air, certain controls are required for all fuel burners.

Primary Safety Controls

These required controls cause the fuel to shut off in the event of ignition failure or flame failure. Except for pot-and-sleeve-

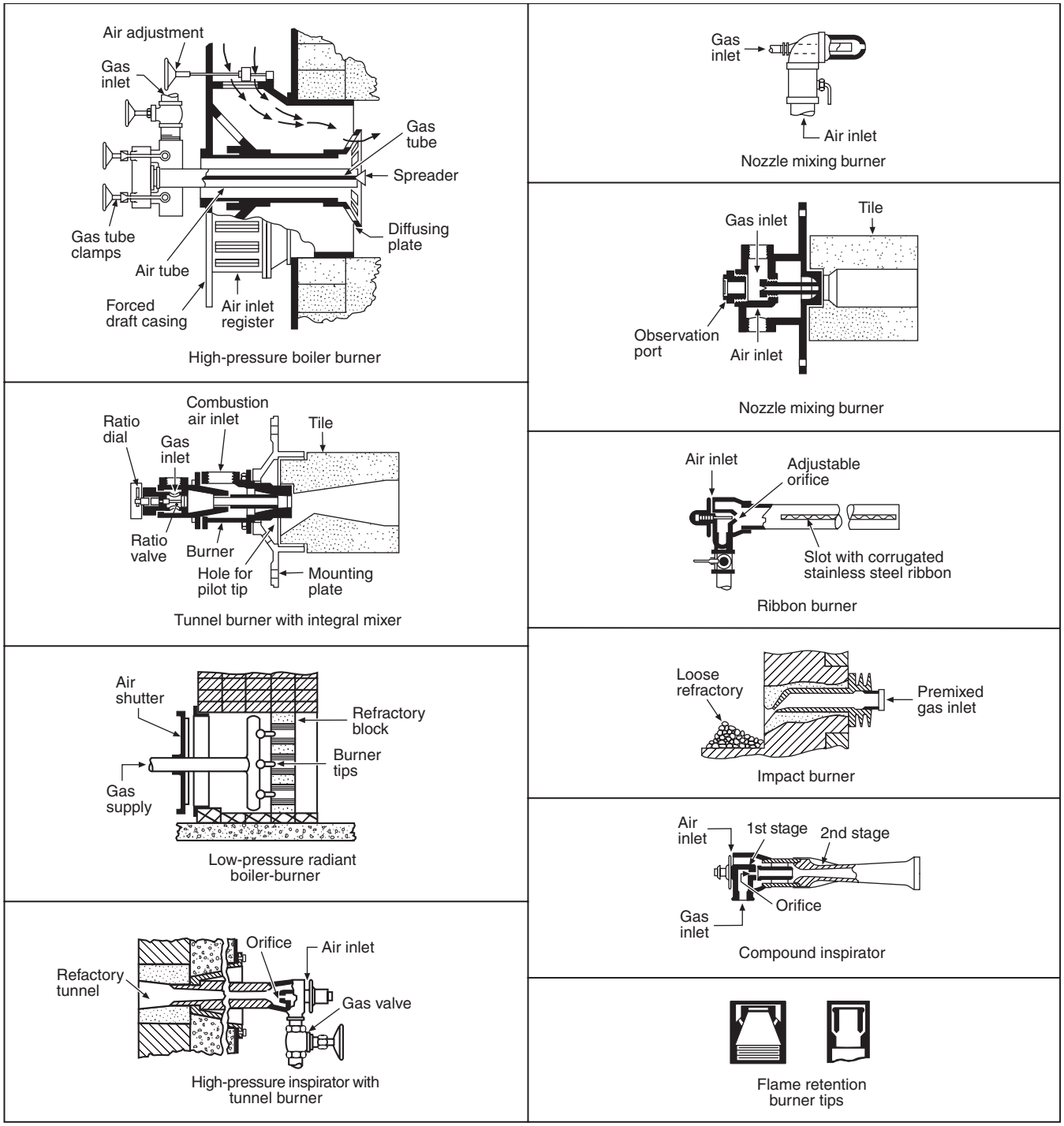


FIGURE 10.2.12 Types of Industrial Appliance Gas Burners

type vaporizing burners, shutoff is usually accomplished via a primary safety control. For gas appliances, an automatic gas ignition system is used. Both types of controls sense the presence or absence of flame. Upon ignition or flame failure, they cause the fuel to be shut off in the prescribed period of time. All fuel to the burner should be shut off. Primary safety controls usually provide for starting and stopping the burner in response to changes in demand (room thermostat, process controller, etc.). Controls for commercial and industrial burners may provide a purge period for air to flow through the appliance prior to starting fuel flow. The control also prohibits main burner fuel from being admitted until the control has proved the existence of the ignition flame.

The discharge of unburned oil from pot-and-sleeve-type vaporizing burners should be prevented by a constant level

valve or by barometric feed. Each of these provisions maintains a predetermined level of oil in the burner below any point of overflow.

Air/Fuel Interlocks

If the safe operation of a burner depends on a forced or induced draft fan or air compressor to supply combustion air, an interlock is needed to shut off fuel in case the air supply is interrupted.

Atomizer/Fuel Interlocks

In an oil-burning system, where air, steam, or other means for atomization can be interrupted without stopping oil delivery to the burner, an interlock must be provided to immediately shut off the oil if atomization fails.

Pressure Regulation and Interlocks

Gas burners and pressure-type oil burners require uniform fuel pressure so fuel burns safely and efficiently. Pressure regulators are used to maintain uniform fuel pressures. In situations where fuel pressure fluctuations can be expected, pressure interlocks are provided, which shut off the fuel to the main burners when the pressure is too low or too high for safe operation.

Oil Temperature Interlocks

Oil burners requiring heated oil for satisfactory operation are equipped with a low oil temperature switch to prevent the burner from starting or to shut it down if the oil temperature falls below the required minimum.

Manual Restart

If a burner is not equipped to provide safe automatic restarting after shutdown, its control system must be arranged to require manual restarting after any control operates to extinguish the burner flame.

Remote Shutoff

It is good practice to provide a remote control for manually stopping the flow of fuel to the burner. An identified switch in the burner supply circuit, placed near the entrance to the room where the burner is located, can be used with electrically powered equipment. A valve in the fuel supply line, operable from a location reached without passing near the burner, can also be used.

Safety Shutoff Valves

Safety shutoff valves prevent the abnormal discharge of fuel. They should be constructed so they cannot be readily restrained or blocked in the open position. Such valves should automatically close when de-energized, regardless of the position of any damper-operating lever or reset handle. Electrically operated valves should not need to be energized to close. Pressure-operated valves should close upon failure of the operating pressure.

Safety Control Circuits

Safety control ac circuits are of the two-wire type with one side grounded. They must not exceed a nominal 120 V and must be protected with suitable fuses or circuit breakers. All switches should be in the hot ungrounded line. The accidental grounding of such a circuit will not cause a required safety control to be bypassed.

Appliances and equipment fired with fuel burners require some additional controls to avoid excessive pressure, temperature, or other abnormal conditions. These controls are covered later in this chapter.

Appliances listed by testing agencies are equipped with all the required safety controls. The application of controls to fuel-burning systems assembled in the field or intended for specific applications should be entrusted only to people specializing in this work. The standards pertaining to fuel-burning equipment referenced in the bibliography include specific information on controls essential to safe operation of fuel-burning equipment.

Safety controls are generally preset by the manufacturer or the installer. Any alteration of these settings or bypassing any safety control could lead to serious consequences. When a faulty control is replaced, a similar model and setting should be used. Figures 10.2.13 and 10.2.14 illustrate typical arrangements of safety valves and interlocks for industrial gas and oil burners, respectively.

HEATING APPLIANCES AND THEIR APPLICATIONS

Central heating appliances, room heating appliances, and miscellaneous heat-producing devices, which are fired by the various fuels and methods discussed, are described here.

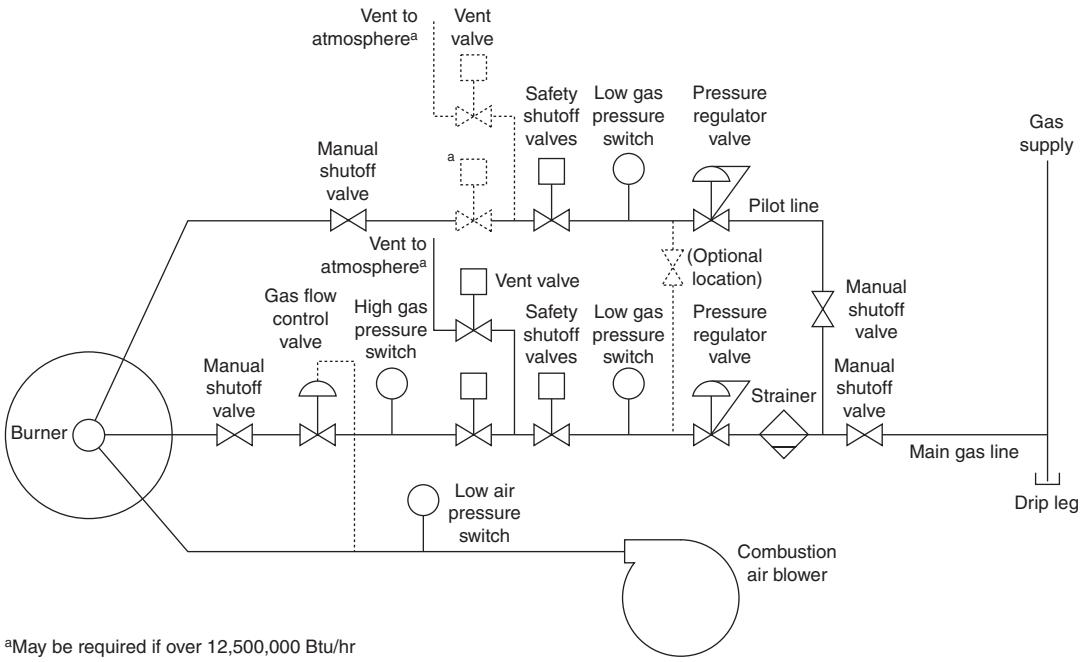
Central Heating Appliances

Central heating appliances are divided into four broad categories: (1) boilers, (2) central furnaces, (3) floor furnaces, and (4) wall furnaces.

Boilers. Boilers are either of the steam or hot water type and are constructed of cast iron or steel (Figure 10.2.15). The *ASME Boiler and Pressure Vessel Code*[4] defines low-pressure boilers (for low-pressure steam heating, hot water heating, and hot water supply) as those steam boilers that operate at pressures not exceeding 15 psig (100 kPa) and hot water boilers as those that operate at pressures not exceeding 160 psi (1100 kPa) and at temperatures not exceeding 250°F (120°C). The *ASME Boiler and Pressure Vessel Code* also covers the construction of power boilers and locomotive boilers.

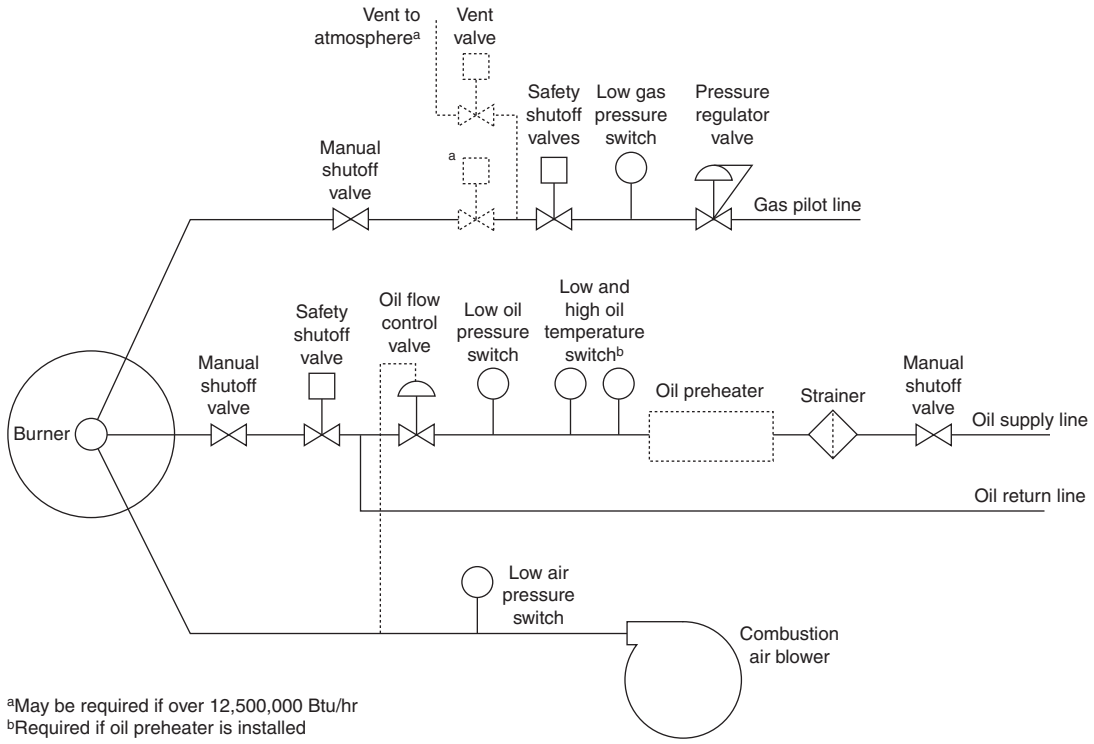
Boilers are equipped with safety devices to prevent overpressure conditions. Automatically fired boilers also have controls that will shut off the burner or electric heating elements under low water conditions or when a predetermined pressure or temperature has been reached.

The fire problems of boilers include their mountings and clearances to combustibles. Explosions resulting from



[a]May be required if over 12,500,000 Btu/hr

FIGURE 10.2.13 Typical Safety Valves and Interlock Arrangement for Industrial Gas Burner



[a]May be required if over 12,500,000 Btu/hr
[b]Required if oil preheater is installed

FIGURE 10.2.14 Typical Safety Valves and Interlock Arrangement for Industrial Oil Burner

unburned fuel accumulations in the combustion chamber or due to overpressure conditions could rupture fuel lines, thus contributing to the potential for subsequent fire or explosion damage.

Central Warm Air Furnaces. The residential types currently installed in the United States are usually equipped with circulating fans, filters, and other features that make them, in effect, air-conditioning systems.

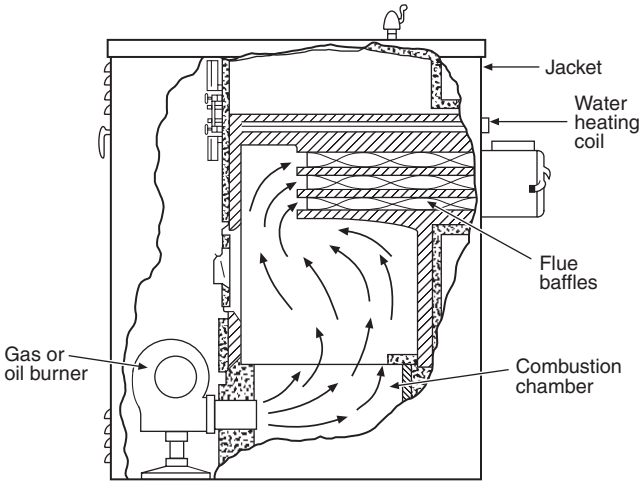


FIGURE 10.2.15 Oil-Fired Steam Boiler

Central warm air furnaces are of the following types:

1. Gravity—depends primarily on the circulation of air by gravity.
2. Gravity with integral fan—fan is an integral part of the furnace construction and is used to overcome internal resistance to airflow.
3. Gravity with booster fan—fan does not restrict flow of air by gravity when fan is not operating.
4. Forced air—equipped with fan that provides the primary means of circulating air (Figure 10.2.16).

Forced-air central warm air furnaces are classified according to the direction of airflow through them, that is, as horizontal, upflow, or downflow.

Gravity furnaces are floor mounted and can heat only spaces above them. Forced-air furnaces can be floor mounted or suspended and can be found on almost any floor of a building, including the attic and roof.

Under some conditions of operation, plenums of warm air heating furnaces can become hot enough to ignite adjacent unprotected woodwork. Clearances or insulation are necessary in these instances. (Complete requirements for installation of systems in residences can be found in NFPA 90B, *Standard for the Installation of Warm Air Heating and Air-Conditioning Systems.*)

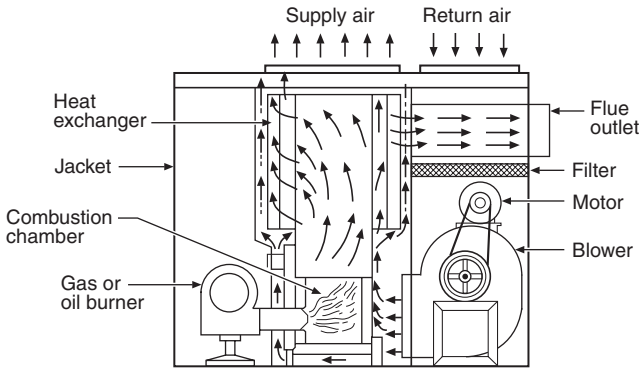


FIGURE 10.2.16 Oil-Fired Forced-Air Furnace

Automatic controls, also called high-limit controls, can shut off the fuel or electric supply whenever the air in the furnace warm air plenum or at the beginning of the main supply duct—at a point not affected by radiated heat—reaches 250°F (120°C) or less, depending on the type of furnace and its installation (Figure 10.2.17). Automatic controls cannot be set above prescribed temperature limits. Some furnaces used only with special duct systems are factory equipped to permit temperatures above 250°F (120°C) at the inlet of the supply ducts.

Central warm air furnaces also can cause fires due to inadequate clearances to combustible construction, lack of proper limit controls, heat exchanger burnouts, and other causes associated with lack of proper installation, servicing, and maintenance.

Pipeless Furnaces. Pipeless furnaces are essentially gravity warm air furnaces that are not connected to ducts. The furnace is mounted directly under the space to be heated. All the air heated in its outer jacket is discharged through a register above the heat exchanger. They are used for heating small homes and other small one-story properties.

Pipeless furnaces can produce dangerously high temperatures, particularly if the air circulation is restricted. For example, if the register in the floor of a small hallway heats adjoining rooms by air circulating through opened doors, the temperature of the entire hall might be raised to a dangerous degree if the doors are closed tightly at a time when the furnace is in full operation. Fires also can occur when clothing left to dry above a central floor register is ignited. It is good practice to equip automatically fired pipeless furnaces with limit controls.

Floor Furnaces. Most oil- and gas-fired floor furnaces are designed so they can be installed in combustible floors (Figure 10.2.18); however, they should not be installed in combustible floors if they have not been listed by a testing laboratory for such use. Clearances should be sufficient not only to protect

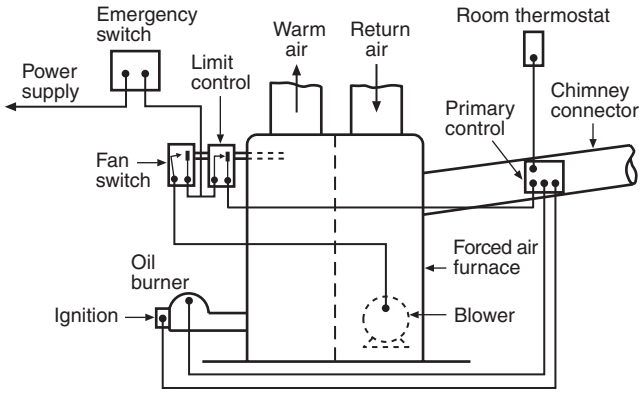


FIGURE 10.2.17 Control Wiring Schematic of Oil-Fired Forced Warm Air Furnace. Certain primary controls are mounted on the burner assembly.

combustible floors and walls, but also to keep the furnace casing and the piping connected to it out of contact with earth or damp materials. Temperature limit controls are provided on floor furnaces to shut off the fuel supply when the temperature of the discharged air reaches a predetermined level.

In auditoriums, public halls, or assembly rooms, floor furnaces should not be installed in the floor of any aisle, passageway, or exitway. Floor furnace registers can become hot enough to cause burns under some conditions; therefore, registers in dwellings should not be located in passageways to bathrooms, where persons would be likely to step with bare feet. Users should be warned against covering registers or placing clothing on them to dry. Older types of floor furnaces do not have a temperature limit control and can become dangerously hot if the air passages are blocked with dust and lint. Inspection and vacuum cleaning or hand removal of this blockage is essential for continued safe operation.

Wall Furnaces. Wall furnaces are self-contained indirect-fired gas or oil heaters installed in or on a wall. They supply heated air directly to the space to be heated, either by gravity or a fan through grilles on openings or boots in the casing supplied by the manufacturer. The furnaces may be of the direct-vent type or are vent- or chimney-connected, depending on the fuel. Limit controls limit outlet air temperature. The fire problems with recessed wall furnaces are similar to those encountered with most warm air furnaces. A wall furnace installation is shown in Figure 10.2.19.

Duct Furnaces. Duct furnaces are installed directly in ducts of some warm air and air-conditioning systems and depend on air circulation from a blower not furnished as a part of the furnace. They can be oil or gas fired or electrical and are equipped with a limit control to shut off the fuel supply or electricity at excessive temperatures.

When duct furnaces are used in conjunction with refrigeration coils in a combined heating and cooling system, the furnace

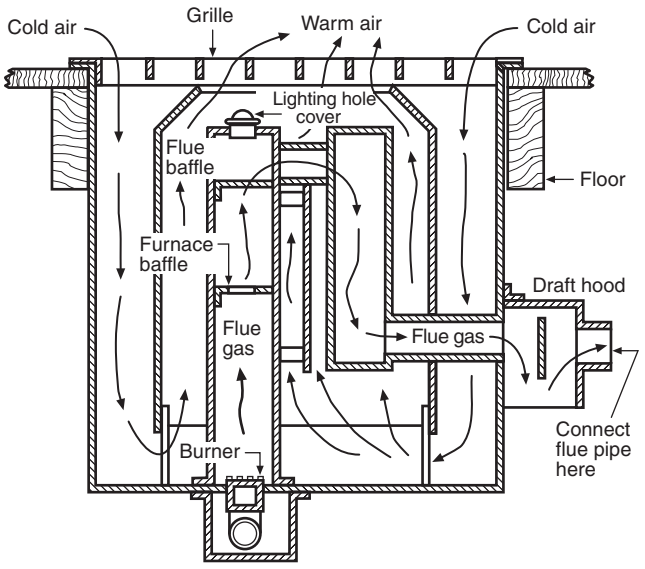


FIGURE 10.2.18 Typical Floor Furnace

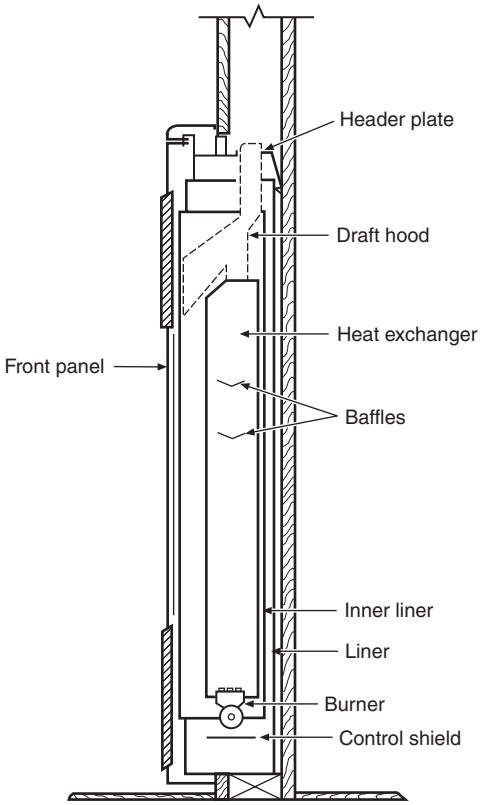


FIGURE 10.2.19 Typical Gas-Fired Wall Furnace

should be located upstream from the refrigeration coil or parallel with it to prevent condensation from corroding the furnace. There are, however, furnaces made of corrosion-resistant material, which may be installed downstream from the refrigeration coil. When the furnace is located upstream from the refrigeration coil, the coil should be designed so that excessive pressures and temperatures will not develop in the coil. A duct furnace installation is shown in Figure 10.2.20.

Warm Air Heating Panels. These are used in low-temperature, forced-air systems to circulate warm air through plenums or chambers that have one or more surfaces exposed to the space to be heated. NFPA 90B gives recommendations for the use, construction, and installation of these panels.

Radiant Heating. Radiant heating uses panels of hot water piping or electric heating elements that usually operate at moderate temperatures. The panels are embedded in plaster walls or ceilings or in cement floors. Hot water pipes or electrical equipment in radiant systems should conform to standard installation practices. NFPA 70 contains specific recommendations on the installation of electrical space heating equipment.

Heat Pumps. A heat pump is a type of forced-air heating system in which refrigeration equipment is used in such a way that heat is taken from a heat source and given up to the conditioned space when heat service is wanted and is removed from the space

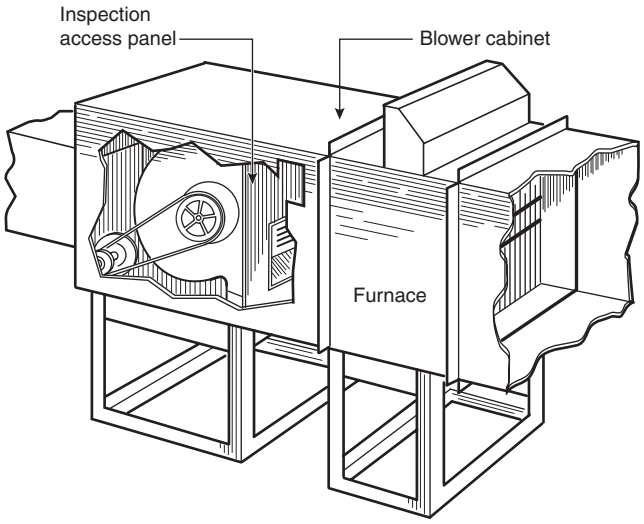


FIGURE 10.2.20 Duct Furnace Installation

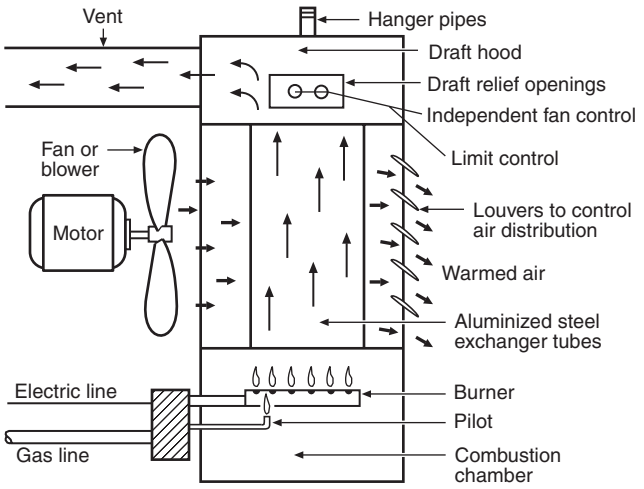


FIGURE 10.2.21 Typical Gas-Fired Unit Heater

and discharged to a heat sink when cooling and dehumidification are desired. These systems frequently have supplemental heating units. In such cases, the units are equipped with an interlock to prevent the unit from operating unless the indoor air circulating fan on the system is running. The units also have temperature limit controls. Hazards are those presented by power, refrigeration equipment, and heat units, if these are part of the system.

Unit Heaters

Unit heaters are classed as self-contained, automatically controlled, chimney- or vent-connected air heating appliances with an integral means for air circulation. They can be floor mounted or suspended and are equipped with temperature limit controls. The term *unit heater* as used in NFPA standards is intended to cover appliances for heating nonresidential properties. Thus, it excludes room heaters, floor furnaces, and similar devices. More specifically, a unit heater is an appliance consisting of a heating element and fan housed in a common enclosure and placed within or adjacent to the space to be heated. Unit heaters should not be confused with heat exchangers, which are equipped with fans to circulate heated air. In the latter type, hot water or steam is piped from a heating unit to the heat exchanger in the area to be heated.

Unit heaters that are designed for connection to a duct system can be considered as central heating furnaces and should be provided with the same safeguards. A typical unit heater is shown in Figure 10.2.21.

Room Heaters and Cooking Appliances

A room heater differs from a central heating furnace in that it is a self-contained air heating appliance designed for the direct heating of the space around it. External pipes or ducts are not used to distribute the heat. Room heaters fall into two general types: circulating and radiant. A fuel-burning circulating heater has an outer jacket surrounding the combustion chamber. It is arranged with openings at the top and bottom so that air circulates between the inner and outer shell. It does not have openings in the sides of the outer jacket in order to permit direct radiation. From a safety point of view, room heaters other than those specifically designed as circulating are classified as being radiant. They include such appliances as wood and coal stoves, electric and gas logs, open-front heaters, wall heaters, gas coal baskets, and fireplace inserts. Care must be taken, especially with heaters that can be moved easily, to place the radiant type so that radiating elements and surfaces are not directed toward walls, drapes, or furniture in close proximity to the heater.

Fuel-burning heaters and residential cooking appliances should be connected to a chimney or vent, when appropriate. The exceptions are gas room heaters and gas cooking appliances listed for unvented use.

Fuel-burning room heaters are not to be installed in sleeping quarters for use of transients, as in hotels and motels, nor in institutions such as homes for the aged, sanitariums, convalescent homes, and orphanages. It is good practice to install direct-vent-type heating appliances in sleeping quarters where heaters are permitted and in rooms generally kept closed.

Solid-Fuel Room Heaters

Fires involving coal and wood stoves or room heaters have dropped dramatically since the early 1980s (Figure 10.2.22). Much of the improvement can be attributed to increased vigilance in the correct installation and operation of the appliances. Fires in solid-fuel room heaters are due primarily to two underlying conditions: (1) inadequate clearances to combustible materials and other installation deficiencies and (2) improper or inadequate maintenance. Some wood stoves need frequent charging, sometimes involving much regulating of draft controls to prevent overheating. Sometimes, too, weather conditions can affect the chimney draft, causing improper combustion.

A solid-fuel heater essentially is a fire chamber surrounded by a decorative enclosure. The chamber might be equipped with

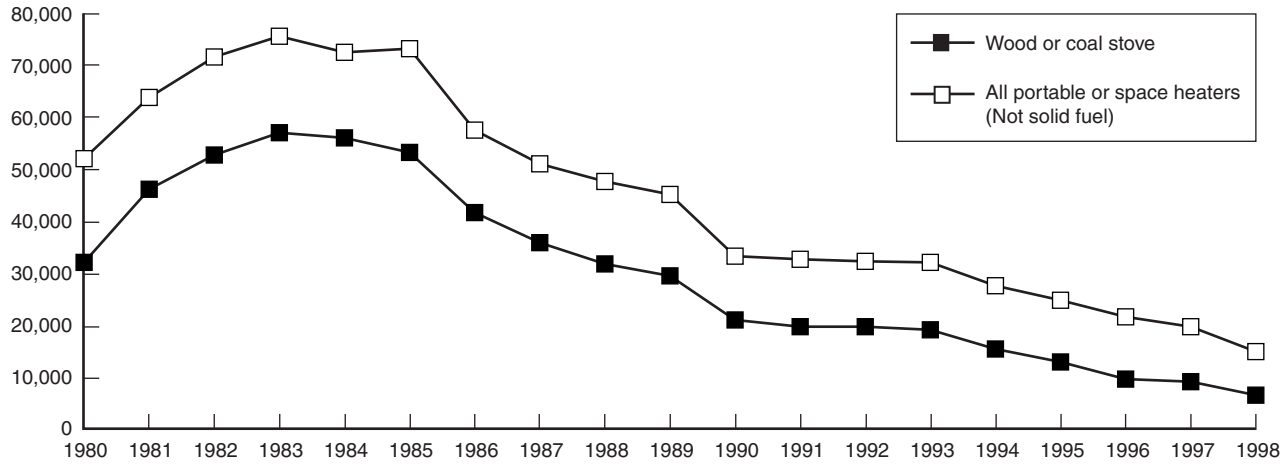


FIGURE 10.2.22 Home Fires Involving Space Heaters, 1980–1998[6]

manual draft controls or a thermostatic control and provided with a chimney connector and other parts that might be required for installation. Instructions that come with heaters that have been listed by testing laboratories are quite precise on the type of heat shielding and the clearances from combustibles that are required.

The vast majority of solid-fuel room heaters are designed to burn only wood, which is easily burned on the bottom of the fire chamber, resting on a bed of firebrick, ashes, or sand. For coal, a grate or other provision to supply air below the fuel bed is needed.

Unless a special chimney is called for by the listing or installation instructions (as in the case of room heaters for use in manufactured homes), the typical solid-fuel heater can be connected to either a standard masonry chimney or any listed factory-built chimney. Laboratory tests for listing heaters establish the dimensions required for adequate clearances. Because clearances from large heaters can exceed 36 in. (0.9 m), the tests may be performed with supplemental heat protection or shielding for walls. For proper clearances and floor protection, see the section of this chapter on installation.

Hazards with Solid-Fuel Room Heaters

Overfiring. If an appliance is overheated deliberately or through neglect, there is a severe and immediate hazard if the unit or its connector glows even a very dull red. Control is to simply close doors and air dampers until things cool down.

Careless Handling of Ashes Containing Live Coals. Ashes should never be collected in combustible containers, nor should the containers ever be placed on a combustible floor.

Inadequate Connector Clearance. Problems involving connector clearance include violations of the required 18 in. (457 mm) clearance or lack of adequate protection where a single wall connector must penetrate a combustible wall to join a masonry chimney. Reduced connector clearances are permissible in some instances, such as the entry of single wall connectors into listed supports for factory-built chimneys. The reduced clearances have been validated by tests and are described in the installation instructions for listed heaters (Figure 10.2.23).

Creosote Accumulation and Fires. Creosote is a collection of tars and other hydrocarbons produced by the pyrolytic distillation of wood. Under ideal conditions, these products are consumed in the flames of a wood fire. When wood is burned in a stove under air-limited conditions, it might not be entirely burned and could deposit on surfaces of the stove, connector, and chimney. Creosote is combustible and, if ignited, can fuel a

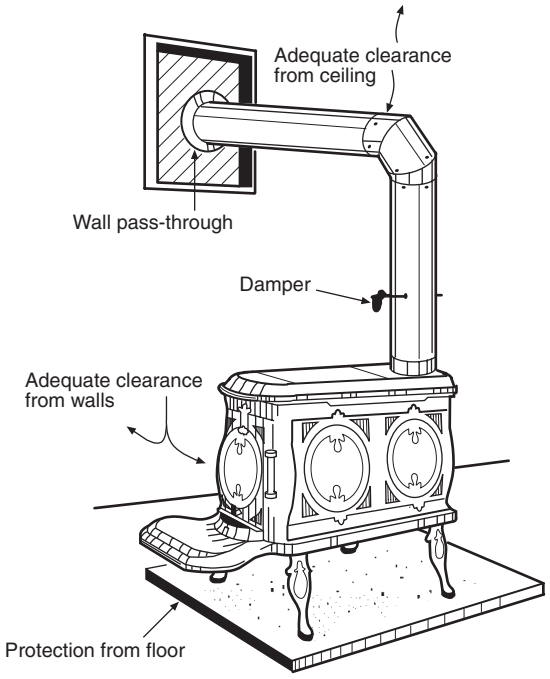


FIGURE 10.2.23 Adequate Clearances Necessary to Ensure Safe Operation of Coal and Wood Stoves

dangerous fire in portions of the venting system not designed to withstand combustion. The fire can damage the system components or spread to the adjacent structure.

Airtight wood stoves, when operated with draft controls restricted or with large fuel loads, can cause a significant buildup of creosote in a short period of time. Therefore, frequent inspection, and, when required, cleaning of the chimney system is necessary when these appliances are used.

The species and moisture content of the wood are not major determinants of the rate of creosote buildup, but habits of stove operation are. Proper sizing of the stove, with respect to the heating need, will help minimize the production of creosote by reducing the need for air-limited, low-temperature operation. The user should avoid long, extended burn cycles and large loads of fuel. The control of creosote and chimney fires is discussed in more detail under "Hazards of Chimneys," later in this chapter.

Restaurant Cooking Appliances

Restaurants employ a variety of cooking devices such as ranges, deep-fat fryers, steamers, broilers, hot plates and griddles, portable ovens, and others. These devices, like other heat-producing devices, require careful installation to avoid overheating of adjacent combustibles. In some of them, grease accumulates, adding to the fire hazard. NFPA 54 contains requirements for the installation of gas-fired restaurant cooking appliances. Ventilation of fixed restaurant cooking equipment is covered in NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations.*

Miscellaneous Heat-Producing Devices

There are so many miscellaneous heat-producing devices that it is unrealistic to treat each individually in this chapter. Certain basic principles apply to all of them, however, including provision for adequate clearances to combustibles, venting products of combustion, adequate air for combustion and ventilation, proper burner controls to safeguard against the hazard of the fuel, proper storage and handling of the fuel, and safety controls to safeguard the heat-producing device.

Testing laboratories test and list many miscellaneous types of heat-producing appliances, such as direct-fired heaters, incubators, lanterns, forges, and torches.

Kerosene Stoves. Self-contained, self-supporting kerosene-burning ranges, room heaters, or water heaters are not connected to chimneys but are equipped with integral fuel supply tanks not exceeding 2 gal (7.6 L) capacity. Terms often applied to kerosene room heaters are cabinet heaters and space heaters. Since they are not connected to chimneys, they can be moved rather easily although they are not considered portable. This feature of kerosene stoves can permit the creation of severe fire and life hazards due to improper placement of the stoves in relation to nearby combustibles and paths of exitways. Kerosene stoves listed by testing laboratories incorporate fire protection features that might be missing from those not listed. Among the more important features of listed stoves are the types of construction materials, primary control valves, and drip pans used in them.

Portable Kerosene Heaters. Portable kerosene heaters are similar in the potential for hazard to kerosene stoves because they are not connected to a chimney and are not required to have a permit for installation and use. The hazard in their use, however, is increased by their even greater portability. They are also subject to misfueling, substitution of gasoline or other inappropriate fuel, and refueling when hot, which can produce flammable vapors. The safest heaters incorporate fire safety features not included in others, such as special types of latching devices and integral sheet-metal trays under the burners to catch oil drips. They usually employ wick-type burners integral with the oil reservoir. Portable kerosene heaters should include a tip-over switch that automatically snuffs the burner if the unit is jostled or tipped.

Conversion Range Oil Burners. Range oil burners, which are found most frequently in the northeastern section of the United States, are designed to burn kerosene, range oil, or similar fuel. They are primarily installed in stoves or ranges originally designed to use solid fuel. They consist essentially of a single- or double-sleeve-type burner assembly, regulating valves, and an oil supply assembly with a suitable supporting stand and seamless connecting tubing. A thermal valve located in the burner compartment of the stove adjacent to the burner is installed in the oil supply line (Figure 10.2.24). Range oil burners should not be mistaken for conversion oil burners of the vaporizing-pot type designed for conversion of central heating appliances.

Salamanders. Salamanders are common miscellaneous portable heating devices. They are used at construction sites and in unheated buildings. Too frequently, a salamander consists of only a metal drum with some holes punched in it for draft and wood scrap and other construction waste materials for fuel. When constructed in this way, such devices present an acute spark hazard and the hazard of carbon monoxide poisoning because they are not chimney connected. Crude salamanders of this type, and gas- and oil-fired salamanders that have not been tested and listed by a laboratory, should not be used.

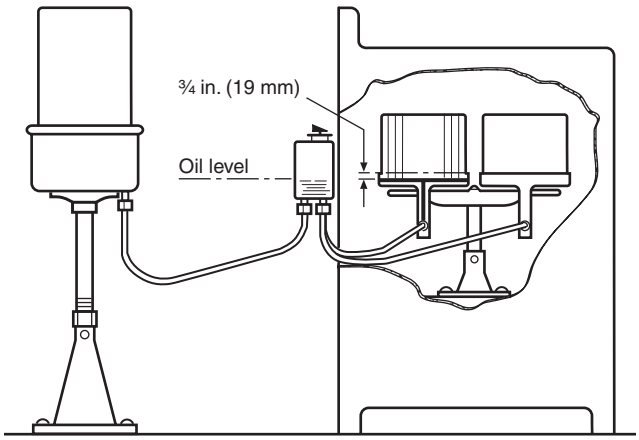


FIGURE 10.2.24 Typical Installation of Conversion Range Oil Burner

UL and CSA International laboratories test and list portable gas- and oil-fired heaters, such as salamanders. One way to use salamanders is to carry heated air indoors through flexible ducts from a heating unit located outdoors. NFPA 58, *Liquefied Petroleum Gas Code,* has extensive material on the use of LP-gas-fired portable heaters.

DISTRIBUTION OF HEAT BY DUCTS AND PIPES

Warm Air Distribution Systems

Central warm air heating systems consist basically of a heat exchanger with an outer casing or jacket that is connected to a system of ducts, air passages, or plenums that carry heated air (the supply side) to the spaces to be heated and return air (the return side) from the heated spaces to the heat exchanger.

NFPA 90B contains specific requirements for systems that are installed in one- and two-family dwellings and other occupancies not exceeding 25,000 ft^3 (700 m^3) in volume. Systems that are installed in spaces exceeding this size are covered in NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems.* This portion of the handbook is confined to a discussion of ducts for warm air heating systems installed in dwellings and other relatively small spaces.

Warm Air Supply Ducts. Warm air ducts must be installed with clearances as given in Table 10.2.2. They are substantially constructed of metal or of Class 0 or Class 1 duct materials and are properly supported and protected against injury. Duct materials are tested and listed by UL in accordance with UL 181, *Standard for Safety Factory-Made Air Ducts and Air Connectors,*[5] and are classified as follows:

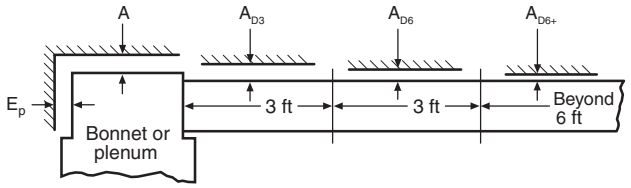
- **Class 0–Air duct.** Air ducts that have a fire hazard classification of zero (flame spread and smoke developed)
- **Class 1–Air duct.** Air ducts that have a flame spread rating of not more than 25 without evidence of continued progressive combustion and smoke developed rating of not more than 50

Supply Air Plenums. It is common practice in some localities to use the crawl space as the supply plenum for warm air heating systems when a one-story single-family house does not have a basement. These systems use a downflow furnace that discharges warm air through directional ducts into the crawl space. An opening cut in the floor of each room of the house and covered with a grille serves as the supply register. The hazards of these systems include use of combustible construction as a plenum, use of the crawl space for storage, presence of a large enclosed combustible area with no limitations on fire spread and with direct openings to every room of the house, and the possibility of reverse flow in the downflow furnace (the cold air return then becomes the supply duct). NFPA 90B gives specific recommendations and limitations applicable to the use of underfloor space as supply plenums, and it should be consulted for detailed guidance.

Horizontal supply ducts and vertical ducts, risers, boots, and register boxes within certain limits of the warm air furnace can reach temperatures that can become hazardous; therefore, safe clearances to combustibles must be maintained. The clearances required for the many possible configurations of warm air ductwork are specifically provided in NFPA 90B, which should be consulted.

Registers. To prevent excessive heat from developing in the duct system, one register or grille must be installed without a

TABLE 10.2.2 Installation Clearances, in Inches, for Horizontal Warm Air Ducts



A—Clearance above top of casing, bonnet, plenum, or appliance determined by Table 10.2.5
A_{D3}—Clearance from horizontal warm air duct within 3 ft (0.9 m) of plenum.
A_{D6}—Clearance from horizontal warm air duct between 3 and 6 ft (0.9 and 1.8 m) of plenum.
A_{D6+}—Clearance from horizontal warm air duct beyond 6 ft (1.8 m) of plenum.
E_P—Clearance from any side of bonnet or plenum.

If A Equals	*A_{D3} Equals*	*A_{D6} Equals*	*A_{D6+} Equals*	*E_P Equals*	*Method of Firing*
1	1	0	0[a]	1	Automatic oil, comb. gas-oil, or gas
2	2	0	0[a]	2	Automatic oil, comb. gas-oil, or gas
6	6	6	0[a]	6	Automatic oil, comb. gas-oil, or gas
6	6	6	1[a]	6	Automatic stoker fired[b]
18	18	6	1[a]	18	Any fuel or control

[a]Clearance A_{D6+} to be maintained to a point where there is a change in direction equivalent to 90 degrees or more.
[b]Furnace must be equipped with limit control that cannot be set higher than 250°F (120°C) and must also have a barometric draft control operated by draft intensity and permanently set to limit draft to a maximum intensity of 0.13 in. water gauge (32 kPa), otherwise clearances should be as indicated by any fuel.
For SI units: 1 in. = 25.4 mm; 1 ft = 0.305 m.

shutter and damper in the duct to it. The exceptions are automatic oil- or gas-fired systems that have approved temperature limit controls or systems with dampers and shutters designed so that they cannot shut off more than 80 percent of the duct area.

Where registers are installed in the floor over the furnace, as in pipeless furnaces or floor furnaces, the register box should consist of a double wall with an air space of not less than 4 in. (102 mm) between walls. Furnaces with a cold air passage around the warm air passage comply with this requirement.

Return Air Ducts and Plenums. The best way to conduct return air to the furnaces and duct heaters is through continuous ducts. Return ducts do not need to be made of the same materials as supply ducts except for those portions directly over the heating surface or within 2 ft (0.6 m) of the outer casing or jacket of the furnace or duct heater. They should not, however, be made of materials more combustible than 1-in. (25-mm) nominal wood boards. Underfloor spaces may be used for return ducts from rooms directly above, but such spaces should be used only if they are not more than 2 ft (0.6 m) in depth from the bottom of floor joists, are clean of all combustible material, and are tightly and substantially enclosed. A vertical stack for return air should not be connected to registers on more than one floor.

The interior of combustible ducts must be lined with metal at points where there is danger from smoldering or burning incandescent particles dropped through a register, such as directly under floor registers and at the bottom of vertical ducts.

Air Filters. Air filters should be the kind that will not burn freely or emit large volumes of smoke or other objectionable products of combustion. Filters qualifying as Class 1 and Class 2, as defined in NFPA 90B, are accepted as meeting these requirements. Only liquid adhesive coatings with a flashpoint of 325°F (163°C) or higher (Pensky-Martens closed-cup tester) are acceptable. Filters are not installed in ducts of heating systems unless the system design calls for them. Otherwise the filters may restrict the flow of air and cause dangerous overheating.

Solid Fuel Add-On Furnaces. Solid fuel add-on furnaces are designed to connect to the existing air distribution ductwork of a house and supply heated air as a supplement to the operation of the regular furnace. Most, though not all, are independently controlled, with a separate thermostat. A wood or coal fire is established in the unit, and the thermostat regulates the flow of air to the combustion chamber, and thereby the amount of heat produced. Properly installed and operated, add-on furnaces can supply all or most of the central heating needs of a home.

However, add-on furnaces can also present some unique hazards. They tend to have large combustion chambers that can be filled with a large volume of wood. When the heating need is not great, the thermostat tends to keep the fire low and smoldering, with consequent production of a large amount of creosote. Add-on furnaces and their venting systems need frequent inspection and cleaning.

NFPA 211, *Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances,* specifically prohibits the use of a chimney flue to vent both a solid fuel appliance and an appliance burning other fuels. Therefore, a properly installed solid fuel add-on furnace must have its own chimney flue, separate from that serving the conventional furnace or water heater.

The method by which the add-on is connected to existing ductwork is critical. Properly configured, the add-on will have its own distribution blower and not rely on the blower of the existing furnace. This allows the supply (hot air) plenum of the add-on to be connected to the supply plenum of the furnace; and the return (cold air) side of the add-on to draw air directly through the return ducting. This is called a *parallel* connection and allows the add-on to function identically with the conventional furnace.

A parallel connection can also be accomplished without connection of the return side of the add-on to the return ducting system. In this configuration, the add-on's blower is simply open and draws air from the surrounding area. This can cause significant depressurization of the basement, which could result in flow reversal of the add-on flue or other appliances in the area, with consequent spillage of combustion products. Such open installations are strongly discouraged.

A connection method that has been frequently used for unlisted and homemade add-on furnaces is a *series* connection. This configuration is definitely hazardous. In this form, the add-on does not have a blower, but attempts to use the existing furnace blower for air distribution. Both the return side and supply side of the add-on are connected to the existing return plenum or ductwork, with a baffle to direct the flow of return air through the add-on. As a result, hot air produced through the add-on is circulated through portions of the furnace and duct system, which were not designed for hot air. Furthermore, in a power failure the add-on will continue to produce heat, but the distribution blower will not run. Very hot air will back up and be concentrated in the return ducting system, which may be constructed of combustible materials. Fires can result from such installations.

Heating Panels. NFPA 90B recommends that heating panels be used only with automatically fired gas- or oil-burning or electric forced warm air systems that will limit furnace outlet air temperature to 200°F (93°C) or systems equipped with steam or hot-water heat exchangers utilizing steam that cannot exceed 15 psig (103 kPa) or hot water that cannot exceed 250°F (120°C).

Panels used with automatically fired forced warm air systems must be of noncombustible material or at least of material with a flame spread rating of not more than 25, as determined in accordance with NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials.*

Where the warm air supply is from a steam or hot-water heat exchanger, the panels may be made of material not more flammable than 1-in. (25-mm) nominal wood boards. No single vertical heating panel should serve more than one story of any building.

Steam and Hot-Water Pipes

The temperature of saturated steam varies with the pressure. For example, at atmospheric pressure the temperature of steam is

212°F (100°C), whereas at 25 psig (172 kPa) its temperature is 266.7°F (130.4°C). Other values of temperature of saturated steam at various pressures are given in Table 10.2.3.

Water at high temperature and pressure is also used for heating. The system pressure must always exceed the pressure at the saturation temperature to prevent the water from flashing to steam. This means that the pressure in high-temperature hot-water systems must exceed the values shown in Table 10.2.3 at the specific temperature at which the system operates. Most systems operate at temperatures between 250 and 430°F (120 and 220°C).

Recommended clearances for steam and hot-water pipes and radiators are given in Table 10.2.4.

Radiators and pipes should not be used as racks for drying purposes. Where radiators are placed in window recesses or concealed spaces, such spaces should be lined with noncombustible material, have ample air circulation, and be kept clean.

INSTALLATION OF HEATING APPLIANCES

Any source of heat is a potential fire hazard unless it is arranged to prevent the possibility of dangerous temperatures developing on adjacent combustible materials. It is possible for wood and certain other combustible materials to ignite at temperatures far below their usual ignition temperatures if they are continually exposed to relatively moderate heat over long periods of time.

TABLE 10.2.3 Temperature of Saturated Steam

Gauge Pressure		Temperature		Gauge Pressure		Temperature	
psi	*kPa*	*°F*	*°C*	*psi*	*kPa*	*°F*	*°C*
0[a]		212.0	100.0	40	275	286.7	141.5
1	6.895	215.4	101.8	45	310	292.3	144.6
2	13.79	218.5	103.3	50	345	297.7	147.6
3	20.69	221.5	105.3	75	517	320.0	160.0
4	27.58	224.4	106.9	100	690	337.8	169.9
5	34.48	227.1	108.4	125	862	352.9	178.3
6	41.37	229.6	109.8	150	1,034	365.9	185.5
7	48.26	232.3	111.3	200	1,379	387.9	197.7
8	55.16	234.7	112.6	300	2,068	421.7	216.5
9	62.06	237.0	113.9	400	2,758	448.2	231.2
10	68.90	239.4	115.2	500	3,448	470.1	243.4
11	75.84	241.5	116.4	600	4,137	488.8	253.8
12	82.74	243.7	117.6	700	4,826	505.6	263.1
13	89.64	245.8	118.8	800	5,516	520.3	271.3
14	96.53	247.8	119.9	900	6,205	534.0	278.9
15	103.4	249.8	121.0	1,000	6,895	546.4	285.8
20	137.9	258.8	126.0	1,500	10,342	597.6	314.2
25	172.4	266.7	130.4	2,000	13,790	636.8	336.0
30	206.8	274.1	134.5	3,211	22,139	706.1[b]	374.5
35	241.0	206.8	138.1				

Note: Superheated steam has a higher temperature than saturated steam at the same pressure, depending upon the degree of superheat.
[a]Zero gauge pressure corresponds to an absolute pressure of 14.696 psi (101.329 kPa).
[b]Critical point, from Keenan's Tables.

TABLE 10.2.4 Installation Clearances for Steam and Hot-Water Pipes and Radiators

Description	Clearances *in.*	Clearances *mm*
A. Hot-water pipes and radiators supplied by automatically fired gas, gas-oil, or oil-burning boilers equipped with limit control that cannot be set to permit a water temperature above 150°F (66°C).	None	
B. Hot-water and steam pipes and radiators supplied with hot water at not more than 250°F (120°C) except as permitted in A above, and with steam at not over 15 psig (103 kPa).	1*	25*
C. Steam pipes carrying steam at pressures above 15 psig (103 kPa), but not over 500 psig (3450 kPa)	6	15

*At points where pipes emerge from a floor, wall, or ceiling, the clearance of the opening through the finish floor boards or wall or ceiling boards may not be less than ½ in. (13 mm). Each such opening must be covered with a plate of noncombustible material.

To safeguard against this possibility, heat-producing appliances must be installed with adequate clearance between the appliance and combustibles. Then, under conditions of maximum heat (long and continued exposure), the temperature of exposed combustibles will not exceed dangerous limits. Minimum clearances for various types of heat-producing devices, which should prevent the temperature from exceeding the maximum in exposed combustibles, have been determined by testing laboratories and through field experience. Table 10.2.5. gives the required standard clearances around and above gas- and oil-fired and electrical residential, commercial, and industrial heat-producing appliances. Table 10.2.6 gives clearances for solid-fuel burning appliances. The term *listed appliances,* which appears in the subheads of the tables, refers to appliances that have been tested by testing laboratories. The proper clearances for these appliances, as determined by tests, are published in a listing. The recommended clearances are also indicated either on the appliance or in the manufacturer's installation manual included with the appliance.

Examples of laboratories that test and list appliances are FM Global Research, Underwriters Laboratories Inc., Underwriters Laboratories of Canada, Intertek and Testing Services, and CSA International.

Modifications of Clearances

Listings of heat-producing appliances and methods for setting clearances between appliances and combustible surfaces are based on criteria in Underwriters Laboratories Inc. test standards:[6]

- Maximum temperature rise of 117°F (65°C) above room temperature on exposed surfaces
- Maximum temperature rise of 90°F (50°C) above room temperature on unexposed surfaces, such as beneath the appliance, floor protector, or wall-mounted protective device

TABLE 10.2.5 Standard Installation Clearances for Nonsolid Fuel Heat-Producing Appliances[a]

These clearances apply unless otherwise shown on listed appliances. Appliances should not be installed in alcoves or closets, unless so listed. For installation on combustible floors, see note b.

Residential-Type Appliances for Installation in Rooms That Are Large[c]		Appliance											
		Above Top of Casing or Appliance		From Top and Sides of Warm-Air Bonnet or Plenum		From Front[d]		From Back			From Sides		
		in.	*mm*	*in.*	*mm*	*in.*	*mm*	*in.*	*mm*		*in.*	*mm*	
Boilers and Water Heaters													
Steam boilers—15 psi (103 kPa)	Automatic oil or comb. gas-oil	6	152		—	24	610	6	152		6	152	
	Automatic gas	6	152		—	18	457	6	152		6	152	
Water boilers—250°F (120°C)	Electric	6	152		—	18	457	6	152		6	152	
Water heaters—200°F (93°C)													
All water-walled or jacketed													
Furnaces—Central													
Gravity, upflow, downflow, horizontal and duct. warm-air—250°F (120°C) max.	Automatic oil or comb. gas-oil	6[e]	152	6[e]	152	24	610	6	152		6	152	
	Automatic gas	6[e]	152	6[e]	152	18	457	6	152		6	152	
	Electric	6[e]	152	6[e]	152	18	457	6	152		6	152	
Furnaces—Floor													
For mounting in combustible floors	Automatic oil or comb. gas-oil	36	914		—	12	305	12	305		12	305	
	Automatic gas	36	914		—	12	305	12	305		12	305	
	Electric	36	914		—	12	305	12	305		12	305	
Heat Exchanger													
Steam—15 psi (103 kPa) max.	—	1	25	1	25	1	25	1	25		1	25	
Hot water—250°F (120°C) max.													
Room Heaters													
Circulating type	Oil	36	914		—	24	610	12	305		12	305	
Vented or unvented	Gas	36	914		—	24	610	12	305		12	305	
	Oil	36	914		—	36	914	36	914		36	914	
Radiant or other type	Gas	36	914		—			18	457		18	457	
Vented or unvented	Gas with double metal or ceramic back	36	914		—	36	914	12	305		18	457	
Radiators													
Steam or hot water	Gas	36	914		—	6	152	6			6		
Ranges—cooking stoves		[f]	[f]							*Firing Side*			*Opp. Side*
Vented or unvented	Oil	30	762		—			9	229	24 in.	10	254	18 in.
	Gas	30	762		—		—	6	152	6 in.	6	152	6 in.
	Electric	30	762		—		—	6	152			152	
Clothes dryers													
Listed types	Gas	6	152		—	24	610	6	152		6	152	
	Electric	6	152		—	24	610	0			0	0	
Incinerators	[g]												
Domestic types	—	36	914		—	48	1219	36	914		36	914	

(continued)

TABLE 10.2.5 Continued

Low-Heat Appliances Any and All Physical Sizes, Except as Noted		Appliance									
		Above Top of Casing or Appliance[h]		From Top and Sides of Warm-Air Bonnet or Plenum		From Front		From Back[h]		From Sides[h]	
		in.	*mm*	*in.*	*mm*	*in.*	*mm*	*in.*	*mm*	*in.*	*mm*
Boilers and Water Heaters											
100 ft^3 (2.8 m^3) or less, any psi steam	All fuels	18	457		—	48	1219	18	457	18	457
50 psi (345 kPa) or less, any size	All fuels	18	457		—	48	1219	18	457	18	457
Unit Heaters											
Floor mounted or suspended, any size	Steam or hot water	1	25		—		—	1	25	1	25
Suspended, 100 ft^3 (2.8 m^3) or less	Oil or comb., gas-oil	6	152		—	24	610	18	18	457	
Suspended, 100 ft^3 (2.8 m^3) or less	Gas	6	152		—	18	457	18	457	18	457
Suspended, over 100 ft^3 (2.8 m^3)	All fuels	18	457		—	48	1219	18	457	18	457
Floor mounted, any size	All fuels	18	457		—	48	1219	18	457	18	457
Ranges—Restaurant Type											
Floor mounted	All fuels	48	1219		—	48	1219	18	457	18	457
Other Low-Heat Industrial Appliances											
Floor mounted or suspended	All fuels	18	457	18	457	48		18	457	18	457
Commercial-Industrial Type Medium Heat Appliances											
Boilers and Water Heaters											
Over 50 psi (345 kPa), over 100 ft^3 (2.8 m^3)	All fuels	48[i]	1220		—	96	2440	36[i]	910	36[i]	910
Other Medium-Heat Industrial Appliances											
All sizes	All fuels	48[i]	1220	36	910	99	2440	36[i]	910	36[i]	910
Incinerators											
All sizes		48[i]	1220		—	96	2440	36[i]	910	36[i]	910
High-Heat Industrial Appliances											
All sizes	All fuels	180[i]	4570		—	360	9140	120[i]	910	120[i]	910

[a]Standard clearances may be reduced by affording protection to combustible material in accordance with Table 10.2.7.
[b]An appliance may be mounted on a combustible floor if the appliance is listed for installation on a combustible floor, or if the floor is protected in an approved manner. For details of protection, see NFPA 211.
[c]Rooms that are large in comparison to the size of the appliance are those having a volume equal to at least 12 times the total volume of a furnace and at least 16 times the total volume of a boiler. If the actual ceiling height of a room is greater than 8 ft (2.4 m), the volume of a room must be figured on the basis of a ceiling height of 8 ft (2.4 m).
[d]The minimum dimension should be that necessary for servicing the appliance, including access for normal maintenance, care, tube removal, and so on.
[e]For a listed oil, combination gas-oil, gas, or electric furnace, this dimension may be 2 in. (50 mm) if the furnace limit control cannot be set higher than 250°F (120°C), or this dimension may be 1 in. (25 mm) if the limit control cannot be set higher than 200°F (93°C).
[f]To combustible material or metal cabinets. If the underside of such combustible material or metal cabinet is protected with asbestos millboard at least ¼ in. (6.4 mm) thick covered with sheet metal of not less than 24 in. (610 mm).
[g]Clearance above the charging door should be not less than 48 in. (1219 mm).
[h]If the appliance is encased in brick, the 18-in. (457-mm) clearance above and at sides and rear may be reduced to not less than 12 in. (305 mm).
[i]If the appliance is encased in brick, the clearance above may be not less than 36 in. (914 mm), and at sides and rear may be not less than 18 in. (457 mm).

TABLE 10.2.6 Standard Clearances for Solid-Fuel-Burning Appliances

(For reduced clearances, see Table 10.2.7.) These clearances apply to listed appliances installed in rooms that are large in comparison with the size of the appliances.

	Above Top of Casing or Appliance, above Top and Sides of Furnace Plenum or Bonnet		From Front		From Back[a]		From Sides[a]	
Appliance Type	*in.*	*mm*	*in.*	*mm*	*in.*	*mm*	*in.*	*mm*
Residential Appliances Steam boilers—15 psi (103 kPa) Water boilers—250°F (120°C) max. Water boilers—200°F (93°C) max. All water-walled or jacketed	6	152	48	1219	6[b]	152[b]	6[b]	152[b]
Furnaces								
Gravity and forced air[c]	18	457	48	1219	18	457	18	457
Room heaters, fireplace stoves, combinations	36	914	36	914	36	914	36	914
					Firing Side		Opposite Side	
Ranges								
Lined fire chamber	30[d]	762[d]	36	914	24	610	18	457
Unlined fire chamber	30[d]	762[d]	36	914	36	914	18	457

[a]Provisions for fuel storage must be located at least 36 in. (914 mm) from any side of the appliance.
[b]Adequate clearance for cleaning and maintenance must be provided.
[c]For clearances from air ducts, see NFPA 90B.
[d]To combustible material or metal cabinets. If the underside of such combustible material or metal cabinet is protected with sheet metal of not less then 24 gauge (0.024 in. [0.61 mm]), spaced out 1 in. (25 mm), the distance shall be permitted to be reduced to not less than 24 in. (610 mm).

Source: NFPA 211, *Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances.*

These requirements are based on the fact that, while the ignition temperature of wood products is generally quoted to be on the order of 392°F (200°C),[7] wood that is exposed to constant heating over a period of time may undergo chemical change, resulting in a much lower ignition temperature and increased potential for self-ignition.

Mitchell[8] presents data on wood fiberboard exposed to temperatures as low as 229°F (109°C) that resulted in ignition after prolonged exposure. MacLean[9,10] reports charring of wood samples at temperatures as low as 200°F (93°C). He concludes that wood should not be exposed to temperatures appreciably higher than 151°F (66°C) for long periods. McGuire[11] suggests that the maximum safe temperatures on the surface of a combustible material adjacent to a constant heat source should be no more than 212°F (100°C).

Clearly, the ignition of wood at moderately elevated temperatures is a complex phenomenon; the length of exposure is indeed an important parameter.[12,13] Although exact limits recommended in the literature vary due to exposure time and details of the tests conducted, documented fires involving the ignition of wood members near low-pressure steam pipes[14] suggest an upper temperature limit for combustible materials exposed to long-term, low-level heating should not be appreciably higher than 212°F (100°C).

The clearances given in Tables 10.2.5 and 10.2.6 will provide reasonable protection for exposed surfaces, including those of considerable area, against assumed conditions of continuous operation of heat-producing appliances at maximum temperatures. However, if the appliance is very large, increased clearances to combustible materials might be required. This is a good reason why all appliances should be installed in accordance with the terms of their listing. Prior to and during the heating season, frequent checks should be made to assure that the area is free of combustibles.

Installing heating appliances that under normal operation will not expose adjacent combustible materials to dangerous temperatures is not sufficient. Clearances and protection also must be designed for reasonable protection when the heating device is operated at its maximum temperature. However, under any conditions of operation the temperature of the exposed combustible materials should not exceed 180°F (82°C). Some provision for ventilation, air circulation, or other method of cooling is necessary to dissipate heat.

In large rooms, a suitable clearance between a heating appliance and combustible material is all that is necessary to prevent ignition. In small rooms or poorly ventilated spaces, particularly where the size of the heating device is large in proportion to the room, dangerous temperatures could be built up no matter how

great the clearance unless some provision is made for cooling by air circulation. Only appliances designed and tested for installation in confined spaces, such as alcoves or closets, are to be installed in such spaces. The clearances specified for them are observed whether the enclosing walls are combustible or noncombustible.

Table 10.2.7 and Figures 10.2.25 through 10.2.30 show how clearances can be reduced by installing protection between the heat-producing device and the combustible material. This information is especially helpful in situations of inadequate clearance in which it would be impractical to move the heat-producing appliance.

TABLE 10.2.7 Reduction of Appliance Clearance with Specified Forms of Protection[a–j]

Clearance Reduction System Applied to and Covering All Combustible Surfaces within the Distance Specified as Required Clearance with No Protection (See Table 10.2.4)	Maximum Allowable Reduction in Clearance (%)		If the required clearance with no protection is 36 in. (914 mm), the clearances below are the minimum allowable clearances; for other required clearances with no protection, calculate minimum allowable clearance from maximum allowable reduction[i,j]			
			As Wall Protector		As Ceiling Protector	
	As Wall Protector (%)	*As Ceiling Protector (%)*	*in.*	*mm*	*in.*	*mm*
3½-in. (90-mm) thick masonry wall without ventilated air space[a]	33	—	24	610	—	—
½-in. (13-mm) thick noncombustible insulation board over 1 in. (25 mm) glass fiber or mineral wool batts without ventilated air space[b]	50	33	18	457	24	610
0.024 in. (0.61 mm) 24-gauge sheet metal over 1 in. (25.4 mm) glass fiber or mineral wool batts reinforced with wire, or equivalent, on rear face with ventilated air space[c]	66	50	12	305	18	457
3½-in. (90-mm) thick masonry wall with ventilated air space[d]	66	—	12	305	—	—
0.024-in. (0.61-mm) 24-gauge sheet metal with ventilated air space[e]	66	50	12	305	18	457
½-in. (13-mm) thick noncombustible insulation board with ventilated air space[f]	66	50	12	305	18	457
0.024 in. (0.61 mm) 24-gauge sheet metal with ventilated air space over 0.024 in. (0.61 mm) 24-gauge sheet metal with ventilated air space[g]	66	50	12	305	18	457
1 in. (25 mm) glass fiber or mineral wool batts sandwiched between two sheets 0.024 in. (0.61 mm) 24-gauge sheet metal with ventilated air space[h]	66	50	12	305	18	457

[a]Spacers and ties must be of noncombustible material. No spacers or ties are to be used directly behind appliance or conductor.

[b]With all clearance reduction systems using a ventilated air space, adequate air circulation must be provided as described in Figure 10.2.27. There must be at least 1 in. (25 mm) between the clearance reduction system and combustible walls and ceilings for clearance reduction systems using a ventilated air space.

[c]Mineral wool batts (blanket or board) must have a minmum density of 8 lb/ft^3 (128.7 kg/m^3) and have a minimum melting point of 1500°F (816°C).

[d]Insulation material used as part of clearance reduction system must have a thermal conductivity of 1.0 (Btu·in.)/(ft^2·hr·°F) or less. Insulation board must be formed of noncombustible material.

[e]If a single-wall connector passes through a masonry wall used as a wall shield, there must be at least ½ in. (13 mm) of open, ventilated air space between the connector and the masonry.

[f]There must be at least 1 in. (25 mm) between the appliance and the protector. In no case must the clearance between the appliance and the wall surface be reduced below that allowed in the table.

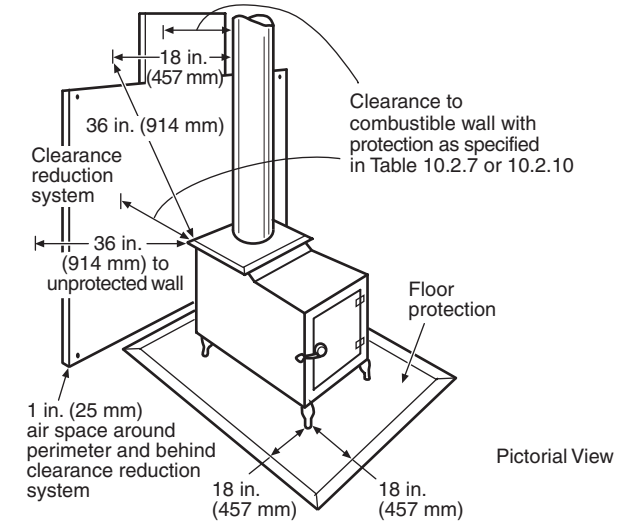
[g]Clearances in front of the loading door or ash removal door, or both, of the appliance must not be reduced from those in Section 9.5 of NFPA 211.

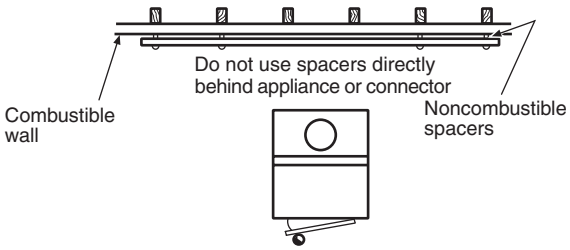
[h]All clearances and thicknesses are minimums; larger clearances and thicknesses shall be permitted.

[i]To calculate the minimum allowable clearance, the following formula can be used: $C_{pr} = C_{un} \times (1 - R/100)$, where C_{pr} is the minimum allowable clearance, C_{un} is the required clearance with no protection, and R is the maximum allowable reduction in clearance.

[j]Refer to Figures 10.2.28 and 10.2.29 for other reduced clearances using materials found in (c) through (j) of this table.

Source: NFPA 211, *Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances*.





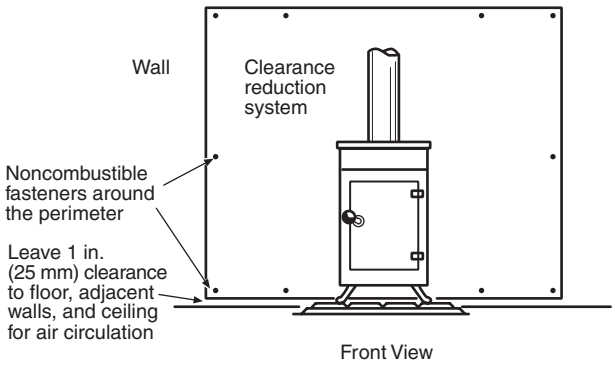
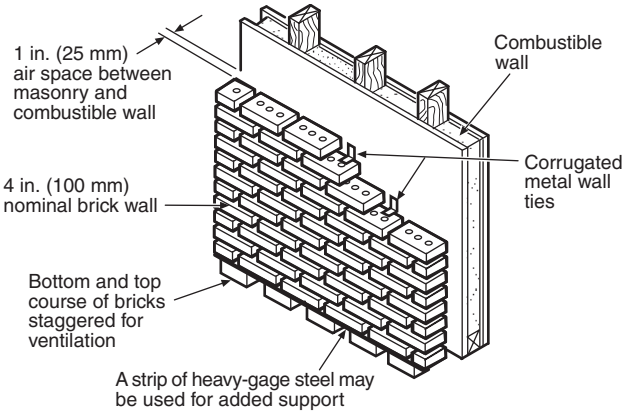
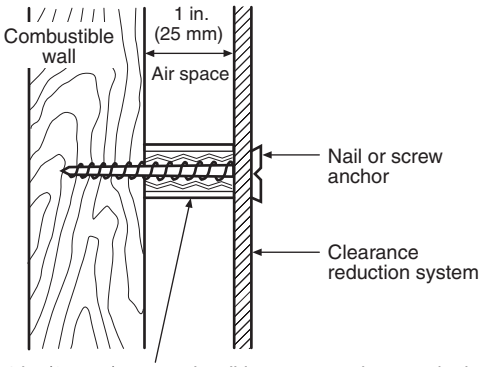


FIGURE 10.2.25 Clearance Reduction System for a Heat-Producing Appliance. The system is a barrier of metal, metal and insulating material, or masonry heat-resistive material with an air space between the barrier and a combustible surface.



Note: Do not place masonry wall ties directly behind appliance or connector.

FIGURE 10.2.26 Masonry Clearance Reduction System



1 in. (25 mm) noncombustible spacer, such as stacked washers, small-diameter pipe, tubing, or electrical conduit.

Masonry walls may be attached to combustible walls using wall ties.

Do not use spacers directly behind appliance or connector.

FIGURE 10.2.27 Anchoring a Clearance Reduction System to a Combustible Wall

Clearance Reduction Systems. If the air space between heating appliances and combustible material is small, a barrier of metal, metal and insulating material, or masonry heat-resistive material should be installed. Metal and masonry shields, or clearance reduction systems, tend also to distribute the heat, preventing in some measure its building up at one location. Except for specific systems described in Table 10.2.7, an air space must be left between the shields and the heat-radiating surface on one side and between the barrier and the combustible material on the other. The air currents set up by this procedure will prevent the combustible material from attaining a dangerous temperature, even with the smaller clearance.

Limitations of Insulation

To make certain that insulating material will provide adequate protection, one needs to understand its limitations. The insulation can be used on the heating appliance or in combination with sheet metal and air spaces (see Table 10.2.7) if its value under such circumstances has been verified by tests. Many heat-producing appliances have built-in insulation, which makes it safer to reduce the required clearances to combustible material.

Insulation alone, however, is not sufficient. Regardless of the thickness of insulation, long continued heat can eventually penetrate it. However, if some method is used to conduct the

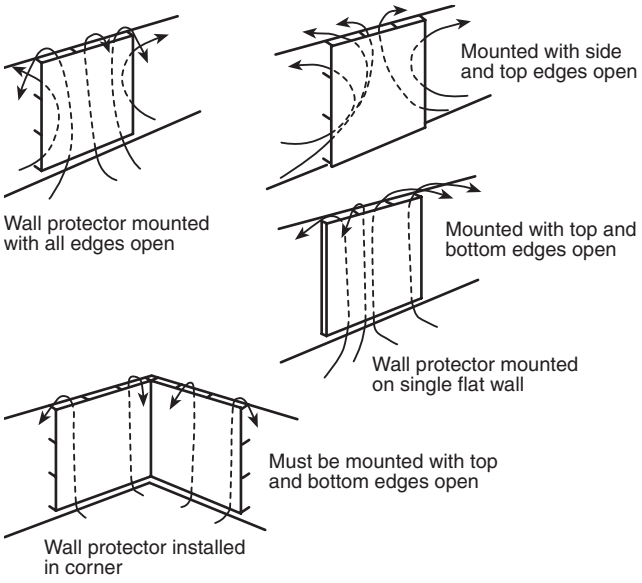
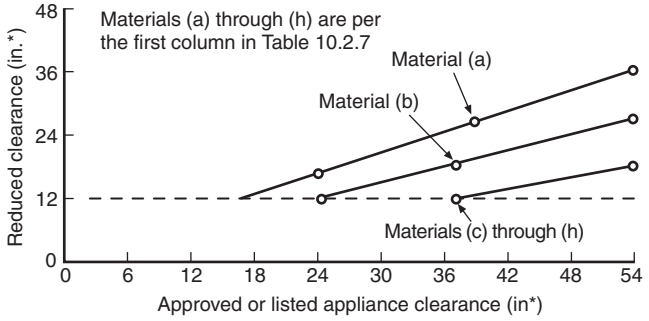


FIGURE 10.2.28 Airflow Patterns for Various Configurations of Clearance Reduction Systems Having an Air Space Between the Barrier and the Combustible Surface It Protects

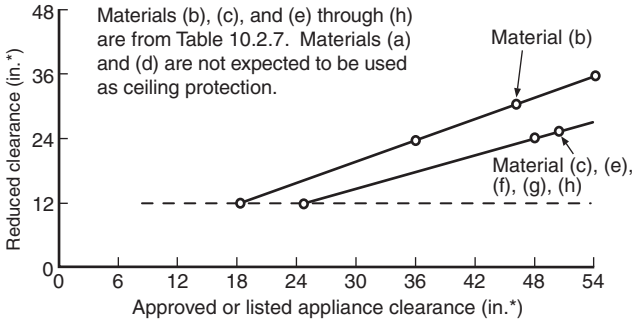
heat away before it reaches the combustible material, the insulation will provide adequate protection.

Continued high temperatures over long periods of time can cause fires under apparently safe conditions. Figure 10.2.31 shows fires caused under conditions that the layperson might consider safe. Solid masses of brick or concrete or plaster finish might not provide any fire protection under some circumstances,



*1 in. equals 25 mm.

FIGURE 10.2.29 Wall Protection Using Materials Specified in Table 10.2.7



*1 in. equals 25 mm.

FIGURE 10.2.30 Ceiling Protection Using Materials Specified in Table 10.2.7

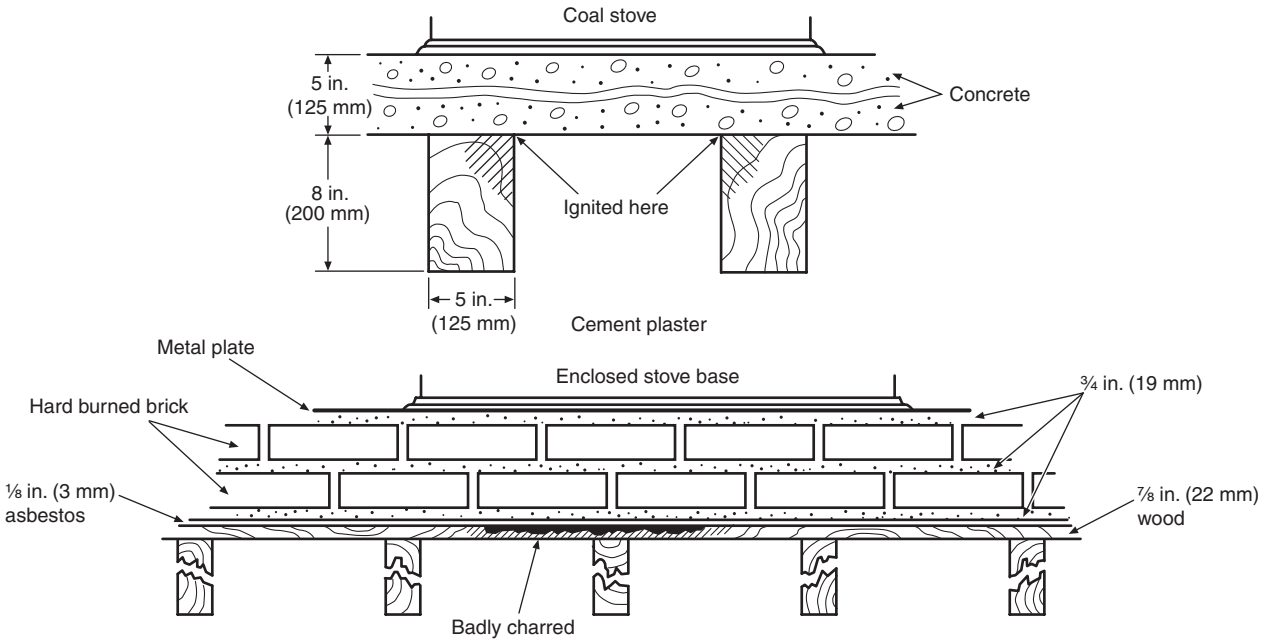


FIGURE 10.2.31 Typical Fires Due to Improperly Installed Heating Appliances

especially where masonry coverings are attached directly to the surface of the combustible material. Heat transfer to the combustible material is usually more efficient as the density of the covering material increases. Therefore, without an air space between the masonry and the combustibles, the heat transfer can actually increase, resulting in the ignition of the combustibles. However, since the masonry products do have a relatively large mass, it will take some time of operation of the appliance to transfer sufficient energy to ignite combustibles. This, however, is entirely dependent on the weight and dimensions of the masonry and the rate of heat transfer from the appliance. The same rationale would also apply to products other than masonry attached directly to the surface of combustibles.

Mountings

The limitations of masonry, concrete, metal, and other materials as insulating mediums apply particularly to the underside of stoves, heaters, boilers, furnaces, and other similar heat-producing appliances. Tables 10.2.8 and 10.2.9 list mountings for various classes of heat-producing appliances.

The testing laboratories indicate in their listings whether the appliances tested may be installed on combustible or noncombustible floors. In some cases, there is a statement on the appliance itself to the effect that it may be installed on a combustible floor. If no such indication appears, however, it is advisable to check the listing for the particular appliance.

Air for Combustion and Ventilation

In many locations, combustion-type heat-producing appliances have ample sources of air for efficient combustion in addition to the ventilation required to prevent undue temperature rises. In basements of dwellings, for example, sufficient air comes in through the cracks around doors and windows.

In relatively tight rooms, such as furnace and boiler rooms, a means to supply air for combustion and ventilation must be provided. Because there are so many variables involved, there is no universally accepted formula for calculating the size of openings necessary to provide adequate air for combustion and ventilation. For example, the tightness and size of the furnace or boiler room, and the operation of exhaust fans and other equipment, would affect the static air pressure in the building. Both NFPA 31 and NFPA 54, as well as other standards pertaining to heat-producing appliances, include specific recommendations on how to supply the air for combustion and ventilation. For certain laboratory-tested appliances, notably gas- and oil-burning appliances for installation in closets, the minimum size necessary to provide enough air for the operation of the unit and ventilation of the room or space is specified for an opening to the heater room or space.

In recent years there has been a clear trend toward tighter, more energy-efficient buildings, particularly houses. Such buildings have less ability to supply the necessary combustion air through natural infiltration. At the same time there has been an increase in the use of high-capacity exhaust and ventilation devices, such as attic fans and down-draft-powered cooking ranges. The operation of such devices tends to forcibly remove more air than can easily be replaced by infiltration. Such buildings are prone to depressurization, where the pressure inside the house, or portions of it, is significantly lower than the atmospheric pressure outside.

Depressurization can cause constant or intermittent spillage of flue gases from combustion appliances. If the drop in building pressure is greater than the draft created in the chimney or vent, flue gases and air will be drawn down through the venting system and into the building—a phenomenon called backdrafting. This has a serious negative effect on indoor air quality. The moisture produced by combustion will raise indoor humidity levels and promote the growth of molds and fungus. If combustion is not complete, carbon monoxide and other products may be introduced to the indoor environment and can become concentrated to dangerous levels.

Direct-vent, "sealed combustion" appliances are essentially immune to such problems, since they take combustion air directly from the outdoors and do not communicate with the indoor atmosphere. Appliances with powered exhausts are also less likely to suffer from backdrafting. For natural draft, conventionally vented appliances, methods of predicting and diagnosing the risk of backdrafting in any particular house are being developed and popularized. Codes are increasingly requiring positive provisions for makeup air in tight, mechanically ventilated houses, so that indoor pressure does not become exceedingly low.

Installation of a natural draft appliance should always include an empirical test of the sufficiency of draft and vent flow. Such tests should be conducted with other exhaust devices operating, including fans and other appliances, to simulate worst-case conditions under which the appliance must properly operate and be fully vented.

Clearances for Servicing

Clearances must also be provided for servicing and maintenance of equipment. Lack of proper servicing and good maintenance can result in fires. If lack of space around an appliance makes accessibility difficult, the appliance, or at least some parts of it, will be neglected. This same reasoning applies to appliances located in out-of-the-way places and places difficult to reach. Suspended furnaces and furnaces in attics and underfloor crawl spaces are typical examples of such installations.

CHIMNEY AND VENT CONNECTORS

Chimney and vent connectors are specifically the pipe or breeching used to connect fuel-burning appliances with the required chimney or vent, unless the chimney or vent is attached directly to the appliance. NFPA 211 includes requirements for chimney and vent connectors and should be consulted for information on materials to be used and the sizing and installation of connectors.

Chimney and vent connectors must be installed with adequate clearances to combustibles. Table 10.2.10 provides guidance for appropriate clearances. Table 10.2.11 shows how clearances can be reduced by installing protection between the connector and combustible material.

TABLE 10.2.8 Floor Mountings for Residential Nonsolid Fuel Heat-Producing Appliances
(See Table 10.2.9 for residential solid fuel appliances)

Type of Mounting	*Required for the Following Types of Heaters and Furnaces*
No Floor Protection:	
Combustible floors.[a]	Residential-type central furnaces so arranged that the fan chamber ccupies the entire area beneath the firing chamber and forms a well-ventilated air space of not less than 18 in. (460 mm) in height between the firing chamber and the floor, with at least one metal baffle between the firing chamber and the floor Low-heat appliances (see Table 10.2.5 for examples) in which flame and hot gases do not come in contact with the base, on legs that provide not less than 18 in. (460 mm) open space under the base of the appliance, with at least one sheet metal baffle between any burners and the floor Other appliances for which there is evidence that they are designed for safe operation when installed on combustible floors
Metal:	
Sheet metal not less than 24 gauge (0.024 in. [0.6 mm]) or other approved noncombustible material, laid over a combustible wood floor.[a]	Heating and cooking appliances set on legs or simulated legs that provide not less than 4 in. (100 mm) open space under the base Ordinary residential stoves with legs Residential ranges with legs Residential room heaters with legs Water heaters with legs Laundry stoves with legs Room heaters with legs[b]
Hollow Masonry:	
Hollow masonry not less than 4 in. (100 mm) in thickness laid with ends unsealed and joints matched in such a way as to provide free circulation of air through the masonry.	Downflow furnaces
Hollow Masonry and Metal:	
Hollow masonry not less than 4 in. (100 mm) in thickness covered with sheet metal not less than 24 gauge (0.024 in. [0.61 mm]), laid over a combustible floor. The masonry will be laid with ends unsealed and joints matched in such a way as to provide a free circulation of air from side to side through the masonry.	Heating furnaces and boilers in which flame and hot gases do not come in contact with the base Floor-mounted heating and cooking appliances Residential stoves without legs Residential ranges without legs Room heaters without legs Water heaters without legs Laundry stoves without legs Residential-type incinerators Restaurant ranges on 4 in. (100 mm) legs Other low-heat appliances on 4 in. (100 mm) legs Medium-heat appliances on legs which provide not less than 24 in. (600 mm) open space under the base
Two Courses Masonry and Plate:	
Two courses of 4 in. (100 mm) hollow clay tile covered with steel plate not less than 3⁄16 in. (5 mm) in thickness, laid over a combustible floor. The courses of tile will be laid at right angles with ends unsealed and joints matched in such a way as to provide a free circulation of air through the masonry courses.	Heating furnaces and boilers in which flame and hot gases come in contact with the base Restaurant ranges Other low-heat appliances
Fire-Resistive Floors Extending 6 in. (150 mm):	
Floors of fire-resistive construction with noncombustible flooring and surface finish and with no combustible material against the underside thereof, or on fire-resistive slabs or arches having no combustible material against the underside thereof. Such construction will extend not less than 6 in. (150 mm) beyond the appliance on all sides, and where solid fuel is used, it will extend not less than 18 in. (460 mm) at the front or side where ashes are removed.	Floor-mounted heating and cooking appliances Residential-type room heaters Residential-type water heaters

TABLE 10.2.8 Continued

Type of Mounting	*Required for the Following Types of Heaters and Furnaces*
Fire-Resistive Floors Extending 12 in. (300 mm):	
Floors of fire-resistive construction with noncombustible flooring and surface finish and with no combustible material against the underside thereof, or on fire-resistive slabs or arches having no combustible material against the underside thereof. Such construction will extend not less than 12 in. (300 mm) beyond the appliance on all sides, and where solid fuel is used, it will extend not less than 18 in. (460 mm) at the front or side where ashes are removed.	Heating furnaces or boilers Restaurant-type cooking appliances Residential-type incinerators. Other low-heat appliances.
Fire-Resistive Floors Extending 3 ft (0.9 m):	
Floors of fire-resistive construction with noncombustible flooring and surface finish and with no combustible material against the underside thereof, or on fire-resistive slabs or arches having no combustible material against the underside thereof. Such construction will extend not less than 3 ft (900 mm) beyond the appliance on all sides, and where solid fuel is used, it will extend not less than 8 ft (2.4 m) at the front or side where ashes are removed.	Medium-heat appliances and furnaces (See Table 10.2.7 for examples.)
Fire-Resistive Floors Extending 10 ft (3.1 m):	
Floors of fire-resistive construction with noncombustible flooring and surface finish and with no combustible material against the underside thereof. Such construction will extend not less than 10 ft (3.1 m) beyond the appliance on all sides, and where solid fuel is used, it will extend not less than 30 ft (9.3 m) at the front or side where hot products are removed.	High-heat appliances and furnaces (See Table 10.2.7 for examples.)

[a]If an appliance is mounted on a combustible floor, and solid fuel is used or the appliance is a domestic-type incinerator, a sheet of ¼ in. (6 mm) asbestos covered by sheet metal not less than 24 gauge (0.024 in. [0.61 mm]) will be required, extending at least 18 in. (460 mm) from the appliance on the front or side where ashes are removed. (The sheet of asbestos may be omitted where the protection required under the appliance is sheet metal only.) For residential-type incinerators, the protection must also extend at least 12 in. (300 mm) beyond all other sides. If the appliance is installed with clearance less than 6 in. (150 mm), the protection for the floor should be carried to the wall.

[b]Floor protection for radiating-type gas-burning room heaters that make use of metal, asbestos, or ceramic material to direct radiation to the front of the device should extend at least 36 in. (900 mm) in front when the heater is not of a type approved for installation on a combustible floor.

TABLE 10.2.9 Floor Mountings for Residential Solid Fuel-Burning Appliances

Kind of Appliance	*Allowed Mounting*
1. All forced air and gravity furnaces, steam and water boilers.	Floors of fire-resistive construction with noncombustible water heaters, fireplace flooring, and surface finish, or fire-resistive arches or slabs. These constructions must have no combustible material against the underside thereof. Such construction must extend not less than 18 in. (460 mm) beyond the appliance on all sides. These appliances must not be placed on combustible floors.
2. Residential type ranges, stoves, room heaters, and combination fireplace stove/ room heaters, having less than 2 in. (50 mm) of ventilated open space beneath the fire chamber or base of the unit.	
3. Residential-type ranges, water heaters, fireplace stoves, room heaters, and combination stove/room heaters having legs or pedestals providing 2 to 6 in. (50 to 150 mm) of ventilated open space beneath the fire chamber or base of the heater.	On combustible floors when such floors are protected by 4 in. (100 mm) of hollow masonry, laid to provide air circulation through the masonry layer. Such masonry must be covered with sheet metal. The required floor protection must extend not less than 18 in. (460 mm) on all sides of the appliance. On noncombustible floors, such floors must extend not less than 18 in. (460 mm) on all sides of the appliance.
4. Residential-type ranges, water heaters, fireplace stoves, room heaters, and combination fireplace stove/room heaters having legs or pedestals providing over 6 in. (150 mm) of ventilated open space beneath the fire chamber or base of the covered heater.	On combustible floors when such floors are protected by closely spaced masonry units of brick, concrete or stone, which provide a thickness of not less than 2 in. (51 mm). Such masonry must be covered by sheet metal. The required floor protection must extend not less than 18 in. (460 mm) on all sides of the appliance. On noncombustible floors, such floors must extend not less than 18 in. (460 mm) on all sides of the appliance.

TABLE 10.2.10 Chimney Connector and Vent Connector Clearances from Combustible Materials

Description of Appliance	Minimum Clearance[a] *in.*	*mm*
Residential-Type Appliances		
Single-Wall Metal Pipe Connectors		
Gas appliances without draft hoods	18	457
Electric, gas, and oil incinerators	18	457
Oil and solid-fuel appliances	18	457
Unlisted gas appliances with draft hoods	9	229
Boilers and furnaces equipped with listed gas burners and with draft hoods	9	229
Oil appliances listed as suitable for use with Type L vents	9	229
Listed gas appliances with draft hoods and other Category I gas appliances listed for use with Type B vents[b]	6	152
Type L Vent Piping Connectors		
Gas appliances without draft hoods	9	229
Electric, gas, and oil incinerators	9	229
Oil and solid-fuel appliances	9	229
Unlisted gas appliances with draft hoods	6	152
Boilers and furnaces equipped with listed gas burners and with draft hoods	6	152
Oil appliances listed as suitable for use with Type L vents[b]		
Listed gas appliances with draft hoods and other Category I gas appliances listed for use with Type B vents[c]		
Type B Gas Vent Piping Connectors		
Listed gas appliances with draft hoods and other Category I gas appliances listed for use with Type B vents[c]		
Low-Heat Appliances		
Single-Wall Metal Pipe Connectors		
Gas, oil, and solid-fuel boilers, furnaces, and water heaters	18	457
Ranges, restaurant-type	18	457
Oil unit heaters	18	457
Unlisted gas unit heaters	18	457
Listed gas unit heaters with draft hoods	6	152
Other low-heat nonresidential appliances	18	457
Medium-Heat Appliances		
Single-Wall Metal Pipe Connectors		
All gas, oil, and solid-fuel appliances	36	914
High-Heat Appliances Masonry or Metal Connectors		
All gas, oil, and solid-fuel appliances[d]		

[a]These clearances apply, except if the listing of an appliance specifies a different clearance, in which case the listed clearance takes precedence.
[b]If listed Type L vent piping is used, the clearance shall be permitted to be in accordance with the vent listing.
[c]If listed Type B or Type L vent piping is used, the clearance shall be permitted to be in accordance with the appliance and vent listing.
[d]Clearances shall be based on good engineering practice and acceptable to the authority having jurisdiction. The clearances from connectors to combustible materials shall be permitted to be reduced, provided the combustible material is protected in accordance with Table 10.2.11.

Source: NFPA 211, *Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances.*

Connectors for residential-type appliances may pass through walls or partitions constructed of combustible material if the connector is either listed for wall pass-through or is routed through a device listed for wall pass-through. Connectors for residential-type appliances with inside diameters less than or equal to 10 in. (250 mm) may pass through walls or partitions constructed of combustible material to a masonry chimney if the connector system selected or fabricated is installed as illustrated in Table 10.2.12. Figures 10.2.32 and 10.2.33 illustrate two example installations in detail.

TABLE 10.2.11 Reduction of Connector Clearance with Specified Forms of Protection[a–h]

Clearance Reduction Applied to and Covering All Combustible Surfaces Within the Distance Specified as Required Clearance with No Protection (see Table 10.2.10)	Maximum Allowable Reduction in Clearance (%)		If the required clearance with no protection is 36 in. (914 mm), the clearances below are the minimum allowable clearances; for other required clearances with no protection, calculate minimum allowable clearance from maximum allowable reduction[f]			
			As Wall Protector		As Ceiling Protector	
	As Wall Protector (%)	*As Ceiling Protector (%)*	*in.*	*mm*	*in.*	*mm*
3½-in. (90-mm) thick masonry wall without ventilated air space	33	—	12	305	—	—
½-in. (13-mm) thick noncombustible insulation board over 1 in. (25 mm) glass fiber or mineral wool batts without ventilated air space	50	33	9	229	12	305
0.024 in. (0.61 mm) 24-gauge sheet metal over 1 in. (25 mm) glass fiber or mineral wool batts reinforced with wire, or equivalent, on rear face with ventilated air space	66	50	6	152	9	229
3½-in. (90-mm) thick masonry wall with ventilated air space	66	—	6	152	—	—
0.024 in. (0.61 mm) 24-gauge sheet metal with ventilated air space	66	50	6	152	9	229
½-in. (13-mm) thick noncombustible insulation board with ventilated air space	66	50	6	152	9	229
0.024 in. (0.61 mm) 24-gauge sheet metal with ventilated air space over 0.024 in. (0.61 mm), 24-gauge sheet metal with ventilated air space	66	50	6	152	9	229
1 in. (25 mm) glass fiber or mineral wool batts sandwiched between two sheets 0.024 in. (0.61 mm) 24-gauge sheet metal with ventilated air space	66	50	6	152	9	229

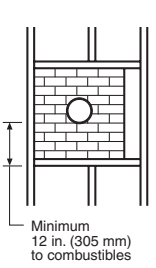
[a]Spacers and ties shall be of noncombustible material. No spacers or ties shall be used directly behind appliance or connector.
[b]With all clearance reduction systems using a ventilated air space, adequate air circulation must be provided. There shall be at least 1 in. (25 mm) between the clearance reduction system and combustible walls and ceilings for clearance reduction systems using a ventilated air space.
[c]Mineral wool batts (blanket or board) shall have a minimum density of 8 lb/ft^3 (128.7 kg/m^3) and have a minimum melting point of 1500°F (816°C).
[d]Insulation material used as part of clearance reduction system shall have a thermal conductivity of 1.0 (Btu·in.)/(ft^2·hr·°F) or less. Insulation board shall be formed of noncombustible material.
[e]If a single-wall connector passes through a masonry wall used as a wall shield, there shall be at least ½ in. (13 mm) of open, ventilated air space between the connector and the masonry.
[f]To calculate the minimum allowable clearance, the following formula can be used:
$C_{pr} = C_{un} \times (1 - R/100)$, where C_{pr} is the minimum allowable clearance, C_{un} is the required clearance with no protection, and R is the maximum allowable reduction in clearance.
[g]There shall be at least 1 in. (25 mm) between the connector and the protector. In no case shall the clearance between the connector and the wall surface be reduced below that allowed in the table.
[h]All clearances and thicknesses are minimum; larger clearances and thicknesses shall be permitted.
Source: NFPA 211, *Standards for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances*.

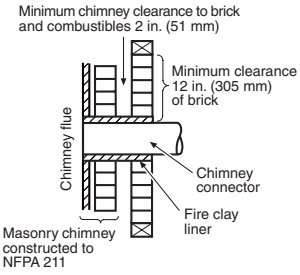
Appliances to Be Chimney or Vent Connected

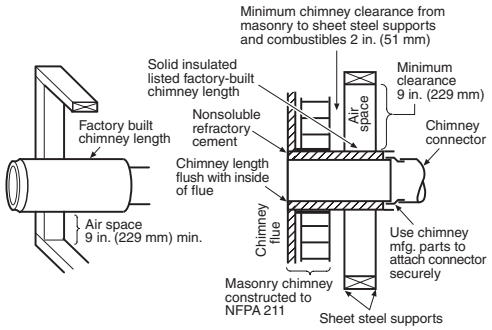
All oil-fired appliances are chimney connected, except direct-fired heaters, listed kerosene stoves, and portable kerosene heaters. All solid-fuel appliances are chimney connected.

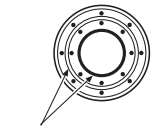
NFPA 54 is quite specific on the types of gas appliances that are required to be vented through vents or chimneys and those that are not so required. Generally, it is the larger types of heating appliances, for example, boilers and furnaces, that require venting, whereas smaller appliances, such as listed cooking stoves and hot plates, do not. However, if several smaller

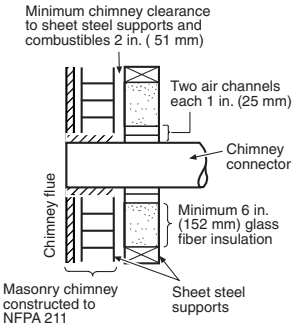
TABLE 10.2.12 Connector Systems and Clearances from Combustible Walls for Residential Heating Appliances

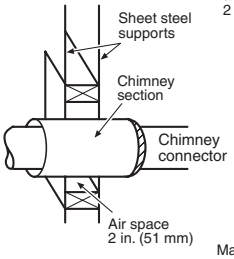


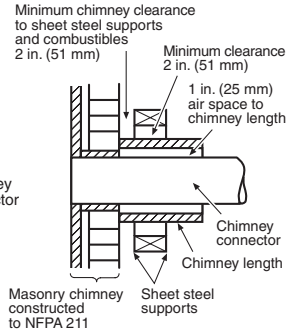












	System	Clearance *in.*	*mm*
A.	Minimum 3.5-in. (90-mm) thick brick masonry wall framed into combustible wall with a minimum of 12 in. (305 mm) brick separation from clay liner to combustibles. Fire clay liner (ASTM C315, *Standard Specification for Clay Fire Linings,* 17 or equivalent) minimum ⅝ in. (16 mm) wall thickness, must run from outer surface of brick wall to, but not beyond, the inner surface of chimney flue liner and must be firmly cemented in place.	12	305
B.	Solid insulated listed factory-built chimney length of the same inside diameter as the chimney connector and having 1 in. (25 mm) or more of insulation with a minimum 9 in. (229 mm) air space between the outer wall of the chimney length and combustibles. The inner end of the chimney length must be flush with the inside of the masonry chimney flue and must be sealed to the flue and to the brick masonry penetration with non-water-soluble refractory cement. Supports must be securely fastened to wall surfaces on all sides. Fasteners between supports and the chimney length must not penetrate the chimney liner.	9	229
C.	Sheet steel chimney connector, minimum 24 gauge (0.024 in. [0.61 mm]) in thickness, with a ventilated thimble, minimum 24 gauge (0.024 in. [0.61 mm]) in thickness, having two 1 in. (25 mm) air channels, separated from combustibles by a minimum of 6 in. (152 mm) of glass fiber insulation. Opening must be covered and thimble supported with a sheet steel support, minimum 24 gauge (0.024 in. [0.61 mm]) in thickness. Support must be securely fastened to wall surfaces on all sides and must be sized to fit and hold chimney section. Fasteners used to secure chimney sections must not penetrate chimney flue liner.	6	152
D.	Solid insulated listed factory-built chimney length with an inside diameter 2 in. (51 mm) larger than the chimney connector and having 1 in. (25 mm) or more of insulation, serving as a pass-through for a single-wall sheet steel chimney connector of minimum 24 gauge (0.024 in. [0.61 mm]) thickness, with a minimum 2 in. (51 mm) air space between the outer wall of chimney section and combustibles. Minimum length of chimney section must be 12 in. (305 mm). Chimney section concentric with, and spaced 1 in. (25 mm) away from, connector by means of sheet steel support plates on both ends of chimney section. Opening must be covered and chimney section supported on both sides with sheet steel supports of minimum 24 gauge (0.024 in. [0.61 mm]) thickness. Supports must be securely fastened to wall surfaces on all sides and must be sized to fit and hold chimney section. Fasteners used to secure chimney sections must not penetrate chimney flue liner.	2	51

Additional requirements:

1. Insulation material used as part of wall pass-through system must be of noncombustible material and must have a thermal conductivity of 1.0 Btu·in./ft^2·°F (3.88 kg·cal/hr·°C) or less.
2. All clearances and thicknesses are minimums; larger clearances and thicknesses are acceptable.
3. Any material used to close up an opening for the connector must be of noncombustible material.
4. A connector to a masonry chimney, except for System B, must extend to in piece through the wall pass-through system and the chimney wall to the inner face of the flue liner, but not beyond.

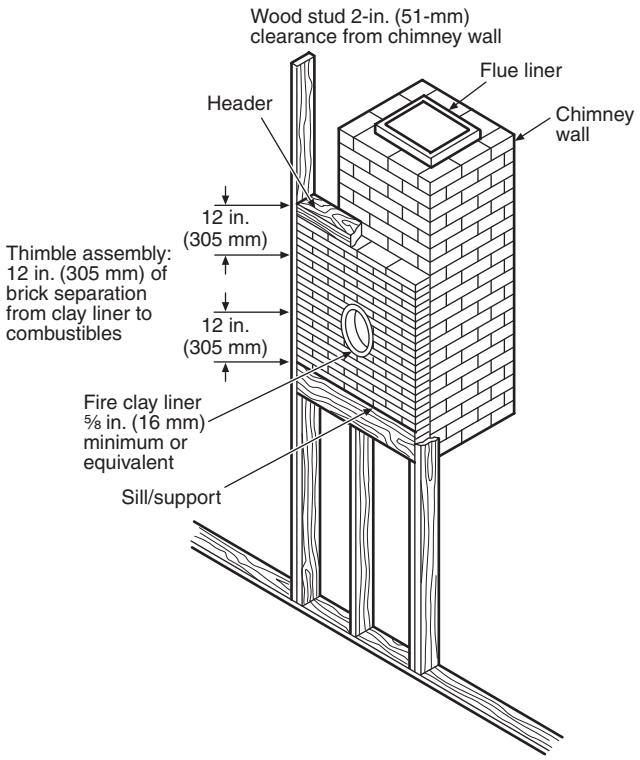


FIGURE 10.2.32 Detail of System A in Table 10.2.12

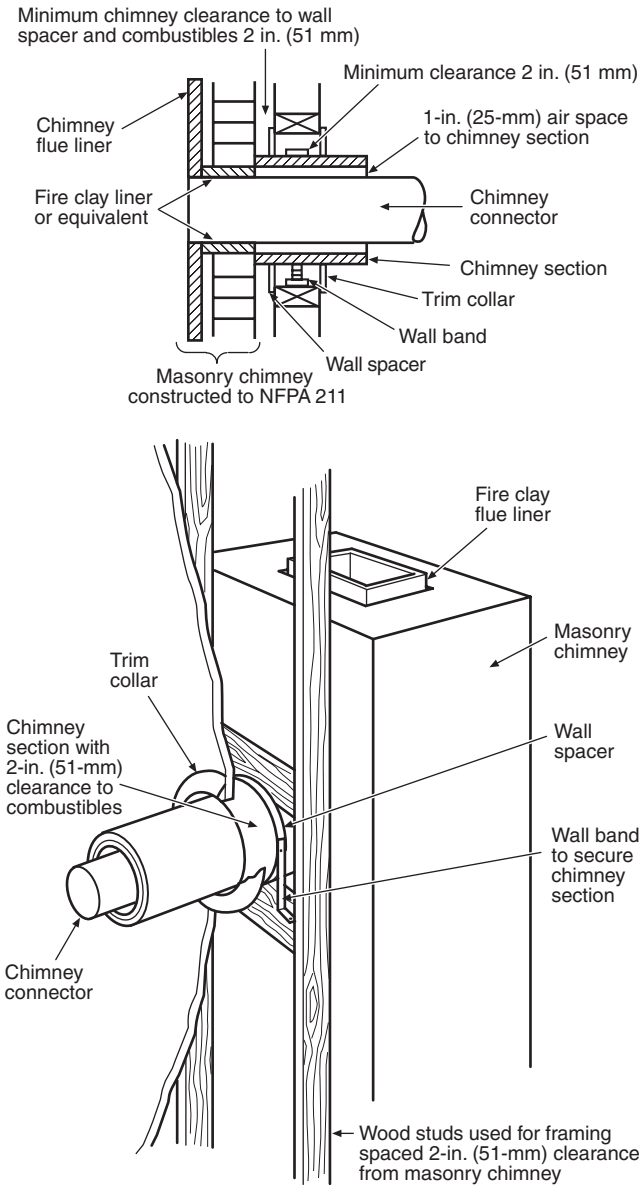


FIGURE 10.2.33 Detail of System D in Table 10.2.12

appliances that normally do not require venting are located within the same space or room, some might require venting if the aggregate input for all the appliances exceeds 20 Btu per hour per ft^3 (0.2 kW/m^3) of the space in which they are installed. NFPA 54 should be consulted for the specifics on the types of gas appliances requiring venting, the conditions under which vents may be omitted or required, and the type of chimney, gas vent, or venting system that can be used and its installation.

Listed unvented room heaters may be used, but care should be taken to follow the manufacturer's instructions. Such heaters are equipped with an oxygen depletion safety shutoff system designed to shut off the gas supply to the heater if the oxygen in the surrounding atmosphere is reduced below about 18 percent. Unvented room heaters are not to be used in institutions, convalescent homes, orphanages, and so on.

A change to the 1996 edition of the *National Fuel Gas Code* allowed listed unvented wall-mounted heaters to be used in bedrooms and bathrooms that meet the following limitations:

1. The installation of unvented space heaters in bedrooms and bathrooms must be approved by the authority having jurisdiction.
2. Heaters in bathrooms must have an input no greater than 6000 Btu/hr (1760 W/hr).
3. Heaters in bedrooms must have an input no greater than 10,000 Btu/hr (2930 W/hr).
4. The bedroom or bathroom must be an unconfined space as defined in the *National Fuel Gas Code,* which means that the room volume must be at least 50 ft^3 for each 1000 Btu/hr (4.8 m^3 per kw) of heater input.

This change was first made as a tentative interim amendment to the 1992 edition of the *National Fuel Gas Code* that was adopted in 1994. It resulted from problems in the southern United States where gas-fired unvented space heaters have a long history of use due to the moderate climate. Old heaters, many installed before 1940, though in need of repair, could not be repaired because parts were not available, nor could they be replaced due to the pre-1994 *National Fuel Gas Code* prohibition of unvented space heaters in bedrooms and bathrooms.

The change was made in the *National Fuel Gas Code* following the introduction of wall-mounted unvented heaters. One concern of the *National Fuel Gas Code* Committee regarding space heaters in bedrooms and bathrooms had been the lack of clearance to combustibles in these small rooms, specifically the possibility that the heaters would be used to dry towels and

clothing, which could create a fire problem. Wall-mounted heaters address this concern. Another concern of the committee regarding these and other space heaters was a means to ensure adequate air of combustion. As a result, the standard to which the heaters are listed requires the use of an oxygen depletion sensor.

Ventilating hoods and exhaust systems may be used to vent gas utilization equipment installed in commercial applications. They may also be used to vent industrial equipment, particularly when the process itself requires fume disposal. If industrial gas utilization equipment is located in a large and well-ventilated space, it may be operated by discharging the products of combustion directly into the atmosphere.

VENTS

Vents are laboratory-tested, factory-built units used to vent fuel-burning, heat-producing appliances. Specific types of vents have specific uses (Table 10.2.13).

Types of Vents

Type B Gas Vents. Type B vents are used to vent listed gas appliances that have draft hoods or are specifically listed to be used with Type B gas vents.

Type BW Gas Vents. Type BW vents are used with listed gas wall furnaces having capacities not greater than that of Type BW gas vents (Figure 10.2.34).

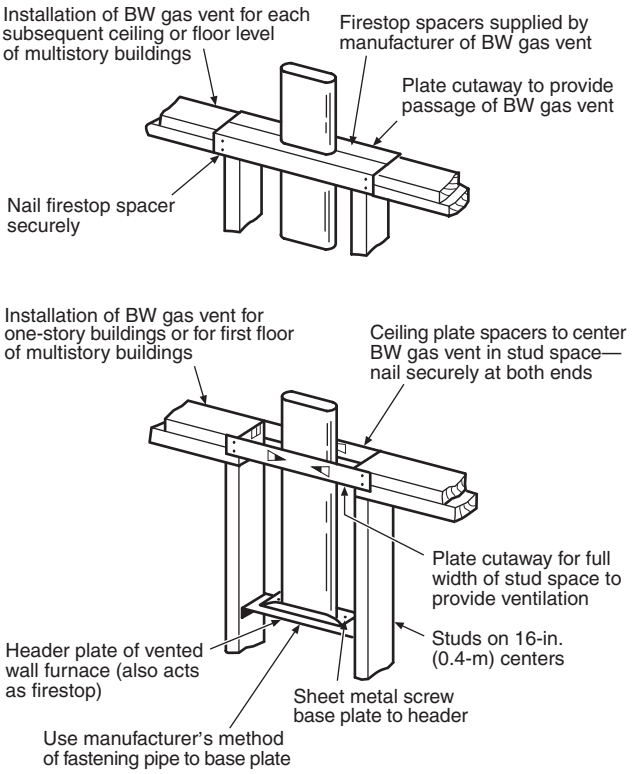


FIGURE 10.2.34 Installation of Type BW Gas Vents for Vented Wall Furnaces

TABLE 10.2.13 Vent Selection Chart

Type of Vent					
Type B—Gas	*Type BW—Gas*	*Type L—Oil*	*Special Gas Vent Systems*	*Pellet Vent*	*Metal Pipe*
Column I All listed gas appliances with draft hoods and other Category I gas appliances listed for use with Type B vents, such as: 1. Central furnaces 2. Duct furnaces 3. Floor furnaces 4. Heating boilers 5. Ranges 6. Built-in ovens 7. Vented wall furnaces listed for use with Type B vents 8. Room heaters 9. Water heaters 10. Horizontal furnaces 11. Unit heaters	Column II 1. Vented wall furnaces listed for use with Type BW vents only	Column III 1. Low-temperature flue gas appliances listed for use with Type L vents 2. Gas appliances shown in Column I	Column IV 1. Listed Category II, III, and IV gas appliances only	Column V 1. Listed pellet-burning appliances listed for use with pellet vents	Column VI 1. Incinerators used outdoors, such as in open sheds, breezeways, or carports 2. Gas appliances shown in Column I 3. Listed residential and low-heat gas appliances without draft hoods, and unlisted residential and low-heat gas appliances with or without draft hoods

Type L Vents. Type L vents are used to vent oil-burning appliances listed for use with Type L vents and gas appliances listed for use with Type B vents.

Special Gas Vents. Special vents are listed specifically for venting Category II, III, and IV gas appliances. Special gas vents must be specified by the appliance manufacturer.

Pellet Vents. Pellet vents are used for venting listed pellet fuel-burning appliances. They are similar in construction to Type L vents and may be additionally listed as such.

Single-Wall Metal Pipe. Single-wall metal pipe, constructed of galvanized sheet steel not lighter than No. 20 galvanized sheet gauge (0.020 in. [0.51 mm]) or other noncombustible corrosion-resistant material, may be used to vent residential-type and low-heat gas appliances equipped with draft hoods. They may also be used to vent incinerators used outdoors, such as in open sheds, breezeways, or carports (see Table 10.2.13). Single-wall metal pipe is not used with solid-fuel appliances, which require either masonry or factory-built chimneys.

Plastic Pipe. Unlisted PVC or other plastic pipe may be used to vent Category IV gas appliances, subject to the specifications and limitations in the appliance manufacturer's instructions.

New Considerations for Venting Gas Appliances

Prior to the 1980s most gas furnaces were of similar design. They typically included an atmospheric burner, supplemented by excess air introduced in and above the combustion zone. Flue gases passed though a clamshell heat exchanger into a draft hood incorporated into or directly attached to the outlet of the furnace. The draft hood allowed for the relief of backdrafts, which would otherwise interfere with combustion, and also allowed a significant amount of dilution air to mix with the flue gases. The flue gas/air mixture was then drawn up the chimney or vent by draft created by the buoyancy of warm gases. Gas furnaces of this design typically operated in the range of 65 to 75 percent annual fuel utilization efficiency (AFUE). Many furnaces manufactured prior to the 1980s remain in service.

During the 1970s and 1980s gas appliance manufacturers responded to both market and regulatory pressures by developing more efficient appliances. The National Appliance Energy Efficiency Act of 1987 (NAEEA) requires that all gas furnaces achieve a minimum AFUE of 78 percent. Most standard gas furnaces now fall in the range of 78 to 83 percent AFUE. Such furnaces are referred to as "mid-efficiency" appliances, to distinguish them from conventional "low-efficiency" designs.

In order to achieve these higher efficiencies, both on-cycle and off-cycle heat losses up the flue needed to be reduced. Conventional furnace design was altered in several ways:

1. The standing pilot was eliminated, replaced by some form of intermittent ignition device (IID).
2. In most designs the draft hood was eliminated, thus reducing on-cycle dilution air and the off-cycle loss of heated room air.
3. The draft hood was replaced by a small fan at the flue outlet of the appliance. This fan provides for a controlled flow of flue gases and excess air through the heat exchanger, and inhibits the flow of heat from the furnace into the flue during the off-cycle. Mid-efficiency furnaces of this design are known as "fan-assisted" furnaces.
4. In some designs the heat exchanger was made somewhat more efficient.

Another class of furnaces, that is, "high-efficiency" condensing furnaces, has evolved. These achieve efficiencies well above 90 percent. Such appliances contain a second heat exchanger that is designed to cool the flue gases below their dewpoint, thereby capturing the latent heat of the water vapor created by combustion. Because condensation takes place intentionally, within the appliance, these furnaces must be constructed of corrosion-resistant materials and designed for suitable disposal of the condensate.

Conventional appliance design (below 75 percent AFUE) allowed for simple and mostly trouble-free venting. Relatively high flue gas temperatures provided adequate draft in most chimney and vent configurations, whereas excess and dilution air helped control condensation by lowering the dewpoint temperature (the temperature below which moisture will condense on flue walls) of the flue gas mixture, and providing a drying flow of air during the off-cycle.

The mid-efficiency and high-efficiency designs create significantly different venting conditions and introduce new considerations in vent design and installation. Reduced loss of heat through the venting system and lower vent gas flow rate result in lower venting system temperatures, with a consequent reduction in available draft and in the surface temperature of venting system components.

Elimination of the draft hood and reduction of dilution air increases the humidity and dewpoint temperature of the vent gases, making them more prone to condensation in the venting system. Because they dry out more slowly, vent system components will be exposed to potentially corrosive condensate for longer periods of time.

Elimination of the standing pilot and off-cycle flow of room air inhibits the drying of vent system components during the off-cycle and lowers the standby temperature of the flue. The reduction in dilution air and use of fan assistance increases the maximum capacity of the venting system; a vent of a given size can handle more gas input to the appliance.

The presence of a fan at the outlet of the appliance increases the likelihood that the vent will become pressurized. If this is intended by the appliance design, the vent must be designed for positive pressure. If this is not intended, the vent must be sized and configured to prevent pressurization.

Vented Gas Appliance Categories

From the standpoint of the general type of venting system required for a gas appliance, the two key variables are (1) the pressure of the gases within the venting system and (2) the temperature of the vent gases. The vent pressure can either be positive (relative to the surrounding atmosphere) or nonpositive (neutral or negative). The temperature of the gases entering the

venting system can either be above or below a critical temperature that is likely to result in an excessive volume or duration of condensation in the vent.

The combination of these two variables creates a matrix of four possible appliance types, or categories, with respect to their venting needs. These vented gas appliance categories are defined in NFPA 54, as follows:

Category I. An appliance that operates with a nonpositive vent static pressure and with a vent gas temperature that avoids excessive condensate production in the vent.

Category II. An appliance that operates with a nonpositive vent static pressure and with a vent gas temperature that may cause excessive condensate production in the vent.

Category III. An appliance that operates a positive vent static pressure and with a vent gas temperature that avoids excessive condensate production in the vent.

Category IV. An appliance that operates with a positive vent static pressure and with a vent gas temperature that may cause excessive condensate production in the vent.

The category of a gas appliance can be determined only in the laboratory, using criteria from the appropriate ANSI appliance test standard. The vent pressure that is produced by the appliance is determined using a special test apparatus. The determination of whether the vent gas temperature will cause or avoid "excessive condensate production in the vent" is unique for each type of gas appliance and is based on an efficiency profile of the appliance type. It is not possible to reliably determine the category of an appliance through testing in the field.

Categorization criteria for every gas appliance type have been or are being developed. The category of an appliance is part of its certification and will be shown on the rating plate. There is no further need to evaluate the category in the field.

Both Category I and III appliances generally fall within the mid-efficiency range. Since both typically have a small fan at the outlet, the major difference between them is whether or not the fan is used to force vent gases through the vent, or simply to pull gases through the heat exchanger, delivering them at neutral pressure to the beginning of the vent. Category IV represents high-efficiency, condensing appliances. Category II appliances are problematic, since they need to operate under natural draft, but without sufficient vent gas temperature to produce much draft. There are few, if any, Category II appliances on the market.

The category of a gas appliance determines the general characteristics of the venting system that must be used. Category III and IV furnaces, which are designed to operate with positive vent gas pressure, must use a vent that can withstand the pressure and be sealed against leakage. Category I and II appliances are expected to be vented by natural draft and must use a vertical venting system sized and configured to develop sufficient draft.

Further, Category I and III appliances have relatively high vent gas temperatures. The vent may not need to withstand severe exposure to condensate but must be able to withstand relatively high temperatures. Category II and IV appliances need not withstand such high temperatures but must be corrosion resistant and designed to contain and dispose of condensate.

Venting Category I Appliances

Category I appliances and low-efficiency, uncategorized appliances are vented through "conventional" venting systems: mainly Type B vents and masonry chimneys. However, venting systems for mid-efficiency, fan-assisted appliances call for careful attention to sizing and factors of vent geometry. For instance, long connector runs between the appliance and vertical vent can cause excessive heat loss and unacceptable condensation. Masonry chimneys, due to their mass, heat up slowly and have limited use with mid-efficiency appliances. Frequently, masonry chimneys must be relined with a lightweight aluminum or stainless-steel liner, in order to provide adequate capacity and minimize condensation. The use of chimneys and vents on the exterior of the building is severely restricted or prohibited in most climate zones by NFPA 54.

Procedures for sizing venting systems for Category I appliances underwent significant changes in the 1990s. NFPA 54 has provided vent sizing tables since the 1950s. These tables were developed for draft-hood-equipped appliances operating in the low-efficiency range. Modern mid-efficiency appliances, without draft hoods, bring different conditions to the vent, which must be anticipated in the sizing regimen.

In-depth research into the venting needs of mid-efficiency appliances, much of it sponsored by the Gas Research Institute (GRI), led to the updating and expansion of the original NFPA 54 sizing tables. The original tables addressed only the *maximum* capacity of vents and chimneys, which corresponded to a minimum size that could be used for an appliance of a given input rate and a given vent geometry to prevent spillage. With the advent of fan-assisted appliances, the maximum capacity (or minimum size) also becomes important to prevent pressurization of the vent by the fan.

The new tables introduce the concept of a *minimum* vent capacity, which is the smallest appliance input rating that can be connected to a given vent. A vent connected to an appliance with an input lower than the vent's minimum capacity will warm up slowly, and condensation will continue until the vent wall is warmer than the dewpoint temperature of the vent gases. This longer "wet time," or exposure to condensate, may lead to corrosion and premature failure of the vent. The minimum capacities are designed to limit the wet time to acceptable levels. The concept of minimum vent capacity results in a maximum vent size that can be used for the given input rate and vent geometry.

For any proposed system, a chimney or vent size must be found that lies between the minimum and maximum. The new tables in NFPA 54 also add a number of conditions and adjustments to the former table values that may further restrict the applicability of a vent. Depending on the details of the system, the choice of acceptable sizes may be quite narrow, or even nonexistent. Combinations of appliance input and vent configuration that were, in the past, used routinely must now be carefully scrutinized and may not be acceptable for mid-efficiency, fan-assisted appliances.

Venting Category III Appliances

Like Category I appliances, Category III appliances are mid-efficiency appliances. However, they are designed to exhaust the products of combustion under positive pressure rather than natural draft. Since the "work" will be done by a fan, such systems can typically be vented horizontally through a sidewall. Thus, they avoid the need for a chimney or other vertical vent running up through, or beside, the building.

Vents for Category III appliances are not designed with reference to standard installation requirements and sizing tables found in codes. Instead, the materials, size, and installation guidelines for each appliance are found in the manufacturer's instructions. Such instructions must be adhered to in order to produce a proper installation.

Category III appliances have relatively high vent gas temperatures, which are under positive pressure within the vent. Therefore, the vent must be of a temperature-resistant material that can be constructed with sealed joints to prevent leakage. A new type of listed vent system, special gas vents, has been developed to meet these requirements (see Table 10.2.13). Such systems must comply with UL 1738, *Standard for Safety Venting Systems for Gas-Burning Appliances*. They are typically formed of a high-temperature plastic resin or stainless steel. Sections of pipe are joined together, using a manufacturer-specified sealant cement.

Since the vent will be subjected to elevated temperature, some degree of condensation, and mechanical stress induced by thermal expansion, it is extremely important that the vent be installed with care. Hangers and other securement of the pipe must be done according to instructions. The specific sealant required by the manufacturer must be used and joints fitted together according to the specified procedure. Some systems require condensate disposal systems and a specific pitch or rise back to, or away from, the appliance. Both appliance and vent manufacturer's instructions must be consulted and followed.

Venting Category IV Appliances

To obtain efficiencies approaching 90 percent or better, the flue gases from high-efficiency, Category IV appliances have been reduced to temperatures as low as 100°F (38°C). Because these temperatures are too low to allow atmospheric venting, mechanical venting is required to exhaust the flue gases under positive pressure. Furthermore, the temperature of the flue gases is low enough to cause condensation of the water vapor in flue gases. Thus, special treatment is needed to provide a venting system that will retain and dispose of the condensate and, in cases of mechanical venting, to prevent leakage of flue gases from the venting system.

Unlike Category I appliances, high-efficiency Category IV appliances do not use standardized, code-specified venting systems. Instead, the type of venting system to be used and any limitations on size and configuration must be specified explicitly in the appliance manufacturer's instructions. Such limitations include maximum length and number of turns in the vent. Typically, manufacturers' instructions specify the use of PVC (or other plastic pipe) or a high-alloy, corrosion-resistant type of stainless steel, such as AL29-4C. These can frequently be run horizontally through a side wall, with an appropriate termination. Many designs use a parallel pipe to bring in combustion air, creating a closed combustion, direct vent system.

Manufacturer's instructions will also specify the method to be used to dispose of condensate, as well as necessary clearances from the vent. The instructions must be followed exactly to ensure a safe and properly performing system.

Installation of Vents

Types B, BW, and L, and Special Gas Vents. Installations must be made in compliance with the terms of their laboratory listings and the manufacturers' instructions, making certain that the required clearances are maintained.

Single-Wall Metal Pipe. The use of single-wall metal pipe is restricted to runs directly from the space in which the gas appliance is located through the roof or exterior wall to the outside. The pipe is not to originate in any attic or concealed space and is not to pass through any attic or inside space, nor through any floor or ceiling. The minimum clearances from combustible material for single-wall metal pipe are as given for connectors in Table 10.2.10. In Figure 10.2.35, "A" equals the required clearance with no protections as specified in Table 10.2.10 and "B" equals the reduced clearance permitted by the types of protection specified in Table 10.2.11. The protection applied to construction using combustible material should extend far enough

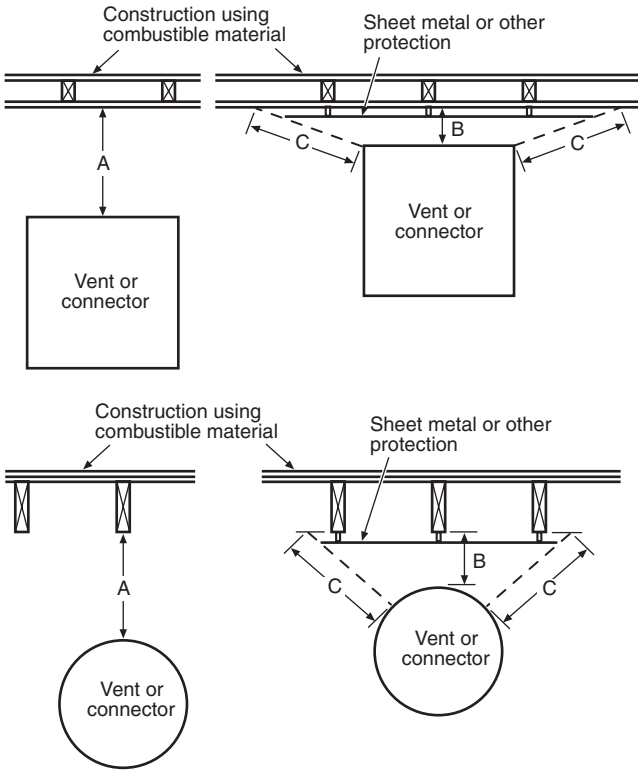


FIGURE 10.2.35 Extent of Protection Required to Reduce Clearances from Combustibles for Vents and Connectors

in each direction to make "C" equal to "A." These clearances may be reduced if appropriate protection is provided for combustible materials (see Table 10.2.11) Where a single-wall metal pipe passes through an exterior wall constructed of combustible material, or the pipe passes through a roof constructed of combustible material, it is protected at the point of passage as specified for connectors in Table 10.2.12. If the appliance the pipe serves is a gas appliance for use with a Type B gas vent, protection is by a noncombustible, nonventilating thimble not less than 4 in. (100 mm) larger in diameter than the pipe and extending not less than 18 in. (457 mm) above and 6 in. (152 mm) below the roof, with annular space open at the bottom and closed at the top.

Venting Capacities. The venting capacities of various sizes of Type B gas vents, chimneys, and single-wall metal pipe used for venting gas appliances are given in tables in NFPA 54. NFPA 54 also contains data that may be used to calculate the size of vents required under various circumstances and to establish configurations of venting arrangements. Approved engineering methods may also be used.

Firestopping. Vents that pass through floors of buildings requiring the protection of vertical openings are enclosed within walls having a fire-resistance rating of not less than 1 hour if the vents are in a building less than four stories in height, and not less than 2 hours if the vents are located in a building four stories or more in height.

Draft Hoods

A draft hood is a device built into an appliance, or made a part of the vent connector from an appliance. It is designed to (1) ensure the ready escape of the flue gases in the event of no draft, backdraft, or stoppage beyond the draft hood; (2) prevent a backdraft from entering the appliance; and (3) neutralize the effect of stack action of the chimney or gas vent upon the appliance operation.

Draft hoods are an important safety feature of gas appliances and are generally required on all vented appliances, except incinerators, dual-oven-type combination ranges, direct-vent appliances, and units designed for power burners or for forced venting by mechanical means. Many newer mid-efficiency appliances replace the draft hood with a fan at the appliance outlet. Such fans do not necessarily pressurize the vent, since they might be designed only to pull the gases through the heat exchanger and deliver them at neutral pressure to the beginning of a natural draft venting system.

CHIMNEYS

Chimneys are classified into three major types: (1) factory built, (2) masonry, and (3) unlisted metal (smokestacks). In addition to the major chimney classes, there are subclasses that involve type of building and surroundings. For example, small, well-insulated, factory-built chimneys may be installed at close clearances in residential frame construction, whereas larger chimneys for the same type of appliances are suitable mainly for noncombustible surroundings or in well-ventilated open-room use at much greater clearance to combustibles. Details of installation for chimneys, fireplaces, and vents are provided in NFPA 211.

Factory-Built Chimneys

A factory-built chimney is an assembly of manufactured components that form a completed chimney. Factory-built chimneys are tested for compliance with safety standards.[15–17]

Factory-built chimneys for use with residential-type appliances are tested fully enclosed to establish a minimum clearance to combustibles not greater than 2 in. (51 mm). The test is conducted using a flue gas generator that simulates an appliance steadily producing 1000°F (540°C) gases. A typical factory-built chimney for residential appliances is shown in Figure 10.2.36.

For building heating equipment (gases to 1000°F [540°C]), commercial ovens and furnaces (gases to 1400°F [760°C]), and medium-heat appliances (gases to 1800°F [980°C]), factory-built chimneys are available in sizes from 10 in. (250 mm) to several feet (1 ft equals 0.3 m) in diameter. These chimneys are tested for the appropriate temperature and are used mainly in noncombustible surroundings, although tested thimbles are available for penetration of combustible roofs. None of these are suitable for close clearance to combustible enclosures; however, this is seldom a problem in the usual large building of masonry or metal construction. A typical unenclosed type of large factory-built chimney for serving building boilers is shown in Figure 10.2.37.

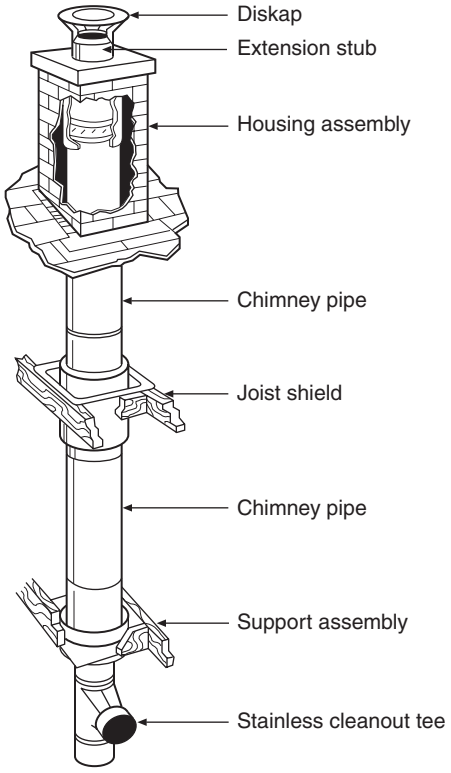


FIGURE 10.2.36 Typical Factory-Built Chimney

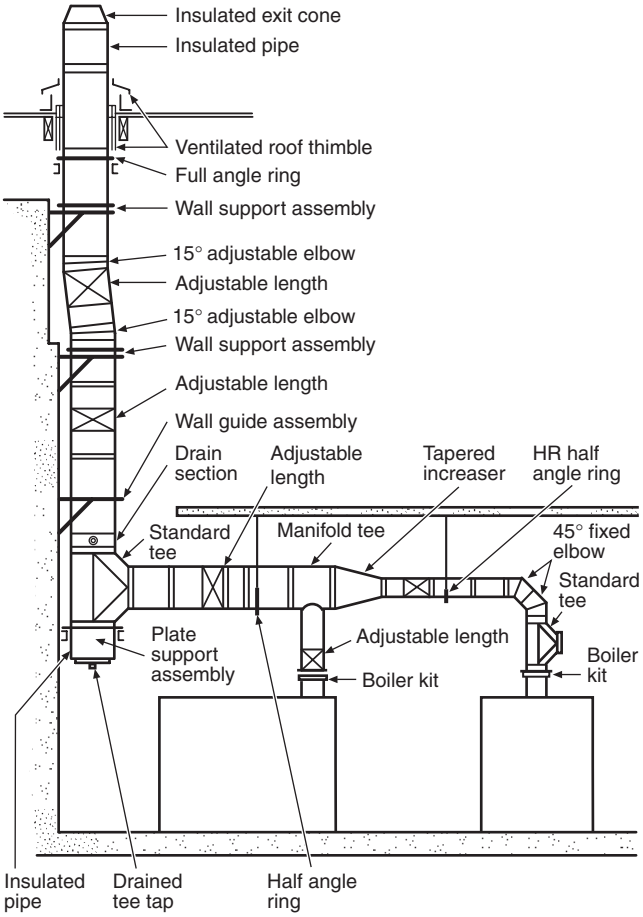


FIGURE 10.2.37 Typical Unenclosed Factory-Built Chimney for Serving Building Boilers

Current information on types, usage, and installation limitations of all UL-listed factory-built chimneys is given in the *UL Gas and Oil Equipment Directory,*[18] published annually with a supplement.

Masonry Chimneys

Field construction requirements for masonry chimneys are detailed in NFPA 211, as well as in building codes. Field-erected masonry chimneys, which are subject to the know-how and ability of available labor, are not tested, except perhaps for a smoke test. A minimum residential masonry chimney consists of a refractory fire clay tile liner and an air space of roughly ½ in. (13 mm) between the liner and brick, with all liner joints grouted both to prevent leakage and to center and support the tile liners (Figure 10.2.38). One course of common brick around the liner suffices for usual residential chimneys. For higher temperature classifications, firebrick is used as the liner, with additional courses of brick for larger size or greater strength and security. All chimneys should, of course, be supported by footings suitable for the chimney size and weight and be provided with cleanouts between the points of entry and the lowest chimney level.

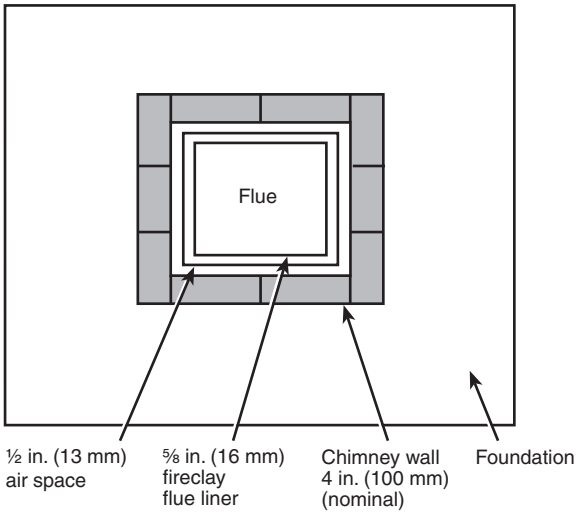


FIGURE 10.2.38 Minimum Residential Masonry Chimney

For residential and low-heat chimneys located entirely or partially inside the building, a minimum of 2 in. (51 mm) of air space is required between the chimney and surrounding combustibles. For residential and low-heat chimneys located entirely outside the building, a minimum of 1 in. (25 mm) clearance is required. For higher heat chimneys, larger clearances are appropriate. All clearances must consist of an air space. Solid material, including building insulation, whether noncombustible or not, must not be allowed to impinge into the required air space clearance.

As a general rule, the best and safest chimney operation and appliance control is obtained with only one appliance attached to a chimney flue. Two or three gas appliances, however, may be connected into a masonry chimney flue at one level of a building, provided that the connector size, its vertical rise, and chimney size and height are in accordance with tabulated capacity data in NFPA 54. The construction of masonry chimneys for open-front fireplaces is the same as for other residential appliances and is specified in NFPA 211.

Flue Liners for Masonry Chimneys. All masonry chimneys must have flue liners. The liner serves several functions that are essential for chimney safety:

1. The liner provides a smooth corrosion- and erosion-resistant surface that is conducive to the flow of flue gases and that protects the brick and mortar flue wall from direct exposure to combustion products.
2. The liner forms a sealed conduit that contains the products of combustion, including gases, moisture, heat, and solids such as soot and creosote, and conducts flue gases to the outside atmosphere.
3. The liner is an important element in the thermal performance of the chimney. The liner, with its surrounding air space, forms a thermal break between the warm flue gases and the chimney wall. This helps maintain the temperature of the gases for good draft and reduces temperatures on the exterior of the chimney wall.

Traditionally, the flue lining for residential and low-heat type chimneys has been a clay flue lining, which has been fired to produce a vitreous, relatively non-porous wall. Manufacturing specifications for clay flue linings are set in ASTM C315, *Standard Specification for Clay Flue Linings.*[19] The general requirements for clay flue linings and their installation are specified in NFPA 211. Clay linings should be installed with small joints struck smooth on the inside, bedded in a non-water-soluble refractory cement, such as a calcium aluminate mixture. All tile sections should be carefully aligned and should never be offset more than 30 degrees from the vertical. Liners should start from a point at least 8 in. (203 mm) below the lowest inlet, and extend continuously to a point at least 2 in. (51 mm) above the chimney crown (splay or wash).

Alternative Flue Lining Systems. A variety of alternative flue lining systems has been developed. These can be used either as the original liner in the chimney, in place of clay lining, or retrofitted into an existing chimney. Relining of chimneys is most often done when the original liner has become damaged or deteriorated or when a smaller flue is needed to serve a new connected appliance.

Although NFPA 211 does provide for the installation of unlisted linings, most alternative lining systems have been tested and listed to UL 1777, *Standard for Safety Chimney Liners.*[17] As with all listed systems, they should be used only for the intended purpose and installed in strict compliance with their manufacturer's instructions.

Most alternative linings fall into one of two types: (1) stainless steel and (2) cast-in-place cementitious mixtures. Stainless steel liners are usually made of a 300 series alloy and can be composed of rigid pipe sections or a continuous flexible tube that can be passed through chimney offsets. Stainless steel linings must be insulated, either with a ceramic blanket wrapped around the pipe before insertion, or with a backfill of a moist vermiculite/cement mixture, depending on the liner listing. Loose, unbound backfills are not permitted. Stainless steel lining systems come with a rain cap tested to exclude most precipitation, as well as other parts that must be used to form a complete listed system.

Cast-in-place liners are usually composed of a proprietary mixture of perlite or vermiculite, and Portland or other cement as a binder. One method involves insertion of a properly sized, sausage-shaped inflated bladder within the chimney, held off the walls by spacers. A very wet slurry of liner mix is then pumped around the tube and allowed to harden. After several days the bladder is deflated and removed, leaving a smooth, formed flue. In another method, a damp mixture is poured in the chimney while a bell-shaped slipform is pulled up, forcing the mixture against the chimney walls. With either method, a second coating of a glazing material may be applied to the flue to reduce moisture penetration.

Special versions of either stainless steel or cast-in-place liner systems can be designed and listed to obviate the need for air space clearances to combustibles normally required for masonry chimneys. These "zero-clearance" liners typically contain more insulating material or wall thickness to reduce the amount of heat reaching the outside of the chimney wall. They are useful for lining existing chimneys that were constructed without proper clearances. To be eligible for this application, the liner will be explicitly labeled for zero clearance and will have special installation requirements that must be followed.

Other specialized subsets of chimney liner systems are those designed only for use with a specific type or class of appliance. The primary example of this are liners for use with Category I gas appliances. Many such systems are made of aluminum, which would not be suitable for the temperatures produced by general residential appliances. They have been tested under the temperature conditions of UL 441, *Standard for Safety Gas Vents,*[20] for Type B gas vents, and can be used for the same applications. They are, however, still chimney liners listed under UL 1777 and must be installed under the conditions appropriate for chimney liners, according to their own manufacturer's instructions. NFPA 54 and NFPA 211 both require that a notice warning against connection of inappropriate appliances be posted near the chimney inlet.

Unlisted Metal Chimneys

Metal chimneys are suitable for all the classes of appliances but are not subjected to safety testing of any kind. They are distinct from factory-built chimneys, which also can be made of metal but are tested and listed assemblies. The major hazard with metal chimneys is inadequate clearance to combustibles where they penetrate ceilings and roofs. For chimneys serving residential-type or low-heat appliances, dimension "A" (Figure 10.2.39) should be at least 6 in. (150 mm). For chimneys serving medium-heat appliances, dimension "A" should be at least 18 in. (457 mm).

Metal chimneys may be of single-wall metal for low-temperature use, such as with gas appliances, or metal lined with firebrick or refractory mortar for medium- and high-heat service. They may be located inside or outside of buildings, but not inside or outside of one- and two-family dwellings or buildings of wood-frame construction. The conditions under which metal chimneys may be used are quite limited and are spelled out in detail in NFPA 211. The standard is also quite specific on acceptable materials of construction.

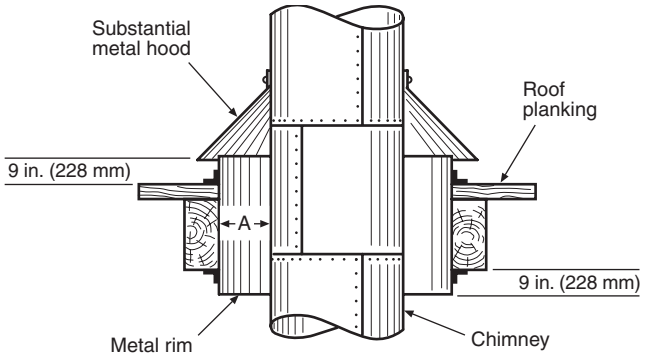


FIGURE 10.2.39 Arrangement of a Metal Chimney Through a Wood Roof

Regardless of permitted clearances, metal chimneys should not be enclosed with combustible construction. It is particularly important that the metal used be resistant to corrosion if the gases are 350°F (177°C) or below, because exposed outdoor portions of the chimney walls may be below the dew point. The resulting continuous condensation can lead to rapid corrosion and very short chimney life.

Chimney Functions

The purpose of a chimney is to create draft or negative pressure to provide combustion air for the fuel or fuel bed and to remove products of combustion from the appliance and building. For open fireplaces or for gas appliances having draft hoods, chimney draft has very little influence on the combustion process; the chimney serves only as a conduit for carrying away the products of combustion. For forced-draft or packaged boilers, the chimney might be under slight positive pressure and, again, serves only as a duct to carry away combustion products. The advantage of the slight positive pressure, commonly from 0.5 to 1.5 in. of water column (120 to 370 Pa), is that it permits use of much smaller chimneys and eliminates some concerns about the draft-producing ability or height of the chimney.

The technology of matching the size, height, and configuration of a chimney to the temperature, type, and quantity of fuel for its correct capacity is covered in the ASHRAE handbook and product directory.[21]

Height of Chimneys

A variety of factors determines the height of any chimney, including the type of appliance, need for draft, roof construction, and building height. The minimum height of a chimney (or gas vent) for gas appliances having draft hoods is based on the height specified in the applicable test standard for that appliance. For example, gas furnaces, water heaters, boilers, and room heaters must pass draft hood spillage tests with 5 ft (1.5 m) of chimney height measured from the draft hood to chimney outlet, while wall furnaces require a vent outlet at least 12 ft (3.7 m) above the floor.

In contrast to these low heights for draft hood appliances, some older types of solid fuel boilers require up to 50 or 70 ft (15 to 20 m) of chimney to produce the draft needed to overcome fuel bed and internal flow resistance and to develop rated heat output.

Residential oil furnaces and boilers with pressure atomizing burners are designed to function with negative outlet draft settings in the range of 0.04 to 0.06 in. of water column (10 to 15 Pa). Manufacturers of factory-built residential chimneys have prepared draft chimney height tables that allow for such factors as the number of connector elbows, fuel input rating, and outlet size, so that an adequate height can be selected.

Building or dwelling height and configuration also govern chimney height. The generally cited rule for minimum height of the chimney outlet is illustrated in Figure 10.2.40. The chimney

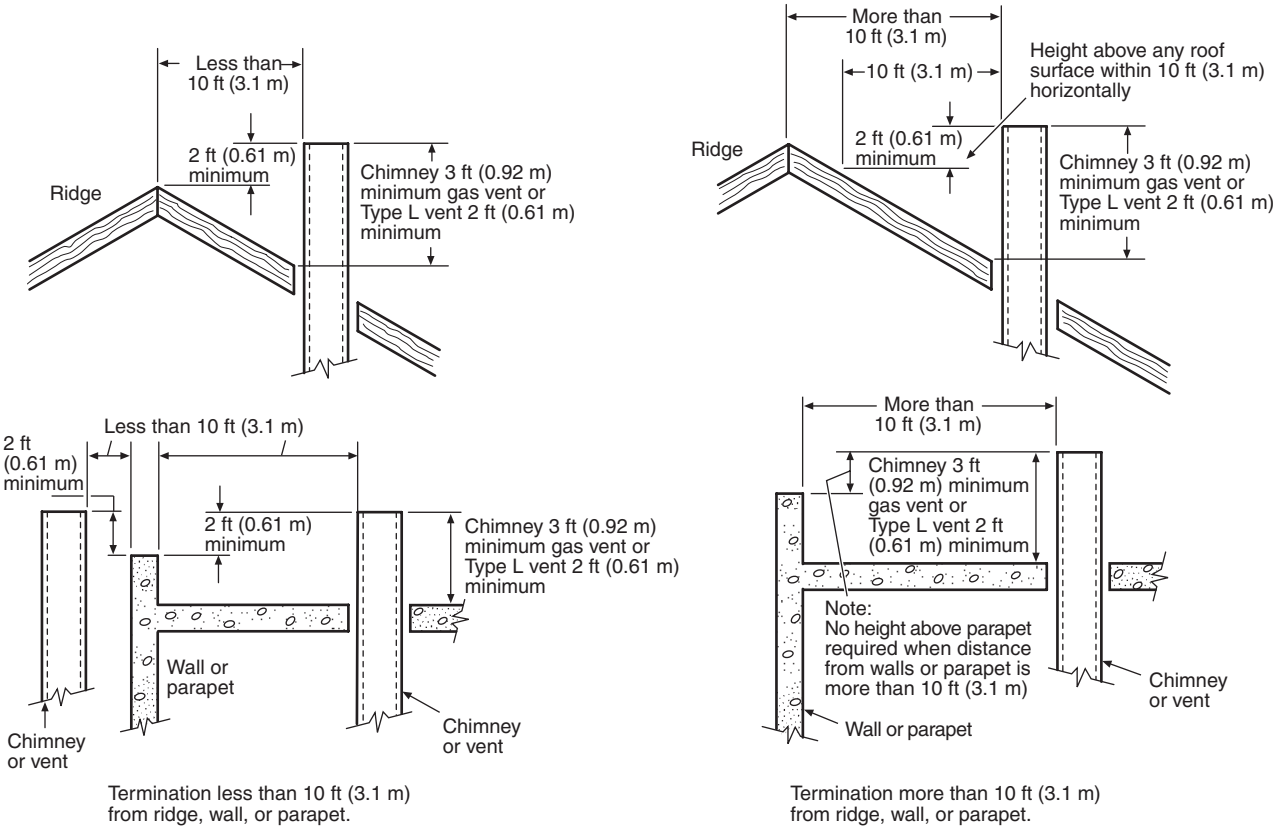


FIGURE 10.2.40 Termination of Vents and Chimneys Above Buildings

height selected must be adequate for proper appliance operation and for adequate chimney flow, as well as for proper height above the roof. Owing to the aerodynamic complexity of buildings, roofs, and chimneys, the dimensions suggested in Figure 10.2.39 sometimes are not adequate for efficient operation, which is attested to by the proliferation of special vent caps, chimney extensions, and other devices used in attempting to cure fireplace or draft problems.

Airflow over the roof must be visualized to analyze a structure for the correct chimney top location and to minimize backdrafts due to wind. Only the pressure or windward side of pitched roofs needs to be considered, because the flow moving up a building wall or toward the ridge separates from the downward side at the ridge or building edge and creates a zone of negative pressure, which circulates and eddies in this protected or cavity zone, as shown in Figure 10.2.41. The building may thus aid or impede chimney flow by using the wind to create a zone of negative or positive pressure at the chimney outlet.

Spark Arresters on Chimneys

Spark arresters are required on refuse burners or incinerators, but are desirable for all solid fuels. If sparks are expected from a fireplace or solid-fuel appliance, a chimney of any kind should have a spark screen and/or the roof surface material should be noncombustible. The usual recommendation for an arrester is for a wire mesh cloth or expanded metal having approximately ½-in. (13-mm) square openings. Smaller openings clog rapidly, whereas larger ones could allow passage of some sparks. Stainless-steel material is recommended, with galvanized steel hardware cloth a poor second choice because the coating soon burns off and frequent replacement is necessary. Factory-built chimney manufacturers offer a variety of chimney cap options with integral and accessory spark-arrester screens.

Selection of Chimneys

As an aid to selecting chimneys, heat-producing appliances have been graded by temperatures developed in the heating media or material being heated, and also by size. The grades of low-, medium-, and high-heat appliances can then be used to choose the chimney (Table 10.2.14). This selection method provides help if the appliance outlet gas temperature is consistent with its grade; however, the precepts of the grading system do not always hold true. With the availability of modern temperature instrumentation and controls and the need to conserve energy, the outlet flue gas temperature and other conditions can and should be known more precisely than heretofore for the vast majority of fuel-burning equipment. This information, which should be readily obtainable from equipment and appliance manufacturers, can offer a logical basis for chimney selection and for determining safe conditions of installation and use.

As an example of a grading inconsistency, a steam boiler operating at more than 50 psig (350 kPa) is classified in some codes as a medium-heat appliance. In selecting a chimney, it could be assumed that the outlet temperature was as high as 1500 to 1800°F (815 to 980°C). Modern multiple-pass boilers, however, operate at controlled outlet gas temperatures only 100 to 200°F (38 to 93°C) above steam temperature. Thus, the correct chimney for even a 150 psig (1000 kPa) steam boiler would be selected for an outlet gas temperature of 365.9°F + 200°F, or 565.9°F (185°C + 93°C, or 278°C). This is well below 600°F (316°C), one minimum temperature at which the medium heat grade begins. Thus, in this instance, neither the grade of appliance based on temperature of the process (2400°F [1300°C] gas in the flame) nor material (365.9°F [185°C] steam) provides a conclusive basis for selecting the boiler's chimney.

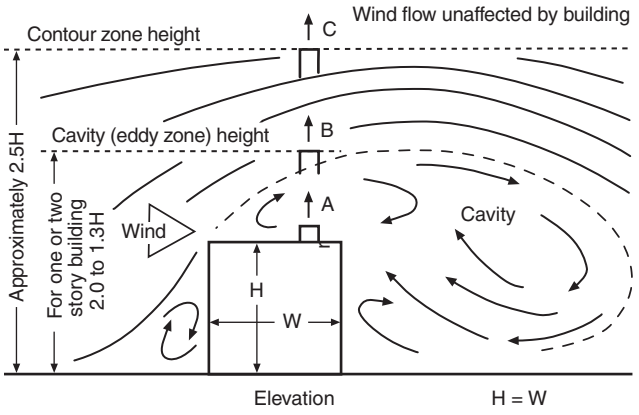


FIGURE 10.2.41 Eddy and Contour Zones Due to Airflow for One- or Two-Story Buildings and Their Effect on Chimney Gas Discharge

Chimney Selection Checklist

Selection of the correct chimney may be aided by the information in Table 10.2.14. (In those areas with adopted building codes, the code requirements take precedence over the generalities in the checklists; however, if special engineering is needed for a particular application, this approach should generally also meet the intent of any modern performance code.)

Hazards of Chimneys

For chimneys serving oil, wood, or coal appliances, fire may occur as a result of one or more of the following elements: (1) operator error or ignorance, (2) control failure, (3) improper installation, (4) use of a defective or unlisted appliance, (5) ignition of combustible soot or creosote deposits in the chimney, (6) serious cracks or internal collapse of the masonry, (7) defective construction, and (8) failure to secure joints of factory-built products.

Even masonry chimneys for gas appliances operating at very low temperatures have their problems. Condensation of flue product moisture could eventually disintegrate the mortar, leaving the chimney weak and easily toppled—a hazard to passersby.

In masonry chimneys, the following conditions can cause a fire in adjacent combustible materials:

1. Filling the space between the chimney and wood framing with insulation, or placing framing into or against the chimney wall. Note that a fill of even noncombustible insulation can be hazardous. Though the insulation itself might not ignite, it

TABLE 10.2.14 Chimney Selection

Column I	*Column II*	*Column III*	*Column IV*	*Column V*
Types of Appliances to Be Used with Each Type Chimney				
Residential-type gas, liquid, and solid fuel-burning applications such as: All appliances shown in column I of NFPA 211, Table 2-2.2 Dual fuel furnaces Fireplace inserts Fireplace stoves Fireplace stove room heaters Freestanding fireplaces Boilers Masonry fireplaces Pellet fuel-burning appliances[a] Ranges Residential incinerators Room heaters Stoves	All appliances shown in Column I Boilers operating at not over 1000°F (538°C) flue gas temperature Low heat nonresidential appliances Building heating appliance	All appliances shown in Columns I and II 1400°F (760°C) nonresidential appliances	All appliances shown in Columns I, II, and III Medium-heat nonresidential appliances	All appliances shown in Columns I, II, III, and IV High-heat nonresidential appliances
Maximum Continuous Appliance Outlet Flue Gas Temperature Under Normal Operating Conditions				
Chimney Type (Select chimney type based on appliance type and flue gas temperature.[b])				
1000°F (538°C)	*1000°F (538°C)*	*1400°F (760°C)*	*1800°F (982°C)*	*>1800°F (>982°C)*
Factory-built residential-type and building heating appliance[c] Masonry, residential type	Factory-built residential-type and building heating appliance[c] Masonry, low-heat type Unlisted metal low-heat type[d]	Factory-built 1400°F Masonry, low-heat type Unlisted metal 1400°F type[d]	Factory-built medium-heat appliance Masonry, medium-heat type Unlisted metal medium-heat type[d]	Engineered high heat type Masonry, high-heat type Unlisted metal high-heat type *(see Note 2)*

[a]See also Table 2.2.2, Listed Pellet Vent in NFPA 211.
[b]Chimneys shown in any column shall be permitted to be used on appliances that can use a chimney shown in any column to the left of that column, provided the chimney meets the provisions of notes a, c, and d.
[c]Factory-built listed chimneys for use with all wood-burning appliances used in one- and two-family dwellings shall meet the Type HT requirements of UL 103, *Standard for Safety Chimneys, Factory-Built, Residential Type and Building Heating Appliance,* or the requirements of CAN/ULC-S629-M87, *Standard for 650°C Factory-Built Chimney Systems for Solid Fuel-Burning Appliances.*
[d]Single-wall chimneys or unlisted metal chimneys shall not be used inside one- and two-family dwellings.
Source: Table 2.2.1, NFPA 211, *Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances,* 2000 edition.

interferes with the dissipation of heat away from the chimney and framing. Temperatures can build to the point where framing separated from the chimney by insulation is exposed to potential ignition. All clearances from chimneys must be maintained as an air space, without a fill of any kind.

2. Using a restrictive chimney cap in combination with cracks or failed mortar in a chimney, which could cause excessive leakage of hot gas at roof level, thus endangering rafters and roofing.

3. Prolonged overfiring, which may cause excessive heating on adjacent walls. At temperatures of 500°F (260°C) on the brick exterior surface, 2 in. (51 mm) clearance to nearby combustibles is of little protective value, particularly if there is little ventilation airflow.

4. Creosote or soot fires, insofar as masonry chimneys are susceptible to collecting creosote deposits. When thick or heavy enough, these deposits can burn long enough to cause outer chimney surface temperatures that can ignite the structure around them. Further, upward gas flow velocity might be sufficient to carry sparks up from the fire or burning creosote and to drop them on the roof. After a severe chimney fire, both the tile liner and bricks might have serious cracks due to thermal expansion.

Factory-built chimneys provide many opportunities for installation errors and shortcuts, which can lead to fire hazards. Among the potential installation errors and shortcuts are the following:

1. Installation of the chimney ceiling support above the ceiling framing. This necessitates passing the single-wall connector through ceiling framing at what could be dangerously close clearance; thus, the hazard might more properly be blamed on the connector.

2. Failure to secure joints or align gas-carrying parts. Many designs of factory-built chimneys allow very little tolerance for misalignment. Failure to make sure that the inner pipes of a multi-wall chimney are aligned and connected can allow flames to enter external passages reserved for cooling airflow.

3. Use of mismatched chimney parts. A given design or brand of chimney is intended to be assembled only with identical parts. There is no interchangeability and it is extremely bad practice to mix multiwall and insulation-filled chimney sections.

4. Failure to maintain proper air space clearances. As with masonry chimneys, close proximity of framing, or filling of the air space with insulation, can cause a fire hazard. Factory-built chimneys are listed for specific clearances, which are shown in the instructions and on labels. When properly used, the required manufacturer's support and spacing parts will enforce proper clearance.

The foregoing installation errors might cause fires at relatively low flue gas temperature; however, even a correctly assembled and installed chimney lacks the capability of repeatedly acting as a combustion chamber.

Chimney or Creosote Fires

The term *creosote* as applied to chimney systems refers to the tarry brown or hard black internal deposits produced by burning wood. Combustion of wood produces varying amounts of complex hydrocarbons that can condense and accumulate inside connector and chimney surfaces. These combustible deposits ignite when temperature is sufficiently high and will burn at temperatures in the range of 1200 to 2000°F (650 to 1100°C). The temperature and duration of the fire both depend on the accumulated thickness of creosote, chemical composition of the deposit, availability of oxygen, type of heating appliance, type of chimney, and so on.

In masonry chimneys, intense fires can cause cracking of tiles and brick masonry, as well as excessive heat transfer through chimney walls and hazardous overheated external surface temperatures. Clay flue liners are quite resistant to high temperatures, when applied gradually. However, chimney fires typically cause a very sudden rise in internal chimney temperature. This results in thermal shock as the hot inner surface of the liner expands against the cooler, inflexible outer portions. Longitudinal cracks in one or more liner sections are a frequent result of chimney fires. Such cracks can appear closed when the chimney is cool, but can open up to measurable dimensions when the chimney is heated by subsequent use.

The likelihood of fire spread to the adjacent structure is related to the duration of the chimney fire. Because of their mass, masonry chimneys produce significant thermal inertia. A short, though intense, chimney fire is less likely to overheat the chimney structure than a longer-lasting fire. It is therefore important that, after initial steps are taken to control a chimney fire, the fire department be called to make sure that it is completely extinguished.

In factory-built chimneys, as with masonry, the effect of chimney fires varies depending on attained temperature. Factory-built chimneys are tested with repeated application of flue gas temperatures up to 2100°F (1149°C) for periods of up to 30 minutes. They can, therefore, be expected to survive a chimney fire in usable condition. This, however, should never be simply assumed; chimney fires can exceed the test temperatures and differential heating of flue surfaces can create unmanageable stresses in the metal. It is not uncommon for the liner of a factory-built chimney to exhibit buckling after a fire. If the buckling is minor, such that flue gases or other combustion products cannot pass beyond the liner, the chimney can continue to be used. If buckling is more significant, the affected section, at minimum, should be replaced. In general, if the outer chimney is not discolored and remains shiny, it is unlikely that any building structural damage has occurred, since shiny surfaces are unlikely to radiate damaging amounts of heat if the chimney is installed at correct clearance.

Inspection after Chimney Fire. If it is suspected that a chimney fire has occurred, both masonry and factory-built chimneys should be thoroughly inspected. The flue surface, in particular, should be closely examined for cracks, holes, missing sections, or distortion. Unless the chimney is very short, such inspections should be done using closed-circuit video inspection equipment, which is the only practical way to view the inaccessible flue surface. The outer chimney surface should be examined as well, for cracks, smoke leaks, or major discoloration. Combustibles surrounding the chimney should be checked for evidence of charring and any insulation removed from required air space clearances. Damaged chimney caps and other appurtenances should be replaced. The chimney should be placed back in service only after any necessary repairs have been made.

Control of Chimney Fires. In wood-burning stoves and heaters having air dampers and doors, reducing the air supply by closing them is the best option to control chimney fires; then the combustion rate in the chimney depends on its air supply. When other appliances are connected to the chimney or a barometric damper is used for draft control, these can supply air and must also be closed to control a chimney fire. Flare-type chimney fire

extinguishers (similar to automotive safety flares) are available that, when activated and placed in the appliance, release a cloud of fire extinguishing agent into the chimney. For the agent to be effective, it must be retained in the chimney. Therefore, the stove should be closed to prevent the agent from being drawn quickly up and out of the chimney. Open-front fireplaces or fireplace stoves without doors may not accumulate creosote rapidly, but under fire conditions air control is difficult. The best policy with fireplaces is routine chimney inspection and mechanical cleaning (brushes and scraping).

Because of the possibility of fire spread to the building structure, occupants should, at minimum, be gathered and prepared to leave the building. The fire department should be immediately called, both as a precaution against fire spread and to ensure that the chimney fire is completely extinguished.

Maintenance and Inspection of Chimneys

To remain safe and effective, chimneys need periodic inspection and maintenance. NFPA 211 requires all chimneys (regardless of the fuel used in connected appliances) to be inspected at least once a year. Such inspections should include, at minimum, examination of the inner flue surface for the presence of combustible deposits and freedom from cracks, gaps, softening, or other damage or deterioration. The outer wall should be examined for missing bricks or mortar and evidence of leakage. Although clearances to the building structure are usually determined at the time of construction, inspection should verify that no insulation or loose combustible material has fallen into the required air space.

For chimneys serving solid-fuel equipment, cleaning of creosote and other combustible deposits from the flue is the most frequent maintenance activity. A common rule of thumb suggests that a buildup of ¼ in. (6.4 mm) in thickness indicates a need for cleaning. This might be most applicable to soft, powdery, or crusty deposits. Deposits of smooth, gummy, or hard tar-glaze, on the other hand, might contain significantly more potential energy, and can fuel a more intense and longer-lasting fire than less dense material. Therefore, when any thickness of tarry deposits is detected, immediate cleaning is in order.

Cleaning of loose deposits is usually done with a stiff wire brush, fitted to the flue dimensions and scrubbed up and down the chimney with rods. More resistant deposits require the use of a flat wire brush or specialized manual scrapers. There are various mechanical devices available that use rotating chains or brush heads to flail and chip hard creosote deposits on the flue walls. In extreme cases, there are chemical treatments that can soften or loosen deposits. Mechanical and chemical cleaning methods should be used only by trained professional chimney service specialists.

NFPA 211 also includes requirements for corrective action when inspection shows that the chimney is no longer suitable for the intended application. Any damage or deterioration, from whatever cause, that impairs the ability of the chimney to conduct the products of combustion directly to the outdoors, while protecting the structure and occupants from heat, leakage, or spillage, is cause for repair or replacement of the chimney. Specifically, with respect to flue lining, NFPA 211 requires repair, replacement, or relining if the lining has "softened, cracked, or otherwise deteriorated such that it no longer has the continued ability to contain the products of combustion, that is, heat moisture and flue gases."

FIREPLACES AND FIREPLACE STOVES

Fireplaces of masonry or factory-built construction are primarily open fire-chamber appliances with no controls on the air supply to the fire. These require a properly sized chimney to carry out the smoke and combustion gases. Fireplace stoves are free-standing, factory-built appliances operating with an open front, but, if these have doors, they may also operate as stoves or heaters with controlled combustion air. The addition of glass doors to a masonry fireplace, or the installation of a closed-front fireplace insert, will transform its combustion characteristics to that of a heater.

Special techniques are required for connection of a heating appliance to a fireplace. The appliance must be directly connected to masonry fireplace flues with a suitable connector extending through the damper and smoke chamber. Appliances must not be inserted in, or connected to, factory-built fireplaces unless the appliance is listed for that fireplace, and then only in strict accordance with manufacturer's instructions.

Masonry Fireplaces

Field-constructed masonry fireplaces must conform to building codes or provisions of applicable standards (e.g., NFPA 211) to ensure safe operation. They may be served by a masonry residential chimney or may use a factory-built chimney with a suitable factory-furnished transition between smoke chamber and chimney. Prefabricated designs of masonry fireplaces and masonry fireplace chimney combinations are available in some localities. When a lining of low-duty firebrick is provided, masonry fireplaces require at least 8 in. (203 mm) of brick thickness or equivalent for the back and sides, with 2 in. (51 mm) clearance to combustibles at the sides and 4 in. (102 mm) minimum clearance from the back. When the lining described above is not used, the thickness of the masonry at the back and sides should not be less than 12 in. (305 mm). The entire fireplace must be supported on a noncombustible footing, with structural floor framing well away from direct heat conduction from the fire zone or external hearth (Figure 10.2.42).

Hearth extensions of approved noncombustible material must be provided for all fireplaces. The hearths must extend at least 16 in. (406 mm) in front and 8 in. (203 mm) beyond the sides of fireplaces with an opening of less than 6 ft^2 (0.56 m^2). If the opening is 6 ft^2 (0.56 m^2) or larger, the hearth must extend at least 20 in. (508 mm) to the front and 12 in. (305 mm) to the sides.

Masonry fireplaces may be built around steel fireplace units or heat circulating forms incorporating an air chamber. A total thickness at back and sides of not less than 8 in. (203 mm) must be provided, of which not less than 4 in. (102 mm) is solid masonry. The same clearances to surrounding combustibles apply to fireplaces with circulators.

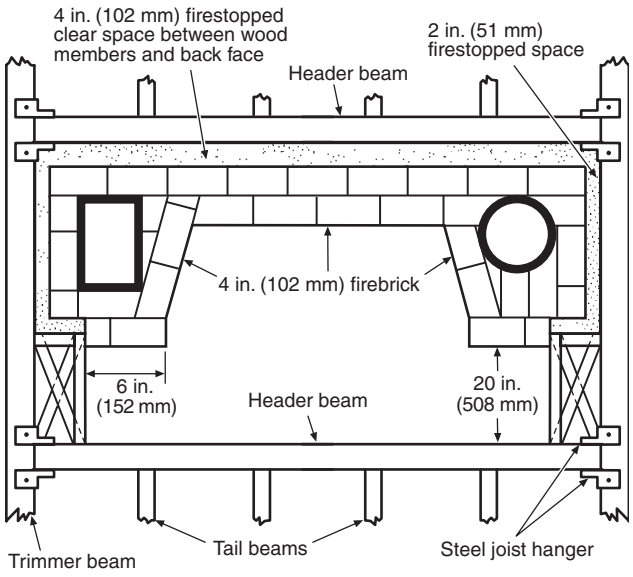


FIGURE 10.2.42 Floor Framing Around a Fireplace, When the Fireplace Opening Is 6 ft^2 (0.56 m^2) or Larger

Factory-Built Fireplaces

Factory-built fireplaces are mainly of metal construction using multiple air spaces, refractory hearths and liners, and insulation to obtain the required level of safety. Factory-built fireplaces are tested and listed to ANSI/UL 127, *Standard for Safety Factory-Built Fireplaces*.[22] Each fireplace must be installed with the specific chimney and other parts called for by the manufacturer's instructions and the terms of its listing.

Combustion Air Inlets

Some fireplaces incorporate a duct to bring combustion air directly to the fire chamber from the outdoors. This theoretically reduces the consumption of room air and minimizes the possibility of excessive depressurization of the house. Because such ducts communicate with the combustion zone, care must be taken to ensure that they do not create a hazard. Building fires can occur if combustion products, such as embers, have entered the duct in proximity to combustible construction.

NFPA 211 does not allow combustion air ducts to terminate within the fire chamber of a fireplace unless the device is listed for such an application. Otherwise, the duct must terminate outside the fireplace; if within 6 in. (152 mm) of the opening, they must be equipped with a guard to prevent the entry of embers, ashes, flame, and so on. The duct itself must be made of 26-gauge galvanized steel or equivalent, and must maintain a 1 in. (25.4 mm) clearance to combustibles.

Factory-built fireplaces may use combustion air ducts that are incorporated into the original design of the listed fireplace, and, if optional, must be a listed accessory to the particular fireplace. They will be accompanied by specific installation instructions and must be installed accordingly.

No combustion air duct should draw air from an attic, basement, garage, or other interior space, or an area where combustible vapors might be present. Any duct that connects directly to the fire chamber should not extend vertically above the fireplace, to avoid the possibility of the duct acting like a chimney and drawing in combustion products.

Chimney Sizes for Fireplaces

For masonry fireplaces, the correct size and height of chimney will ensure that all smoke, fire, and gas goes up the chimney. Although imprecise, there are several rules of thumb for sizing fireplace flues. For very short chimneys (less than about 15 ft [4.6 m]), the actual cross-sectional area of the flue should be at least one-eighth of the area of the frontal opening of the fireplace. For chimneys of normal height, rectangular flues should be at least one-tenth of the fireplace opening; round flues should be at least one-twelfth of the opening. The nominal size of tile liner must be carefully checked to ensure that the internal cross-section area is adequate. In addition, the area of opening through the damper throat must be approximately twice the required flue area or greater, or it may reduce flow and possibly cause smoking.

For factory-built fireplaces, the chimney and, therefore, the flue size, is an integral part of the appliance design. Only the chimney specified or supplied by the fireplace manufacturer should be used. There are also factory-built fireplaces made of masonry material that are assembled on site from precast components. Some of these come with an integral chimney, whereas others specify a particular size chimney of conventional construction. Some of these fireplaces use advanced principles of airflow through the fireplace and can use unconventionally small flue sizes; ratios of fireplace opening area to flue area of 20:1 are possible with some designs.

Charts are available for factory-built and masonry chimneys in the ASHRAE handbook and product directory[21] and in manufacturers' literature that indicate the correct chimney size and height in relation to frontal opening, based on an average room air velocity of not less than 0.8 ft/sec (0.24 m/sec) into the opening. This minimum velocity rule is valid for a wide variety of open fire chamber combustion systems, including masonry fireplaces as well as combination room heaters and fireplace stoves.

Factory-Built Fireplace Stoves

These free-standing units are usually of metal or combination metal and refractory construction and may require a specific type of chimney and special connectors, or may be connected to any acceptable chimney by conventional means. Fireplace stoves are tested and listed (see ANSI/UL 737, *Standard for Safety Fireplace Stoves*),[23] but if the stove has doors it becomes a combination fireplace and room heater, and to be listed for operation with doors closed it must also comply with ANSI/UL 1482, *Solid Fuel Type Room Heaters*.[24]

Investigation of many combination fireplace stove heater designs has demonstrated the validity of the geometrical relationship between heater size and required clearance. Simply

stated, larger units may require greater than standard clearance. To be sure of correct installation, the manufacturer's installation instructions for listed stoves and heaters should be scrupulously observed. These instructions have been reviewed for consistency with test results and are as essential to the safety of an installation as are the design features of the stove.

Although untested fireplace stoves and related heaters can be installed and operated safely, they are seldom accompanied by carefully written instructions. Many imitations of listed designs can be found that are sold through retail outlets having little interest in the final installation. The lack of clear instructions and warnings poses many hazards to the consumer.

Hazards of Fireplaces and Their Chimneys

Open fireplaces, transferring heat primarily by radiation from the fire, can create several kinds of hazards:

1. Ignition by radiation of furnishings or walls located too close to the fire.

2. Ignition of furnishings or carpeting by sparks or from logs rolling out of the fire. For large, high fireplaces having a high fuel capacity, the 20 in. (508 mm) hearth width requirement may be grossly inadequate.

3. Ignition of combustible structural materials by excessive heat conducted through hearth or fireplace walls, which can make prolonged overfiring of a masonry fireplace dangerous.

4. Escape of gases from the opening into a construction gap between the fireplace shell and the front facing wall. This is a common installation fault with factory-built fireplaces, since a smoking unit—one with insufficient chimney flow—allows very hot gas to escape into this area.

5. Sparks and embers falling onto a combustible floor between the fireplace and its hearth extension. This can be prevented by placing the masonry or factory-furnished hearth extension flush against the front of the fireplace, or by using a sheet of metal at the floor surface under the joint between the fireplace and its hearth.

6. Burning highly combustible solid materials, such as a dried Christmas tree and wrappings. The high gas temperatures resulting may ignite creosote deposits, or cause damage to the masonry. The high rate of burning may cause the flames, heat, and smoke to billow out of the fireplace opening, possibly igniting nearby combustibles.

7. Use of any flammable liquid to start or rekindle a fire, or in any room with or near an open fire.

8. Failure to clean the chimney whenever creosote deposits build up to dangerous thickness. A layer of creosote 1⁄16 in. (1.6 mm) thick in an 8-in. (200-mm) size chimney 15 ft (4.6 m) high contains as much as 122,000 Btu (128 MJ) of fuel. If this burns off in 15 min, the resulting temperature could reach 1700°F (930°C) at a heat release rate as high as 488,000 Btu per hour (140 kW).

9. Use of an incorrect or mismatched chimney. For safe operation, many types of factory-built fireplaces require a chimney that interconnects with its air passages. Failure to connect the fireplace to this specific chimney could be extremely dangerous and clearly violates installation requirements and the listing.

10. Failure to install firestopping around chimneys, which might be termed an indirect installation hazard. This will not start a fire, but, if one starts elsewhere, the lack of firestopping may cause severe losses. Because of the numerous possibilities for operator or construction errors in the vicinity of the fireplace itself, every precaution should be taken to prevent rapid involvement of the entire structure in case of fire. Many modern single and multiple residences of frame construction use a chase or vertical enclosure, inside or external to the dwelling, containing one or more fireplace chimneys. The absence of floors or other internal framing makes it easy to install all the chimneys, but also provides an ideal passage for rapid vertical spread of flame to upper levels and the roof. The shape and size of firestopping for this sort of installation cannot readily be anticipated by the fireplace manufacturer, but carefully fitted sheet metal or lath and plaster may limit the spread and allow time for effective fire fighting.

SUMMARY

Heating systems and appliances are frequent causes of fire because they operate at high temperatures and sometimes can involve hazards such as combustible mixtures and fuels. There are many different components involved in a heating system, including various types of fuel, heating applications, firing methods, distribution systems, storage, vents, chimneys, and fireplaces. Each type of fuel and heating system component is associated with potential fire hazards. Proper installation, operation, and maintenance in accordance with the fire codes are the keys to fire safety and prevention.

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21. *1996 ASHRAE Handbook—HVAC Systems and Equipment,* American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, 1996.
22. ANSI/UL 127, *Standard for Safety Factory-Built Fireplaces,* Underwriters Laboratories Inc., Northbrook, IL, 1996.
23. ANSI/UL 737, *Standard for Safety Fireplace Stoves,* Underwriters Laboratories Inc., Northbrook, IL, 1996.
24. ANSI/UL 1482, *Solid Fuel Type Room Heaters,* Underwriters Laboratories Inc., Northbrook, IL, 1998.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the heating systems and appliances discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 31, *Standard for the Installation of Oil-Burning Equipment*
NFPA 54, *National Fuel Gas Code*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 70, *National Electrical Code®*
NFPA 85, *Boiler Room Combustion Systems Hazards Code*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 90B, *Standard for the Installation of Warm Air Heating and Air-Conditioning Systems*
NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations*
NFPA 211, *Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*

Chapter 3

Building Transportation Systems

Edward A. Donoghue

Chapter Contents

Code Requirements
Elevators
Dumbwaiters
Escalators
Moving Walks
Tests and Inspections

Key Terms

accessibility, building transportation system, dumbwaiter, elevator, elevator car, escalator, hoistway, machine room, moving walk

Building transportation systems are mechanical/electrical systems that transport people or materials vertically or horizontally in a building. They provide conveyance for building occupants or selective, noncontinuous movement of materials. Unlike materials-handling systems, they are not part of a manufacturing process and are not designed to continuously move material.

Because of their impact on fire safety, building transportation systems must be considered during the design stage and should be integrated with the total building fire protection system. Hazards associated with these systems must be included in any prefire planning and fire protection survey.

Building transportation systems, such as elevators and escalators, make high-rise buildings feasible. Today, accessibility requirements mandate elevators in most buildings with two or more stories. Although it is unrealistic for multistory buildings to function without elevators, elevator hoistways can contribute to the spread of smoke and/or fire. On the other hand, an elevator is a necessary tool for fire-fighting operations in high-rise buildings.

The discussion of elevators, dumbwaiters, escalators, and moving walks in this chapter is intended to complement NFPA *101®*, *Life Safety Code®*, and *NFPA 5000®*, *Building Construction and Safety Code®*, which requires elevators and escalators to be installed in accordance with ASME A17.1, *Safety Code for Elevators and Escalators.*[1] U.S. building codes also refer to ASME A17.1.

In Canada the *Safety Code for Elevators,* CSA B44,[2] applies in lieu of ASME A17.1. The ASME A17 and CSA B44 Elevator Safety Codes are essentially fully harmonized. In April 2007 the *Safety Code for Elevators and Escalators,* ASME A17.1/CSA B44-2007, was published as the successor to ASME A17.1 and CSA B44. The model building code in Canada is the National Building Code of Canada (NBCC).

This chapter examines the various building transportation systems—elevators, escalators, dumbwaiters, and moving walks—that transport people or materials vertically or horizontally in a building.

The following chapters are pertinent to the subject matter of this chapter and should be reviewed for a more comprehensive view of fire problems associated with building transportation systems: Section 18, Chapter 1, "Confinement of Fire in Buildings"; Chapter 3, "Smoke Movement in Buildings"; and Chapter 4, "Venting Practices." See also Section 8, Chapter 3, "Materials-Handling Equipment," for other-than-freight elevators and dumbwaiters.

CODE REQUIREMENTS

Requirements for the installation of equipment for elevators, dumbwaiters, escalators, and moving walks appear in ASME A17.1/CSA B44. Current ASME A17.1/CSA B44 code requirements provide a framework for standards of safety for products whose technologies have become state-of-the-art and commonplace. In a progressive elevator industry, designs and products emerge that are not specifically covered in ASME A17.1/CSA B44. Since code requirements cannot anticipate future

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development and innovation in the elevator industry, ASME A17.1/CSA B44 is written to reflect state-of-the-art technologies following its introduction.

With new materials and processes in mechanical, structural, electronic, and optics areas, in addition to analytical capabilities now available, the need for flexibility to introduce products resulting from maturing technical developments is heightened. The ASME A17 and CSA B44 committees have responded to this need with the new ASME A17.7/CSA B44.7, *Performance-Based Safety Code for Elevators and Escalators.*[3] ASME A17.7/CSA B44.7 requires compliance with ISO-based Global Essential Safety Requirements (GESRs). Design compliance with GESRs is evaluated to ensure that the hazards have been addressed and mitigated using a risk assessment (RA) process. Finally the design along with the RA documentation is presented to an Accredited Elevator/Escalator Conformity Organization (AECO) to review and evaluate for compliance with ASME A17.7/CSA B44.7. Once the AECO is satisfied a certificate of compliance will be issued. The process is outlined in Figure 10.3.1.

ELEVATORS

An elevator is defined as a hoisting and lowering mechanism equipped with a car that moves within guides and serves two or more landings.[1] The two major elevator types, classified by their driving means, are electric and hydraulic.

Types of Elevators

Electric Elevators. An electric elevator's power source is an electric motor. The most common electric elevator is the electric traction elevator that employs a grooved traction drive sheave, over which pass suspension ropes that are attached to the car and counterweight (Figure 10.3.2). This arrangement is very simple and safe, allowing its use in buildings of any height. An inherent safety feature is traction loss when the car or counterweight is at its travel limit. The car or counterweight cannot be pulled into the overhead structure, provided proper traction ratios are provided.

Another, older type of electric elevator is the winding drum machine elevator. In this arrangement, suspension ropes are attached to, and wind onto, a winding drum. Counterweight ropes also may be fastened to, and wind onto, the drum. Winding drum machines typically have no counterweights, but older designs may have a car counterweight and/or a drum counterweight. It is possible for either the elevator car or counterweight to be pulled dangerously into the overhead structure.

Hydraulic Elevators. Hydraulic elevators are powered by liquid under pressure, in a hydraulic jack (Figure 10.3.3). The rise, or travel, of a direct plunger hydraulic elevator is limited to the length of its piston, usually six floors or less.

Another type of hydraulic elevator is the roped hydraulic elevator. This elevator type has its plunger, or piston, connected to the car with wire ropes or indirectly coupled to the car by wire ropes and sheaves.

Classification of Elevators by Use. Elevators are classified according to use as either passenger or freight elevators. A passenger elevator's primary use is to carry persons other than an operator and persons necessary for loading and unloading. A freight elevator is used primarily for carrying freight; only the operator and persons who unload and load the freight are permitted to ride, unless the elevator has been designed to comply with the provision in ASME A17.1/CSA B44 as a freight elevator permitted to carry passengers. Freight elevators will have a sign advising who is permitted to ride. A service elevator is officially classified as a passenger elevator that is designed to carry freight.

Construction

Hoistway Construction. Elevators travel in a vertical space or opening, called a hoistway or shaft, that extends from the pit floor of a building to the floor, or roof, above. ASME A17.1/CSA B44 requires that hoistway construction conform to the applicable building code or, in the absence of local code, to provisions of one of the model building codes.

Although elevators made high-rise buildings practical, they also created new, complex, potentially dangerous fire safety challenges. Hot smoke and gases from fire, if allowed to accumulate at the top of the elevator hoistway, can result in mushroom fires on upper floors served by the elevator. This occurs because an enclosed elevator hoistway acts as a chimney or flue due to stack effect. This generally results in the movement of smoke and combustion products from lower to upper building levels.

The stack effect may also adversely affect elevator door closing, even under normal conditions. ASME A17.1/CSA B44 specifies the maximum door closing force and kinetic energy for safe automatic door closing. Pressure differentials must be taken into account to safely regulate door closing operations.

All model building codes require venting of elevator hoistways. Most require venting of the hoistway for elevators serving three or more stories. Some local codes permit venting through the machine room, with mechanical or natural venting from the machine room to the outside. This practice may result in premature loss of elevator service in a fire emergency due to elevated machine room temperatures and/or smoke damage to the control system. Most codes restrict the size of the opening in machine room floors. For fully sprinklered buildings that have no sleeping rooms, some codes allow sprinklers in the hoistways in lieu of hoistway venting.

Some local codes require pressurization of the hoistway to a specified minimum positive pressure above the pressure of the elevator lobby. When a pressurized hoistway is provided, it should contain a vent that opens automatically in case of power failure. A manual means should also be provided to vent smoke that penetrates the hoistway. Due to numerous variances and rapid developments in this area, local code requirements should be checked.

When designing a hoistway pressurization system the following issues need to be taken into consideration. The kinetic energy and closing forces on elevator doors are regulated by ASME A17.1/CSA B44, *Safety Code for Elevators and Escalators.* The limitations on the maximum kinetic energy and door

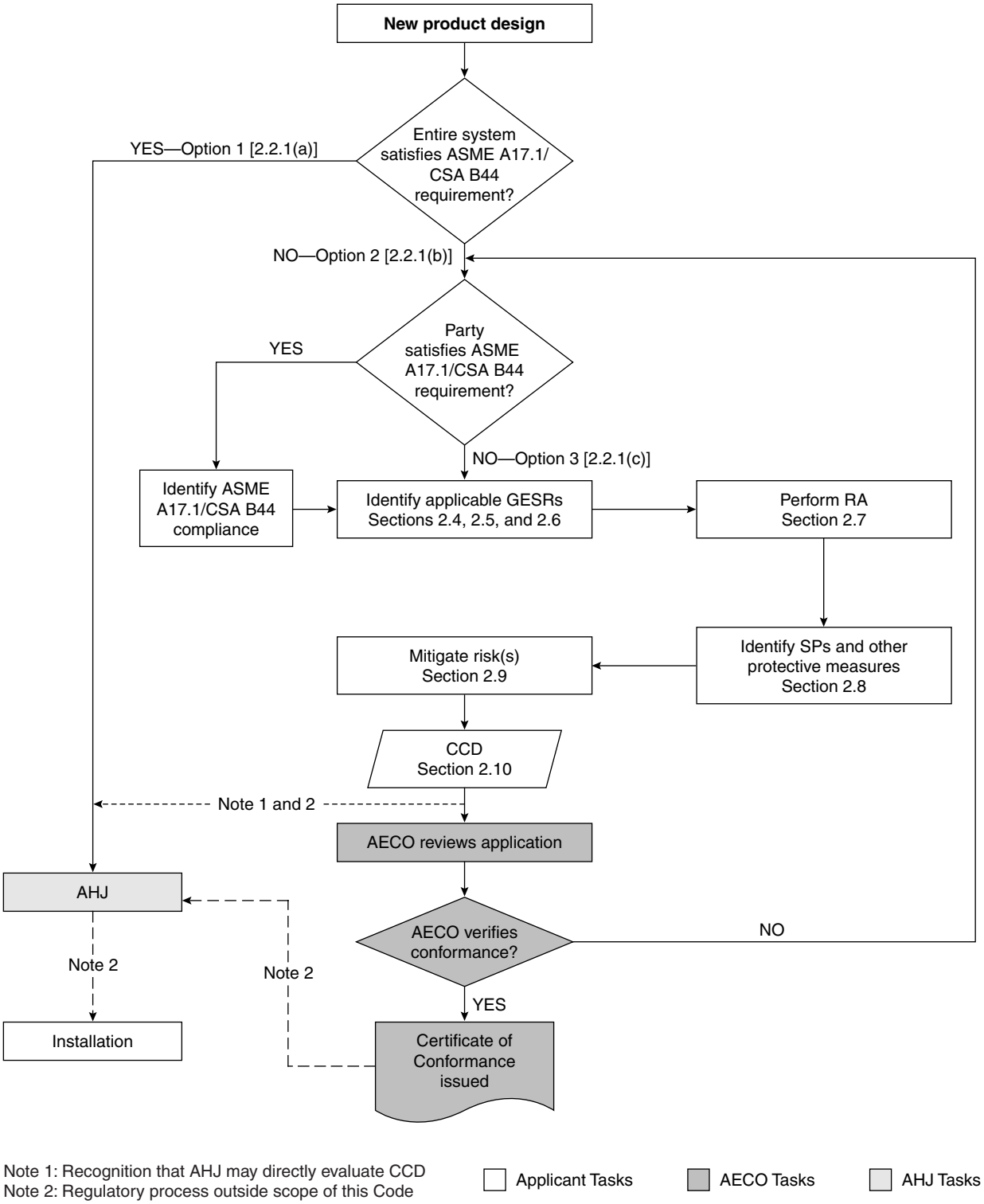

FIGURE 10.3.1 Elevator/Escalator ASME A17.7/CSA B44.7 Design Compliance Process (Source: Reprinted from ASME A17.7/CSA B44.7-2007 by permission of the American Society of Mechanical Engineers. All rights reserved.)

closing forces are critical to ensure the safety of passengers entering and exiting elevator cars. Excessive pressurization will lead to jamming of the elevator doors due to the high pressures. A pressure of 0.35 in H_2O (8.7 Pa) will produce lateral force on each panel of a landing door of about 28 lb (12.7 kg) on a 44 in. (1117.6 mm) door. This force will also be in the opposite direction of the normal forces to which the door panel is normally subject. In all likelihood open elevator doors will not be able

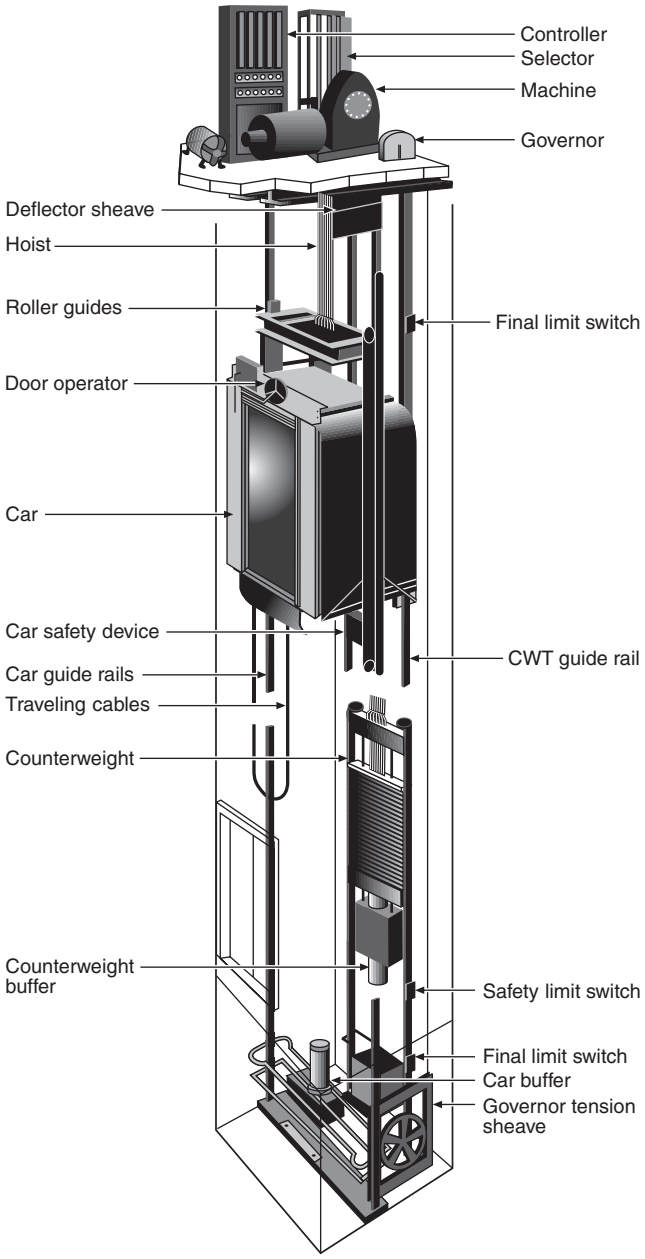

FIGURE 10.3.2 Electric Traction Elevator (Source: National Elevator Industry, Inc.)

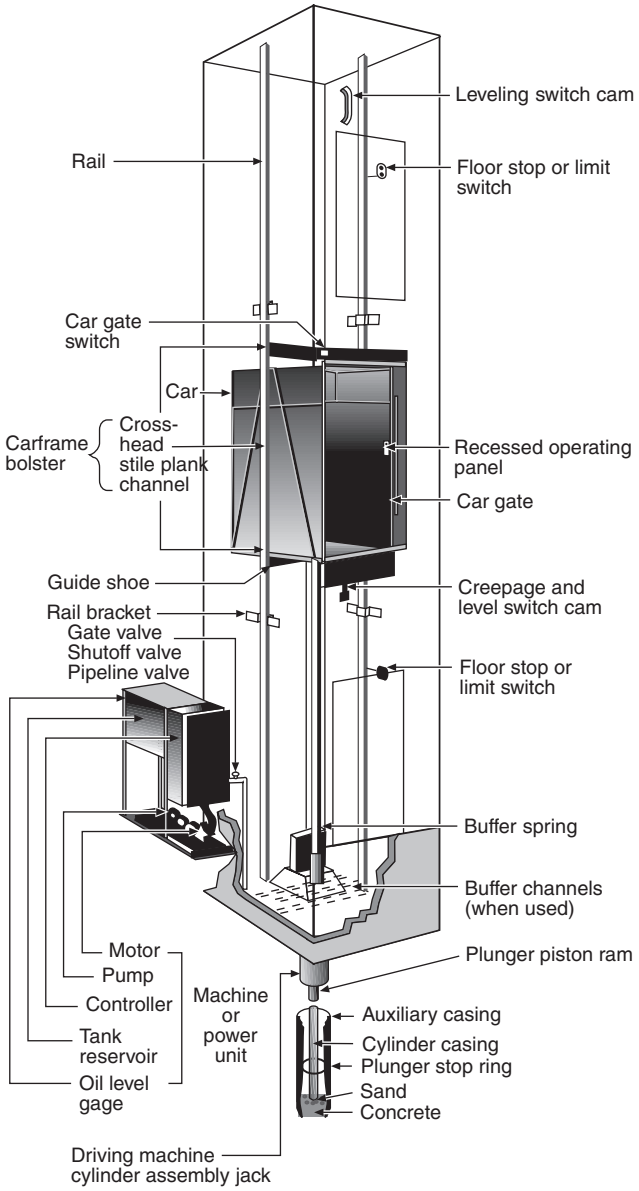

FIGURE 10.3.3 Direct Plunger Hydraulic Elevator (Source: National Elevator Industry, Inc.)

to power close once pressurization is activated. The following scenarios are typical of some of the conditions that could be encountered:

- Elevators operating on normal service; pressurization activated due to fire in building; Phase I not activated by smoke detector in elevator lobby, machine room, or hoistway; elevators doors open to accept or discharge passengers; elevator doors unable to overcome pressure and close; elevator service in building is lost one car at a time.
- Elevator operating on normal service; pressurization activated due to fire in building; Phase I activated by smoke detector in elevator lobby, machine room, or hoistway or by Phase I key switch; elevators at landings with open doors not able to overcome pressure and close doors; cars do not return on Phase I to designated landing; arriving fire fighters will not find all elevators at designated landing and lose valuable time searching for cars not recalled on Phase I to designated landing. (Phase operations are discussed later in this chapter.)
- Elevators at designated landing that have returned on Phase I; arriving fire fighter activates Phase II; doors not able to overcome pressure and close; fire fighters lose use of elevators.

Elevator hoistway enclosure walls are normally fire partitions with a fire resistance rating of 2 hours. Some situations require no fire resistance rating. For example, an elevator that

serves only open balconies without penetrating separate fire-resistant areas of a building does not require a fire-resistant hoistway. In other cases, the fire resistance rating may be required on only one or two walls. An example is an observation elevator that permits exterior viewing by passengers, where entrances to the elevator penetrate fire-resistant walls.

The maximum number of elevators permitted in a single hoistway is controlled by building code requirements, which are intended to limit the potential of a fire knocking out all elevator service in a structure. For buildings with three or fewer elevators, codes generally permit all elevators to be in the same hoistway enclosure. Four elevators require at least two separate hoistway enclosures, and, where there are more than four elevators, no more than four can be enclosed in the same hoistway enclosure.

Hoistway Entrances. If the hoistway wall is load bearing, it can support the hoistway entrance operating mechanisms and locking devices. If the walls are not load bearing, other building structures must support the hoistway entrance operating mechanisms and locking devices. Elevator entrance frames are not designed to carry the weight of the wall above, so a lintel must be provided.

Elevator hoistway entrance assemblies customarily have been rated at 1½ hours, but they may be rated at 1 hour or ¾ hour. A labeled entrance ensures that the hoistway entrance door assembly can meet the fire safety requirements specified by building codes and NFPA 80, *Standard for Fire Doors and Other Opening Protectives.* The label is visible from the hoistway. Arrangements must be made with the elevator company so the label can be safely seen from the top of the car.

In masonry construction, passenger elevator doors typically overlap the wall by ¾ in. (19 mm). When this requirement is met, the frames, if supplied, are not required to be labeled. Masonry-type walls generally consist of brick, concrete block, or reinforced concrete construction. All three materials are fire resistant.

Drywall Enclosure Construction. Drywall construction largely supplanted masonry construction as the most prevalent hoistway construction used today throughout North America. Early elevator entrance installations in drywall were similar to masonry installations. However, some design changes were made to ensure the integrity of the interface between the entrance assembly and the drywall construction. Brackets were placed within the frame of the entrance assembly to accept "J" struts furnished by the drywall contractor.

The "J" strut is vitally important in ensuring a proper entrance frame drywall interface. Drywall frames must be labeled unless the door panel overlaps the wall by ¾ in. (19 mm), an atypical condition. There is no difference in the door panels. Figure 10.3.4 shows a cutaway view of a drywall entrance assembly interface.

The drywall entrance assembly is critical to the fire performance of masonry and drywall elevator door entrances. The entrance frame assembly, including the frame, door panels, hardware, and so on, is labeled as part of the drywall entrance enclosure. Prior to the use of drywall for hoistway enclosures, the entrance frame was only decorative and not part of the labeled entrance assembly (see the ASME A17.1/CSA B44 handbook for more information).[4]

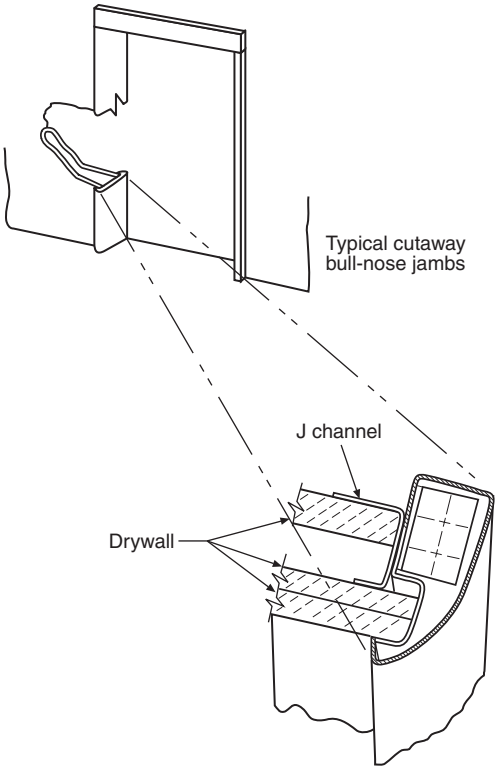

FIGURE 10.3.4 Interface Between Drywall Construction and Bull-Nose Doorjamb of an Elevator Entrance

Drywall construction with stone veneers is available but has not been investigated by testing laboratories under fire conditions; therefore, the performance of such construction cannot be accurately predicted. Engineering judgment can be applied when comparing stone-faced drywalls with solid masonry walls. In drywall construction, the application of the facing material could affect the interface between the door and steel frame.

Entrance Fire Test and Marking. ASME A17.1/CSA B44 requires entrances installed in fire-resistive enclosures to be subjected to type test specified in NFPA 252, *Standard Methods of Fire Tests of Door Assemblies,* or UL 10B.[5] In Canada, NBCC requires entrances installed in fire-resistive enclosures to be subjected to the standard fire exposure test described in CAN-S104.

The classification marking, or label, on passenger elevator door panels covers the design and construction of the door panels only. In addition to the door panels, when the panel does not overlap the wall ¾ in. (19 mm), the fire door frames and transom, if provided, must be labeled.

Hardware also must be labeled for a completely listed entrance assembly. Passenger elevator door hardware consists of a header; track hangers; pendant bolts; floor sill with guides, sill support plates, and brackets; retaining angles; and closure assemblies. Each component must be labeled individually. For

hardware packaged and shipped as a single unit, ASME A17.1/CSA B44 permits one label for all components. ASME A17.1 also permits a single label for the entire entrance when it is shipped as a single package and duplicates the tested assembly. Typically freight entrances and dumbwaiter entrances are provided with a single label.

Door Gasketing Materials. Listing agencies have classified gasketing materials for use on elevator fire door and frame assemblies. Individual gasketing materials are investigated for use on particular frame or door types and for specific fire duration periods. The basic standards used to investigate gasketing materials are Underwriters Laboratories Inc.'s *Fire Test of Door Assemblies* (UL 10B)[5] and *Standard for Air Leakage Tests of Door Assemblies* (UL 1784).[6] However, the tests do not evaluate the potential adverse effect on door operation.

Fire departments consider in-car elevator operation crucial in a high-rise fire. A question arises: Does gasket material affect elevator door operation? The kinetic energy and door-closing forces of power-operated doors are regulated for passenger safety by ASME A17.1/CSA B44. When the doors are almost closed, the closing speed must be reduced. Friction from the gasket material may prevent complete closure, immobilizing the elevator and exposing the elevator hoistway to smoke, hot gases, and fire. Another question is what effect this seal will have on doors designed to close automatically if the car leaves the landing zone for any reason.[7] ASME A17.1/CSA B44 requirements address the safety needs of passengers, including fire fighters, when gasketing is provided on elevator entrances.

Although enclosing elevator lobbies with smoke and draft control doors is perhaps not as aesthetic as the architect and building owner would like, it is the most practical substitute for gasketing elevator entrances, as a means of controlling the movement of smoke into the elevator hoistway. An enclosed lobby also could serve as an area of rescue assistance for the disabled in a fire and as a safe staging area for fire fighting.

Machine Room Construction. Most building codes require machine room enclosures to be constructed of equally fire-resistant material as that provided for the hoistway enclosure. When a non-fire-resistant hoistway is constructed for an electric or hydraulic elevator and when the building code permits, the machine room enclosure must be of noncombustible material extending to a height of not less than 6 ft (1.83 m). Machine rooms access doors are to be kept closed and locked, and entry is required by ASME A17.1/CSA B44 to be restricted to authorized personnel familiar with the precautions that are necessary around moving elevator machinery. Machine room floors should be kept free of oil and grease. Material not necessary for the maintenance or operation of the elevator should not be stored in the machine room. Flammable liquids with flashpoints of less than 110°F (43°C) should not be kept in the machine room. ASME A17.1/CSA B44 requires an extinguisher for use on Class A, B, and C fires in all machine rooms; the extinguisher should be conveniently located near the access door.

ASME A17.1/CSA B44 requires elevator machinery to be in a room that contains only elevator equipment. Machine rooms that are not located at the top of hoistways should not contain equipment inessential to the operation of the elevator, because a fire that starts in a basement machine room has a clear unobstructed path to the hoistway. Previously, ASME A17.1/CSA B44 permitted a machine room located above the hoistway to contain other equipment essential to building operation, provided the elevator equipment was separated from the other equipment by a metal grill or solid partition at least 6 ft (1.83 m) high.

The ambient temperature and humidity in the elevator machine room is critical, especially for modern solid state controls. ASME A17.1/CSA B44 requires that machine room temperature be maintained in the range the equipment manufacturer specifies. ASME A17.1/CSA B44 requires that the temperature and humidity range be permanently posted in the machine room. Loss of elevator service in a fire emergency may result if the elevator machine room HVAC is shut down.

Sprinklers in Hoistways and Machine Rooms. NFPA 13, *Standard for the Installation of Sprinkler Systems,* outlines provisions for sprinklers installed in elevator hoistways and machine rooms. ASME A17.1 does not require sprinklers, but, when installed, sprinklers must meet NFPA 13. CSA B44, likewise, does not require sprinklers, but, when installed, sprinklers must meet NBCC requirements. Before considering the installation of sprinklers in spaces containing elevator control equipment, certain potential problems should be analyzed. One should consider whether any water discharge on the control equipment may adversely affect the elevator's safe operation. Water has been known to short safety circuits and allow an elevator to run with an open car or hoistway door. In addition, wet brakes may be unable to stop and hold an elevator.

ASME A17.1/CSA B44 requires that, when a sprinkler in the machine room or hoistway when the sprinkler is more than 2 ft (610 mm) above the pit floor is discharged, the main line power source to the elevator be disconnected. *NFPA 72®, National Fire Alarm Code®,* contains details on how to implement this requirement. In a fire, the sequence of events would probably be as follows:

1. A smoke detector in the machine room, hoistway, or elevator lobby recalls the elevator.
2. The main line power automatically disconnects.
3. The sprinkler discharges.

Even if the smoke detector is not activated or if all elevators have not been returned to the lobby, stopping the car and containing the passengers is considered safer than allowing operation to continue with the sprinkler discharging. Fire fighters should be aware that, if fire is in the elevator machine room, the elevators with machinery in that room will not be available for their use.[8]

There have been numerous requests for delaying the removal of power from the elevator and sprinkler activation to allow for the completion of Phase I recall, or for the elevator to stop at the next available floor and open its doors. This is not practical if either the elevator control system is involved in the fire or the ambient temperature in the machine room is significantly above the design tolerance for the equipment. ASME A17.1/CSA B44 recognizes delaying the disconnecting of power and activation of a sprinkler provided it is accomplished independent of the elevator control system.

NFPA 13 requires sprinklers at both the top and the bottom of the shaft. The sprinklers may be omitted when the elevator shaft is enclosed with noncombustible materials and combustible hydraulic fluids are not present in the shaft. A potential problem is the interpretation of this provision relative to an electric traction elevator installation with oil buffers. In addition, sprinklers may be omitted from the top of noncombustible elevator hoistways of passenger elevators complying with ASME A17.1/CSA B44.

Elevator Car Construction. ASME A17.1/CSA B44 requires that all material exposed to the car interior and the hoistway be metal or glass, or have a flame spread rating of 0 to 75 and smoke development rating of 0 to 450. Materials must be tested in their end use configuration. Padded protective linings for temporary use in passenger cars during freight handling also must meet these criteria.

The smoke development rating for materials in cars is equal to NFPA *101,* requirements for an exit passageway in a fire-resistant building. Smoke development characteristics of materials may be more crucial than flame spread, as passengers in a confined enclosure box may not be able to escape rapidly. In Canadian jurisdictions enforcing NBCC, where the elevator is designated as a fire fighter elevator, the flame spread rating for walls and ceilings is 0 to 25 and for floors 0 to 300. The smoke development rating for walls and ceilings is 0 to 100 and for floors 0 to 300.

Napped, tufted, woven, looped, and similar materials must be subjected to a vertical burn test in their end use configuration, as specified by ASME A17.1/CSA B44. This test is based on applicable portions of FAA Regulation 25.853, in addition to the flame spread and smoke development test NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials.* Such material, located on elevator car walls, can be easy to ignite inadvertently. Tufted material, such as carpeting, may accumulate dust, which could increase the possibility of ignition and flame spread.

Floor covering, underlayment, and adhesive are required to have a critical radiant flux of not less than 0.45 W/cm^2, as measured by NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source.* The level of critical radiant flux acceptable for floor systems in elevator cars is based on the assumption that occupants of an elevator may not be able to escape rapidly. The flux level equals the requirements for health care facilities.

Handrails, operating devices, ventilating devices, signal fixtures, audio and visual communications devices, and their housings are not required to meet any of these criteria because they are deemed to contribute little to fire load in relation to overall elevator car assembly.

Accessibility Considerations. Two national standards address accessibility requirements for elevators: (1) ADAAG, *Americans with Disabilities Act Accessibility Guidelines,*[9] and (2) ICC/ANSI A117.1, *American National Standard for Accessibility.*[10] Both standards require all passenger elevators to be made accessible to the disabled. ADAAG will most likely be replaced with ADA/ABAAG, *Americans with Disabilities Act/Architectural Barriers Act Accessibility Guidelines,*[11] over the next few years. Planned and practiced procedures are needed to evacuate the disabled in a fire. Additional information on accessibility requirements for elevators can be found in *ADA and Building Transportation.*[12] In Canada, accessibility requirements can be found in the NBCC and ASME A17.1/CSA B44 Appendix E.[3]

Emergency Lighting, Alarm, and Communications. ASME A17.1/CSA B44 requires emergency lighting on all elevators. The power source must originate on the elevator to ensure that passengers are not thrust into total darkness if building power fails. The building emergency power source is not a recognized alternative to this requirement, because this source generally would not respond to a branch circuit failure and usually is activated only on loss of the building power supply. Moreover, it would rely on the elevator's traveling cables to supply lighting power, which would be useless if the lighting problem were in the traveling cables.

Major changes have been made recently in ASME A17.1/CSA B44 regarding emergency alarms and communications. The code requires a means for all passengers, both able-bodied and disabled, to communicate in an emergency. Requirements were prepared to address the following reported deficiencies with the prior code requirements:

1. Reports of passengers being trapped overnight or on weekends and holidays
2. Alarm bells being ignored
3. Alarm bells not working
4. No one accepting responsibility or accountability for providing assistance
5. Deficiencies with new technology being utilized

The ASME A17.1/CSA B44 code requires the call be directed 24/7 to authorized personnel (trained) who are responsible for taking appropriate action. The location and elevator number are also required to be automatically transmitted at the time of the call.

In addition to these requirements, the model building codes require all elevators in high-rise buildings to have a fire department communication system from the elevator lobby, car, and machine rooms to the building's central control station.

Electrical Requirements. ASME A17.1/CSA B44 requires electrical wiring for elevators, escalators, moving walks, and dumbwaiters to conform to NFPA 70, *National Electrical Code®,* or in Canada CSA C22.1, *Canadian Electrical Code.* Electrical equipment must be certified and labeled as complying with CSA B44.1/ASME A17.5.[13]

Elevators in Fire Emergencies

High-rise buildings present new and different problems to fire suppression forces, including elevator use during emergencies. Elevators are unsafe in a fire for several reasons:

1. Persons may push a corridor button and wait for an elevator that may never respond, losing valuable escape time.
2. Elevators do not prioritize car and corridor calls, and one of the calls may be at the fire floor.

3. Elevators cannot start until the car and hoistway doors close, and panic could lead to elevator overcrowding and door blockage, which would thus prevent closing.
4. Power can fail at any time during a fire, thus leading to entrapment.

The elevator can be delivered to the fire floor when the following occurs:

1. An elevator passenger presses the car button for the fire floor
2. One or both of the corridor call buttons is pushed on the fire floor
3. Heat melts or deforms the corridor push button or its wiring at the fire floor
4. The elevator functions normally at the fire floor, as in high or low call reversal

ASME A17.1/CSA B44 recognizes all these unsafe conditions and mandates Fire Fighters' Emergency Operation on all new elevators. *NFPA 72* contains requirements for the automatic fire alarm system and initiating devices that provide the signal to the elevator control system for initiation of Phase I operation. The provision that allows fire-fighting personnel to operate the elevator from within the car, or emergency in-car operation, is commonly referred to as Phase II.

Phase I Operations. Phase I is the automatic or manual return, or recall, of elevators to a designated level or alternate level. Phase I also ensures that an elevator is not available to the general public during a fire. If the fire is in the designated level elevator lobby, the elevator will be recalled to an alternate level.

Designated level is defined as the main floor or other floor that best serves the needs of emergency personnel for fire-fighting or rescue purposes. Emergency personnel can use a three-position—on, off, reset—key-operated switch in the designated-level lobby to control each group of elevators. Another two-position—on, off—key-operated switch may be provided in the building's central control station. In the on position, the switch instructs all controlled elevators to return nonstop to the recall floor. All registered calls will be canceled. An ascending elevator will stop and reverse direction, without opening its doors.

Hoistway doors on the recall floor should remain open. On arrival, fire fighters have little time to learn whether the elevators are present. Open hoistway doors will reveal those elevators that have been recalled, as well as those that need to be located to ensure that no passengers are trapped. To help emergency personnel locate errant elevators, hall position indicators are required to remain operative during emergencies.

The open hoistway door at the designated level will admit air to the hoistway. If the fire is on a floor below the neutral pressure plane, the additional air will reduce the amount of smoke that can enter the hoistway from the fire floor, a beneficial side effect. If the fire is above the neutral pressure plane, flow of air from the hoistway to the floor will increase, which is also beneficial.

Visual and audible signals alert passengers in an automatically operated elevator to an emergency and can help minimize any apprehension that the passengers have as the elevator returns to the recall floor. In an attendant-operated elevator, this signal alerts the attendant to the emergency so that he or she can return the car immediately to the recall floor.

Elevator recall systems combine a key-operated switch with an automatic fire alarm system, using smoke detectors at each floor lobby. Elevator recall by the smoke detector is the same as placing the key switch in the on position. The only difference is that the smoke detector at the designated level will recall the elevator to an alternative level. If the automatic recall sent the elevator to the alternative level, the key switch will override the designated level smoke detector and recall the elevator to the designated level. The key switch will not recall an elevator to the alternative level.

To advise the public that elevators may not be available during a fire, a pictograph should be posted above all elevator hall call buttons.[1] Some jurisdictions may require different wording and pictographs, but the message is similar.

Phase II Operations. Phase II fire fighters' operation benefits fire fighters who must have the elevators for their own use. It is standard operating procedure in high-rise structures for fire fighters to use elevators not only to carry equipment for fire-fighting or evacuation purposes, but also to deliver fire personnel to nonfire floors.

The current ASME A17.1/CSA B44 calls for Phase II operation on all new elevators. The rule considers the need for fire fighters to evacuate disabled persons during an emergency. This code has also standardized operation procedures, regardless of the elevator manufacturer.

The switch keys required for Phase I and Phase II operation must be the same to ensure a speedy response to an emergency. Operating procedures must be incorporated with, or adjacent to, the Phase I and Phase II key-operated switches to provide emergency personnel quick access to instructions during an emergency. Fire fighters should also be aware that when the visual signal required by ASME A17.1/CSA B44 is flashing, it signals an impending problem and continued use of the elevator is not advised.

ASME A17.1/CSA B44 does not require standby power for elevators. This requirement is found normally in the building code. However, the safety code does require that elevator operation be the same when standby power is supplied as it is when normal power is supplied. ASME A17.1/CSA B44 does require that a manual selection switch be provided for fire fighters to select the car(s) to which standby power is to be directed.

Use of Elevators in a Fire. As a result of the September 11, 2001, attacks on the World Trade Center, code provisions for emergency egress from tall buildings are being reexamined. There is renewed interest in the use of elevators for both occupant egress and fire fighter access. Therefore a Workshop on the Use of Elevators in Fires and Other Emergencies was held in Atlanta, Georgia, March 2–4, 2004. This workshop was co-sponsored by American Society of Mechanical Engineers (ASME International), National Institute of Standards and Technology (NIST), International Code Council (ICC), National Fire

Protection Association (NFPA), U.S. Access Board, and the International Association of Fire Fighters (IAFF).

The workshop focused on the two following general topics:

1. Use of elevators for egress
2. Use of elevators by fire fighters

The workshop consisted of plenary sessions during which selected papers were presented, as well as Breakout Sessions for attendees to brainstorm various ideas and develop recommendations. The recommendations have been forward to numerous code and standards writing organizations.

The ASME A17 committee has also organized two task groups with participation from the groups mentioned above to evaluate and prepare code requirements, if appropriate. The task groups are currently developing hazard analyses for their assigned topics. Once the hazard analyses are completed and risks identified, code proposals will be developed and submitted to the applicable codes and standards-writing organizations.

Evacuation from a Stalled Elevator. ASME A17.1/CSA B44 requires a written elevator evacuation plan. Trained elevator personnel should perform any evacuation of passengers from a stalled elevator car. Their expertise ensures that evacuation is carried out in a manner that is safe for both the passengers and the rescue party. However, waiting for trained elevator personnel may be impossible in a life-threatening emergency. Under such conditions, passenger evacuation must be performed by carefully selected and trained personnel. Planned and practiced procedures are needed to ensure the safety of rescued passengers and members of the rescue party. Any rescue party should be cautioned never to try to move an elevator from the machine room. Only trained elevator personnel should attempt this. ASME A17.4, *Guide for Emergency Personnel,*[14] details procedures to follow in performing a safe evacuation.

DUMBWAITERS

A *dumbwaiter* is a hoisting and lowering mechanism, used exclusively for carrying materials, with a limited size car that moves in guides in a substantially vertical direction. Dumbwaiters must conform to requirements of ASME A17.1/CSA B44. A dumbwaiter is actually a small elevator used for a variety of purposes, such as mail distribution in office buildings; distribution of medication, food, and supplies in hospitals; and the moving of books from floor to floor in a library. A dumbwaiter can be loaded and unloaded manually or automatically at the floor or at a counter. Dumbwaiter car size is restricted to discourage riding. When dumbwaiters penetrate fire-resistant floors, their hoistway construction is critical. Requirements for a dumbwaiter hoistway are the same as those for an elevator. The section on elevator hoistway construction earlier in this chapter details fire-resistant hoistway enclosures and entrances.

ESCALATORS

The escalator is another type of vertical people mover. An *escalator* may be defined as a power-driven, inclined, continuous stairway used for raising or lowering passengers. In the early days, escalators were found principally in department stores and in bus and airline terminals. Today, they are common in office buildings, hospitals, banks, sports arenas, and other locations where many people must be moved quickly from one floor to another.

Fire Protection of Escalators

NFPA *101* requires that escalator floor openings be enclosed or protected like other vertical openings. In completely sprinklered buildings, escalators need not be enclosed if they are protected by alternative means.

The sprinkler draft curtain method is detailed in NFPA 13 and consists of surrounding the escalator opening with an 18-in. (457-mm) deep draft stop located on the underside of the floor to which the escalator ascends. A row of automatic sprinklers located outside the draft stop surrounds the escalator well. Figure 10.3.5 shows a typical installation. Two methods recognized in previous editions of NFPA *101* and found in existing buildings are the sprinkler vent method and the spray nozzle method.

Sprinkler Vent Method. An automatic fire or smoke detection system, an automatic exhaust system, and an automatic water curtain are combined in the sprinkler vent method. When a detector senses a fire, the automatic damper opens, thereby venting smoke and gases. Replacement air is drawn through the outdoor air intake above the escalator opening. To control smoke, an exhaust rate of about 60 air changes per hour is required. The sprinkler curtain provides a thermal barrier. The system needs to be carefully designed so that both sprinklers and vents are effective. For more information, see Section 18, Chapter 4, "Venting Practices." Figure 10.3.6 shows a typical installation.

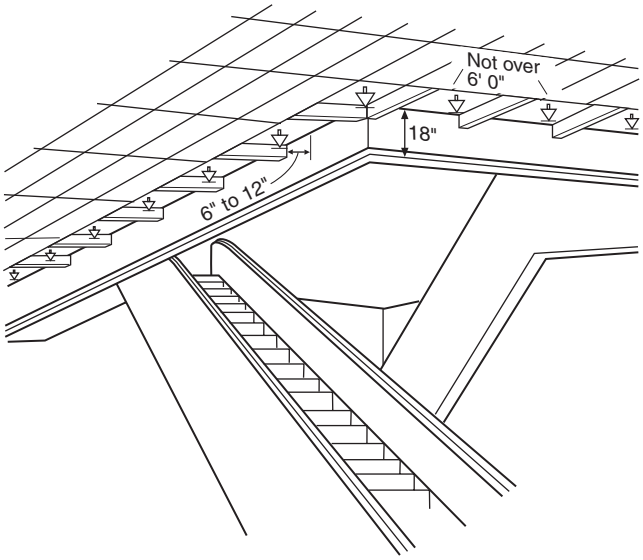

FIGURE 10.3.5 Sprinklers Around an Escalator

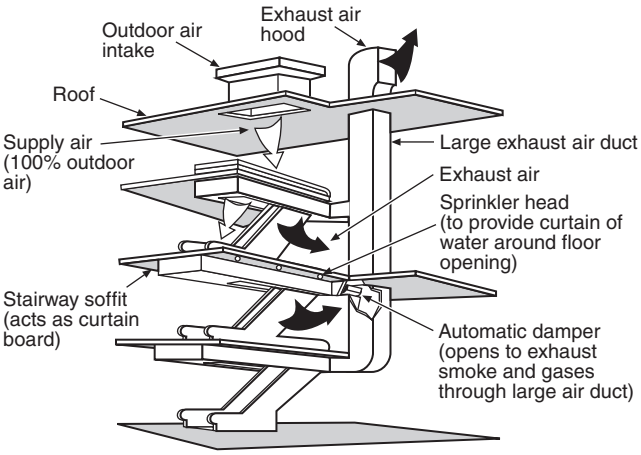

FIGURE 10.3.6 Sprinkler Vent Method Installation

Spray Nozzle Method. The spray nozzle method combines an automatic fire or smoke detection system and a system of high-velocity water spray nozzles. There must be enough spray nozzles with discharge angles such that the escalator opening between the top of the wellway housing and the treadway will be completely filled with a dense water spray when the system operates.

Escalator Enclosures

The two methods of enclosing the escalator opening used in both new and existing buildings are the rolling shutter method and the partial enclosure method.

Rolling Shutter Method. In the rolling shutter method, escalators above the street floor may be protected by automatic self-closing rolling shutters that completely enclose the top of the escalator wellway. To avoid injury, the escalator must stop automatically before the shutter begins to close. The shutter should close slowly and have a pressure-sensitive leading edge that will stop the shutter on contact. Figure 10.3.7 shows a typical rolling shutter escalator installation.

Rolling steel shutters are not recommended at the tops of escalators below street floors, even though the stairways are not required exits under the provisions of NFPA *101*. In an emergency, persons seeking egress from basements served by escalators could be trapped by a closed rolling shutter at street level, even though approved means of egress are available to them.

Partial Enclosure Method. Two fire-rated enclosures, one for the down escalator and one for the up escalator, can prevent the spread of smoke and fire. Automatic fire doors release when fire is detected. The door(s) must signal the escalator when they are not in the full open position and the escalator must then stop automatically. The enclosure should have a fire-resistant rating equal to that of the floor/ceiling assemblies, and there should be no unprotected escalator penetration of more than two

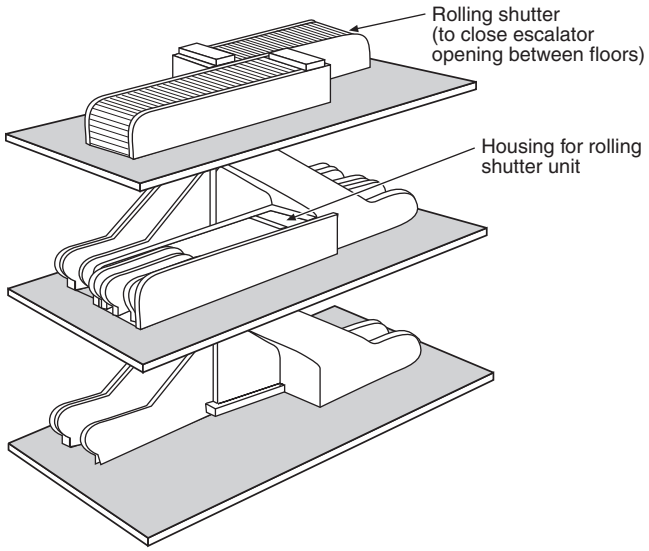

FIGURE 10.3.7 Rolling Shutter Escalator Installation

floors. Figure 10.3.8 shows a typical partial enclosure escalator installation.

Escalators in Fire Emergencies

In new buildings, escalators cannot be used as part of the means of egress. Modern escalator design requires the removal of steps for normal maintenance, thus rendering the escalator unusable. A stopped escalator also presents a tripping hazard, due to the nonuniform riser height of the first and last few steps. In some existing buildings, escalators are part of the means of egress. These escalators should be arranged to operate only in the direction of egress, or they should be stopped during a fire. Where the evacuation plan calls for escalator use, efficient crowd control is required to avoid serious crowding and potential panic. NFPA *101* requires the openings for existing escalators used as required exits to be enclosed in the same manner as exit stairs.

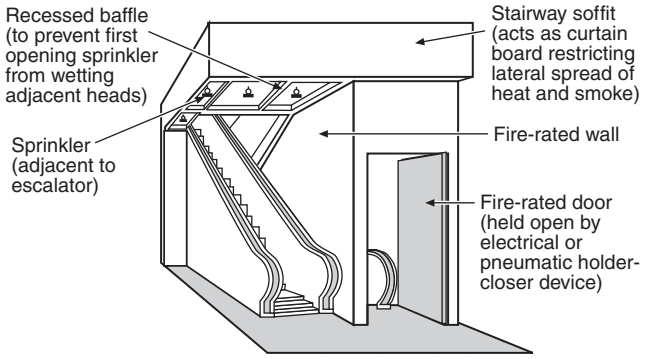

FIGURE 10.3.8 Partial Enclosure Escalator Installation

Another important factor in escalator fire prevention is keeping truss and machine areas free from oil, grease, and dust. A periodic cleaning schedule should be implemented.

MOVING WALKS

A *moving walk* is a moving device on which passengers stand or walk. Its passenger-carrying surface remains parallel to its direction of motion and is uninterrupted. Moving walks may be installed at an incline between two floors. The same fire prevention features described for escalators apply to moving walks. Some moving walks use a combustible belt, essentially the same as a large conveyor belt. This belt has the potential to spread a fire by itself. All moving walks can carry burning items along their lengths.

TESTS AND INSPECTIONS

At minimum, existing elevators and escalators should be required to conform to the requirements of ASME A17.3, *Safety Code for Existing Elevators and Escalators.*[15] NFPA *101* requires existing equipment to conform to this code. Existing installations that do not meet this code must be upgraded. When an existing installation is upgraded, at a minimum it must comply with ASME A17.1/CSA B44, Section 8.7. Existing installations required to meet more stringent requirements must continue to meet those requirements.

Elevators, dumbwaiters, escalators, moving walks, and other passenger conveyance equipment that are required to conform to the requirements of ASME A17.1/CSA B44 must be tested and inspected periodically. ASME A17.2, *Guide for Inspection of Elevators, Escalators, and Moving Walks*[16] should be used as a guide for these inspections. The quality of inspections depends upon the inspector's competence. ASME QEI-1, *Standard for the Qualifications of Elevator Inspectors,*[17] establishes uniform criteria for this purpose and serves as a standard for the expertise necessary to perform inspections.

SUMMARY

This chapter is not intended to be a complete, authoritative explanation of building transportations systems, but rather an overview of the fire protection issues normally associated with building transportation. Additional information on building transportation equipment can be found in the ASME A17.1/CSA B44 *Handbook on Safety Code for Elevators and Escalators.* Over the next few years, the technology and state of the art will advance rapidly. Machine room-less elevator equipment will become common for low- and mid-rise elevator application. New material will replace the steel hoisting ropes on electric elevators, and the control systems will become more advanced, using smart logic to anticipate user demands. The ASME A17.1/CSA B44 elevator code is already being revised to address the safe application of new technology.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on building transportation systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of these documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 70, *National Electrical Code®*
NFPA 72®, *National Fire Alarm Code®*
NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA *101®*, *Life Safety Code®*
NFPA 105, *Standard for the Installation of Smoke Door Assemblies and Other Opening Protectives*
NFPA 252, *Standard Methods of Fire Tests of Door Assemblies*
NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 5000®, *Building Construction and Safety Code®*

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Chapter 4

Air-Conditioning and Ventilating Systems

William A. Webb

Chapter Contents

System Types and Operation
Location of Equipment
Fresh Air Intakes
Air Cooling and Heating Equipment
Air Filters and Cleaners
Air Distribution
Restricting Spread of Smoke and Fire
Fans and Controls
Unit Air Conditioners
Maintenance
Energy Conservation

Key Terms

air-conditioning or comfort-cooling equipment, air distribution system, air intake, duct, fire confinement, fire damper, HVAC, plenum, smoke control, smoke damper

The term *air conditioning* has been defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) as "the process of treating air to simultaneously control its temperature, humidity, cleanliness, and distribution to meet the comfort requirements of the occupants of the conditioned space." Air-conditioning and ventilating systems, except for self-contained units, invariably involve the use of ducts for air distribution. The ducts, in turn, present the possibility of spreading fire, fire gases, and smoke throughout the building or area served. This and other potential hazards of air conditioning and ventilating systems are the subjects of this chapter.

Installation and protection of air heating systems are discussed in Section 10, Chapter 2, "Heating Systems and Appliances." Fire confinement, smoke movement, and venting practices are addressed in Section 18, Chapter 1, "Confinement of Fire in Buildings"; Section 18, Chapter 3, "Smoke Movement in Buildings"; and Section 18, Chapter 4, "Venting Practices."

Details on safeguarding against these hazards are presented in NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems.* See also the *ASHRAE Handbook 2004 Systems and Equipment* from the American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc.

SYSTEM TYPES AND OPERATION

The several types of air-conditioning systems include (1) systems in which air is filtered or washed, cooled and dehumidified in summer, and heated and humidified in winter; (2) systems in which air is filtered, cooled, and dehumidified; and (3) systems in which air is filtered, heated, and humidified. Figure 10.4.1 depicts a typical arrangement of the various components of a central air-conditioning system. A ventilating system simply supplies or removes air by natural or mechanical means to or from a space. The air may or may not be conditioned.

Referring to the typical system depicted in Figure 10.4.1, a fresh air intake duct connects directly to the system's return duct. From this point, the mixture of fresh and recirculated air passes through the air-conditioning equipment. The air is subjected to several operations in this equipment, including filtration or cleaning, heating or cooling, and humidification. The conditioned air is then circulated throughout the area served via the duct system (Figure 10.4.2). Those systems that do not recirculate any air take all of their makeup air directly from the outside. A building may contain more than one system, not necessarily of the same type.

LOCATION OF EQUIPMENT

Fans, heaters, filters, and associated equipment that make up a central system air-conditioning unit are preferably located in a room separated from the rest of the building area by walls, floor, and

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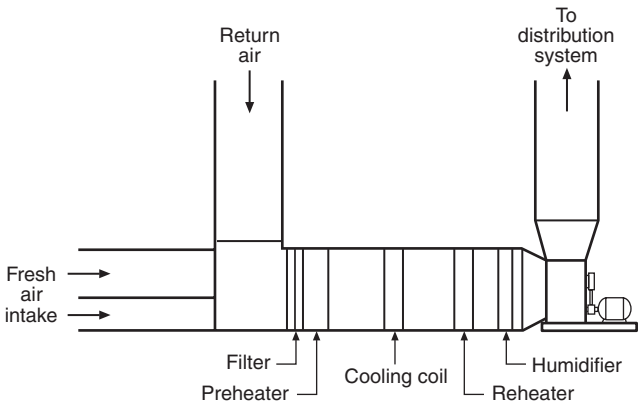

FIGURE 10.4.1 Typical Arrangement of Component Parts of a Central Air-Conditioning System

floor-ceiling assembly providing a minimum 1-hour fire resistance rating. This arrangement prevents a fire involving the equipment from immediately spreading to adjacent areas of the building. Such an arrangement also prevents access to the equipment by unauthorized persons. Ideally, service rooms housing air-conditioning equipment are protected by automatic sprinklers. At minimum, smoke detectors should be provided and arranged to initiate an alarm and shut down the air-conditioning system. No combustible storage should be allowed in the equipment room.

FRESH AIR INTAKES

The location selected for the fresh air intakes of a system is critical because fire, fire gases, or smoke originating outside the building can easily be drawn in through these intakes and spread throughout the building. Where such a hazard may exist, protection can be provided by the installation at the intakes of fire dampers or smoke dampers that are controlled by fire and smoke detectors.

When considering the location of exterior fresh air intakes, thought must be given to the possibility of sparks or other products of combustion from an exposed fire chimney or incinerator stack being drawn into the system. Consideration should not be limited to adjacent buildings or combustible storage. The possibility of fire from a different section of the same building or an adjoining building exposing the intakes is a factor that must also be considered. Since smoke usually rises, the lower the intakes are installed, the less the possibility of drawing in smoke.

All air intakes must be provided with screens of corrosion-resistant material to prevent material from entering the system. Mesh size is limited to ¼ to ½ in. (6 to 13 mm) for residential occupancies and ½ to 1 in. (13 to 25 mm) for other occupancies. Proper maintenance includes periodic removal of any accumulated rubbish or other waste from the immediate vicinity of the intakes. Some fresh air intakes are fitted with a filter that is subject to the same hazards mentioned later in this chapter, under "Air Filters and Cleaners." These filters should be protected and maintained accordingly.

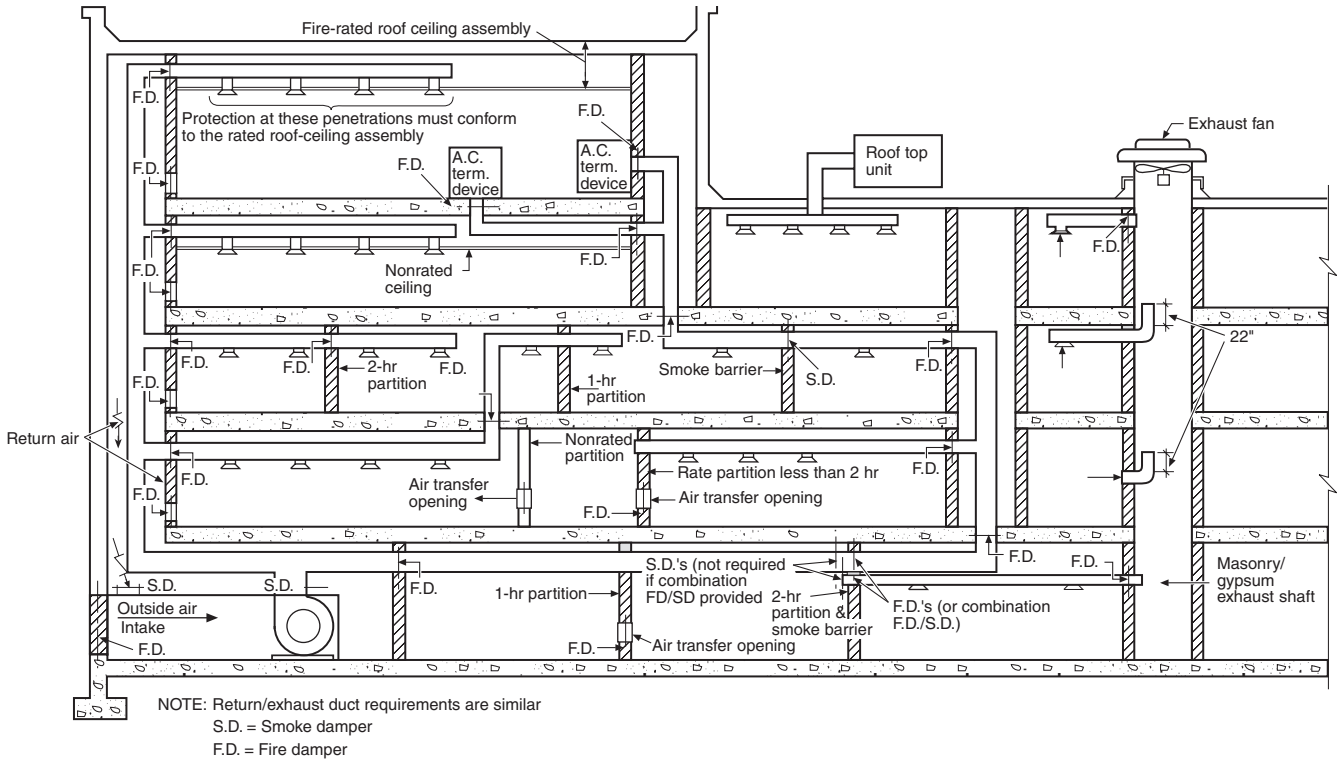

FIGURE 10.4.2 Typical Building Duct Installation Illustrating Required Protection of Walls, Ceilings, Floors, and Shafts

AIR COOLING AND HEATING EQUIPMENT

Air cooling equipment presents two basic classes of hazards: (1) those of the electrical equipment and (2) those of the particular refrigerant used. It is important that the cooling equipment be properly installed and maintained. Installation of all electrical equipment should follow both the manufacturer's recommendations and NFPA 70, *National Electrical Code®*.

One of the problems associated with refrigeration units is the explosion hazard due to overpressurization of the refrigerant. Proper safety controls can mitigate this problem.

As a result of the Montreal Protocol and the ban on some ozone-depleting refrigerants, the industry is actively seeking to develop acceptable substitutes.

At present, an array of candidate refrigerants are being used by manufacturers. The properties of candidate substitute refrigerants are being thoroughly tested. However, some appear to have flammability, explosive, and toxicity characteristics that have not been adequately addressed. In addition, there are requirements for maintenance personnel to capture and reprocess ozone-depleting refrigerants. Venting to the atmosphere is no longer permissible. Properties of refrigerants can be found in the ASHRAE *Safety Code for Mechanical Refrigeration.*[1]

AIR FILTERS AND CLEANERS

The types of air filters and cleaners used in air-conditioning and ventilating systems fall into three general categories: (1) fibrous media unit filters, (2) renewable media filters, and (3) electronic air cleaners. The first two are true filters; the last is a static precipitator. Air filters and cleaners pose a potential hazard due to their function of removing entrained dust and other particulate matter from the air stream. This material builds up on the filter media or precipitator collection plates and, if ignited, may burn, potentially producing large volumes of smoke. The smoke and other combustion gases can be circulated throughout the building by the air handling system, thus posing a direct threat to life safety. Not to be overlooked is the possibility that a filter medium may be coated with a combustible adhesive or may itself be combustible.

Underwriters Laboratories Inc. (UL) lists two classes of filter media:[2]

Class 1. Filters that, when clean, do not contribute fuel when attacked by flame and emit only negligible amounts of smoke

Class 2. Filters that, when clean, burn moderately when attacked by flame, emit moderate amounts of smoke, or both

Both of these classes include renewable (washable and reusable) media and replaceable (disposable) media.

Class 1 filter media are preferred, particularly for systems serving places of assembly, such as theaters, auditoriums, and department stores. Class 1 filter media are also the obvious choice for systems serving occupancies whose contents are easily susceptible to smoke damage. However, any filter media, if not cleaned or replaced regularly, may become hazardous due to accumulation of combustible dust and so forth. Appendix B of NFPA 90A contains recommendations for cleaning filters.

Fibrous Media Unit Filters

Fibrous media unit filters are placed into the air stream and remain there until the pressure drop across the filter reaches some critical point due to the buildup of entrained material. At this point, the filter is either removed, cleaned, and reinstalled, or simply discarded and replaced with a new filter. Fibrous media unit filters are of either the viscous-impingement type or the dry-media type.

The viscous-impingement type of filter is characterized by flat or pleated panels of relatively coarse fiber mats. Porosity of the panel is high. The fibers are coated with an adhesive that traps any material entrained in the air stream. The mats are ½ to 4 in. (13 to 102 mm) thick, 1 and 2 in. (25 and 51 mm) being most common. This type of filter is most effective when air velocity ranges from 400 to 700 ft/min (122 to 213 m/min). Most of these unit filters are ready for replacement when the pressure drop reaches ½ in. of water (124 Pa). The renewable panels must be washed with steam or a hot detergent solution, then recoated with fresh adhesive.

Dry media unit filters are flat or pleated panels of relatively fine fibers, usually ½ to 2 in. (13 to 51 mm) thick. As their name implies, these filters have no adhesive coating. Porosity is not as great as for the viscous-impingement-type filter; hence, particulate removal is greater, depending on fiber size and porosity. These filters are most effective with an air velocity of 90 to 500 ft/min (27 to 152 m/min). Pressure drop may reach as much as 2 in. of water (500 Pa) before replacement is necessary. Disposable dry fibrous media unit filters, particularly of the deep-pleated design, are fast becoming the standard for large central air-conditioning systems. The dry media classification of air filters also includes membrane and high-efficiency types, which are used to ultraclean air for clean rooms and similar areas.

Renewable Media Filters

Renewable media air filters can more accurately be termed *moving curtain* air filters, since they operate in exactly such a fashion. The medium, whether viscous coated or dry, is supplied on a large roll and extends across the air stream. Either a timer, light-sensitive device, or pressure switch may be used to activate a motor drive, which feeds fresh media across the air stream and winds the dirty media onto a takeup spool. Generally, controls are provided that de-energize the drive motor when the media supply is almost exhausted, thus preventing the media from being completely wound onto the takeup spool. A signal indicates that a fresh roll is needed. Operating velocities range from 200 to 500 ft/min (70 to 152 m/min), with the dry media types requiring the lower velocities. Filter thickness varies from ½ to 2½ in. (13 to 63 mm).

Electronic Air Cleaners

Electronic air cleaners use the principle of electrostatic precipitation to remove entrained dust and particulate matter. There are several types of electronic air cleaners, but their basic operation

is similar. Entrained particles in the air stream pass through intense, nonuniform electrostatic fields and, due to electric polarization, are collected either on a filter or on charged plates. In some units, equipment is provided to preionize the particulate matter.

Special Industrial Filters and Air Cleaners

Many industrial applications of air cleaning involve more than the usual filtering and cleaning methods previously cited. Exhaust systems for flammable vapors, dusts, and other materials in suspension require equipment for recovering the suspended material.

Air cleaning to limit contamination and pollution is of interest to industry and public health authorities. Whatever the reason for specialized air cleaning and whatever the type of equipment used, the selection and protection of the equipment are of concern as the fire hazards are similar to more common types of air cleaning equipment.

One current industrial application of air filtering is in clean rooms where high-efficiency particulate air (HEPA) filters are used to filter the atmosphere. These filters must pass an operational efficiency test of 99.97 percent efficiency with 0.3 micron particles. The filters are tested and labeled by UL in accordance with UL 586, *Standard for Safety High-Efficiency, Particulate, Air Filter Units.*[3]

Protection for Air Filters and Cleaners

Fire in the filters or air cleaning equipment can release copious quantities of smoke or fire gases that can be distributed by the air handling equipment throughout the area served. Adequate protection to minimize the possibility of such an occurrence must be designed into and around the air-conditioning system.

Some method is necessary to prevent smoke and fire gases from being distributed by the main supply fan to all areas served by the system. To accomplish this, detectors (either heat or smoke, depending on the size of the system) are located in the main supply duct, downstream of the filters or air cleaner, to sense smoke or particles of combustion. The detectors are interlocked so as to shut down the entire air-conditioning system upon activation. The detectors also control the operation of smoke dampers located in the main supply and return ducts, thus isolating the entire air-conditioning section of the system.

With specific regard to viscous impingement filters, the adhesive used should have a flashpoint of not less than 325°F (163°C) via the Pensky-Martens closed tester.[4] Also, combustible adhesives should be stored in a safe location, remote from the equipment room housing the air-conditioning equipment.

Fire protection should include facilities for manual fire fighting, usually portable fire extinguishers. Fans, motors, pumps, control circuits, and so on all point to the need for extinguishers suitable for electrical (Class C) fires; however, dry chemical (Class B) extinguishers would be more suitable for use on filters, especially the viscous-impingement type, because the chemical powder would readily adhere to the coated media.

The operational voltage and amperage of electronic air cleaners is lethal; therefore, interlocks should be provided on every access door and panel so that the equipment is immediately shut down if any one of them is opened. An alarm should also be incorporated into this safety interlock circuit.

AIR DISTRIBUTION

Air is distributed in air-conditioning and ventilating systems by ducts and plenums. Ducts are to an air-conditioning or ventilating system what pipes are to a water system—a means of distribution. The space between the ceiling and floor or roof slab is often used as a means to collect and return air. In some cases a raised floor is used to distribute supply air. Both of these arrangements are plenums and are a means to reduce distribution ductwork.

In fire situations, the air distribution system may transport deadly smoke and products of combustion instead of breathable air. If proper design and installation precautions are not taken, smoke, fire gases, heat, and even flame can spread throughout the area served by the duct system. Exit corridors used as plenums, lack of smoke detection activated control equipment in the system, and lack of required fire and smoke dampers in appropriate walls, ceilings, or partitions can lead to tragic situations.

Ducts

Construction. Ducts may be fabricated of metal, masonry, or other noncombustible material. The thickness of materials used in metal ducts of various sizes and methods of bracing, reinforcing, and hanging are covered in the duct manuals of the Sheet Metal and Air Conditioning Contractors' National Association, Inc. (SMACNA).[5] SMACNA also publishes manuals on the installation of glass fiber ducts.

UL tests and lists duct materials in accordance with UL 181A, *Standard for Safety Air Ducts and Air Connectors*[6] and UL 181B, *Standard for Safety Closure Systems for Use with Flexible Air Ducts and Air Connectors.*[7] These standards set limits on such characteristics as flame spread and flame penetration. Materials are classified as follows:

Class 0. Air ducts and connectors having surface burning characteristics of zero

Class 1. Air ducts and connectors having a flame spread rating of not over 25, without evidence of continued progressive combustion, and a smoke developed rating of not over 50

Class 2. Air ducts and connectors having a flame spread rating of not over 50, without evidence of continued progressive combustion, and a smoke developed rating of not over 50 for the inside surface and not over 100 for the outside surface

In addition to the above, Class 0 and Class 1 materials must pass a 30-minute flame penetration test, and Class 2 materials must pass a 15-minute flame penetration test.

NFPA 90A gives other mandatory provisions for duct linings and coverings, duct tapes, and bands. It also places limitations on the use of flexible duct connectors that must pass through walls, partitions, floors, or ceilings intended to afford fire resistance or smoke control.

NFPA 90A has a provision that gypsumboard may be used for negative pressure or return air ducts and for shafts subject to specific conditions. Gypsumboard shafts must be constructed in accordance with the Gypsum Association *Fire-Resistance Design Manual,*[8] must be constructed airtight, and must be designed to handle structural and air pressure loadings.

Installation. By their very nature, ducts provide a means for transferring heat, fire gases, and flame, thus resulting in the spread of fire from one area to another. In addition, at some point, a duct probably will pass through a wall, partition, floor, or ceiling that is designed specifically to provide fire resistance. Literally, a hole has been poked through a fire-rated design. The duct is intended to fill the opening. If the installation has been made without proper firestopping, safeguards will not have been accomplished. Also, under severe fire exposure, the duct may eventually collapse, creating an opening in the fire barrier. Fire dampers provide a method of protecting such penetrations.

In the gauges commonly used, some sheet metal ducts, if properly hung and adequately firestopped, may protect an opening in a building construction assembly for up to 1 hour. Therefore, ducts passing through fire barriers having a rating of up to 1 hour of fire resistance may present no extraordinary hazard. If the wall, partition, ceiling, or floor is required to have a fire-resistance rating of more than 1 hour, a fire damper is required to protect the opening. Where it is necessary for a duct to pierce a fire barrier, an automatic closing fire damper or fire door assembly should be installed at the wall opening. NFPA 90A provides comprehensive recommendations and requirements for location of fire dampers in rated assemblies.

Plenums

A plenum is a compartment or chamber to which one or more air ducts are connected and that forms part of the air distribution system. It can be used to supply air to the occupied area or it can be used to return or exhaust air from the occupied area.

A raised floor plenum is the space between the top of the finished floor and the underside of a raised floor when it is used as part of an air distribution system. It can be used to supply air to the occupied area or to return or exhaust air from the occupied area.

NFPA 90A describes limitations on the materials used to construct plenums as well as materials that may be used within a plenum. In each case the limitations are intended to restrict the combustibility of the materials in the plenum to reduce fire and smoke spread through the air distribution system.

Corridor Air Systems

Egress corridors in occupancies where people will reside should not be used as a component of the air distribution system in order to avoid a fire in one area spreading smoke through the corridor to another area in which occupants may be sleeping. There are exceptions in NFPA 90A that allow the corridor to supply air to ancillary spaces such as toilet rooms. Another exception recognizes that there may be some air movement between the corridor and adjacent spaces. The exception allows air movement where the door clearances on the egress corridor do not exceed the clearances for fire doors contained in NFPA 80, *Standard for Fire Doors and Other Opening Protectives.* Egress corridors that are part of an engineered smoke control system may be used to distribute air to achieve the smoke control objective. Detention facilities that have open grates have an exception.

RESTRICTING SPREAD OF SMOKE AND FIRE

As previously mentioned, NFPA 90A provides details of how HVAC systems are to be designed to safeguard against spreading fire, fire gases, and smoke throughout the building or area served. To achieve this objective, the HVAC system can be shut down and the fire area isolated or compartmented. Another approach is to allow fans to continue to run, using the air duct system for emergency smoke control. NFPA *101®*, *Life Safety Code®*, recognizes both approaches. NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences;* NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces;* and the ASHRAE manual *Design of Smoke Management Systems*[9] provide guidelines for smoke control system and smoke management system design.

Fire Dampers

Fire dampers and ceiling dampers are tested and listed for use in air-conditioning and ventilating ducts by UL in accordance with UL 555, *Standard for Safety Fire Dampers,*[10] and UL 555C, *Standard for Safety Ceiling Dampers.*[11] These dampers include single-blade, multiblade (Figure 10.4.3), and interlocking-blade

FIGURE 10.4.3 Typical Multi-Blade Fire Damper (Source: Courtesy of Ruskin Air and Sound Control)

FIGURE 10.4.4 Typical Static Fire Damper (Source: Courtesy of Ruskin Air and Sound Control)

(Figure 10.4.4) types, all actuated by fusible links. Most fire dampers are designed for vertical installation, although some can be installed horizontally as well.

Dampers are required to close against the maximum calculated airflow of that portion of the air duct system in which they are installed. Those that are intended to close under airflow are labeled for use in Dynamic Systems; those that are intended to close after airflow has stopped by automatically shutting down the fan or airflow in the event of a fire are labeled for use in Static Systems.

UL labels dampers for dynamic systems at 1000 ft/min (5 m/sec) intervals starting at 2000 ft/min (10 m/sec). Damper installation details are covered in manufacturers' installation instructions and in the SMACNA damper guide.[12]

Smoke Dampers

Smoke dampers (Figure 10.4.5) are required in air-conditioning or ventilating ducts that pass through required smoke barrier partitions. NFPA 90A requires smoke dampers to operate automatically on detection of smoke and must function so that smoke movement through the duct is halted. Basically, they simply interrupt airflow through the duct. NFPA 90A permits the use of fire dampers for smoke control purposes. Obviously, a combination fire and smoke damper must meet the requirements for both. Smoke dampers are tested and classified by UL in accordance with UL 555S, *Standard for Safety Smoke Dampers.*[13]

Damper Operators

Smoke dampers, combination fire and smoke dampers, and reopenable fire dampers are installed with damper operators to provide automatic operators. Operators can be electric or pneumatic. Damper operators used in smoke control applications are provided factory installed by the damper manufacturers as a means to establish that the combination of damper and operator perform properly.

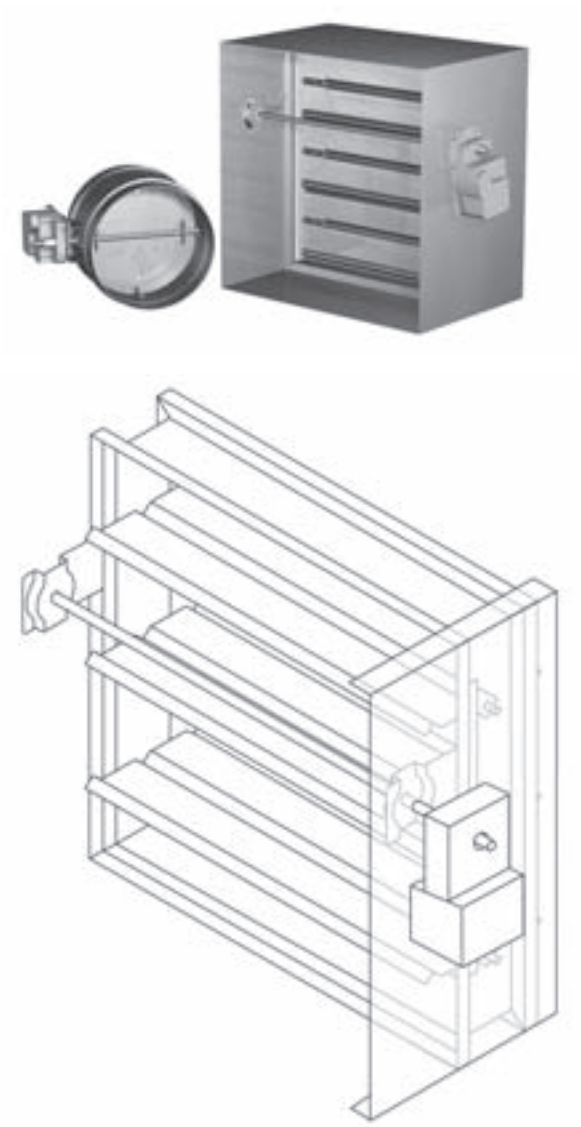

FIGURE 10.4.5 Smoke Dampers (Source: Courtesy of Greenheck Fan Corp.)

Smoke Detectors

Smoke detectors must be installed in all air-conditioning or ventilating systems of over 15,000 ft^3/min (425 m^3/min) capacity. Further, smoke detectors for use in ducts must include features in their design specifically for this purpose. Smoke detectors may shut down the air-conditioning or ventilating system, sound alarms, operate smoke control dampers, activate fire suppression equipment, or initiate active smoke control functions. Detectors with adjustable sensitivity are preferred in order to minimize false alarms due to incidental dust or other particulate matter.

These smoke detectors are located in the main supply ducts, downstream of air filters or air cleaners, and in the main return

ducts prior to exhausting from the building or joining the fresh air intake ducts. Smoke detectors at these locations are primarily intended to prevent smoke circulation throughout the entire area served by shutting down the air handling system. Also they prevent circulation of smoke from a fire in the air filters, air cleaners, belts, and motors. Due to dilution effects of air picked up from various branch return ducts, these smoke detectors cannot be expected to reliably provide "early warning" smoke detection. For this reason, additional smoke detectors may be provided, for example, in the main branch return duct from each floor or major area division. Such detectors could also be tied into a zoned fire alarm system; however, such an arrangement is not a substitute for a smoke detection system for building protection. For guidance on smoke detector location, see *NFPA 72®, National Fire Alarm Code®*.

FANS AND CONTROLS

It is attractive to use the air-conditioning or ventilating system for smoke control and smoke removal in case of fire. Tests have demonstrated the effectiveness of pressurizing emergency exit stairwells and elevator shafts to prevent smoke migration from the fire floor to other parts of a building during evacuation.[14,15]

The fan unit on an air-conditioning system should not in itself present undue hazard if properly installed and firmly supported on a rigid foundation. It should also be readily accessible for cleaning, servicing, and lubrication. Fans should be provided with excess vibration switches and wired to sound an alarm and initiate system shutdown when bearing failure is imminent.

Fan motors installed inside ducts or plenums need protective devices to cut off power before temperatures reach a point that smoke may be generated. Most fractional horsepower motors have over-temperature protective devices. Thermal overload relays are recommended for fan motors of one horsepower or larger.

Electric wiring to all components should follow NFPA 70. All electrical equipment should be listed by a qualified electrical testing laboratory. Wiring installed in ducts, plenums, and other spaces used for environmental air should meet the requirements of NFPA 262, *Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces.*

All air-conditioning or ventilating systems need manual shutoffs for use in case of fire or other emergency. This shutoff should be well identified and located where it is readily accessible, such as near building exits. In systems of 2000 to 15,000 ft^3/min (57 to 425 m^3/min) capacity, it is good practice to provide automatic shutoff controls triggered by thermostatic devices in the same locations as recommended for smoke detectors. A setting of 136°F (58°C) for the thermostatic device in the return air stream and a setting of 50°F (10°C) above maximum operational temperature for the device in the supply stream are recommended.

UNIT AIR CONDITIONERS

The term *unit air conditioner* may include any factory-produced unit serving one room or area. Such units do not involve the hazard of spreading fire from floor to floor or area to area as do ducted systems. However, if improperly designed, installed, or maintained, they may involve the other hazards associated with larger systems. For example, any window-sill-type unit can overheat through failure of its thermal relay. This could lead to ignition of wire insulation or filter media, and the fire could spread to curtains or the wood sash of the window. Defective wiring could lead to the same condition. A common problem involving these units is that they are too frequently plugged into outlets on branch circuits not designed to carry the design load or on an already overloaded circuit. This practice directly violates principles of NFPA 70.

MAINTENANCE

Maintenance and cleaning are of utmost importance to safe operation of any air-conditioning or ventilating system. Filters must be changed or cleaned as frequently as necessary. Ducts, particularly on the return side of the system, must be cleaned out periodically to prevent hazardous accumulations of combustible dust and lint. Evidence of any defect of wiring or electrical equipment must be checked out immediately and corrected. Repairs on ducts or equipment casings that require welding or cutting should be protected by complete shutdown of the system and thorough cleaning of the area. If possible, the duct section to be repaired should be isolated from the rest of the system.

Proper maintenance includes periodic testing of all fire protection devices, including fire suppression equipment, smoke control and fire dampers, fire detectors and alarms, and even vibration switches on fans. A regular testing program should be established. For fire dampers, such testing should include removing fusible links, operating the damper, and lubricating parts as necessary. If such testing is outside the function of regular maintenance staff, it should be contracted to an outside agency.

ENERGY CONSERVATION

Energy conservation practices require a careful evaluation of the design and control of HVAC systems. To reduce electrical costs, fans are turned off during various portions of the day and during unoccupied hours. Without airflow, the duct fire and smoke detectors may not detect fire and thereby will not provide the protection that may be assumed as inherent in HVAC systems. The use of variable volume air systems is increasing as these systems have an overall lower energy use than most other systems. The variation in duct airflow in such systems can create a problem with the sensitivity of the duct-mounted detectors and cause false readings and alarms. Fan cycling and variable volume systems can also cause variations in air pressure relationships of the occupied spaces. An area may have a positive pressure relationship to another area when the fans are operating in one mode, and when the fans are cycled a completely different relationship can occur, which can affect the performance of detection and control systems and calls for careful design evaluation.

SUMMARY

The ducts used in air-conditioning and ventilating systems present the possibility of spreading fire, fire gases, and smoke

throughout a building. For that reason, the location of equipment and the fresh air intakes, the types of air filters and cleaners, the system of ducts and plenums, and the use of fire and smoke dampers are crucial in limiting and containing a fire. Just as critical are the choices of type of equipment, proper maintenance of that equipment, and energy conservation measures.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on air-conditioning and ventilating systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 70, *National Electrical Code®*
NFPA 72®, *National Fire Alarm Code®*
NFPA 80, *Standard for Fire Doors and Other Protective Openings*
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*
NFPA *101®*, *Life Safety Code®*
NFPA 252, *Standard Methods of Fire Tests of Door Assemblies*
NFPA 262, *Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces*

Reference

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Chapter 5

Ventilation of Commercial Cooking Operations

David P. Demers

Chapter Contents

Ventilation
Components
Fire Concerns with System Operation Design
Fire Concerns with System Component Design
Fire Concerns with System Maintenance

Key Terms

cooking appliance (floor-mounted restaurant type), duct, duct system, exhaust system, grease, grease duct, grease filter, grease removal devices, hood, makeup air, replacement air, restaurant, ventilation (mechanical), ventilation (natural)

Fires in commercial cooking establishments are a serious concern. Many commercial cooking operations are part of assembly, educational, and health care occupancies where a fire could create a significant exposure to life safety. In the case of an institutional occupancy, the inability to provide meals on a continuing basis could result in a major relocation of facility occupants.

Fires in commercial cooking equipment, such as fires in cooking equipment in U.S. homes, have a relatively high frequency but a relatively low average severity. For example, there were nearly 5000 cooking equipment fires reported to U.S. local fire departments per year in 1994–2005 in eating and drinking establishments, with associated losses of $42 million per year. This represented 44 percent of reported fires but only 23 percent of associated direct property damage. In every property type, cooking equipment fires account for a much larger share of fires and injuries than of direct losses or deaths.

The reasons for the relatively high frequency are straightforward. An ignition source is usually available from the cooking operation itself, the fuel load can be significant due to the buildup of grease and cooking residue, the air supply is designed to be effective, and mitigation efforts require significant inspection and maintenance.

The reasons for low average severity are also straightforward. Cooking equipment fires typically occur while an awake, unimpaired adult is nearby, if not continuously focused on the cooking activity. Such fires usually begin with a small initial fuel source, in a location where quick response is not blocked.

One of the factors in severe fires is early spread into the ventilation equipment. Ventilation of commercial cooking operations is the subject of this chapter.

Ventilation and fire control for commercial cooking operations must be considered as a major building "system" with several components. Each of those components must be properly addressed for the fire safety system to be effective. The components include the following:

- Hood(s)
- Grease removal devices
- Exhaust duct system
- Air movement system
- Auxiliary equipment
- Fire-extinguishing equipment
- Operating procedures
- Inspection, cleaning, and maintenance procedures
- Training of facility management and employees

There are unique requirements for recirculating systems downdraft and solid fuel cooking operations. Large-scale cooking operations for the food service and supply industry also have special considerations.

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This chapter discusses those aspects of ventilation and fire protection systems in commercial food establishments that can have an effect on a fire relative to its initiation, spread, containment, and suppression. It also provides definitions, an overview of typical ventilation systems and their components, and a breakdown of the factors that can cause problems due to poor design or maintenance.

Information relating to this subject can be found in Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems"; and Section 18, Chapter 4, "Venting Practices."

The referenced NFPA standards apply to both commercial cooking and industrial cooking establishments such as bakeries.

VENTILATION

Ventilation is the replacement of stale, noxious, or contaminated air with clean—or at least cleaner—air. The moving of the air may replace the original air with new outside air, or it may clean and recirculate the original air. The temperature of outside replacement air is usually controlled. Common ventilation processes include heating and air conditioning by forced air, exhaust systems of all types, and air distribution and transfer systems.

Natural Ventilation

Natural or gravity ventilation is accomplished without mechanical assistance and can be provided by openings to the outside, draft stacks, and pressure differentials due to height or temperature. Natural draft exhaust systems are not specifically addressed in this chapter, although brick ovens and open barbecue pits are used for commercial cooking. These systems rely almost totally on natural draft. A natural draft makeup/supply system could be merely a screened open door or window to the outside. This chapter also does not address such exterior openings, except that if the openings are closed, makeup air is not available, and the exhaust system will not work properly. If a strong wind is blowing in through the opening, the draft could also cause the exhaust system not to work. Either condition can cause grease to build up on the surfaces of the room and thus increase the potential hazard and spread of a fire.

Mechanical Ventilation

Mechanical ventilation is accomplished with fans to create the pressure differentials necessary to produce the desired flows of air. Mechanical ventilation systems are specifically addressed in this chapter.

Exhaust

Exhaust is the ventilation process that draws noxious air-entrained particulates and vapors from a cooking operation, collects them in a hood, and contains them in a duct for transport to the outside or to equipment that cleans the air before discharging it to the outside or returning it to the area of origin. In a closed area, such as a kitchen, exhaust cannot operate at the flows required without having an equal supply of makeup air available. In the context of this chapter, exhaust primarily applies to the commercial cooking exhaust systems that are designed to capture, contain, and remove from the kitchen the effluents of the cooking operations. Other exhaust systems in a commercial cooking establishment can be for removal of heat and fumes from restrooms, dishwashers, and refrigeration condensers.

Makeup Air/Replacement Air

Makeup air and *replacement air* are the terms commonly used to refer to the air that has to be brought into a space to limit pressure gradients so the exhaust process can operate as designed. This air may be brought directly into a space via ducts or indirectly via openings from adjacent areas. The quantity of makeup air must be of a sufficient flow rate to allow the exhaust system to operate within its pressure differential design parameters yet not be so great as to create a positive pressure within the cooking area. A slight negative pressure in a commercial kitchen is usually desirable to reduce cooking odor migration to other spaces.

COMPONENTS

Exhaust Systems

An exhaust system consists of the hood over the cooking appliance(s), the ductwork connecting the hood to the exhaust fan, the exhaust fan itself, and all grease filtration devices and other effluent control devices within the system (Figure 10.5.1). The concept of the exhaust system is that the system will capture all the cooking effluent within the hood, contain it there until it is removed by the duct and fan system, and transport it through the duct system to the outside. Within the system, the effluent is treated for removal of effluent contaminants (grease, gases, odors). In some newer systems (designated recirculating units) for commercial cooking, the effluent contaminants are considered removed to such a thorough degree that the final air is able to be returned to the same space as the cooking operation instead of having to be discharged outside.

Hoods

Canopy Hoods. A canopy hood is one whose lower edges overhang the outer edges of the cooking appliance by a minimum of 6 in. (152 mm) on all sides of the cooking appliance that are not closed off between the cooking surface and the lower edge of the hood. If at least the rear side of the hood is closed off to the cooking appliance by a wall or panel, it is then called a wall canopy (Figure 10.5.2). If no side of the hood is closed off to the cooking appliance, it is called an island canopy (Figure 10.5.3). Very often, island canopy hoods are double wide when installed over two rows of cooking appliances that are back to back. Canopy hoods are required to be at a minimum of 6.5 ft (2 m) above the floor to prevent most people from hitting their heads on them. Such height above the cooking surface generally requires that canopy hoods operate at high levels of exhaust.

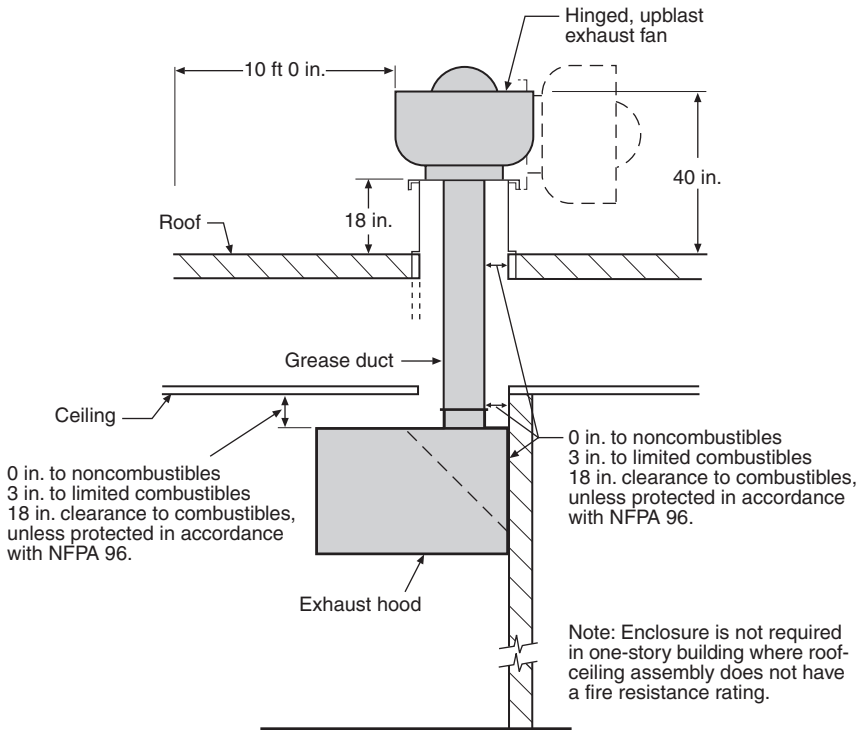

FIGURE 10.5.1 Typical Cooking Exhaust System

Noncanopy Hood. Noncanopy hoods come in many styles. They are noncanopy in that they do not meet the overhang and minimum height above the floor requirements of the canopy hoods. Noncanopy is a poor definition, since it defines what they are not, rather than what they are. They have many different names, such as backshelf, high-sidewall, eyebrow, cap, and high-velocity. In general, they are mounted much closer to the cooking surface and are usually required to have the front lower lip no more than 3 ft (0.9 m) above the cooking surface. This style is especially true of the backshelf, high-sidewall, and

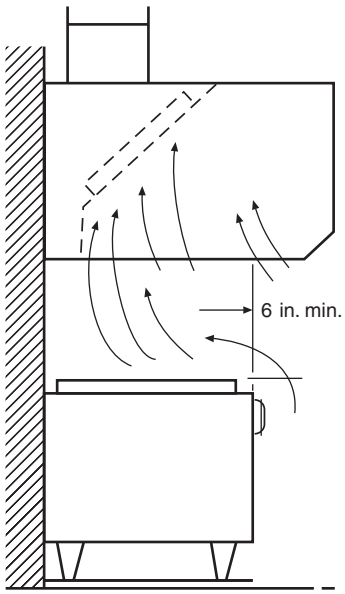

FIGURE 10.5.2 Wall Canopy Hood

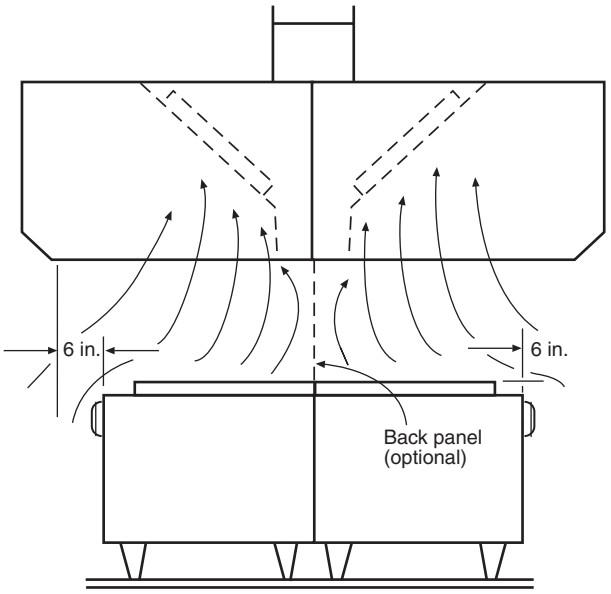

FIGURE 10.5.3 Island Canopy Hood

high-velocity hoods, which are primarily the same style hood with different names (Figure 10.5.4). Since noncanopy hoods are so low, they almost always have a setback from the front of the cooking appliance; that is, the front lower lip of the hood is behind the front edge of the cooking surface to minimize the possibility of hitting one's head when bending over the cooking appliance. If there is a conveyor chain or other feeding/retrieval device at either end of the cooking appliance, it generally is not covered by any portion of the hood, though local codes may alter this.

Two variations of a canopy hood are the cap hood and the eyebrow hood. They are generally mounted on or just above taller cooking appliances, such as multideck ovens and broilers. The cap hood looks somewhat like a baseball cap, with the main part of the cap (the hood) over the cooking appliance to gather heat, and the smaller bill part in front of the appliance to gather heat and effluent from the front when the doors are opened (Figure 10.5.5). The eyebrow hood is equivalent to the bill part of a cap hood but is just the portion that is over the front of the cooking appliance (Figure 10.5.6). Both hood styles are also used over chain broilers, grills, and dishwashers. Canopy hoods, at times, are also used in every application where noncanopy hoods are used. New styles of commercial cooking such as self-contained broilers and grills and downdraft appliances have required more performance-related requirements to address the ever present fire hazard. All of the systems will still require fire suppression.

Exhaust Ductwork

Single Exhaust Duct System. A single exhaust duct is one that serves one exhaust hood only. It will typically be of the same cross section from one end to the other and have one single fire suppression system for the entire exhaust system, including the appliances, hood, and all ductwork.

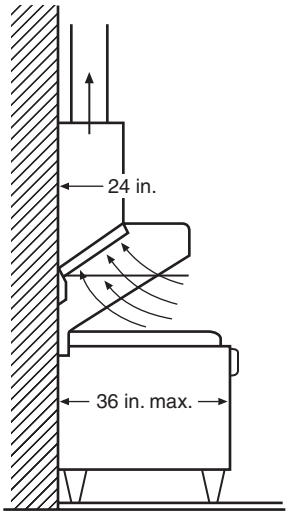

FIGURE 10.5.4 Noncanopy Backshelf Hood

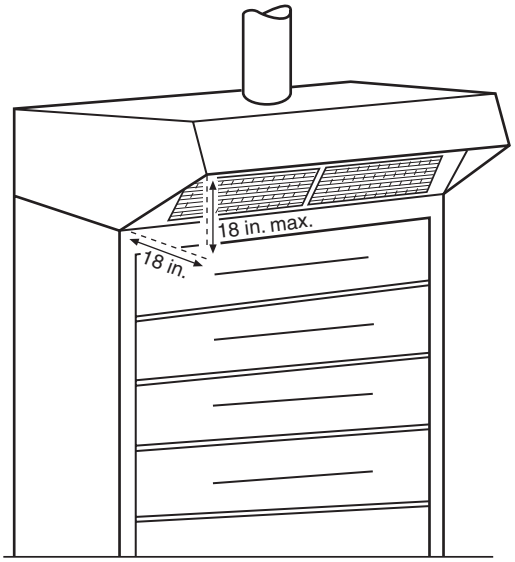

FIGURE 10.5.5 Cap Exhaust Hood

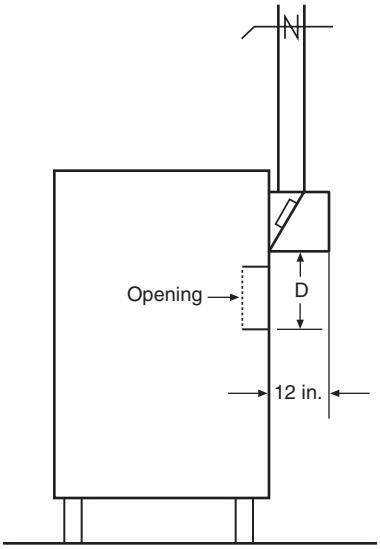

FIGURE 10.5.6 Eyebrow Exhaust Hood

Manifold Exhaust Duct System. A manifold exhaust duct system serves more than one exhaust hood. The cross section is at its smallest as it leaves each single hood and increases in cross section as it joins with another branch duct, thereby forming a common duct, and increases further in cross section as each additional branch duct enters the common duct (Figure 10.5.7). Manifold exhaust duct systems typically have separate fire suppression systems for each exhaust hood and its appliances and also for each branch duct. All the individual suppression systems will operate simultaneously for the protection of the common duct. However, there may be separate suppression systems for the branch ducts or for all or portions of the common exhaust

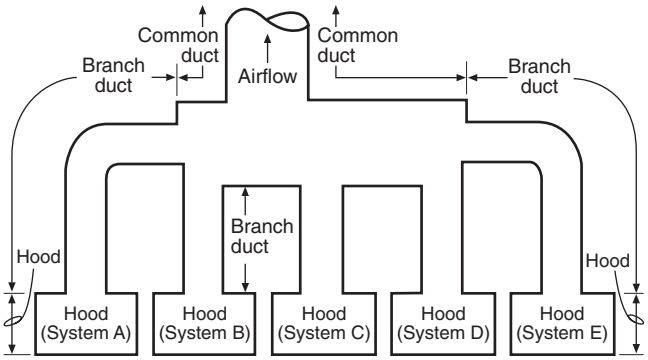

FIGURE 10.5.7 Manifold Exhaust Duct System

duct. In those cases, there are multiple ways to actuate the individual systems and provide for shutdown of the individual appliances. For more information, see NFPA 17, *Standard for Dry Chemical Extinguishing Systems;* NFPA 17A, *Standard for Wet Chemical Extinguishing Systems;* and NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations.*

Exhaust Fans

Connections of fans to ductwork are required to be liquidtight at all temperatures. It is common practice for standard ventilation systems to have flexible connections to limit vibrations and sound transmission of operating fans; however, such flexible connections are not permitted on cooking ventilation systems.

Upblast Fan. An upblast fan is one that terminates an exhaust duct system (Figure 10.5.8). It is located on the roof, sitting on a curb, with the inlet at its base and the discharge at its top pointing upward. For grease exhaust applications, it is required to be listed for the application. It is also required by NFPA 96 to be restrained and hinged to tilt back for easy and direct access to the exhaust duct for inspection and cleaning. Typically, it will operate only on single exhaust duct systems or small manifold exhaust duct systems, not operating much over 1.5 in. of water column static pressure (373 Pa).

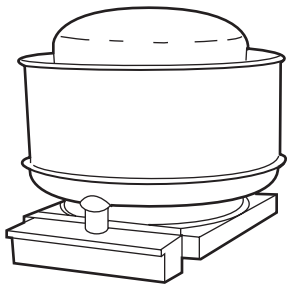

FIGURE 10.5.8 Upblast Exhaust Fan

Utility Fan. A utility fan is one that typically sits on the roof at the termination of the exhaust duct system, but it may also be found inside the building above the kitchen, with discharge ductwork leading it to the outside of the building. When installed on the roof, it sits beside the curb, with the duct coming out of the curb and leading into one side of the fan. The fan discharge is out of an opening that is perpendicular to the inlet and able to rotate the inlet so it can discharge to either side or up or down (Figure 10.5.9). The discharge is sometimes ducted to get it more than 10 ft (3.1 m) away from any fresh air inlet or put in a box to separate much of the grease from the air. It is capable of operating on both large single and manifold duct systems with high static pressure.

In-Line Fan. An in-line fan is almost always found inside the building at the same level as the kitchen but in a back room. It is typically round in shape like a large duct section, with the inlet duct connection at one end, and the outlet duct connection at the opposite end (Figure 10.5.10). The vane-axial fan blade

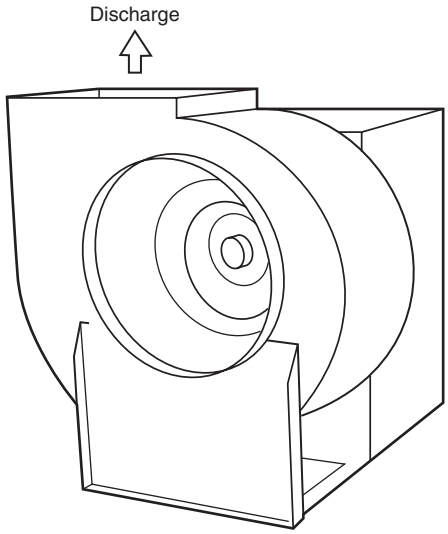

FIGURE 10.5.9 Utility Exhaust Fan

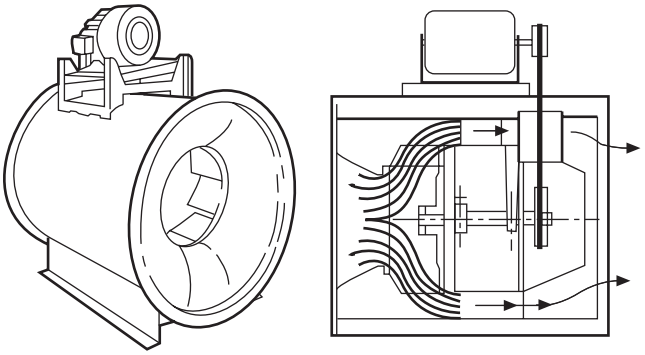

FIGURE 10.5.10 In-Line Exhaust Fan

is located in the center so the whole fan is "in line" with the ductwork, and thus its name. It must be flanged and bolted to the ductwork at each end, in order that it can be removed for service. In some rare cases, only the fan and motor section are flanged and bolted. In either case, in-line fans are more difficult to service and are typically used only where other types of fans are not practical. Flexible connectors are not allowed on this type of fan.

Makeup Air System

The makeup air system contains all the components (fans, ducts, registers, etc.) that provide for the delivery of the outside makeup air to the vicinity of the exhaust hood.

Integral Makeup Air. Integral makeup air is the method of delivering a portion of the outside makeup air directly to a separate chamber of the exhaust hood (Figure 10.5.11). Within the hood, the makeup air is introduced through registers or slots into the inside of the hood (short circuit), downward out the front lower edge of the hood (air curtain), or horizontally out the front of the hood (face discharge), or in multiple combinations of these. The makeup air may be provided without tempering of the short circuit and air curtain air flows. Hoods without tempered makeup air can be subject to performance variations, as the seasonal changes bring a change to the temperature and density of the makeup air. This method provides only a portion of the makeup air required with the rest supplied from other sources.

Nonintegral Makeup Air. Nonintegral makeup air is the method of delivering the makeup air to the kitchen space or adjoining area(s) through ducts and registers (Figure 10.5.12). Such air is always tempered in all but the mildest of climates.

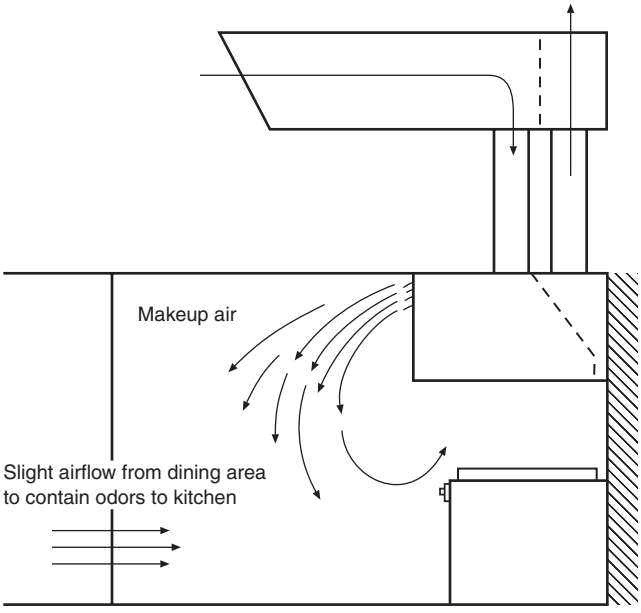

FIGURE 10.5.11 Integral Makeup Air Hood

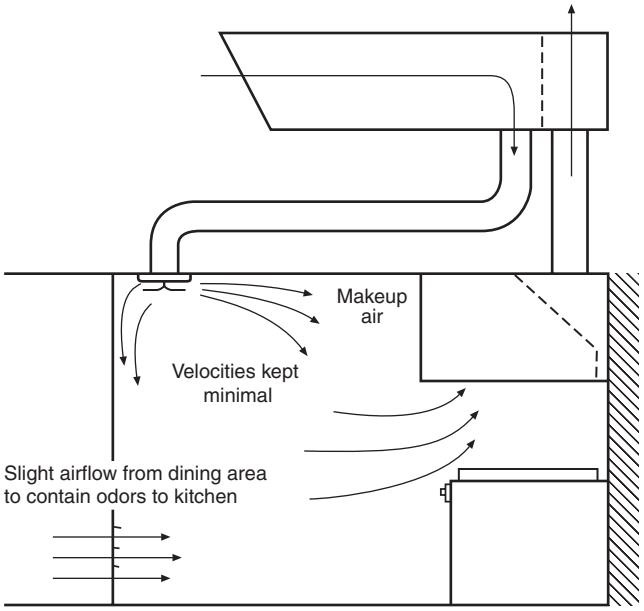

FIGURE 10.5.12 Nonintegral "Standard" Makeup Air Hood

Controls

Control circuits may be manual or automatic. Automatic control circuits are called interlock control circuits. Interlocks provide for safe cooking operation by ensuring that:

1. Cooking cannot operate unless the fire suppression system is armed
2. Cooking cannot operate unless the exhaust fan and makeup air fans are on
3. Cooking is shut down in the event of operation of the fire suppression system

Only the last of these is required by codes, but all are recommended and often put into practice.

Operating Controls/Interlocks. Operating systems use many types of controls. Among them are controls that operate cooking appliances and exhaust system components, and safety controls that are built into the cooking appliances and exhaust system components to control or shut down the components or system under emergency conditions. Many restaurants still operate with manual controls, but it is safer to have interlocked control systems. A typical operating interlock control system will not allow cooking to operate unless the exhaust is operating, and will not allow the exhaust to operate unless the makeup air is also operating. A wide variety of controls exist that may be optionally included with these, but most often the control systems are quite simple and use few of the optional controls. These extra controls may be as complicated as controls that regulate the appliance and room temperatures during high- and low-volume periods, the amount of fresh and exhaust air, and the economizer performance of the heating, ventilating, and air conditioning (HVAC) equipment. With some gas stoves and

ovens and with solid-fuel cooking there are often a number of manual controls.

Fire Controls/Interlocks. There are fire detectors to sense a fire and initiate action by the suppression system, and there is a minimum interlock consisting of a switch to shut off the fuel to the cooking appliance in the event of the suppression system operation (Figures 10.5.13). There should be additional controls to sound a local fire alarm, to sound a central alarm in a larger building, or even to notify a local fire department. There is always a manual means of operating the built-in fire suppression system (Figure 10.5.14).

FIRE CONCERNS WITH SYSTEM OPERATION DESIGN

Ventilation Flows

Exhaust. Exhaust flows must be adequate to capture and contain the effluents of the cooking process. If so, they are also adequate to capture and contain the small or short-term fire. But this does not mean they will be adequate to capture and contain the effluents of a serious and longer-term grease fire. The expansion of vapors due to the higher temperature fires will ultimately exceed the capacity of the hood if the fire burns long enough and the fire will escape from the hood.

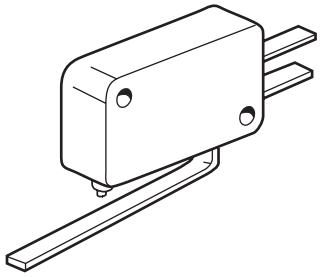

FIGURE 10.5.13 Fire System Interlock Switch

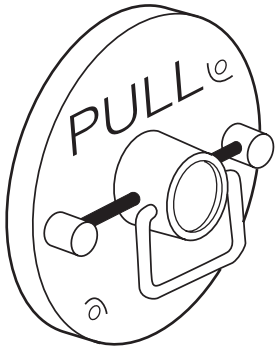

FIGURE 10.5.14 Fire System Manual Pull

Makeup/Replacement Air. The makeup/replacement air is critical to provide proper airflow.

Controls

Operating Controls. If there is no interlock between the cooking appliances, exhaust, and makeup air, or if the interlock fails, it increases the chance of noncontainment of the cooking effluent and increases the potential hazard in the event of a fire. Failed thermostats and high-limit temperature controls that can no longer shut off the cooking appliance cause fires every year in cooking appliances due to appliance overheating and autoignition of the oil or shortening in the cooking process. The same scenario occurs on manually controlled cooking equipment when pots of oil are left unattended and overheat to the point of autoignition. Where no interlock exists between the exhaust fan and cooking appliance, or if it fails, a fire can start in the hood, especially over gas-operated appliances, due to the flue gases overheating grease buildup in the hood to the point of autoignition.

Fire Interlock. The most serious fire interlock failures are the ones that fail to permit the suppression system to operate. These include grease-plugged detector line elbows that do not permit the cable to move, detector links that are too grease coated and insulated to respond in time to the fire, or detector links that are held closed with a wire from some previous maintenance operation. Another serious fire interlock failure is one that will not shut down the fuel that heats the appliance due to a failed interlock switch or a jammed mechanical gas valve. Other potential failures include defective switches or open wires in alarm circuits. These situations are the basis for the required 6-month control inspection.

FIRE CONCERNS WITH SYSTEM COMPONENT DESIGN

Exhaust Hoods

The three primary fire concerns with the exhaust hood are that it is (1) able to extract and drain the maximum amount of grease possible from the effluent to minimize any subsequent fire, (2) able to contain a fire within itself should one occur, and (3) protected from adjacent combustible surfaces so that it will not ignite them by radiant effect. In order to do so, the hood must be of adequate size and operate at adequate airflow and have a reasonably efficient filtration system, that it be of such structure to stay intact during a fire so that the fire cannot escape, and that it be installed in such a way as to provide protection between itself and adjacent combustibles so that it cannot radiate heat sufficient to ignite them.

Filters

Hoods may contain removable baffle filters, or they may have larger filtration baffles that may be removable in cassette form, or filters may be built in (Figure 10.5.15). The removable filtration devices must be removed from the hood to be cleaned. The

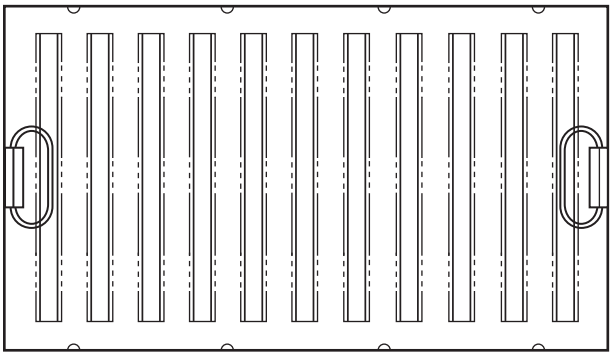

FIGURE 10.5.15 Grease Filter

built-in units are cleaned in place with a detergent and water wash system. It is very important for fire safety that all filtration devices be cleaned at least once a day. Further, while dirty filters are being cleaned, removable devices must have replacement units installed at all times when the appliances are still turned on. Operating the exhaust with filters removed will put much more grease into the hood and duct systems. It will also lower the static pressure so much that it will dramatically increase the amount of air being exhausted and unbalance the system. In the case of manifold exhaust systems, removing filters from one hood will increase the exhaust at that hood but dramatically lower it at all the other hoods connected to that manifold system. As a result, the other hoods will leak grease vapors into the space, which defeats the purpose of the hoods and increases the fire hazard potential. Filters in the hood must be tightfitting on all four sides in order to preclude any grease or fire bypassing them.

Exhaust Ducts

There are two essential requirements for exhaust ducts, relative to fire protection. The first is that the duct must be so solidly welded or assembled (listed ducts only) from one end to the other so that a fire within a duct cannot escape through the duct wall to a hidden combustible area. The second is that there must be adequate clearance or protection around the ductwork so that the radiant heat due to a fire will not be able to ignite any combustible products that may be close to the duct. This requirement prevents the duct from causing a fire to start in combustible concealed spaces of a building.

Duct integrity and construction are critical for containment of grease and any fires that may occur. All seams, joints, penetrations, and duct-to-hood collar connections are required to be liquidtight at all temperatures and have continuous external welds. Duct materials are required to be at least 0.054 in. (1.37 mm) (No. 16 MSG) carbon steel or 0.043 in. (1.09 mm) (No. 18 MSG) stainless steel. Specially listed grease ducts or assemblies can have other joining methods and construction.

Proper ductwork is constructed without dips or traps that can hold grease and are designed to be pitched to drain back to hoods or to special grease drains. The exhaust fan must be designed to drain grease to a closed external container. Discharge from the fan or the duct that terminates the system must not direct the flow toward the roof or any combustible surfaces, nor toward any operable windows or doors. These precautions serve two purposes: (1) to prevent a fire from igniting any combustible surfaces and (2) to keep a fire and any grease discharge from blocking proper ventilation or egress from building openings.

Exhaust Dampers

A fire damper sometimes is placed in a hood at the duct connection to the hood (Figure 10.5.16). Its intent is to prevent fire from getting into the ductwork. This is a controversial aspect of exhaust systems because there are advantages and disadvantages to the use of dampers.

Advantages. Fire dampers are helpful in commercial kitchen hood/duct systems because:

1. They keep fire out of existing ducts that may be substandard and would not contain the fire.
2. They keep the fire contained to the kitchen level of multistory buildings, thereby reducing the potential hazard of fire spreading to other floors and tenants.
3. They provide increased safety in the event the fire suppression system does not function.

Disadvantages. Fire dampers are problematic in commercial kitchen hood/duct systems because:

1. A properly designed and installed duct system can exhaust the fire and smoke out of the building in a safe manner if the system is designed to handle such fires, making a damper unnecessary.
2. Closing the damper will back the fire and smoke into the kitchen space, spreading the fire more quickly, and the smoke will make it much more difficult for the fire service to fight the fire.
3. A fire kept out of the duct system and in the kitchen space can spread to combustible or grease-coated ceiling and wall

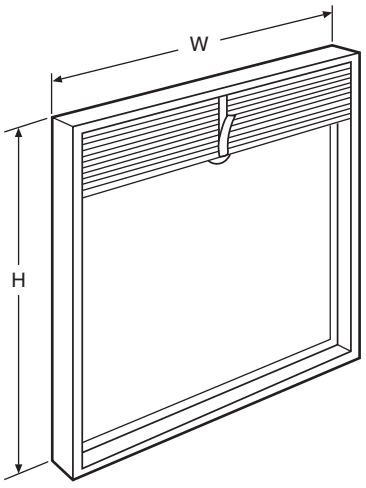

FIGURE 10.5.16 Fire Damper

surfaces, and from there to other hidden areas, increasing the hazard to other tenants and building areas.

4. The exhaust ducts may be so dirty that the damper cannot fully close so that the fire spreads to the ductwork anyway, or the fire gets into the ductwork before the damper closes, so the damper has only provided a false sense of security and makes it more difficult to access the fire in the duct.

It is clear that much of the concern with dampers has to do with the proper condition of the ductwork beyond the dampers, including its integrity and clearance to combustibles. If a hood assembly is listed, it must be installed in accordance with its listing and manufacturer's instructions.

Exhaust Fans

There are two primary concerns with exhaust fans relative to fire hazard. First, the fan must not trap grease within itself but drain it to an external covered metal container of not more than 1 gal (3.785 L) capacity. This minimizes the chance of the fan contributing fuel to any fire and places the drained grease in a sealed container of limited capacity that is not likely to catch on fire. Second, the fan must not discharge its effluent toward any combustible surface that might catch fire or toward any operable door or window or vent that might be a point of egress or fresh air for the occupants. This requirement limits a fire that may come from the discharge of a fan or the terminal section of ductwork and prevents fire spread to other combustible surfaces. Further, it allows building reentry and a path of potential egress. Fans should be mounted with hinges so that one person can easily lift the unit to gain access to the grease duct for cleaning. NFPA 96 requires fans to be hinged, but most mechanical codes do not.

Grease Extraction/Control Devices

Many commercial cooking establishments have additional grease extraction or control devices downstream of the hood in order to more completely remove the grease and odors from the effluent stream. This feature is required in many jurisdictions in order to reduce local environmental concerns and complaints. These devices may be installed in ceiling spaces or mezzanines, but most are installed on rooftops immediately before the fan. Some units have integral fans.

These units consist of various stages of filtration devices that may be metal baffles, metal mesh filters, dry bed or pleated filters, electrostatic precipitators, afterburners, or water-wash devices. All are designed to remove the remaining grease from the system. The afterburners also remove odors. Systems also can use activated carbon or some other chemical catalyst or odor control spray to control odors.

Each of these devices (except the afterburner) carries with it the possibility of igniting or providing fuel for a fire. (The afterburner has built-in safety controls and cabinetry to preclude a runaway fire in it.) Each of these units should be provided with a fire detection and suppression system that provides protection in the event of a fire. The cabinetry of the units should be of the same gauge as the ductwork to which it is attached and the access panels should match those of the ductwork, or the unit should be listed for equivalency with these requirements and applications in a grease-laden environment. (See NFPA 96 for fire safety requirements for such units.)

Grease Gutters, Cans, and Containers

Grease gutters may exist under the filter rack of a hood, around the lower perimeter of a hood, and on one or more sides of a cooking appliance. They are pitched to drain to a remote grease container. Grease cans or containers collect the grease from the gutters. They are also found as open or closed pans or containers under certain sections of cooking appliances and at the drain of grease fans. The obvious fire hazard with all of these is that they contain extra fuel in the event of a fire. For increased fire safety, the amount of grease that is contained in these at any time must be kept to a minimum. Therefore, the gutters should be pitched as much as practical to minimize the grease they can hold. Containers, cans, and pans should be kept at the minimum volume necessary to get through one major rush period, and not be expected to hold the grease for the entire day in a high-volume operation. NFPA 96 limits the container to 1 gal (3.785 L) capacity. It is also best that the container be capped on top, with only the minimum opening necessary to permit the grease to enter. Should a fire get into such a container, it most likely would smother itself rather than burn all the fuel.

Appliance Position

It is important that appliances be positioned under the hood in their designated position for three reasons. First, it ensures that the effluent generated by the appliance will be captured and contained by the hood and exhaust system and not escape into the room where it can extend the fire hazard potential. Second, in the event of a fire in the appliance, it ensures that the flames will be contained in the hood for the longest time possible, limiting the fire hazard potential. Third, it ensures that the fire suppression system nozzle will be able to apply the chemical suppressant to the fire as designed for that appliance and, thus, extinguish the fire.

Some appliances are supplied with appliance locks to ensure that they maintain their positions. Locator blocks on the floor or rear wall that position the appliances are also good. But even where these do not exist, it is important that operating personnel realize the importance of keeping the appliances in their designated positions under the hood.

Fire Suppression

In commercial cooking operations, the fixed fire suppression system is considered the primary means of fire control, with portable fire extinguishers being secondary. This approach to fire suppression requires special training of kitchen workers. Inadequately trained workers can exacerbate fire conditions by using water, milk, or other liquids on fires in cooking equipment. Major flare-ups and injuries can occur when workers try to extinguish fires using flour or cornstarch rather than baking soda (sodium bicarbonate).

At one time, dry chemical (sodium bicarbonate) fire suppression systems were the most common type to protect

commercial cooking equipment. Such systems, however, lack the cooling capability needed to pass UL 300, *Standard for Safety Fire Testing of Fire Extinguishing Systems for Protection of Restaurant Areas.* Now, wet chemical systems are the most common types used for fire suppression. Automatic sprinklers are also used, and the application is addressed by codes and standards. Large-scale food production lines frequently use carbon dioxide systems because carbon dioxide is a clean agent, which reduces the amount of cleanup and subsequent production downtime. There is a new trend to utilize water mist suppression systems for industrial-type cooking.

Fire Detectors. Fire detectors are used to activate the fixed fire suppression system (Figure 10.5.17). Whether they are of the mechanical link or electronic sensor type, they must be applied at a rating and location that permit them to respond *promptly* to any abnormal temperatures in the effluent from the cooking operation. With late activation, fire may have already spread to areas beyond the range of the suppression system, or the ignited surfaces may be so hot, especially in the case of deep fryers, that even if the suppression system initially puts out the fire, there will be reignition because the suppression agent will break down before the surfaces can cool. Whatever the autoignition temperature of the greasy surfaces, once the suppression system has discharged, the surface temperatures must cool at least 50°F (28°C) below the autoignition temperature if the surface is not to reignite.

The best way to choose the proper link rating and location is to monitor the temperatures of the normal effluent airstream under maximum cooking conditions. This monitoring is not often possible or practical, so an estimate is made and a rating and location selected. Even if this is all that can be done initially before the restaurant opens, temperature monitoring with a remote recorder can be done later, and then within a very short time the actual maximum normal temperature can be known and the link rating adjusted accordingly. Remember, a *fast* response is necessary, not just a response. The longest preburn time for systems listed to UL 300 is 2 minutes. Most of the older systems were listed for only 1 minute preburn. Links are normally installed behind filters, many feet above the cooking surface. It could easily take much more than 2 min for a fire in a single vat under a canopy hood to raise the temperature of a link to its rating, especially if a link is not directly in the line of flame and air flowing over it is diluted by the cooler air from the rest of the cooking operation. It is not unusual for fire to completely bypass links for 5 minutes or more. It is better to install more links than thought necessary, since the path of the flames and hot air will be strongly affected by the airflows created by the exhaust system.

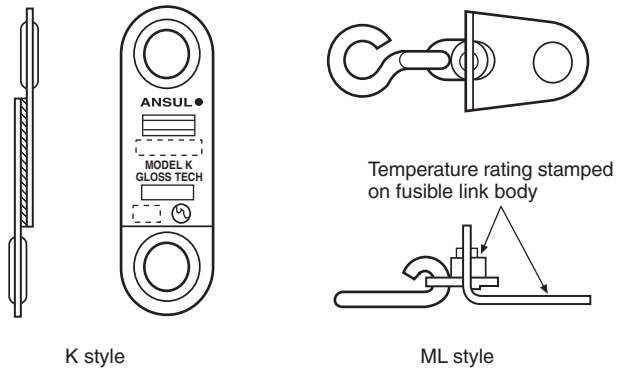

FIGURE 10.5.17 Detector Links

Fire detectors should be inspected a minimum of every 6 months, and mechanical links should be changed a minimum of every 6 months. Inspection must include that the rating and position of the detector are still appropriate for the application, especially for appliances that may have changed since the last inspection. Detectors covered with an insulating layer of grease or carbon can have a slower response time than designed. All detectors must have clean surfaces; otherwise, they should be changed out for new detectors.

Detection Lines/Elbows. Detection line conduits and the pulley elbows in them need to be inspected every 6 months, including doing a trip of the actuator by cutting the terminal link. This inspection will show that the cable is free to move in the conduit system. In grease exhaust applications, it is not unusual for grease to get into the horizontal conduits or into the pulley elbows and harden to such an extent that the cable cannot move. When this problem occurs, the system cannot operate automatically, which presents a serious fire hazard. If a cable will not move or moves only sluggishly, the conduits and elbows should be dismantled to find the problem. If they cannot be cleaned, they should be replaced.

Another concern with pulley elbows is when they are located in the hot flue gas from gas-fired appliances. When this problem occurs and they are not rated for such applications, they will melt in such a way as to seize the cable in the elbow, and, again, the cable will not be able to move when needed. Visual inspection will usually show this problem, but it can also be noted with an end-of-line detector test.

Makeup/Replacement Air

Integral. Where makeup air is integral to the hood, it is possible that some grease can also get into this makeup air compartment whenever it might be turned off. Grease deposited in hidden areas can spread a hood fire to this point when makeup air discharges inside the hood.

Nonintegral. Makeup replacement air can disturb the capture of the hood to the extent that grease leaves the hood and enters the room. Therefore, if a fire develops and grows rapidly, it will also leave the hood and track along the grease path provided by the escaping cooking effluent. This situation can create uncontrollable fire spread.

Operation During Fire. There is a tendency in some jurisdictions to have all supply air shut down in the event of fire. This action is not always proper. If the hood is able to capture all grease vapors properly, and if there is no fire damper at the hood/exhaust duct connection, it is better to keep the makeup air operating in the event of an appliance or hood fire, as there is an increased

chance the hood will be able to contain the fire and smoke. If the makeup air is shut off, the hood will be short of available air and will not be able to continue exhausting properly.

FIRE CONCERNS WITH SYSTEM MAINTENANCE

Maintenance is essential to ensure that a system performs as designed. Both the components and the system as a whole must be kept physically and operationally in the condition for which they were designed. Adjustments, repairs, and replacements must be made as necessary. Maintenance personnel must identify each part of proper system design and performance and review them on a regular basis to catch and correct the first slip from "normal." This maintenance will keep the system working as designed.

Ventilation Flows

The purpose of ventilation systems in commercial cooking applications is to keep greasy effluents captured, contained, and evacuated through the exhaust system, and keep the kitchen environment grease free. Any decay in the performance or flows of the systems may cause grease vapors to leak from the hood into the kitchen space, contaminating the area with fuel. In the event of fire in a faulty system, the flames may leave the hood more quickly and ignite the grease deposits in the room, seriously increasing the fire hazard. Airflows of the exhaust and makeup air should be checked at least once a year or more often if it is noticed that the hood is not capturing the effluent properly.

Exhaust Hoods

The primary fire concern with hoods is that they be kept (1) in the same structural condition in which they were installed, assuming compliance with NFPA 96, and (2) clean so they will not sustain a fire and transport it into the duct. No holes can be cut in the hood, no service lines run through it, and no notching made in end panels to provide additional clearance. The welded shell of the hood is supposed to be able to contain a fire. When holes are put in it, or its perimeter is cut and notched, it can no longer provide this function and the fire hazard increases. Penetrations through the hood structure to mount fire suppression system components or other equipment such as lighting should be sealed with locked screws and sealant.

The hood must be kept clean. The filters should be cleaned daily, and the interior surfaces of the hood (both in front of and behind the filters) should be cleaned to bare metal at least once a week. If the hood surfaces and filters are clean, there is little chance of a fire in an appliance spreading to the ductwork. (See NFPA 96 for a recommended frequency of cleaning for the exhaust system, based on type of fuel, type of cooked product, and volume of cooking.)

Grease Filters

Grease filters installed in hoods should typically be cleaned a minimum of once a day to minimize the grease buildup and reduce the fire hazard. The cleaning should be done after operating hours, or the facility should have a spare set of filters to install. The hood must not be operated without filters, as this increases the fuel loading in the hood and duct, and it will unbalance the ventilation.

Filters should be in good physical condition, with flat squared frames and no baffles damaged or missing. Damaged filters should be replaced immediately—they cannot filter effectively, and, more important, they cannot stop flame penetration into the hood. Mesh filters are not acceptable.

Some hoods have permanent grease filtration devices, and these will have built-in detergent and water-wash systems to clean the grease filtration devices on a daily basis. It is important that these cleaning systems be maintained in good working order to keep the grease filtration devices clean and reduce the fire hazard. Problems to watch for include cleaning systems without any detergent and systems with controls or water shut off, so they cannot operate. This violates the listing of the unit, thus increasing the fire hazard. Hoods with automatic washdown should be set to self-clean a minimum of once a day, and more frequently if conditions warrant. The washdown system should be inspected for proper operation at least once a month to ensure that all nozzles are open, pressures are adequate, and the controls are cycling properly.

Additional Grease Extraction/Control Devices

Some exhaust systems have additional grease removal devices somewhere in the duct system after the hood. They may be in the false ceiling space, in a mezzanine, or on the roof. These extraction devices also contain various types of filters. These filters must be cleaned or replaced according to the manufacturer's instructions. Failure to clean the filters builds up unnecessary fuel in the system, seriously reducing the airflow, and may cause the hood not to capture the vapors as designed. It is necessary with these units to make sure that the filters are in good physical condition so the grease cannot bypass them and to make sure that they are in place so they can function properly. Failure to keep these components operating as designed seriously increases the fire hazard. These units should be inspected a minimum of once a month to be sure the filters are still performing properly and that all panels, seals, and suppression system components are in good condition.

Exhaust Ducts

Exhaust ducts should be fully welded or possibly bolted if a listed duct system. Remodeling of the building, or other trades working in the vicinity of the ducts, can cause damage or changes to the ducts that reduce their integrity. Any time work is performed in the vicinity of the ducts, they should be inspected after the work is complete.

Many ducts also have bolted or gasketed connections at the hood or fan. These require more attention, as they are more subject to decay from normal use and vibration. Any grease leaks seen around these points are reason to have the connection checked and repaired, as necessary.

If, for some reason, a facility has an existing duct that is not fully welded, or in other ways does not fully meet NFPA 96,

it is all the more important to establish regularly scheduled inspection of the duct to ensure that grease leaks do not exist and that other damage has not occurred. Proper, frequent cleaning of ducts is critical.

Makeup Air Systems

The makeup air system is needed to provide replacement air to balance that taken out by the exhaust system. The makeup air system must operate whenever the exhaust is operating, be matched to the quantity of air taken out by the exhaust system, and not interfere with the performance of the exhaust hood.

The makeup air system usually operates at considerably higher air velocities than the exhaust system, and usually approaches the hood at different angles than those established by the exhaust airflows. Where these angle differences exist, they should be neutralized by distance before the makeup air nears the hood so as to not adversely affect the capture and containment effect of the exhaust airflows.

Makeup air introduced integrally at the exhaust hood is more likely to have a negative effect on capture and containment than makeup air introduced at the far side of the room from the exhaust hood. Therefore, integral makeup air needs more frequent attention to maintain proper performance. Some hoods with integral makeup air have operator-adjustable diffusers that can be set to operator preference for the season, but this adjustment can adversely affect the capture and containment performance of the hood.

Ambient conditions not acceptable to facility personnel should be brought to the attention of the design engineer. Fire safety should not be compromised for the sake of employee comfort.

Service Panels/Gaskets/Hardware for Hoods and Ducts

Inspection panels are often installed in ductwork and in some hoods in order to inspect and clean the ducts and hoods. When in place, these panels must have integrity equivalent to welded ductwork, which requires that (1) the panel be ridged and conform to the shape of the opening, (2) the gasket be complete and adequately thick to seal the full perimeter of the opening, and (3) the hardware used to hold the panel closed be tightened securely in order to create a grease-tight seal. If a panel cannot be sealed as described above, it must be repaired immediately. Panels that cannot seal will leak grease, possibly allowing burning grease to escape from the opening to ignite combustibles in the vicinity. This can spread a fire to relatively hidden areas that are difficult to locate. The integrity of these components should be closely inspected each time they are used.

Clearance to Combustibles

All hoods, ducts, fans, and other components of exhaust systems are required by codes to have adequate clearance to combustibles so as not to ignite the combustibles from the radiant heat of the metal shell in the event of an internal fire. Sometimes this clearance is provided by insulation and air gaps, sometimes it is provided by a noncombustible or fire-rated chase, and sometimes it is provided by only a physical distance to the closest combustible surface. Any protective system provided around the exhaust system must be kept intact, in order to maintain this crucial clearance. Chases must have access panels to enable inspection and cleaning. Access panels in the chases must be kept in good condition and secured in place in order to maintain the designed protection. These panels should be inspected and maintained with attention equivalent to that given the panels in the ductwork itself. In cases where there is only open space between the exhaust system and combustible construction, it is important to maintain that space. It is not uncommon in commercial cooking operations to use false ceiling and attic spaces for storage of combustible products. Where this is done, and the same spaces contain unprotected exhaust ductwork, it is best to put a wire mesh or expanded metal fence around the ductwork to ensure that no combustible materials can come closer than 18 in. (457 mm) to the ductwork.

Appliances

Grease effluent is produced by the products cooked on appliances. Much of the grease effluent is carried into the exhaust system, but a large quantity of grease stays with the cooking appliance. Fryers hold shortening in the vats. Grills collect grease on the surface, and then it drains (or is scraped) into scrap cans on the side or front of the grill. Ovens and some broilers usually have grease baked on the interior surfaces, but this grease can run out of drain openings to cups. Charbroilers usually burn grease in the fire or on the hot elements, but much of it just settles at the bottom of the bed. Fire safety requires that, where grease collects inside appliances or in containers from appliances, it be frequently removed during the day and not allowed to spill over onto the floor. Inspections and cleanings should occur multiple times each day to minimize the immediate hazard, and to facilitate the cleanup of the grease. The floor, wall, and rear area of appliances should be cleaned at least once a day.

Grease often condenses on the outside of appliances and hoods, or on lower hood or wall parts below any grease gutter. Most of this grease will drain onto the floor, and a path will show on the wall or side of the equipment. It is important for fire safety that such occurrences be corrected with additional gutters and remote covered grease cups, or that they be frequently addressed during each day with manual cleaning. Otherwise, there will be a buildup of mostly hidden grease that will create a fuel source in the event of fire.

As many appliances age, they develop internal grease leaks that permit a grease buildup in the immediate vicinity of the gas burner or electrical elements. This grease buildup can quickly become the source of a fire, and there is no detection or suppression system within this appliance area to suppress the fire when it occurs. Therefore, it is essential to inspect such areas and keep them grease-free. All grease leak sources should be located and repaired immediately. These repairs are especially important for fry vats, as a leaking vat can drain grease onto a burner and cause an immediate and serious fire.

Changes. Fire suppression systems are installed in hoods to protect the specific appliances that are under the hood at the time of original installation of the system. If these appliances are

later repositioned or changed out for other appliances, the suppression system may no longer be able to provide suppression for the new arrangement. Menu changes can impact the type and location of equipment. When appliances are repositioned or changed out for other appliances, even if the change involves only a different input rating or a different fuel, the local AHJ must review the system and see if it is still adequate or if a detector, nozzle type, or nozzle location needs to be changed. All restaurant operators should be aware of this concern. A change to solid fuel cooking takes special consideration.

Seals. Some appliances, notably closed ovens, must be sealed during normal cooking operations to contain the grease and other effluents. If a fire should occur in such an appliance and the seal is not complete, fire can escape from the appliance rather than be contained and smothered. It is important that all such seals be kept in good order to ensure fire safety.

Fire Dampers

Fire dampers in grease exhaust systems should only be installed in listed hoods at the hood to duct connection, or they may be a component of a listed grease extraction system that is installed downstream of the hood. In either case, they need to follow the same inspection schedule as the suppression system detectors, and they have the same problems if the detector link becomes grease or carbon coated. Exhaust hoods with integral makeup air supplies usually have fire dampers installed in the supply duct to hood connection, or at one or more of the makeup air register openings. Their links have the same inspection and replacement schedule.

Fire dampers need to be checked for proper and full operation. The damper should be able to close fully and rapidly. If it moves sluggishly or does not close fully, its track is coated with grease buildup, and it must be cleaned. If the fire damper cannot close quickly and completely, it cannot be effective.

Gas Valves

Any gas valve can stick open, but it is more likely to occur with mechanical gas valves than with electrical gas valves (Figures 10.5.18 and 10.5.19). Mechanical gas valves have openings that permit grease to get inside part of the mechanism, which causes it to seize or slow down. These must be operationally checked every six months. If any delay or incomplete closure is noted, the valve must immediately be cleaned or replaced. With mechanical gas valves, it is necessary to ensure that the cable line is not binding in any way and causing the problem.

Shunt Trip

Electrically powered equipment utilizes a shunt trip breaker that will cause the circuit to be de-energized on activation of the fire suppression system.

SUMMARY

Ventilation and fire protection systems for commercial cooking operations provide invaluable services to the industry and permit such operations in many locations where the potential for fire hazard is great due to the fuel, product, and greasy effluent that are inherent in commercial cooking operations. Systems can be designed to not only provide their prime function of capturing, containing, and removing the greasy effluent but also to contribute positively to a fire-safe environment. Knowledge exists for safe design and should be conveyed to facility operators, service personnel, and local inspectors. It is important that these people know the value of each component of the systems for operational and fire safety, and how to keep the components and the system in proper working order so that they can continue to safely provide their intended functions. As more education is provided on these issues, the fire safety record will improve.

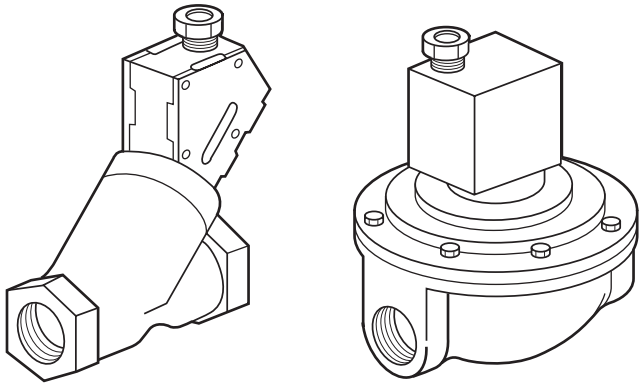

FIGURE 10.5.18 Mechanical Gas Valves

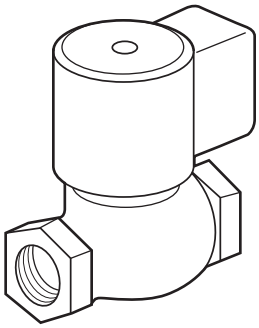

FIGURE 10.5.19 Electrical Gas Valve

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on venting systems for commercial cooking equipment discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
NFPA 17A, *Standard for Wet Chemical Extinguishing Systems*
NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations*

Chapter 6

Boiler Furnaces

Revised by

L. Jeffrey Mattern ❑ Eugene Catania ❑ Shelton Ehrlich

Chapter Contents

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Fuels
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Open Register Lightoff and Continuous Purge Procedure
Fire and Explosion Protection
Special Considerations for Small Boilers
Interlocks, Alarms, and Operator Competence

Key Terms

atomizer, burner flame, circular burner, fire-tube boiler, fluidized bed combustion (FBC) boiler, furnace, natural gas–fired boiler furnace, oil-fired boiler furnace, pulverized coal, Saybolt Universal Seconds (SUS), selective catalytic reduction (SCR) boiler, waste fuel, water-tube boiler

More than any other single invention, the steam engines of Newcomen and Watt led to the modern age. The primitive boilers that produced the steam for these early engines consisted of a furnace, a space for burning the fuel, and a separate boiler, with a large copper pot heated from beneath. Improvements in iron fabrication techniques made possible the integration of the furnace and boiler.

Although this chapter discusses water-tube boiler furnaces, the safety principles outlined also apply to fire-tube boilers. Fuel-burning systems and related control equipment for single- and multiple-burner boiler furnaces are discussed here. Furnaces for fuels burned in suspension and in fluidized beds are included; other solid-fuel-burning units, such as stokers, are not.

Further, it is not the intent of this chapter to include start-up, shutdown, or operating procedures or a detailed description of interlock and trip systems. This information is contained in the applicable NFPA standards listed at the end of this chapter.

For related topics see also Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 7, Chapter 3, "Storage of Gases"; Section 8, Chapter 10, "Stationary Combustion Engines and Fuel Cells"; Section 10, Chapter 1, "Emergency and Standby Power Supplies"; and Section 10, Chapter 2, "Heating Systems and Appliances."

OVERVIEW

Development of Boiler Furnaces

In fire-tube boilers, the furnace is a large central horizontal tube surrounded by a water-filled boiler. The hot exhaust gases pass out of the furnace and then back through tubes that traverse the boiler. Failure to keep water in fire-tube boilers led to catastrophic boiler explosions, resulting in many deaths in the mid-nineteenth century. (Such explosions still occur occasionally.) Boiler explosions were especially a problem on early steamships, where exposed occupants had fewer options to escape the consequences of them. The deadliest fire or explosion in U.S. history was a boiler explosion and ensuing fire aboard the SS *Sultana* on the Mississippi River on April 27, 1865, where 1547 people died. Inventors were kept busy trying to solve this problem, as well as automating the feeding of coal by use of mechanical stokers. Another important "invention" of the time was the establishment of the Steam Boiler Assurance Company in 1859 in the United Kingdom, the beginning of the boiler inspection and insurance industry.

Further, material improvements led to the development of the water-tube boiler. Here the water is in the tubes and the hot gases pass across the tubes. Although individual water tubes could still burst, boiler safety was much improved. With the development of pulverized coal firing, water-tube boilers would grow to enormous size. The increase in size led to the possibility of catastrophic

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furnace explosions. Steady improvements in design, materials, instrumentation, operator training, and supervision [addressed by the American Society of Mechanical Engineers (ASME International), insurance companies, NFPA, authorities having jurisdiction, etc.] have led to a great reduction in fire-tube boiler explosions and water-tube boiler furnace explosions.

The Combustion Process

Combustion is the rapid combination of oxygen with combustible elements of a fuel. There are three important combustible elements: (1) carbon, (2) hydrogen, and (3) sulfur. When burned to completion with oxygen, these elements unite according to the following:

$$C + O_2 = CO_2 + 14{,}100 \text{ Btu/lb (or 32,797 kJ/kg) of carbon}$$

$$2H_2 + O_2 = 2H_2O + 61{,}100 \text{ Btu/lb (or 142,119 kJ/kg) of hydrogen}$$

$$S + O_2 = SO_2 + 3980 \text{ Btu/lb (or 9258 kJ/kg) of sulfur}$$

Waste gases rich in carbon monoxide (CO) are often burned in boilers and release 4347 Btu/lb (10,111 kJ/kg) of CO. CO boilers or incinerators generally utilize a refractory-lined and auxiliary-fueled chamber to maintain temperatures needed to combust the CO in the off gas.

To compete effectively, designers must carefully balance the need to provide for complete combustion against the capital cost of the boiler and the auxiliary power needs. The key factors, often referred to as the "three Ts" of combustion, are (1) *time,* set by the size of the furnace; (2) *temperature,* set by the arrangement of heat-removal surfaces and the hydrogen content of fuel, its moisture and excess air; and (3) *turbulence,* set by the skill of the designer in manipulating flows of air and fuel and the interaction between all the burners in the furnace. A fourth critical factor is *continuity,* that is, the need to supply fuel, air, and ignition source on an uninterrupted basis.

Not only must the fuel and air be supplied continuously, but also the ratio of fuel to air must be kept constant within a relatively narrow range. The burner designer and the limits built into the automatic controls provide that the ignition source (feedback from the fuel just burned) be available for the fuel just entering. When any of these factors go awry (e.g., the fuel is interrupted for a few seconds; the airflow suddenly increases, say because a blockage is removed; or the burner does not hold the flame close), then ignition can be lost and the controlled flammable mixture becomes an uncontrolled explosive mixture. A large boiler-furnace is always just a few seconds away from catastrophe. It is only through the skill of the many people responsible for ensuring that events are always correct that large furnace explosions are so remarkably rare. Increasing sophistication in flame detection, condition monitoring, and other safety systems assist those people in maintaining this safe margin.

Figure 10.6.1 shows how fuel and air are introduced and burned in a furnace through a modern low-NO_x burner. Pulverized coal, carried by a small stream of air termed *primary air,* is injected through the center of the burner and meets with the swirling bulk of the air, termed *secondary air.* The several functions of this burner can be seen in the figure: a zone just at the burner outlet in which fuel is ignited and partially burned, but with a strong deficiency of air (A); and a second zone in which thermal NO_x is reduced to N_2 (C). The mixing and burning of the remaining air and residual fuel (the *char* that remains after the volatile fuel components have been driven off near the burner) takes place in the furnace. Radiation from the brightly luminous flame and the recirculation of hot gas due to turbulence provide a stable ignition source. The combustion process

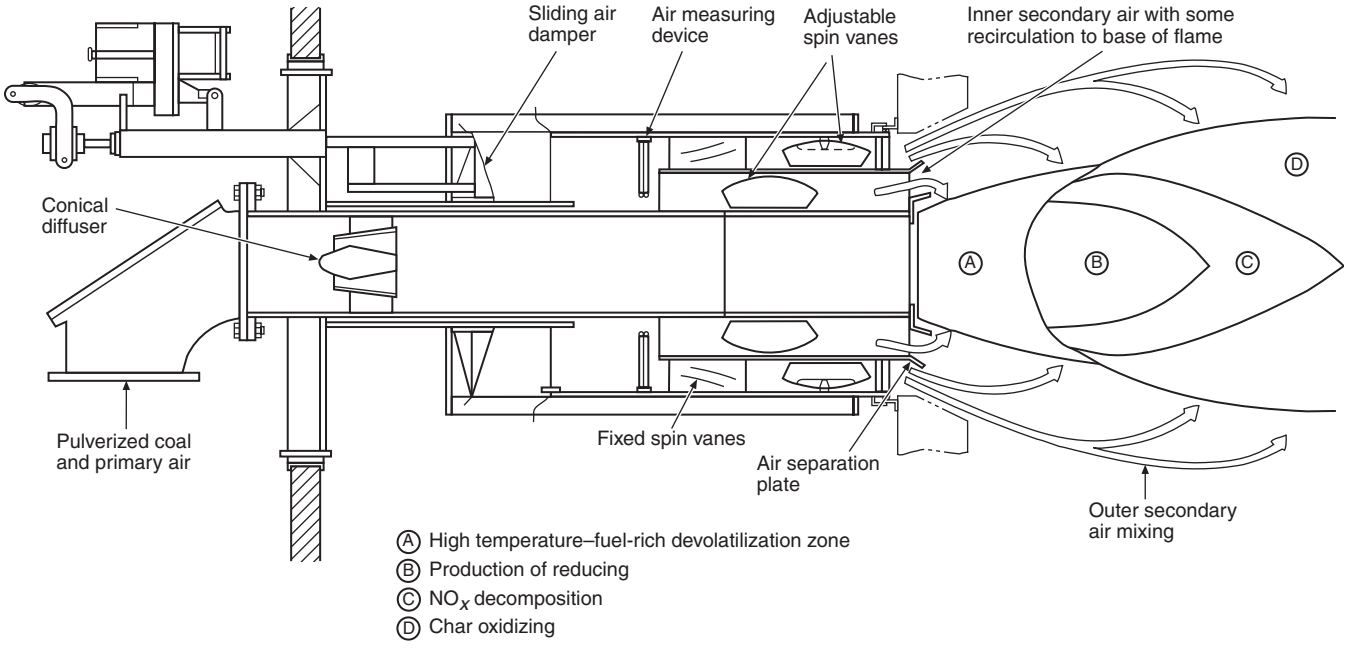


FIGURE 10.6.1 Burner Flame Conditions

proceeds toward completion through a wide range of fuel-air ratios, fuel-rich just at the burner exit and fuel-lean at the furnace exit.

The introduction of low-NO_x burners and overfire air systems (OFA) on existing and new coal boilers results in staging of the combustion process. In the near burner area, fuel-rich combustion conditions require the precise control of fuel and air so that high combustibles and unburned carbon content can be contained. Recent developments in burner system design include individual burner fuel flow monitoring and balance of individual coal burners with separate burner airflow measurement and control. By closely controlling the air-to-fuel ratio in near burner areas, the lowest NO_x values can be achieved while minimizing formation of combustible gases and unburned carbon in the fuel burned. Minimizing the NO_x produced in the flame basket also allows lesser usage of feed gases (e.g., ammonia) to downstream SCR systems.

FUELS

After several periods of rapidly rising oil prices, coal became the least expensive boiler fuel almost everywhere in the world. However, in 1999 natural gas use surpassed coal use for all thermal energy uses including heating processes and electricity. Some large boilers, built when fuel prices were more competitive, still burn residual fuel oil because (1) they are incapable of burning coal or (2) the use of very low sulfur fuel oil is virtually mandated. Other boilers, particularly in gas-producing regions, were designed to burn natural gas when gas prices were maintained low via federal controls. In winter, when gas is urgently required by pipelines, many of these boilers will burn distillate oil. Most boilers in commercial installations and in small industries also use natural gas and clean oil, although all fuels are, to some extent, used.

After a period when most new generation in the United States consisted of gas-fueled combined cycle units, large upswings in gas pricing coupled with high demand from competing users have impacted the cost and use of these plants for base-loaded around-the-clock operation. Recently, the use of large coal-fired or waste solid fuels has become a factor in planning new generating plants. Environmental regulations have required the use of strict environmental controls in the design of these new plants, including scrubbers, bag house, and selective catalytic reduction (SCR) units, as well as wider use of large circulating fluid bed (CFB) boilers. Likewise, older base-loaded, solid-fuel-burning units are having their operating life extended through major component upgrades, coupled with the addition of new environmental components to comply with environmental requirements.

In recent years, with the commercialization of fluidized bed combustion and a federal law making the use of waste fuels especially profitable for independent power production, a wide array of waste fuels is now used. Included are wood wastes, petroleum coke, coal-mining residues, and many others. Still, the dominant fuel worldwide remains coal, and its dominant form is a finely pulverized powder with a mean particle size under There are also waste fuels produced in oil refineries, chemical plants, paper mills, and so on that are burned in specially designed furnaces that demand special precautions in addition to those described here for the more common fuels.

With the large number of combined cycle gas turbine power plants installed in recent years, they will remain a major source of power for future generation scenarios. See Section 10, Chapter 1, "Emergency and Standby Power Supplies"; and Section 8, Chapter 10, "Stationary Combustion Engines and Fuel Cells," for some discussion of gas turbines. In a combined cycle the hot turbine exhaust generates steam in a boiler, called a *heat recovery steam generator* (HRSG). To maintain steam temperature and pressure at all loads, many of these HRSGs are also fired with natural gas or light oil, and they have many features in common with other boilers. However, the profusion of HRSG designs and supplemental firing schemes has led to a number of serious accidents. For more information on HRSGs, see NFPA 85, *Boiler and Combustion Systems Hazards Code.*

OIL- AND GAS-BURNING SYSTEMS

The burner is the principal component of oil- or gas-firing systems. Its purpose is to introduce fuel and air into the furnace in the proper proportion, swirl, and droplet size to sustain efficient combustion. The combustion efficiency of a burner (and furnace) should be as high as possible to minimize energy lost as either unburned fuel or excess air.

Normal use of a boiler requires operation at different outputs to meet varying loads. The specified operating range for a burner is the ratio of full-load heat production of the burner to the minimum load at which the burner is capable of stable ignition and reliable operation. For example, with a multiple burner-boiler rated at 1,000,000 lb/hr (450,359 kg/hr) steam capacity, a load range of 4:1 on the burners means that the unit can provide stable ignition and complete combustion at any load from its rated capacity down to 250,000 lb/hr (113,400 kg/hr) without requiring one burner to be taken out of service.

Because of the chemistry of combustion, more than the quantity of theoretical air is necessary to achieve essentially complete combustion. The amount of excess air needed for complete combustion with minimum stack loss must be balanced against compliance with NO_x emission requirements. The excess air normally required with coal, oil, and gas, expressed as a percentage of theoretical air, is given in Table 10.6.1. Many boilers operate with substantially higher excess air levels, some because of the particular fuel, the furnace design, or poor attention to optimum performance.

A frequently used burner for gas and oil is the circular burner (Figure 10.6.2). Normally, the capability of an individual circular burner is limited to about 200 million Btu/hr (58,620 kW). The tangentially displaced doors built into the air register provide the turbulence necessary to mix the fuel and air and to produce a stable flame. While the fuel is introduced to the burner in a fuel-rich mixture in the center, the direction and velocity of the air and the fuel-dispersion pattern thoroughly mix the fuel with the combustion air. A burner specially designed for low NO_x emissions is shown in Figure 10.6.3. An airflow monitor is incorporated in this burner to allow for balancing airflow from burner to burner.

TABLE 10.6.1 Usual Amount of Excess Air Required for Complete Combustion

Fuel	*Type of Furnace of Burner*	*Excess Air (wt.%)*
Pulverized coal	Completely water cooled	15–20
Crushed coal	Cyclone furnace	10–15
	Fluidized beds	15–20
Fuel oil	Oil burner, register type	5–10
	Multifuel burners and flat flame	10–20
Natural gas	Register-type burner	5–10

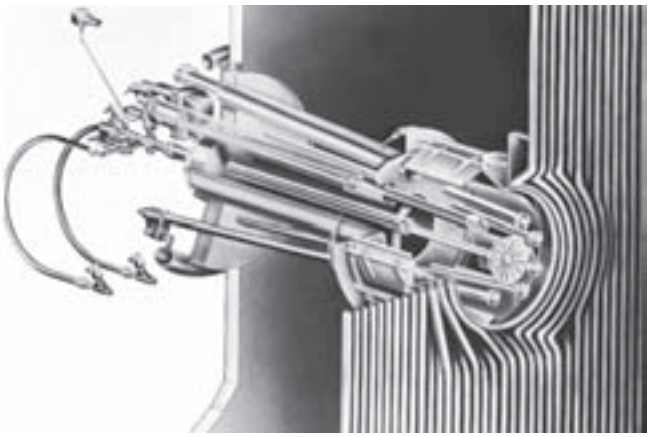


FIGURE 10.6.2 Circular Register for Gas and Oil Firing (Source: The Babcock & Wilcox Co.)

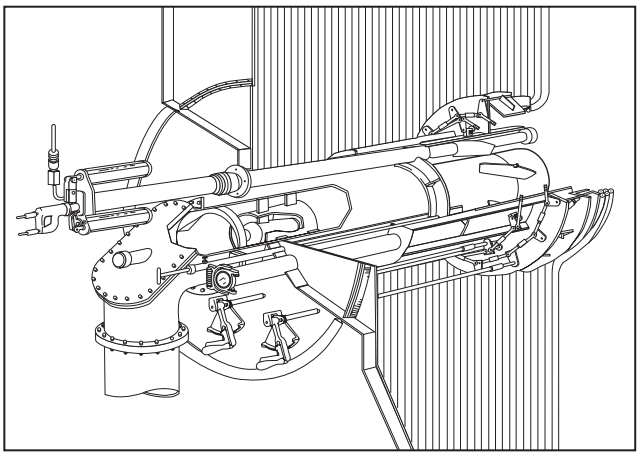


FIGURE 10.6.3 Burner for Low Emissions of NO_x (Source: The Babcock & Wilcox Co.)

Oil Burners

A main function of an oil burner is to atomize the oil, that is, turn the thick stream of oil into a very fine mist of oil droplets. This process provides the large oil surface area needed for rapid ignition and, as each droplet is surrounded by air, complete combustion. There are a number of types of oil atomizers, but the discussion here is limited to the two most popular types: (1) steam or air atomizers and (2) mechanical atomizers.

For proper atomization, oil heavier than No. 2 must be heated to reduce viscosity to between 100 and 150 SUS.* Steam or electric heaters are used to raise the oil temperature to the required level—approximately 135°F (57.2°C) for No. 4 oil, 185°F (85°C) for No. 5, and 200°F (93.3°C) to 220°F (104.4°C) for No. 6. With certain oils, better combustion is obtained at somewhat higher temperatures than are required for atomization. However, oil must not be heated to the point where vapor binding might occur in the fuel pump; this could cause flow interruptions and loss of ignition.

It is also important that oil be free of acid, grit, and other foreign matter that might clog or damage burners or their control valves. In order to prevent a loss of fuel, flow strainers installed to remove particles must be cleaned as often as an increasing pressure drop indicates.

Steam or Air Atomizers. Generally, the steam or air-oil atomizer operates by producing a steam-fuel (or air-fuel) emulsion that atomizes the oil through the rapid expansion of the steam (or air) when released into the furnace (Figure 10.6.4). The atomizing steam must be dry because moisture causes pulsations that can lead to loss of ignition. Where steam is not available, moisture-free compressed air is substituted.

The steam atomizer performs efficiently over a wider load range than do other types of atomizers. Normally, it properly atomizes oil down to 20 percent of rated capacity (turndown = 5:1); in some instances, steam atomizers have been successfully operated at 5 percent of capacity. This high level of turndown can be inconsistent with high efficiency because the total airflow must not be permitted to fall below 25 percent of full capacity rate (the purge rate). Also, these extremes in range cannot be fully utilized because the temperature of the furnace falls below that needed to complete combustion despite the excellent quality of atomization.

Mechanical Atomizers. In the mechanical atomizer, the pressure of the fuel itself is used as the driving force for atomization. A wide variety of mechanical atomizer designs has been developed over the years. Excessive maintenance is required to keep those having rotating mechanical parts that are close to the furnace operational.

Return-flow atomizers are used for many marine installations and some stationary boilers where the use of steam or air is inappropriate, impractical, or uneconomical (Figure 10.6.5). Oil pressure required for these atomizers ranges from 600 to 1000 psi (4.14 to 6.90 MPa), depending on capacity, load range, and fuel.

*Abbreviation for Saybolt Universal Seconds. This is the efflux time in seconds of 60 ml (approximately 2 oz) of sample flowing through a calibrated universal orifice in a Saybolt viscometer under specified conditions.

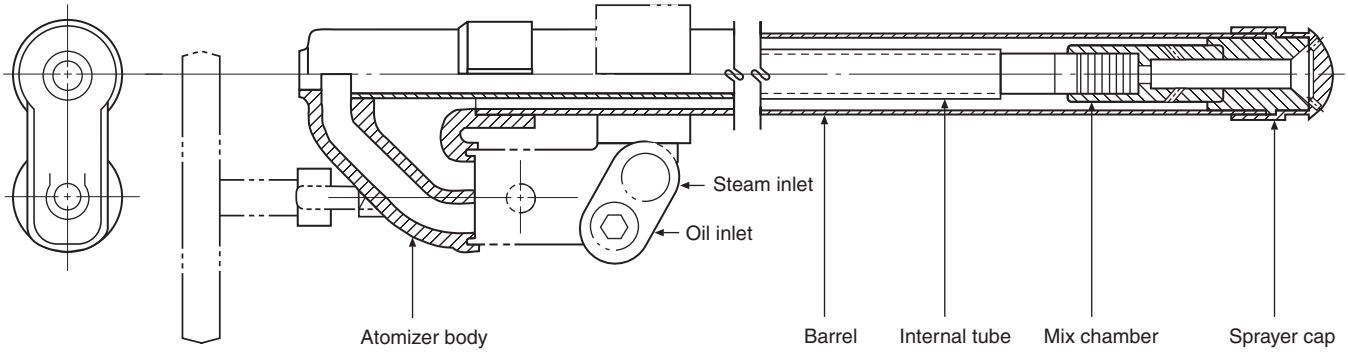


FIGURE 10.6.4 Steam-Fuel Atomizer Assembly (Source: The Babcock & Wilcox Co.)

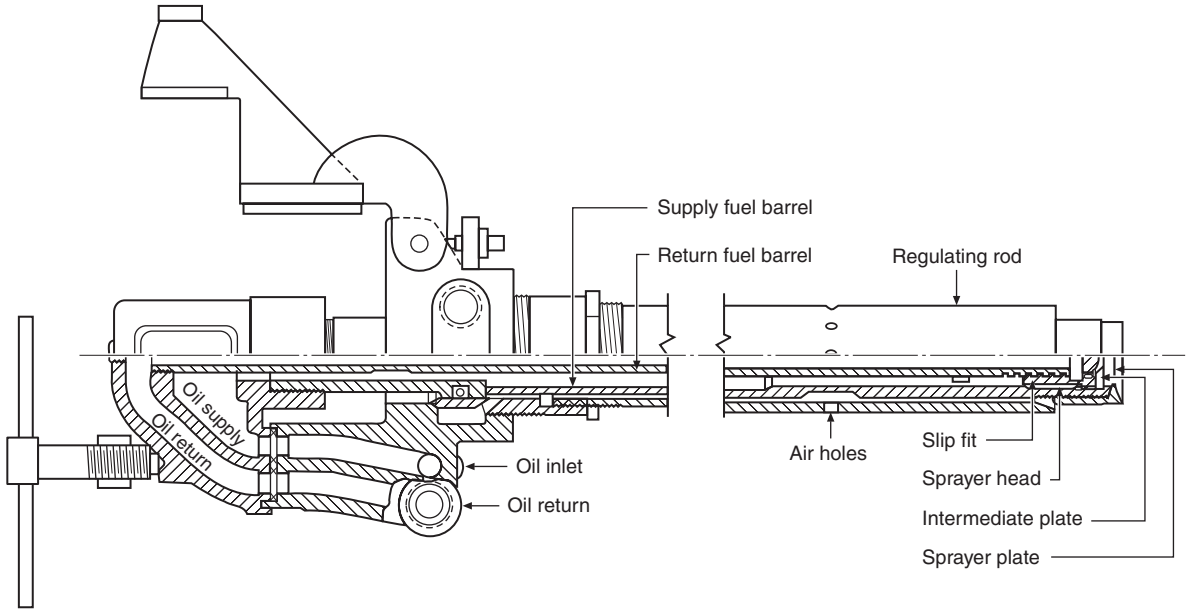


FIGURE 10.6.5 Mechanical Return-Flow Oil Atomizer Assembly (Source: The Babcock & Wilcox Co.)

Mechanical atomizers are also available in sizes up to 200 million Btu/hr (58,620 kW) input. The acceptable operating range may be as much as 10:1 or as little as 3:1, depending on the maximum oil pressure used, the furnace configuration, air temperature, and burner throat velocity. Return-flow atomizers are ideally suited for standard grades of fuel oil where it is desired to meet load variations without changing sprayer plates or bringing burners in and out of service.

Natural Gas Burners

Natural gas is the ideal boiler fuel, requiring no preparation for combustion and minimal postcombustion pollution control. Basically, gas burners mix fuel and air in either of two ways: (1) premix or (2) external mix. With the advent of stringent NO_x emission regulations, changes were required in the design and operation of large gas burners.

In a premix burner, gas and a portion of the air are mixed before the mix is introduced to the burner nozzle. A common method involves mixing gas and air in the suction side of a mechanical blower. Another method uses the venturi effect, wherein a gas jet creates a negative pressure at the air input orifice and draws air into the mixer. This design is familiar on kitchen stoves and home heating furnaces. The third premix method also uses the venturi effect but, in this case, an air jet draws fuel gas into the mixer, thus requiring a gas regulator to reduce fuel gas pressure to atmospheric before gas and air are mixed.

In external-mix gas burners, the fuel and air are mixed external to the nozzle. When external-mix gas burners have individual elements or spuds (Figure 10.6.6), part or all of the gas discharges in front of the impeller. This provides a local fuel-rich zone and thus serves as an ignition stabilizer at high gas flow rates. The burner contains several spuds, each a gas pipe with a number of precisely drilled holes near the tip, to discharge gas for ignition at the burner throat. Depending on

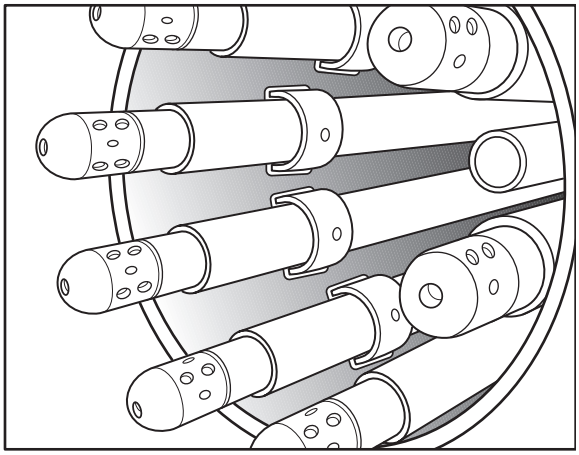


FIGURE 10.6.6 External-Mix Gas Burner with Individual Spuds

the manufacturer, each spud might be fitted with a flame holder or might share a common flame stabilizer to provide a local fuel-rich zone to stabilize ignition at low inputs. Gas ports are relatively large in order to minimize plugging. The spuds shown in Figure 10.6.6 can be withdrawn for service while the burner is in operation. Gas spuds are located so that oil will not impinge on them in multifuel burners.

With the proper selection of control equipment, a multifuel-fired furnace with a multiple spud-type burner is capable of changing from one fuel to another without a drop in steam pressure or output and is also capable of simultaneously firing natural gas and oil in the same burner. The control system's primary function is to achieve complete and efficient combustion by balancing fuel in the proper relationship with burner airflow. This type of element is designed for use with natural gas or other gaseous fuels containing at least 70 percent methane, 70 percent propane, or 25 percent hydrogen by volume. The element is also designed for a maximum input of 200 million Btu/hr (58,600 kw) per burner.

To provide safe operation, ignition of a gas burner should remain close to the burner impeller(s) throughout the full range of allowable gas pressures, at both normal airflows and abnormally high airflows. Ideally, it should be possible, at the minimum load, to pass full-load airflow through the burner without loss of ignition. It should also be possible to pass as much as 25 percent in excess of theoretical air at full load without loss of ignition. With this range of airflow, it is not likely that ignition can be lost, even momentarily, during some upset in airflow.

PIPING AND CONTROL DEVICES

Fuels must be essentially free of contamination and be under control to ensure combustion safety. The design and reliability of fuel-handling systems are, therefore, important factors in minimizing the risk of fire or explosion.

Oil-Fired Systems

The fuel-oil supply system should be designed to ensure a continuous, steady flow of fuel that will meet the requirements of the boiler over the entire load range. This includes coordinating the main fuel control valve, burner safety shutoff valve, and associated piping volume to prevent fuel pressure transients that might exceed stable flame burner limits as a result of placing burners in or taking them out of service (Figure 10.6.7).

Fill and recirculation lines should be connected to storage tanks so that they always discharge below the liquid level. This will avoid excess evaporation and the generation of static electrical charges in free-falling fuel.

Strainers, filters, traps, and sumps are some of the devices that are used to remove contaminants from oil systems. Examples of contaminants are salt, sludge, water, and a variety of abrasive particles such as sand and corrosion products. It is good practice to route piping and locate valves to minimize their exposure to (1) temperature extremes that might alter the oil's viscosity or pressure and (2) physical damage in the event of an explosion.

Burner shutoff valves should be located as close to the burner as possible to minimize the volume of oil that might remain in the burner line downstream of the valve. This will minimize the oil that could drain into the furnace following an emergency trip or burner shutdown. Positive means must be provided to prevent oil from leaking into an idle burner.

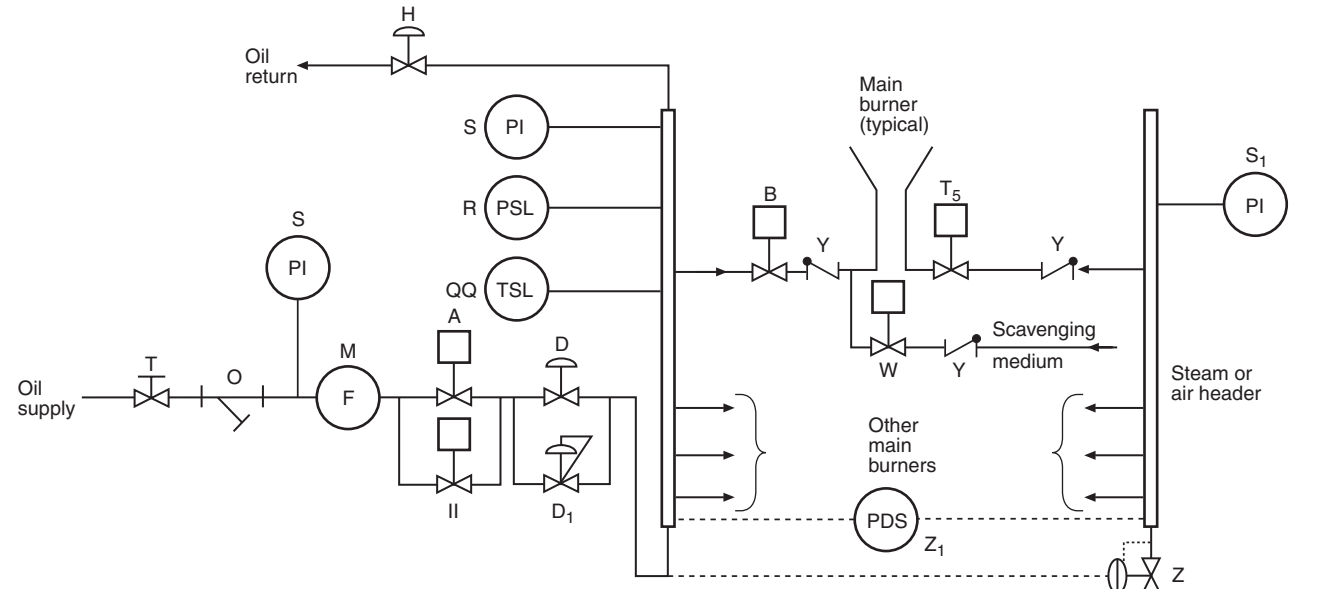
Fuel oil must be delivered to the burners at a specific temperature and pressure for proper atomization. Provisions must be made for adequately recirculating the oil to control its viscosity at the burners for initial lightoff and subsequent operation. Systems must also prevent excessively hot oil from entering fuel-oil pumps; otherwise, the pumps might vapor-bind and interrupt the supply of oil to the burners.

Positive means are needed to prevent fuel oil from entering the burner header system through the recirculating valves, particularly from the fuel supply system of another boiler. Check valves have been undependable for this function in heavy oil service. Provisions should also be made for clearing (scavenging) the passages of an atomizer into the furnace when a burner is taken out of service.

Gas-Fired Systems

Natural gas fuel-supply systems must be able to provide a continuous, steady flow of fuel over the entire load range. This includes coordination of main fuel control valve, burner safety valves, and the associated piping volume to avoid large gas pressure transients. Transients could cause burner limits to be exceeded and result in an unstable flame condition as burners are placed in or taken out of service. A well-designed system will also be capable of stable gas supply, despite anticipated furnace pressure pulsations.

The fuel supply system components located outside the boiler room need to be arranged to prevent excessive fuel gas pressure in the burner supply system, even in the event of failure of the main supply constant gas pressure regulator(s) (Figure 10.6.8). Usually, this is accomplished by providing a full relieving capacity pressure relief valve vented to a safe location. Where full relieving capacity is not installed, a high-supply gas pressure trip should be installed.



A	Main safety shutoff valve	R	Burner header low fuel pressure switch
B	Individual burner safety shutoff valve	S	Fuel pressure gauge
D	Main fuel control valve	S_1	Atomizing medium-pressure gauge
D_1	Main fuel bypass control valve (optional)	T	Manual shutoff valve
H	Recirculating valve (optional for unheated oil)	T_5	Atomizing medium individual burner shutoff valve, automatic
II	Circulating valve	W	Scavenging valve
M	Flow meter	Y	Check valve
O	Cleaner or strainer	Z	Differential pressure control valve
QQ	Low-temperature or high-viscosity alarm switch	Z_1	Differential pressure alarm and trip switch

FIGURE 10.6.7 Typical Main Oil Burner—Steam or Air Atomizing

A	Main safety shutoff valve	O	Cleaner or strainer
B	Individual burner safety shutoff valve	P	Restricting orifice
C_1	Burner header atmospheric vent valve	Q	Burner header high fuel pressure switch
C_2	Individual burner atmospheric vent valve	Q_2	High fuel supply pressure switch
D	Main fuel control valve	R	Burner header low fuel pressure switch
D_1	Main fuel bypass control valve (optional)	R_1	Burner header low fuel pressure switch (alternate location)
I	Charging valve (optional) (must be self-closing)	R_2	Low fuel supply pressure switch
J	Constant fuel pressure regulator	S	Fuel pressure gauge
K	Pressure relief valve	T	Manual shutoff valve
M	Flow meter		

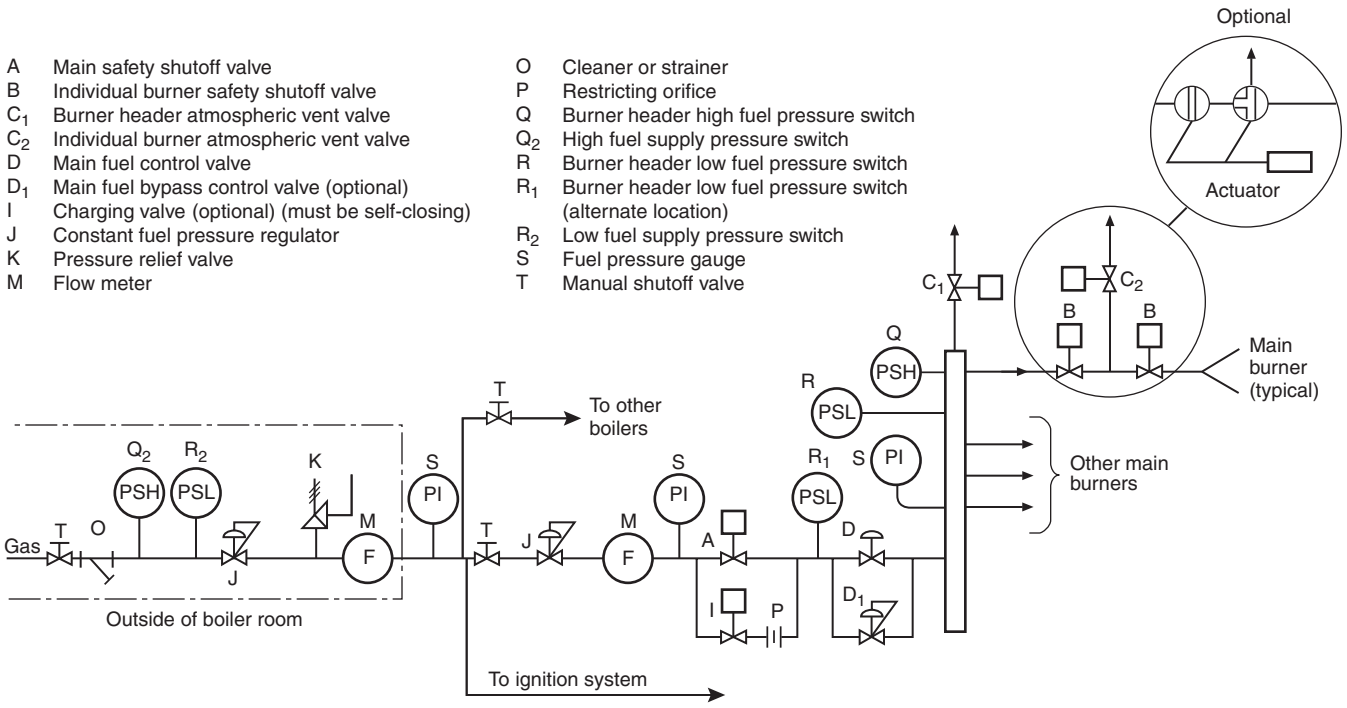


FIGURE 10.6.8 Typical Fuel Supply System for Natural Gas–Fired Multiple-Burner Boiler Furnace

The gas-fired system should have the following:

1. Positive means to prevent gas from leaking into an idle furnace
2. Piping vents located upstream of the last shutoff valve in any line to a main burner or igniter
3. Provision for leak tests and repair of the piping system
4. Permanent provisions to include means for making easy and accurate tightness tests of the main gas supply safety shutoff valves as well as the individual burner gas safety shutoff valves
5. Vents located so that there is no possibility of vented gas entering the boiler room or adjacent buildings
6. Vents placed high enough that escaping gas will not be a fire hazard
7. Header vent lines that run independently
8. Igniter vent subsystem that runs independently of the burner vent subsystem so there is no chance of backflow into the burner
9. No cross-connection between venting systems of different boilers

PULVERIZED COAL SYSTEMS

One of the variables in the design of a pulverized coal supply system is the location of the primary air fan relative to the air heater and pulverizer. The combination shown in Figure 10.6.9 is known as a "cold" system and includes a large primary air fan supplying drying air via the air heater to a group of pulverizers. The other basic system provides hot air to individual primary air fans for each pulverizer located downstream of the air heaters.

Pulverized-coal-fired systems capable of burning a wide range of coal fuels have several necessary functions. Raw stored coal must be transferred to the pulverizer in measured and controlled quantities. Hot air mixed with tempering cool air is blown into the pulverizer to dry the coal (see Figure 10.6.9). The mix temperature is controlled by the temperature of the air-coal stream at the outlet of the pulverizer, based on the type of coal being pulverized. A temperature that is too low, as when particularly wet coal is being fed, will impair pulverization. A temperature that is too high can cause coking and risk a fire in the pulverizer and burner piping.

Fuel changes in existing plants, brought about by economic or environmental benefits, must be carefully weighed by the user. Changes in coal qualities, such as heat content, hardness, moisture, and so on, may challenge the ability of existing pulverizer systems to dry and deliver an adequate supply of pulverized fuel to the boiler. The adequacy of pulverizer fuel systems to accommodate these fuel changes should be investigated when contemplating changes in fuel source.

The advent of NO_x emission regulations has increased the likelihood of unburned carbon in the fly ash. It is therefore even

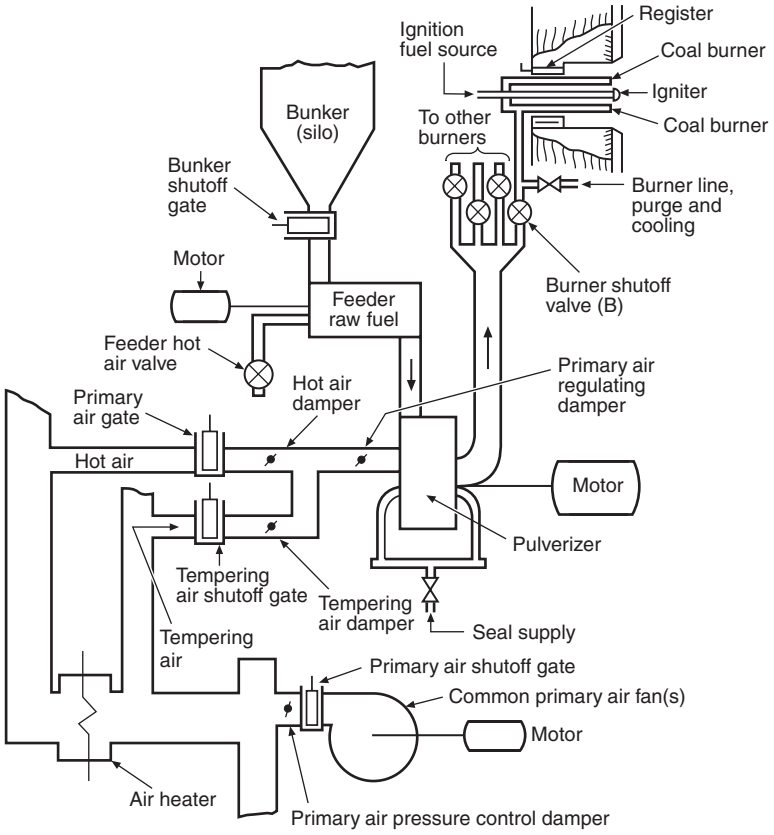


FIGURE 10.6.9 Direct-Firing System for Pulverized Coal

more important than in the past that coal be pulverized to the specified fineness. Testing and pulverizer maintenance will ensure proper sizing. Where needed, improved classifiers can be retrofit on existing pulverizers. On existing systems where additional fineness is desired, rotating, or dynamic, classifiers have been successfully retrofit on existing pulverizers. They are also an option on newly installed systems.

The primary air is designed to transport the fine coal from each pulverizer to its several associated burners in controlled amounts, well distributed among the burners. It is important to establish that the transport velocity in each pulverized coal pipe is equal. Periodic retesting is also required.

At the burner, the coal-air mixture is combined with a measured amount of secondary air to serve the following several purposes:

1. The fuel must be volatilized and completely consumed in a continuous process starting with an initial zone of stable ignition at the burner and continuing through the combustion process with minimum unburned combustibles in the stack gas and ash hoppers.
2. The total air to each burner and to the burner zone must contain the lowest level of excess air possible to minimize stack losses and NO_x while achieving a high level of combustion efficiency.
3. The air should surround the combustion process at each burner to minimize reducing atmospheres at tube surfaces. Some boilers are equipped with an "air boundary" to protect tubing near the burners.
4. Stable ignition is necessary at each burner to ensure continuous combustion. A means of flame detection is also needed at each burner. The ability to distinguish main and igniter flame separately is important, especially in starting and stopping burner operation.

Products of combustion are transported from the furnace through platen and pendant superheater and reheater surfaces, through the convection pass including the economizer surface, and through the air heater to accomplish the necessary heat transfer before being transported to the air pollution control system(s) by the induced draft (ID) fan. The boiler is designed, based on the specified coal, to minimize slag and other solid deposits on the heat transfer surfaces. As is the case with pulverized fuel systems, drastic changes in coal quality must be investigated with regard to their effects on combustion and slag formation in the furnace and downstream surfaces. Steam temperature and other unit performance parameters may change as a result and changes may be necessary to effectively use the new fuels.

The largest modern boilers are capable of supplying steam to 1300 MW reheat turbines. This large capacity coupled with poorer fuel quality created the need for large pulverizers capable of processing 75 tons (68.04 metric tons) or more of coal per hour. The pulverizer shown in Figure 10.6.10 is a roll-and-race type that utilizes three large-diameter rolls spaced equally around the mill. The rolls are mounted on axles; in turn, the roll assemblies are attached by a pivoted connection to a stationary overhead frame that keeps them in their roll path while permitting limited radial freedom of movement. Grinding pressure is supplied by springs that apply force to the axles of the rolls. The grinding ring rotates at low speed and is shaped to form a race in which the rolls run.

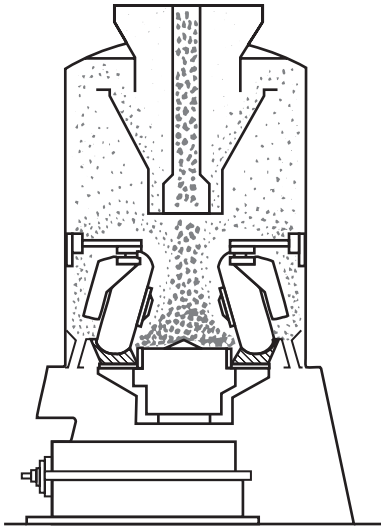


FIGURE 10.6.10 Large Coal Pulverizer

Raw coal is fed into the mill either inside or outside of the grinding race. It immediately mixes with the partially dried and ground coal that is circulated within the grinding zone by the airflow through the pulverizer. Coal fines are carried by the air to the classifier. The finest fraction of the coal, along with the air, leaves the pulverizer through the outlet pipes. Oversize coal is returned to the grinding zone through a seal at the bottom of the classifier.

FLUIDIZED BED COMBUSTION

The world's first fluidized bed combustion (FBC) boiler, a 0.5 MW(e) pilot unit, was placed in service in 1967. After being commercialized, hundreds of FBC units of moderate size, 10 to 200 MW(e), have been built around the world to exploit the availability of low-cost waste fuels. Several are over 300 MW (e). In 2009 a 460 MW(e) FBC will be placed in commercial service in Poland. There are many diverse FBC designs for the smaller units but the larger units use what is termed "circulating fluidized bed" technology.

Characteristics of FBC

The two central characteristics of the fluidized bed boiler, when compared to stokers and pulverized coal, are (1) the bed and (2) the bed temperature. *Bed* refers to the pile of granular solid particles in which the fuel is burned. Air flowing up from beneath and through the bed causes the individual granules to separate and move about. Fuel added to the bed is ignited by the hot bed particles. In turn, the burning fuel transfers the heat of combustion to the inert bed particles.

The bed, cooled by a variety of techniques, moderates the combustion and keeps the bed temperature in the range of 1500°F

(815°C) to 1650°F (899°C) (Figure 10.6.11), which, in turn, leads to reduced slagging and fouling, lower emissions of NO_x, and an environment where added limestone (primarily $CaCO_3$) can react with sulfur. The moderate combustion temperature and turbulence also provide an ideal environment for the combustion of a wide variety of low-grade fuels, for example, anthracite culm to wood wastes, as well as high-grade coal.

To control the bed temperature at about 1500°F (815°C), roughly 50 percent of the heat of combustion must be removed as rapidly as it is released. The bed solids play this role by giving up heat to boiler, superheater, and reheater surfaces, both inside and outside the furnace boundaries. In bubbling fluidized beds, water tubes are often placed in the combustion bed itself. Particles also recycle within the furnace, giving up heat to the water walls. In a circulating fluidized bed (CFB), heat is also transferred from the bed particles to the water walls and, in some designs, to a bubbling bed external to the furnace (see Figure 10.6.11).

CFB systems currently have the dominant market share. Although combustion and other system hazards are similar for bubbling and circulating FBCs, the remainder of this discussion describes CFBs.

To control NO_x, air is admitted both below and above the dense bed. Although the split of fluidizing (primary) and secondary air varies between designs, the values are roughly 50/50. Thus, the dense bed operates with an air deficiency; that is, it is fuel rich, and more than half the combustion occurs above the dense bed. This mode of operation is analogous to that of the low-NO_x burner shown in Figure 10.6.1. The temperature of the gas-solids stream leaving the furnace is roughly at the same temperature as the dense bed. Further, 99+ percent of the solids are removed by the large cyclone for recycling to the furnace.

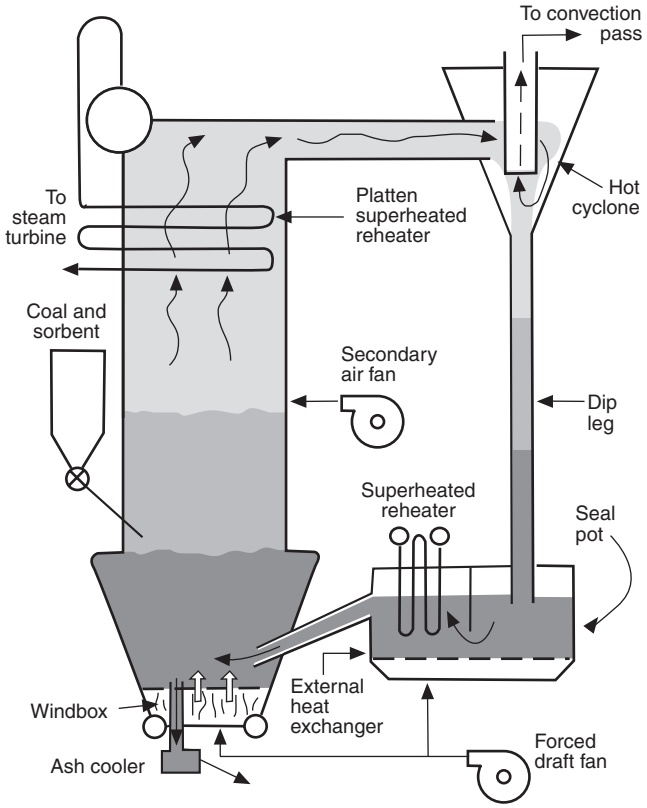


FIGURE 10.6.11 Circulating Fluidized Bed Boiler

SPECIAL FBC HAZARDS

Most potential FBC hazards are similar to those of suspension-fired boilers. In particular, storage of the fuels in piles and bins always poses the risk of spontaneous combustion. Owners of FBC plants should become familiar with the practices of industries that produce the waste fuels the FBC will be burning. There are, however, some hazards unique to FBCs. For this new technology, it is important that operators be trained to deal with relatively rare but serious possibilities. The special hazards are as follows:

1. *Hot solids spills.* A large FBC contains many tons of very hot aerated solids. Bottom ash-removal pipes have failed in several plants, leading to large spills. Plant designers should avoid placing critical components and controls in the vicinity of a potential spill point. Several maintenance workers have died when hot solids in the dip leg and seal pot of one unit flowed into the adjacent empty furnace many hours after the CFB was shut down.

2. *Lime burns.* Removal of most of the fuel's sulfur requires limestone feed rates that exceed the stoichiometric ratio of calcium to sulfur (40 lb/32 lb [18 kg/15 kg] C 1:1). Ratios of 2:1 or more are not unusual, which means that the fly ash and bottom ash are rich in CaO, that is, quicklime. High temperature can be generated when quicklime is mixed with water deliberately, as in an ash conditioner, or inadvertently, as when in-furnace maintenance is required. Removal of the bed before furnace entrance is now the common practice.

3. *Steam generation after trip.* The mass of hot particles contains sufficient sensible heat to continue steam production at near full capacity for several minutes after the fuel source is tripped if the fluidizing airflow is continued. Thus, a loss of feedwater should lead to a fan trip as well as a fuel trip.

4. *Operation at very high fuel-air ratios.* Because of the mass of hot solids, an FBC's inherent combustion stability permits operation with as much as four times the normal fuel-to-air ratio. In several such cases, the accumulation of fuel in the bed led to a rapid increase in bed temperature when some operational change occurred. It might also lead to a furnace explosion.

Although FBCs do have some special hazards that need to be considered by designers and operators, the safety record over FBCs' commercial history has been quite good. To start an FBC, it is necessary to heat the bed material to above the ignition point of the main fuel by use of oil or gas burners. Just as in any boiler, FBCs are most vulnerable to explosion during start-up. (See hazards discussed for oil and gas firing.)

BOILER-FURNACE HAZARDS

Explosion and fire are the most serious potential hazards in boiler-furnaces and their associated pipes, ducts, fans, and fuel bunkers. Explosions occur when an ignition source contacts a combustible mixture of fuel and air. When a combustible mixture has accumulated in a large, confined space of the equipment, a very damaging explosion can occur. Such accumulations can result from an equipment malfunction or an operator error associated with an inadequate or improper purge or incorrect operation of burner equipment. Because even a minute ignition source might initiate a substantial explosion and ignition sources abound in a furnace, for example, static electricity, hot slag, or glowing fly ash in a hopper, safe operation must emphasize avoiding creation of a large combustible mixture.

A temporary loss of flame caused by an interruption in fuel, air, or ignition energy can allow a combustible fuel–air mixture to accumulate before ignition is reestablished. Any momentary fuel-rich operation might also lead to a combustible accumulation. For example, leaking fuel could vaporize and collect in an idle furnace only to ignite explosively when the first burner is lighted. In multiburner units, the undetected loss of flame at a burner could allow an explosive mixture to accumulate somewhere in the volume of the furnace, only to be ignited by other burners. The classic example of operator error is failure to purge the furnace of combustible mixtures between repeatedly unsuccessful attempts to lightoff the burner. Another is to ignore the implications of small explosions, that is, puffs that do no damage but could be symptoms of a serious defect.

Modern burner management and flame detection systems are designed to assure proper sequencing and safe operation of the burner and fuel supply system. Maintaining that equipment in a fully functional mode will assist the operator in assuring safe operation and in taking appropriate action if an upset or abnormal condition is detected. Bypassing of these systems or its components must be carefully considered as it places a greater burden on operating personnel, who may not have the ability to monitor all the components of a modern boiler system and its many subsystems.

Hazards of Oil Firing

Fuel oil is a complex blend of hydrocarbons having a wide variety of molecular weights and boiling, freezing, and flashpoints. At a sufficiently high temperature fuel oil will partially volatilize, thereby creating new and unpredictable liquids, gases, and solids. Boilers have been fired with unrefined crude oil containing very volatile light ends, such as propane, butane, and pentane. However, with the rise of oil prices this is no longer common. Refined boiler fuels have had the light ends removed to produce gasoline and other valuable products and are thus less volatile. A new fuel form termed *Orimulsion*™ is a blend of bitumen (e.g., tar) and water. Any water-containing fuels can pose a hazard when separated water, rather than fuel, is pumped through the burner.

No. 1 and No. 2 fuel oil, and fuels commonly known as kerosenes, range oil, furnace oil, and diesel oil, are called *distillates,* whereas No. 5 and No. 6 fuel oil are referred to as *residuals.* Most large boilers designed for oil are designed for Nos. 5 or 6 oil. Distillates are used in boilers designed for natural gas as the primary fuel. Very volatile oils (sometimes used in very cold regions), crude oil, and many by-product fuels require that electrical motors, switches, and other components be designed to explosionproof standards.

For heavy oils (Nos. 4, 5, and 6), preheating is necessary to reduce the viscosity of the oil flowing to the burners and ensure proper atomization. This preheating is an important part of an integrated safety system designed to avoid flame interruptions. Also, if sludge is allowed to accumulate in storage tanks, it could plug strainers or burner tips. Water normally accumulates below the stored oil, which is less dense; it is therefore important to design tank suction lines so that they draw from above any potential water level.

Oils from different sources, even with similar specifications, can sometimes cause problems when stored in the same tank due to chemical reactions. When oil shipments having widely different viscosities or gravities are stored in the same tank, a significant change in fuel input rate (without a corresponding change in airflow) can occur and impair complete combustion. In any event, fuel oils should be tested for their conformance to specifications soon after receipt.

Where the same burner is used for heavy and light oil (depending on price or availability, for example), special care must be taken that the correct valve settings and interlocks are selected. When very light oils with low electrical conductivity are used, static electricity can build up and provide an uncontrolled ignition source. Light or heavy, oil leaks pose a potential fire hazard. Assembly and disassembly of pipes and equipment should be done with care to avoid leaks. Leaks that do occur should be promptly stopped and cleaned up.

Combustion efficiency of mechanical atomizing burners can be affected by a wear-induced change in orifice size. Improper cleaning can also damage burner tips. Individual burners operating fuel rich or with very low excess air can cause combustibles to accumulate in the furnace. Periodic flow testing may be necessary. Unsafe operating conditions can also be created by the failure of personnel to reinstall a tip, gaskets, or sprayer plate during burner reassembly.

Major oil flow transients can be caused by rapid operation of an oil supply valve, individual burner shutoff valve, or the regulating valve in the return oil line from the burner header. Uncontrolled changes in the fuel input to the furnace can produce hazardous conditions.

Oil flow to individual oil guns can also be adversely affected by such conditions as variations in burner elevation, distance from the regulating valve, and pipe size, all of which can be hazardous on low-pressure burners.

Hazards of Gas Firing

Hazards in gas-fired systems start with gas leaks and the development of fuel-rich mixtures within the boiler or ductwork. Potentially hazardous accumulations can also develop in other building areas, particularly where gas piping is routed through spaces that are not adequately ventilated. Unlike oil, gas leaks are not visible and plant noise can prevent the leak from being

heard. Odorants might or might not be present at sufficient concentration to be detected via the nose.

Within the furnace it is possible for air-fuel ratios to be altered severely without producing any visible evidence at the burners, furnace, or stack, thus allowing a combustible mixture to accumulate over time. Combustion control systems, when responding to falling steam flow or pressure due to an increase in demand for fuel, are potentially dangerous unless protected or interlocked to prevent the creation of a fuel-rich mixture and a loss of ignition.

Whereas gas liquids are normally removed in or near the gas fields, natural gas might be *wet*. A wet gas implies the presence of liquid fuel components, which, if carried into the burners, can result in momentary increases in fuel input and/or a flameout, followed by possible reignition and explosion. For this reason, systems using wet gas require special attention.

Gases supplied from one or more sources can introduce unacceptable hazards if they have significant differences in volumetric heating value due to the ratios of propane, butane, and so forth, to methane. With such variable supplies, it is necessary to provide instruments that are responsive to variations in heat value (e.g., specific gravity or heating value meters), and appropriate alarm and combustion compensation devices. Similar problems will be encountered if proper recharging of the gasline does not follow line maintenance.

Discharges from relief valves will produce a particular hazard unless vent lines are carefully designed with all potential weather conditions considered to avoid reentry of gas into the boiler room. Purging preceding maintenance can also lead to a hazard.

Burner pulsation or combustion-driven oscillations remain a mystery associated with gas firing and, to a lesser degree, with oil firing. When one or more burners on a large unit begin to pulsate, there is a feedback mechanism that leads to variations in furnace pressure, fuel input, and heat release. The action can become violent as each pulse adds energy to the next oscillation. At times, the whole boiler can shake. Adjusting only one burner might start or stop pulsation. At times, only minor burner adjustments will eliminate pulsation. In other instances, it might be necessary to make physical alterations to the burners. Alterations might include modifying the gas ports, impinging gas streams on one another, or installing a device that changes the fuel-air mixing characteristics.

Hazards of Pulverized Coal Firing

When coal is crushed, fresh reactive surfaces become available for oxidation. The coal in the storage bunkers ahead of any pulverizer is subject to self-heating and, in cases where the heat is not dissipated, spontaneous combustion. The three conditions that can lead from moderate self-heating to uncontrolled combustion are (1) excessive fines, (2) a source of air, and (3) storage for an extended period. Once a mass of coal is burning, quenching with water will lead to a reaction between water and hot carbon, producing combustible CO and H_2. Dealing with a bunker fire by running coal into the boiler via feeders, pulverizers, and burners is discouraged, as it can lead to pulverizer fires or explosion. In addition, the burning material is likely to damage fuel system components, such as feeders and internal pulverizer bearings. Self-heating can be detected by monitoring the CO content of the air in the empty space above the coal. Thermocouples can also be useful, but they can easily miss a hot spot since crushed coal is actually a good thermal insulator.

Very wide variations in the size of raw coal, moisture, or clay content can cause erratic feeding of the coal to the pulverizer and, often, complete stoppages. As-received coal might contain foreign matter, such as scrap iron, blasting wire, railroad ballast, wood, rags, excelsior, and so on, which could interrupt the coal feed, damage or jam equipment, or cause a spark within a pulverizer.

A large boiler may burn 100 lb (45.4 kg) of pulverized coal per second, but as little as 0.05 oz per cu ft (0.05 kg/m^3) of air forms an explosive mixture; therefore, as little as 3 lb per 1000 cu ft (1.0 kg per 20 m^3) can be hazardous. Thus, an explosive mixture will develop very quickly if a momentary flameout occurs. A special hazard is methane gas released from freshly crushed or pulverized coal, which can accumulate in enclosed spaces, such as bunkers, and within pulverizers and burner piping.

Pulverized coal, entrained in the primary air stream, is conveyed through pipes from the pulverizer to the burners. To prevent flashback or settling of coal particles in the burner pipes and preignition, it is necessary to establish a minimum air coal velocity for the pulverizer, generally in the range of 60 to 870 ft/sec, depending on volatility, temperature, and the existence of long horizontal runs of coal piping. Pulverizer condition may result in coarser particles, which may cause coal layout at higher velocities. Provisions should be made for cooling and emptying pulverizers and/or burner lines when the burners they supply are shut down to avoid spontaneous combustion and explosion in the pulverizer or burner lines. In addition, burners that have been out of service may have components that are at elevated metal temperatures from the furnace radiant heating. To prevent coking of the coal on initial introduction to the hot burner, performing a purge of cool primary air prior to coal flow initiation is also recommended.

Pulverizer fires and explosions are serious hazards. A sudden, large increase in temperature of the mixture leaving the pulverizer or in the temperature of the casing indicates that a pulverizer fire has started. Fires are caused by (1) feeding burning fuel from the bunkers or (2) spontaneous combustion of fuel in the pulverizer or piping. Although pulverizers are now designed to withstand a substantial overpressure, a fire is still serious and should be dealt with promptly. In a major overpressure incident, substantial damage and rapid escape of fire can be experienced in connecting components such as air ducting. Personnel in the area can be subject to severe injury. When a fire is detected in a pulverizer system, in addition to the steps listed later, a visible and audible warning system should be activated as soon as possible and all personnel should steer clear of the immediate hazard area until the hazard is abated. Essential personnel should exercise extreme caution in addressing the situation and performing their function once the situation appears under control.

The general steps for extinguishing the fire are as follows:

1. Remove the pulverizer from service without emptying to avoid creating a sudden air-rich (explosive) mixture condition.

2. Prevent air infiltration by closing all burner line valves and inlet air dampers and sealing the air valve.
3. Admit steam or inert gas into the pulverizer through the connection provided to
   (a) Smother the fire.
   (b) Maintain an inert atmosphere until the coal has been removed and the housing has cooled.
4. Dump the coal stored in the pulverizer through the pyrite gates.
5. Rotate the pulverizer without operating the primary air fan to complete the swirling and cleaning procedure.

Many manufacturers recommend the introduction of an inerting medium during routine start-up and shutdown sequencing of the pulverizer. Various pulverizer manufacturers have different requirements, and some of these precautions are guided by coal qualities.

Hazards of Low-NO_x Firing

Some steps, such as the following, taken to reduce emissions of existing units could lead to furnace safety problems:

1. NO_x reduction methods might reduce the margins of safety formerly available to prevent accumulation of unburned fuel during upsets.
2. Flue gas recirculation, a common method of reducing NO_x production, requires that operators be aware of the oxygen content of the combustion "air" and/or have knowledge of the distribution of air and of recycled flue gas.
3. Unburned combustibles often increase with low-NO_x firing. This means that horizontal ducts and hoppers can contain smoldering, carbon-rich ash—a hidden ignition source. Reliable CO analyzers are available for detection of combustible gases that are indicative of fuel-rich or imbalanced air-fuel mixing conditions in the furnace. Properly placed systems will alert an operator to conditions that may require action to correct.

Hazards of Fluidized Bed Firing

Attempting to start main-fuel flow before the bed is at the proven temperature for that particular fuel can lead to a furnace explosion. Interlocks are to be provided to prevent such maloperation and must be reset, after testing, when a very different coal is to be fired. Hot restarts without a purge, for example, following an emergency trip, are permitted only if the temperature of the fluidized bed is high enough to ensure proper ignition of fuel.

Although flame detectors are useful for proving a pulverized coal flame, they are not useful in FBC. Instead, the bed temperature is proved safe by a number of in-bed thermocouples. The thermocouple readings are only reliable indicators of an average "safe" bed temperature when the bed is actively fluidized and thus thoroughly mixed.

OPEN REGISTER LIGHTOFF AND CONTINUOUS PURGE PROCEDURE

Furnace explosions in large water-tube boilers in the 1960s led to the codification of the open-register lightoff and continuous purge procedure for all fuels. This procedure maintains airflows at or above the prescribed minimum of 25 percent of full-load *mass* rate airflow during all operations of the boiler. Until the 1995 edition of NFPA 8502, *Standard for the Prevention of Furnace Explosions/Implosions in Multiple Burner Boilers*—now NFPA 85, *Boiler and Combustion Systems Hazards Code*—the *volumetric* airflow rate was specified in recognition that mass flow rate must be increased at low (during start-up and shutdown) air temperature to maintain air and gas velocities. In any event, the continuous purge procedure has been shown to prevent the inadvertent accumulation of a hazardous air-fuel combustible mixture in the furnace or setting.

The continuous purge procedure is based on the concept that three basic conditions will significantly improve the margin of safety, particularly during start-up. These conditions are as follows:

1. Minimum number of required equipment manipulations, thus reducing the likelihood of operator errors or equipment malfunctions
2. Means for establishing the desired fuel-rich condition at individual burners during lightoff
3. A very air-rich furnace atmosphere during lightoff and warm-up, created by maintaining total furnace airflow at the same rate as that required for furnace purge

In its simplest form, the basic procedure that satisfies these three operating objectives is as follows:

- Place all or most of the burner air registers in a predetermined open position.
- Purge the furnace and boiler settings with the burner air registers in that same predetermined position. The total airflow for purge must not be less than 25 percent or more than 40 percent of full-load mass airflow.
- Light the first burner or group of burners without any change in airflow setting or in burner air register position.

At initial start-up a boiler should be tested to determine whether any modifications are required to obtain satisfactory burner ignition or to satisfy other design limitations during lightoff and warm-up. For example, some boilers will be purged with the registers in the normal operating position. In this event, it might be necessary to momentarily close the registers of the burner being lighted to establish ignition. However, unnecessary modifications in basic procedure are to be avoided, thereby satisfying to the greatest degree possible the three basic objectives given previously, particularly that of minimizing equipment manipulations.

Suggestions have been made to modify the continuous purge requirement to allow improved NO_x control and increased efficiency at low loads. No changes have been approved by the NFPA committee, since tests and data do not exist that prove reducing airflow below 25 percent (or purge) can be done safely.

FIRE AND EXPLOSION PROTECTION

Prevention is clearly the key to fire and explosion protection. Good facility design, selection of reliable equipment, system monitoring, and malfunction alarm instrumentation are key

elements in preventing fires and explosions in boiler furnace systems. With the cost of a major boiler explosion ranging to $100 million, replacement power costs included, operator training and maintenance critical to prevention are obviously worth the cost.

The entire system—boiler, furnace, fuel supply, air supply, vents, piping, and ducts—is designed to specific parameters and for specific operating limits. At no time should these limits be exceeded without a detailed engineering analysis and the modifications indicated. This is particularly relevant when new emission standards are imposed on an operational plant.

SPECIAL CONSIDERATIONS FOR SMALL BOILERS

Large boilers will be constructed as separate structures, but small boilers (under 12,500,000 Btu/hr [3,663 kW]) are often installed in existing buildings. Good facility design requires the boiler be installed in a separate room or structure, preferably of noncombustible construction. Boilers should be set on concrete floors or platforms that extend beyond the equipment for a distance of at least 4 ft (1.2 m) in each direction. If they must be set on combustible floors, there should be sufficient air circulation beneath the furnace to keep the temperature of the combustible floor below 160°F (71°C). (See Section 10, Chapter 2, "Heating Systems and Appliances," for an explanation of the temperature limits for protection of combustible surfaces.) This protection can be provided, for example, by laying 4 in. (102 mm) thick hollow masonry block covered with sheet metal on the floor.

If possible, metal chimneys or smokestacks should not pass through combustible floors, ceilings, or walls. If such chimneys must pass through combustible roofs, sufficient clearance and/or insulation should be provided to keep the temperature of the combustible materials below 160°F (71°C). Generally, minimum clearance is considered to be 18 in. (457 mm).

INTERLOCKS, ALARMS, AND OPERATOR COMPETENCE

A system of interlocks should be provided to prevent improper sequencing by operating personnel and to shut down operations if certain critical malfunctions occur. Both audible and visual alarms serve to warn operators to take certain corrective steps; others may indicate what automatic functions have occurred to reduce a hazard. New boilers should not be fired until adequate safeguards have been installed and tested. Bypassing safety interlocks with electrical jumpers, for example, should *never* be permitted by the contractor or the owner.

Safe operation cannot be ensured solely by equipment design and adherence to the manufacturer's operating instructions. Competent operators who understand the processes involved are also needed. Technical competence should be maintained by a program of periodic retraining so that increasing familiarity with the system does not tempt operating personnel to take shortcuts in operating procedures or to bypass safety devices. Where operator error has been responsible for a serious accident, inadequate training has often been found to be the root cause.

A program of preventive maintenance is needed for the equipment and control devices. Poor preventive maintenance will lead to the need for costly corrective maintenance. A comprehensive equipment history that records, for each date, the conditions found, work done, and the changes made will provide the records needed to plan the next maintenance effort. Forms for these records are often available from the boiler's insurer. Cleanliness and good housekeeping will also contribute to the prevention of fire and explosion. Where pulverized coal is the fuel, care should be taken in cleaning dust settled on ledges (and other spills) so as not to create a combustible dust cloud.

For smaller units, automatic sprinklers are commonly required in combustible boiler rooms; however, in noncombustible boiler rooms, where the potential for sustained fire is slight, portable fire extinguishers or small hose lines might be adequate. Additional guidance on fire protection for fuel-supply systems can be found in Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; and Section 7, Chapter 3, "Storage of Gases."

SUMMARY

In fire-tube boilers a water-filled boiler surrounds the furnace, which is a large central horizontal tube. Hot exhaust gases pass from the furnace through the tubes that traverse the boiler. Boiler explosions led to many deaths in the mid-nineteenth century. Material improvements led to the development of the water-tube boiler, in which the hot gases pass across the water-filled tubes, thereby improving boiler safety. This chapter described the combustion process, discussed fuels used in boiler furnaces, and examined oil- and gas-burning systems and the hazards of pulverized coal firing, of low NO_x firing, and of fluidized bed firing.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for boiler furnaces discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 54, *National Fuel Gas Code*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 85, *Boiler and Combustion Systems Hazards Code*

References

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FM Global, "Oil- and Gas-Fired Single-Burner Boilers," Property Loss Prevention Data Sheet 6-4, FM Global, Norwood, MA.
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SECTION

11

Fire Prevention Practices

Steven F. Sawyer

11.1 Waste Handling and Control
11.2 Housekeeping Practices
11.3 Building and Site Planning for Fire Safety
11.4 Fire Hazards of Construction, Alteration, and Demolition of Buildings
11.5 Control of Electrostatic Ignition Sources
11.6 Lightning Protection Systems

The fire prevention practices section focuses on selected activities that offer a high potential for preventing unwanted ignition. The reader is also encouraged to review Section 6, "Characteristics of Materials and Products"; Section 7, "Storage and Handling of Materials"; Section 8, "Special Equipment"; Section 9, "Processes and Facilities"; and Section 10, "Building Services."

The first two chapters in Section 11 address the related topics of waste and housekeeping. Chapter 1, "Waste Handling and Control," covers fire safety aspects of waste management processes, as well as systems and equipment used for waste treatment and disposal. Incinerators, waste compactors, and shredders are among the topics discussed. Chapter 2, "Housekeeping Practices," defines good housekeeping and presents the essentials of good housekeeping, in addition to describing specific steps related to building care and maintenance, floors, occupancy and process housekeeping, outdoor housekeeping practices, and inspections.

Chapter 3, "Building and Site Planning for Fire Safety," considers building interior design, building design and fire department operations, building design and fire suppression, and site planning. Exposure protection is also covered.

The contents of Chapter 4, "Fire Hazards of Construction, Alteration, and Demolition of Buildings," include construction and alterations, supervision of fire protection, demolition operations, asbestos removal, and underground operations.

The last two chapters in the section address fire prevention activities related to various forms of electricity. Chapter 5, "Control of Electrostatic Ignition Sources," defines static electricity and includes discussion on charge separation, dissipation of static electricity, control of ignitable mixtures, flammable liquids and gases, dusts and fibers, and static detectors.

Chapter 6, "Lightning Protection Systems," discusses the nature of lightning, describes the need for lightning protection, and presents a theory of lightning protection. The chapter then covers the protection of property and people from lightning.

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Chapter 1

Waste Handling and Control

Lawrence G. Doucet ■ Sharon S. Gilyeat

Chapter Contents

Solid Waste Management Systems
Solid Waste Storage Rooms
Waste Chutes and Handling Systems
Incinerators
Waste Compactors
Shredders
Industrial Waste Systems and Equipment
Waste Materials
Waste Management Systems
Treatment and Disposal Systems
Ultimate Disposal
Codes, Regulations, and Standards

Key Terms

chimney, chute, hazardous waste, incineration, incinerator, industrial waste, shredder, waste chute, waste compactor, waste handling, waste management, waste processing, waste storage, waste treatment

Although typical waste is rarely a source of ignition, it is a potential source of fuel for fires, and it can be ignited from other sources. Therefore, a proper and efficient waste management system incorporating prompt treatment and disposal is essential for good fire safety. This chapter covers fire safety aspects of waste management processes, as well as systems and equipment used for waste treatment, and disposal.

For related topics, see Section 11, Chapter 2, "Housekeeping Practices"; and Section 11, Chapter 4, "Fire Hazards of Construction, Alteration, and Demolition of Buildings."

SOLID WASTE MANAGEMENT SYSTEMS

Waste Management Defined

Waste management generally comprises the collection, internal transport, interim storage, treatment, and the final, or ultimate, disposal of waste or the residues resulting from waste treatment operations. A great variety of alternative processes and equipment are available for providing these functions as part of a total waste management system. Depending on specific waste types, constituents, forms, characteristics, quantities, and generation rates, waste management systems can range from a few simple processes to a complex combination of many processes.

Related Terms Defined

Waste Handling. Waste handling generally refers to those processes associated with the movement of waste after its creation. It comprises the collection of waste at points of generation, the transport of waste to storage areas or treatment systems, and the unloading of waste from the transport system. Waste handling systems can range in sophistication from fully manual to fully automatic operation. Waste handling systems and equipment typically include conveyors, chutes, carts, transport vehicles, elevators, and lifts. Waste handling systems also comprise equipment and devices for loading or charging waste into treatment systems and processes. For example, a mechanical loading device could be part of a system for charging solid waste into an incinerator or compactor.

Waste Storage. Waste storage includes the interim containment of accumulated waste within a confined and controlled area, after its collection and transport, and prior to subsequent handling, processing, treatment, or disposal. Depending on waste type, composition, characteristics, method of containment at points of generation, and means of collection and transport, stored waste can be loose, compacted, shredded, or in another processed form. Waste can also be stored in bulk, such as

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in pits or silos, or in individual containers, such as carts, drums, corrugated boxes, special cartons, or bags.

Waste Processing. Waste processing generally includes functions that change or alter the physical characteristics of waste by changing its shape, size, uniformity, or consistency. Such processing is usually provided to facilitate waste handling, storage, treatment, recycling, or disposal operations. Typical waste processing systems and equipment include compactors, shredders, crushers, pulpers, pulverizers, baggers, encapsulators, extruders, and dewatering devices.

Waste Treatment. Waste treatment systems generally comprise devices and technologies for changing the physical, chemical, biological, and/or other waste stream characteristics to render the waste safe for disposal or for compliance with specific waste disposal regulations. For example, waste treatment systems are used for decontaminating infectious waste, for detoxifying or neutralizing hazardous waste, for destroying sharp items such as scalpel blades and needles found in medical waste, and for destroying obnoxious waste such as disposed animal carcasses. Typical waste treatment systems include incinerators, steam sterilizers or autoclaves, shredders, encapsulators, and an array of other processes, such as alkaline digestion, microwaving, infrared radiation, and gamma radiation.

SOLID WASTE STORAGE ROOMS

Rooms in a building or structure that are used for the storage or handling of waste in any form and in amounts exceeding 0.765 m^3 (1 yd^3) uncompacted measure are subject to the requirements of NFPA 82, *Standard on Incinerators and Waste and Linen Handling Systems and Equipment.* The walls, ceilings, and floors of such rooms are required to have fire resistance ratings of at least 2 hours protected by 1½-hour opening protectives. In addition, such rooms require automatic sprinklers in accordance with NFPA 13, *Standard for the Installation of Sprinkler Systems.*

WASTE CHUTES AND HANDLING SYSTEMS

Types of Waste Chutes

Waste chutes are basically fixed systems for transporting waste from points of generation or interim storage to centralized areas for collection, processing, treatment, or disposal. There are five types of chute systems:

General access, gravity-type system
Limited access, gravity-type system
Pneumatic system
Gravity-pneumatic system
Multiloading pneumatic system

General Access, Gravity-Type System. A general access, gravity-type chute consists of an enclosed vertical passageway through which waste is transferred downward by gravity alone. Occupants of buildings having this type of chute have unlimited access to the chute.

Limited Access, Gravity-Type System. A limited access, gravity-type chute is similar to a general access type except that access is restricted. Entry is gained through locked chute doors or locked service opening room doors. These chutes are used primarily in health care occupancies.

Pneumatic System. A pneumatic type of chute system uses airflow to transport waste from chute service openings to a central collection area. Such systems have chutes that may run horizontally, vertically, or inclined, depending on blower and design characteristics. High-velocity air, which typically transports waste through the chutes at speeds of about 60 mph (79 km/hr), is aspirated through the top of the chute and exhausted at its termination. These systems are often used in hospitals, but they can be used in any size or type of building. Figure 11.1.1 shows a diagrammatic view of a pneumatic chute system.

Gravity-Pneumatic System. A gravity-pneumatic type of chute system uses a conventional gravity-type chute to feed a collecting chamber, which, in turn, is connected to a pneumatic chute system.

Multiloading Pneumatic System. A multiloading pneumatic type of chute system is similar to a pneumatic type system except that entry is gained through automatic, or self-closing, positive-latching inlet doors. The doors are interlocked such that only one can be opened at a time and not when the material damper is open.

Waste Chute Design and Construction

Proper waste chute design and construction are critical to fire safety in waste handling systems. Should a fire break out, waste chutes could readily serve as channels capable of carrying smoke and flames throughout a building or facility. Also, they are often considered waste storage areas because they could

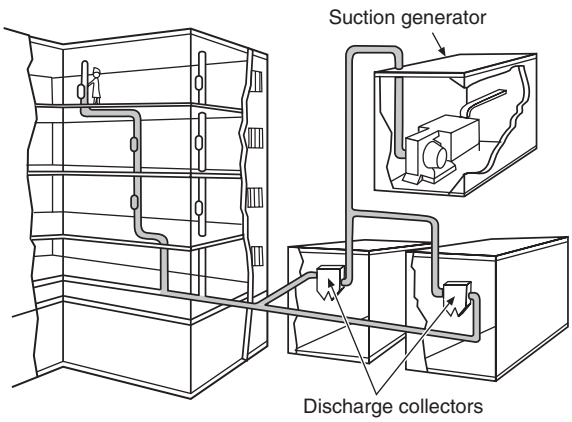


FIGURE 11.1.1 Buildingwide Pneumatic Chute System

become clogged with waste during use and, thus, present fire and smoke hazards. Criteria relative to chute construction, chute enclosures, fire dampers, sprinklers, service openings, and the like are all directed toward minimizing and controlling potential fire hazards. In this regard, strict adherence to the standards in NFPA 82 is required.

Chute Construction. Gravity-type chutes may be constructed of unlined steel, refractory-lined steel, or masonry. Pneumatic waste handling systems are required to be constructed of unlined steel. All unlined chutes are to be fabricated of stainless, galvanized, or aluminized steel for corrosion resistance. Separate design and construction criteria are specified for each type of chute in NFPA 82 for providing structural integrity combined with adequate fire safety measures.

Chute Size. Gravity-type chutes are required to be not less than 22.5 by 22.5 in. (570 by 570 mm) or not less than 24 in. (610 mm) inside diameter. Pneumatic system chutes are required to be not less than 16 in. (406 mm) inside diameter, but they may be smaller if all waste loaded into the chute is first shredded. Waste types and volumes, waste container sizes, user habits, and specific applications must be carefully considered before minimum sizes for chutes and service openings are accepted. For example, a kitchen compactor might produce a typical package measuring 16 by 16 by 9 in. (406 by 406 by 230 mm), which would have a recommended chute diameter of about 36 in. (915 mm).

Chute Service Openings. Properly sized chute service openings are necessary to prevent chute clogging. Oversized openings increase the probability that overly large waste containers or excessive quantities of waste will be loaded into the chute and become clogged. Standards for maximum service opening sizes, developed to prevent such conditions, are as follows:

1. General access gravity chute loading doors are limited to one-third of the cross-sectional area of a square chute and 44 percent of the cross-sectional area of a round chute.
2. Limited access gravity-type chute loading doors are limited to two-thirds of the cross-sectional area of the chute.
3. Pneumatic chute loading doors may have width equivalent to the diameter of chute and the height can be a maximum of 1½ times the diameter of the chute. The minimum door dimension permitted is 18 in. (45.72 cm).

Protection of Chute Openings. Chute service openings are required to be equipped with fire-rated door assemblies to prevent or minimize the spread of chute fires. Without adequate opening protection, the chute can serve as a vertical flue, spreading fire and smoke to multiple floors in a building. Chute doors must be self-closing and positive-latching. Also, pneumatic system service openings are required to have two electrically interlocked doors. For structural integrity, door frames are required to be securely fastened to both the chute and chute enclosure walls.

Chute Enclosures and Penetrations. In order to ensure fire integrity, chute system enclosures, including floor and wall penetrations, require fire-rated protection. Metal chutes, which in themselves offer no fire resistance, must be totally enclosed within masonry walls or other noncombustible, fire-rated material. However, masonry chutes meeting the fire resistance requirements of NFPA 82 are not required to be separately enclosed. If a masonry chute penetrates a floor without closing the opening entirely, the space between the floor and chute is required to be filled with material equivalent to the floor in fire resistance.

Wherever a waste chute penetrates a fire-rated floor-and-ceiling assembly, fire wall, or other fire-rated assembly, a fire damper is not required if the chute is enclosed totally within a fire-rated shaft. Schematic diagrams of typical chute system fire rating requirements are shown in NFPA 82.

Chute Discharge and Terminal Rooms. Waste chutes are required to discharge or terminate in an enclosed room or compartment separated from other parts of the building. Because waste contained within a chute-terminal enclosure area is subject to a potentially high fuel load and uncontrolled burning, the walls, ceiling, and floor of the room or compartment must have a fire resistance rating of 1 or 2 hours, depending on the number of stories in the building and whether a gravity or pneumatic system is used. Terminal enclosures are required to have fire-rated opening protection and automatic sprinklers. These requirements recognize the potential seriousness of fires from waste, which can be difficult to control and can generate large quantities of smoke.

In gravity-pneumatic-type chute systems, the collecting chambers, which can be considered interim discharge or terminal points, are vulnerable to potential fires. They are required to be adequately sprinklered and provided with ready access for fire-fighting measures. Also, the valve room of the system is required to be sprinklered to aid in cooling the space.

Some older gravity-type chute systems discharged directly into an incinerator, and, in some systems, the waste chute also served as the incinerator chimney. Because of the tremendous potentials for fire and smoke hazards, virtually all of these older installations have been discontinued or abandoned. Today, waste chutes are not permitted to discharge directly into an incinerator. Furthermore, because of the inherent difficulties in maintaining fire integrity, systems for automatically transferring waste from chute terminal enclosures directly into an incinerator are not recommended.

Chute Sprinklers. NFPA 82 requires chutes to be sprinkler protected. Chutes require automatic sprinklers at the top, at the lowest inlet level, and at alternate floor levels. Specific requirements for chute sprinklers are in NFPA 13. A good practice is to locate sprinklers where they can be inspected and maintained and yet be out of reach of vandals and beyond the range of falling waste.

Chute Service Opening Rooms. For many years it was general practice to locate chute service openings in public corridors for convenience's sake. This arrangement increased the risk associated with chutes, because any fire in the chute directly affected the exit access corridor system in the building. For this

reason, and for obvious aesthetic and sanitation reasons, NFPA 82 now requires every service opening to be located in a room or compartment separated from other parts of the building by a fire-rated enclosure consistent with the rating of the chute enclosure. Fire-rated opening protectives, including self-closing and latching doors, are also required.

INCINERATORS

Incineration Defined

Incineration is an engineered process using high-temperature combustion for the treatment and disposal of waste. Properly designed and operated incinerator systems can reduce the weight and volume of most municipal, commercial, and institutional solid waste by as much as 95 percent, thereby greatly reducing off-site haulage and disposal costs. Incinerators are often used for the destruction of biomedical and pathological waste at health care facilities, universities, research facilities, and the like. Incinerators are also used for the destruction of hazardous and toxic wastes. In addition, incineration with waste heat recovery is an attractive and cost-effective alternative energy source for many facilities. In terms of fire safety, incineration enables prompt and complete waste destruction, which substantially reduces interim waste storage requirements and associated potential fire hazards.

Incinerators of the past comprised little more than enclosed, single-chamber fireboxes in which uncontrolled burning took place. Such systems provided poor waste destruction and were notorious sources of smoke and odor problems. However, modern incinerator technology offers systems that are readily capable of meeting demanding waste destruction and performance requirements in compliance with stringent environmental regulations. In addition, properly designed, constructed, and operated incinerator systems can be completely fire safe.

Incineration Fire Safety

The very nature of incineration presents potential fire hazards. It typically involves the storage and handling of combustible, sometimes highly volatile waste; the presence of high-temperature, flaming combustion; the exhaust and ducting of high-temperature combustion gases; the handling of hot ashes; and the presence of fuel handling and combustion systems.

Incineration fire safety must fully take into account not only obvious measures, such as the presence of sprinklers and room fire rating, but also less apparent, indirect measures as related to facility planning and design, such as system layout, equipment orientation, waste flow patterns, system operations, and maintenance practices.

Solid Waste Incinerator Categories

There are several different incinerator technologies and designs and wide variations in the types and characteristics of waste that can be incinerated. This section is not intended to cover all of the different technology variations and associated design and construction details for each possible type of solid waste incinerator system. All solid waste incinerator systems and facilities are required to incorporate design details, construction quality, control features, and other measures, as needed, to minimize fire hazards to the extent possible. The basic types of solid waste incinerators that are typically used in industrial, institutional, and commercial facilities are as follows.

Multiple-Chamber Incinerator. A multiple-chamber type incinerator consists of a primary combustion chamber and one or more secondary chambers; it is designed to operate with high-excess combustion air levels—typically 200 to 300 percent. Waste is loaded into the primary chamber for combustion and burnout, and most combustibles entrained in flue gases exiting the primary chamber are fully combusted in the secondary chambers. These types of incinerators are designed and constructed in accordance with standards developed in the mid-1950s. They are almost exclusively used today for burning pathological-type waste, such as animal carcasses and remains (Figure 11.1.2).

Controlled-Air Incinerator. A controlled-air type incinerator is designed on the basis of a two-stage combustion process. In the first stage, waste charged into a primary combustion chamber is burned under starved-air, or oxygen-deficient, conditions. In the second stage, smoke and volatile gases from the primary chamber are combusted in the secondary chamber under excess-air conditions—typically 100 to 200 percent. Controlled-air type incinerators are also commonly called modular combustors and pyrolytic type incinerators. It is estimated that most of the solid waste incinerators built over the last 30 to 40 years have been of the controlled-air type (Figure 11.1.3).

Rotary Kiln Incinerator. A rotary kiln type incinerator comprises a cylindrical combustion chamber, or kiln, that is oriented at a slight incline to horizontal and that rotates slowly on its axis. Waste is loaded at one end, and kiln rotation provides turbulence for thorough waste destruction as well as for enabling the discharge of ash residues from the opposite end. Combustibles entrained in the flue gases from the kiln are burned in a separate secondary chamber. Rotary kiln incinerators have primarily been used in large-capacity industrial and commercial applications burning hazardous waste and widely varying waste mixtures containing sludge-like waste.

Design and Construction

Incinerator systems and equipment, including hot flue gas ductwork, or breechings, and stacks, are subject to extremely severe operating conditions. These include very high and widely fluctuating temperatures; thermal shocks from loads of wet waste; ash residues that damage incinerator refractory linings by slagging and spalling; explosions within combustion chambers from such items as aerosol cans; corrosive attacks from acids and other chemicals; and mechanical scraping and abrasions from metal objects in the waste stream, as well as from operating and cleanout tools. Accordingly, it is critical that incineration systems be suitably designed, constructed, structurally supported, and reinforced to resist any cracking, warping, or distortions that might be caused by such severe conditions and that could allow flames

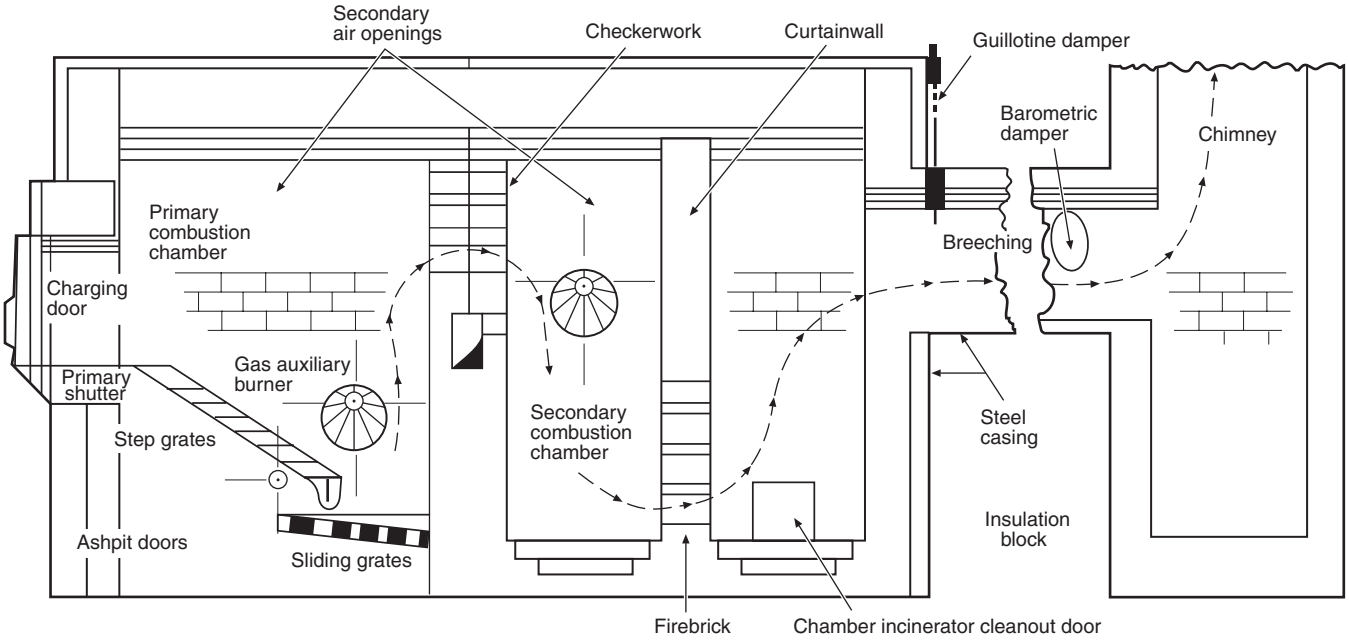


FIGURE 11.1.2 Typical In-Line Type Multiple-Chamber Incinerator

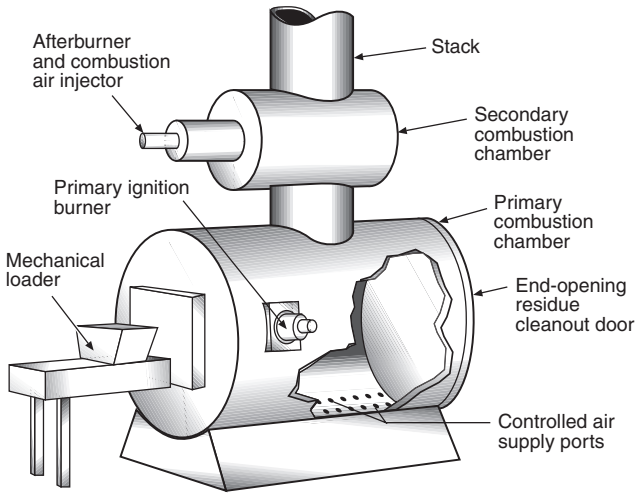


FIGURE 11.1.3 Typical Controlled-Air Incinerator

and hot gases to escape into building areas. Also, the temperatures of exterior surfaces, such as furnace and breeching casings and cleanout doors, must be limited by proper design and construction. Incinerator casings normally accessible to personnel must be insulated, shielded, or appropriately shrouded so that surface temperatures do not exceed 160°F (71.1°C). Handles of operating doors and similar devices must be designed for a maximum 40°F (25°C) rise if metallic and 60°F (37.5°C) rise if nonmetallic. In addition, incinerators must be equipped with a suitable explosion-relief door or panel with an effective area of 1 ft^2 per 100 ft^3 (0.0929 m^2/2.83 m^3) of primary combustion chamber volume.

Location and Arrangement

Incinerator systems and associated facilities are required to be well planned, designed, and implemented to ensure maximum fire safety protection at all times. For example, waste and ash residue containers must never block or obstruct waste charging and cleanout operations or access to work areas or passageways. Waste handling patterns should be such that waste can be charged in a smooth, efficient manner. All parts of the incinerator system, including the ash removal and handling areas, all combustion chambers, and breechings must be easily and safely accessible for routine inspection, cleaning, repair, and servicing. In addition, clearances from furnace charging openings, and between the incinerator top and sides to combustible materials, must be in full compliance with codes and standards.

Waste Charging Systems

The charging of waste into an incinerator has a particularly high fire hazard potential, because the waste loading process typically provides a direct interface between high-temperature, flaming combustion conditions within the incinerator and surrounding building areas. Accordingly, incinerator system design, construction, components, and operating measures must be implemented to ensure that flames and combustion products do not escape from the incinerator into building areas during waste loading procedures or at any other times. Two basic methods of solid waste incinerator charging are manual loading directly through a charging door and mechanical loading with an automatic charging system.

Direct Manual Loading. Direct manual loading has mostly been used on incinerators that burn less than a few hundred

pounds per hour, as well as on systems that are batch loaded or that require loading at infrequent intervals. The environmental regulations in many states have made direct manual loading unacceptable because of its potential to cause excessive air pollution emissions. On those systems where manual loading is allowed, fire prevention measures and design precautions must be implemented, whereby the time that the charging door is open is minimized, and control devices or measures are in place to prevent waste spillage and blockage. The following specific measures should be provided:

1. Charging-door openings large enough to accept the largest or bulkiest waste items without blockage or obstruction. Clear opening areas should not be less than 24 by 24 in. (610 by 610 mm). However, excessively oversized openings must be avoided.
2. Charging-door openings and frames that have smooth edges and are free of projections that may catch or hang up waste materials and cause spillage.
3. Charging doors that operate easily and have positive latching devices and handles that remain relatively cool. Guillotine-type charging doors should be counterweighted or motor operated.
4. Interlocks to stop primary chamber burners from firing when the charging door is opened.
5. Loading trays, where appropriate, in front of charging doors to assist operators in handling and loading heavy and unwieldy waste materials.

Mechanical Loading. Automatic, mechanical charging systems are almost always used on incinerators greater than about 300 lb/hr (230 kg/hr) capacity and, where controlled, charging rates are needed. They are also employed on smaller capacity systems where a continuous airlock interface is required or when mandated by environmental regulations. Mechanical loaders are also used to protect against incinerator overcharging conditions.

NFPA 82 requires that waste charging systems be provided with appropriate controls that will prevent the direct discharge of flames, combustion gases, and heat from the incinerator during waste loading operations. To accomplish this requires a mechanical loader system. NFPA 82 also stipulates that the only exceptions to this requirement are those incinerators that are loaded on a batch basis, whereby the charging door is not opened while waste combustion is taking place.

The most common type of mechanical loading system is termed a *hopper/ram loader,* as shown in Figure 11.1.4. Typically, waste is put into the charging hopper and, on actuation of a system-start switch, the hopper cover closes, the fire door opens, the charging ram injects the waste into the primary chamber, the charging ram returns, the fire door closes, and the hopper cover opens for the next loading cycle. The charging hopper volume and a loading cycle timer help limit the amount of waste that can be loaded into the incinerator per hour, which helps prevent overcharging. In effect, an airlock interface is provided between the incinerator and ambient conditions, because the fire door and hopper cover are not both opened simultaneously and one of them is always in the closed position.

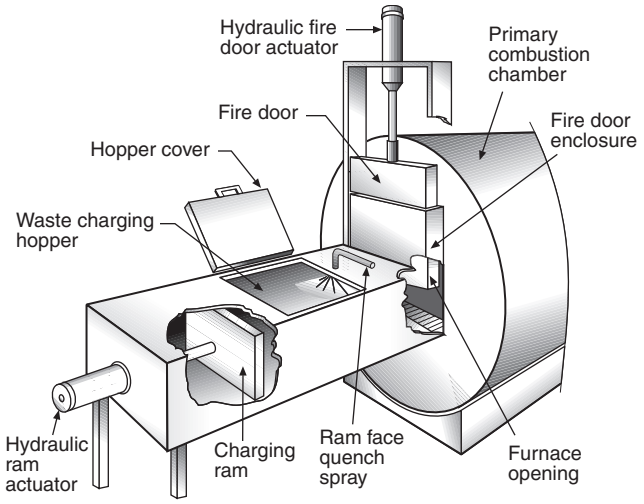


FIGURE 11.1.4 Typical Mechanical Loader

Two potential causes of fire and smoke problems that must be guarded against in hopper/ram loader systems are as follows:

1. *Partial closing of fire door.* Waste can lodge under the fire door and prevent it from closing tightly. This waste could ignite and spread fire back into the hopper and beyond. A partially closed door could also significantly affect incinerator draft, or negative pressure conditions, which in turn could result in heavy smoke escaping from under the partially closed door. To prevent this condition, the fire door should be closed by power, not gravity, in order to seal the opening as tightly as possible should any waste become lodged beneath.

2. *Ram ignition hazards.* When the charging ram injects waste into the incinerator, its face is directly exposed to high temperatures. Eventually, it could heat up enough to be a potential fire hazard. The hot ram face could cause plastic waste bags and similar materials to melt and adhere to it. If these items do not drop from the ram during a particular loading cycle, they could become ignited and carried back into the hopper where they could ignite waste in the hopper.

To prevent this condition, the charging ram should be cooled either by internal water circulation or by a water-spray system that quenches the ram face after every charging stroke. In addition, the loading-hopper volume should be such that a single ram stroke completely empties it of waste. This will minimize the risk of waste being in the hopper to catch on fire. Additional recommended considerations to protect against accidental ignition of wastes in loading hoppers include the following:

- Provision of a flame scanner for immediate detection of hopper fires. Actuation of the scanner could sound an alarm, activate a hopper water-spray system, and/or automatically initiate the loading sequence to inject the burning materials into the incinerator.
- A high-temperature, automatic sprinkler directly over the hopper which is independent of the room sprinkler system

- A manually actuated water spray located above the loading hopper
- An emergency switch that would override the normal automatic loading-cycle-control sequence and cause immediate injection of hopper contents into the incinerator

Residue Removal and Handling Systems

Residue, or ash, removal and handling systems range from fully manual to fully automatic. Because of high costs, space limitations, operational complexities, and technological limitations, older incinerators, and those of small capacity, are cleaned out manually. However, almost all newer incinerators, and almost all incinerators burning more than about 1000 lb/hr (454 kg/hr), are equipped with either an automatic or a semiautomatic ash removal and handling system.

Manual Residue Removal. Manual residue removal cleanout involves the raking or shoveling of ashes from the primary chamber into barrels, bins, or tubs, and sometimes directly onto the floor. Small-capacity incinerators can be readily cleaned from outside the primary chamber through a cleanout door. However, large-capacity incinerators might require the operator to enter the primary chamber for ash cleanout procedures. Except for small-capacity incinerators that are operated infrequently, and which have small ash volume accumulations, manual ash removal is onerous, objectionable, and potentially dangerous in many respects, including intensive, difficult labor requirements; dangers to personnel from heat, ash, dust, and noxious gases; and fire hazards from the handling and containment of unquenched ash residues and embers.

The spraying of water into incinerators to facilitate ash removal by quenching is not recommended because the water will damage the furnace refractory due to thermal shock. As such, water quenching for cooling and dust suppression should be limited to ash already removed from the incinerator.

Ash cleanout without proper containment or quenching is a potential fire hazard if the ashes are hot or contain embers or smoldering material. Also, hot ash containing partially burned items and carbon residues could readily ignite when exposed to ambient air during cleanout procedures. Because of these conditions, NFPA 82 requires that a specially designed system and appropriate measures be implemented to adequately quench and/or fully contain ash residues removed from the incinerators during cleanout. Such measures could include water sprays, a wet quench pit, or a special containment enclosure to enable ash cleanout with minimal exposure to ambient conditions.

Automatic Residue Removal. These systems utilize moving grates, transfer rams, rotating kilns, pulse hearths, or other mechanisms to transfer and discharge ash residues from primary chambers into containment and handling devices. With semiautomatic type systems, ashes are collected in residue carts for subsequent transfer and dumping for eventual off-site disposal. With fully automatic systems, ashes are discharged onto a conveyor or a similar device that continuously and automatically transfers them to a large container for off-site disposal. Most residue conveyor systems are equipped with water troughs or sumps that fully saturate, or quench, the ashes. With cart-type containment systems, the ashes are typically quenched by water sprays surrounding the discharge chute from the incinerator.

For fire safety protection, it is recommended that ash carts used in both manual and semiautomatic type systems be handled with care and, prior to off-site disposal, stored in a fire-rated area in a location that is isolated from stored waste materials. Even when quenched by water sprays or hoses, the containers might still be very hot, and residues within them might tend to ignite spontaneously if disturbed and exposed to room air. It is also recommended that consideration be given for dumping ash carts either directly into an off-site transfer truck or at a landfill rather than within facility building areas.

Incinerator Chimneys and Breeching Systems

The design, construction, termination, and clearances of incinerator chimneys and flue gas ducting, or breeching, systems are required to be designed and constructed in strict accordance with NFPA 82 and NFPA 211, *Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances,* as well as per applicable building, fire, and mechanical codes.

Chimneys and breeching systems handling low-temperature, wet, and saturated incinerator flue gases downstream from a scrubber system used for air pollution control must be designed and constructed to withstand acidic corrosion conditions. Chimneys and breeching systems handling high-temperature flue gases should be refractory lined and insulated. Special design, construction, and materials are needed for scrubber by-pass chimneys that are used for ducting both hot and wet saturated flue gases. It should be noted that no single type of chimney-refractory lining, construction material, or family of materials is suitable for ensuring chimney integrity and fire safety for all incinerator operating conditions and waste types. Such materials must be carefully evaluated and selected for each site-specific application.

NFPA 82 stipulates that chimneys for incinerators serve no other purpose and that they must not be connected to boiler chimneys unless they are of suitable construction and properly designed and controlled for serving both services.

Auxiliary Fuel Systems

Incinerators require auxiliary, or supplemental, fuel for ignition, warm-up, and maintaining proper, elevated combustion temperatures. Most incinerators fire either natural gas or distillate fuel oil. It is imperative that auxiliary fuel systems, including storage and handling systems, burners, and controls, be installed and tested in accordance with all applicable requirements of local codes and NFPA standards. Burners should be of a type specifically designed and constructed for use in incinerator systems. Burners should also be equipped with automatic ignition systems, flame safeguards, and management systems.

Combustion and Ventilation Air

Depending on the types and heating values of waste burned, incinerators typically require 10 to 20 lb of combustion air per lb (10 to 20 kg of combustion air per kg) of waste incinerated. Ventilation air is required to remove heat that is normally transmitted, or

radiated, through incinerator casings and associated equipment into surrounding spaces, in order to maintain comfortable operating conditions and acceptable incinerator-room temperature levels. Insufficient supply of combustion and ventilation air can result in operational problems and unsafe conditions. Incinerator room areas that are confined spaces or enclosed by tight-fitting partitions are required to be provided with an air-supply louver or air-supply blower system in strict accordance with NFPA 82 requirements, as well as those of NFPA standards applicable to fuel-fired burners. Louvers and ducts providing direct outside air are required to be sized for a minimum of 1 $in.^2$ (645.2 mm^2) of free area per 4000 Btu/hr (1172 W/hr) of total heat input.

Electrical Service

Power and control wiring, including electrical components and control devices, are required to be designed and installed in accordance with applicable local codes and NFPA 70, *National Electrical Code®*. It is recommended that wiring and conduit not be attached directly to incinerator casings, and wiring within about 1 ft (0.30 m) of incinerator casings should have high-temperature insulation. It is also recommended that incinerator system control panels not be located less than 3 ft (0.92 m) from incinerator or hot breeching casings. Wiring, relays, transformers, and other electronic devices for auxiliary burners and other appurtenances should be either remotely mounted or protected from high-temperature damage.

Incinerator Rooms

Incinerators, including associated waste and residue handling systems, are required to be located in a separate, fire-rated room or compartment with fire-rated opening protectives. Such rooms may also be contained in the same enclosure with the building heating system and equipment.

Incinerator Operations

Well-trained operating personnel are required to properly manage the severe and complex operating conditions typical of incinerator systems. Training programs and comprehensive operating and maintenance manuals and instructions are highly recommended and mandated in the environmental regulations of many states. Such training should ensure not only proper incinerator operations but also the continued implementation of safe operating conditions.

WASTE COMPACTORS

Waste compactors are devices that use electromechanical-hydraulic means to reduce the volume of waste and to package it in the reduced condition. Both domestic and commercial-industrial compactors are governed by NFPA 82.

Domestic Compactors

Commonly called kitchen compactors, domestic compactors are designed for use in dwellings and apartment units for compaction of single-family residential waste. Both under-the-counter and movable types are commercially available. Domestic compactors reduce the fire hazard of stored waste by retaining it in a metal container under compaction. However, they must have the capability for manual opening such that waste can be readily removed in the event of equipment electrical failure.

Commercial-Industrial Compactors

Commercial-industrial compactors are typically used in multiple-family dwellings and in many other occupancies as a prime waste treatment system to deal with limited waste storage areas and to facilitate waste handling operations. They may be located either indoors or outdoors, and can be either chute-fed or hand-fed. The four types of these compactors follow:

Bulkhead Compactor. With a bulkhead type compactor, waste is compacted against a fixed plate or bulkhead. When the compacted block is ready for removal, a bag is inserted into the unit and filled with the compacted block.

Extruder Compactor. With an extruder type compactor, waste is forced through a cylinder having a restricted cross-sectional opening. Waste becomes compacted as it is pushed through the cylinder by a driving force. At the cylinder discharge, waste is extruded into a "slug," which is broken off and either bagged or placed into a container. The operation of this type of compactor is shown in Figure 11.1.5.

Carousel Bag Packer Compactor. With a carousel bag packer type compactor, waste is compacted sequentially into bag-lined containers mounted on a carousel type mechanism. As each bag is filled, the carousel rotates to place another bag in position to be filled.

Container Packer Compactor. With a container packer type compactor, waste is compacted directly into a bin or container. When full, the bin or container is either manually or mechanically removed from the compactor unit and replaced with an empty bin or container.

Chute-fed compactors are required to be provided with an automatic, special, fine-water-spray sprinkler in the compaction

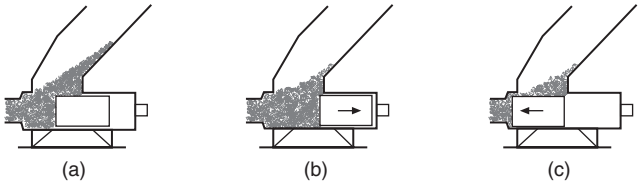


FIGURE 11.1.5 The Sequence of Operation of an Extruder-Type Refuse Compactor. Waste falling from the chute (a) trips a sensor and starts the compacting cycle. The ram moves backward (b) to let refuse fall into the compactor chamber and then moves forward (c) to push the waste through a system of restrictors that compacts the waste and pushes it out of the machine.

chamber. However, hand-fed compactors do not require such protection.

Compaction containers are required to be provided with either a hose connection located near the top of the unit that is suitable for standard fire-fighting equipment, or with an access door that can be opened without disconnecting the container from the compactor.

Chute Termination Bins

Most waste chutes serving compactors do not feed directly into the compactor but into a small storage chamber, a chute connector, or an impact area that is usually large enough to temporarily hold small quantities of waste. Waste collected within these chute termination bins can be potential fire hazards. Accordingly, chute-fed bins are required to be equipped with sprinklers and access doors sufficiently large enough to enable direct access to the interim storage areas in the event of fire. However, if a compactor is loaded manually from a large bin with an open top, the bin need not be sprinklered, because it is sufficient to rely on the sprinklers protecting the compactor room for fire protection.

The bottom enclosure areas of termination or storage bins require special design considerations as needed to enable direct access in the event of fire conditions. For example, should there be an equipment failure, waste will build up not only in the chute termination chamber but also in the chute itself. Subsequently, in the event of a fire and sprinkler discharge, the weight of watered-down waste could become excessive and jam bin closure and discharge devices. Accordingly, sufficient strength should be built into these devices such that they can be operated without breakage or binding under such conditions. A more favorable alternative would be a system that allows discharge into other receptacles, bins, or equipment without the possibility of excessive chute collection.

Compactor Rooms

Compactor systems are required to be enclosed within fire-rated rooms with suitable fire-rated opening protectives as well as with automatic sprinklers.

Compaction ratios, which express the differences in volumes between uncompacted waste and compacted waste, vary widely as a function of waste types and the design capabilities of the particular compactor units and types. Compaction ratios typically range between about 3 to 1 (3:1) and as much as about 5 to 1 (5:1) or greater for special systems. Therefore, compacted waste has widely varying densities, and, if ignited, it can burn to produce large volumes of smoke relatively difficult to extinguish. Accordingly, the storage of compacted waste in buildings should be minimized to the extent possible.

SHREDDERS

Shredders—as well as granulators, grinders, pulpers, chippers, and the like—are sometimes used to process or treat solid waste for volume reduction in order to minimize storage space requirements and to facilitate systems where waste must be mechanically transferred before storage or subsequent treatment. Waste feed bins and hoppers serving shredders are potential fire hazards, and it is strongly recommended that they be protected by automatic sprinklers. If shredders are fed by chutes, it is required that design arrangements be made such that the shredder feed can be diverted or bypassed to enable shredder repairs and servicing and to prevent waste accumulations within the feed chute. All bypass areas and storage areas are required to be sprinklered and enclosed within fire-rated rooms with suitable fire-rated opening protectives. The discharges from shredders are also required to have sprinkler protection.

Potentially explosive conditions are inherent with high-speed type shredders because their operations can produce dust-laden air mixtures that, under certain conditions, could be ignited and deflagrated very rapidly. A recommended method of protection against such possibilities is to provide an explosion-suppression system within the shredder room and an explosion vent, preferably above the shredder, to safely relieve the impacts of a rapid pressure buildup or explosion.

INDUSTRIAL WASTE SYSTEMS AND EQUIPMENT

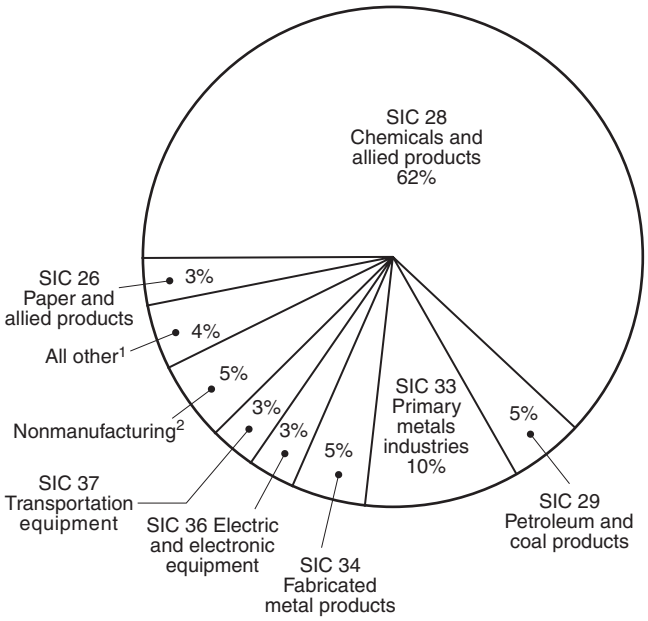
The term *industrial waste* generally describes waste emanating from manufacturing facilities, processing plants, factories, and the like. However, it essentially has no meaning without further definition, because it encompasses an almost infinite variety of waste.

According to best available estimates, in excess of about 6.8 billion metric tons of industrial waste is generated annually in the United States, of which about 36 million metric tons is designated as hazardous, according to the U.S. Environmental Protection Agency (EPA).[1] Hazardous waste must be managed and disposed of in compliance with specific EPA regulations.

The approximate distribution of hazardous waste generated by major industries is shown in Figure 11.1.6.[1] Table 11.1.1 lists annual waste generation rates for prominent manufacturing industries.

Under the Resource Conservation and Recovery Act of 1976 (RCRA), the EPA instituted a complex set of regulations for controlling hazardous waste from generation through final disposal. This is known as "cradle-to-grave" control. To deal with dumpsite cleanup costs and liabilities not covered by RCRA, the EPA enacted legislation known as the "Superfund" bill. The Toxic Substances Control Act of 1976 (TSCA) was established to regulate chemicals not controlled under other regulations. This act, for example, specifies disposal requirements for polychlorinated biphenyl compounds (PCBs).

For most industries, particularly those generating hazardous waste, the evaluation and selection of waste management and disposal systems is difficult and complex. First, there are numerous options and alternative technologies available, each with differing benefits, risk factors, and costs. Second, the forms and properties of waste vary widely and greatly impact the feasibilities and cost-effectiveness of the alternative technologies. Third, regulatory requirements and restrictions may limit the suitability of various technologies. These complexities and multiplicities are also site specific, making it necessary to evaluate



All other[1]

SIC 22 Textile mill products
SIC 24 Lumber and wood products
SIC 25 Furniture and fixtures
SIC 27 Printing and publishing
SIC 30 Rubber and miscellaneous plastic products
SIC 31 Leather and leather tanning
SIC 32 Stone, clay, and glass products
SIC 35 Machinery except electrical
SIC 38 Instruments and related products
SIC 39 Misc. manufacturing industries

Nonmanufacturing categories [2]

SIC 5085 Drum reconditioners
SIC 07 Agricultural services
SIC 5161 Chemical warehouses
SIC 40 Railroad transportation
SIC 55 Automotive dealers and gasoline service stations
SIC 72 Personal services
SIC 73 Business services
SIC 76 Misc. repair services
SIC 80 Educational services
SIC 82 Health services

FIGURE 11.1.6 Distribution of Hazardous Waste Generation by Standard Industrial Classification (SIC)

TABLE 11.1.1 Industrial Solid Waste Generation Rates

Industry	*Major Constituents in the Waste*	*Amount (million tons)*
Pulp and paper	Wood fiber, coal and bark ash, heavy metals, sulfates, acids, dioxins	2250
Iron and steel	Heavy metals, acids	1300
Chemicals	Chemical, inorganic and organic	979
Stone, clay, glass, concrete	Earthen-type materials, some heavy metals	622
Food	Organic wastes	374
Textiles	Organic wastes, heavy metals, dyes	254
Plastics	Solvents and organic chemicals	181
Petroleum refining	Oils, phenols, ammonia, sulfides	169
Agricultural and fertilizer chemicals	Earthen materials, radioactive gypsum, acids, heavy metals, pesticide residues	166
Metals other than iron	Heavy metals	67
Water treatment	Alum, lime, heavy metals	59
Rubber	Plastics, organic chemicals, carbon, pigments	24
Transportation equipment	Oils, heavy metals, organic chemicals, paints, acids	13
Leather	Oils, heavy metals, organic materials, dyes	3
Miscellaneous	All types	63

Source: U.S. Congress, Office of Technology Assessment, *Managing Industrial Solid Wastes from Manufacturing, Mining, Oil and Gas Production, and Utility Coal Combustion,* OTA-BP-0-82, 1992.

options and alternatives for each facility on an individual, case-by-case basis.

WASTE MATERIALS

Industrial waste is as varied as the raw materials used in production and manufacturing operations. However, the nature of the industry generally determines the nature of its waste. A furniture plant, for example, discards wood scraps, sawdust and shavings, fabric scraps, glues, stains, and varnishes. Within any specific industry, there can be many different types and forms of waste materials, ranging from plant trash to spent chemicals and aqueous sludges. Other items may include production residues and by-products, packaging scraps, reject products, returned goods, and even animal carcasses from biomedical and veterinary research activities. Such waste can be in the form of solids, sludges, liquids, or gases. The waste can be hazardous or nonhazardous, and combustible or noncombustible.

Hazardous Waste

Hazardous waste is generally defined as any waste, or combination of wastes, that poses a substantial danger or risk, now or in the future, to human, plant, or animal life, and that cannot be handled or disposed of without special precautions. The RCRA regulations covering hazardous waste are contained in Title 40 of the Code of Federal Regulations (CFR) Parts 239 through 299. RCRA hazardous categories include those wastes that have specific, defined characteristics making them toxic, flammable, corrosive, reactive, or explosive. The RCRA regulations also include specific listings of disposed chemicals, residues, by-products of manufacturing process, various substances, and an array of waste sources that must be managed, treated, and disposed as being hazardous. In addition, other waste categories that might be considered potentially hazardous or requiring special handling, treatment, and disposal under other regulations include low-level radioactive waste and infectious or biomedical waste. If improperly handled or disposed, hazardous waste can contaminate surface and ground waters, soils, and the ambient atmosphere. It could potentially poison, burn, maim, blind, and kill people and other living organisms. Most hazardous waste is nondegradable and persists in nature indefinitely. Depending on

treatment and disposal methods, some can accumulate in living things and some work their way into the food chain. Also, some can catch fire or explode at normal temperatures and pressures when exposed to air or water, or by being jarred or dropped.

Radioactive waste is regulated by the Nuclear Regulatory Commission (NRC). Biomedical or infectious waste is regulated by state and local environmental agencies and health departments. Biomedical waste management is not regulated on a federal level. The EPA, however, has promulgated regulations governing new and existing medical waste incinerators, and the Department of Transportation (DOT) has promulgated regulations governing the off-site transport of biomedical waste.

Hazardous Characteristics

The characteristics that define hazardous waste, according to RCRA and other regulations, are ignitability, corrosivity, reactivity, toxicity, explosivity, radioactivity, and infectiousness.

Ignitability. Liquid waste is considered ignitable, or flammable, if its flashpoint is less than 140°F (60°C). This consists mainly of contaminated organic solvents, but can include oils, plasticizers, complex organic sludges, off-specification chemicals, and pharmaceutical by-products.

Nonliquid waste is considered ignitable if it is capable, under standard temperatures and pressures, of causing fires through friction, absorption of moisture, or through spontaneous chemical changes. These include pyrophoric materials, such as phosphorous and aluminum alkyls, which ignite when exposed to air.

Organic vapors can be ignitable if released in combustible concentrations. Vapors can travel considerable distances, reach an ignition source, and ignite. NFPA 86, *Standard for Ovens and Furnaces,* identifies specific requirements for the safe venting of such gases.

Corrosivity. Corrosive waste can severely damage skin and other living tissues, as well as materials, such as metals and finished surfaces. Wastes are defined as corrosive if their pH values are 2 or less, 12 or more, or if they corrode steel at a rate greater than ¼ in. (6.35 mm) per year. These wastes typically comprise strong acids and alkalis.

Reactivity. Hazardous waste characterized as reactive is normally unstable and readily undergos violent changes without detonation. Some reactive wastes are capable of detonation or explosive decomposition at standard temperatures and pressures. Also, some reactive wastes react violently with water, and some form potentially explosive mixtures or toxic vapors if mixed with water. Reactive materials, such as sodium, potassium, and aluminum alkyls, react violently with water and burn fiercely. Strong oxidizers in contact with organic materials can cause rapid combustion or explosion.

Toxicity. Toxic waste kills, poisons, or produces injury on contact with or through accumulation in or on the body of a living organism. This can occur by inhalation or through contaminated food or water. It is both a short-term and long-term problem. Toxic waste might contain either metals, such as arsenic, barium, cadmium, chromium, mercury, and lead, or synthetic chlorinated organics, such as various pesticides. RCRA specifies an extraction procedure test to determine whether such materials are present in significant concentrations to be designated a toxic hazard.

Explosivity. Explosive waste consists mainly of obsolete ordinance and manufacturing wastes from commercial explosives industries. It can also contain waste from the manufacturing of various propellants and pyrotechnics. However, some waste types are formed as carbon and organic dusts that can be potentially explosive in various air concentrations when exposed to ignition sources such as open flames or sparks.

Radioactivity. Most radioactive waste consists of conventional, nonradioactive materials contaminated with radionuclides in concentrations ranging from parts per billion to as much as 50 percent. These are typically called *low-level radioactive wastes.* The biological hazards from radioactive materials are due to the effects of penetrating and ionizing radiation rather than chemical toxicity. The long-term hazards associated with specific radioactive waste are not necessarily proportional to the nominal level of radioactivity, but rather to the specific toxicity and decay rate of each radionuclide that might be present.

Radioactive waste is often generated from biomedical-type research activities. These wastes typically comprise items such as animal carcasses and liquid scintillation counting (LSC) vials having tracer-level, or low-level, concentrations of radioactivity. The NRC specifies maximum permissible concentration (MPC) levels in the environment for the spectrum of radionuclides.

Infectiousness. Waste characterized as being potentially infectious contains pathogens, or disease-producing microorganisms, that are capable of producing disease in humans. However, to be considered a health risk, such pathogens must be virulent, or living, in significant concentrations, and there must be a means by which they can enter the human body such as through inhalation, ingestion, moist body parts, or puncture wounds. Industrial wastes that are potentially infectious are almost exclusively generated from biomedical research activities.

Waste Characterization

Waste stream characterization provides the starting point for designing and selecting waste management, treatment, and disposal systems. This process involves identification of average or representative waste compositions and properties, deviations from the averages, and the forecasting of likely changes.

A characterization program usually begins with a detailed inventory and classification of all waste stream sources, components, and constituents. These are then organized into various groupings or categories to facilitate further evaluations. Typical groupings include form, such as solids, sludges, and liquids; combustible versus noncombustible; and hazardous versus nonhazardous. See Table 11.1.2 for an example of a waste classification system.[2]

The next step in a characterization program usually involves the determination of the physical and chemical properties of the

TABLE 11.1.2 Waste Classification System

Class	*Remarks*	*Example*
I. Solid wastes		
A. Putrescibles		
Household garbage		
Vegetable and fruit processing wastes		
Animal manure		
Dead animals		
Meat, poultry, and seafood processing wastes		
Others, not elsewhere classified*		
B. Bulky combustibles	*Bulky* is defined as a material of a size to present problems by jamming in a compaction truck hopper, an incinerator feed chute, or other such problems in handling or disposal. Its dimensions may not be defined, except by the size and nature of handling or disposal equipment.	
Wood		Timbers, pallets, cross-ties
Paper and paper products		Large cardboard packing boxes, boxcar linings
Cloth		Filter cloths, mattresses
Plastics		Styrofoam™ logs, polystyrene sheets, garden hose
Rubber		Belting, tires
Leather		Conveyor belting
Yard and street wastes		Tree limbs
C. Bulky noncombustibles		Drums, bedsprings
Metal		Carboys, bathroom fixtures
Mineral		
D. Small combustibles	*Small* is defined as a piece of waste material of a small enough size to present no danger of jamming equipment, or otherwise causing problems because of its size. It refers to the size of a piece of the material, not the size of the delivered load.	
Wood		
Paper and paper products		
Cloth		Gloves
Leather		Shoes
Plastics		Milk cartons
Rubber		Galoshes, butyl rubber crumbs
Yard and street wastes		Street sweepings, leaves
E. Small noncombustibles		
Metal		Cans
Mineral		Bottles
Ashes		Furnace ashes
F. Nonempty cans, bottles, and drums	This functional class will require precise definition of the contents by one of the other classes. This establishes the quantity of material delivered in this manner instead of in bulk form.	Bottles of wastes from laboratories
G. Gas cylinders		Oxygen, acetylene
H. Powders and dusts		
Organic		Pesticides, grain dusts, chemical powders, coal dusts
Metallic inorganic		
Nonmetallic inorganic		
Explosive		

TABLE 11.1.2 Continued

Class	*Remarks*	*Example*
I. Pathological wastes Cloth, paper, and plastic Animal and human wastes Instruments and utensils		
J. Sludges	Materials that are solid in appearance, but are wet, either from water or liquid organics. The solids portion is classified.	
Chlorinated		
Brominated		
Fluorinated		
Acid		
Alkaline		
Water-reactive (unhydrolyzed)		
Air-reactive	May represent a material highly reactive with the moisture or oxygen in the air	
Putrescible	May represent the wet form of any of the materials listed under the functional class of the same name, but also includes such materials as wastewater treatment plant sludges	
Miscellaneous organic		
Metallic inorganic	Refers to metals in the uncombined form	Particles of metal in oil
Nonmetallic inorganic	Inorganic compounds	Filter cakes, $CaCO_3$ precipitate
K. Demolition and construction	This functional class is subdivided into the analytical classes shown for bulky and small, combustibles and noncombustibles. It is included as a separate class to quantify materials from this source and to recognize that a delivery may contain a wide mixture of large and small combustibles and noncombustibles.	
L. Abandoned vehicles		
M. Radiological wastes	This functional class will require further definition by one of the other classes. It must be considered to define this type of contamination to refuse, and to consider the special measures involved.	
II. Liquid wastes		
A. Wastewaters	Waste liquids composed almost entirely of water, but containing contaminants in low enough concentration (usually much less than 1.0 percent) to be handled through a sewer system to a wastewater treatment plant. This definition is proposed for exclusion purposes, because these wastes are not normally considered as refuse.	
B. Contaminated waters	Waters containing contaminants in a concentration too high, or of a nature, that handling through a wastewater treatment plant is unacceptable	
Chlorinated		
Brominated		
Fluoridated		
Acid		
Alkaline		Blood, grease
Putrescibles		
Insoluble oils		
Soluble oils		
Toxic organics		
Toxic inorganics		
Soluble metals		
Others (not elsewhere classified)*		

(continued)

TABLE 11.1.2 Continued

Class	*Remarks*	*Example*
II. Liquid wastes *(continued)*		
C. Liquid organics	Liquid at all ambient temperatures	
Chlorinated		
Brominated		
Fluoridated		Many solvents
Sulfurated		
Acid		
Alkaline		
Water-reactive (unhydrolyzed)		
Shock-reactive		
Toxic and hazardous		Pesticides
Soluble metals		
Others (not elsewhere classified)*		
D. Tars	Stiff materials that are semisolid at low ambient temperatures.	
Chlorinated		Chlorinated-substituted hydrocarbons
Brominated		Brominene-substituted hydrocarbons
Fluorinated		Fluorine-substituted hydrocarbons
Sulfurated		Sulfur-substituted hydrocarbons
Acid		Low pH, corrosive solvents
Alkaline		
Water-reactive		Unhydrolyzed materials that react violently with water
Chemically reactive		
Self-reactive (monomers)		
Toxic and hazardous		Sodium, calcium
Soluble metals		
Others (not elsewhere classified)*		
E. Slurries	Liquid materials that contain solids, but that readily flow or pump. The liquid and solid materials are both classified.	
Organic in water		
Inorganic in water		Lime slurry
Organic in liquid organic		
Inorganic in a liquid organic		Metallic sodium in oil
III. Gaseous wastes	This classification is restricted to those gaseous materials that have been or might become the responsibility of a disposal group or department to treat, burn, or otherwise alter before discharge to the atmosphere.	
A. Odorous		Mercaptans, H_2S
B. Combustible particulate		
Solids		
Mists		
C. Organic vapors		Volatile solvents
D. Acid gases		SO_2, HCl

**Others (not elsewhere classified)* represents the "cleanest" of material and is not intended as a catch-all grouping.

Source: U.S. Congress, Office of Technology Assessment, *Managing Industrial Solid Wastes from Manufacturing, Mining, Oil and Gas Production, and Utility Coal Combustion,* OTA-BP-0-82, 1992.

waste materials or groups of waste materials. Physical properties of concern typically include physical state, size, shape, weight, volume, density, temperature, viscosity, and pressure. Chemical properties typically include elemental constituents, toxicity, corrosivity, explosivity, flashpoint, heat of combustion, and products of combustion. Table 11.1.3 is a comprehensive checklist of parameters that may be significant in a waste characterization program.[3]

Depending on the specific waste, sufficient characterization data might be readily available in published literature, from faculty records, and/or in engineering handbooks. When such data are not available or are inadequate, laboratory testing and analytical work might be required. Waste testing methodologies are typically done in accordance with American Society for Testing and Materials (ASTM) procedures. Hazardous waste sampling and analysis procedures are usually in accordance with "Test Methods for Evaluating Solid Waste—Physical/Chemical Methods," SW-846, as published by the EPA.

WASTE MANAGEMENT SYSTEMS

A great variety of alternate processes and equipment is available as part of a total industrial waste management system. Depending on the specific types, forms, quantities, and hazardous constituents of the waste, management systems can range from a few simple processes to a complex combination of many processes.

Waste handling systems and equipment include conveyors, chutes, carts, and transport vehicles, elevators, and lifts, as well as pumps and piping for liquids, and ducts and blowers for gases, vapors, and fumes. These systems can range in sophistication from fully manual to fully automatic operation.

Systems for storing and handling liquid chemical wastes often require special designs and safety provisions. Problems of concern typically include viscosity, freeze protection, abrasion, corrosion, slagging, and adverse chemical reactions, such as spontaneous ignition, rapid heat release, foaming, precipitation, solidification, and the vaporization of low-boiling-point compounds. Safety provisions include spill and runoff containment, static electricity prevention, flame arresters, and systems for handling the vapors or fumes vented from the storage tanks. In addition, special precautions are sometimes necessary to ensure that incompatible wastes are segregated to prevent undesirable reactions.

For safely handling vapors from industrial ovens and furnaces, dilution air is often required such that the combustible concentrations are below 50 percent, and usually less than 25 percent, of lower explosive limits (LELs). Potentially explosive dusts require controls to prevent combustible air mixtures from forming and being ignited.

See Table 11.1.4 for applicability of various waste management and disposal methods for different waste classes.

TREATMENT AND DISPOSAL SYSTEMS

Because of the high costs and liabilities typically associated with waste treatment and disposal, initial efforts are usually directed at reducing waste quantities, as well as eliminating or minimizing hazardous constituents. Techniques include reuse and recycling of materials that would otherwise be waste, changes in manufacturing and production operations, and substitutions of raw materials to others generating less waste. Also, substitutions and reductions in the use of hazardous and toxic chemicals can result in reduced hazardous waste disposal requirements.

Industrial and hazardous waste processes include physical treatment, chemical treatment, biological treatment, and thermal treatment. They provide such functions as volume reduction, the separation of waste stream components, and the destruction and detoxification of hazardous constituents. Often several treatment processes are linked in series to provide a required degree of treatment. Residues from solid waste treatment processes require disposal, such as land burial, and, if the residues have hazardous characteristics or contain hazardous constituents in unacceptable concentrations, they require disposal in a permitted hazardous waste landfill or disposal site.

The selection of treatment processes for any particular application depends on the type, form, and quantities of waste, required performance to satisfy environmental requirements, and overall system economics. Table 11.1.5 summarizes the available hazardous waste treatment and disposal processes, as discussed below.

Physical Treatment

Physical treatment processes generally provide for separation of waste stream components. These processes are particularly useful for concentrating specific hazardous constituents from dilute waste solutions or mixtures, thereby reducing the overall quantities requiring disposal as hazardous waste. These also provide for the recovery of specific materials in resource recovery operations such that the recovered materials and/or remaining constituents need not be treated as hazardous waste.

The following processes are potentially feasible for the physical treatment of waste:

- Absorption
- Centrifugation
- Dialysis
- Electrodialysis
- Electrolysis
- Electrophoresis
- Filtration
- Flocculation
- Flotation
- Freeze crystallization
- Freeze drying
- Freezing
- High-gradient magnetic separation
- Reverse osmosis
- Stripping
- Ultrafiltration
- Zone refining

Chemical Treatment

Chemical treatment processes are particularly useful for the detoxification of hazardous waste stream components and constituents. They also provide for the separation and possible recovery and reuse of specific waste stream components. However, they are generally limited to liquid forms of waste materials. The following chemical treatment processes are potentially feasible for waste:

- Chemical oxidation
- Chemical reduction

TABLE 11.1.3 General, Physical, and Chemical Parameters of Possible Significance in the Characterization of Solid Wastes

General Parameters

Compositional Weight Fractions
A. Domestic, commercial, and institutional
  Paper (broken into subcategories)
  Food wastes
  Textiles
  Glass and other ceramics
  Plastics
  Rubber
  Leather
  Metals
  Wood (limbs, sawdust)
  Bricks, stones, dirt, ashes
B. Other municipal
  Dead animals
  Street sweepings
  Catch-basin cleanings
C. Agricultural
  Field
  Processing
D. Industrial
E. Mining/metallurgical
F. Special
  Radioactive
  Munitions, etc.
  Pathogenic
  Moisture

Process Weight Fractions
Combustible
Compostable
Processable by landfill
Salvageable
Having intrinsic value

Physical Parameters

Total Wastes
Size
Shape
Volume
Weight
Density
Density stratification
Surface area
Compaction
Compactability
Temperature
Color
Odor
Age
Radioactivity
Physical state
  Total solids
  Liquids
  Gas
Solid Wastes
Soluble (%)
Suspendable (%)
Combustible (%)
Volatile (%)
Ash (%)
  Soluble (%)
  Suspendable (%)
Hardness

Particle Characteristics
Shape distribution
  Shape
  Surface
  Porosity
  Sorption
  Density
  Aggregation
Liquid Wastes
Turbidity
Color
Taste
Odor
Temperature
Viscosity data
  Specific gravity
  Stratification
Total solids (%)
  Soluble (%)
  Suspended (%)
  Settleable (%)
Dissolved oxygen
Vapor pressure
Effect of shear rate
Effect of temperature
Gel formation

Gaseous Wastes
Temperature
Pressure
Volume
Density
Particulate (%)
Liquid (%)

Chemical Parameters

General
pH
Alkalinity
Hardness ($CaCO_3$)
MBAS (methylene-blue active substances)
BOD (biochemical oxygen demand)
COD (chemical oxygen demand)
Rate of availability of nitrogen
Rate of availability of phosphorus
Crude fiber
Organic (%)
Combustion parameters
  Heat content
  Oxygen requirement
  Flame temperature
  Combustion products (including ash)
  Flashpoint
  Ash-fusion characterization
  Toxicity
  Corrosivity
  Explosivity
  Other safety factors
  Biological stability
  Attractiveness to vermin

Inorganic and Elemental
Moisture content
Carbon
Hydrogen
P_2O_5 and phosphate
Sulfur content
Alkali metals
Alkaline-earth metals
Precious metals
Heavy metals
  Mercury
  Lead
  Cadmium
  Copper
  Nickel
Toxic materials
  Chromium
  Arsenic
  Selenium
  Beryllium
  Asbestos
Eutrophic materials
  Nitrogen
  Potassium
  Phosphorus

Organic
Soluble (%)
Protein nitrogen
Phosphorus
Lipids
Starches
Sugars
Hemicelluloses
Lignins
Phenols
Benzene oil
ABS (alkyl benzene sulfonate)
CCE (carbon chloroform extract)
PCB (polychlorinated biphenyls)
PNH (polynuclear hydrocarbons)
Vitamins (e.g., B-12)
Insecticides (e.g., Heptochlor, DDT, Dieldrin, etc.)

Source: N. S. Ulmer, "Physical, and Chemical Parameters and Methods for Solid-Waste Classification," Open-File Progress Report RS-03-68-17, U.S. Environmental Protection Agency, Washington, DC, 1970.

TABLE 11.1.4 Waste Management and Disposal Methods for Different Waste Classes

	Potential Hazards				Management Methods															
Waste Classification Utilization Chart	*Toxicity*	*Explosiveness/Flammability*	*Pathogenicity*	*Radioactivity*	*Std. Storage*	*Spec. Storage*	*Std. Coll. Vehicle*	*Spec. Coll. Vehicle*	*Std. Pipeline*	*Spec. Pipeline*	*Compaction*	*Grinding*	*Pulping (w/H_2O)*	*Composting*	*Incineration*	*Incineration (Liquid)*	*Incineration (Spec.)*	*Chemical Treat. or Alteration*	*Sanitary Landfill*	*Ocean Disposal*[a]
Solid wastes																				
Putrescible			X		X		X													
Bulky combustible						X		X			X	X	X	X	X				X	
Bulky noncombustible						X		X			X	X			X		X		X	
Small combustible					X		X				X								X	
Small noncombustible					X		X				X		X	X	X				X	
Nonempty cans, bottles, drums[b]	X	X	X	X	X	X	X	X				X					X		X	
Gas cylinders		X				X		X				X					X		X	
Powders and dusts		X				X		X				X					X		X	
Pathological wastes	X		X	X		X		X				X			X		X	X	X	
Sludges	X					X		X				X			X		X	X	X	X
Demolition and construction						X		X				X					X		X	
Abandoned vehicles						X		X			X	X					X		X	
Radiological waste				X		X		X				X					X		X	X
Liquid wastes[c]																				
Wastewaters									X									X		
Contaminated waters[d]	X			X		X		X	X	X					X	X	X			
Liquid organics[d]	X		X			X		X	X	X								X		X
Tars	X	X				X		X	X	X						X	X	X		
Slurries	X					X		X	X	X						X		X		X
																X				
Gaseous wastes[c]																				
Odorous	X	X				X		X									X	X		
Combustible particulate		X				X		X									X	X		
Organic vapors	X	X				X		X									X	X		
Acid gases	X	X				X		X									X	X		

[a]Ocean disposal as locally permitted or approved—not recommended procedure.
[b]For contents treatment, see proper classification; this class for container only.
[c]Final disposal of these wasted requires an initial transformation to the solid class (except as noted).
[d]Pipeline selection dependent on specific contaminant.

Hydrolysis
Liquid-liquid solvent extraction
Neutralization
Ozonation
Photolysis

Thermal Treatment

Thermal treatment processes use temperatures ranging from as low as 250ºF (182ºC) to over 20,000ºF (12,000ºC). Such processes include pyrolysis, incineration, high-temperature plasmas, infrared radiation, and microwaving. Thermal treatment processes can be designed to destroy, disintegrate, or dispose of virtually all types and forms of waste and hazardous waste constituents, but only organic constituents can be destroyed by thermal treatment processes involving combustion or pyrolysis. Some industries utilize thermal treatment processes in conjunction with their production operations for the conversion, reclamation, and reuse or recovery of residues and by-products.

Table 11.1.6 summarizes the basic parameters of the most common industrial waste incinerator systems.[4] The following section includes general descriptions of thermal treatment processes used for waste treatment.

TABLE 11.1.5 Hazardous Waste Treatment and Disposal Processes

Processes	*Functions Performed*[a]	*Types of Waste*[b]	*Forms of Waste*[c]	*Resource Recovery Capacity*
Physical treatment				
Carbon sorption	VR, Se	1, 3, 4, 5	L, G	Yes
Dialysis	VR, Se	1, 2, 3, 4	L	Yes
Electrodialysis	VR, Se	1, 2, 3, 4, 6	L	Yes
Evaporation	VR, Se	1, 2, 5	L	Yes
Filtration	VR, Se	1, 2, 3, 4, 5	L, G	Yes
Flocculation/setting	VR, Se	1, 2, 3, 4, 5	L	Yes
Reverse osmosis	VR, Se	1, 2, 4, 6	L	Yes
Ammonia stripping	VR, Se	1, 2, 3, 4	L	Yes
Chemical treatment				
Calcination	VR	1, 2, 5	L	
Ion exchange	VR, Se, De	1, 2, 3, 4, 5	L	Yes
Neutralization	De	1, 2, 3, 4	L	Yes
Oxidation	De	1, 2, 3, 4	L	
Precipitation	VR, Se	1, 2, 3, 4, 5	L	Yes
Reduction	De	1, 2	L	
Thermal treatment				
Pyrolysis	VR, De	3, 4, 6	S, L, G	Yes
Incineration	De, Di	3, 5, 6, 7, 8	S, L, G	Yes
Biological treatment				
Activated sludges	De	#	L	No
Aerated lagoons	De	3	L	No
Waste stabilization ponds	De	3	L	No
Trickling filters	De	3	L	No
Disposal/storage				
Deep-well injection	Di	1, 2, 3, 4, 6, 7	L	No
Detonation	Di	6, 8	S, L, G	No
Engineered storage	St	1, 2, 3, 4, 5, 6, 7, 8	S, L, G	No
Land burial	Di	1, 2, 3, 4, 5, 6, 7, 8	S, L	No
Ocean dumping	Di	1, 2, 3, 4, 7, 8	S, L, G	No

[a]Functions: VR = volume reduction; Se = separation; De = detoxification; Di = disposal; St = storage.
[b]Waste types: 1. inorganic chemical without heavy metals; 2. inorganic chemical with heavy metals; 3. organic chemical without heavy metals; 4. organic chemical with heavy metals; 5. radiological; 6. biological; 7. flammable; 8. explosive.
[c]Waste forms: S = solid; L = liquid; G = gas.

Pyrolysis. Pyrolysis is a thermal treatment process similar to incineration except that decomposition occurs in the absence of oxygen. Heat usually is added externally and temperatures typically are maintained lower than incineration temperatures.

The pyrolysis process basically distills volatiles from the waste, leaving inorganics, or ash, and fixed carbon, or char, behind. The volatiles emitted from the waste are typically combusted in a separate chamber into which excess air and heat are added, but they can also be burned as fuel in a boiler or furnace. If the remaining inorganics have nonslagging characteristics and comprise only a small percentage of the solid residues, the char can also be burned as fuel.

Pyrolysis is a potentially useful process for treating waste containing salts, metals, and other contaminants that would otherwise inhibit conventional incineration system operations. However, several types of incinerators, including rotary kilns, multiple-hearth incinerators, and special designs, can be operated in a pyrolytic mode.

Incineration. Incineration is an engineered process that uses high-temperature combustion. Variables most affecting incineration system design, construction, and operations include waste combustibility and heating values, operating temperatures, retention times for both waste and products of combustion, turbulence within the combustion zones, and emission requirements. There are many basic types of industrial incinerators. Each is generally suitable for specific waste types, forms, and quantities, and each has limitations, advantages, and disadvantages.

The standard, basic types of industrial incinerators include the following.

Multiple-Chamber Incinerator. The description of multiple-chamber incinerators is similar to that of general solid waste

TABLE 11.1.6 Summary of Waste Incinerators

Type	*Process Principle*	*Application*	*Combustion Temp.*	*Residence Time*
Rotary kiln	Slowly rotating cylinder mounted at slight incline to horizontal; tumbling action improves efficiency of combustion	Most organic wastes; well suited for solids and sludges; liquids and gases	1500–3000°F (815–1650°C)	Several seconds to several hours
Multiple hearth	Solid feed slowly moves through vertically stacked hearths; gases and liquids fed through side ports and nozzles	Most organic wastes, largely in sewage sludge; well suited for solids and sludges; also handles liquids and gases	1400–1800°F (760–980°C)	Up to several hours
Liquid injection	Vertical or horizontal vessels; wastes atomized through nozzles to increase rate of vaporization	Limited to pumpable liquids and slurries (750 SSU or less for proper atomization)	1200–3000°F (650–1650°C)	0.1 to 1.0 sec
Fluidized bed	Wastes are injected into a hot agitated bed of inert granular particles; heat is transferred between the bed material and the waste during combustion	Most organic wastes; ideal for liquids; also handles solids and gases	1400–1600°F (760–870°C)	Seconds for gases and liquids; longer for solids
Pyrolysis	Thermal decomposition in the absence of oxygen; transforms organic materials into solids, liquids, and gaseous organic materials of simpler structure	Primarily as fuel; useful with solids and sludges; potential for resource recovery of breakdown products	900–1500°F (480–815°C)	Normally 12 to 15 min

Source: T. T. Chen, M. Chen, and J. Lauber, "Incineration of Toxic Chemical Wastes," *Pollution Engineering,* Oct. 1978.

type incinerators. This type of incinerator is usually limited to solid waste, but special hearth designs can accommodate sludges, and liquid waste can be burned in suspension.

Controlled-Air Incinerator. The description of controlled-air incinerators is similar to that of general solid waste type incinerators. This type of incinerator is usually limited to solid wastes, but limited quantities of sludges can be co-combusted and liquid waste can be burned in suspension.

Rotary Kiln Incinerator. The description of rotary kiln incinerators is similar to that of general solid waste type incinerators. Rotary kilns are versatile systems suitable for combusting most types and forms of waste, including solids, sludges, liquids, fumes, and volatile organic compounds. Liquid waste can be burned in suspension or loaded in drums or containers.

Multiple-Hearth Incinerator. The multiple-hearth type incinerator is almost exclusively used to burn or treat sludge-like residues and waste. Waste is fed at the top of the furnace and moves slowly downward across and through vertically stacked refractory hearths within a vertically oriented, cylindrical chamber. Rotating rabble arms with plow blades move waste across each hearth row so that it eventually falls downward to each hearth level through openings. These can be designed to accommodate granulated solid waste, and liquid waste can be injected between various hearths.

Fluidized-Bed Incinerator. With a fluidized-bed type incinerator system, waste is injected into a very hot, rapidly agitated bed of granular particles, such as sand, that are suspended within a cylindrical chamber by a high-pressure blower. Rapid combustion takes place and the heat of combustion is transferred to the sand bed. The system is primarily limited to organic sludges, but it can be designed to accommodate granulated solid waste and the injection of liquid waste into the bed.

Infrared Treatment Devices. With infrared treatment devices type systems, waste is heated by infrared heating elements such that volatile organics are driven off and, depending on waste type and form, deformation takes place. Such systems are usually limited to sludge-like materials and granulated solids. They can be either batch-fed processes or continuous-fed processes using conveyor belts.

Plasma Arc Treatment Systems. Plasma arc treatment type systems use high-temperature plasmas, comparable to those created by welding arcs, into which virtually any type or form of waste can be loaded and destroyed or disintegrated.

Liquid Injection Incinerators. Liquid injection incinerator type systems generally refers to those systems designed to burn liquid waste in suspension within a combustion chamber. Depending on heating value and hazardous constituents and characteristics, liquid waste can sometimes be injected through

TABLE 11.1.7 Matrix for Matching Waste Type with Incineration Process

Waste Type	*Rotary Kiln**	*Multiple Hearth**	*Fluidized Bed**	*Liquid Incinerator*	*Multiple-Chamber Incinerator*
Solids					X
Granular homogeneous	X	X	X		X
Irregular bulky (pallets, etc.)	X				
Low melting point (tars, etc.)	X		X	If material can be melted and pumped	
Organic compounds with fusible ash constituents	X	X			
Gases					
Organic vapor-laden			X		
Liquids					
High organic strength aqueous wastes, often toxic	If equipped with auxiliary liquid injection nozzles		X		
Organic liquids	If equipped with auxiliary liquid injection nozzles		X	X	
Solids/liquids					
Waste contains halogenated aromatic compounds (2200°F [1204°C] minimum)	X	X	If liquid		
Aqueous organic sludges	Provided waste does not become sticky on drying	X	X		

*Suitable for pyrolysis operation.

Source: D. Hitchcock, "Solid Waste Disposal: Incineration," *Chemical Engineering,* May 21, 1979.

nozzles or combusted through a conventional fossil fuel–fired burner system.

Gaseous Waste Incinerators. Gaseous waste incinerator type systems generally refer to systems designed for the combustion of vapors, fumes, volatile organics, odors, and the like. Three basic types of gaseous waste incinerators are flares, thermal burners, and catalytic burners:

- *Flares.* Flares involve open burning of combustible gases that are either near or above their lower explosive limits (LELs) of concentration or above their upper explosive limits (UELs) of concentration.
- *Thermal burners.* Thermal burners involve the combustion of dilute, or low-combustible, gases in the presence of a burner flame within a chamber.
- *Catalytic burners.* Catalytic burners involve the combustion of dilute gases that are preheated, exposed to a catalyst material, and oxidized at relatively lower temperatures.

Table 11.1.7 shows the incinerator technologies that are best suited or recommended for different waste types and forms.[5]

Other thermal treatment technologies, including variations to conventional incineration, used for waste include the following:

- Incineration in conventional boilers
- Cement kiln incineration
- Industrial furnace or oven incineration
- At-sea incineration
- Mobile incineration

Steam sterilization, or autoclaving, is a thermal treatment process for infectious waste. Autoclave equipment is designed to kill pathogens in waste by exposing them to relatively high temperatures, typically between about 240 and 280°F (about 116 to 138°C), for periods ranging from about 15 minutes to several hours. Retention times for effective treatment are dependent on steam temperatures and pressures, types and forms of the waste, quantities of waste, and the specific type and design of the autoclave system.

Biological Treatment

Biological waste treatment processes utilize microorganisms for the decomposition of organic compounds in the waste stream. These are most applicable to aqueous waste streams containing solids or solvent organics. Composting is also a biological treatment process used for solid and sludge-like waste. The following biological treatment processes are potentially feasible for waste:

- Activated sludge
- Aerated lagoons
- Anaerobic digestion
- Composting and co-composting
- Enzyme treatment
- Trickling filters
- Stabilization ponds

ULTIMATE DISPOSAL

Ultimate disposal refers to the final treatment or disposition of treated and untreated waste and residues. For example, with solid waste incineration a significant quantity of ash residues as well as sludge from a connected air pollution control system require transport and off-site disposal at a permitted site. If the residues contain significant levels of listed hazardous constituents, they may likely require disposal as hazardous waste at a permitted facility. Likewise, ash residues from incinerating low-level radioactive waste would likely require disposal at a site meeting NRC standards if radionuclide concentrations exceed MPC limits. Ash residues from the incineration of infectious and nonhazardous wastes must typically be analyzed to determine whether heavy metal concentrations exceed specified toxicity concentration levels before they can be placed in landfills. Alternate disposal processes include land burial, deep-well injection, and ocean dumping.

Land Burial

Two basic types of land burial are termed sanitary landfills and secure, or industrial, landfills. Both types are engineered systems and must be designed, constructed, and operated to meet stringent regulatory standards.

Sanitary Landfills. Sanitary landfills are used primarily for the disposal of municipal type solid waste that is considered nonhazardous. At sanitary landfills, waste is covered daily with earth to minimize health vector problems, blowing of debris, and open burning, and they are equipped with liners to prevent contamination or leaching into ground or surface waters. They are also equipped with venting systems to release gases generated during waste decomposition, as well as monitoring and test wells for ensuring continued integrity of liners.

Secure Landfills. Secure landfills, which are primarily used for the disposal of hazardous waste, are subject to RCRA regulations. These also require special liner materials to prevent leaching, special caps to prevent surface exposures, venting systems for handling gases, and monitoring and test wells for verifying the integrity of liner structures.

Deep-Well Injection

Deep-well injection involves the pumping of liquid waste into underground cavities or reservoirs that have been identified as being geologically secure. Because a prime concern is to protect all usable underground water, the reservoirs must be located far below potable water aquifers and isolated by thick, nearly impermeable strata, such as shale, limestone, or dolomite. Average well depths are about 5000 ft (1525 m), with some as deep as 10,000 ft (3050 m). Most are located in the southwestern part of the county where the geology can accommodate this disposal technology.

Ocean Dumping

Sewage sludge, industrial waste, and explosives have been dumped at sea for years in designated and approved locations. The U.S. Army Corps of Engineers and the U.S. Coast Guard are basically responsible for the sea transportation and disposal areas for such wastes. The primary concern with this type of disposal is the threat to marine life and coastal areas from improperly sealed waste containers or from uncontained waste having potentially toxic constituents. Because of washups of sewage sludge on beaches across the country, national legislative measures were promulgated to outlaw ocean dumping of such waste. Table 11.1.8 compares key parameters of the major hazardous waste treatment and disposal technologies.[6]

CODES, REGULATIONS, AND STANDARDS

The proper and safe management and disposal of industrial waste requires in-depth knowledge and a full understanding of the waste properties, alternative treatment technologies and processes, and all applicable regulations, codes, and standards. The following are the most significant regulations.

Federal Codes and Regulations for Waste Management and Disposal

1. Resource Conservation and Recovery Act of 1976 (RCRA), Subtitle C, Hazardous Waste Regulations, 40 CFR, parts 260–265 and 122–124
2. Nuclear Regulatory Commission (NRC), Part 20, Standards for Protection Against Radiation, 10 CFR
3. Toxic Substances Control Act of 1976 (TSCA)
4. Clean Air Act of 1963 (CAA) and Clean Air Act Amendments of 1970 and 1990, including:
   (a) National Ambient Air Quality Standards (NAAQS)
   (b) National Emission Standards for Hazardous Air Pollution (NESHAP)
   (c) Prevention of Significant Deterioration (PSD)
   (d) Nonattainment Regulations (NA)
5. Federal Pesticide Control Act of 1972; also known as Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)
6. Oil Pollution Act of 1961
7. Federal Water Pollution Control Act of 1948 (FWPCA)
8. Occupational Safety and Health Act of 1970 (OSHA), including National Institute of Occupational Safety and Health (NIOSH)
9. Hazardous Substances and Hazardous Waste Response, Liability and Compensation Act; also known as “Superfund”

TABLE 11.1.8 Comparison of Some Hazard Reduction Technologies

	Disposal		Treatment		
	Landfills and Impoundments	*Injection Wells*	*Incineration and Other Thermal Destruction*	*Emerging High-Temperature Decomposition*[a]	*Chemical Stabilization*
Effectiveness: how well it contains or destroys hazardous characteristics	Low for volatiles, questionable for liquids; based on lab and field tests	High, based on theory, but limited field data available	High, based on field tests, except little data on specific constituents	Very high, commercial-scale tests	High for many metals, based on lab tests
Reliability issues	Siting, construction, and operation uncertainties: long-term integrity of cells and cover, liner life less than life of toxic waste	Site history and geology; well depth, construction, and operation	Monitoring uncertainties with respect to high degree of DRE; surrogate measures, PIC incinerability[b]	Limited experience mobile units; on-site treatment avoids hauling risks; operational simplicity	Some inorganics still soluble; uncertain leachate test; surrogate for weathering
Environmental elements most affected	Surface and groundwater	Surface and groundwater	Air	Air	Groundwater
Least compatible wastes[c]	Liner reactive; highly toxic, mobile, persistent, and bioaccumulative	Reactive; corrosive; highly toxic, mobile, and persistent	Highly toxic and refractory organics; high heavy metals concentration	Some inorganics	Organics
Costs: low, moderate, high	L to M	L	M to H (Coincin. = L)	M to H	M
Resource recovery potential	None	None	Energy and some acids	Energy and some metals	Possible building material

[a]Molten salt, high-temperature fluid wall, and plasma arc treatments.
[b]DRE, destruction and removal efficiency. PIC, product of incomplete combustion.
[c]Wastes for which this method may be less effective for reducing exposure, relative to other technologies. Wastes listed do not necessarily denote common usage.

Source: "Technologies and Management Strategies for Hazardous Waste Control," OTA-M-197, Congressional Office of Technology Assessment, Washington, DC, Mar. 1983.

General Standards for Waste Materials and Their Management

NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 430, *Code for the Storage of Liquid and Solid Oxidizers*
NFPA 484, *Standard for Combustible Metals*
NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*
"Sampling and Analysis Methods for Hazardous Waste Incineration," 1st ed., Contract 68-02-3111, Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency, Washington, DC, Feb. 1982
"Test Methods for Evaluating Solid Waste—Physical/Chemical Methods," SW-846, Revision B, Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency, Washington, DC, July 1981

General Standards for Waste Treatment and Disposal Systems

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 82, *Standard on Incinerators and Waste and Linen Handling Systems and Equipment*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 801, *Standard for Fire Protection for Facilities Handling Radioactive Materials*

General Standards for Burners and Equipment

NFPA 31, *Standard for the Installation of Oil-Burning Equipment*

NFPA 54, *National Fuel Gas Code*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 850, *Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations*
UL 296, *Standard for Safety Oil Burners*
UL 372, *Standard for Safety Primary Safety Controls for Gas- and Oil-Fired Appliances*
UL 795, *Standard for Commercial-Industrial Gas Heating Equipment*

The above list of codes and standards is not all-inclusive. Other agencies, such as Industrial Risk Insurers (IRI), American National Standards Institute (ANSI), Underwriters Laboratories (UL), and American Society for Testing and Materials (ASTM), may have standards applicable to specific waste management and disposal operations. In addition, state and local regulations and requirements may be more stringent than federal regulations or standards.

SUMMARY

Waste management must take into account potential fire hazards that can arise starting at points of generation, through waste handling processes, internal transport, interim storage, treatment, and final disposal. The design, construction, and use of waste handling and treatment systems and equipment, such as chutes, incinerators, compactors, and shredders, must take fire safety into full account and require strict adherence to all applicable codes and regulations. Waste generated at industrial type facilities varies widely and typically requires special design consideration for proper, safe, and efficient treatment and disposal in compliance with highly complex regulations. One important aspect of minimizing fire hazards in industrial waste management is reducing the quantity of waste, as well as its hazardous constituents by reusing and recycling materials, by changing manufacturing and production operations, by substituting raw material to others generating less waste, and/or by substituting and reducing hazardous chemicals.

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6. "Technologies and Management Strategies for Hazardous Waste Control," OTA-M-197, Congressional Office of Technology Assessment, Washington, DC, Mar. 1983.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on waste handling and control discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 31, *Standard for the Installation of Oil-Burning Equipment*
NFPA 54, *National Fuel Gas Code*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 82, *Standard on Incinerators and Waste and Linen Handling Systems and Equipment*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA *101®*, *Life Safety Code®*
NFPA 211, *Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances*
NFPA 484, *Standard for Combustible Metals*
NFPA 801, *Standard for Fire Protection for Facilities Handling Radioactive Materials*

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Fire Protection Guide to Hazardous Materials, 13th ed., National Fire Protection Association, Quincy, MA, 2001.
"Serious Reduction of Hazardous Waste," OTA-ITE-318, Congressional Office of Technology Assessment, Washington, DC, Sept. 1986.
UL 296, *Standard for Safety Oil Burners*
UL 372, *Standard for Primary Safety Controls for Gas- and Oil-Fired Appliances*
UL 795, *Standard for Commercial-Industrial Gas Heating Equipment*

Chapter 2

Housekeeping Practices

L. Jeffrey Mattern

Chapter Contents

Good Housekeeping Defined
Essentials of Good Housekeeping
Building Care and Maintenance
Occupancy and Process Housekeeping
Outdoor Housekeeping Practices
Inspections

Key Terms

combustible refuse, dust, exhaust duct, facility manager, hazardous waste, materials handling and storage, solvents

Good housekeeping is the keystone to good fire prevention. Housekeeping, in terms of fire prevention, refers not only to a sense of cleanliness, but also to a sense of orderliness, as well as repair and maintenance. All of these aspects are important in the prevention of fire, the minimization of fire spread, the preservation of clear escape paths, and the ability to easily access areas to fight a fire, should one occur. Good housekeeping is a basic requirement for all types of facilities, from the smallest business occupancy to the largest manufacturing plant or warehouse.

A fire at a textile location in North Carolina in 1999 demonstrates how a combination of poor housekeeping situations can result in a very significant fire. Waste product was staged on the floor near an electrical motor. The motor failed, with the resultant arcing igniting the waste material. This quickly grew into a sizeable fire. Before sprinklers could operate and control the fire, lint on the tops of piping, conduit, and ducts above the fire area ignited, allowing the fire to quickly flash along the piping, conduit, and ducts. Some of the burning lint fell to the floor, igniting some 30 spot fires throughout the weaving area of the mill.

In a 2000 incident at a Pennsylvania newspaper printing plant, waste materials were placed in noncombustible open-top containers adjacent to the presses. An electrical arc in a motor controller directly above one of the containers allowed sparks to fall and ignite the waste material. The fire quickly spread to ink residue that was not properly cleaned from areas around the press. The residue allowed fire to spread to the shielded areas of the press. The press was severely damaged.

In one final example, oily residue was not cleaned from the underside of a roof at a West Virginia steel mill (1989). A fire in a press pit quickly spread to the oily residue on the underside of the roof and further spread the full length of the building. Had the roof been properly cleaned, it is expected that the fire would have been contained to the area of the press pit.

Good housekeeping means minimizing the quantity of unstored, exposed combustibles. The combustibles in question can be separated into waste and clutter, where waste refers to combustibles of no value that have not yet been removed and clutter refers to combustibles with value that are out because they are being, have been, or will be worked on. Most of this chapter addresses waste, because there are a number of generic types of waste and a number of generic strategies for minimizing its accumulation. Clutter is different. To determine whether clutter is unnecessary, it is necessary to analyze work flows, work spaces, storage space, methods of accessing and returning stored materials, and all other specific characteristics of a particular facility and its operations. It can be all too easy for clutter to accumulate in a busy environment where cleanup activities never seem to be as important or as urgent as other assignments. At the same time, an inordinate focus on reducing clutter can achieve a largely aesthetic benefit while interfering with efficient work flow and routines. Generic advice that is realistic and effective is elusive, and so this chapter will offer little generic advice.

This chapter provides an overview of good housekeeping practices. It provides specific details for some high-frequency housekeeping hazards and also highlights common housekeeping aspects that lead to deficiencies that need attention in many facilities.

It is important that each facility have a written, effective housekeeping program in place. To be effective, this program should include the involvement of all facility employees. An important part of this program should be a fire safety plan that includes housekeeping practices. In addition,

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the plan should include provisions for inspections, equipment layout, storage and handling practices, and an effective preventive maintenance program to limit or eliminate potential sources of ignition.

In addition to reduced fire hazards, a well-planned housekeeping program can yield the following benefits:

- Reduced operating costs
- Increased production
- Improved production control
- Conservation of material and parts
- Reduced production time
- Better use of space
- Improved traffic flow (i.e., permits faster travel)
- Reduced accident rate

For additional information on related topics see Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems"; Section 8, Chapter 1, "Air-Moving Equipment"; Section 7, Chapter 5, "Hazardous Waste Control"; and Section 11, Chapter 1, "Waste Handling and Control."

GOOD HOUSEKEEPING DEFINED

Good housekeeping is really common sense. It is not a sophisticated concept. It relates to keeping everything in its place, keeping facilities and equipment in good repair and in good operating condition, and keeping processing areas free of accumulations of by-products and waste materials. Identifying the amount of such accumulations is sometimes a most difficult task. What may be acceptable for one operation might be excessive for another. In some areas of a facility, it is necessary to regulate such personal practices as smoking, which, without reasonable controls, could lead to hazardous conditions. It is fundamentally based on occupancy-specific operating conditions. Good housekeeping is important; however, it is essential that the criteria for good housekeeping be clearly spelled out in advance and that the criteria be documented.

In looking at the theory of accidents, one can find information that can help in the prevention of fire. For each serious fire that is reported, there might be 10 minor fires; 100 "close calls" or near misses that could have led to fires; and 1000 unsafe conditions, recognized or unrecognized, that could have led to near misses. These hypothetical illustrative numbers might be high or low, but the bottom line is that many conditions do exist in the workplace that can cause a fire. And, in fact, a facility might be fortunate enough while having these conditions, even over a long period of time, to not experience a fire.

If one can recognize hazardous conditions and eliminate them, the potential for a disastrous fire in the workplace will be substantially reduced. This can be accomplished through good inspection procedures and good housekeeping practices.

Poor housekeeping contributes to loss potential by increasing fire and explosion hazards in several ways. Poor housekeeping:

- Provides a greater combustible loading for the initial fire to feed on
- Creates a greater continuity of combustibles, which makes it easier for fire to spread
- Creates the potential for flash fire or dust explosions when layers of lint or dust are allowed to accumulate
- Allows spills or drips of flammable or combustible liquids to accumulate, which could catch fire (including spontaneous ignition in some situations)
- Increases the potential for spontaneous ignition

When not properly addressed, friction, static, or electrical connections can be sources of ignition. Poorly controlled smoking policies can lead to a source of ignition.

In addition to the increased hazard, poor housekeeping can have a negative effect on production. Quality is hard to maintain when the workspace is crowded and messy. Efficiency suffers because people normally tend to work more productively and more accurately if their surroundings are clean and in good order. Maintenance of good workspaces and adequate aisle spaces to allow not only the free flow of materials into and out of the work area but also good exit capabilities is as important as keeping things clean and well laid out. Thus, good housekeeping will not only prevent fires and possibly save lives, but it can improve production and employee morale as well.

ESSENTIALS OF GOOD HOUSEKEEPING

The degree of effort and attention needed for proper housekeeping is influenced, of course, by the type of building and the overall size of the facility involved. But most significant are the specific occupancies of the facility. Some processes produce more waste, leakage, and vapors than others, thus contributing to the challenges in maintaining good housekeeping. In addition, the acceptable level of cleanliness varies from occupancy to occupancy. What is satisfactory in a foundry would not be tolerable in an office building. And the cleanliness of the average office would hardly be satisfactory for a semiconductor "clean room."

To have good housekeeping, the program must start at the top. In today's business atmosphere, all sorts of titles are used, from the traditional manager and supervisor to the title of team or crew leader. Whatever the title, the top facility manager/team leader must set the tone. This is not to say that an individual supervisor/team leader/crew leader at the department level cannot go it alone, but the success of such efforts will be much improved if the top management of the facility is behind the program. To begin, team leaders (at all levels) must define what is meant by good housekeeping. To do this, each level of leadership should inspect the plant and then determine the following:

- Is the present level of housekeeping acceptable?
- Are the appropriate tools provided for general plant cleanup? Are they available for emergency cleanup?
- Are adequate storage areas provided for both incoming raw materials and outgoing products?
- Are leadership's offices reflective of the good housekeeping required of the facility areas?
- Are adequate waste receptacles provided?

Proper housekeeping does not just happen. It requires visible support of and direction from management as well as the cooperation of all employees, visitors, and vendors. Management cannot merely decree that good housekeeping is a desired goal. It is important that management provide a written policy regarding facility cleanliness and general housekeeping. Good housekeeping requires effort from everyone.

First, management must set the tone, specifically, the level of acceptable housekeeping. Next, management must enlist the aid of everyone to help. Employee ideas should be solicited on how to maintain good housekeeping. Management must either act on the employee ideas or explain why it cannot. It is important that all employees accept the responsibility for housekeeping in their respective areas. Ensuring that materials, tools, wastes, and so on, are placed in their proper locations is the job of each employee who handles them.

Safety inspections are important. When doing so, management must demonstrate with their actions and words the level of housekeeping they will accept. Where proper housekeeping does not exist, it is usually because inadequate attention is paid to, or inadequate action is taken in, one or more of the areas of communications, equipment, layout and storage, environment, and personnel.

Communications

Management must publicize its commitment to good housekeeping. This publicity must be reinforced periodically and recognition given whenever notable improvement or outstanding performance takes place. Team leaders must provide feedback to management on how the program is working and what they need to meet the program goals through safety inspection reports prepared by team leaders and employees and periodic inspections by management. In addition, team leaders must be able to meet with management periodically to review performance, to revise goals, and to offer and substantiate recommendations. These team leaders should also encourage feedback from employees in the form of suggestions and constructive criticism. One important place to discuss these issues is at monthly safety meetings. Assign employees to teams to find innovative methods to identify solutions to problems that have been brought forth either through inspections or by employee suggestions. The worker who uses the area can often readily identify more efficient housekeeping methods.

Equipment

Housekeeping efforts should not flounder from lack of necessary tools or equipment. The simple step of placing a sufficient number of easily accessible wastebaskets or trash receptacles at points of need can reduce the amount of waste deposited on the floor or in the product. In some production and handling areas, dust, lint, and other waste might be produced constantly. In these cases, vacuum pick-up stations tied into an exhaust and collection system might be needed at specific points of waste generation. Keep in mind that this dust or lint might be combustible, and care must be taken to ensure that there is no possibility to ignite this material. For area cleaning, powered floor sweepers or rail-mounted traveling cleaners might be necessary. Areas in which large quantities of scrap or discarded packaging materials continuously accumulate might need not only large trash containers but also motorized equipment that can be emptied or replaced frequently. In areas where grease or oil can accumulate, a high-pressure steam floor-washing system might be required. A well-planned preventive maintenance program on all equipment will find and eliminate leaks of liquid, electrical hazards, static buildup, and friction caused by lack of lubrication.

Layout and Storage

Overcrowding is a major impediment to proper housekeeping. Blocked or restricted aisles limit access and hamper efficient cleaning and trash pickup, not to mention slowing egress. Lack of sufficient workspace and storage capacity results in inefficient operations, an inability to maintain order, and worker frustration. The creative use of racks, shelving, and bins, or marking aisles and storage areas by painting lines on the floor can provide solutions.

With its negative influence on good housekeeping, disorganized and haphazard storage is usually a detriment to effective fire protection as well. Fire extinguishers, small hose stations, and sprinkler system control valves can become blocked and inaccessible, whereas other fire equipment, such as fire doors, can be made blocked and, thus, inoperable. Last, in a fire emergency, it will be more difficult for the industrial fire brigade or the public fire service to attack and extinguish a fire even in a facility protected by automatic sprinklers.

Environment

Equally important as the natural environment is the artificial environment created in the workplace. The control of process fumes, vapors, and dusts required for the well-being of the worker has also had a beneficial impact on overall cleanliness in many work areas. Consideration should be given to totally enclosed dust and vapor-tight process equipment in addition to the ventilation equipment mentioned previously (Figure 11.2.1).

Personnel

Employees must be informed on the necessity of keeping their respective work areas clean as a critical part of a housekeeping program. To do this, management must constantly communicate to the employees what is acceptable and unacceptable about the way the facility is being maintained from a housekeeping standpoint. In addition, employees should be encouraged to discuss ways to eliminate hazards and improve working conditions.

BUILDING CARE AND MAINTENANCE

Basic Requirements for Good Housekeeping

The three basic requirements for good housekeeping are proper layout and equipment, correct materials handling and storage, and cleanliness and order. Any facility that implements these basics has laid the foundation for good housekeeping. Using

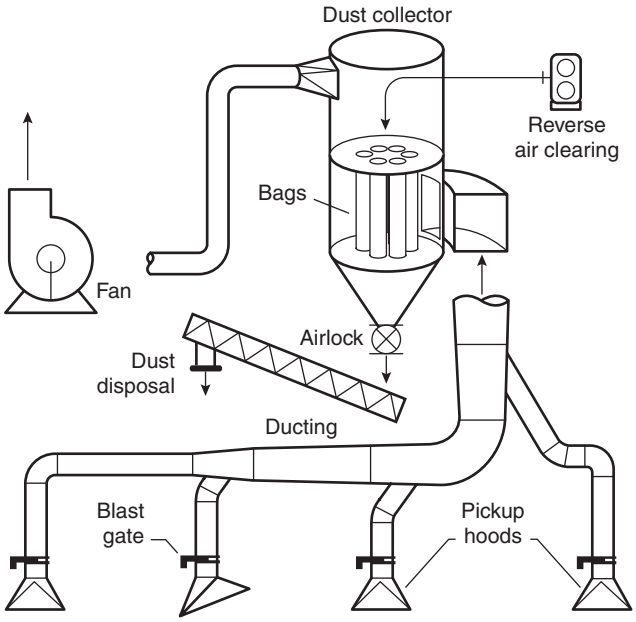

FIGURE 11.2.1 Dust Collection System (Source: http://en.wikipedia.org/wiki/Dust_collector)

FIGURE 11.2.2 Oily Waste Can (Source: Courtesy of the Protectoseal Company)

them, the facility can develop special housekeeping practices to deal with its own specific problems. In pursuing cleanliness and order, effective care and maintenance of buildings require special housekeeping practices to reduce the fire danger to buildings.

Proper Layout and Equipment. Good industrial engineering not only facilitates the movement of raw materials, in-process goods, and finished product but also concentrates the hazards associated with specific aspects of the product process in a single area. For example, in a woodworking facility, all handling of flammable liquids and associated cleaning materials are in one area of the plant. Wiping rags can be concentrated and stored in the appropriately listed waste material storage container (Figure 11.2.2). Doing so does not negate the importance of periodic removal of such waste material but does limit the exposure to these materials.

Correct Materials Handling and Storage. Proper material handling allows for materials to be moved to their specified location without staging them in an area that does not contain the needed level of fire protection, most specifically, automatic sprinklers designed for the hazard. For example, hazardous materials are typically received at the loading dock. Such materials should be properly coded by the supplier so that, when they are received, they are readily identified and can be moved expeditiously to their designated, adequately protected, special hazards storage area, versus being left on the loading dock, which might not be designed for such storage.

Cleanliness and Order. The type of operation will dictate the level and frequency of cleaning required. Many locations will only require cleaning once per day, but some manufacturing processes might require cleaning at the end of each shift, or possibly even periodically during the shift.

Floors

The general care, treatment, cleaning, and refinishing of floors can present a fire hazard if flammable solvents or finishes are used or if combustible residues are produced in quantity. One option is a floor cleaning system that does not use flammable solvents or finishes. In general, cleaning solvents with flashpoints below room temperature are too dangerous to use to clean floors. When selecting a cleaning agent, care should be taken about its toxicity to employees and to the environment if it is eliminated through the sewer system. Safe materials are available for most of the following purposes.

Sweeping Compounds. Many excellent compounds are available for sweeping floors and absorbing oily materials. Noncombustible materials should be used for this purpose. Sawdust and similar combustible materials should be avoided or, if used, should be disposed of in covered metal containers.

Floor Oils. Compounds containing oils and low-flashpoint solvents are a hazard, particularly when freshly applied. In addition, component oils might be subject to spontaneous heating. To reduce the fire hazard, suitable attention must be given to the safe storage of oily mops, sponges, and wiping rags in metal or other noncombustible containers. Any combustible oil used to excess increases the combustibility of the floor. Oil-soaked floors, the product of years of use, also show increased combustibility.

Floor Waxes. Waxes formulated with low-flashpoint solvents are hazardous, especially when used with electric polishers. In

such instances, ignition might result from friction and sparking. Water-emulsion waxes are preferable.

Dust and Lint

A necessary procedure for many occupancies is the removal of combustible dust and lint accumulations from walls, ceilings, and exposed structural members. Unless this procedure is performed safely, as by vacuum cleaners or air-moving (blower and exhaust) systems, the removal procedure could present a fire or explosion hazard. In some cases, vacuum-cleaning equipment must have dust-ignition-proof motors to ensure safe operation in dust-laden atmospheres.

It does not take a lot of "fugitive" dust on building system components, process equipment, utility lines (such as pipes or conduit), or ductwork to create a fire or explosion hazard. Dusts of organic materials such as wood, food products, paper, and so on of the correct particle size with a depth of less than ⅛ in. (3 mm) can, under the right set of conditions, result in a flash fire or explosion. Some believe that as little as 1/32 in. (0.8 mm) of finely divided dust can propagate a flash fire. Typically, a severe explosion can occur if a localized or primary explosion at a piece of equipment shakes the building, dislodging dust that has accumulated on surfaces at some distance above the floor, resulting in an area-wide flammable cloud of dust that can be ignited by the flames from the primary explosion. In such a scenario, the secondary explosion causes the most severe damage.

Flash fires occur when there are lesser amounts of dust. These flash fires occur when a flame impinges on the dust accumulation, and the fire spreads along the surface of the building system component, utility lines, or ductwork. The fire spread can be rapid, as with lint, or slow but progressive, as with many dusts. One of the hazards of flash fires is that they can lead to drop-down conditions where burning material falls on combustible materials near floor level, igniting them, which can result in many spot fires throughout a facility and can open many sprinkler heads, often overtaxing water supplies.

When cleaning, care should be taken not to dislodge into the atmosphere any appreciable quantities of combustible dust or lint that might ignite or form an explosive mixture with air. A great deal of cleaning work can be eliminated by installing dust collection equipment with pickup ducts at points where dust is liberated from processing machinery and conveying the dust to dust collectors outside the building.

The preferred method of cleaning is with the use of soft brooms and brushes and with vacuum equipment to avoid getting the dust in suspension. "Blowing down" dust with compressed air is the least desirable approach for removing dust from high-level points of accumulation, as this can create dangerous dust clouds. If blow-down is the only option, it should be done with extreme care and when all equipment is shutdown. The area should also be inspected for other sources of ignition, which should be eliminated. In most localities, it is possible to obtain the services of reliable professional industrial cleaning specialists to remove dust accumulations safely. These services use large vacuum trucks with hoses that can be used throughout a facility.

Furniture Polishes. Furniture polishes containing oils subject to spontaneous heating become hazardous when rags that are saturated with these polishes are not disposed of properly. An example of such occurred when personnel were using rags soaked in linseed oil to refinish the wood panel wall of an office. At the end of the day, the soiled rags were thrown in a cardboard carton. Some 4 hours later, the rags heated, ignited, and resulted in a prolonged, uncontrolled fire. Such oil-soaked rags should be placed in metal or other noncombustible containers.

Nonhazardous Cleaning Agents. Flammable solvents need not be used since a number of nonhazardous cleaning agents are available. These relatively safe materials are stable and have high flashpoints and low toxicity. There are several commercial stable solvents available that have flashpoints ranging from 140 to 190°F (60 to 88°C) and have a comparatively low degree of toxicity. Safe materials are available for most of the preceding purposes.

Concealed Spaces and Plenum Areas. These areas present a serious fire exposure to a facility if not kept clean and free of combustible material. Concealed spaces below floor areas (crawlspaces) and even raised floors in computer rooms, for example, can become an accumulation point for trash and debris. Also, crawlspaces can be a "temporary" storage area for material to be used for future installation of equipment.

In occupancies where manufacturing processes produce dust or lint, concealed spaces above the ceiling and below the floor can be accumulation points for the dust and lint. If these spaces are not protected with automatic sprinklers and a fire enters these spaces, a severe challenge for manual fire fighting can be created, as it becomes very difficult to identify exactly where the fire is concentrated.

Another area of concern is plenum spaces. A plenum is a space used for moving air from one point to another. Plenums can be between a finished ceiling and the roof or floor above, or between a finished raised floor and the ceiling of the floor below or the grade level floor. These areas typically accumulate large quantities of cable and associated materials. The cables should be noncombustible, limited combustible, or meet the requirements of a variety of fire tests as defined in NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems.* Additionally, any unused cable or other materials should be removed from the space. (See Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems.")

Periodic inspections of concealed spaces and plenum areas are an important part of the facility housekeeping inspection.

Exhaust Ducts and Related Equipment

Exhaust ducts from the hoods over cooking ranges, such as those found in cafeterias, can present problems because grease condenses inside the ducts and on exhaust equipment. Sparks from the range or, more often, from small fires in overheated cooking oil or fat can ignite grease accumulations. Without these grease accumulations in the hood and duct, stovetop fires can often be readily extinguished. Fires are a special danger in frying because cooking oils and fats are heated to their flashpoints

and can reach their autoignition temperatures when accidentally overheated or spilled on the hot stovetop.

Grease Removal Devices. All exhaust systems for cooking equipment must be equipped with grease removal devices. These include such items as grease extractors, grease filters, or special fans designed to remove grease vapors effectively and provide a fire barrier. Grease filters, including frames, and other grease removal devices should be made of noncombustible materials.

Ducts. There is no practical method for preventing all kitchen duct fires, but the danger can be minimized through a combination of precautions as outlined in NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations.* It is good practice to clean hoods, grease removal devices, fans, ducts, and associated equipment frequently. The exhaust system should be inspected daily or weekly, depending on its use, to determine if grease or other residues are accumulating in it. Clean ducts are essential to fire safety, but cleaning them is a difficult and unpleasant job. One source of help is a commercial firm that specializes in this sort of work. Automatic duct cleaning systems are also available that are designed to clean the ducts on a daily or other scheduled basis. In any case, never try burning the grease out; it is a dangerous practice, even though duct systems installed according to NFPA standards are designed to withstand burnout.

In cleaning the exhaust system, avoid using flammable solvents or other flammable cleaning aids. Do not start the cleaning process until all electrical switches, detection devices, and extinguishing system supply cylinders have been turned off or locked in a "shut" position. Doing so will prevent both the exhaust fan and the fire extinguishing system (if the exhaust duct is equipped with one) from actuating accidentally. Once the cleaning process is completed, the switches and other controls should be returned to normal operating positions. Should a fire occur during cleaning, it should be understood that the fire extinguishing system should be manually operated.

Satisfactory cleaning results can be obtained with a powder compound consisting of one part calcium hydroxide and two parts calcium carbonate. This compound saponifies the grease or oily sludge (i.e., converts it to soap), thus making it easier to remove and clean. The process requires proper ventilation. Another cleaning method is to loosen the grease with steam and then scrape the residue out of the duct. This can to be quite effective.

Spraying duct interiors with hydrated lime after cleaning is a fire prevention method used commercially. This procedure tends to saponify the grease and can facilitate subsequent cleaning, but it does not provide permanent fire retardancy.

The use of a professional cleaning company or specially trained employees should be considered to ensure proper handling of the dust and dirt from ducts. This is especially true if the dust is combustible or explosive, since special equipment is needed to clean this type of system. (See Section 8, Chapter 1, "Air-Moving Equipment.")

Ducts Carrying Solid Materials. Ducts that carry solid materials must have the proper pickup and carrying velocities in order to assure that dust at the work site is minimized and that dust traveling through the ducts does not settle out along the flow path. The proper velocities for the type of dust to be transported virtually assures that there will be a minimal accumulation of dust in the duct and at the workstation. Periodic inspections of the ducts should be conducted to assure that materials have not accumulated within the ducts. Where accumulations are detected, frequent cleaning is necessary until modifications can be made to assure proper velocities. (See Section 8, Chapter 1, "Air-Moving Equipment.")

Other Duct Systems. Air distribution duct filters should be changed frequently. Particular attention should be given to building ventilation systems, including fire cutoff devices. In today's tight building design, it has been shown that microorganisms can build up and cause problems in these systems, or cause illness. Dirty outlets on ceilings and walls are evidence of the effects of neglect.

OCCUPANCY AND PROCESS HOUSEKEEPING

Housekeeping programs for a particular occupancy or process must give special consideration to disposal of rubbish, control of smoking habits, and other housekeeping hazards. It is a good idea to have an inspection of facilities by security officers after employees have left a facility for the day or weekend. This inspection should occur about 1 hour after the facility has been vacated and should be repeated on a regular basis while the facility is vacated.

Disposal of Rubbish

The key is not to give fire a place to start. The proper handling and disposal of rubbish is an integral part of the housekeeping process, and its success depends primarily on having and observing a satisfactory routine. The proper and regular disposal of combustible waste products is of the utmost importance.

In both industrial and commercial properties, the removal of combustible waste products at the end of each workday or at the end of each work shift is a common practice. In some occupancies, more frequent waste disposal is necessary. In others, the collection, storage, and disposal routine varies with the nature of the plant operations. In all cases, however, an adequate program for dealing with this problem is a fire safety essential. Keeping a place tidy also depends on providing enough wastebaskets, bins, cans, and other proper containers so that building users will find tidiness convenient.

Recycling. The problem of accumulating combustible waste has increased with the advent of recycling efforts. Many building owners supply small personal recycling containers at each worker's desk (Figure 11.2.3) and larger storage containers, or bins, to collect the recyclable material from the individual containers (Figure 11.2.4). The bins are then emptied at a larger collection point. The collection and storage process of this recycling material has resulted in delayed removal of many types of combustible waste from a building or property. It is important to recognize this situation and to attempt to control the loca-

FIGURE 11.2.3 Typical Personal Recycling Container

tion and amount of recyclable material in buildings as well as the ignition sources in the vicinity of its storage. Proper storage prevents the spread of fire in these areas.

Waste disposal sites should be equipped with the means to extinguish or control the spread of fire in the disposal area until the arrival of the fire department. The fire department should evaluate the fire potential and work with the property owner to ensure adequate water supplies for fire department use in case of fire. Ensuring adequate water supplies might require extending water mains with additional hydrants or, if the site is remote from a municipal water system, the provision of on-site water storage.

Burning or smoldering debris should be dumped at a specific site used exclusively for hot debris. The debris should be monitored, wet down if necessary, and, when cold, placed with normal debris.

There have been many dumpster fires that extended into an adjacent building because the dumpster was not placed a sufficient distance from the adjacent building. For example, in Figure 11.2.5 the dumpster is placed directly against the building's exterior wall.

Dumpsters should be placed a minimum of 10 ft (3 m) from combustible walls, openings, combustible roof eaves, or any other area that might pose a fire risk. The 10 ft (3 m) is measured perpendicularly from the farthest projection, as shown in Figure 11.2.6. Permanent barriers should be installed to ensure that dumpsters are not inadvertently placed within 10 ft (3 m) of these combustible building components.

FIGURE 11.2.4 Storage Bin for Recyclables

Receptacles. Noncombustible containers should be used for the disposal of waste and rubbish. This is true even of such small receptacles as ashtrays and wastebaskets and applies, of course, to the larger units found in commercial and industrial properties. Industrial waste barrels should be made of metal and equipped with fitted covers. Care should be taken to avoid mixing waste materials where such mixing introduces hazards of its own. Although plastic receptacles are popular because they are quiet, attractive, and scratch and dent resistant, only noncombustible containers should be used for rubbish disposal.

Segregation of Waste. It is not good housekeeping practice to dump all manner of dry waste down refuse chutes or to place it in a common bin or storage receptacle. For example,

FIGURE 11.2.5 Dumpster Against Building Exterior

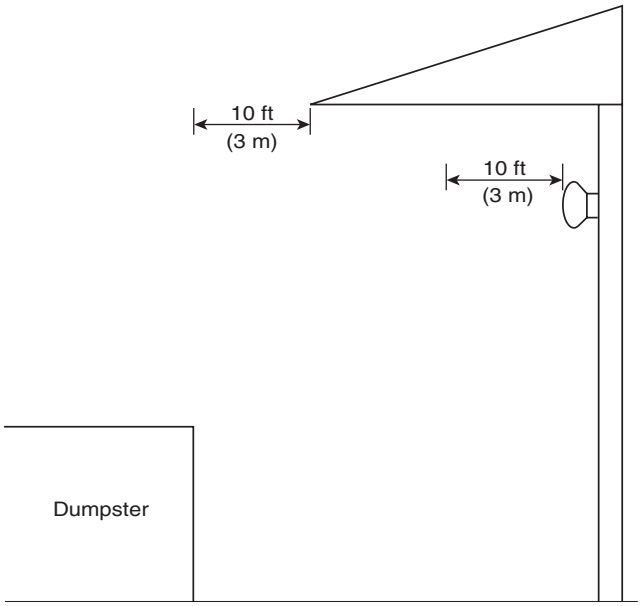

FIGURE 11.2.6 Distance Measurements

combustible metal dusts and metal powders dumped into chutes might explode if ignited. Mercury batteries and pressurized containers, such as the ubiquitous aerosol can, might also explode when incinerated or mixed with rubbish that is subsequently burned. Precautions should be taken to keep combustible items separate from each other and from noncombustible items.

Some materials are susceptible to spontaneous heating. These materials should not be combined with other materials. They should be placed in a closed, noncombustible container. Materials of this type are common in furniture refinishing, floor and wood wall refinishing, spray painting, and similar operations. Waste rags associated with materials such as nitrocellulose and linseed oil are of particular concern.

In the United States, requirements of the U.S. Environmental Protection Agency (EPA) and the state waste control departments must also be considered. Many countries have similar regulations on waste disposal. Agencies that govern these regulations should be consulted in order to establish appropriate waste disposal procedures.

Most chemicals must be handled in a specific prescribed manner. In the United States, rules are contained in the Resource Conservation and Recovery Act (RCRA) and the Hazardous Waste Amendment to that act. Contact the EPA and local state agencies for further information. Many countries have similar regulations on handling chemicals. Agencies that govern these regulations should be consulted in order to establish appropriate chemical handling procedures.

Control of Ignition Sources

Control of Smoking. Although society in general has made many changes in the smoking habits of employees, there are still a significant number of employees who smoke. From the standpoint of fire safety, the best policy is to prohibit smoking altogether. This eliminates the possibility of smoking materials being improperly discarded. It is critical that such a policy be strictly enforced and have the support of all employees. Where this is not a possible consideration, smoking regulations must be specific as to location and, preferably, time. Areas in which smoking is permissible, as well as those areas in which it is limited or prohibited entirely, must be clearly marked by appropriate signs that leave no question as to what is allowed where (Figure 11.2.7).

In addition to sensible regulations, smoking control also requires adequate receptacles for spent smoking materials. Properly designed ashtrays are essential to safe smoking. They should be made of noncombustible materials with grooves or snuffers that hold cigarettes securely. Their sides should be steep enough to force smokers to place cigarettes entirely within the ashtray. In industrial buildings, large containers of sand are often used to conveniently and safely extinguish and dispose of spent smoking materials.

Improperly designed ashtrays can constitute a hazard, particularly if they allow a lit cigarette or cigar to fall or roll away. A lighted butt also might easily come in contact with combustible materials and start a fire under certain circumstances. The contents of ashtrays must be disposed of carefully because a live butt might well be mixed in with apparently innocuous ashes. If lighted smoking materials were to be dumped into an ordinary wastebasket, they could set paper or some other piece of combustible rubbish on fire. To prevent this from happening, reserve special covered metal containers for discarded smoking materials only.

Control of Static. Static can be produced by the flow of dissimilar materials past each other. For example, liquid or dust conveyed through a pipe or duct can produce an electrical potential. Under the right conditions, if adequate oxygen is present, a static discharge can occur that will ignite the flammable vapor or combustible dust. Another source of static electricity-induced fires is associated with flammable liquid dispensing. It is important that low conductivity flammable liquids have a good bonding system where the dispensing object, the receiving object, and the ground device are all interconnected (bonded together). If the grounding system is defective, flammable liquids being dispensed can be ignited. If spills and droppings of such flam-

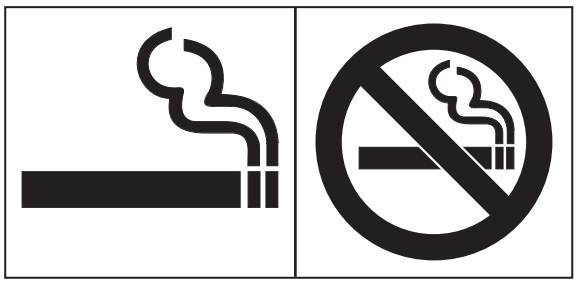

FIGURE 11.2.7 Examples of Signs Permitting or Forbidding Smoking in Designated Areas

mable liquids are present, the fire can quickly spread beyond the point of origin. Part of the site-preventive maintenance program should be periodic inspection and testing of all grounds, including building grounds and bonding.

Control of Friction. A preventive maintenance program must be in place to identify and eliminate potential sources of friction. Lubrication is one important part of this program. Additionally, in areas where there is potential for friction, it is important that housekeeping be of high quality to ensure that debris is not a "wick" to spread a fire to surrounding materials. An example of friction-associated problems is the drive roller on rubber belt conveyor systems. These rollers need to be inspected periodically for proper lubrication. Overheating can ignite not only the rubber belt but also any surrounding debris associated with an inadequate housekeeping program.

Control of Electrical Hazards. Routine inspections should identify overloaded electrical circuits, excess electrical extension cords, frayed cords, missing grounding plugs, and so forth. Infrared testing can also be an important feature of preventing fires of electrical origin. A good housekeeping plan that manages the proper disposal of waste materials and the removal of residue from manufacturing processes helps minimize the potential for a common electrical fault from spreading beyond the point of origin.

Industrial Housekeeping Hazards

Some industrial occupancies have special housekeeping problems inherent to the nature of their operations. For these particular problems, specific planning and arrangements are necessary.

Clean Waste and Rags. Clean cotton waste or wiping rags are generally considered to be mildly hazardous, chiefly because they are readily flammable when not baled, and there is always the likelihood that dirty waste can become mixed with them. The presence of dirty waste or small amounts of certain oils can lead to spontaneous heating. Reclaimed waste is considered somewhat more hazardous than new waste. It is common practice to handle clean waste in the same manner as dirty waste, although the fire hazard is relatively small.

Large supplies of clean waste are best kept in bins made entirely of metal and provided with covers that are normally kept closed. Several bins can be provided where the supplies are large or where different kinds of waste are kept. The covers on such bins should be counterweighted so that they can be readily raised and lowered. The counterweight ropes can have fusible links to ensure that the covers are closed automatically in the event of fire.

Local supplies of clean waste are usually kept in small, properly marked waste cans. Providing local supply points for clean waste can help eliminate the practice of keeping waste in clothes lockers, drawers, benches, and similar locations. If clean waste is put in such places, workers might mistakenly believe that other, more oily waste is also allowed there when, in fact, the combination of the two can result in fire. These same policies should apply to reused (clean) cotton gloves and possibly also to cotton coveralls and uniforms.

Coatings and Lubricants. Paints, greases, and similar combustibles are widely used in industrial occupancies, and a good housekeeping program will make sure that their combustible residues are collected and disposed of safely. The discharge of vapors from spray booths should be so arranged that the vapors are conducted directly to the outside, and the residues accumulate safely. Use of wash-water spray booths for painting should also be considered. No matter the type of spray booth, it is important that "overspray" be removed from the walls of the spray booth, any area outside the booth, the area behind the filter bank on a dry spray booth, and the exhaust stacks on all type booths. Only nonferrous scraping tools should be used for such cleaning activities. The residue removed should be placed in a closed noncombustible container to await disposal.

Drip Pans. Drip pans are essential at many locations, notably under motors, machines using cutting oils, and bearings, as well as beneath dispensing drums or other containers for flammable and combustible liquids. Drip pans should be made of noncombustible material and contain an oil-absorbing compound. The exception is where flammable liquids are dispensed, in which case the drip pan should be a listed device that would include a flame arrestor screen. All drip pans should be inspected, emptied, and cleaned periodically. At some industrial occupancies, commercial oil-absorbing compounds consisting largely of diatomaceous earth are used instead of sawdust or sand. Although not a recommended practice, regular removal of such oil-soaked material is an important aspect of good housekeeping.

Flammable and Corrosive Liquids Waste Disposal. The disposal of combustible liquid waste often presents a troublesome problem. Any waste material that is a corrosive liquid (PH ≤ 2 or ≥ 12.5), or is a liquid with a flashpoint of 140°F (60°C) or less, is considered a hazardous waste under the United States Federal RCRA. Regulatory agencies in other countries have similar regulations. Drums of this waste must be labeled in accordance with these regulations, which includes labeling the liquid as hazardous waste in accordance with the requirements of the governing local codes. These waste products must be disposed of in a facility that is licensed to handle this waste. Care should be taken to ensure that the facility taking the waste does in fact properly dispose of it. (See Section 7, Chapter 5, "Hazardous Waste Control.")

Flammable Liquid Spills. Flammable liquid spills can be anticipated wherever such products are handled or used and some means of coping with these spills must be kept on hand. These means include a supply of suitable absorptive material and special tools to help limit the spill. Workers should understand and promptly take the steps needed to cut off sources of ignition, ventilate the area, and safely dissipate any flammable vapors.

Flammable Liquid Storage. Flammable liquids should be stored in a segregated area. Good housekeeping practices will ensure that only limited quantities of flammable and combustible liquids are kept on the production floor or work area. These should be protected in suitable containers. No storage of flammable liquids should be allowed in the general storage area,

except as allowed in NFPA 30, *Flammable and Combustible Liquids Code.* Combustible liquid storage should be limited and protected as allowed in NFPA 30 (Figure 11.2.8). Any spills of these materials should be cleaned promptly.

Oil Puddling. Accumulations of oil can present a housekeeping problem at industrial locations where a considerable amount of oil is used. Poor maintenance of industrial hydraulic oil operated equipment such as hydraulic oil pumping systems, extruders, presses, lathes, and elevator equipment can result in oil leaks that eventually form puddles. These puddles can form on floors surrounding the equipment, as well as on and under the equipment. Although most oils used in hydraulic oil systems have high flashpoints, any combustible oil can be a source of fire or lead to an enhanced fire spread, particularly when it is found in puddles that contain accumulations of debris. Puddled oil and materials used to absorb oil spills should be disposed of in metal barrels. Frequent inspection and cleaning of these areas are an important aspect of the housekeeping program.

Oily Waste. Oily wiping rags, sawdust, lint, clothing, and other items can be highly dangerous, particularly if they contain oils subject to spontaneous heating. To dispose of all such materials in ordinary quantities, a standard waste can that has been listed and labeled by testing organizations is best. For large amounts, heavy metal barrels with covers are ideal. Good practice calls for cans containing oily waste to be emptied daily and for wiping rags to be kept in covered metal containers until they can be laundered.

Packing Materials. Almost all packing materials are combustible and, consequently, hazardous. Cellular plastic packing pellets and rigid forms, excelsior, shredded paper, sawdust, burlap, and other such materials should be treated as clean waste. However, large quantities might have to be kept in special vaults or storerooms. Automatic sprinklers are the best protection for areas where considerable quantities of packing materials are stored or handled. These areas also require an extra level of attention to assure that transient materials are cleaned up and returned to their receptacles.

Used or waste packing materials and the crating materials from receiving and shipping rooms must be removed and disposed of as promptly as possible in order to minimize the danger of fire. Ideally, the packing and unpacking processes should be conducted in an orderly manner so that excessive quantities of packing materials do not become strewn about the premises. A specially marked (or identified) area should be provided to accumulate this material. This area should be cleaned frequently and the debris removed to an outside storage receptacle. Outside receptacles should be noncombustibles and placed at least 10 ft (3.048 m) from building walls of combustible construction or where there are windows and doors that can provide an avenue of fire spread.

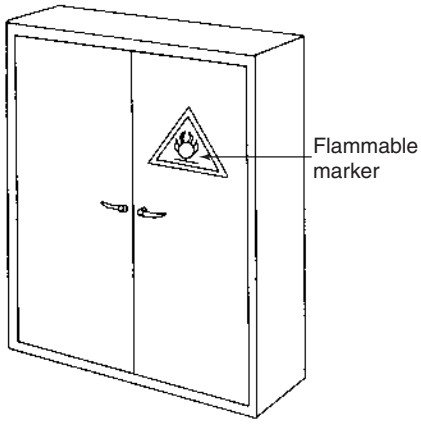

FIGURE 11.2.8 Metal Flammable Liquid Storage Cabinet

OUTDOOR HOUSEKEEPING PRACTICES

Good housekeeping practices are as essential outdoors as they are indoors. Failure to comply with good housekeeping practices outdoors can threaten the security of exposed structures and goods stored outside. The accumulation of rubbish and waste and the growth of tall grass and weeds adjacent to buildings or stored goods are probably the most common hazards. A regular program for policing the grounds is essential.

Grass and Weed Control

Tall grass, dry weeds, and bushes around buildings, along highways, on railroad properties, and along the streets of large industrial and commercial complexes present a definite fire hazard. Fires can spread from one building to another or from the vegetation to the building. To reduce this hazard, vegetation around buildings and outside storage should be controlled or destroyed through the use of common herbicides.

Outdoor Storage

Goods stored outdoors should be properly separated from buildings of combustible construction and from other combustible storage that might constitute an exposure hazard. Passageways between storage piles should also be unobstructed and clear of combustibles. These separations can become blocked by transient storage such as contractors' shacks, discarded crates, pallets, or other combustibles. The housekeeping staff must see to it that these separations are never blocked, even temporarily. Obstructed aisles and dedicated space separations not only can lead to the spread of fire from one area of storage to another but also hamper fire-fighting operations.

Proper housekeeping also requires that smoking in outdoor storage areas be prohibited. Suitable signs should be posted.

Outdoor Rubbish Disposal

Combustible waste materials stored outdoors to await subsequent disposal as rubbish should be placed not less than 10 ft (3 m), and preferably 50 ft (15 m), from buildings, and at least 50 ft (15 m), from public roadways and sources of ignition, such

as incinerators. They should also be enclosed with a secure noncombustible fence of adequate height.

The most satisfactory solution to the rubbish disposal problem is regular collection and removal from the premises. Burning rubbish is generally unsafe and is usually not permitted in developed urban and suburban areas. If burning is permitted and is conducted, it should be done in a noncombustible container or enclosure equipped with a well-maintained spark arrestor.

INSPECTIONS

Housekeeping inspections are an important part of an overall housekeeping program. This type of program should be combined with a complete safety inspection program. This type of inspection has four main objectives:

- Maintain a safe work environment
- Control unsafe actions of employees
- Maintain operations profitability (and product quality)
- Maintain operations to meet or exceed acceptable safety and government standards

Although the word *housekeeping* is never mentioned, it does not take much imagination to see good housekeeping is involved in each objective. Good housekeeping is an essential part of any successful safety program, and that includes the fire safety program.

There are several types of inspections. Some involve preventive maintenance of equipment, such as lubrication of equipment or checking the continuity of static electricity grounding systems. (Figure 11.2.9 presents a sample checklist of inspection activities.) Others involve inspection and testing of fire protection equipment. But most important is a regular inspection by the team leader and facility management. These inspections must be well defined. The program should include what areas are to be inspected, how often the inspections should be made, what is acceptable performance, and who will conduct the inspections.

One of the most time-consuming parts of an inspection is writing a report. Computers and bar coding can help. Bar coding is commonly used to identify products and equipment. However, bar codes can also be used in the identification of hazards. The facility inspector can carry a bar-code reader and recorder. Bar codes identify the department, date, and time of the inspection, as well as the inspector. Common hazards for the facility are entered on a bar-code list carried by the inspector. For each item or hazard on the list, a recommendation is also keyed into the computer program. The inspector simply scans the bar code for the desired item. At the completion of the inspection, the information is downloaded into a computer and a report is printed. This format also allows comments to be made where employees have made positive contributions to the housekeeping program. This positive reinforcement will encourage employees to continue their good work. This computer format also allows for follow-up to housekeeping recommendations. It is very important that, when recommendations are made, positive change results in the area. This change can either be the action recommended or another action that provides equal protection.

Fire-Safety Checklist

Electrical equipment

No makeshift wiring
Extension cords serviceable
Motors and tools free of dirt and grease
Lights clear of combustibles
Circuits properly fused or otherwise protected
Equipment approved for use in hazardous areas (if required)
Ground connections clean and tight and have electrical continuity

Friction

Machinery properly lubricated
Machinery properly adjusted and/or aligned

Special fire-hazard materials

Storage of special flammables isolated
Nonmetal stock free of tramp metal

Welding and cutting

Area surveyed for fire safety
Combustibles removed or covered
Permit issued

Open flames

Kept away from spray rooms and booths
Portable torches clear of flammable surfaces
No gas leaks

Portable heaters

Set up with ample horizontal and overhead clearances
Safely mounted on noncombustible surface
Secured against tipping or upset
Not used as rubbish burners
Combustibles removed or covered
Use of steel drums prohibited

Hot surfaces

Hot pipes clear of combustible materials
Ample clearance around boilers and furnaces
Soldering irons kept off combustible surfaces
Ashes in metal containers

Smoking and matches

"No smoking" and "smoking" areas clearly marked
No discarded smoking materials in prohibited areas
Butt containers available and serviceable

Spontaneous ignition

Flammable waste material in closed, metal containers
Piled material, cool, dry, and well ventilated
Flammable waste material containers emptied frequently
Trash receptacles emptied daily

Static electricity

Flammable liquid dispensing vessels grounded or bonded
Proper humidity maintained
Moving machinery grounded

Housekeeping

No accumulations of rubbish
Safe storage of flammables
Passageways clear of obstacles
Automatic sprinklers unobstructed
Premises free of unnecessary combustible materials
No leaks or dripping of flammables and floor free of spills
Fire doors unblocked and operating freely with fusible links intact

Extinguishing equipment

Proper type
In working order
In proper location
Service date current
Access unobstructed
Personnel trained in use of equipment
Clearly marked

FIGURE 11.2.9 A Sample Fire Safety Checklist

When a bar-code system does not fit the inspection program, one may find that a checklist will be a valuable aid.

To prevent inspections from taking considerable time, the inspector should:

- Have a definite schedule
- Inspect only one part of the department at a time
- Rotate inspection responsibilities among department members
- Make a point of looking for housekeeping problems as part of a daily routine

Trading inspections between departments can help increase inspection effectiveness; monotony can distort evaluation of real problem areas.

SUMMARY

Housekeeping practices are an integral part of any program to prevent or limit fire's spread. Building care and maintenance, occupancy and process housekeeping (including disposal of rubbish and control of ignition sources), appropriate outdoor housekeeping practices, and inspections are key elements.

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Reference to the following NFPA codes, standards, and recommended practices will provide further information on housekeeping practices discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 82, *Standard on Incinerators and Waste and Linen Handling Systems and Equipment*
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations*

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Chapter 3

Building and Site Planning for Fire Safety

Albert M. Comly, Jr.

Chapter Contents

Building Interior Design Considerations
Building Design and Fire Department Operations
Building Design and Fire Suppression
Site Planning
Exposure Protection

Key Terms

building height, building separation, defend-in-place, evacuation (total), evacuation (zoned), exposure protection, fire lane, HVAC, security, site planning

Effective, fire-safe design begins with conscious analysis and decision making early in the design process. This broad overall approach includes consideration of both interior building functions and layout, as well as exterior site planning. This chapter presents some broad guidelines to be considered by building designers in analyzing fire protection measures that must be provided for a fire-safe environment for structures and their sites. Detailed information of the various aspects of fire-safe site planning and building design can be found elsewhere in this handbook, particularly in the other chapters in this section.

To effectively incorporate the building's fire defenses into the design, the fire safety objectives must first be identified. Section 1, Chapter 2, "Fundamentals of Structurally Safe Building Design," briefly discusses a systematic approach to assessment of fire safety objectives. Decisions must then be made regarding the means to achieve the objectives. The fire safety concepts tree in Section 1, Chapter 2, can be used to obtain an overall perspective of the fire safety system. Venting in conjunction with sprinkler protection continues as a subject of some controversy and is discussed in greater detail in Section 18, Chapter 4, "Venting Practices."

Concepts of egress design, an extremely important part of the design process, are discussed in Section 4, Chapter 3, "Concepts of Egress Design." That chapter, based on NFPA *101*®, *Life Safety Code*®, describes the elements that must be considered when designing adequate egress in buildings for life safety from fire.

For design issues, therefore, see Section 1, Chapter 2, "Fundamentals of Structurally Safe Building Design"; Section 4, Chapter 3, "Concepts of Egress Design"; and Section 18, Chapter 4, "Venting Practices." For other related topics see Section 13, Chapter 5, "Wildland Fire Management"; Section 15, Chapter 1, "Fixed Water Storage Supplies for Fire Protection"; Section 15, Chapter 2, "Water Supply Requirements for Public Supply Systems"; and Section 15, Chapter 6, "Water Distribution."

BUILDING INTERIOR DESIGN CONSIDERATIONS

The architectural design of a building has a significant influence on its fire safety capabilities and performance. In addition to the design of the structure and shell of the building itself, the interior layout and spatial flow, circulation patterns, interior finish materials, and building services are all important factors in the level of fire safety in a building. The design of the building and the relationship of the building to the site or lot can enhance the efficiency of fire department operations by reducing dependence on manual suppression, if the design is executed appropriately. Consequently, fire department operations should be considered in all phases of design.

The primary concept of creating fire safety in structures today involves the philosophy that the building itself must be designed to be either self-protecting or self-controlling from fire and fire spread. This is particularly important as buildings become more complex and exhibit features that

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are contradictory to fire department operations, such as sealed environments for energy efficiency and security against intrusion. The design features that are used should consider the local fire-fighting resources that are available and be effected to reduce the reliance on the intervention of the fire service to ensure fire safety. A building should not be designed today that relies solely on the fire service to provide complete protection for the occupants of the building and property; it must include both active and passive building fire defenses to provide reasonable safety from the effects of fire.

Interior Layout

The interior layout of a building influences safety in two distinct ways: (1) The relative use of interior walls, doors, and other elements of compartmentation, combined with the approach to air handling, the use of open floor plans, and many other barrier-related choices, influence the speed and breadth of spread of fire and smoke. Because smoke and toxic gases are the cause of most deaths due to fires, it is not enough to contain the fire itself in order to protect occupants. (2) The relative complexity of the layout will either reduce or increase the time required for potentially endangered occupants to escape, the likelihood that they will find a way to safety in any reasonable space of time, and the possibility that they will move toward greater hazard rather than away from it.

The role of fire effects as a cause of fatal injury is not the only reason to focus on the role of the interior layout in separating occupants and fire effects. Long before they cause fatal injury, smoke and toxic gas reduce visibility, thereby hindering or reducing the ability to find a safe way out, and cause physical irritation and disorientation, further reducing the speed, effectiveness, and efficiency of escape.

Architectural layout and normal circulation patterns are important elements in emergency evacuation. For example, many large office buildings are a maze of offices, storage areas, and meeting rooms. Even under normal conditions, a visitor can become confused and have difficulty exiting the building. Clearly marked emergency travel routes can enhance life safety features in all buildings.

Building Height

The height of the building also has an impact on the fire safety potential of a building. Under optimum conditions, modern fire department aerial equipment only reaches the equivalent of the seventh floor of a building. Occupants on floors above that level must be evacuated by means of interior stairs. The attack at the World Trade Center Towers in 2001 demonstrated the difficulties that arise in evacuating tall buildings—including the time necessary and the impact of crowded stairs on fire fighter access. Mitigating the impact of building height requires careful attention to the layout and construction of stairs and other key building layout elements.

Building Security

Protecting buildings from unwanted intrusion and from all types of crimes has led to the installation of sophisticated and difficult-to-penetrate security hardware and systems. These systems result in the delay of access for fire fighters to an emergency in a building. Worse, they can delay the evacuation and exit of the occupants from a building. Interconnection of security and locking systems with building alarm systems can unlock doors and facilitate emergency movements. Stairs normally equipped with locks to prevent entry from the stair tower to the floor can be made accessible by the use of electrically operated locks. Another means that can be incorporated in the building design is a key lock box—providing the fire department with access to a building without waiting for someone with a key and requiring less time than forcible entry. Careful consideration must be given to the relationship between building security and emergency operations in a building.

BUILDING DESIGN AND FIRE DEPARTMENT OPERATIONS

From the beginning of the building project, the building designer should consult fire department personnel about fire suppression operations in a building. Normally the code review and planning process will serve this purpose. Such consultation is particularly important in the design phase of a building project. In this way, the designer can incorporate features into the building that will aid, rather than hinder, fire suppression and emergency operations.

Briefly, the operations may be broadly grouped as rescue, fire control, and property conservation. The first priority of any fire-fighting operation is rescue, which is defined as the removal of trapped and injured occupants and the search of all areas to ensure that all occupants are out of the building. The larger the building, the greater the number of fire-fighting personnel that must be committed to the rescue operation. In some cases, simultaneous fire suppression operations will be necessary to complete the rescue operation. Significant design features that are necessary in larger buildings include areas of refuge for the physically disabled, fire department controls for ventilation systems, and emergency communications to critical locations in the building.

Accessibility for Fire Fighting

Building design features are important factors in the spread of fire and the ease of suppression. One of the most important design features involves access to the fire. This includes access to the exterior and interior of the building by fire fighters and their equipment.

Access to the building itself requires roads and fire lanes that are designed to withstand the weight of the heaviest fire apparatus expected to respond. These access lanes must be designed to allow fire equipment to get close enough to all sides of the building for rescue and fire suppression functions. These access lanes must be of sufficient width to ensure they will not be obstructed when needed. NFPA 1, *Uniform Fire Code™,* NFPA 1141, *Standard for Fire Protection in Planned Building Groups,* and NFPA 1144, *Standard for Protection of Life and Property from Wildfire,* are consistent in requiring minimum widths of 20 ft (6.11 m) and 13.5 ft (4.11 m) vertical clearance for fire ac-

cess. Widening of paved surfaces to 26 ft (7.99 m) for the use of aerial apparatus is recommended. These widths do not include any allowance for parking. If parking is present in these areas, the space must be added to these widths. NFPA 1, 1141, and 1144 address turning radii by requiring approval by the local authority having jurisdiction. Some commonly used dimensions are a 22 ft (6.7 m) inside turning radius and 50 ft (15 m) outside turning radius. Larger equipment may need even greater radii.

Access to the interior of a building can be greatly hampered where large areas exist and where buildings have blank walls, false facades, solar screens, or signs covering a high percentage of exterior walls. Obstacles that prevent ventilation allow smoke to accumulate and obscure fire fighters' vision. Lack of adequate interior access can also delay the occupants' evacuation or prevent fire department rescue of trapped occupants or initiation of fire suppression efforts.

Windowless buildings and basements present unique fire-fighting problems, requiring careful consideration on the part of the building designer to mitigate these problems. The lack of natural ventilation facilities, such as windows, contributes to the buildup of dense smoke and intense heat, which hampers fire-fighting operations and endangers occupants trapped in these occupancies. For this reason, automatic sprinkler protection is required for windowless buildings by most building codes to extinguish or control a fire before it reaches life- and property-endangering intensity.

Any spaces in which adequate fire-fighting access and operations are restricted because of architectural, engineering, or functional barriers should be provided with automatic extinguishing systems. A complete automatic sprinkler system is generally the best solution to this problem. Other methods can be incorporated in appropriate design situations, such as access panels in interior walls and floors, fixed nozzles in floors with fire department connections, automatic smoke venting, and pressurization of certain building areas, although none of these items can take the place of, or be considered equivalent to, a complete automatic sprinkler system.

Ventilation

Ventilation is an important fire-fighting operation. It involves the removal of smoke, gases, and heat from building spaces. Ventilation of building spaces performs the following important functions:

1. Protects life by removing or diverting toxic gases and smoke from locations where building occupants must find temporary refuge.
2. Improves the environment in the vicinity of the fire by removal of smoke and heat. This enables fire fighters to advance closer to the fire and extinguish it with a minimum of time, water, and damage.
3. Controls the spread or direction of fire by setting up air currents that cause the fire to move in a desired direction. In this way, occupants or valuable property can be more readily protected.
4. Allows the release of unburned, combustible gases before they develop a flammable mixture, thus avoiding a backdraft or smoke explosion.

The building design engineer should consult NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems,* or NFPA 90B, *Standard for the Installation of Warm Air Heating and Air-Conditioning Systems,* in the design of air-conditioning, heating, and ventilating ductwork and related equipment for all buildings.

The building designer should be conscious of these important fire ventilation functions and provide effective means of facilitating venting practices whenever possible. Designers should also be conscious of system effects, including the interaction of fire-fighting ventilation with a building's HVAC system and the effects of ventilation on the effectiveness of automatic detection and suppression equipment. This may involve access panels, moveable windows, skylights, or other means of readily venting a structure in case of a fire emergency. Emergency controls on mechanical equipment may also be an effective means of accomplishing fire ventilation. Each building has unique features, and, consequently, a unique solution should be incorporated into each design. NFPA 204, *Standard for Smoke and Heat Venting,* should be consulted for additional information on venting. Training for the use and operation of these unique features should be given to fire fighters as part of a preplan for operations at the site, or staff on site should assist fire fighters in the operation of these ventilation systems.

Water Supply and Use

Water is the principal agent used to extinguish building fires. Although other agents may occasionally be employed (e.g., carbon dioxide, dry chemical, foams and surfactants, and halons), water remains the primary extinguishing agent of the fire service. Consequently, the building designer should anticipate the needs of both the fire department and automatic extinguishing systems and provide an adequate supply of water at adequate residual pressure. (See also Section 15, Chapter 1, "Fixed Water Storage Supplies for Fire Protection"; Section 15, Chapter 2, "Water Supply Requirements for Public Supply Systems"; and Section 15, Chapter 6, "Water Distribution.") The Appendices in NFPA 1 are another good source of information on water supply and flow requirements for fires.

In cities, water is normally supplied to the building site by water mains that are part of the municipal water distribution system. Cities may not be able to supply a sufficient amount of water at required pressures to every part of the city. Consequently, alternative means, including pumps and tanks, must designed as part of the building fire protection systems. These systems can then be supplemented, if necessary, by pumps on fire department apparatus.

Careful attention must be given to water supply, distribution, and pressure for emergency fire conditions. High-rise buildings are particularly sensitive because of the higher water pressures required due to the building height. Large-area buildings must also be given careful attention as to water supply needs.

Fire conditions or fire loads that require operation of a large number of sprinklers or use of a large number of hose streams can reduce pressure in sprinkler and standpipe systems to the point where residual pressures in the distribution system are adversely affected. Fire department connections for sprinkler and

standpipe systems, so the fire department can augment system pressure, are therefore important components of the building fire defenses. The building designer must carefully consider installation details of fire department connections to ensure they will be easily located, readily accessible, and properly marked. Locations for the connections should always be approved by the local fire department.

BUILDING DESIGN AND FIRE SUPPRESSION

The building designer has a significant influence on the relative ease and effectiveness of fire suppression operations. It is important not only to incorporate the needs of the fire service into the functional layout of the building and its services but also to properly plan for automatic fire detection and extinguishing capabilities.

Compartmentation

Fire-fighting efficiency decreases rapidly as the fire spreads vertically or past major horizontal barriers. Fires on two or more floors or filling a very large floor space are extremely difficult to control and extinguish by manual fire-fighting methods. Building designs that utilize unprotected vertical openings, such as open stairwells, curtain wall construction not sealed at each floor, poke-through assemblies, and air-handling ductwork (without dampers), provide avenues for vertical fire spread. It is more difficult to isolate a space completely in modern construction than it was in pre-World War II construction, yet isolation can be accomplished if attention is paid to the details of design and construction. Tested details for all components of the modern building are now documented and readily available, as well as computer modeling programs that can demonstrate what might happen within a building without exposing that building to the effects of an actual fire. These details and components of modern construction work best when they are combined with an active construction inspection program.

Detection, Alarm, and Communications

Time is the most significant factor concerning fire control. The time for fire control includes several distinct segments, including fire detection, occupant notification, fire department notification, fire department response, fire situation assessment, suppression activities, and overhaul operations. In the early development stages of a fire, a matter of minutes is a significant factor both in life safety and in manual fire extinguishment capabilities. Consequently, effective fire detection becomes a vital element in fire safety. After a fire or smoke detector is activated, appropriate action must be initiated. This may involve alarm, communications, fire suppression, or a combination of these activities. An alarm may alert building occupants to the existence of a fire, but what action should then be taken? Evacuation is the normal procedure in smaller buildings. In high-rise buildings, however, total evacuation takes much more time. Consequently, zoned evacuation and/or safe areas of refuge may be considered within the building, and instructions could be given to building occupants concerning the appropriate course of action. This "defend in place" approach is reasonable for localized or minor emergencies. Ultimately, evacuation of the public from problem areas is the most desirable strategy and is consistent with the training that the public receives beginning in elementary school.

Communications are vital in occupant safety and fire control. Communications help warn occupants, provide instructions for action, alert the fire department early about the existence and location of a fire, and can assist the fire department in manual fire suppression. Too often, fire department notification has been delayed because occupants were under the mistaken impression that a local fire alarm system notified the fire department.

Communications systems that are intended to provide emergency voice messages and to give evaluation directions must be designed to meet the survivability requirements in *NFPA 72®*, *National Fire Alarm Code®*, to ensure that they will operate in the adverse conditions found in building emergency situations.

Automatic Fire Suppression

For more than a century, automatic sprinklers have been the most important single system for automatic control of fires in buildings. Many desirable aesthetic and functional features of buildings that might offer some concern for fire safety can be protected by the installation of a properly designed sprinkler system.

Among the advantages of automatic sprinklers is that they operate directly over a fire and are not affected by smoke, toxic gases, or reduced visibility. In addition, much less water is used because only those sprinklers fused by the heat of the fire operate, particularly if the building is compartmented. Sprinkler systems must be designed and installed to provide this level of protection. (See NFPA 13, *Standard for the Installation of Sprinkler Systems*.) Other automatic extinguishing systems (carbon dioxide, dry chemical, halon agents, high-expansion foam) also provide protection in certain portions of buildings or types of occupancies for which they are particularly suited. Other advantages that sprinklered properties may offer include allowance of alternative designs, reduction of some features, and lower insurance rates.

SITE PLANNING

The architect must use a given site in designing the building and adapt the functional and engineering considerations to the particular site conditions that are present. In a similar manner, the architect should consider site features in arriving at decisions on fire protection. A particular set of site characteristics may significantly influence the type of building fire defenses incorporated by the design team. Among the more significant features are traffic and transportation conditions, fire department access, and water supply. Water supply was discussed briefly earlier in this chapter. A few additional considerations are given here.

Traffic and Transportation

Time is a vital factor in fire control. The response time of the fire department can be a major component of the overall time

for fire control. Fire apparatus must respond to a location via streets at all times of the day. Depending on traffic conditions, apparatus can be seriously delayed in responding to some locations.

It may or may not be helpful to consider limited access highways for fire department response. Highways may attract motorists, thus improving traffic conditions on other city streets. On the other hand, the limited access highway may divide a community into sections. Means of travel to locations intermediate to the access points can be delayed. This can have a significant effect on response times and must be considered by the design team in selecting the appropriate fire defenses for the building. Lengthy response times may dictate greater built-in fire protection capability.

Fire Department Access

Ideal exterior accessibility occurs where a building can be approached by fire department apparatus from all sides. This, unfortunately, is not often possible. In congested areas, only the sides of buildings facing streets may be accessible. In other areas, topography or other obstacles can prevent effective use of apparatus in combatting the fire.

Some shopping centers and buildings that are located some distance from the street make the approach of apparatus difficult. If obstructions or topography prevent apparatus from being located close enough to the building for effective use, such equipment as aerial ladders, elevating platforms, and water tower apparatus are rendered useless. Valuable manpower must be expended to carry ground ladders or hand carry hose lines long distances.

The matter of access to buildings has become far more complicated in recent years. The building designer must consider this important aspect in the planning stage. Inadequate attention to site details can place the building in an unnecessarily vulnerable position. If its fire defenses are compromised by preventing adequate fire department access, more complete internal protection in the building itself must make up the difference. If fire department access is limited or nonexistent, complete automatic sprinkler protection should be provided throughout the structure. Other features may be required.

Location of Hydrants

An adequate water supply delivered with the necessary pressure is important to control a fire. In many new developments, such as shopping centers, apartments, and housing projects, inadequate attention is given to the number and location of hydrants. There are situations that present extremely difficult fire-fighting problems where water mains are so small and hydrants are so poorly spaced that adequate water to control a fire is unavailable. The building designer must consider the importance of an adequate and accessible water supply in the planning and design of a building. NFPA 14, *Standard for the Installation of Standpipe and Hose Systems,* and NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances,* provide good sources of information for the planning and design of site-related fire defenses.

EXPOSURE PROTECTION

A fire in one building creates an external fire hazard to neighboring structures by exposing them to heat by radiation and convection, as well as to the danger of flying brands from the fire. Any or all of these sources of heat transfer may be sufficient to cause an ignition in the exposed structure or its contents. This part of the chapter describes a method for evaluating exposure severity and suggests methods for protecting buildings from exterior fire exposures. These methods are aimed at protecting combustibles within, and on the exterior of, an exposed building. NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures,* is a source for further information on exposure protection.

Factors Influencing Severity of Exposure

When discussing protection from exposure fires, there are three conditions to be considered: (1) exposure to horizontal radiation, (2) exposure to flames issuing from the roof or top of a burning building in cases where the exposed building is greater in height than the burning building, and (3) airborne debris or brands that can be carried to a new building to start a fire. Radiation exposure can result from an interior fire where the radiation passes through windows and other exterior wall openings. It can also result from the flames issuing from the windows of the burning building or from flames of the burning facade itself (Figures 11.3.1, 11.3.2, and 11.3.3). In the Burlington Building in Chicago in 1922, fire in a group of brick, wood-joisted buildings spread across the 80 ft (24 m) street to ignite the upper seven floors of the 15 story office building, which was of fire-resistive construction but lacked exposure protection for street-front windows. Wind carried hot gases against the Burlington Building. Updraft due to convection made exposure most severe above the level of exposing buildings (see Figure 11.3.1). In Wellesley, Massachusetts, a fire started, igniting a building in Newton by radiated heat across the Charles River, a 100 ft (30 m) distance, against the wind. The river prevented access for fire department operations to protect the exposure (see Figure 11.3.3). Distances of 10 to 20 ft (3 to 6 m) between frame buildings, as commonly specified by building codes, do not eliminate exposure hazard but usually provide space for fire department operations (see Figure 11.3.2).

A number of factors significantly influence the danger and intensity of exposing fires to neighboring structures. Among the more important parameters is the severity of the exposing fire (total energy of the fire) itself. It involves both the temperatures developed within the exposing fire and the duration of burning. NFPA 80A describes means for protecting buildings from fire damage resulting from exposure to an exterior fire in an adjacent structure or property. In the past, NFPA 80A categorized exterior exposures into three levels of exposure severity—light, moderate, or severe. The classifications were based on (1) the average combustible load per unit of floor area and (2) the average flame spread ratings of the interior wall and ceiling finishes.

Besides the temperature and duration of the exposing fire, other variables influence the severity of exposure on buildings. Some of these variables include the following:

1. Exposing fire
   a. Type of construction of exterior walls and roofs

FIGURE 11.3.1 The Burlington Building (right), Chicago, March 15, 1922

FIGURE 11.3.2 Typical Ignition of Wood-Frame Dwelling by Heat Radiated from an Exposure Fire

b. Width of exposing fire
c. Height of exposing fire
d. Percent of openings in exposing wall area; exterior walls that are combustible or that do not have sufficient resistance to contain the fire should be treated as having 100 percent openings
e. Ventilation characteristics of the burning room
f. The fuel dispersion, or surface-to-volume ratio of the fuel
g. The size, geometry, and surface-to-volume ratio of the room involved
h. The thermal properties, conductivity, specific heat, and density of the interior finish
i. Whether or not the exposing building is fully sprinklered

FIGURE 11.3.3 Fire Starting in Wellesley, Massachusetts

2. Exposed building
   a. Type of construction of exterior walls and roofs
   b. Orientation and surface area of exposed exterior walls
   c. Percent of openings in exterior wall area
   d. Protection of openings
   e. Exposure of interior finish and combustibles to the radiation, convection, and flying brands of the exposing fire
   f. Thermal properties, conductivity, specific heat, density, and fuel dispersion of the interior finish materials and the building contents
   g. Whether or not the exposed building is fully sprinklered
3. Site and protection features
   a. Separation distance between exposing and exposed building
   b. Shielding effect of intervening noncombustible construction
   c. Wind direction and velocity
   d. Air temperature and humidity
   e. Accessibility for fire-fighting operations
   f. Extent and character of fire department operations
   g. Built-in fire protection features

Finally, it is worth noting that during construction a large building is more vulnerable to an exposing fire and thus more dangerous than it will be when it is completed. Also, buildings in the wildland/urban interface have unique exposure problems. (See Section 13, Chapter 5, "Wildland Fire Management" for additional discussion of this topic.)

Design Guidelines for Exposure Protection

When analyzing or designing a building for exposure protection, two situations are considered. The first occurs where the exposing building is equal or greater in height than the exposed building. In this case, only the thermal radiation from walls or wall openings is considered. The second case arises when the exposing building is shorter than the exposed building. This will affect the walls and wall openings for some distance above the exposing building—requirements for which are usually found in the building code.

Naturally, site conditions and economic constraints preclude the opportunity of providing most buildings with the calculated separation distance. When this occurs, the separation may be reduced by protecting the structure. NFPA 80A addresses the exposure risk by considering the following means of exposure protection, listed below without any prioritization:

1. Buildings
   - Separation between buildings
   - Total automatic sprinkler protection
2. Walls
   - Blank walls of noncombustible materials
   - Barrier walls (self-supporting) between building and exposure
   - Masonry parapet walls or horizontal extensions that extend beyond the construction
   - Automatic exposure protection sprinkler systems for combustible walls
3. Wall openings
   - Elimination of openings by filling with equivalent construction
   - Glass block panels in openings
   - Fire-rated windows and frames
   - Automatic exposure protection sprinkler systems
   - Listed automatic window sprinklers
   - Listed automatic fire shutters on openings
   - Listed automatic fire doors on door openings
   - Listed automatic fire dampers on wall openings

Additional means of protection are continually being developed, including new glazing materials and rated frames and fire-retardant coatings. As new means become available, due diligence is necessary to assure that they have been properly tested and approved. Means that require manual operation at the time of the exposure should not be used. Assuming that someone will be present to activate a device or will arrive in time is contrary to the concept of built-in protection.

These methods should be evaluated for suitability along with consideration of other potentially adverse effects and conditions including convected heat, flame impingement, and small flying brands associated with winds, as well as the beneficial effects of fire department operations. Additionally, the potential duration of the exposing fire and the fire load should be included in the final evaluation of the specific condition or detail.

Selecting the means of protection should consider the means, the appropriateness of the application, the contributing conditions, and duration of the exposure. Another step in the selection must be confirmation of the approval of the means and the specific installation for the intended use. Standards such as NFPA 80 for fire doors and windows and NFPA 13 for automatic sprinklers are basic resources for those approvals. Deviations from the approved methods of installation should be avoided.

The separation of the building to be protected from the potential exposure risk is the other key consideration in the overall protection scheme. NFPA 80A presents a series of tables that provide separation distance adjustments based on the construction of the walls (combustibility and materials), the presence of openings, and the means of protection selected for the building.

It should be noted that none of these measures is necessary, or even desirable, when both the exposing and exposed properties are provided with a complete fire sprinkler system.

SUMMARY

This chapter presented broad guidelines that building designers should follow to provide fire-safe environments for structures and their sites. The design of a building directly affects its fire safety capabilities and performance, including fire department operations, fire suppression, and exposure protection of other buildings. Site planning is equally important, in terms of traffic and transportation, fire department access, and water supply.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on building and site planning for fire safety. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 72®, National Fire Alarm Code®
NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 90B, *Standard for the Installation of Warm Air Heating and Air-Conditioning Systems*
NFPA *101®*, *Life Safety Code®*
NFPA 204, *Standard for Smoke and Heat Venting*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 1141, *Standard for Fire Protection in Planned Building Groups*
NFPA 1142, *Standard on Water Supplies for Suburban and Rural Fire Fighting*
NFPA 1144, *Standard for Protection of Life and Property from Wildfire*

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Chapter 4

Fire Hazards of Construction, Alteration, and Demolition of Buildings

Richard J. Davis

Chapter Contents

Planning
Construction and Alterations
General Concerns
Supervision of Fire Protection
Demolition Operations
Asbestos Removal
Underground Operations

Key Terms

construction, demolition, exposure protection, hot work, rehabilitation, renovation, temporary structure, welding blanket, welding pad

Buildings and other structures, regardless of construction type or construction method, are more vulnerable to fire when they are under construction, alteration, or demolition than when completed or when the demolition is finished. The reason for this is that when fires occur, they are likely to spread more rapidly due to the absence or impairment of fire suppression and detection systems, lack of compartmentation, and the presence of heavier concentrations of readily ignitable combustibles than would be expected during normal use. In new construction, fires can more easily cause severe damage because of incomplete structural systems, lack of applied fire-resistant materials, and the exposed condition of the structure. The use of hot work in these operations also increases the likelihood of a fire. Fires can also cause the destruction of building materials stored on site, lengthy delays in project completion, long-term business interruption, and injury or the possible loss of life.

Based on information gathered from 1995 to 2005 by a large industrial and commercial insurance carrier,[1] 46 percent of construction-related fires were caused by hot work, 14 percent were caused by incendiarism or vandalism, 8 percent were of electrical origin, 20 percent were undetermined, and most of the remaining causes were related to smoking or heating equipment. This included a total of 132 fire losses with a gross loss cost of $238 million (Table 11.4.1).

This chapter discusses the fire hazards associated with the construction, alteration, and demolition of buildings. Special situations, such as asbestos removal and underground structures, are also discussed. Practices for the prevention of fires, prefire planning, storage of combustible materials, and installation of fire protection systems are specifically addressed in the chapter.

Additional information on hazards associated with building construction, fire protection systems, and prefire planning can be found in Section 1, Chapter 2, "Fundamentals of Structurally Safe Building Design"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 7, Chapter 3, "Storage of Gases"; Section 9, Chapter 6, "Welding, Cutting, and Other Hot Work"; Section 11, Chapter 3, "Building and Site Planning for Fire Safety"; Section 12, Chapter 11, "Industrial Fire Loss Prevention"; Section 12, Chapter 17, "Pre-Incident Planning for Industrial and Municipal Emergency Response"; Section 16, Chapter 3, "Automatic Sprinkler Systems"; Section 16, Chapter 10, "Standpipe and Hose Systems"; and Section 19, Chapter 1, "Types of Building Construction."

PLANNING

Construction operations can be made reasonably safe in new construction, rehabilitation, or demolition projects with adequate planning, proper allowances in job estimates, and proper on-site supervision and control. Although new construction, rehabilitation, and demolition projects differ

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TABLE 11.4.1 Structure Fires in Properties That Are Under Construction, Major Renovation, or Demolition, 1999–2002 Annual Averages

Building Status	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
Under construction	4,800	6	97	235
Under major renovation	3,900	9	98	85
Under demolition	2,300	0	16	11
Total	11,100	15	211	331

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, deaths and injuries to the nearest one, and direct property damage to the nearest million dollars. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey and Marty Ahrens, "Structure Fires in Properties under Construction, Major Renovation, or Demolition, 1999-2002 Annual Averages," Fire Analysis and Research Division, NFPA, Mar. 2006.

greatly in the scope of work, they have many fire safety items in common. These common items relate to establishment and maintenance of on-site fire protection, provisions for temporary fire protection, and maintenance of means of escape for workers and others in the building. NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations,* contains measures that, with prefire planning, will help prevent fire or at least minimize damage when fire occurs.

Security guard service on construction sites is recommended during nonworking hours. Patrols should be planned so that no portion of the job site is overlooked. The use of guard clock and time recording systems is recommended to ensure patrols have been made. Guards should be briefed on the fire protection measures available on the job site, on developments during the workday that affect fire hazards and fire protection capabilities, and on emergency procedures. Provision (either a telephone or a fire alarm box) should be made for notifying the fire department in the event of a fire. Provision for security service should be considered as a part of the project planning stage. NFPA 601, *Standard for Security Services in Fire Loss Prevention,* should be consulted for planning security service.

In any project, whether new construction, rehabilitation, or demolition, the fire department should be kept aware of construction progress. The fire department can thereby provide for command posts and prefire plans and be ready to deal with unusual problems encountered during the course of the project.

CONSTRUCTION AND ALTERATIONS

Site Preparation

Site preparation is the first item necessary in any new construction project. This involves the removal of brush, trees, and debris from the site prior to the start of construction. Although such land clearing provides for control of natural cover fuel fires, it mainly provides site accessibility for construction. Today's methods of site preparation differ from the "scorched earth" methods of years ago in that the preservation of as much natural vegetation as practical is desired. This should present no serious fire problem as long as temporary buildings and materials storage are properly isolated from any natural cover fuel by fire breaks of at least 30-ft (9.2-m) width.

Of prime importance for site preparation is the establishment of roadways and the installation of a water supply for fire protection. Many jurisdictions now require that permanent all-weather roads and site utilities be provided before construction begins. Construction site access by temporary or permanent all-weather roadways should be provided, as well as water service for fire protection, prior to the start of construction.

Although it is usually more economical to provide permanent water service to serve the construction fire protection needs early in the project, it is sometimes necessary to provide temporary water service in the form of aboveground water mains, tanker trucks, or ponds.

Temporary Buildings

Temporary buildings are commonly used on construction sites for the storage of tools and equipment, and serve as temporary offices for the construction management team. The use of mobile structures, such as converted manufactured homes or trailers, is common at large construction projects. The location of these temporary buildings can create a serious exposure hazard either to the building under construction or to the group of temporary buildings themselves. Often mobile structures are attached or installed adjacent to each other, creating a larger building with greater hazards than one structure alone.

It is important to consider the added exposure protection necessary if several temporary or mobile structures are on the same site. Single-story unprotected temporary buildings of combustible construction, or with combustible contents, should be located according to Table 11.4.2. When the separation distance between temporary structures is less than the minimum separation distance as specified in the table, then the exposing wall length is the sum of the individual exposing wall lengths of the temporary structures. Providing automatic sprinkler protection in the temporary buildings can be used to reduce the separation distance between temporary structures by 75 percent.

The fire hazards are much the same whether a mobile structure or a temporary structure is used. Overloaded temporary wiring, incorrectly installed portable or temporary heating equipment, and inadequate control of open-flame devices are examples of the common hazards. The high level of fuel load in the form of construction materials, construction plans, specifications, and other documents further increases the fire hazards. In

TABLE 11.4.2 Separation Distances

Temporary Structure Exposing Wall Length		Minimum Separation Distance	
m	*ft*	*m*	*ft*
6	20	9	30
9	30	11	35
12	40	12	40
15	50	14	45
18	60	15	50
>18	>60	18	60

Notes:
1. Where the separation distance between temporary structures is less than the minimum separation distance, then the exposing wall length shall be considered to be the sum of the individual exposing wall lengths of the temporary structure.
2. A 75 percent reduction in separation distances shall be permitted to be applied, provided automatic sprinkler protection is used in the exposing structure.
3. The separation distances apply to single-level structures only. This table does not apply to multilevel, unsprinklered structures. A level, where applying this table, is 3600 mm (144 in.).

Source: NFPA 241, *Standard for Safeguarding Construction, Alterations, and Demolition Operations,* Table 4.2.1, 2004, pp. 241–245.

addition, the use of space (sometimes concealed) beneath these temporary structures for miscellaneous storage can be hazardous. Such spaces and storage can be subject to vandalism and arson. Incendiary or suspicious causes are by far the number one cause accounting for nearly one half of the reported fires in these temporary buildings (what the fire incident codes call "contractors' sheds"). Vegetation growing under, or left in, these spaces can also create hazards.

The protection of these structures, especially mobile structures, is usually possible by the installation of a residential-type sprinkler system using listed plastic pipe that can be connected to the on-site water supply. The cost of this protection is low for the mobile structures, since there is only a one-time installation cost, and connection costs on the site are minimal.

Loss Prevention During Construction

Normal construction practices require considerable amounts of combustible building materials, forms, and scaffolding, which tend to accumulate in congested areas. Temporary storage of combustible materials in the yard or on the roof should be kept to a minimum and limited to 6 ft (1.8 m) in height and one or two pallet widths. Where space permits, combustible storage should be located at least 30 ft (9 m) from the structure being exposed. Those areas of a building where the fire-resistant coatings for structural steel have not been completed should not be used for the storage of combustible items. Foamed plastic materials should be stored only to a maximum height of 5 ft (1.5 m) and only in areas where automatic sprinkler protection is in service.

Water service at the site should be adequate not only for the final building construction needs, but also for fire protection during construction, in view of the amount of combustibles present. In multistory structures, either temporary or permanent standpipes should be put into service as each floor is constructed to provide fire-fighting capability. Temporary standpipe service is usually a dry standpipe with proper valves at each floor. A fire department siamese connection, easily accessible to fire department pumpers, should be provided at the street. If the siamese connection is located inside the construction site, clear access to the siamese connection via all-weather roads should be maintained. Large signs indicating the location of the fire department connection and the top level of the standpipe should be installed to assist the local fire department.

Temporary enclosure of buildings is common and should only be done with care. Only flame-resistant tarpaulins or materials of similar fire-retardant characteristics should be used (Figure 11.4.1). If temporary enclosure is required, metal or fire-retardant-treated wood forms spaced about every 4 ft (1.2 m) should be used to support the material. The enclosure materials should be securely fastened or guarded to prevent contact with heaters or other sources of ignition. Fabric or plastic film should meet the requirements of NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films.* Tarpaulins that appear weathered may have lost their fire-retardant qualities and should not be used.

Combustible formwork is a constant source of danger to concrete buildings under construction. Concrete should be poured as quickly as possible after combustible forms have been constructed and the forms removed as soon as possible after the concrete has set properly. During the time the forms are in place, storage and construction operations on that floor should be held to a minimum and ignition sources should be eliminated. Noncombustible forms should be used whenever possible

FIGURE 11.4.1 Large Sheets of Plastic Enclose Buildings Under Construction to Confine Heat

(Figure 11.4.2). Yard storage of combustible forms should be at least 30 ft (9 m) from the building.

Where fire-resistant coverings for structural members are specified, they should be applied as soon as possible to afford fire protection to beams, columns, and other structural elements early in the construction phase.

Rubbish and trash accumulations can present a serious fire hazard on the construction site. Daily cleanup of scrap lumber, cardboard, and other debris removes the fire hazard and provides a safer working environment. Trash containers should be provided on site for proper storage of debris and should be located at a safe distance from the building.

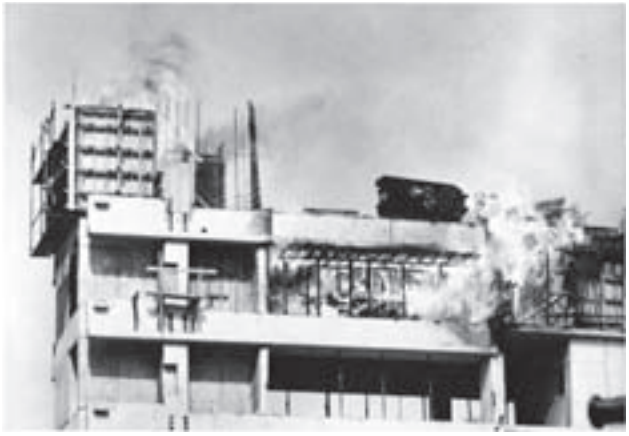

FIGURE 11.4.2 Burning Wood Formwork for Cast-in-Place Floor and Wall Panels in a Parking Garage

GENERAL CONCERNS

Hot work and trash removal are concerns with construction, alteration, and demolition. Asbestos removal is a concern during some alteration and demolition projects.

HOT WORK PERMIT

STOP!
Avoid hot work or seek an alternative/safer method, if possible.

This *Hot Work Permit* is required for any temporary operation involving open flames or producing heat and/or sparks. This includes, but is not limited to: brazing, cutting, grinding, soldering, torch-applied roofing and welding.

Part 1

Instructions

1. Fire safety supervisor:
   A. Verify precautions listed at right (or do not proceed with the work).
   B. Complete and retain Part 1.
   (Part 1A is for quality assurance documentation, if necessary.)
   C. Issue Part 2 to person performing hot work.

Hot work by
☐ Employee
☐ Contractor

Date | Job number

Location/building and floor

Nature of job

Name (print) and signature of person performing hot work

I verify the above location has been examined, the precautions checked on the Required Precautions Checklist have been taken to prevent fire, and permission is authorized for this work.

Name (print) and signature of fire safety supervisor/operations supervisor

Permit Expires | Date | Time a.m. p.m.

Note: Emergency notification on back of form.
Use an appropriate for your facility

To order additional hot work permits or other FM Global resources, order online 24 hours a day, seven days a week, at www.fmglobalcatalog.com.

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Required Precautions Checklist

☐ Available sprinklers, hose streams and extinguishers are in service/operable.
☐ Hot work equipment in good working condition.

Requirements within 35 ft. (11 m) of hot work

☐ Flammable liquid, dust, lint and oily deposits removed.
☐ Explosive atmosphere in area eliminated.
☐ Floors swept clean.
☐ Combustible floors wet down, covered with damp sand or fire resistive sheets.
☐ Remove other combustible material where possible. Otherwise, protect with FM Approved welding pads, blankets and curtains, fire resistive tarpaulins or metal sheets.
☐ All wall and floor openings covered.
☐ FM Approved welding pads, blankets and curtains installed under and around work.
☐ Protect or shut down ducts and conveyors that might carry sparks to distant combustible material.

Hot work on walls, ceilings or roofs

☐ Construction is noncombustible and without combustible covering or insulation.
☐ Combustible material on other side of walls, ceilings or roofs is moved away.

Hot work on enclosed equipment

☐ Enclosed equipment cleaned of all combustible material.
☐ Containers purged of flammable liquid/vapor.
☐ Pressurized vessels, piping and equipment removed from service, isolated and vented.

Fire watch/hot work area monitoring

☐ Fire watch will be provided during and for 60 min. after work, including any break activity.
☐ Fire watch is supplied with suitable extinguishers, and where practical, a charged small hose.
☐ Fire watch is trained in use of equipment and in sounding alarm.
☐ Fire watch may be required in adjoining areas, above and below.
☐ Monitor hot work area for an additional three (3) hours after the 60 min. fire watch.

Other precautions taken

☐

FIGURE 11.4.3 Hot Work Permit (Source: © 2006 FM Global. Reprinted with permission. All rights reserved.)

Hot Work

Hot work such as cutting and welding operations must be carefully controlled, and proper safeguards utilized. Fires started by welding, cutting, plumbing, or other torches account for one of the largest shares of construction fires. A permit system that specifies controls for safe welding should be used. Combustible materials within 35 ft (11 m) of any cutting or welding operation need to be protected by being relocated, covered with noncombustible materials, or, as a last resort, being wet down prior to and during the operation. Follow the fire protection procedures in NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work.*

Listed welding blankets and welding pads are now available[2] for use in covering combustibles at or near a hot work operation. A *welding blanket* is a heat-resistant fabric designed to be placed in the vicinity of a hot work operation. It is intended for use in horizontal applications with light to moderate exposures such as that resulting from chipping, grinding, heat treating, sand blasting, and light horizontal welding. It is designed to protect machinery and prevent the ignition of combustibles such as wood that are located adjacent to the underside of the blanket. A *welding pad* is a heat-resistant fabric designed to be placed directly under a hot work operation such as welding or cutting. It is intended for use in horizontal applications with severe exposures such as those resulting from molten substances or heavy horizontal welding. It is designed to prevent the ignition of combustibles that are located adjacent to the underside of the pad.

The hot work permit serves several functions: evaluation of the fire hazards in the immediate area where hot work is to be performed, specification of requirements for fire suppression, elimination of hazardous activities, and notification of the security service of the location of the hot work. The construction manager should designate an individual, other than the operator of the heat-producing equipment, to complete the permit. Figure 11.4.3 is a sample two-part hot work permit; the second part should be posted in the hot work area.

A qualified individual should be assigned the responsibility of being the fire watch during hot work operations. It is

HOT WORK PERMIT

STOP!
Avoid hot work or seek an alternative/safer method, if possible.

This *Hot Work Permit* is required for any temporary operation involving open flames or producing heat and/or sparks. This includes, but is not limited to: brazing, cutting, grinding, soldering, torch-applied roofing and welding.

Part 1A

Instructions

1. Fire-safety supervisor:
   A. Verify precautions listed at right (or do not proceed with the work).
   B. Complete and retain Part 1.
   C. Issue Part 2 to person performing hot work.

Hot work by:
☐ Employee
☐ Contractor

Date | Job number

Location/building and floor

Nature of job

Name (print) and signature of person performing hot work

I verify the above location has been examined, the precautions checked on the Required Precautions Checklist have been taken to prevent fire, and permission is authorized for this work.

Name (print) and signature of fire-safety supervisor/operations supervisor

Permit Expires | Date | Time a.m. p.m.

Note: Emergency notification on back of form.
Use as appropriate for your facility.

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Required Precautions Checklist

☐ Available sprinklers, hose streams and extinguishers are in service/operable.
☐ Hot work equipment in good working condition.

Requirements within 35 ft. (11 m) of hot work

☐ Flammable liquid, dust, lint and oily deposits removed.
☐ Explosive atmosphere in area eliminated.
☐ Floors swept clean.
☐ Combustible floors wet down, covered with damp sand or fire-resistive sheets.
☐ Remove other combustible material where possible. Otherwise, protect with FM Approved welding pads, blankets and curtains, fire-resistive tarpaulins or metal shields.
☐ All wall and floor openings covered.
☐ FM Approved welding pads, blankets and curtains installed under and around work.
☐ Protect or shut down ducts and conveyors that might carry sparks to distant combustible material.

Hot work on walls, ceilings or roofs

☐ Construction is noncombustible and without combustible covering or insulation.
☐ Combustible material on other side of walls, ceilings or roofs is moved away.

Hot work on enclosed equipment

☐ Enclosed equipment cleaned of all combustible material.
☐ Containers purged of flammable liquid/vapor.
☐ Pressurized vessels, piping and equipment removed from service, isolated and vented.

Fire watch/hot work area monitoring

☐ Fire watch will be provided during and for 60 min. after work, including any break activity.
☐ Fire watch is supplied with suitable extinguishers, and when practical, a charged small hose.
☐ Fire watch is trained in use of equipment and in sounding alarm.
☐ Fire watch may be required in adjoining areas, above and below.
☐ Monitor hot work area for an additional three (3) hours after the 60 min. fire watch.

Other precautions taken

☐ _____

FIGURE 11.4.3 Continued

important that the fire watch be located in a position to observe where the falling hot materials land. This may be in a location not directly within the cutting and welding operation area.

For additional hot work guidelines, see Section 9, Chapter 6, "Welding, Cutting, and Other Hot Work."

Trash Removal

It is common practice to provide chutes for the removal of trash and debris from the upper floors. If chutes are used, they should be noncombustible and erected outside the building. By installing the chute as straight as possible, the potential for obstructions in the chute will be minimized.

Although noncombustible trash chutes are recommended, combustible plastic trash chutes are often found in use. Although NFPA 241 recommends that protection be provided for combustible trash chutes, no consensus method of protection exists. A possible method of protection is a sprinkler(s) to protect the inside of the chute. Precautions would be needed to prevent damage to the sprinkler head from debris thrown into the chute. This would include the provision of a recess in the top section of the chute and any intermediate sections where sprinklers are installed. Sprinklers should also be protected with a guard (such as used for in-rack sprinklers) and connected to any available water supply using a flexible sprinkler connector and a small hose. Tall chutes would require intermediate protection.

Dumpsters should be separated from combustible construction or unprotected windows (Figure 11.4.4).

CASE STUDY: Combustible Construction Debris. A five-story, wood-framed building was being constructed in an urban area. Sprinklers were to be installed within the next few weeks, and much of the combustible construction materials had not yet been sheathed with a thermal barrier. Scraps of combustible materials were discarded into a dumpster placed at ground level. The dumpster was immediately adjacent to the new building and a plastic trash chute was being used to feed the dumpster. The dumpster was full and trash bags were backing up into the chute. Cigarette butts were later found in some of the unburned trash bags in the dumpster. A fire started within the dumpster, ignited the plastic trash chute, and spread to the building under construction (Figure 11.4.5). The fire completely destroyed the building under construction and spread fire to many other buildings in the neighborhood (Figure 11.4.6). A total of over 20 buildings and 20 vehicles were damaged by the fire. Windows in a brick building across the street and at least 100 ft away were broken from the fire (Figure 11.4.7). This fire emphasizes the need to empty dumpsters when full, to keep dumpsters away from combustible buildings, to use noncombustible trash chutes, and to control ignition sources on the job site. It also emphasizes the importance of expediting the installation of sprinklers and the vulnerability of combustible construction materials before they are sheathed.

Temporary Heating

Salamanders and other temporary heating devices have been responsible for numerous fires that have resulted in millions of

FIGURE 11.4.4 Dumpster Separated from Building at Construction Site

FIGURE 11.4.5 Fire That Started in Combustible Waste in Dumpster, Spread via Plastic Trash Chute

FIGURE 11.4.6 Five-Story Building Under Construction Completely Involved in Fire

FIGURE 11.4.7 Damage to the Neighborhood. Windows broke in brick building 100 feet from the fire.

dollars in property losses. When salamanders are in use, they should be visually inspected every one-half hour to ensure that combustibles have not blown over or fallen near the temporary heating device. This may require the use of security guards during nonconstruction hours. During windy periods, it may be necessary to constantly attend the temporary heating devices being used. Any object that is too hot to touch should be moved or the heating device relocated. Liquefied petroleum gas (LP-gas) cylinders used to fuel temporary heating devices should be securely fastened to prevent falling. Visual inspection should also ensure that the heating appliance is operating properly. Requirements in NFPA 58, *Liquefied Petroleum Gas Code,* should be followed for LP-gas heating device operation. Permanent heating plants and temporary nonfired heat exchangers can often be used to supplant the more hazardous salamanders.

Flammable and Combustible Liquids

Flammable and combustible liquids present obvious fire protection problems. They should be stored and handled in approved metal containers or in their original shipping containers. Containers should be tightly closed when not in use. Some materials, such as contact cement, are extremely hard to pour, and should be left in their original containers. Care must be taken to ensure that these liquids are not stored in exits or stairways and that they do not block access to fire-fighting equipment. Quantities of more than 25 gal (95 L) of flammable or combustible liquids should be stored in approved flammable liquid storage cabinets or other acceptable structures. See Section 4.3 of NFPA 30, *Flammable and Combustible Liquids Code,* for maximum storage quantities for cabinets. NFPA 30 also provides information for the safe handling, dispensing, and storage of flammable and combustible liquids. Storage of more than 60 gal (227 L) of Class I and Class II liquids should be at least 50 ft (15 m) from buildings under construction. The area around the outside flammable liquid storage area should be maintained free of combustible materials, such as weeds, debris, and construction materials.

Internal combustion engines for pumps, air compressors, and so on, should be placed to avoid the discharge of the exhaust near or contacting combustibles. A minimum of a 6-in. (152-mm) clearance to combustibles should be maintained if the exhausts are piped to the exterior. The engine should be shut down and allowed to cool prior to refueling to prevent flash fires. Electric, hydraulic, or pneumatic-driven equipment should be used in underground or basement locations or windowless buildings.

Roofing Operations

Tar and asphalt kettles should be located outdoors and should not be located on a roof. Uninsulated fuel containers should be kept at least 10 ft (3 m) from the burner flame and should be secured to prevent tipping or falling over. Metal covers (at least 14 gage) should be provided to smother potential fires in asphalt and tar kettles. At least one 20-B-rated fire extinguisher should be located no less than 5 ft (1.5 m) and no greater than 25 ft (7.6 m) of horizontal travel distance of every roofing kettle at all times. If the roof is of combustible construction, at least one 2A:20-B:C-rated fire extinguisher should be available on the roof. Should a fire occur, it is important to remember that water thrown into the tar kettle may cause the tar to froth and it may overflow the container. Roofing mops should never be left indoors near ignition sources or combustible materials. Roofing mops soaked with tar can be susceptible to spontaneous ignition; however, modern roofing materials are less susceptible to this problem. To reduce this problem, mops should be spun to remove excess tar and hung or placed so that the mop head is not in contact with combustible materials or other mop heads.

During some roofing operations, it may be necessary for a fire watch to also be located under the roof. Particular attention should be paid to areas, such as around flashing, that are being heated by torches. The fire watch should have a portable fire extinguisher or water-charged hose line that can be used to extinguish small fires that start from hot slag or sparks when steel deck is being welded in place. The fire watch should not have any other duties during this time and should remain as the fire watch after the hot work has been completed. Security guard services should pay additional attention to areas where hot work was conducted during the previous shift.

Torch-applied roofing systems should be installed using extreme caution. All roofers who use a torch should be trained by someone who has passed the Certified Roofing Torch Applicator (CERTA) program implemented by the Midwest Roofing Contractors Association (MRCA) and the National Roofing Contractors Association (NRCA). Torch-applied roofing is considered hot work, and fire watches should be maintained during and after torch use. The area under the roofing operation should also be checked frequently by the fire watch. The NRCA recommends a minimum 2-hour fire watch after work is complete, including checks of the top and bottom roof surfaces for smoldering. Care must be taken so that the membrane is not overheated or excessively smoking.

The flame of the torch should not come in contact with wood nailers, cant strips, or metal flashing. Nor should the torch be used where the flame impingement cannot be fully observed. Extreme caution should be used near penetrations such as exhaust vents because flames could ignite grease and lint accumulations. Such accumulations should be cleaned before roofing work is started. Ventilation equipment should be shut down. A base ply should be used to protect wood deck, combustible insulation or cover boards (such as foam, kraft-faced glass fiber or wood fiber, oriented strand board, or OSB), small crevices, or plastic fastener plates. Small torches may be used to heat the underside of the membrane away from these areas before securing the membrane. Hot trowels should be used to feather seams at laps and flashings. For additional information, refer to FM Global Property Loss Prevention Data Sheet 1-33, *Safeguarding Torch-Applied Roof Installations.*[3]

Some types of single-ply roof covers such as polyvinyl chloride (PVC), thermoplastic polyolefin (TPO), or chlorosulfonated polyethylene (CSPE or Hypalon®) require the use of either solvent or heat welding of the laps. Other types like ethylene propylene diene monomer (EPDM) require the use of solvents to clean membrane laps prior to adhering.

Permanent Safeguards

In most construction operations, the progress of the work toward completion gradually enhances the safety of the structure. As the need for combustible formwork and scaffolding, materials storage, temporary buildings and trailers, and other inherent hazards diminishes, they should be removed from the site.

Fire fighter access to the structure is important. Installation of permanent stairways and stairway enclosures should be completed as quickly as possible. Fire barriers and other essential features that provide for the confinement of fire should be installed as early as possible. Penetrations of fire-resistant construction made for building services should be sealed with a fire-rated material immediately after the building services are installed. The fire rating of the sealant should be the same as the structural element that has been penetrated. The integrity of all fire cutoffs should be maintained.

In buildings without automatic sprinkler systems, or those in which the installation of water tanks and other fire protection equipment must wait for the completion of the structural elements, standpipe and hose systems may provide the only reliable source of water for fire fighting during the construction of the project. In buildings where automatic sprinkler protection is to be a part of the permanent protection for the building, the sprinkler system should be installed as building construction progresses. Many fires have occurred only a few days prior to the anticipated completion of a sprinkler system. Sprinkler systems should be installed, tested, and operating prior to significant combustibles being introduced into the structure and immediately following combustible construction. Blank gaskets and blind flanges used to activate sprinkler protection by sections, as construction work is completed, should be provided with lugs that are painted red, or otherwise clearly marked when installed. Doing so will help ensure that the gasket or flange is removed when the system is extended.

Permanent standpipe and hose systems should be installed as construction work progresses and should not wait for the final structural shell to be completed. Permanent wiring systems should replace temporary wiring as rapidly as possible, and certainly as soon as formwork is removed from concrete construction.

SUPERVISION OF FIRE PROTECTION

All construction, renovation, and demolition projects should have a qualified person functioning as the fire protection manager and assigned responsibility for fire prevention and protection activities. On smaller projects, this responsibility may be assumed along with other responsibilities by one individual. This person should also have full authority to enforce fire prevention procedures required for the project. In renovations of occupied buildings, a fire protection manager should be appointed by the building owner. Although responsibility for fire protection rests with the owner, steps to accomplish effective loss prevention are normally carried out by the contractor.

The fire protection manager should develop a written prefire plan in cooperation with the responding local fire department and the owner's fire brigade if present. At a minimum, the prefire plan should identify emergency access roads, fire-fighting water supplies, nature of the construction project, site-specific hazards, emergency contact lists, and on-site fire-fighting capabilities. Since construction projects are constantly changing, the prefire plan should be flexible. The prefire plan should be shared with the local fire response agency at least every six months, or more often as changes in construction warrant.

Even with a local fire department response, contractors and security guards should be trained in the use of portable fire extinguishers and standpipe hose lines. On large projects, consideration should be given to establishing a fire brigade using either contractor employees or dedicated fire brigade members. NFPA 600, *Standard on Industrial Fire Brigades,* provides additional information on the equipment and training requirements for fire brigades and employee fire fighting. The fire brigade may also be involved in other emergency response functions, such as first aid, confined space entry, or technical rescue (e.g., trench, low-angle, or high-angle rescue).

Fire prevention should be a regular topic at contractor safety meetings, which are often called "tailgate talks." All fires should be investigated by the fire protection manager and needed changes in construction-related activities or fire prevention requirements communicated to all workers.

Rehabilitation Projects

There has been a great deal of rehabilitation of older buildings in recent years. This effort is partly the result of a desire to preserve historic structures and partly a result of rising construction costs. From a fire protection standpoint, rehabilitation projects can produce fire-safe buildings if the extensive compartmentation usually present in older buildings is at least partially preserved.

Code-Related Issues. From a building code standpoint, existing buildings being rehabilitated usually must meet current code requirements for means of egress, fire protection, and light and ventilation.

In buildings with historic significance, it is sometimes undesirable to provide all of the code-required safeguards, as these changes may destroy the historic features. The use of equivalency concepts to provide the level of safety intended by a particular code is usually possible when it is impractical to meet the letter of the code. Otherwise, the safety of the occupants takes precedence, and the proper safeguards must be installed to ensure life safety. Although improvement of exits to total code compliance may not be possible, providing other compensating features in the building to control fire and smoke may result in equivalent safety. These compensating features may involve the installation of automatic sprinkler protection, smoke detection systems, and smoke-control systems. Design equivalency should be evaluated carefully to ensure that a level of life safety comparable to that required by the applicable code is being maintained.

The U.S. Department of Housing and Urban Development (HUD) has produced guidelines for the rehabilitation of buildings. An interesting feature of these guidelines is a volume that provides fire-resistance information on older methods of

building construction.[4] This information is extremely valuable when attempting to evaluate the fire resistance ratings for existing building structural systems and fire barriers. Similar literature is available from the National Institute of Building Sciences (NIBS).[5]

Life Safety. In some rehabilitation projects, the renovations must be made while the building is partially occupied. Special precautions must be taken in these cases. The most important of these is the maintenance of proper exits from the building. Not only must exits be provided for building occupants but also at least one exit must be provided for building trades workers in the construction areas. The accumulation of trash and other debris must be kept to a minimum and refuse removed daily.

If fire suppression, detection, or alarm systems are being renovated, their downtime must be kept to a minimum. Proper planning can eliminate unnecessary downtime. Isolation of parts of systems is usually possible to ensure operation in unaffected areas of the building. If it becomes necessary to shut down entire systems, a fire watch should be posted near the main control to restore service in case of fire. Some form of reliable communication should be established if the main control is remote from the work area. This precaution is especially important in sprinklered buildings. Removing the entire sprinkler system as part of a rehabilitation project can have disastrous results.

Means of egress should be readily available to building occupants during normal working hours. Therefore, alterations to means of egress should be accomplished during off-hours. In some cases, rerouting of traffic may be a practical alternative. In all cases, exit systems and fire protection systems should be restored at the end of each work day.

In cases where additions to buildings block existing exits, provision must be made for alternative means of egress or for a protected path of travel. The use of combustible materials in temporary exit construction should be avoided.

DEMOLITION OPERATIONS

If not properly controlled, demolition operations can create more serious problems than construction operations. Buildings under demolition can suffer the same lack of compartmentation and lack of built-in fire protection, but with their demolition rubble, they may have even more readily ignitable fuel load. Demolition operations should include precautions to ensure maintenance of fixed fire protection systems for as long as possible.

Fire Protection Systems

Automatic sprinkler systems should be modified to allow their removal on a floor-by-floor or area-by-area basis. The conversion of a wet system to a dry system fed only by a fire department connection is sometimes possible and provides good protection for the building as well as for fire-fighting personnel.

Standpipe and hose systems should also be removed floor by floor and should be the last fire protection feature removed. This maintains fire-fighting capability to otherwise demolished floors. A wet standpipe can be easily converted to a dry standpipe.

Trash Removal

It is common practice to provide chutes for the removal of trash and debris from the upper floors. If chutes are used, they should be noncombustible and erected outside the building. By installing the chute as straight as possible, the potential for obstructions in the chute will be minimized.

Structural Integrity

Cutting holes through floors to provide an inside chute should be avoided, since this creates a vertical opening through which fire can spread rapidly from floor to floor. Holes in floors also cause potential safety problems for fire fighters. Walls should remain intact as long as possible.

Figure 11.4.8 shows the results of a demolition operation that violated these principles. The sprinkler system had been shut down about a week before the fire instead of being shut down in stages as demolition progressed. Contrary to good practice, holes had been made in the floors to facilitate the removal of debris. The results were disastrous: not only was the building being demolished destroyed by fire, but also the fire spread to four other buildings.[6]

Utilities

Prior to the start of demolition, gas supplies should be shut off and capped outside the building. Electrical circuits should be reduced to a minimum, and those circuits that remain energized should be labeled. Discontinued lines should be physically disconnected.

FIGURE 11.4.8 Fire Originating on the Top Floor of a Partially Demolished Building and Involving Four Other Buildings

Explosives

Use of explosives requires special precautions. Explosives should be used and stored in accordance with NFPA 495, *Explosive Materials Code.*

ASBESTOS REMOVAL

Asbestos removal can be part of a demolition or alteration project. Fires during asbestos removal operations present several additional problems in addition to the issues previously discussed. The potential for exposure of fire fighters and construction workers to hazardous materials outside the containment area impacts access and fire-fighting operations. Maintenance of the containment area may reduce fire detection and will lengthen the amount of time before manual fire suppression by workers outside the containment area is possible. The widespread use of plastic film and tarping may also contribute to the fire load and fire spread.

With the exception of minor asbestos removal, the fire department and any on-site emergency responders should be notified at least 24 hours prior to the start of an asbestos removal operation. The prefire plan developed for the project should also address any asbestos removal operations. Plastic film used in the project should meet the requirements of NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films.* Reflective signs indicating the presence of asbestos should be posted at the entrances, exits, decontamination areas, and waste disposal areas.

UNDERGROUND OPERATIONS

Underground construction projects are common, especially those related to tunnels. Fires in these structures are particularly difficult to suppress and can cause significant damage and delays in the completion of construction. An important cause of these fires is improper precautions taken during hot work operations.

Hot Work Permits

Standard hot work precautions, including a fire watch and removing combustible materials, should always be followed. Particular attention should be paid when a combustible film membrane, such as high-density polyethylene, is used as a moisture barrier behind the rib structure of a tunnel. Cutting of rib spikes used to hold hoses and cables can transmit sufficient heat to ignite the plastic membrane.

Fire Protection

Water for fire fighting should be provided by means of a standpipe system with fire hose connections a maximum of every 300 lineal ft (92 m). Provisions for additional air supplies for fire-fighting personnel should also be made. Some tunnels use an emergency car that is equipped with wheels the same gage as the muck car tracks. This car can be used to either transport fire fighters or emergency equipment into the tunnel.

Mobile mining equipment used underground should be equipped with a fire suppression system. The system should be either automatically or manually activated. See NFPA 122, *Standard for Fire Prevention and Control in Metal/Nonmetal Mining and Metal Mineral Processing Facilities,* for further information.

Prevention

Storage of combustible materials should be limited and properly protected and arranged to prevent ignition or contribution to a fire.

Monitoring of methane is a high priority during underground operations. This is particularly important at the face of any tunnel bore or where the geology indicates the presence of organic material. All personnel, including fire fighters who enter a tunnel or underground construction site, must use the sign-in, sign-out board that is usually located adjacent to the underground entrance.

SUMMARY

Construction, alteration, and demolition operations can cause severe fires to occur. Control of combustibles, careful use of temporary electrical service and heating equipment, and control of hot work operations will reduce that probability. Proper fire protection management, prefire planning, and reasonable fire protection will help limit the extent of damage from such a fire. Precautions to reduce the risk of arson are especially important, as that is the leading cause of construction fires.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the fire hazards of construction, alteration, and building demolitions discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 51, *Standard for the Design and Installation of Oxygen–Fuel Gas Systems for Welding, Cutting, and Allied Processes*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 58, *Liquid Petroleum Gas Code*
NFPA 122, *Standard for Fire Prevention and Control in Metal/Nonmetal Mining and Metal Mineral Processing Facilities*
NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations*
NFPA 495, *Explosive Materials Code*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 601, *Standard for Security Services in Fire Loss Prevention*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*

Chapter 5

Control of Electrostatic Ignition Sources

Don R. Scarbrough

Chapter Contents

Static Electricity Defined
Charge Separation
Dissipation of Static Electricity
Control of Ignitable Mixtures
Flammable Liquids
Gases
Dusts and Fibers
Static Detectors
Definitions

Key Terms

bonding, charge separation, conductor, discharge energy, grounding, ignitable mixtures, induction, nonconductor, static electricity, surface charge

Static electricity as a source of ignition is a hazard common to a wide variety of industries and processes. This chapter explains the nature of static electricity and the means and methods of eliminating or minimizing it as an ignition source.

Information on the hazards of static electricity in specific circumstances and processes can be found in the following chapters: Section 2, Chapter 8, "Explosions"; Section 6, Chapter 8, "Dusts"; Section 6, Chapter 10, "Gases"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 8, Chapter 13, "Electrical Systems and Appliances"; Section 9, Chapter 2, "Spray Finishing and Powder Coating"; and Section 17, Chapter 8, "Explosion Prevention and Protection."

Additional information can be found in NFPA 77, *Recommended Practice on Static Electricity,* and in the bibliography at the end of this chapter.

STATIC ELECTRICITY DEFINED

The term *static electricity* as used in this chapter refers to the electrification of materials through the physical processes described later and the effects of the positive and negative charges so formed, particularly where their release constitutes a fire or explosion hazard. Other electrical terms used in this chapter are defined at the end of the chapter.

When an electric charge is present on or in a nonconductive body and it is trapped or prevented from escaping, it is termed *static electricity.* Electricity on a conducting body that is in contact only with nonconductors or is otherwise isolated from the earth is also prevented from escaping and is therefore nonmobile or "static." In either case, the body on which this electricity is evident is said to be "charged."

Around 1890, electricity was described as a "subtle agent, without weight or form, that appears to be diffused through all nature, existing in all substances, which gives no indication of its presence in the latent state, but is capable of producing sudden and destructive effects in its active state." With the discovery of the electron, this definition now seems prophetic and the adjective "static" more meaningful. Electricity can move freely through some substances, such as metals, that are called "conductors," but can flow with difficulty or not at all through or over the surface of a class of substances called "nonconductors," "insulators," or "dielectrics." This latter group includes gases, glass, amber, resin, sulfur, paraffin, most synthetic plastics, and most petroleum oils (hydrocarbons).

The development of an electrical charge in itself might not be a potential fire or explosion hazard. There must also be a discharge or sudden recombination of separated positive and negative charges. For static electricity to be a source of ignition, four conditions must be fulfilled:

1. There must be an effective means of separating charge.
2. There must be a means of accumulating the separated charges and maintaining a suitable difference of electrical potential between them.

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3. There must be a discharge (release of charge) of adequate energy.
4. The discharge must occur in an ignitable mixture.

Static electricity can be produced as the result of motions that involve the separation or pulling apart of contacting surfaces, usually of dissimilar substances, either liquid or solid, one or both of which is usually a poor conductor of electricity. Charges separated by this mechanism are usually referred to as being the result of "frictional" or "triboelectric" charging. Examples of such motion that are commonly found in industry are the following:

- Motions of all sorts that involve friction between contacting surfaces, usually of dissimilar liquids or solids
- Steam, air, or gas flowing from any opening in a pipe or hose when the steam is wet or the air or gas stream contains particulate matter
- Separation of a stream of liquid from a hose, faucet, or pouring spout
- Pulverized materials passing through chutes or pneumatic conveyors
- Nonconductive power or conveyor belts when in motion
- Moving vehicles

Accumulation of separated charges typically takes place on the surface of a nonconductive solid, within the body of a nonconductive liquid, or on a dispersed fog or mist. Appreciable charge can be accumulated within the body of a nonconductive solid that has been subjected to high-energy bombardment with electrons or ions in a particle accelerator. There will always be an electric field where such charges accumulate and these electric fields can have a profound effect on surrounding materials, particularly ungrounded conductors.

Charge can appear on the surface of a conductive object when that object is simply brought into the electric field of another object that bears a static electric charge. This is known as *induction* and results fundamentally from manipulation (through repulsion and attraction) of the inherently balanced charges within an uncharged conductive object to produce separate regions on its surface that bear balanced but opposite charges.

An initially uncharged surface can become charged through *contact* with another object or surface that is charged. For example, a pail placed to collect a falling stream of liquid or pulverized material poured from a faucet or other container (the stream therefore being charged by *separation*) will become charged by contact with the charged stream of material.

Yet another mechanism for placing charge upon a surface involves *bombardment* of the surface with charged molecules (ions) of air, which themselves have been charged by a corona from a high-voltage electrode. This mechanism is usually intentional, for example, impressing a charge on the drum of a photocopy machine.

Other processes through which charge is imparted to an object or fluid involve exposure to an electron beam or flow of a liquid around a high-voltage electrode. These techniques are commonly referred to as *charge injection.*

The separation of static electric charges cannot be prevented absolutely, because the intrinsic origins of static electricity are present at every interface. The object of most electrostatic corrective measures is to provide a means whereby charges separated by whatever cause can recombine harmlessly before sparking potentials are attained. If hazardous conditions cannot be avoided in certain operations, means must be taken to ensure that there are no ignitable mixtures at points where static electric sparks might occur.

CHARGE SEPARATION

When two bodies composed of dissimilar materials are in close physical contact, there is likely to be a transfer of free electrons between them, one giving up electrons to the other, and an attractive force is established. When the bodies are separated, work must be done in opposition to these attractive forces. The expended energy reappears as an increase in electrical tension or voltage between the two surfaces. If the bodies are insulated from their surroundings, both are said to be "charged"; the one having the excess of electrons is said to have a negative charge, whereas the other is said to have an equal positive charge. If a conductive path is available between them, the charges thus separated will reunite immediately. If no such path is available, as is the case with insulators, the charges will remain and an electric field will result.

In many cases, one of the objects has a deliberate or inherently conductive path to the earth, and its charge is immediately lost to the earth, which is considered to have an infinite capacity to absorb or give up electrons. The other (insulated) object now retains its charge and would hold this charge indefinitely, except for the fact that it must somehow be supported and no supporting insulator (even air) is a perfect nonconductor.

If one of the bodies is itself a nonconductor, the flow of electrons across its surface is inhibited, and the charge tends to remain at the points where electron transfer originally occurred. A highly charged insulating surface can be discharged with the appearance of a spark by bringing an "earthed" conductor close to it, but only a limited area will be so discharged. Sparks so produced seldom release enough energy to cause ignition. Thus, nonconductors, the bodies most directly involved in charge separation, are usually not directly responsible for fires and explosions. (There are exceptions, which are discussed later in this chapter.) However, such charges can in some cases be the agency for building up or accumulating a charge on a conductive body, which can release all of its stored energy in an incendive (ignition-capable) spark.

On a conductive body the charge is free to move. Because like charges repel each other, the charges will distribute themselves evenly over the surface. If the body is of irregular shape, charge will concentrate in areas having a small radius of curvature: the smaller the radius, the higher the concentration of charge and the higher the electric field in the area having the small radius of curvature. For a point, if the voltage is high enough, the electric field (voltage gradient) will exceed the breakdown strength of air (about 3,000,000 V/m), and the air will become ionized and a corona or brush discharge will result.

Like charges repel each other and unlike charges attract because of forces resident in the electrical fields that surround

them. These forces have a strong influence on nearby objects. If the neighboring object is a conductor, it will experience a separation of charges by induction. Its repelled charge is free to give or receive electrons as the case may be; if another conductor is brought near, the transfer might occur through the agency of a spark, very often an energetic spark. When the inducing charge is moved away from the insulated conductor, there follows a reversed sequence of events and sparks can result. Thus, in many situations, induced charges are far more dangerous than the initially separated ones on which they are dependent.

Storage

Two conductive bodies separated by an insulator constitute a capacitor (sometimes called a condenser), and where a potential difference is applied between these bodies, charge can be stored. One body receives a positive and the other an equal negative charge. In many instances involving accumulation of static electricity, one of the bodies is the earth, the insulating medium is the air, and the insulated body is some object to or from which a charge (electrons) has been transferred by one of the mechanisms previously described.

When a conducting path is made available between two conductive bodies, the energy stored on them is released, that is, the capacitor is "discharged," possibly producing a spark. The energy so stored and released is related to the charge, Q, the capacitance of the conductive body, C, and the voltage, V, in accordance with the following:

$$\text{Energy} = \tfrac{1}{2}CV^2 = \tfrac{1}{2}QV = \tfrac{1}{2}Q^2/C \quad (V = Q/C)$$

where energy is in joules; capacitance, C, is in farads; charge, Q, is in coulombs; and voltage, V, is in volts.

Discharge Energy

The ability of a discharge to produce ignition of a flammable mixture is governed largely by the energy transferred to the mixture, which will be some fraction of the total stored energy available because some energy is expended in heating the electrodes. Experiments at atmospheric pressure with plane electrodes have shown that the spark breakdown voltage has a minimum value at a critical short gap distance—about 350 V for the shortest measurable gap (about 0.01 mm). Increased gap distance requires proportionately higher voltages. At close spacing, the electrodes can be so close to the ignitable mixture that they adsorb enough heat to preclude ignition of the mixture.

Progressing from lowest to highest intensity, discharges through air can occur as corona, brush, spark, or propagating brush discharge. Corona discharge is generally thought of as not energetic enough to ignite gases and vapors. Brush discharges range from corona levels to higher energies that are capable of igniting gases and vapors but not capable of igniting common dusts. Spark discharges and propagating brush discharges are capable of igniting gases, vapors, and dusts.

At most favorable electrode spacing, tests have shown that optimum mixtures of saturated hydrocarbon vapors and gases in air require about 0.25 mJ of discharge energy to produce ignition. This level of discharge energy is typical of flammable vapors; however, there are many exceptions. The capacitance necessary to store this level of energy depends on the amount of charge (or voltage) on the capacitor. This leads to the question of how small a capacitor can be and still hold enough charge to ignite the typical hydrocarbon vapor. Experience has shown that a beverage can is big enough. In the same vein, uncomfortable discharges from the human body (usually at the fingertips) are energetic enough.

Manifestation of Static Electricity

Static electricity will be manifest only where highly insulated bodies or surfaces are found. If a body is "charged" with static electricity, there will always be an equal and opposite charge produced. If a hazard is suspected, the situation should be analyzed to determine the location of both charges and to see what conductive paths are available to both of them. Since no object can be entirely insulated from the earth, there will always be a path for charges to dissipate (discharge).

Problems arise where the rate of charge accumulation exceeds the rate of dissipation. If the resistance to ground is less than 1,000,000 Ω (1 MΩ), there are no practical systems that will accumulate charge fast enough to lead to problems of ignition with ordinary gases, vapors, or dusts. In many cases, resistance to ground will be much greater. Tests of such high-resistance paths should be made with an applied potential of 500 V or more, in order that any minor interruption (e.g., paint or grease film or air gap) will be broken down and a correct reading of the resistance obtained. Resistance as high as 1000 MΩ might provide an adequate leakage path in many cases; however, when charges are generated rapidly (e.g., pneumatic transport) a resistance as low as 1 MΩ might be required.

Ignitable Mixtures

Elimination of ignitable mixtures in the areas where sparks of static electricity can occur is the surest method of preventing static electricity-caused fires. The subject of ignitable mixtures is beyond the scope of this chapter but is discussed in other NFPA literature, for example, NFPA 30, *Flammable and Combustible Liquids Code*; NFPA 77, *Recommended Practice on Static Electricity;* NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*; and NFPA 921, *Guide for Fire and Explosion Investigations.*

DISSIPATION OF STATIC ELECTRICITY

A static charge that already exists can be removed or allowed to dissipate itself. One obvious way to accomplish this is to reduce the resistance between where the charge resides and ground. Another way is to neutralize the charge by adding an equal charge of opposite polarity.

Humidification

A static charge cannot persist except on a body insulated from its surroundings. Most commonly encountered materials that

are not usually thought of as conductors, such as fabrics, paper, wood, concrete or masonry foundations, and so on, have a certain amount of moisture on their surface in equilibrium with that in the surrounding atmosphere. This moisture content varies, depending on the weather, and it controls to a large measure the surface conductivity of the material and, thus, its ability to allow the escape of static electricity. In an analogous manner, under some conditions water vapor will condense on the surface of some nominally insulating materials, notably glass and porcelain, to render the surface conductive enough to allow static charges to dissipate.

The surface conductivity of the materials under discussion (wood, paper, etc.) is controlled by the water content of the air. Under conditions of high humidity, the materials in question will reach equilibrium conditions containing enough moisture to make the surface conductive enough to prevent accumulations of static electricity. The generating mechanism might still be present, but the rate of charge dissipation exceeds the rate of charge generation and the charge leaks away so fast that no observable accumulation results.

At the opposite extreme, that is, with low humidity, these same materials might dry out, become good insulators, and manifestations of static electricity become noticeable. There is no definite boundary line between these two conditions.

Where static electricity has introduced operational problems, such as the adhesion or repulsion of sheets of paper, layers of cloth, fibers, and the like, humidifying the atmosphere has proved to be a solution. It is usually stated that a relative humidity of about 50 percent or higher at normal room temperature will avoid such difficulties.

Unfortunately, it is not practical to humidify all occupancies in which static electricity might be a hazard. Some operations must be conducted in an atmosphere having a low humidity to avoid deleterious effects on the materials handled. High humidity can also cause intolerable comfort conditions in operations where the dry bulb temperature is high. On the other hand, a high humidity might advantageously affect the handling properties of some materials, thus providing an additional advantage. In some cases, localized humidification produced by directing a steam jet onto critical areas can provide satisfactory results without the need for increasing the humidity in the whole room. However, it must be remembered that steam that contains droplets of water can itself generate static electricity. This situation can sometimes be overcome by using a low-velocity jet of humidified air.

Humidification is not a cure for all static electricity problems. In particular, it must be remembered that the conductivity of the air is not appreciably increased by the presence of water in the form of a gas. If static electricity accumulates on some surface that is heated above normal atmospheric temperature (e.g., cloth passing over heated rollers), increasing the relative humidity in the surrounding air might do no good whatsoever.

Another situation where the control of atmospheric humidity appears to accomplish little is in controlling the charge of static electricity that appears as a space charge in the body of oils. In order to dissipate, such a charge must move through the body of the liquid; therefore, altering the surface conductivity of the oil does little, if anything, to help in the dissipation process.

Therefore, increasing the relative humidity of the atmosphere to 50 percent or higher at ordinary room temperatures might eliminate static electricity problems where the surfaces on which the charge accumulates can reach equilibrium with the atmosphere, such as paper or wood. For heated surfaces and for electrostatic charges in oils and other liquid and solid insulating materials, high humidity will not provide a means for draining off charges and some other solution must be sought.

Bonding and Grounding

Where natural conditions, including humidity, do not ensure a conductive path to prevent accumulation of static electricity, artificial conducting paths (bonding, grounding) might be necessary. *Bonding* is the process of connecting two or more conductive objects together by means of a conductor. *Grounding* (earthing) is the process of connecting one or more conductive objects to the earth and is a specific form of bonding. A conductive object can also be grounded by bonding it to another conductive object that is already connected to the ground. Some objects are inherently bonded or inherently grounded by their contact with the earth. Examples are underground piping or large storage tanks resting on the ground. Bonding eliminates the potential difference between conductive objects. Grounding eliminates potential differences between objects and the earth.

When grounding and bonding wires are used to dissipate static electric charges, the currents are quite small and even the smallest of wires are usually adequate to carry the current. The currents encountered in the bond connections used in the protection against accumulations of static electricity are on the order of microamperes (one millionth of an ampere). However, the wires used for bonding and grounding must be able to withstand the rigors of the workplace. The acceptable resistance in a ground connection depends on the type of hazard for which it is intended to give protection. To prevent the accumulation of static electricity, the resistance need not be less than 1 MΩ and in most cases may be even higher. To protect electrical power circuits, the resistance must be low enough to ensure operation of the fuse or circuit breaker under fault conditions. Any ground that is adequate for power circuits or lightning protection is more than adequate for protection against static electricity.

A bond or ground is composed of suitable conductive materials having adequate mechanical strength, corrosion resistance, and flexibility for the service intended. Since the bond or ground does not need to have low resistance, nearly any conductor size will be satisfactory from an electrical standpoint. Solid conductors are satisfactory for fixed connections. Flexible conductors are used for bonds that are to be connected and disconnected frequently. Conductors can be insulated, although this is not necessary, or uninsulated. Some prefer uninsulated conductors so that defects can be easily spotted by visual inspection. If insulated for mechanical protection, the concealed conductor should be checked for continuity at regular intervals, depending on the inspector's experience. Connections can be made with pressure-type ground clamps, brazing, or welding. Battery clamps, or magnetic or other special clamps, ensure good metal-to-metal contact. A special situation requiring substantial conductors might arise if there is a possibility that a ground wire might be

called upon to carry current from power circuits or lightning protection systems.

Ionization

Were it not for cosmic radiation, air would be nonconductive in its normal state. But, under certain circumstances, air can become sufficiently conductive to bleed off electrostatic charges. For instance, cosmic radiation creates ion pairs in the air. An electric field from an accumulated charge will attract its opposite counterpart ion and repel its like counterpart ion such that the accumulated charge will slowly dissipate. This process is usually too slow to be of much commercial value, but similar mechanisms can be employed.

Static Comb. A static electric charge on a conducting body is free to flow and, on a spherical body in space, it will distribute itself uniformly over the surface. If the body is not spherical, self-repulsion will cause the charges to concentrate on the surfaces having the least radius of curvature.

If the body is surrounded by air (or other gas) and the radius of curvature is reduced to almost zero, as with a sharp needle point, the charge concentration on the point can produce ionization of the air, rendering the air "conductive." As a result, whereas a surface of large diameter can receive and hold a high voltage, the same surface equipped with a sharp needle point can reach only a small voltage before the leakage rate through the self-ionized air equals the rate of generation.

A *static comb* is a metal bar equipped with a series of such needle points. A variation uses a metal wire surrounded with metallic tinsel. If a grounded static comb is brought close to an insulated charged body (or a charged insulating surface), ionization of the air at the points will provide enough conductivity to make the charge speedily leak away or be "neutralized." This principle is frequently employed to remove the charge from fabrics, power belts, paper, and plastic webs.

Electrical Neutralization. The electrical neutralizer is a line-powered high-voltage device that is an effective means for removing electrostatic charges from materials, such as cotton, wool, silk, or paper in process, manufacturing, or printing. It produces a conducting ionized atmosphere in the vicinity of the charged surfaces, enabling the charges to leak away to an adjacent grounded conducting body. Electrical neutralizers should not be used where flammable vapors, gases, or dust might be present, unless approved specifically for such locations.

Radioactive Neutralizer. Another method for dissipating static electricity involves ionization of the air by radioactive material. Such installations require no redesign of existing equipment, but engineering problems are involved, such as elimination of health hazards, dust accumulations, determination of radiation required, and proper positioning in relation to the stock, machine parts, and personnel. These considerations are best worked out in consultation with radiation specialists.

Open Flame. Ionization of the air can also be obtained by an open flame. This method is frequently used in the printing industry to remove static from paper sheets as they come off the press, thus avoiding the mechanical problems involving one sheet of paper adhering to another, but obviously avoiding ignition.

CONTROL OF IGNITABLE MIXTURES

Despite efforts to prevent accumulation of static electric charges, which should be the primary aim of good design, there are many operations involving the handling of nonconductive materials or nonconductive equipment that do not lend themselves to this built-in solution. In these cases it becomes necessary to provide other measures to supplement or supplant static electricity dissipation. For example, where a normally ignitable mixture is contained within a small enclosure, such as a processing tank, an inert gas can be used to render the vapor space safe from ignition. When operations are normally conducted in an atmosphere above the upper flammable limit, it might be practical to apply the inert gas only during the periods when the mixture passes through its flammable range.

Mechanical ventilation can be used in many instances to dilute an ignitable mixture to a point below its normal flammable range, that is, below the lower flammable limit. Also, by directing the air movement, it might even be practical to prevent the flammable liquids or dusts from approaching an operation where an otherwise uncontrollable electrostatic hazard exists. To be considered reliable, mechanical ventilation should be interlocked with the equipment it protects to ensure proper operation. Where a static electricity-accumulating piece of equipment is unnecessarily located in a hazardous area, it should be relocated to a safe location.

FLAMMABLE LIQUIDS

Charge Generation in Liquids

Static electric charge can be generated when liquids having a low conductivity move in contact with other materials. This occurs commonly in operations in which liquid flows through pipes and in which liquid is mixed, poured, pumped, filtered, or agitated. Under certain conditions, particularly with liquid hydrocarbons, with high-velocity flow and with filtration through nonconducting, resin-bonded media, static electricity can accumulate on the body of the liquid. If the accumulation is sufficient, a static electric spark can occur even though all conductive equipment is properly grounded. If the spark occurs in the presence of an ignitable vapor-air mixture, ignition is likely. Therefore, steps must be taken to prevent the simultaneous occurrence of these three conditions: low conductivity, energetic manipulation, and ignitable mixture.

Before transfer is started, contact should be made between the filling nozzle and the container, and the contact should be maintained throughout the filling operation. With this procedure, any difference in potential between the container and nozzle will be dissipated before the filling operation is started and differences in potential between the nozzle and container are prevented from forming during the filling operation. See

Figure 11.5.1 for methods of bonding containers and nozzles during container filling.

The relative static electricity-accumulating tendencies of a number of petroleum products have been measured in laboratory tests.[1,2] In general, aliphatic solvents and lower boiling point hydrocarbons exhibited lower charging tendencies than did higher boiling products. However, the charging tendency of any given product was found to vary widely from one sample to the next.

The conductivity of a liquid is a measure of its ability to hold a charge. The lower the conductivity, the greater the ability of the liquid to hold a charge. If the conductivity of a hydrocarbon liquid is greater than 50 pS/m (picosiemens per meter), any charges that are generated will dissipate without accumulating to a hazardous potential as long as all of the associated conductive equipment is properly grounded.

Free Charges on Surface of Liquid

If an electrically charged liquid is poured, pumped, or otherwise transferred into a tank or container, the unit charges of similar sign (i.e., + or –) within the liquid will be repelled from each other toward the outer surfaces of the liquid, including not only the surfaces in contact with the container walls but also the top surface adjacent to the air space. It is this latter charge, often called the *surface charge,* that is of most concern in many situations.

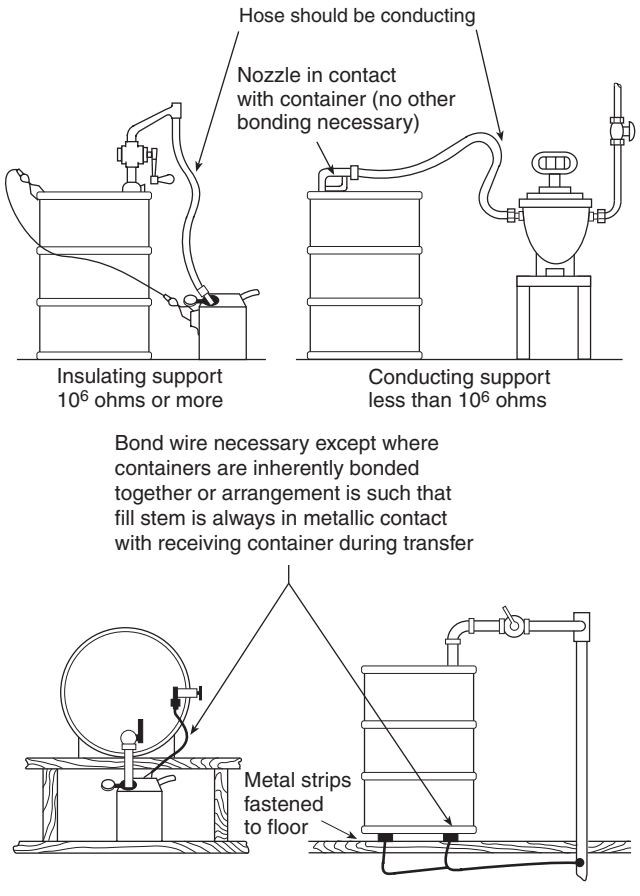

FIGURE 11.5.1 Recommended Methods of Bonding Flammable Liquid Containers During Container Filling

In most cases, the container is made of metal and is conductive. Two situations can occur, somewhat different with respect to protective measures, depending on whether the container is in contact with the earth or is insulated from it. Examples of these two situations are (1) an ordinary storage tank resting on earth, concrete, or another slightly conducting foundation, and (2) a metal can resting on a plastic surface.

In the first situation, the metal vessel is connected to ground. The charges that reach the surfaces in contact with the vessel will reunite with charges of opposite sign that have been attracted there. During this process, the tank and its contents, considered as a unit, are electrically neutral; that is, the total charge in the liquid and on its surface is exactly equal and opposite to the charge on the interior of the tank shell. This charge on the tank shell is "bound" there, but gradually disappears as it reunites with the charge migrating through the liquid. The time required for this to occur is called "relaxation time." The relaxation time depends primarily on the conductivity of the liquid. It might be a fraction of a second or several minutes.

During this process, the tank shell is at ground potential. Externally, as already mentioned, the container is electrically neutral. But internally, there could be differences of potential between the container wall and the fluid, lasting until charges on the fluid have gradually leaked off and reunited with the unlike charges on the tank walls.

If the potential difference between any part of the liquid surface and the metal tank shell should become high enough to cause ionization of the air, electrical breakdown can occur and a spark might jump to the shell. A spark across the liquid surface is an ignition hazard where flammable vapor-air mixtures are present. No bonding or grounding of the tank or container can remove this internal surface charge.

In the second situation, where the can is highly insulated from the earth, the charge on the liquid attracts an equal and opposite charge to the inside of the container. This leaves a "free" charge on the outside of the can, of the same sign as that in the liquid and of the same magnitude. This charge can escape from the can to the ground in the form of a spark. In filling a gasoline can resting on a plastic bedliner of a pickup truck, it is this source of sparking that is suspected of creating an ignition potential in some situations; in this case, the spark jumps from the edge of the fill opening to the fill pipe, which is at ground potential. This hazard can be easily controlled by removing the can from the vehicle and placing it on the ground, where any accumulated charge can leak to the earth.

The foregoing discusses the distribution of charges delivered into a container with a flowing stream. Further generation or separation can occur inside the container in several ways to produce a space or surface charge: (1) flow with splashing or spraying of the incoming stream, (2) disturbance of "water bottoms" by the incoming stream, (3) bubbling of air or gas through a liquid, (4) jet or propeller blending within the tank, or (5) the settling out of a water layer from a hydrocarbon.

These charges on the surface of a body of liquid cannot be prevented by bonding or grounding, but can be rendered harm-

less by inerting, that is, displacing part of the oxygen with a suitable inert gas, or by increasing the concentration of flammable gas in the vapor space to a point above the upper flammable limit. In some cases, additives can be used to increase the conductivity of the liquid such that the charge will rapidly relax and prevent a hazardous condition from developing.

It must be recognized that mists and foams of flammable and combustible liquids can be ignited by static electric sparks in much the same way as dusts can be ignited. Ignition is possible even though the liquid in the mist is below its flashpoint.

GASES

Gases not contaminated with solid or liquid particles will not generate any electrification in their flow. When flowing gas is contaminated with dust, metallic oxides, scale particles, or with liquid particles or spray, however, electrification is possible. A stream of such particle-containing gas directed against a conductive body will charge the latter unless it is grounded or bonded. Compressed air or steam containing particles of condensed water vapor often manifests strong static electric charges when escaping.

Carbon dioxide, discharged as a liquid from orifices under high pressure (where it immediately changes to a gas and "snow"), can result in electrostatic accumulations on the discharge device and the receiving container. This condition is not unlike the effect from contaminated compressed air or from steam flow where the contact effects at the orifice play a part in the accumulation of static electricity. High-pressure carbon dioxide should not be discharged into flammable atmospheres because it presents a high risk of ignition due to static electric spark.

Hydrogen-air and acetylene-air mixtures can be ignited by a spark energy of as little as 0.017 mJ. In the pure state, no static electric charges are generated by the flow of hydrogen. However, as gaseous hydrogen is commercially handled in industry, such as flowing through pipelines, discharging through valves at filling racks into pressure containers, or flowing out of containers through nozzles, the hydrogen will often be found to contain particles of oxide carried off from the inside of the pipes or containers. In this contaminated state, hydrogen can accumulate a static electric charge.

DUSTS AND FIBERS

Charge Generation in Dust

As previously pointed out, the flow of a stream of gas containing small particles can result in a separation of electrons and the accumulation of a static electric charge on any insulated conductive body with which it comes in contact. Also, dust displaced from a surface on which it rests can develop a considerable charge. The ultimate charge depends on the inherent properties of the substance, size of particle, amount of surface contact, surface conductivity, gaseous breakdown, external field, and resistance to leakage in a system. Greater charges develop from smooth rather than from rough surfaces, probably because of greater initial surface contact. Electrification develops during the first phase of separation.

Charge separation seldom occurs if both materials are good electrical conductors, but it is likely to occur with a conductor and a nonconductor or two nonconductors. When like materials are separated, as in dispersing quartz dust from a quartz surface, positive and negative charges are developed in the dispersed dust in about equal amounts to give a net zero charge. With materials differing in composition, a charge of one polarity might predominate in the dust. Each of the materials becomes equally charged but with opposite polarity.

Charge generation in moving dust normally cannot be prevented. The method of dispersion of the dust, the amount of energy expended in dispersal, the degree of turbulence, and the composition of the atmosphere usually affect the magnitude and distribution of the charges in the dust.

Not only can dust participate in the generation of static electricity, it can also be the material ignited by a discharge spark. A suspension of finely divided combustible particles in air has much the same properties as a flammable gas-air mixture, except for a generally higher ignition energy. (With some metallic dust, ignition energy is comparable to gas-air mixtures.) It can burn to produce explosive effects. Dusts have a lower flammable limit, usually referred to as the "minimum explosible concentration," but no strictly definable upper limit.

Ignition of Dust by Static Electric Discharge

Clouds and layers of many combustible dusts (with or without a volatile constituent) have been ignited experimentally by static electric discharge. With dust clouds, it has been shown that a minimum ignitable dust concentration exists below which ignition cannot take place regardless of the energy of the spark. At the minimum ignitable dust concentration, a relatively high energy is required for ignition. At higher dust concentrations, less energy is required for ignition.

A layer of combustible dust can be ignited by static electric discharge and will burn with a bright flash, glow, or, for some metallic dusts, with flame. Apparently, there is little correlation in the minimum energy required for ignition of dust layers and clouds. Layers of some metallic dusts, such as aluminum, magnesium, titanium, and zirconium, require less energy for ignition than carbonaceous materials.

Primary explosives, such as mercury fulminate, are readily initiated by static electric discharge. Steps necessary to prevent accidents caused by static electricity in explosives manufacturing operations and storage areas vary considerably with the ignition sensitivity of the material being handled.

In most instances in which static electricity was authentically established as the cause of ignition of a dust, the spark occurred between an insulated conductor and ground. Propagating brush discharges from insulators, however, have been shown to be incendive to dust clouds and to the dust within a pneumatic transport system when thin wall insulative hose is used. The dust within a metallic dust collector duct has been shown to be ignited when an insulative coating was formed inside a wye where thermoplastic dust has impact fused. It has not been verified experimentally that a dust cloud can be ignited by

discharge within itself, that is, in a manner analogous to lightning, in experiments conducted within silos having a radius up to 16 ft (5 m).

STATIC DETECTORS

The following devices have an application in the measurement and determination of static electricity within the limitations of each device as described.

Electroscopes

The leaf electroscope is a simple but sensitive device that indicates the presence or absence of electric charge by the repulsion of its leaves when the device is charged. Only units intended as portable dosimeters for ionizing radiation and one or two classroom demonstration models are available.

Neon Lamps

A small neon lamp or fluorescent tube will light up feebly when one terminal is grounded (or held in the hand) and the other makes contact with any sizeable conductor that carries a charge potential of 70 V or more. Like the electroscope, it gives but little quantitative information; however, when it passes current, it might give a rough idea of the rate at which charges are being produced in certain operations. Adjustable series-parallel groupings of such lamps and small capacitors can be arranged to give a semblance of quantitative information.

Electrostatic Voltmeters

These meters operate by electrostatic attraction between movable and stationary metal vanes. A small current is required to deflect the needle, but no current is passed to maintain the deflection because one set of vanes (usually the stationary one) is very highly insulated. Small, portable, accurately calibrated instruments are available in several ranges from 100 to 10,000 V. This type of meter can be used for quantitative electrostatic analysis.

Electrometers

Electrometers are frequently used for laboratory and field investigations of static electricity. These instruments employ special input stages designed for high input resistance and low grid current and can be used in several ways. With a small antenna mounted on the grid terminal, they are very suited for detecting transient electrostatic charge effects; in the presence of a constant field, the charge induced on the grid will leak off and the meter pointer will return to zero. However, as the rate of leakage is not high, the electrometer finds considerable use for "on-the-spot" checks. Often electrometers are equipped with high-resistance terminal shunts to convert them to current meters in the nanoampere range. They can thus be used in many applications to indicate the rate of charge development. A simple adaptation converts the instrument into a megohm meter, as explained in the manufacturer's instruction manual. Electrometers can be rather expensive and require a user of some sophistication.

Field Mills

A field mill is a device that overcomes the serious limitations of the electrometer in that it provides a continuous indication of charge by providing its own transients in the form of continuous grid modulation. It can therefore "look" at a distant charge and determine its sign and potential. The electrical field extending from the charge is "chopped" by a motor-driven variable condenser or window. The resulting pulsations are transformed, amplified, and rectified to give a dc meter deflection proportional to the strength of the field. A similar instrument of suitable design can be immersed in a liquid, as in a pipeline, to measure charge density. Since a field mill senses an electric field, it likewise senses the presence of an accumulated charge. Thus, field mills are handy devices for qualitatively determining the presence of an accumulated charge; with some modest experience, they can even be quantitative.

DEFINITIONS

Some terms used in this chapter are defined as follows.

Brush Discharge. A form of corona discharge in which brighter "fingers" or "streamers" can be seen. Brush discharges are capable of igniting flammable gases and vapors, but not dusts.

Capacitance. The ability to store an electric charge. Electrons received by an electrically neutral body of conductive material, such as a person, a car, or an aircraft, raise the voltage at a rate determined by the surface area and shape of the body. The voltage is determined by the surface characteristics (capacitance) of the body and the number of electrons on this surface. The larger the body, the more electrons are needed to raise the voltage a specific amount; hence, the higher the capacitance of the body.

Capacitance is measured in "farads" or millionths of a farad (i.e., microfarads). Millionths of one millionth of a farad are called picofarads.

Charge. Measured in coulombs or fractions thereof, the quantity of separated electrons on the body (negative charge) or the quantity of separated electrons not on the body (positive charge). Electrons cannot be destroyed, short of an encounter with antimatter (a positron); so when an electron is removed from one body, it must go to another body. Thus there are always equal and opposite charges produced. Since it would be awkward to say there are 6,240,000,000,000,000,000 electrons on a body, the body is said to have a charge of one coulomb. A coulomb is simply a name for this specific quantity of electrons. In electrostatics an even more practical unit is a microcoulomb, representing a charge of electrons.

Corona. A type of air discharge that can occur between flat electrodes or as a single-point discharge at an electrode that has a very small radius or a point. The discharge has a faint blue glow and can make a hissing sound. Corona discharge is usually not capable of causing ignition of ordinary gases and vapors; however, acetylene, carbon disulfide, and hydrogen are among the exceptions.

Current. A measure of the flow of electricity. Just as waterflow is measured in terms of the amount of water that passes a certain point in a specific period of time (liters per min), so too is the flow of electrons past a certain point measured by time. The flow of electrons is called current. Current is measured in terms of electrons per second, coulombs per second, or amperes. When dealing with static electricity, current is commonly limited to the microampere range.

Energy. The ability to do work. Energy is measured in joules or fractions thereof. A spark is energy being expended. The measure of energy takes several forms. Often it is physical energy, which is measured in joules. If it is heat energy, it is measured in calories (cal), and if it is electrical energy it is measured in watt-seconds or in joules. A joule is the energy expended in one second by an electric current of one ampere in a resistance of one ohm (approximately 0.738 foot-pound). Static electric discharge energy is usually measured in thousandths of a joule (millijoules or mJ). A static spark must contain a minimum amount of energy to ignite flammable or combustible materials.

Incendive. Capable of causing ignition. A discharge that has enough energy to ignite an ignitible mixture is said to be incendive. Thus an incendive spark can ignite an ignitible mixture and cause a fire or explosion. A nonincendive discharge does not possess the energy required to cause ignition even if it occurs within an ignitible mixture.

Incendivity. The ability of a discharge to ignite an ignitible mixture. The energy level required for incendivity varies as described in the text.

Potential. Stored energy is able to do work. In electricity, this ability is expressed in terms of the potential of doing work. Potential in electricity is measured in terms of volts, kilovolts, or millivolts. Potential, or voltage, is measured from a base point. This point can be any voltage but is usually "ground," which is theoretically zero voltage. When one point with a potential of x volts to ground is compared with another point with a potential of y volts to ground, then it is said that a potential difference of x–y volts exists between the two. Then, when a point with a potential of 2500 volts to ground is compared with a point with a potential of 1500 volts to ground, the potential difference is 4000 volts.

Propagating Brush Discharge. An energetic discharge from an insulative surface on which an intense charge has been stored. To store adequate charge, the insulator must be thin (less than 6 mm) and be backed by a conductive surface that is either grounded or at opposite polarity. The discharge is branched, occurs over an area of several square centimeters, and produces a loud popping sound.

Resistance. Electrical current encounters difficulty in passing through an electrical circuit or conductor. This difficulty can be measured and is called resistance. Resistance can be measured in terms of voltage drop over a part of the circuit but is usually measured in terms of ohms or megohms. The resistance of a circuit in ohms is equal to the ratio of voltage in volts to current in amperes.

Spark. An energetic discharge, usually accompanied by a popping sound, that occurs when air or gas between two charged conductors becomes highly ionized, enough to break down conducting current through a distinct, luminous channel.

SUMMARY

Ignition caused by static electricity is a potential fire hazard in many operations and processes. Static electricity is produced by motions involving the separation or pulling apart of contacting, usually dissimilar, surfaces, one or both of which is usually a poor conductor of electricity. Whenever possible, ignitable mixtures should be removed from areas where sparks of static electricity can occur. Another way to reduce the hazard is to dissipate the static electricity through a variety of means, including humidification (50 percent or higher at normal room temperature), artificial conducting paths (bonding or grounding), or ionization of the air. In cases where dissipation is not possible, measures must be taken to reduce the flammability of ignitable mixtures, for example, by inert gas or mechanical ventilation. Certain operations are especially hazardous with regard to static electricity and require precautionary measures. Such operations include flammable liquid flowing through pipes or being mixed, poured, pumped, filtered, or agitated and gaseous hydrogen flowing through pipelines or discharging through valves at filling racks into pressure containers or flowing out of containers through nozzles. Dust presents a particular hazard as it can both generate static electricity and be ignited by it. Several devices can be used to detect and measure the presence of static electricity, including electroscopes, neon lamps, electrostatic voltmeters, electrometers, and field mills.

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2. Walmsley, H. L., "The Avoidance of Electrostatic Hazards in the Petroleum Industry," *Journal of Electrostatics* (special issue), Vol. 27, No. 1–2, 1992.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on electrostatic ignition sources discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*
NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals*
NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities*
NFPA 70, *National Electrical Code®*
NFPA 77, *Recommended Practice on Static Electricity*

NFPA 385, *Standard for Tank Vehicles for Flammable and Combustible Liquids*
NFPA 407, *Standard for Aircraft Fuel Servicing*
NFPA 484, *Standard for Combustible Metals*
NFPA 495, *Explosive Materials Code*
NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*
NFPA 655, *Standard for Prevention of Sulfur Fires and Explosions*
NFPA 664, *Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities*
NFPA 850, *Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations*
NFPA 1124, *Code for the Manufacture, Transportation, Storage, and Retail Sales of Fireworks and Pyrotechnic Articles*
NFPA 1125, *Code for the Manufacture of Model Rocket and High Power Rocket Motors*

Chapter 6

Lightning Protection Systems

John M. Caloggero

Chapter Contents

Factors in the Need for Lightning Protection
Nature of Lightning
Traditional Theory of Lightning Protection
Property Protection
Protection of Persons

Key Terms

bonding, conductors, grounding, infrastructure, lightning protection, pilot streamer, resistivity, striking distance, surge protection devices

From 1994 to 1998, lightning caused an estimated 35,000 fires per year as reported to U.S. municipal fire departments, with associated annual losses of 12 civilian fire deaths and $223 million in direct property damage. From 1995 to 2004, lightning was also cited for 489 deaths.

Unlike many other causes of death and injury that one can run away from, lightning strikes before the warning thunder. The principles of protection and personal safety are well known and spelled out in NFPA 780, *Standard for the Installation of Lightning Protection Systems.* It must be remembered, nevertheless, that lightning involves many uncertainties and that, although a given pattern of lightning behavior might be probable, there is no guarantee that a lightning discharge will not deviate from that pattern.

For related information on lightning protection, see Section 9, Chapter 11, "Protection of Wastewater Treatment Plants"; and Section 21, Chapter 10, "Marine Vessels."

FACTORS IN THE NEED FOR LIGHTNING PROTECTION

Frequency and Severity of Thunderstorms

The frequency of thunderstorms varies throughout the world. The severity of thunderstorms, as distinguished from their frequency of occurrence, is much greater in some locations than in others. Hence, the need for protection varies geographically, although not necessarily in direct proportion to thunderstorm frequency. A few severe thunderstorms a season can, in fact, make the need for protection greater than a relatively large number of storms of lesser intensity. Figure 11.6.1 shows statistical data on the yearly number of flashes to ground per km^2 due to thunderstorms in the United States. Note that the highest flash density is encountered in south-central Florida. The data show the average number of lightning flashes per year for the United States. Eleven years of lightning data were collected to make the flash density map in Figure 11.6.1. Measured lightning flash density has been corrected for NLDN detection efficiency.

Since 1894, the recording of thunderstorms has been defined as the local calendar day during which thunder was heard. A day with thunderstorms is recorded as such, regardless of the number occurring on that day. The occurrence of lightning without thunder is not recorded as a thunderstorm. Figure 11.6.2 illustrates statistical data on the frequency of thunderstorms in Canada, and Figure 11.6.3 shows the data for the world.

Earth Resistivity

Figure 11.6.4 illustrates the estimated average resistivity of the earth, measured at various locations in the United States, in ohm-meters. Resistivity is measured in ohm-centimeters and is defined as the resistance in ohms of a cube of material measured in centimeters. In Figure 11.6.4, however, it is measured in ohm-meters. The highest resistivity is located in the northeastern segment of the country, with 2000 ohm-meters measured in Long Island, New York, northern New Hampshire, and Vermont. Structures in these areas are susceptible to more frequent lightning strikes.

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FIGURE 11.6.1 Statistics for Continental United States Showing the Average U.S. Lightning Flash Density in Flashes/km^2/Year (Source: Global Atmospherics, Inc.)

Value and Nature of Building and Contents

Buildings and structures that are essential to life safety or are considered critical infrastructure, such as hospitals, fire stations, police stations, military facilities, emergency management and power plants, and water treatment facilities, should have a lightning protection system installed if they are located in areas where lightning commonly occurs. Some buildings have an uninsurable historical or cultural value. The type of building construction also influences the degree of protection to be considered. Some buildings require no supplemental lightning protection due to their construction. The real or intangible value of the building's contents must also be considered, and, in some cases, attention must be given to the nature of the contents and its susceptibility to damage by induced lightning currents, for example, storage of explosives.

Appendix L of NFPA 780 contains a risk assessment guide that provides guidelines for assessing the need for lightning protection. Not part of the requirements of NFPA 780, the appendix is included there for informational purposes only. NFPA does not mandate that lightning protection systems be installed in specific buildings or structures; however, Appendix L of NFPA 780 does provide a method for determining the need for lightning protection based on a risk assessment of computed values.

Personnel Hazards

The lightning hazard is a major concern not only to personnel in buildings or structures, but also to persons involved in outdoor activities at golf courses, football stadiums, and the like. Early warning systems can be installed to warn of approaching

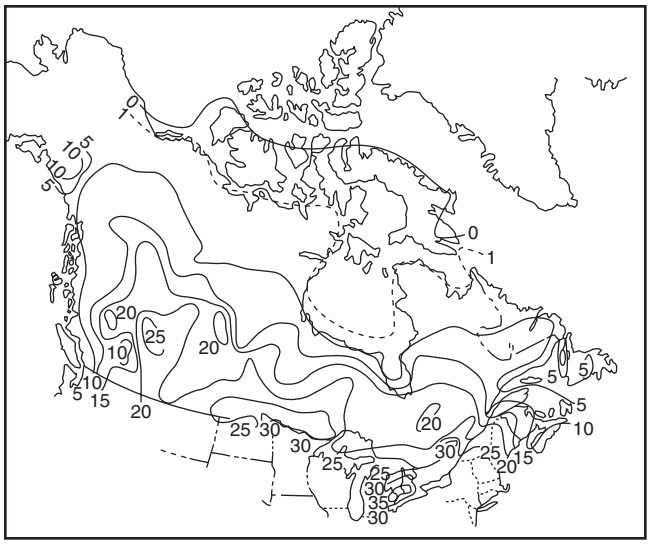


FIGURE 11.6.2 Canadian Statistics Showing Annual Average of Days with Thunderstorms in the Period 1957 to 1972 (Source: Meteorological Division, Department of Transportation, Canada)

storm cells. Because a lightning strike may lead to considerable discomfort, if not injury or death, lightning protection may be necessary to eliminate possible personnel hazards in buildings of any type (other than those constructed of structural steel framing).

Relative Exposure

Lightning will nearly always strike the highest point in its area of impact. In closely built-up towns and cities, this means the hazard is not as great to one-story buildings or individuals outside as it is in open country. In rural areas, however, a one-story barn is likely to be the tallest object in its area. In hilly or mountainous areas, a building located on high ground is usually subject to greater hazard than is one in a valley or in an otherwise sheltered area.

Indirect Losses

In addition to direct losses (e.g., damage to buildings or their contents by lightning, fire resulting from lightning, death of livestock, etc.), there could be indirect losses. Interruption of business, computer, or farming operations, especially at certain times of the year, can involve losses quite distinct from and in addition to those arising from direct property damage. In some cases, whole communities depend on the integrity of a single structure for a measure of safety and comfort, for example, the brick chimney of a water pumping plant or a hospital smokestack. A stroke of lightning to the unprotected chimney of a plant of that sort might have serious consequences, resulting in lack of sanitary drinking water, irrigating water, water for fire protection, or lack of medical services when most needed during stormy weather, or some similar effect.

NATURE OF LIGHTNING

The planet and its atmosphere can be viewed as a large spherical capacitor, with the earth at about 300,000 volts negative,

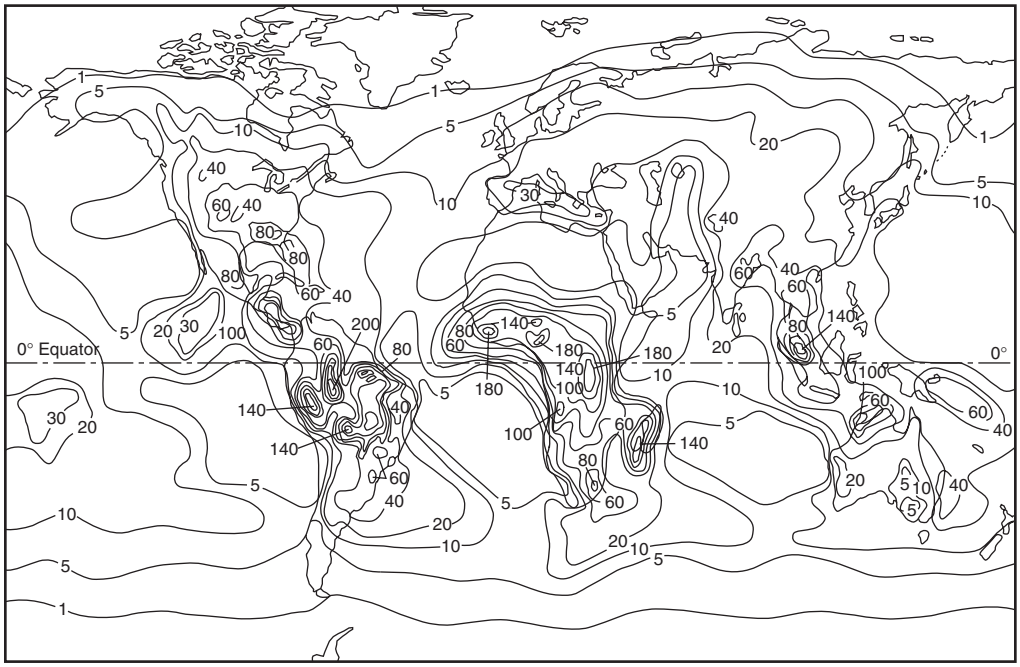


FIGURE 11.6.3 Annual Frequency of Thunderstorm Days as Compiled by the World Meteorological Organization, 1956 (Source: World Meteorological Organization)

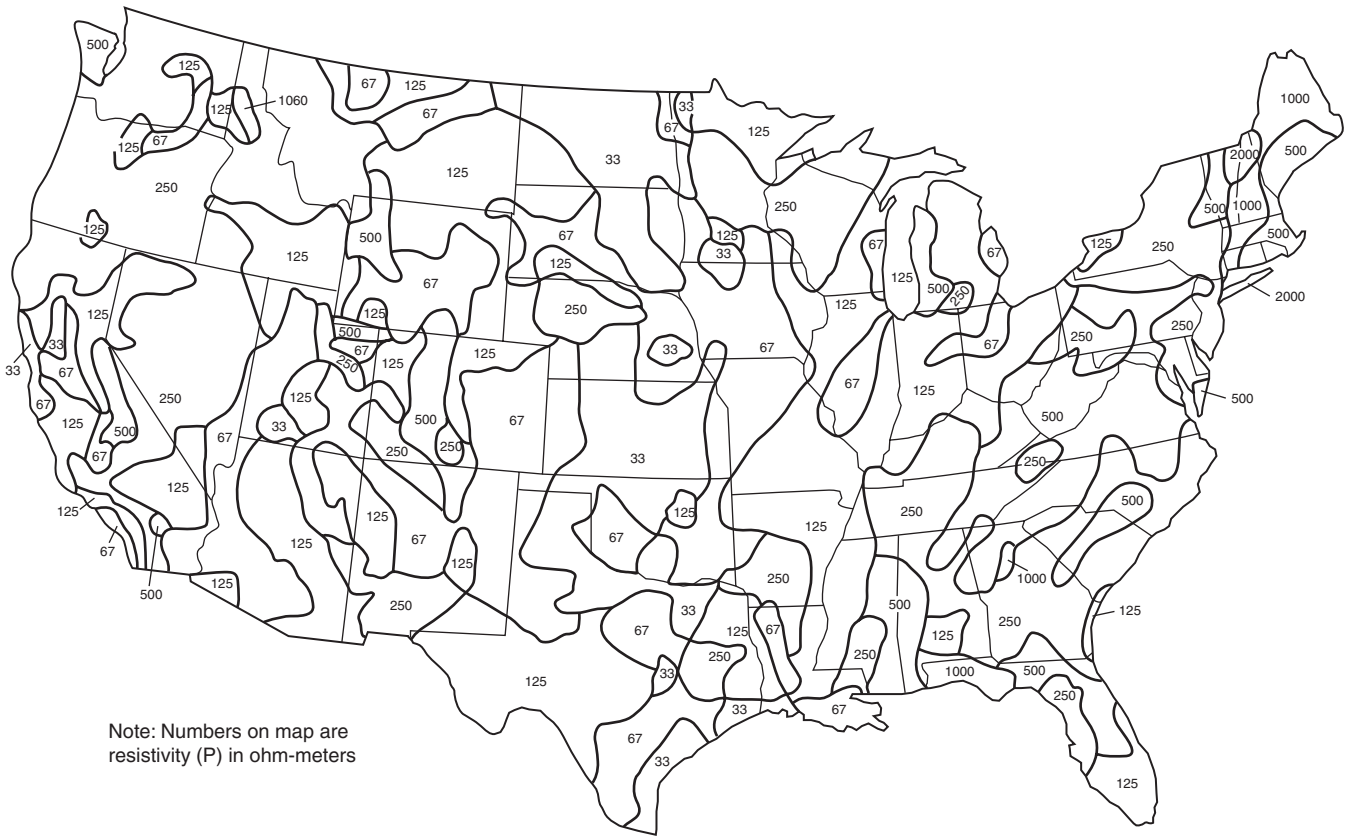


FIGURE 11.6.4 Estimated Average Earth Resistivity in Continental United States

with respect to the upper ionosphere. This potential difference powers a flow of electricity from the earth to the atmosphere. The rate of current flow, calculated at approximately 1400 to 1800 A, is spread out over the earth's entire surface. Therefore, this amounts to about 0.00009 A/mi^2 (0.000035A/km^2). Under clear, normal conditions, the electrostatic field intensity at the earth's surface is 150 to 200 volts per meter (V/m) of elevation. As a thunderstorm approaches, the potential difference rises to 10,000 to 30,000 V/m of elevation.

Air currents pick up moisture as they pass over large bodies of water, such as lakes, rivers, and oceans. This air mass is heated when it passes over warmer land masses, causing it to rise. As the moist air mass passes through the 14,000 ft (4200 m) elevation, the moisture condenses and forms ice crystals. The ice crystals in an active cloud become positively charged, whereas the water droplets usually have negative charges. Due to these conditions, a thundercloud normally develops a positive charge at the upper level and negative charge at the lower level. An electric field now exists within the cloud as well as above and below it. This negative charge in the lower level of the cloud induces a positive charge in grounded objects below it. Sharp pointed objects, such as flagpoles, steeples, corners of buildings, and trees, develop concentrated fields at these locations, resulting in a point-discharge current of a few amperes that moves upward in the electric field.

As the voltage between the earth and the cloud increases, the lightning discharge to earth starts at the cloud, progressing in incremental steps with a faintly luminous discharge, called a leader stroke in lengths of about 65 ft (20 m). The current in these leaders is estimated at about 200 amperes. When the faint lightning leader reaches an upward leader, an intense flash can be seen traveling upward to the cloud. This is called the return stroke and is a direct short circuit between the negative portion of the cloud and the electrostatically induced positive charge of the earth.

The development of a stepped leader is diagrammed in Figure 11.6.5. When sufficient charge has built up on a cloud, a "pilot streamer" will develop in a generally downward direction. This streamer ionizes a path in the air. The current associated with it is small, on the order of only a few amperes. The streamer initially extends on the order of 150 ft (45.7 m) below the cloud. After a pause of about 50 microseconds, the streamer will proceed for a second step, again generally downward but usually in a somewhat different direction from the initial step. Subsequent steps occur at intervals of about 50 microseconds. The path of each step is essentially straight, but each new step generally takes a different direction. The change in direction at each junction results in the zigzag path characteristic of lightning. Branches can (and often do) occur but, for simplification, these are not shown in Figure 11.6.5.

As the leader progresses downward, it creates a highly conductive ionized path in the air. Thus, the tip of the leader essentially remains at cloud potential, and the voltage gradient between the tip and the earth increases as the tip progresses

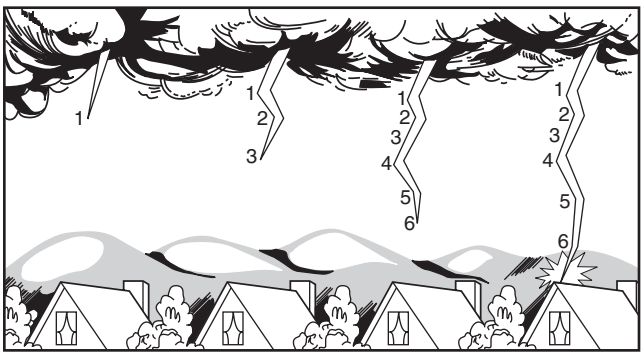


FIGURE 11.6.5 Development of a Stepped Leader

downward. At some critical point (point 6 in Figure 11.6.5), the voltage gradient becomes high enough to break down the remaining air gap, and the initial stroke to ground is completed. The point from which the final breakdown occurs is called the point of discrimination; the distance over which this breakdown occurs is defined as the striking distance.

As many as 40 component strokes have been observed in a single flash. Speeds range from 100 mi/sec (161 km/sec) for the first pilot leader stroke to 20,000 mi/sec (32,190 km/sec) for the main stroke. Currents average about 24,000 A but range up to 270,000 A in extreme cases, lasting for a few millionths of a second, but lesser currents are present for a longer period. Potentials have been estimated as high as 15 million volts.

Because of the high voltage and rapid changes in current flow, induced charges are produced that can be hazardous. Thus, NFPA 780 requires the interconnection (bonding) of metallic masses as a part of any lightning protection system, which will keep all electrically conductive components at the same potential. Bonding minimizes the likelihood of arcing between the electrically conductive components of the building and equipment in the building.

Lightning causes fire when sufficient heat is produced to ignite combustible materials in the vicinity of the lightning strike. Substantial damage, however, can be produced without resulting in fire. Dry wood beams in houses struck by lightning can be severely splintered and windows can be blown outward due to pressure wave produced from the implosion. Such damage primarily results from pressure generated by the expanding lightning channel. Because some effects of lightning can be indirect, it is not necessary for lightning to strike a building to cause damage. Lightning striking an overhead wire can be conducted over the wire to a building, where severe damage to the building wiring concealed within walls and ceiling is not visible without opening the walls. Conductor insulation and cable sheathing can be melted and decrease the dielectric strength of the insulation. This occurrence can result in a delayed reaction that could further result in arcing and a fire within the walls at a later date. Therefore, lightning arresters (surge arresters) should be provided to minimize such damage. Although there are several types of surge arresters, all permit the free flow of lightning charges to ground, while preventing the flow of ordinary electric current over the same path. The surge arrester should be backed up with a surge protective device (SPD). SPDs are required to be installed on electrical or electronic system conductors that leave a building or structure to supply electric power, signal, data, and communications systems in another structure, where the conductors are run in excess of 100 ft (30 m) and are not buried or installed in a grounded metallic conduit or tubing.

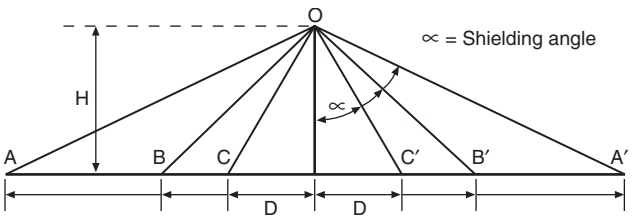
TRADITIONAL THEORY OF LIGHTNING PROTECTION

The theory of lightning protection is simple—to provide means by which a lightning discharge can enter or leave the earth without damaging the protected property. There is no evidence that any form of protection can prevent the occurrence of a lightning discharge. A lightning protection system has two functions: (1) to intercept a lightning discharge before it can strike the object protected and (2) to discharge the lightning current harmlessly to earth.

Conventional Concept

The zone protected by a grounded rod or mast is conventionally taken as the space enclosed by a cone that has its apex at the top of the mast. Similarly, the zone protected by a grounded horizontal overhead wire is conventionally taken as a triangular prism, with the upper edge along the wire. In either case, the degree of protection is generally assumed to be a function of the shielding angle, that is, the angle between an element of the cone and a vertical line through the apex, or between the side of the prism and the vertical plane through the horizontal wire. This is sometimes expressed as the ratio of the horizontal distance protected to the height of the mast or wire.

Figure 11.6.6 illustrates this concept and tabulates some generally accepted zones of protection. NFPA 780 states that, for structures not greater than 50 ft (15 m) in height, a horizontal distance equal to the height of the rod or mast has been found to be substantially immune to direct strokes. This horizontal distance extends to twice the height of the rod or mast if the structure does not exceed 25 ft (7.6 m) in height. The *British Standard Code of Practice,* "The Protection of Structures



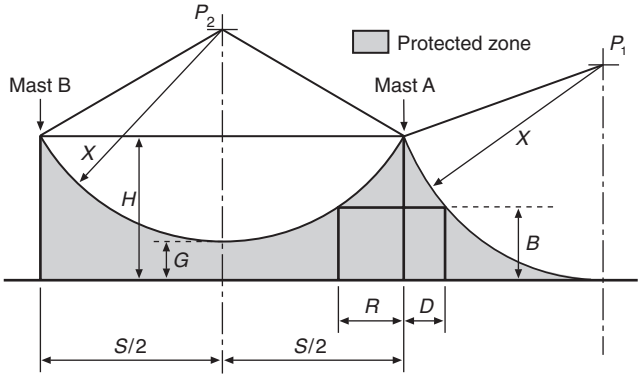
Zone	D/H	∝	Authority	Recommended for
AOA′	2/1	63°	NFPA	Ordinary cases
BOB′	1/1	45°	NFPA	Important cases
COC′	0.58/1	30°	British code	Ordinary structures
			British code	Danger structures

FIGURE 11.6.6 Conventional Concept of Protected Zones

Against Lightning,"[1] states that a shielding angle of 45 degrees provides an acceptable level of protection for ordinary structures, but for structures with explosives or highly flammable contents, the shielding angle should not exceed 30 degrees. Both codes indicate that complete protection cannot be guaranteed in any case. It is assumed, however, that the criteria presented reduce the probability of lightning strikes to a practical minimum. Although these criteria provide essentially complete protection in most cases, theoretical consideration indicates that even the 30° shielding angle is not always adequate.

Geometric Concept of Lightning Protection

The geometry of lightning protection is illustrated in Figure 11.6.7, which shows a hypothetical cross section of an area protected by two vertical masts (or horizontal overhead wires). Consider first a downward leader descending to the right of Mast A. Final breakdown will occur when the leader tip approaches within a specified distance, *X* (the striking distance), of any grounded object or surface. If the point of discrimination, *P* (the point at which final breakdown will occur), is equidistant from the tip of the mast and the ground, either the mast or the ground can be struck. If *P* is close to the mast, it will intercept the stroke; if *P* is farther from the mast, the ground will be struck. If any structure to the right of the mast extends aboveground to within a distance less than *X* of point *P,* the structure will be struck.



P_1, P_2 = Point of discrimination
X = Striking distance
R, D = Horizontal distances for protected height B
G = Minimum elevation completely protected

$$D = H\sqrt{\frac{2X}{H}} - 1 - B\sqrt{\frac{2X}{B}} - 1 \qquad (H \le X)$$

$$R = (H-G)\sqrt{\frac{2X}{(H-G)}} - 1 - (B-G)\sqrt{\frac{2X}{(B-G)}} - 1$$

$$G = H - X + \sqrt{X^2 - \left(\frac{S^2}{2}\right)} \qquad (S \le 2X)$$

For $H > X$,

$$D = X - B\sqrt{\frac{2X}{B}} - 1$$

FIGURE 11.6.7 Geometric Concept of Lightning Protection

It can be seen that the zone protected by a single mast or by an outside mast of a multimast system, in a direction away from the other masts, is bounded by the arc of a circle of radius *X,* passing through the tip of the mast and tangent to the ground. Geometrically, it can be shown that the protected distance *D,* at an elevation *B* aboveground, is given by the expression shown, where *H* is the height of the mast aboveground and *X* is the striking distance.

Similarly, for a leader extending downward between the two masts, the protected zone is bounded by the arc of a circle of radius *X* passing through the tips of the two masts. If the masts are close enough together, the space between them is completely protected for an elevation above ground, which is a function of mast height *H* and spacing *S.* In this case, the protected distance *R* at elevation *B* and the minimum elevation *G,* which is completely in the protected zone, are given by the two expressions shown.

These equations hold only if *H* is less than or equal to *X* and *S* is less than or equal to 2*X*. Furthermore, *G* must be positive. If *G* is negative, complete protection does not exist between the two masts, and the equation for *D* holds.

The geometric concept shows that the protected zone is not a cone or prism but is bounded by surfaces generated by concave arcs. This fact is not generally appreciated, although it is at least partially recognized in transmission line shielding. Furthermore, the protected distance is seen to be a function of:

1. Striking distance
2. Height of mast or overhead wire above ground
3. Distance between two or more masts or overhead wires

Figure 11.6.7 shows why the protected zone between two masts is greater than the total of the zones of the two masts considered individually. Previous NFPA lightning protection codes recognized this qualitatively but not quantitatively. The figure also shows why the shielding angle required on transmission lines decreases as tower (and overhead ground wire) height increases.

Striking Distance

The striking distance is related to the potential of the lightning stroke, which is directly related to the charge on the cloud. Because the peak stroke current is also related to the charge on the cloud, it can be shown that the striking distance is directly related to the peak stroke current. For a given mast or ground wire height, the protected distance increases with increasing striking distance. Thus, an adequately designed lightning protection system provides maximum protection against what could be the most damaging strokes. Because minimum protection exists for a minimum striking distance (and minimum stroke current), the lightning protection system should be designed to protect against minimum anticipated striking distances.

The peak stroke current is usually at least 10,000 A. This corresponds to a striking distance of slightly over 100 ft (30.5 m). It is, therefore, believed that a protective system based on this minimum striking distance will essentially provide complete protection. This scenario is considered to be a reasonable design basis.

Design Curves

Using the derived equations and an assumed striking distance, the protection provided by a single mast (or horizontal overhead wire) can be readily calculated. Similarly, the configuration of masts or overhead wires required to protect a given structure can be investigated. However, the calculations are tedious, and it is not convenient to determine directly by simple algebra the mast or overhead wire height required to protect a structure of given dimensions. Hence, curves showing the relationship between protected zones and various mast or horizontal overhead wire configurations are useful. Such curves can be readily constructed graphically (Figures 11.6.8 and 11.6.9). In Figure 11.6.8, the solid curves are the geometric concept, with a striking distance of 100 ft (30.5 m). The dashed lines are the conventional concept, with a shielding angle of 45 degrees. H equals the height of the mast or horizontal wire. In Figure 11.6.9, the striking distance is 100 ft (30.5 m). H equals the height of the horizontal wire, S is the spacing between masts or wires, and B is the height protected above ground.

PROPERTY PROTECTION

Components

Air Terminals. According to current United States practice, as indicated in NFPA 780, conditions required for protection of ordinary buildings are met by placing metal air terminals on the uppermost parts of the building or its projections, with conductors connecting the air terminals with each other and to the ground. By this means, a relatively small amount of metal, properly proportioned and distributed, affords a satisfactory degree of protection and can be installed in a way that interferes only minimally with the contour and appearance of the building. In the current *British Standard Code of Practice*,[1] the use of pointed air terminals (vertical finials) is not considered essential, except where dictated by practical considerations.

One theory states that a protective system based on a minimum striking distance of 100 ft (30.5 m) for structures containing flammable liquids and gases will provide 99.9 percent protection, and a minimum striking distance of 150 ft (45.7 m) will provide 99.5 percent protection for ordinary structures that are generally capable of withstanding minor direct strikes.[2–4] This theory supports the use of 10 in. (254 mm) minimum height air terminals above the object to be protected at 20 ft (6.1 m) maximum intervals. A convenient geometric equation

$$Y = \sqrt{R^2 - (R - h)^2}$$

where

Y = Radius of horizontal protected zone

R = Striking distance

h = Height of air terminal

illustrates that a striking distance of 100 ft (30.5 m) will provide a 12.9 ft (3.9 m) radius of horizontal protected zone or 25.8 ft (7.9 m) horizontal protected zone between air terminals, and a striking distance of 150 ft (45.7 m) will provide a 15.8 ft (4.8 m) radius of horizontal protected zone or 31.6 ft (9.6 m) horizontal protected zone between air terminals.

The subject of sharply pointed versus blunt air terminals is under study by the NFPA Lightning Protection Committee. According to Moore et al.,[5] pointed air terminals have a built-in defense against lightning strikes. The strength of the electric field

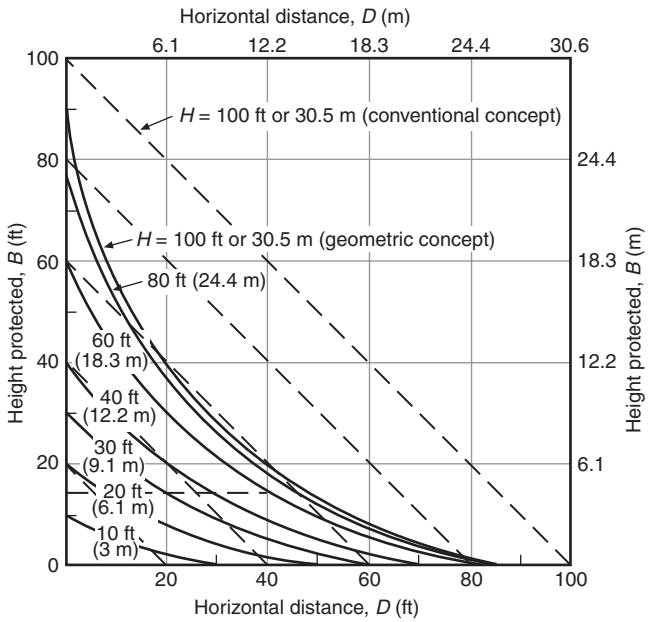


FIGURE 11.6.8 Zone Protected by a Single Mast, Horizontal Wire, or Air Terminal

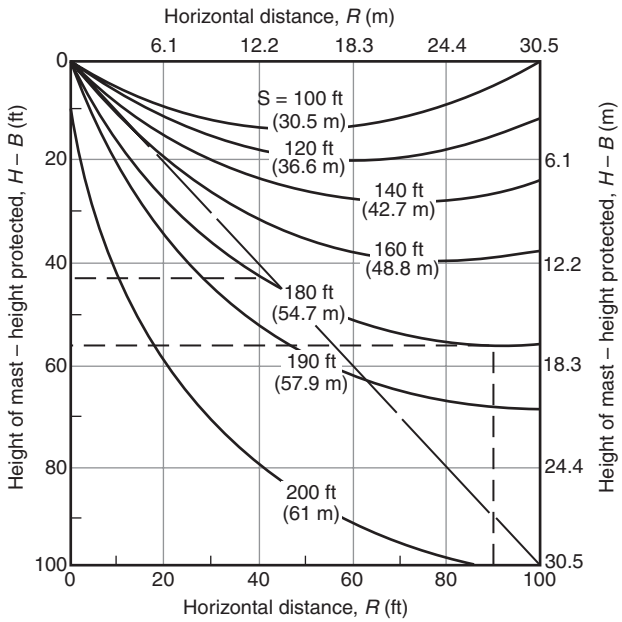


FIGURE 11.6.9 Zone Protected by Two Masts, Two Horizontal Wires, or Two Air Terminals

around the tip of an air terminal is limited by a phenomenon called "point discharge." When the electric field reaches a certain strength but before lightning strikes, the stepped leader current flows from the air through the air terminal to the ground. The effect is called point discharge because the point is letting the surrounding air lose charge or discharge electricity. A pointed air terminal will presumably discharge sooner than a blunt one. Accordingly, Moore et al.[5] concluded that a blunt air terminal is more likely to intercept a lightning strike and complete a circuit.

Conductors. NFPA 780 specifies the use of copper or aluminum metals for lightning conductors. When copper and aluminum are used together, special precautions must be taken against electrolytic corrosion. Conductors are coursed along ridges of sloping roofs, around the edges of flat roofs, and vertically from these and from the air terminals to ground. Vertical runs are designated as "down conductors," and there are never fewer than two on any kind of structure, except for flagpoles, masts, spires, and similar structures. The down conductors are normally placed at diagonally opposite corners of square or rectangular structures, but other factors, such as direct coursing, security against displacement, location of metallic elements in the structure, location of water pipes, and favorable ground conditions, need to be considered in determining optimum placement. For detailed instructions about the installation of conductors, their form and size, and about the installation of air terminals, refer to the latest edition of NFPA 780.

The down conductors to ground must be substantial and must provide a reasonably direct path. The blocking effect (choke) of electrical induction must be avoided. For example, a lightning conductor that is installed within a piece of iron pipe for mechanical protection must be bonded to the pipe at both ends to reduce the choke effect on the conductor, which increases the impedance of the conductor.[6]

Grounding. Ground connections are essential if a lightning protection system is to be effective; every effort should be made to provide ample contact with the earth (Figure 11.6.10). Resistance of the protective system to ground is not critical. However, resistance and surge impedance must be low enough to prevent side flashes between the down conductor and other grounded objects. The resistance also must be low enough to prevent

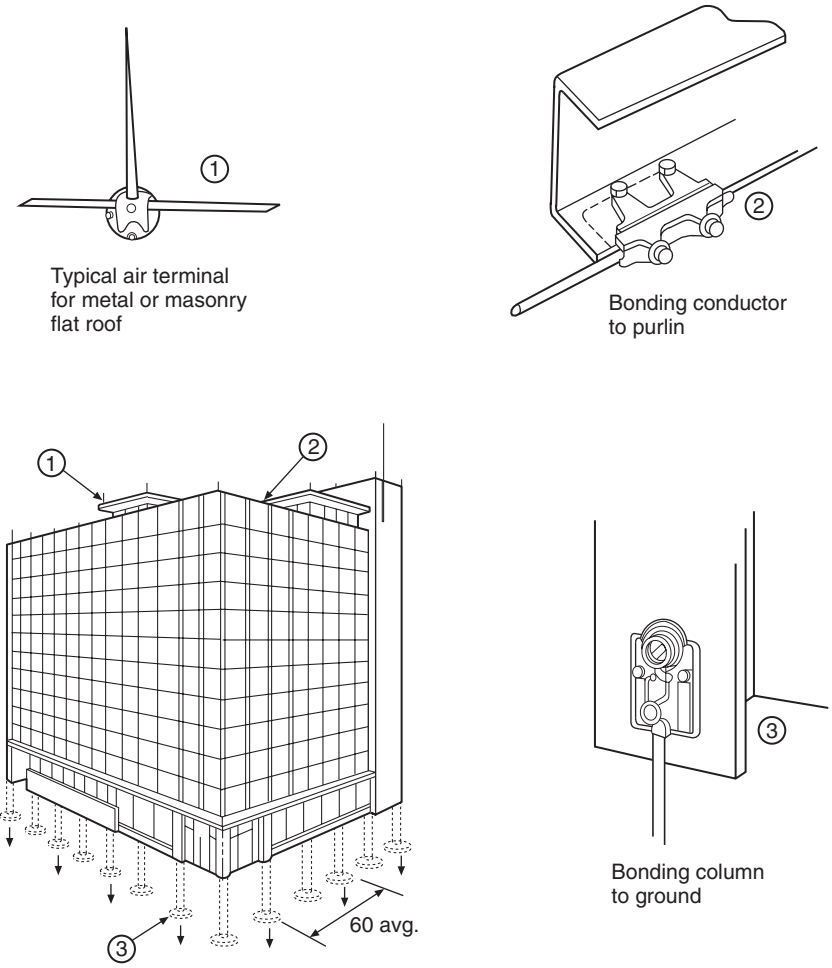


FIGURE 11.6.10 Grounding and Bonding of Lightning Down Conductors. Water pipe ground (if pipes are metallic) can be made at 1, 2, or 3.

excessive voltage gradients in the soil surrounding the ground electrode. Excessive voltage gradients can be dangerous or fatal to people or animals that might be standing or walking in the vicinity when a lightning stroke occurs. If the down conductor is remote from other grounded objects and people or animals are not likely to be near the ground electrode during a lightning storm, a relatively high ground resistance can be tolerated. Otherwise, an extensive wire network will need to be laid on the surface.

NFPA 780 does not specify any maximum recommended ground resistance. The *British Standard Code of Practice*[1] recommends a maximum resistance of 10 Ω for a lightning protection system that will normally include two or more ground electrodes. Also 10 Ω is generally considered a reasonably good ground resistance for transmission towers. In this case, a high ground resistance might result in flashover to the line conductors, even though the overhead ground wire intercepts the direct lightning stroke. The U.S. Department of Agriculture recommends a ground resistance not greater than 50 Ω as acceptable for protection of farm structures.

The ground resistance of a ground electrode is directly proportional to soil resistivity. Soil resistivity varies over wide limits, as shown in Figure 11.6.4; nevertheless, 10,000 Ω/cm is a reasonable order of magnitude average for many areas. Figure 11.6.11, which is based on derived equations,[7] has been prepared to show the variation in resistance to earth of vertical rods or pipes as a function of length in 10,000 Ω/cm soil. For other soil resistivities, the resistance to ground can be obtained by multiplying the indicated resistance by the known soil resistivity divided by 10,000. Vertical rods driven into the ground are commonly used as grounding electrodes. In addition, where buried metallic water pipes are nearby, it is required to connect the lightning protection ground system to the piping system.

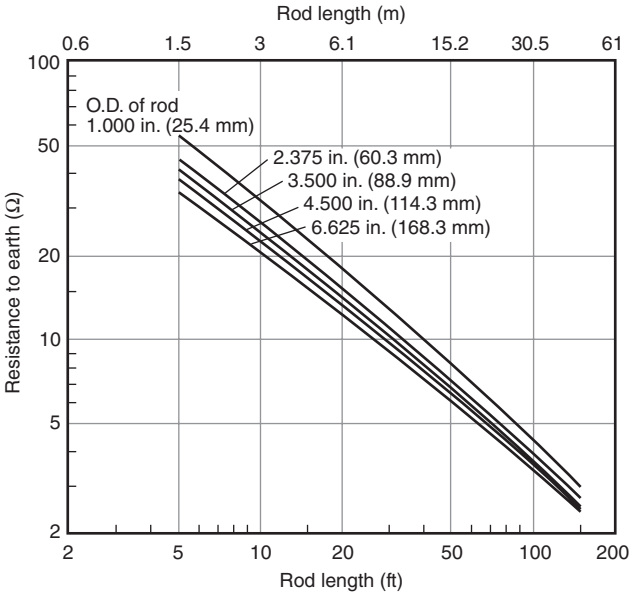


FIGURE 11.6.11 Resistance of Vertical Ground Rods in 10,000 Ω/cm Soil

If bedrock is on or near the surface, it would be impossible to make a ground connection in the ordinary sense of the term because most kinds of rock are insulating or at least of high resistivity and, in order to obtain effective grounding, other and more elaborate means are necessary. An effective method to achieve grounding is to use an extensive wire network (grid) laid on the surface of the rock surrounding the building, to which the down conductors are connected. Another method is to install a ground ring interconnecting the down conductors, with metal straps running outward in a radial formation on the surface of the rock from each of the down conductors. One ground ring should be installed at the bottom of the foundation to which the down conductors or structural steelwork are connected, with a second ring conductor provided by blasting a circular trench around the periphery and placing in it a strip conductor. The blasted area should be thoroughly compacted with backfill, and the two ground ring conductors should be electrically interconnected. Using one of these methods would make the distribution of the electrical potential around the protected building substantially the same as if it were resting on conducting soil; the resulting protective effect would be equal.

For sandy soil or any dirt covering the foundation, a concrete-encased electrode (commonly called a Ufer ground, after the inventor Herb Ufer) should be installed for new construction. This electrode consists of steel reinforcing bars or rods tied together in the footing of the foundation that is in direct contact with the earth.

In general, the extent of the grounding arrangements will depend on the character of the soil, ranging from simple extension of the conductor into the ground where the soil is deep and of high conductivity, to an elaborate buried network where the soil is very dry or of very poor conductivity. Where a network is required, it should be buried if there is soil enough to permit it, as doing so adds to its effectiveness. Its extent will be determined largely by the judgment of the person planning the installation, following the minimum requirements of NFPA 780, and keeping in mind that, as a rule, the more extensive the underground metal available, the more effective the protection.

Protection of Structures (Traditional Systems)

Underwriters Laboratories Inc. "Master Label Service" for Lightning Protection Systems. Underwriters Laboratories Inc. (UL) has had a "Master Label Service" for lightning protection systems since 1923. It provides for both factory inspection and labeling of lightning protection materials (components), as well as field inspections of a substantial number of installations for which Master Labels have been issued. The service covers the installation of labeled lightning protection materials (components) on all types of structures, with the exception of those used for the production, handling, or storage of ammunition, explosives, flammable liquids or gases, and explosive ingredients. Protection of electrical transmission lines and equipment is not within the scope of the "Master Label Service."

Structural Steel Buildings. Buildings constructed of structural steel framing can be protected by the installation of air terminals at the high parts of the building, connecting such air terminals to

the metal framing, and grounding the framing at the bottom end. This construction assumes that the structural steel framework is inherently electrically continuous or is made electrically continuous by bonding. Grounding is required from approximately every other steel column around the perimeter and is arranged so that grounds average not more than 100 ft (30.5 m) apart, except as noted in the following.

Air terminals are not required if the steel columns extend at least 10 in. (254 mm) above the object to be protected. Air terminals are not required on metal roofs where the metal is not less than 3⁄16 in. (4.8 mm) thick.

Additional grounding is not required if the steel column extends 10 ft (3.05 m) or more into the earth or is connected to a concrete-encased electrode.

Reinforced Concrete Structures. Reinforced concrete buildings in which the reinforcing rods are electrically bonded together and grounded are similar to structural steel buildings in regard to lightning protection. In usual building practice, as successive reinforcing bars are fitted, they are made to overlap lengthwise with bars already installed and are then tied together with metal binding wire. With thousands of such connections in a completed framework, the electrical resistance is fully acceptable for the purpose of lightning protection. However, if the reinforcing rods are electrically discontinuous, the building should be treated the same as a building of nonconducting materials. Lightning strokes to reinforced concrete buildings where there are insulating gaps between reinforcing rods can cause cracks at places where beams and floor slabs are connected to their supports. Prestressed concrete buildings are a particular problem. If the wires in precast units are not interconnected (as they frequently are not), individual units are isolated and when a lightning charge is induced, serious damage can result.

Metal-Roofed and Metal-Clad Buildings. Metal roofing and siding must not be substituted for the main conductors and air terminals of a lightning protection system, unless constructed of 3⁄16 in. (4.8 mm) minimum sheet metal that has been made electrically continuous by bonding or an approved interlocking contact. This requirement is because there is a likelihood that lightning will puncture thinner sheet metals and ignite wood framing.

Tanks Containing Flammable and Combustible Liquids and Gases. Tanks containing flammable and combustible liquids or flammable gases stored at atmospheric pressures have been ignited by lightning. Fires can be started by direct hits, which ignite vapors escaping from metal floating roof tanks. Roofs of wooden tanks can ignite from a direct strike. A lightning stroke in the vicinity can, by induction, produce sparks that might ignite such vapors. If there are openings in the roof, either intentional or unintentional, externally ignited vapors might carry flame inside the tank, resulting in an explosion or fire if it contains a flammable or combustible vapor-air mixture.

Aboveground tanks storing flammable or combustible liquids or flammable gases at atmospheric pressures are considered to be reasonably well protected against lightning if constructed entirely of steel, and if (1) all joints between steel plates are riveted, bolted, or welded; (2) all pipes entering the tanks are metallically connected to the tank at point of entrance; (3) all vapor openings are closed or are provided with flame arresters (for Class I liquids as defined by NFPA 30, *Flammable and Combustible Liquids Code*); (4) the tank and roof are constructed of 3⁄16 in. (4.8 mm) minimum thick sheet metal so holes will not be burned through by lightning strokes; and (5) the roof is continuously welded, bolted, or riveted and caulked to the shell to provide a vapor-tight seam and electrical continuity. Where additional protection is desired, the internal supporting members of the roof can be bonded to the roof at 10 ft (3.05 m) intervals or an overhead ground-wire system or mast protection can be installed in accordance with NFPA 780 (Figure 11.6.12).

Steel tanks in direct contact with the ground or aboveground steel tanks connected to extensive properly grounded metallic piping systems are considered to be inherently grounded. Steel tanks with wood or other nonmetallic roofs are not considered self-protecting, even if the roofs are essentially vapor-tight or sheathed with thin metal. Such tanks should be protected by an overhead catenary ground-wire system or mast protection (see Figure 11.6.12).

Floating roof tanks with hangers located within the vapor space can be protected by bonding the roof to the shoes of the seal at 10 ft (3.05 m) intervals around the circumference of the tank and by providing insulated joints or installing jumper bonds around each pinned joint of the hanger mechanism. Floating roof tanks without vapor spaces do not appear to need lightning protective measures.

Aboveground storage tanks or containers of flammable liquids or liquefied petroleum gas under pressure are considered to be safe from lightning-caused explosions because the vapor-air mixture is "too rich" to burn and the vapor is contained within the tank.

Tall Structures. Spires, masts, and flagpoles of materials other than metal and other slender structures require one air terminal extending 10 in. (254 mm) or more above the uppermost point, a down conductor, and a ground terminal in compliance with NFPA 780. Church steeples will require one air terminal with a two-way path to ground at the extremities and additional air terminals on the lower-level portion that is outside of the steeple's zone of protection.

In Great Britain, brick chimneys, church spires, and so on are protected by two down conductors connected at the top to an existing metal cap or to a circular conductor with no air terminals (Figure 11.6.13[1]). Note the absence of air terminals on the lower-level portion; protection is provided by an elevated conductor above the ridge. Metal smokestacks need no protection against lightning other than that provided by their construction if they are grounded.

Trees, Other Specialized Structures, and Facilities. Trees are sometimes provided with lightning protection if they are especially valuable, are of historical significance, overhang buildings, or provide a shelter for livestock. Guidance on the installation of lightning protection is given in the appendices of NFPA 780, such as for (1) parked aircraft; (2) livestock in fields;

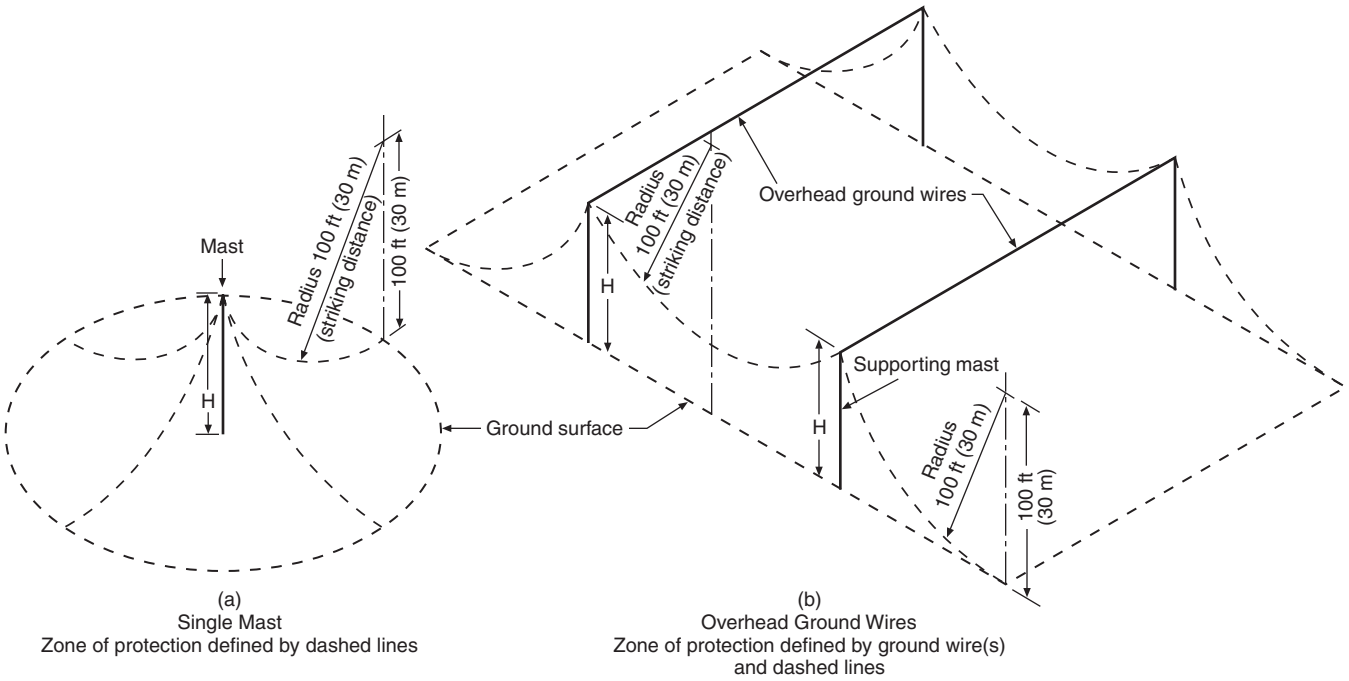


FIGURE 11.6.12 Zone of Protection for Mast Height H

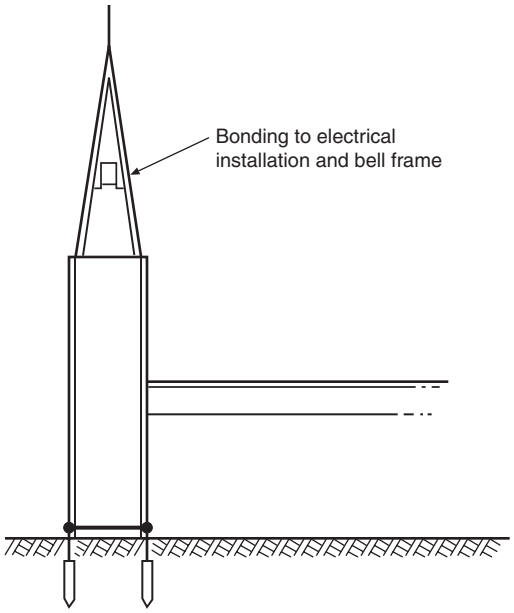


FIGURE 11.6.13 Installation of a Lightning Protection System in a Church Steeple According to *British Standard Code of Practice*[1] Requirements

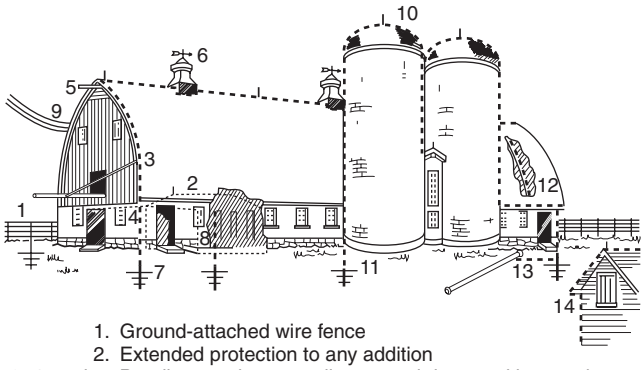


FIGURE 11.6.14 Lightning Protection System on a Typical Large Barn

and (3) picnic grounds, playgrounds, ballparks, and other open places (Figure 11.6.14).

Grounding Metal Masses (Bonding). Extensive masses of metal that form part of a building or its appurtenances, such as metal ventilators and television or radio antennas, must be bonded to the lightning protection system. Nevertheless, the grounding of metal windowsills could be a hazard to human life in the event of a direct lightning strike. Details are given in NFPA 780, under "Metal Bodies," "Potential Equalization," and "Bonding of Metal Bodies," which determine the need for bonding and require loop conductors around a structure at various levels to be bonded to

all down conductors. This standard provides an equipotential ground grid that causes the different metal components in the structure to be at the same voltage, thereby minimizing the shock and arcing hazard and also decreasing the amount of current that could affect computers and other electronic equipment.

Maintenance

Proper maintenance of lightning protection systems is essential. Particular attention should be given to air terminals and connections in the vicinity of water gutters and ground rod connections, as rods might be broken or corroded at ground level or just below, where the damage is not apparent. Materials (components) might be missing because of storm damage or stolen because of their value.

Surge Arresters and Suppressors on Electrical Apparatus and Circuits

The installation of surge arresters on power and communications lines where they enter structures and at power utility plants is covered in Article 280 of NFPA 70, *National Electrical Code*®. The use of secondary service arresters on electric services is required for buildings equipped with a UL Master-Labeled Lightning Protection System. Such arresters can be installed at the yard pole, at the outside electric service entrance, or at the interior service entrance equipment, depending on local regulations. Home lightning protectors are available that are designed for installation at the dwelling weatherhead or indoors at the service entrance equipment. These protectors (arresters) drain lightning surge-induced charges harmlessly to ground and then open to restore electrical service to normal. Before a secondary service arrester is installed, it should be determined that the neutral wire is grounded.

With the installation of sophisticated electronic equipment in many homes and in industry, it is imperative that surge arresters and transient voltage surge suppressors be incorporated to complete the lightning protection system. The surge arrester should be coupled with a transient voltage surge suppressor on branch circuits that serve computers and electronic appliances. These devices are constructed as portable (plug-in) or permanently wired units.

In the United States, except on the Pacific Coast where lightning storms are infrequent, most electric utilities install lightning arresters on the primaries of important transformers on systems of 44,000 V or less.

PROTECTION OF PERSONS

The risk of direct lightning strike is greatest among persons whose occupations keep them outdoors. Prevention of injuries due to lightning or lightning-induced fire involves a combination of protection of the structure from fire due to lightning and the usual steps to protect occupants of a building from injury due to fire.

Guide for Personal Safety During Thunderstorms

Persons should not go out of doors or remain outside during thunderstorms, unless it is necessary. They should seek shelter inside buildings, vehicles, or other structures or locations that offer protection from lightning, such as the following places:

- Dwellings or other buildings that are protected against lightning
- Underground shelters, such as subways, tunnels, and caves
- Large metal or metal-framed buildings
- Large unprotected buildings
- Enclosed automobiles, buses, and other vehicles with metal tops and bodies
- Enclosed trains and streetcars
- Enclosed metal boats or ships
- Boats that are protected against lightning
- City streets that are shielded by nearby buildings

If possible, they should avoid the following places that offer little or no protection from lightning:

- Small unprotected buildings, structures, barns, sheds, and so on
- Tents and temporary shelters (not lightning protected)
- Automobiles (nonmetal top or open tops)
- Recreational vehicles (nonmetal or open)

They should also avoid use of or contact with electrical appliances, telephones, and plumbing fixtures. Certain locations are extremely hazardous during thunderstorms and should be avoided if at all possible. Approaching thunderstorms should be anticipated and the following locations avoided when storms are in the immediate vicinity:

- Open fields, athletic fields, hilltops, and golf courses
- Parking lots and tennis courts
- Swimming pools, lakes, and seashores
- Areas near wire fences, clotheslines, overhead wires, and railroad tracks
- Areas under isolated trees

In the preceding locations, it is especially hazardous to be riding in or on any of the following during lightning storms:

- Open tractors and other farm machinery operated in open fields
- Golf carts, scooters, bicycles, and motorcycles
- Open boats (without masts) and hovercraft
- Automobiles (nonmetal top or open)

It might not always be possible to choose an outdoor location that offers good protection from lightning. Persons should follow these rules when there is a choice in selecting locations:

- Seek low-lying areas; avoid hilltops and other high places.
- Seek dense woods; avoid isolated trees.
- Seek buildings, tents, and shelters in low areas; avoid unprotected buildings and shelters in high areas.
- If you are isolated in an exposed area, believe a lightning strike is imminent, and cannot reach shelter, crouch as low as possible, with your feet close together to minimize the area of the body in contact with the ground. Do not lie flat on the ground or place your hands on the ground.

SUMMARY

Lightning or lightning-caused fire results in dozens of deaths a year. The need for lightning protection depends in part on geography, because the frequency and severity of thunderstorms vary throughout the world. The degree of lightning protection installed should take into account the nature of the building. For instance, certain types of buildings that are essential to life safety, such as hospitals, police and fire stations, and military installations, or historically important buildings should have lightning protection systems installed if they are in vulnerable areas. However, some buildings do not require supplemental protection because of their construction. Although no lightning protection system can prevent the occurrence of a lightning discharge, protection is achieved by intercepting the current, which is then discharged harmlessly into the earth. A lightning protection system usually consists of a grounded metal mast or multimast system, overhead wires, or air terminals. The type of lightning protection system needed is determined by the physical characteristics of the building and the properties of its contents.

For personal protection against lightning, certain areas such as golf courses, swimming pools, areas near railroad tracks, and areas under isolated trees should be avoided during thunderstorms. Vulnerable vehicles such as open cars, tractors, or boats and electrical appliances and plumbing fixtures should also be avoided. People who find themselves out of doors should seek shelter in a lightning-protected building or, if this is not possible, seek low areas or dense woods. An individual who is isolated in an exposed area should crouch down with feet close together and with hands off the ground.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on lightning protection systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 70, *National Electrical Code®*
NFPA 302, *Fire Protection Standard for Pleasure and Commercial Motor Craft*
NFPA 780, *Standard for the Installation of Lightning Protection Systems*

ANSI Standards, Surge Arresters

ANSI/IEEE C62.1–1989, *Gapped Silicon-Carbide Surge Arresters for Alternating-Current Power Circuits*
ANSI/IEEE C62.11–1993, *Standard for Metal-Oxide Surge Arrestor for AC Power Circuits*
ANSI/IEEE C62.31–1987, *Specifications for Gas Tube Surge-Protective Devices, Test*
ANSI/IEEE C62.32–81, *Standard Test Specifications for Low-Voltage Air Gap Surge-Protective Devices (Excluding Valve and Expulsion Devices)* (R1994)

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Dedication

In recognition of his extraordinary service as founder and professor of the fire protection engineering program at the University of Maryland, as chairman of the NFPA Board of Directors, as chairman of the NFPA Standards Council, as leader and mentor, this handbook is dedicated to Dr. John L. Bryan.

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Preface

The *Fire Protection Handbook*®—there is no other fire protection reference quite like it. For more than a century, the *FPH*™ has been *the* compilation of fire protection data and best practices. This 20th edition honors the traditions of thoroughness and accuracy that make this handbook so central to any fire protection library. At the same time, this edition includes new and expanded information throughout. For example, there are 25 new chapters and more than 500 new figures and tables. The pool of authors grew from 247 in the 19th edition to our current 260.

FPH users face a unique challenge: navigating quickly though such a wealth of information. This edition includes several new features to make it easier for readers to find the information they need. The most obvious change is the use of a second color to highlight important information such as subheads and expanded cross references to related chapters.

Other changes include the following:

- The addition of new features such as "Key Terms" and "Chapter Contents"—tools to help make the information easier to find
- The reorganization of the sections, so that each section contains fewer chapters

Clearly, a big team participated in creating the *FPH*. The authors are at the center of that team—and I'm particularly grateful for the evening and weekend time they devoted to their chapters. The authors were unfailingly cheerful and were marvelous at fitting the *FPH* into their busy lives and careers.

The section editors recruited authors, reviewed draft material, and resolved technical differences. They were simultaneously diplomats and technical taskmasters responsible for as many as 24 chapters. Their job was far from simple. The three associate editors completed a particularly important job in reviewing new chapters.

Special places in heaven are reserved for my colleagues, Robine Andrau (who timed her retirement to accommodate the *FPH* schedule), Betsey Henkels, and Michael Gammell. They faced a huge manuscript—a stack of paper and electronic files equivalent to 12,000 pages and 2,500 illustrations—and tamed it, one page at a time.

Many other people contributed to this handbook in large and small ways. We all share a simple goal of making our world a bit safer. I tip my hat to you all.

Pam Powell
Managing Editor and Senior Product Manager

Introduction

This is the 20th edition of the *Fire Protection Handbook*®. It has changed significantly since its inception in 1896 as the *Handbook of the Underwriter's Bureau of New England.*

The original author, Everett U. Crosby, was manager of the Underwriter's Bureau and one of the stock fire insurance company executives who came together to develop a consistent set of sprinkler rules in 1895 that led to the formation of NFPA. He also became the first secretary of NFPA, serving from 1896 to 1903, and was chairman of the executive committee from 1903 to 1907. Henry A. Fiske, who later succeeded Crosby as manager of the Underwriter's Bureau, joined Crosby as co-editor of the second edition in 1901. The third edition in 1904 was called the *Handbook of Fire Protection for Improved Risks,* and the fourth edition in 1909 became known as the *Crosby-Fiske Handbook of Fire Protection,* the title used until the 10th edition in 1948. H. Walter Forster, chair of NFPA's Safety to Life Committee, joined the editorial team in 1918 and became an editor for the sixth edition in 1921.

In 1935, Crosby, Fiske, and Forster donated all rights to their handbook to NFPA, which published the eighth and all subsequent editions. By the 11th edition, in 1954, the work was entitled the *NFPA Handbook of Fire Protection.* From the 12th edition in 1962 to this 20th edition, the handbook has been known simply as the *Fire Protection Handbook.*

The explosion of fire-related technology and fire protection knowledge during the last quarter of the twentieth century and into the beginning of the twenty-first century has driven exhaustive changes in the format and content of the *FPH*™. The original 5" × 7" pocket handbook is now a two-volume 8½" × 11" set.

As the most pressing concerns of fire protection have evolved—from property protection concerns of the late 1800s, through life safety concerns for public occupancies in the beginning of the 1900s, to the computer-modeled, risk assessment–based systems approach in use today—the number of subjects covered by the *FPH* has increased greatly.

Creation of the *Fire Protection Handbook* through 20 editions and 111 years has involved literally thousands of fire protection experts from within and without NFPA. It is their expertise that has established the *Fire Protection Handbook* as *the* reference source for fire protection practitioners worldwide.

Every effort has been made to make the content consistent with the best available information on current fire protection practices. If readers discover errors or omissions, the editors would appreciate those shortcomings being called to their attention. In offering this edition of the *Fire Protection Handbook,* the editors solicit suggestions for improvements to make future editions increasingly useful.

Arthur E. Cote, P.E., FSPE
Editor-in-Chief
NFPA Executive Vice-President and Chief Engineer (retired)

SECTION 12

Non-Emergency Fire Department Functions

John A. Granito

12.1 Planning for Public Fire-Rescue Protection
12.2 Organizational Benchmarking and Performance Evaluation
12.3 Needs Assessment and Hazard Analysis
12.4 Managing Fire-Rescue Departments
12.5 Information Management and Computer Technology
12.6 Liability of Fire Service Organizations for Negligent Fire Fighting
12.7 Safety, Medical, and Health Issues and Programs
12.8 Effect of Building Construction and Fire Protection Systems on Fire Fighter Safety
12.9 Fire and Emergency Services Protective Clothing and Protective Equipment
12.10 Training Programs for Fire and Emergency Service Personnel
12.11 Industrial Fire Loss Prevention
12.12 Disaster Planning and Response Services
12.13 GIS for Fire Station Locations and Response Protocols
12.14 Fire Rescue Stations and Fire Service Training Centers
12.15 Public Emergency Services Alarm, Dispatch, and Communications Systems
12.16 Fire Department Apparatus and Equipment
12.17 Pre-Incident Planning for Industrial and Municipal Emergency Response
12.18 Pre-Incident Planning for Emergency Response
12.19 Community Risk Reduction

Section 12 of the *Fire Protection Handbook*® presents, in nineteen chapters, an overview of the policy, planning, organizational, and management issues that are basic—and often most challenging—to fire department, municipal, and corporate officials as they strive to keep their people, property, and environments safe by maintaining effective fire-rescue organizations. Chapters 2, 3, 12, and 13 are new; other chapters have been significantly revised.

The purpose of Chapter 1, "Planning for Public Fire-Rescue Protection," is to demonstrate that adequate fire protection and related public safety services are essential and that both the level and types of services provided should be carefully considered choices based on adequate information. Topics covered include integrated risk management, planning processes, evaluation as part of planning, and public protection classifications.

Chapter 2, "Organizational Benchmarking and Performance Evaluation," examines organizational benchmarking and performance evaluation from a systems perspective in order to include the key elements of success for a fire department performance management system. Steps to implement a new system are discussed.

The purpose of Chapter 3, "Needs Assessment and Hazard Analysis," is to demonstrate the interrelationship of numerous routine or special activities that can be conducted as a component of a comprehensive needs assessment and hazard analysis—that is, the identification of the challenges faced and the resources needed to manage these challenges.

Chapter 4, "Managing Fire-Rescue Departments," provides an overview of the elements involved in organizing, administering, and managing agencies that provide fire and rescue response services.

Chapter 5, "Information Management and Computer Technology," introduces information technology and networks, as well as their application to management, emergency response and operations, and internal and public communications. Systems integration is also discussed.

Chapter 6, "Liability of Fire Service Organizations for Negligent Fire Fighting," explains legal concepts such as discretionary functions immunity, governmental immunity, liability, limited damages, negligence, public duty rule, punitive damages, and tort claims act. The chapter applies these legal concepts to the fire service environment.

Chapter 7, "Safety, Medical, and Health Issues and Programs," outlines the history of safety and health legislation as it applies to fire departments and describes relevant NFPA standards and

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requirements within the context of that history. The chapter concludes with a description of the risk management program that is detailed in NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program.*

The next three chapters relate to fire fighter safety. As presented in Chapter 8, "Effect of Building Construction and Fire Protection Systems on Fire Fighter Safety," fire department personnel have a very strong interest in building construction. The chapter outlines simplified principles of building construction, building codes, and building construction classification, as well as specific concerns such as building collapse.

Chapter 9, "Fire and Emergency Services Protective Clothing and Protective Equipment," describes NFPA and OSHA involvement in standards for personal protective equipment, discusses third-party certification, and offers guidelines for cleaning and maintaining personal protective equipment. Chapter 10, "Training Programs for Fire and Emergency Service Personnel," is an overview of the broad challenge of providing training for fire and emergency service personnel. The chapter presents information on the need for training, organization of training delivery, ensuring quality instruction, internal and external training programs, training safety, and records.

Chapter 11, "Industrial Fire Loss Prevention," examines the need to minimize fire loss from the corporate perspective. Topics addressed in this chapter include emergency management, fire prevention, fire risk management, hazard identification, and the role of industrial fire brigades.

Chapter 12, "Disaster Planning and Response Services," outlines the phases of emergency preparedness, techniques for a hazard vulnerability analysis, and identification of critical facilities and infrastructure. Continuity of government and continuity of operations are among the other subjects presented.

Chapter 13, "GIS for Fire Station Locations and Response Protocols," explains the use of geographic information systems in fire station location planning and site selection factors. GIS response protocols are introduced.

The next three chapters address fire department resources. Chapter 14, "Fire Rescue Stations and Fire Service Training Centers," provides a general overview of the steps necessary to develop fire stations and fire training centers. Chapter 15, "Public Emergency Services Alarm, Dispatch, and Communications Systems," provides an overview of public emergency services communication systems. This chapter addresses issues related to the design, installation, operation, maintenance, and management of such systems and the facilities that house and support them.

Chapter 16, "Fire Department Apparatus and Equipment," contains information on the standards used and procurement policies that should be followed in specifying and acquiring apparatus and equipment. The chapter discusses inspection, maintenance, testing, and retirement of apparatus and equipment.

The next two chapters address pre-incident planning. Chapter 17, "Pre-Incident Planning for Industrial and Municipal Emergency Response," defines pre-incident planning, introduces the process, and identifies data needed for pre-incident planning. Chapter 18, "Pre-Incident Planning for Emergency Response," explains how pre-incident planning allows fire-fighting personnel to view conditions within a structure or site, evaluate what these conditions are likely to develop into in the event of an emergency, and then develop strategies for dealing with the potential problems.

Chapter 19, "Community Risk Reduction," presents components and fundamentals of a community risk reduction initiative, outlines risk reduction strategies, and discusses the roles of leadership and community engagement in the community risk reduction process.

Chapter 1

Planning for Public Fire-Rescue Protection

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Key Terms

benchmarking, deployment, emergency medical services, fire prevention, Fire Suppression Rating Schedule (FSRS), Insurance Services Office (ISO) grading schedule, master planning, needs assessment, public fire protection, risk management, rural fire protection, technical rescue, urban fire protection

The purposes of this chapter are to demonstrate that adequate fire protection and related public safety services are essential components of any community and that both the level and types of services provided should be conscious and carefully considered choices of the community, which are made with, and based on, adequate information. As adequate public protection is designed, careful planning needs to be done to ensure that fire fighter safety is not compromised. Objective planning and evaluation can ensure that a community's desire for a stipulated level of protection is being met in as cost-effective a manner as possible.

Certain NFPA publications, including a number of codes, standards, and recommended practices, contain information that is related to this chapter. Many of these publications are listed in the bibliography at the end of this chapter.

Several other chapters in Section 12 provide information useful in the self-assessment of a public fire protection system: Chapter 2, "Organizational Benchmarking and Performance Evaluation"; Chapter 3, "Needs Assessment and Hazards Analysis"; Chapter 5, "Information Management and Computer Technology"; Chapter 7, "Safety, Medical, and Health Issues and Programs"; Chapter 12, "Disaster Planning and Response Services"; Chapter 18, "Pre-Incident Planning for Municipal Emergency Response"; and Chapter 19, "Community Risk Reduction."

INTEGRATED RISK MANAGEMENT

Growing national and international awareness of the staggering costs, both in life and dollars, of fire fighter line-of-duty deaths and injuries has given rise to the development of a newer, more comprehensive planning approach. Developed first in the United Kingdom, it is termed *integrated risk management*. This refers to a planning methodology that recognizes that citizen fire safety, plus the protection of property and the environment from fire and related causes, must include provisions for the reasonable safety of emergency responders. Chief Fire Officer Paul Young summarized the 2003 UK government white paper entitled *Integrated Risk Management and Firefighter Safety in the United Kingdom* as follows:

> Mandated Integrated Risk Management in the UK Fire and Rescue Service means that suppression resources are to be allocated on the basis of risk rather than the number of buildings in an area. This means assessing the risks faced, taking preventative action, and deploying the right resources in the right place at the right time.
>
> Far too few resources were devoted to residential areas, where most fire deaths occur, and too many resources were devoted to business districts where fewer deaths occur. Fire and rescue authorities must create local plans for fire and other emergency incidents based on local risks. There is much greater flexibility in managing risk this way, rather than under the old national standardization of response.

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A modern and effective fire and rescue service should serve all sections of our society fairly and equitably by:

- Reducing the number of fires and other emergency incidents
- Reducing loss of life in fires and accidents
- Reducing the number and severity of injuries in fires and other emergency incidents
- Reducing the commercial, economic, and social impact of fires and other emergency incidents
- Safeguarding the environment and heritage (both built and natural)
- Providing true value for money spent

A very important by-product of reducing the number of fires and other incidents is a reduction in the exposure of fire fighters to risk, thus improving their safety. Fewer incidents mean fewer road accidents and fewer fire fighter fatalities and injuries at the scene. The integrated risk management program (IRMP) should also ensure that the optimum operational response is made to any given incident to reduce deaths and injuries among the public. However, to do that, the response needs to be operationally effective, and that means that fire fighter crewing levels need to be adequate and, therefore, safe for the tasks. Inadequate crewing levels are not only unacceptable on the grounds of fire-fighter safety, but on the grounds of public safety as well.

In addition, fire-fighter safety depends on individual competence. Investigations into fire-fighter deaths have demonstrated often that there was no objective way of demonstrating that the fire fighters were competent to carry out the role they were performing at the time. That they had been trained did not mean that they had demonstrated their competence in a way that could be validated.

Because of this, the Integrated Personal Development System is introducing into the UK Fire and Rescue Service a competence-based training and development process that seeks to ensure that all members of the workforce can demonstrate that they are competent to carry out their role. You cannot be safe if you are not competent.

The IRMP drives the planning process for not only vehicle and equipment requirements, but also crewing arrangement, training and development, and many other factors. In short, it provides that an evidence-based approach to the management and delivery of fire and rescue Services.

BACKGROUND ISSUES CONCERNING FIRE PROTECTION

Because the safety of people, property, and the environment is so vital, questions that focus on the organization and deployment of fire-fighting resources are especially important to communities. Prompted by escalating costs, issues relating to fire suppression have attracted a great deal of public attention, even though fire fighting is but one part of what constitutes community fire protection. Although fire prevention and fire protection engineering efforts are typically less costly in the long run than fire fighting, questions relating to the appropriate size, deployment, and response protocols of fire-fighting forces remain paramount.

Financial, Technical, and Responsibility Issues

Nevertheless, governmental and public concerns that focus exclusively on emergency response issues to the exclusion of adequate provisions for the prevention of fire and other emergencies are more costly and less effective. A total fire and related protection program, which includes the application of resources to comprehensive fire prevention and life safety, provides the most effective and efficient means of saving lives, property, and the environment, plus increases the operational safety of fire fighters.

The first issue is created by the relatively high cost of fire stations, fire apparatus and equipment, on-duty personnel, and line-of-duty deaths and injuries. A second set of issues is technical in nature, dealing with the number of responders necessary to be on duty and to be dispatched, with what should be the maximum allowable time for response, and with other related technical and operational questions including the necessity for safety officers and rapid intervention teams.

The third issue considers what the process should be for determining the answers to the following technical, operational, and safety questions:

- Should communities assess their own needs and resources and provide individualized answers, or should national standards be applied?
- How should national standards and recommended practices be formulated?
- Should noncompliance with a national or industry standard expose officials to penalties?
- Should fire chiefs be obligated to inform fully their local officials concerning local hazards, risk levels, and levels of service actually available?
- Should local officials keep citizens fully informed concerning available emergency service capabilities?

These and similar questions have generated much debate about the processes of planning and evaluating community fire and rescue defenses.

Unfortunately, it appears possible that even those who are genuinely concerned with evaluating and planning for local fire, rescue, and emergency medical services may blend together the issues of cost, technical correctness, safety, and responsibility for resource decisions. When this happens, communities cannot be sure that the resulting delivery system is the most appropriate obtainable for the available financial resources.

Of course, there are multiple demands for local municipal funds. Thus, emergency protection must be fitted into a larger community priority listing of needs and desires. However, proper placement in the listing requires that a true and accurate description be publicized of existing capability compared

with accurately described community hazards, response history, and call demand predictions. When the issues are erroneously blended together, citizens may believe that adequate, timely, and safe response is available when indeed it is not and may give higher budget priority to another community interest. Or citizens may be unduly anxious over erroneous observations that fire defenses are much too meager and that even more resources must be allocated. In addition, official planning and community concern may ignore the vital issues of hazard mitigation, comprehensive prevention, and life safety education.

Publicizing the Need for Prevention Programs

Citizens are often subjected to opposing budget arguments concerning protection levels and frequently lack the knowledge necessary to arrive at sound conclusions. This understandable lack of technical expertise underscores the necessity for accurate, well-balanced, and forthright information to be widely disseminated among those who will both receive and pay for service delivery. Hazard analysis and risk assessment are extremely important.

Partly because the benefits of active comprehensive prevention programs, public safety education, and fire protection engineering efforts are not well advertised, there often is little pressure exerted on their behalf. Thus, relatively few resources are allocated to these efforts in many communities when compared with allocations for suppression work. Even though it certainly is true that the least harmful fires are those that never occur, most communities fail to consider a total fire protection plan as a wise and cost-saving instrument. The benefits of residential and high-rise fire sprinklers are well documented, for example, yet conflicting pressures have often curtailed their use. The funds allocated to fight the fires that do start, however, can be quite high. Much more emphasis is needed on the total protection program if communities and their fire fighters are to be made reasonably safe at reasonable costs. The evaluation and planning of public fire protection, then, must consider total protection efforts. Benchmarking and performance evaluation play key roles in the planning process. Efforts certainly must include provisions for emergency response, but also such efforts as locally adopted codes and ordinances, built-in structural protection, inspection programs, public education for all groups, building plan reviews, and so on must be included. The same concept, of course, applies both to the preventive and emergency-type prehospital medical services fire departments often provide.

Developing a Prevention Plan

A practical approach to the development of a community's mid- to long-range plan is first to generate a view of what the community will be by the time of the planning horizon. That information comes from an analysis of past development combined with projections of demographic changes, economic development or decline, major roadway programs, annexations, significant building projects, and so on.

The second step is to assess realistically the strengths and weaknesses of the existing fire protection system, including codes, standards, and ordinances relating to safety, fire prevention efforts, public safety education programs, and emergency response capability. This is an important facet of the risk management process.

Answering the question of what the response strength should be involves an honest assessment of stations and their locations, vehicles and equipment, staffing numbers and provisions, breadth and depth of the various service delivery areas, training and other support activities, success rate in handling emergencies, mutual-aid arrangements, dispatch and communication provisions, and response times.

In 2001 the NFPA consensus standard building process produced two new standards, one for substantially career fire departments (NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*) and the other for substantially volunteer departments (NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments*).

Applying NFPA Standards

NFPA 1710 (2004 edition) deals with the time frame for response to fire and medical incidents for the first-due engine company, for the entire first alarm assignment, and for the first level, basic, and advanced emergency medical responders. The number of fire fighters necessary for initial suppression attack and their roles are specified in the standard, as are other aspects of organization, suppression, operations, emergency medical and other responses, special services, staffing, and so on.

NFPA 1720 (2004 edition) addresses the organization, operation, and deployment of those departments that are substantially volunteer in staffing. Recognizing the response time differences that often occur between in-station responders and volunteers who likely are not at the station, NFPA 1720 calls for minimum numbers of fire fighters depending on local population density per square mile, and differing maximum response times, which are also related to population density.

The third step is to project the needed capabilities and capacity of the fire protection system and its vitally important fire department component as the community changes. Any additional needs of the system and the fire department, so that they can meet the projected demands, represent the content components of the plan. How that plan may be financed and implemented, and the time and timing required constitute the strategic and tactical planning necessary for success.

A major challenge in this "discovery" process often lies in assessing the existing protection system and its fire department, and in determining the steps needed to bring both to the strength required by projected demands. Additionally, tests of efficiency, cost-effectiveness, economies of scale, and other sound business practices must be applied.

The following basic questions are to be raised concerning this entire process:

- What types and levels of protection does this community need both now and to meet the upcoming community profile?

- How are the details of these needs best determined?
- What process and whose expertise should be used to arrive at the answers?
- Is fire fighter safety carefully considered?
- How may the correctness of the answers be tested?
- Are the answers as cost-effective as possible?
- How can any needed improvements best be funded?
- What should be done during and after the planning process to win the support of those directly affected by changes and those who will have to pay for any improvement?
- How and when should the plan be updated?

STEPS IN PLANNING

Public fire protection, emergency medical services, and technical rescue provisions need to be carefully planned and require that certain logical steps be taken to achieve a comprehensive, acceptable, and workable plan. There are two important aspects to any good plan: (1) the plan itself, which must be feasible and directed toward clear goals; and (2) the process by which the plan is developed, which must ensure that all major goals are considered and every constituency to be affected by the plan is reasonably involved in the planning process or made well aware of its consequences prior to plan approval.

Without adequate involvement of the necessary constituencies, implementation of the plan may likely fail because of a lack of cooperation and commitment. For a satisfactory plan to evolve, the planners must decide the end results they wish to achieve (goals), determine the status of the fire protection system in relation to those goals (evaluation), and calculate how much and what kinds of progress actually can take place over a certain period of time (objectives, tactics, time frame). Each of these three steps—setting goals, evaluating, working out the details—requires the collection and analysis of relevant information. Broad goals are achieved through planned strategies and precise objectives are achieved through implemented tactics. Each must be relevant to the other. Local data collection and information management systems are vital to planning.

Careful consideration of these important factors, which will vary considerably from one community to another and which must take into account assets, liabilities, challenges, and available resources, leads to what is often referred to as a *strategic plan.*

Evaluation of Fire Protection Services

Because some degree of public fire protection is almost always in place, it is common for the entire process to begin with both a local hazards analysis and risk assessment, plus an evaluation of the fire protection that is already available. See Section 12, Chapter 3, "Needs Assessment and Hazards Analysis." The information obtained from the evaluation, when analyzed in terms of broad, generally recognized public fire protection goals, identifies needs and provides responsible community officials with the approximate parameters of the plan to be developed.

It is important to take into consideration those fire protection and other public safety services that may be provided by a fire/rescue department and that will meet specific local needs. Examples of this are hospital transportation by a fire department ambulance and responsibility for emergency management and disaster services.

Typical fire department services include fire prevention programs—such as code administration and enforcement through plans review, inspection services, and public education—as well as fire suppression, technical rescue, emergency medical, hazardous materials response, and disaster response. Various other public services, such as health screening programs, are conducted more and more often by progressive departments. This approach to broad-based community safety service takes advantage of departmental resources, such as neighborhood fire stations and on-duty personnel, experience in public service and education, and the typically high regard in which fire departments are held by citizens.

Community Involvement

As already noted, the plan cannot be developed without the involvement of a wide variety of community groups. Even if the various constituencies seem willing to allow fire protection officials to develop and write the comprehensive plan without their consultation, the fire officials should be cautious; the citizens eventually must be willing to accommodate and pay for the implementation. Because a comprehensive plan envisions a larger group or system of integrated parts, a number of organizations and agencies outside the fire department will need to play important roles in implementation of the plan. Local elected officials typically play key roles in plan approval, implementation, and funding.

Modern practices make it necessary for fire departments to work cooperatively with a variety of agencies and organizations. These range, for example, from the local building code enforcement staff to the U.S. Coast Guard for hazardous materials spills near navigable waterways. Good planning requires consultation with all operational components on a continuing basis. A good plan today is better than a perfect plan that might be developed tomorrow.

As noted, one basic aspect of a comprehensive public fire protection plan is the concept that it is infinitely better for a community to prevent fires altogether, or to mitigate them automatically through fire safety education and built-in fire protection features, than to depend solely on the fire suppression capabilities of the community's fire department. The goal of reducing the incidence and effects of fire involves all aspects of fire prevention. Historically, much more energy and many more resources have been devoted to evaluating, planning, and implementing fire suppression/fire-fighting capabilities than fire prevention capabilities. Simply stated, the United States as a whole has focused more on "fire engines and fire fighters" than on public awareness and built-in mitigation features. That focus is still necessary and exceedingly important, but effort must also be placed on measures that do not depend solely on fire suppression personnel to reduce the toll of fire. Planning groups often have difficulty, however, in evaluating the degree of effectiveness of such multifaceted fire protection programs.

Three Types of Analysis

A reasonably effective method exists for conducting the evaluation, involving three kinds of analysis.

Community Record Keeping. The first kind of analysis requires the community, typically through the fire department, to maintain consistent and carefully recorded information each year concerning the number of fires that occur and the cost of those fires in lives and dollars including wages and tax revenues lost. When those human and physical costs are added to the expense of maintaining fire prevention and suppression systems, plus the cost of fire insurance, a standardized total cost of fire to the community can be compared with that same cost in earlier years, or over an average of three or more years. Necessary adjustments for inflation, community growth or decline, and other important variables can be made by local officials, thus permitting a community to compare its present to its prior fire performance.

Benchmarking. The second kind of analysis most useful in determining cost-effectiveness involves communities identifying other communities that are similar in ways important to fire protection (such as services desired, size, construction, hazards, and geography) and comparing their own total performance to the total performance of the similar communities. This process, termed *benchmarking,* has become a popular methodology. However, the number of site-specific variables may be so high and the span of differences so great that comparisons prove confusing. Benchmarking requires cautious application. See Section 12, Chapter 2, "Organizational Benchmarking and Performance Evaluation."

Needs Assessment and Hazard Analysis. The third kind of analysis, although self-conducted, is formatted and guided by the fire department accreditation process now available in the United States. See Section 12, Chapter 3, "Needs Assessment and Hazards Analysis."

In the first analysis, the community uses an internal data source (itself) as a yardstick, and in the second analysis it uses an external yardstick (other communities). As more data are collected concerning the total cost of fires in various communities operating with different public fire protection plans, any given community will be able to benefit relatively quickly not only from its own experience but also from the experiences of others. The Commission on Fire Accreditation International, which was developed by the International Association of Fire Chiefs in conjunction with other national organizations, provides a standardized methodology for fire departments to assess and rate themselves—with the assistance of a visiting team—along a series of categories important to community protection. Performance indications serve as points of measurement and are important components of this accreditation process. More and more departments are using this process to evaluate their condition and to benefit from both the process and the accreditation status.

Important to this planning process is the ability and willingness of the community to finance and otherwise support the total level of fire protection required by the plan's goals. Examples include legislation dealing with the retrofitting of sprinkler systems, or innovative thinking that produces a core group of senior citizen volunteers who conduct fire safety programs for their peers. In some states built-in fire protection requirements are set at the state level, and local government may not increase the level of fire safety provided by building features (automatic fire sprinklers, noncombustible roofing, etc.).

Although fire protection officials must always be concerned with reducing the total cost of fire (fire loss, plus costs of insurance, prevention, and suppression), citizens living in tight economic times will ultimately reserve the right to make decisions, or trade-offs, concerning the level of protection they wish their tax dollars to purchase. However, the safety of emergency responders cannot be reduced as part of a cost-reduction program.

To assist citizens in making decisions concerning budgets, fire protection officials must accurately describe the effect on total cost if additional or fewer resources are applied to particular prevention or suppression efforts. This kind of technical knowledge and analytical ability of officials provides a crucial element to comprehensive planning and evaluation. It is one of the most important responsibilities of the public fire protection officer.

One of the most serious issues faced by public officials and residents is that of adequate fire department staffing. In communities served by volunteer fire fighters, there may be serious volunteer recruitment and retention problems or problems in providing timely response during working hours when many of the volunteers may not be in the community they protect. In communities served by career, full-time fire fighters, restricted budgets often limit the number of fire-fighting vehicles ready to respond, or the crew size for each vehicle and, thus, the total number of trained personnel responding to the incident in time to mount an effective offense against the fire, often termed "initial attack." Fire protection officers and municipal officials need to communicate objectively the level of service being provided and how changes in fire department resources will affect that level of service. That is, the type and level of risk should be expressed in terms understandable to the fire protection nonexpert and in terms neither over- nor understated. Of course, the fire department must bear the responsibility of formulating and operating a cost-effective organization, no matter what level of service is desired.

EVALUATION AS PART OF PLANNING

In addition to assessing the capabilities of the fire department and related aspects of fire protection, fire officials evaluating the capability of the existing fire protection system must take a number of factors into account. Examples include known combustibles, the life hazard that exists, fire frequency, climatic conditions, demographic and geographic factors, and a basic consideration of the specific role of a public fire department in providing fire protection to the community. Failure to consider each of these factors adequately can lead to a large-loss fire. A fire department's suppression capabilities can never be expected to compensate totally for the deficiency or lack of built-in fire protection systems.

Local Capability and Capacity for Fire Suppression

Two concepts are useful in local suppression considerations. First is the "capability" of the fire department to respond within a short time with sufficient trained personnel and equipment to rescue any trapped occupants and confine the fire to the room or building of origin on initial attack. How many crew members and vehicles of various types are necessary depends on the type of call and the conditions of the local community, which either aid or hinder fire fighting. These variables, which certainly number more than 20, range from water supply and sprinkler ordinances to weather conditions and the age of buildings. See Section 12, Chapter 18, "Pre-Incident Planning for Emergency Response."

Thus the evaluation of local fire suppression capability, although no more important than the evaluation of local prevention and public safety education efforts, is a necessary effort for two primary reasons. First, most communities have little understanding of either the level of local protection available or the level necessary for reasonable community well-being. Second, the time availability of volunteers is quite limited, and the cost of full-time career personnel typically is significant. The actual number of available crew members—although exceedingly important—may not be realized by nonfire officials and citizens. This lack of information concerning actual resources can lead to a false sense of security.

The second concept is that of "capacity," which is the ability of the fire department to respond adequately to multiple-alarm incidents ("sustained attacks") and/or simultaneous calls of any type, including emergency medical responses. If alarm patterns are examined, the volume of multiple alarms and simultaneous response demands over a period of time can be approximated. Larger municipalities typically average more demand for capacity and, thus, typically have larger departments; but, obviously, remaining capacity is diminished as suppression units are deployed, even in the largest departments. It must be recognized that although a few fireground tasks may be performed sequentially, most need to be performed simultaneously, and the latter requires more personnel.

Evaluation Factors

In evaluating both local response capability and capacity, officials need to consider the following: in many areas it is relatively easy to increase capacity (through the use of mutual aid and group or entire shift callbacks), but it is much more difficult to improve capability, which requires immediate *response* of nearby forces. A common rule of thumb is that a community using on-duty crews at fire stations should be able to have an initial attack team composed of an entire first-alarm response on the scene within approximately 10 minutes of receipt of the alarm. This equates to about 8 minutes of running time.

Another rule of thumb is that, for a totally volunteer, nonstaffed station, the average time from when a call is received to the moment a crewed vehicle leaves the station could be 6 minutes or longer. In those situations, then, the "call to on-scene time" for a 6-minute run is about 12 minutes for one or more vehicles.

Several techniques are used by progressive fire officials to help mitigate these handicaps to achieving adequate response capability and capacity. These techniques include using *automatic,* immediate mutual-aid response from nearby departments, rapid callback systems, volunteer personnel who "bunk in" at stations, part-time or full-time on-duty crew members (combination department), special shift arrangements, elaborate regional mutual-aid agreements, and other methods. "Doing more with less" is a popular concept, but there are limits that must be realized.

As part of a local response evaluation, fire officers and other community officials can determine the status of their response forces by establishing what capabilities and capacities are necessary for adequate protection of their area and then determining what is available.

Following a local hazard analysis, for example, the following types of "what should be" questions concerning what *is needed for adequate response capability* may be posed:

- Maximum time for call processing at dispatch center
- Minimum number of persons on first-out pumpers
- Minimum number of persons on first-out aerial
- Minimum number of persons on first-out heavy rescue
- Minimum number of persons on first-out emergency medical service (EMS) vehicle
- Weekday get-out time for first-due unit
- Weekday get-out time for second-due unit
- Nighttime get-out time for first-due unit
- Nighttime get-out time for second-due unit
- Maximum clear weather running time (pumper) in district
- Maximum clear weather running time (aerial) in district
- Maximum clear weather running time (EMS) in district
- Number of qualified fire fighters plus incident commander to be at scene within 8 to 10 minutes of dispatch
- Number of qualified fire fighters plus incident commander to be at scene within 15 minutes
- Number of minutes for mutual aid to arrive at scene

Figure 12.1.1 illustrates one method for listing the actual response capability of a department for a simple, single-family-dwelling fire. Figure 12.1.1 can be expanded to include first-alarm fire responses to other types of occupancies. Response times can be verified and listed for the components of the first-alarm assignment, and other questions can be posed to identify local response capacity to handle multiple and/or simultaneous alarms.

An important stipulation put into effect in 1995, and continuing, is that a minimum of four trained personnel be at the scene of a structure fire before an interior attack can be launched, except under the most extenuating circumstances. Both the U.S. Occupational Safety and Health Administration (OSHA) and the National Fire Protection Association (NFPA) have issued documents dealing with this. Also, in the United States and in certain other countries, various governmental agencies have issued regulations and advisories concerning the necessity for certain emergency operations to have trained incident commanders and standby safety/rescue crews present, as well as to have a defined incident command system operating. Local officials are well advised to have current infor-

Number of Resources Dispatched	Confirmed Working Single-Family-Dwelling Fire
Chief(s)	
Aides or incident command technicians	
Company officers	
Fire fighters, including "flying squads"	
Single-purpose emergency medical technicians (EMTs)	
Standard pumpers	
Quints	
Aerials	
Ladder tenders	
Ambulances	
Heavy (technical/urban) rescues	
Light/medium rescues	
Mini/midi attack pumpers	
Special operations (air, lighting, etc.) units	
"Flying squad" vehicles	
Mobile command vehicles	
Safety officer	
Rapid intervention team	
Other (types)	

FIGURE 12.1.1 Typical, Actual, First-Alarm Fire Attack Assignment

mation concerning all applicable federal (national), state, and provincial requirements, as well as applicable NFPA codes, standards, and recommended practices, as issued from time to time.

Rural Fire Protection

One principal difference between operation of rural and urban fire departments is that rural departments must deal with water supply issues with a broader variety of solutions than most urban departments. Rural fire department operations and apparatus emphasize not only fire-fighting requirements but also the provision of water for fire fighting. Rural fire apparatus must have large water tanks to permit effective initial attack on fires while supplementary water supplies are being brought into action. Supplementary water supplies include drafting sources on or adjacent to rural properties, and mobile water tanker vehicles for transporting water from more distant sources. Also in use are portable folding canvas tanks into which tank trucks quickly discharge their water supply through special dump valves. Rural fire departments often use apparatus and hose to relay water from sources several thousand feet (1000 ft equals 304.8 m) from the emergency. Initial response of pumpers, tankers, and auxiliary apparatus should be adequate for a quick attack on the burning property. With adequate highways and well-designed apparatus, it is often possible to bring substantial fire-fighting forces to an emergency in rural areas in sufficient time for a properly planned and executed initial fire attack operation to be effective, even though many of the personnel may arrive in private automobiles. Many rural properties are now located in areas that enjoy some level of fire protection. Some properties, of course, may have to depend entirely on their own private fire protection and whatever help they may obtain from forestry agencies or distant fire departments.

Newer approaches to fire insurance rating give "protected" status to property without a municipal water supply system if a fire station is within five travel miles and a stipulated gallons per minute flow can be maintained by the local department, as mentioned later in this chapter.

Fire-Fighting Apparatus. Minimum protection for a rural area would include a pumper with a large water tank and a water tank vehicle responding on an initial alarm. Properly designed tanks should be able to transport water from a source 1 mi (1.6 km) from the scene so a minimum of 250 gpm (946.25 L/min) can be pumped at the fire scene by the pumper. Because a larger flow is often required to provide adequate fire protection services, additional tankers must be used, or drafting sources within reasonable distance of the fire scene must be identified. Programs that encourage the construction of year-round rural drafting sites are to be encouraged. Rural apparatus should carry 3½-in. (89-mm) or larger supply hose to provide adequate water supply at the fire scene. It is always advisable to lay large-diameter fire hose from the water supply source to as near the fire scene as possible in order to avoid extensive friction loss. At the emergency, large-diameter hose is sometimes connected into smaller handlines, or used more often to supply another pumper from which handlines are extended. Other pieces of equipment, such as rescue and aerial ladder vehicles, should be provided as needed to carry out the mission. Elevated master streams are not needed extensively in rural operations, and sometimes ladder truck equipment for rescue, forcible entry, ventilation, and salvage operations is carried on pumpers and equipment vehicles.

To be even minimally effective in controlling a fire, the initial responding apparatus should reach the emergency scene before very rapid fire spread. As is the case in urban fire fighting, this move is termed "initial attack" and is aimed at stopping the fire as close to the point of origin as possible. So-called "sustained attack" attempts to reduce the loss to the exposed adjoining or nearby property. Because of longer response times, rural

departments may find themselves in the sustained attack, or "defensive," mode on arrival. Unless sufficient water can be made available within a short time frame, the British thermal units (Btu) generated by the burning material cannot be absorbed so the temperature is not reduced sufficiently to extinguish the fire. Successful rural protection planning generally boils down to response times and water availability.

Hazardous Materials and Structures. Of special concern are the sometimes extensive supplies of fertilizer and pesticides located on rural properties. Response crews must be alert also to the possibility of above- and below-ground storage tanks for fuel and other products. The safe operations guidelines for hazardous materials response are applicable in rural as well as urban areas.

Another concern for rural fire protection exists because so many large and diverse types of structures are located in rural areas. These structures include warehouses, truck centers, product distribution facilities, processing plants, storage buildings, centralized schools, churches, trailer parks, and others.

In addition, the extension of existing housing developments and the construction of new residential and commercial structures immediately adjacent to wildland areas, or in the midst of such areas, have brought about a significant increase in wildland–urban interface fires, which present new challenges to both urban and rural fire departments.

However, it is possible to give such counsel if one can make certain assumptions that may be controlled by the community. These assumptions relate primarily to the presence of appropriately placed smoke detectors and other types of fire detection devices and a means to relay that alarm to the fire suppression agency, but they also include the existence of enforced building codes that provide some degree of resistance to fire spread from the room of origin, rural sprinkler systems, home escape plans, and so on.

Urban Fire Protection

In urban areas, inadequate fire department response to initial alarms can be a major factor in fire losses due to high population and structural densities. The number of simultaneous fire-fighting operations that may need to be conducted at the incident also dictates the total amount of personnel and equipment needed to provide effective fire-fighting operations. In any "working" structural fire, several operations must be carried on simultaneously and the fire attack must be made from several points. This attack cannot be accomplished by the crew of a single fire apparatus. Multiple apparatus must be positioned properly, and adequate waterflow made available to cope with the amount of fuel (fire load) involved or exposed.

Structural Fire Suppression. In simplest terms, structural fire suppression in an urban setting involves the accomplishment of at least the following tasks, many of which must occur almost simultaneously to ensure effective and safe operations (the proper sequence will vary, depending on circumstances, as will additional tasks):

- Command, control, and coordination of the incident (to ensure both effectiveness and safety of the fire fighters)
- Adequate on-scene radio communication among attack forces
- Application of water in appropriate quantities (dependent on the fire environment and other factors)
- Provision of appropriate source of water supply for above
- Ventilation of smoke and other hazardous products of combustion from the fire area to the outside
- Search for and rescue of fire victims
- Forcible entry
- Control of utilities
- Salvage and other property conservation operations
- Standby rapid intervention/fire fighter rescue
- Provisions for emergency medical services

At large-structure fires, additional fire-fighting personnel are needed to cover the various points of fire attack. In some cases various functions can be handled more efficiently by specially trained crews such as rescue companies and hazardous material teams operating from specially equipped apparatus.

Determination of Required Equipment and Personnel. The number of personnel and equipment necessary to accomplish the above will vary with a number of factors (i.e., the expectations placed on the mobile suppression group, the material burning, the construction of the building, the type of built-in protection provided, separation between buildings, availability of water supply, the number and physical and emotional condition of persons in the fire building, the type of equipment available to fire fighters, the level of proficiency of the fire suppression crew [including the commanders], etc.). Hence, it is difficult to determine a minimum number of fire fighters or equipment required without careful, objective planning, and without considering the important variables. Obviously, personnel needs will differ significantly between a small detached structure fire and a high-rise fire. Pre-incident planning is essential. Some general considerations may, however, be listed as follows:

- The more arduous the expectations placed on the mobile fire suppression crew, the greater the required resources. (For example, the community that expects its fire department to contain fires to the room of origin should expect to provide more fire suppression resources than the community that expects its fire department only to prevent the spread of fire from one building to another. Given the same level of protection demands, the community that leaves all fire protection to the mobile fire suppression force will require a more extensive suppression force than the community that requires a high level of built-in protection.
- The more extensive the concentrated fire potential, the greater the required fire suppression resources. For example, given the same expectations of its mobile fire suppression force, a community having high-rise buildings, a high population density, and extensive industrial risks will normally require greater fire suppression resources than a largely residential community.
- The broader the services provided by a fire protection agency, the greater the need for resources. For example, a fire agency providing emergency medical services will, given the same level of expectations for its mobile suppression forces, re-

quire more resources than an agency providing only fire protection services, assuming a significantly increased *total* workload demand, including a significant increase in simultaneous calls.

- The greater the geographic area protected, the greater the resource requirement of the mobile fire suppression forces. That is, given the same service level expectations, a community providing service to 20 mi^2 (52 km^2) will require more resources than a community providing protection to only 10 mi^2 (26 km^2); this is caused by the need for timely arrival at the scene of fire, medical, or environmentally threatening incidents. Computerized geographic information systems and accompanying computerized response maps have the powerful ability to demonstrate visually the response effectiveness of various station locations.

In most smaller and medium-size communities, all initial-response (first-alarm) apparatus will not arrive at the fire scene simultaneously. In many departments with on-duty personnel, apparatus have to respond from more than one station, and some apparatus have longer travel times to the fire scene. In volunteer departments, personnel must travel varying distances to get to the fire station or the fire scene, and, thus, all apparatus cannot go into operation at the same time. Those fire fighters and vehicles that cannot arrive at the fire scene within the first critical time period have limited impact on the initial attack, regardless of the department's response assignment ("running card"). Communities may have a false sense of security in this regard, until actual response times are tested and working initial-attack personnel counted.

Minimum Manning. The critical numbers for policy makers to use in planning related to staffing of shifts and apparatus crews—sometimes termed "minimum manning"—are those that describe how many trained personnel can arrive within a stipulated initial attack time frame. Ideally, all or most will arrive as composite crews and not as individuals.

The total minimum fire force recommended for any community is necessarily dependent on community hazards and the expectations of the community and the members of the mobile fire force. Objective planning and evaluation are necessary to determine the resources required for effective and safe fire suppression operations that will meet community requirements.

Some fire agencies are addressing the suppression challenge with different arrangements of fire crews within the communities than were heretofore generally accepted (e.g., use of multipurpose apparatus task force assignments and differential staffing). It is important to note that, although these different approaches may augment flexibility, they do not appear to reduce the number of suppression personnel required to carry out fire-fighting operations safely.

It does seem reasonable to say that not fewer than two fire suppression vehicles and a command officer should respond to any structure fire and that the number of personnel responding should be sufficient to carry out the tasks indicated above, and whatever else is typically necessary in local operations, in a timely fashion. Normative data are available from some cities. It is relevant to note that, in a broad spectrum of environments that are protected by numerous urban departments, as observed by evaluation teams, between 19 and 23 personnel typically constitute the first alarm assignment to a confirmed single-family-dwelling fire.

Where necessitated by fire frequency or response distances, additional pumpers, ladder trucks, and tankers may be needed. Reserve apparatus is desirable not only to permit the repair of first-line equipment without reducing available fireground forces but also to provide additional fire-fighting units during major emergencies. Specialized vehicles for hazardous materials response, heavy-duty and specialized rescue—including boats—lighting equipment, breathing apparatus bottles, emergency medical response, and so on, also must be planned for. If these cannot be made available locally, then mutual-aid arrangements are needed. Different types of vehicles may be necessary for the various levels of emergency medical response: first responder or basic life support, advanced life support, and hospital transport. Commercial, industrial, and mercantile areas generally require additional apparatus, or more, in response to the initial alarm. If properties with considerable life hazard are involved (schools, hospitals, nursing homes, etc.) additional resources should be considered for initial alarms. Especially large numbers of personnel are needed for search and rescue operations in these properties, with several fire fighters required to "sweep and search" each floor (Table 12.1.1).

The required fire-fighting units should arrive on scene close enough in time after the initial alarm to operate as an effective fire-fighting unit following planned tactical procedures.

Operating Personnel Safety Concerns

Over the past several years, prompted by continuing line-of-duty fire fighter deaths and injuries, additional safety protocols have been instituted by OSHA, NFPA, the National Fallen Fire Fighters Foundation Initiative, various state agencies, fire departments, labor organizations, and other groups. These protocols call for on-scene safety officers, incident command teams, rapid intervention teams for fire fighter rescue, personnel accountability systems, plus other provisions to increase responder safety. Other provisions focus on the safety of emergency medical responders, technical rescue specialists, hazardous materials responders, and so on. All of these imply that the necessary additional personnel will be present at incidents in addition to those needed to conduct typical operations.

Evaluating Workload. In evaluating the adequacy of fire protection in any given area, planners must give major consideration to the ability of the fire department to handle efficiently any reasonably anticipated workload. This assessment requires an evaluation of the possibility of simultaneous working fires and other emergencies; weather factors that may contribute to the spread of fire, the delay in response, or the possibility of slow operations at the scene; and other demographic or geographic conditions that might affect the frequency, severity, and spread of fire occurrence and the response time of initial fire-fighting units.

Where fire frequency is such that any fire company may expect two or three working fires per day, or where structures to be protected require a heavy initial response, closer geographic spacing of or increased personnel assigned to individual fire companies may be necessary. The number of other fire-fighting or related operations such as grass, brush, rubbish, and automobile

TABLE 12.1.1 Typical Initial Attack Response Capability Assuming Interior Attack and Operations Plus Command Capability

	Description	*Personnel and Apparatus*
High-hazard occupancies	Schools, hospitals, nursing homes, explosives plants, refineries, high-rise buildings, and other high life hazard or large fire potential occupancies	At least 4 pumpers, 2 ladder trucks (or combination apparatus with equivalent capabilities), 2 chief officers, and other specialized apparatus as may be needed to cope with the combustible involved; not fewer than 24 fire fighters and 2 chief officers. Extra staffing of units first due to high-hazard occupancies is advised. One or more safety officers and a rapid intervention team(s) are also necessary.
Medium-hazard occupancies	Apartments, offices, mercantile, and industrial occupancies not normally requiring extensive rescue or fire-fighting forces	At least 3 pumpers, 1 ladder truck (or combination apparatus with equivalent capabilities), 1 chief officer, and other specialized apparatus as may be needed or available; not fewer than 16 fire fighters and 1 chief officer, plus a safety officer and a rapid intervention team.
Low-hazard occupancies	One-, two-, or three-family dwellings and scattered small businesses and industrial occupancies	At least 2 pumpers, 1 ladder truck (or combination apparatus with equivalent capabilities), 1 chief officer, and other specialized apparatus as may be needed or available; not fewer than 14 fire fighters and 1 chief officer, plus a safety officer and a rapid intervention team.
Rural operations	Scattered dwellings, small businesses, and farm buildings	At least 1 pumper with a large water tank (500 gal [1.9 m^3] or more), one mobile water supply apparatus (1000 gal [3.78 m^3] or larger), and such other specialized apparatus as may be necessary to perform effective initial fire-fighting operations; at least 12 fire fighters and 1 chief officer, plus a safety officer and a rapid intervention team.
Additional alarms		At least the equivalent of that required for rural operations for second alarms; equipment as may be needed according to the type of emergency and capabilities of the fire department. This may involve the immediate use of mutual-aid companies until local forces can be supplemented with additional off-duty personnel. In some communities, single units are "special called" when needed, without always resorting to a multiple alarm. Additional units also may be needed to fill at least some empty fire stations.

fires and emergency rescue operations may also require greater-than-normal staffing of equipment and closer spacing of fire companies. Major structural fires may result when the normal first-alarm coverage in a district is depleted through coverage of these other emergencies, making remaining fire-fighting forces inadequate. Staffing fire apparatus at a level below minimum requirements can result in less effective and less safe fire-fighting performance. This factor also has an adverse effect on the number of required fire companies for various alarms, because additional fire companies must be dispatched to the scene of an emergency to provide adequate total staffing.

Effective Pumper Companies. The desirable practice of assigning emergency medical responsibility to the fire department must be calculated into the staffing formula. It is also difficult to obtain effective teamwork and coordination with understrength crews. Some fire departments have attempted to solve this problem by supplementing their crews with part-time or volunteer fire fighters, or by providing off-duty fire fighters with tone-activated radio receivers and paying them for overtime when they respond to a fire. The on-duty personnel make the initial fire attack and holding action whereas off-duty personnel provide the additional assistance needed for continuing fire-fighting operations. Although useful and possibly less costly in the short run, efficiency is lost, and increased fire losses can be expected with this arrangement. Such protection should not be relied on to replace adequately the required staffing and equipment needed immediately at the scene for initial attack and rescue.

Personnel requirements are not merely a matter of numerical strength, but are also based on the establishment of a well-trained and coordinated team necessary to utilize complicated and specialized equipment under the stress of emergency conditions. Attempting to operate more fire companies than can be effectively staffed, even if some response distances must be somewhat increased, most often is less desirable than fewer but appropriately staffed companies. The effectiveness of pumper companies must be measured by their ability to get required hose streams into service quickly and efficiently. NFPA 1410, *Standard on Training for Initial Emergency Scene Operations,* should be used as a guide in measuring this ability. Seriously understaffed fire companies are generally limited to the use of small hose streams until additional help arrives. This action may be totally ineffective in containing even a small fire and in conducting effective rescue operations.

Supplementing Fire Protection Coverage. Consideration must be given also to maintaining an adequate concentration of additional forces to handle multiple alarms at the same fire,

while still providing minimum fire protection coverage for the other areas under fire department protection. If available personnel prove adequate for routine fires but inadequate for major emergencies, arrangements should be made to supplement the fire protection coverage by calling back the off-shift personnel and by promptly calling nearby fire departments for mutual aid. Off-shift personnel may operate reserve apparatus or relieve or supplement personnel on the fireground. Fire companies not dispatched or utilized on the fire scene should be repositioned throughout the remaining area of the jurisdiction to ensure minimum response times to other alarms.

Reserve apparatus should be properly maintained and equipped, and when placed in service should be staffed to a degree commensurate with standard fire apparatus requirements. Because it may take up to 30 minutes or more to place reserve units in service with personnel recalled in an emergency, these reserve units should not be completely relied on to immediately provide an adequate level of fire protection services.

Concern must be shown, under legislation and local policy, for the health and safety of fire fighters and others, for environmental protection, and for the rights of those being served. Officials must demonstrate reasonable and prudent action with establishment of incident command systems, for example, and the appointment of qualified safety officers and rapid intervention team protocols.

Cooperation Among Fire Departments

In cases in which several fire departments occupy adjacent or contiguous territories, arrangements (often termed "line response") should be made for joint response along common boundaries to high-risk hazards and for assistance in covering vacant fire stations at times of major fires. In areas where the nearest fire station or mobile unit to the incident address is not a part of the fire department district to which the address belongs, the nearest station or unit—by prearrangement—may still be dispatched to save time. This methodology is termed "closest station response." Mutual aid or mutual response should not be relied on for routine emergencies, because there could be times when local commitments will preclude the anticipated assistance. Mutual-aid agreements do not reduce the responsibility of each jurisdiction to maintain adequate facilities to handle normal fire protection needs. It also must be assumed that teamwork and tactical efficiency at a fire will be somewhat less than that expected of equal units from the same department under a united command. Often, however, specialized units (such as hazardous materials response teams) are organized to protect larger areas encompassing several fire departments.

Fairly often, consideration is given in the evaluation and planning process to the concept of merging or consolidating with one or more other departments. This unification is viewed as a possible way to attain economies of scale and to increase the breadth of service delivery to the combined area. On occasion, merging has been necessary because one district has insufficient funds available to retain viability. Other times a volunteer department may not have sufficient available personnel. Although the official combining of two or more departments may be wise, careful consideration must be given to the possible gains and losses and to the understanding that the combination of two very weak departments does not typically result in a new, strong department.

Two or more departments and often a significant number of departments in a large area—such as a county or region—may benefit greatly from what is termed "functional consolidation." This concept does not have the various departments relinquishing individual autonomy but rather cooperating and, thus, achieving economies of scale and service increases. Functional consolidation ranges from joint dispatch and stations to group purchasing and training, and from regional special response teams to combined fire prevention. Intergovernmental service contracts can facilitate these cooperative ventures.

Planning for volunteer departments in which there is a scarcity of response personnel may involve the addition of full-time or part-time personnel to carry part of the workload. So-called combination departments appear more and more necessary as community demographics change and workload increases. Various methodologies are used to produce response crews. These plans include using students and others as station "bunkers," rotating volunteer-duty shifts, using on-call personnel, and making automatic mutual-aid agreements.

Basing Response Requirements on Waterflow

In the past it was a common practice to relate the number of pumping engines and their pumping capacity, and other apparatus personnel requirements, to the population to be protected. With the industrialization of many areas and the construction of commercial shopping centers, hospitals, schools, and nursing homes in residential areas, it is possible that concentrations of life hazard and property value in areas of small or large populations may require substantial fire-fighting forces. Those with the responsibility for providing public fire protection must be prepared to cope with fire potential in any location in the jurisdiction. Fire department response requirements are now based on the waterflow in gpm (L/min) that may have to be applied. A rule of thumb is to provide one company for each 250 gpm (946.25 L/min) that may be needed in an interior attack, plus personnel for rescue and other operations that need to be performed simultaneously with the advancing of hose lines.

Some may argue that it is not the public's responsibility to provide adequate fire protection to high-hazard risks that should have built-in fire protection systems. However, failure to attempt to provide fire protection for large taxable values on which the economy of a community may be based would place the community's fiscal viability at risk. Burned-out businesses may not rebuild, and then local people will lose employment. Also, fire spread to other properties is possible.

Setting Time Requirements

Time is another critical factor in the evaluation of public fire protection. It is generally considered that the first-arriving piece of apparatus should be at the emergency scene in 5 minutes of the sounding of the alarm at the fire station, because additional minutes are needed to size up the situation, deploy hose lines, initiate search and rescue, and so on. In dense urban settings the desired response time is often shorter, and 4 minutes for the

first-responding pumper is a rule-of-thumb maximum time for 90 percent of an urban area. An old adage says that the first 5 minutes of most fires is the determining factor as to whether that fire will remain a small fire or become a large fire. Although this may not always be true, delays in sounding an alarm obviously must be minimized or eliminated, as well as delays in responding and initiating rescue and attack. Time, however, cannot become the all-important factor at the expense of safety. In the interest of safety, some departments have responding vehicles run to certain calls without the use of warning devices and obeying all traffic laws ("run silent alarms").

Specialized Apparatus

There are numerous instances in which highly specialized apparatus and equipment must be available to municipalities. One category of specialization concerns apparatus designed to handle hazardous materials, including spills of petroleum products and other chemicals that require special extinguishing agents such as foams or dry powders, and special equipment to apply these agents. These dangerous substances may be present because of airports, marinas, manufacturing or storage facilities, or transportation routes in the district. Another category of specialization includes apparatus and equipment needed because of particular structures or facilities such as research laboratories, hospitals, high-rise buildings, oil and gas wells, and seaports. In some communities, fire departments are expected to conduct specialized functions such as extricating at automobile wrecks and performing water and mountain rescue, as well as providing emergency medical services. These services also require special equipment and possibly special vehicles. The necessity for many departments to deliver at least first-responder emergency medical service, and for the delivery of a wide variety of technical rescue and disaster response services, cannot be overlooked.

As with standard fire-fighting equipment and apparatus, specialized tools cannot be used effectively and safely unless personnel are highly trained in their use under a wide variety of circumstances. Whether personnel are volunteer or career, in rural or urban areas, no plan can be implemented and no reasonable level of protection afforded to the community unless well-designed and well-managed training programs are carried out.

Progressive departments of all types and sizes also concentrate on providing a broad range of community-oriented services.

Fire Prevention

The term *fire prevention* as used here generally includes inspections, education, and equipment meant to reduce the occurrence of fire and to mitigate the effects of that fire prior to the arrival of the mobile suppression force. As an example, the installation of a sprinkler system is not designed to prevent fire but to control it in its very early stages; the "Stop, Drop, and Roll" message of the NFPA's *Learn Not to Burn*® program is clearly a mitigation rather than a prevention effort. Other education efforts, such as NFPA's *Risk Watch*® program, are directed at stopping the occurrence of fire and in promoting a wide range of safe behaviors. See Section 12, Chapter 19, "Community Risk Reduction."

Evaluating Prevention Activities. As noted previously, fire prevention activities are somewhat difficult to evaluate. In a real sense, if prevention activities are effective, fires and fire-related tragedies occur with less frequency. There is a reduction or absence of fire activity, and these results are statistically evident although they do not appear in dramatic news clips and photographs. Some departments do report not only dollar amounts of fire loss but also the value of structures that were threatened by fire and thus "saved." Without careful and systematic long-term record keeping concerning the incidence of fires, fire losses, and related tragedies, the effect of prevention programs cannot be documented. Inability of fire officials to demonstrate the value of committing some additional community resources to the broad range of possible prevention activities may well result in a withdrawal of resources from prevention programs and a subsequent increase in the need for a much larger suppression budget. Rational decisions and sound recommendations concerning evaluation and planning cannot be made unless fire officials learn what changes there can be to total fire cost by reallocating resources applied to the total fire defense system.

Planning requires recognition of the component and integrated parts of a fire prevention system. Until recent years prevention was often greatly limited or nonexistent in most smaller communities. In urban areas it was limited frequently to the periodic inspection of certain types of buildings. More modern approaches to fire prevention recognize that a comprehensive program includes all organized activities, other than suppression, that reduce the incidence of fire and fire-related losses. Ideally, these activities would be carried out in communities of every size, whether rural or urban, with appropriate adjustments made for community size, type, location, and fire history. Community- and neighborhood-based focus programs, often emanating from the local station, appear to have excellent effects.

Categorizing Prevention Activities. Prevention activities may be categorized in several ways, but it is usually helpful to group them as follows:

- Activities that relate to construction, such as building codes, the approval of building and facility plans, and occupancy certification and recertification for new occupants; also included may be a sign-off for the presence of smoke detectors when new or old properties are sold
- Activities that relate to the enforcement of codes and regulations, such as inspections of certain occupancies, the licensure of certain hazardous facilities, the design of new regulations and codes, and legislation to adopt existing model codes
- Activities that relate to the reduction of arson, such as fire investigation, the collection of information, public education, and data related to setting fires; included may be arson investigation and related court proceedings, and programs such as counseling for juvenile firesetters
- Activities that relate to the collection of data helpful in improving fire protection, such as standardized fire reporting, case histories, and fire research
- Activities that relate to public education and training, including fire prevention safeguards, evacuation and per-

sonal safety steps, plant protection training for industrial and other work groups, hazardous materials and devices safeguards, and encouragement to install early warning and other built-in signaling and extinguishing devices; very popular are programs for school children, such as NFPA's *Learn Not to Burn* curriculum and self-help classes such as water safety, urban survival, and similar "Stay Alive 'Til We Arrive" projects

An analysis of the community's fire history, conducted during the evaluation phase of the fire protection plan, will usually indicate to fire experts and citizen groups which categories need strengthening. Comparing the number of fires and fire-related incidents, plus fire loss (property, life, injury) statistics over several years as more prevention activities are phased in, provides an assessment of program effectiveness. Calculating the total cost of fire to a community (fire loss plus prevention costs plus suppression costs plus fire insurance costs) will enable the fire department and the community to estimate the efficiency or cost-effectiveness of a proposed prevention program.

PUBLIC PROTECTION CLASSIFICATIONS

Fire Department Service-Level Analysis

The public, fire and other government administrators, organized labor, fire protection organizations, and the fire service in general have for many years sought to find a generally accepted method for the evaluation of services provided to a community by its fire protection agency. The approaches have been as varied as the fire service agencies being evaluated and the parties doing the evaluation. This has resulted in the application of inconsistent methodology and criteria.

For many years material developed by NFPA has been used in the analysis of services provided by fire protection organizations. However, the application of NFPA materials has been inconsistent. The fire department accreditation program is entirely voluntary, and Insurance Services Office (ISO) reviews are typically conducted whenever there is an indication that changes have occurred that would point toward a potential revision to the classification number.

Insurance Services Office (ISO) Fire Suppression Rating Schedule (FSRS)

Although not all states in the United States use the latest edition of the Insurance Services Office (ISO) grading schedule, and it is not used in other nations, it is applied to public fire departments in 48 states. (Two states—Louisiana and Washington—use an earlier edition of the grading schedule.) The purpose is to aid in the calculation of fire insurance rates and is not for property loss prevention or life safety purposes.

The service focus of ISO has broadened considerably over the past few years. The ISO prepares Public Protection Classification (PPC) reports for over 43,000 fire protection districts in the United States. In addition ISO has created a Building Code Effectiveness Grading Schedule to determine how well a municipality enforces its building code.

Furthermore, the new ISO Community Outreach Program collects information on essential fire protection features within a community. This information will lead to sound benchmarking data, permitting individual communities to better assess their own safety level and to respond accurately when completing the Commission on Fire Accreditation International's self-assessment forms.

In a January 2001 survey of 502 U.S. fire chiefs and fire department officials, 92 percent responded that their ISO Public Protection Classification number is a direct reflection of the improvements made in their community. They reported that important local uses of the ISO PPC program are as follows:

- Helping save lives and property (90%)
- Helping save money on fire insurance (67%)
- Planning for and budgeting for changes in community fire protection (61%)

The older form of the grading schedule (1974) contains more categories and more items than the schedule in current use. However, the older form is still applied in two states and is still used by some community officials as a reference tool in self-evaluations.

In Section I of the ISO grading schedule, the result and classification apply to properties with a needed fire waterflow of 3500 gpm (13,248 L/min) or less. Private and public properties with larger needed flows are individually evaluated in the grading schedule. The result and classification apply to properties with a needed fire waterflow of 3500 gpm (13,248 L/min) (134 Section II).

With improved ratings, fire insurance companies that subscribe to the ISO rating system usually lower commercial and residential fire insurance premiums to reflect the projected decrease in loss severity. At least one insurance company is using a somewhat broader approach to determine premium costs for residential properties, by reviewing total insurance costs for all hazards across zip code or other defined areas and evaluating the fire exposure separately.

The *Grading Schedule for Municipal Fire Protection,* developed originally by the National Board of Fire Underwriters (NBFU) and continued by its successor, the American Insurance Association, and then by the ISO, has provided a guideline for municipalities to classify their fire defenses and physical conditions. The gradings obtained under the schedule are used in establishing base rates for fire insurance purposes. The schedule has been subject to change with the state of the art, and sweeping changes were made in the 1980 edition with the development of a revised FSRS, and with additional changes in 1995, 1998, and 2003. Other changes will continue to be made as warranted. With the 2003 revisions (under certain circumstances), credit for a minimal water supply (4000 gallons [15,140 L]) may now be given for property within 5 road miles (8 km) of a fire station, even though a municipal water supply system is lacking.

The current ISO grading schedule reviews and correlates those features of public fire protection that have a significant effect on minimizing fire damage. Credit is given for existing fire protection, instead of debit for what is not in place.

The Fire Suppression Rating Schedule (FSRS) produces 10 different Public Protection Classifications, with Class 1,

representing an exemplary fire suppression delivery system, and Class 10, not meeting FSRS criteria. The FSRS simply defines different levels of public fire suppression capabilities that are credited in the individual property fire insurance rate relativities.

Starting in 1975, on a state-by-state basis following Insurance Department approval, ISO implemented the Commercial Fire Rating Schedule (CFRS), which was a major revision to the method used to develop individual property rate relativities. The CFRS was later replaced by the Specific Commercial Property Evaluation Schedule (SCOPES). The SCOPES reviews and correlates the construction, occupancy, exposures, and private and public fire protection (represented by the Public Protection Classification number). This correlation allows development of an equitable rate relativity applicable to the individual property. To this rate relativity, affiliated companies add their cost of doing business and profit margins to produce the applicable fire insurance rate. The FSRS represents a revision in the method used to derive the Public Protection Classification number used in the SCOPES. The Public Protection Classification number is also used as a rate relativity variable for most class-related properties, in addition to construction and occupancy variables.

The *Grading Schedule for Municipal Fire Protection,*[1] although a much-improved system from previous editions, was not developed as an integral part of the individual property rating system. The previous schedules were somewhat independent primarily due to their historical development by the National Board of Fire Underwriters (NBFU), which was not an insurance rating organization. The previous schedules were used more to quantify underwriting information but did define different levels of public fire protection that could be used for a specific rating.

The FSRS is designed to assist in an objective review of those features of available public fire protection that have a significant influence on minimizing damage once a fire has occurred. This revision ties logically to the review of contributive and causative hazards that can be identified using the SCOPES.

FSRS Class Groupings

As stated earlier, the ISO prepares Public Protection Classification (PPC) reports for over 43,000 fire protection districts in the United States. Districts include political jurisdictions identified as counties, cities, towns, villages, municipalities, and fire districts. A district may support an organized fire department or contract with an existing fire department for fire suppression services. Each PPC report is prepared using an information base established from a city grading evaluation conducted by one of ISO's regional field representatives, who are highly trained in the application of the FSRS. ISO conducts municipal surveys in 45 of the 50 states. Mississippi and Washington State have elected to use the 1974 edition of the FSRS. Hawaii, Idaho, and Louisiana administer the current edition of the FSRS through state rating organizations. The District of Columbia and New York City are not graded using the FSRS.

The scope, objectives, and methods of application for the current FSRS are significantly different from previous grading schedule documents. Technological change in the real world is reflected in all elements of the current grading schedule pertaining to the three major items of coverage, which are as follows:

- Receiving and handling fire alarms
- Fire department
- Water supply

Today, the FSRS provides an objective tool for the review of city public fire suppression facilities, equipment, and programs. Credits are assigned for specific fire protection features covered by the grading schedule. Calculating deficiencies on individual items has been dropped; the percentage of adequacy is now determined for each item. Each grading schedule survey involves an extensive review of fire department records, field surveys of the city, and the testing of fire protection equipment and municipal water-supply systems.

Information gathered during the field survey is applied to the individual items in the grading schedule using quantitative analysis. The city's fire suppression potential capability is then assigned a Public Protection Classification number according to the following class groupings:

- Classes 1 through 8 are the protected property classification. All properties assigned a Class 1 through 8 have a recognized fire department with engine company response limited to 5 travel miles (8 km) in most states and a recognized water delivery system. The minimum water supply from each credited fire hydrant is 250 gpm (946 L/min) for a 2-hour duration; therefore, a recognized water system must also deliver the same minimum flow and duration.
- Class 8B recognizes a fire protection delivery system that is superior to Class 8 except for a lack of water supply system capable of the minimum Fire Suppression Rating Schedule (FSRS) fire flow criteria of 250 gpm (946 L/min) for 2 hours.
- Class 9 is the semiprotected property classification. All properties assigned a Class 9 have a recognized fire department generally limited to 5 travel miles (8 km). However, structural property is beyond 1000 feet (305 m) of a recognized water supply. The current FSRS provides a documented method for fire departments to deliver adequate water to fire sites using mobile water tankers to permit structural property in Class 9 areas to qualify for a protected property classification (Classes 1 through 8). Water delivery demonstration projects have improved Class 9 PPC districts all the way to a Class 4.
- Class 10 is the unprotected property classification for structural property. Class 10 property is generally located beyond 5 travel miles (8 km) of a recognized fire station, regardless of available water supply. Only a selected few insurers will write insurance policies for Class 10 property. When available, the insurance rates are very high compared to other property classes.

Scope and Content of the FSRS

The grading schedule is divided into two major sections: the public fire suppression and the individual property fire suppression.

Section I: Public Fire Suppression. This section is applied to develop a Public Protection Classification (PPC) for all class-rated properties and for specifically rated properties in a city

with a needed fire flow (NFF_i) of 3500 gpm (13,249 L/min) or less. The section is, in turn, divided into three major items for evaluation, which are as follows:

1. *Section 400: receiving and handling fire alarms.* Ten percent of a city's overall grading is based on how well the alarms are received and the fire department is dispatched. ISO evaluates the alarm-dispatch center by looking at the telephone service capability, the number of telephone lines coming into the center, the listing of emergency numbers in the area telephone book, and the number of operators on duty in the center at all times. The ISO review also examines all dispatch circuits and the electronic methods used to notify fire fighters of the location of fire incidents. The ISO uses NFPA 1221, *Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems,* as a guide for grading public sector fire alarm systems.

2. *Section 500: fire department.* Fifty percent of the city's overall grading is based on the fire department evaluation. The grading schedule considers a first-alarm assignment to be a minimum of two engine companies and one ladder-service company to all structure fires. ISO evaluates the distribution of engine companies and ladder-service companies for response areas of the city in accordance with whether the built-on area of the city has a first-due engine company within 1.5 mi (2.4 km) and a ladder-service company within 2.5 mi (4 km).

ISO also checks to determine whether the permanently mounted pumps on the fire apparatus are tested regularly and inventories are taken of each engine company's complement of fire hose, nozzles, self-contained breathing apparatus (SCBA), and small equipment items. Furthermore, ISO checks on the number and type of ladders, including both ground and aerial ladders, plus service equipment that includes salvage covers, power saws, ventilation equipment, and lighting equipment. Finally, ISO reviews fire company records to determine the following:

- Extent of structural fire suppression training provided to fire company personnel
- Actual personnel who participate in training programs
- Number of fire fighters who respond to structure fires
- Level of building familiarization and documented prefire planning conducted by fire personnel

ISO references several NFPA standards in the evaluation process of fire departments.

3. *Section 600: water supply.* Forty percent of the grading is based on the city's water supply. ISO examines the following three components of each water system to assure that sufficient water capacity, flow rate in gallons (liters) per minute, and pressure at 20 psi (138 kPA) residual pressure, are available at selected sites throughout the city:

- Water-supply works
- Water-supply mains feeding fire hydrants
- Fire hydrant installation, maintenance, and inspection; the water-supply works and pipe distribution system account for 35 percent of the entire city grading. To accomplish an analysis of a given water system, the ISO field representative does the following:
  - Examines whether sufficient water is available for fire suppression beyond the city's maximum daily consumption
  - Surveys all components of the water supply system, including stationary pumps, filtration capacity to provide potable water, and potable water storage to supply water mains
  - Observes fire-flow tests at representative locations in the city to determine the rate of flow provided by water mains
  - Counts the distribution of fire hydrants up to 1000 feet (305 m) from representative categories of property throughout the city; the classes of property evaluated include but are not limited to industrial, commercial, educational, religious, health care, and residential
  - Considers the size, type, and installation of fire hydrants, along with the operating condition of all fire hydrants

Fire hydrants should receive semiannual inspection, as outlined in the American Water Works Association Manual 17, *Installation, Field Testing, and Maintenance of Fire Hydrants.*

Section II: Individual Property Fire Suppression. This section develops Public Protection Classification for specifically rated properties that have a needed fire flow greater than 3500 gpm (134,248 L/min). The following are supporting topics on Public Protection Classification:

1. *Preparing for an ISO grading evaluation.* A city can maximize earned credits through a systematic and proper preparation for an ISO grading evaluation. Doing so involves having in place current maps, inventories, equipment test records, and personnel reports for the ISO field representative to review and evaluate in accordance with each item documented in the FSRS. The chief executive officer (e.g., mayor, city manager) of a city can request from ISO (or obtain from its website http://www.isomitigation.com) a presurvey information packet that details the information requested when an ISO field representative visits a city.

2. *Impact of a city's public protection class on fire insurance premiums.* Theoretically, the better a city's classification, with Class 1 being the best class, the lower will be both insurance rates and insurance premiums when compared to a higher class number. This is generally true for a commercial property that is specifically rated by the insurance industry. Other factors, however, enter into the premium calculation, including the following:

- Fire protection equipment such as installed fire extinguishers, early warning detection and fire alarm systems, smoke control systems in some occupancies, and, most importantly, the installation of automatic sprinkler systems
- Fire loss, or loss costs, to the insurance industry in the city or county where the building risk is located

It needs to be recognized that individual insurance companies may file with state insurance commissions for "rate deviations" from "standard rates" for specific classes of property

based on that company's loss experience and insurance reserves. This practice underscores the highly competitive nature of the property insurance industry today.

PLANNING PROCESSES

Whenever a community—rural, suburban, or urban—considers its fire defenses, it must scrutinize the past and present and make predictions or forecasts for the future. Reviewing the past is called *data analysis* and depends on good record keeping. *Evaluation,* which is looking at the present, requires the ability to examine a situation objectively. The process of forecasting future conditions and preparing for them requires that a planning process be followed. This *planning* process results in a plan and its implementation, so that future challenges to the community are met. As the plan is implemented, the process must include the establishment of a *feedback loop,* providing a continuing assessment of how well the plan is contributing to successful completion of goals and objectives, and feeding revised data back into the plan so continuing redesign occurs.

Fire protection organizations, and especially fire departments, need to develop several kinds of plans related to fire prevention and fire suppression. These plans should be quite specific, directed at clearly defined goals, and operational over a relatively brief time period (usually from 1 to 5 years). Typically, such plans are internal to the department and do not involve broad-based planning groups from the outside. Examples of these types of plans, which are most often technical in nature, are apparatus replacement plans, training program plans, revised initial-response plans, plans for a special hazardous-materials attack unit, and plans for adapting fireground procedures to incorporate the use of larger-diameter hose. However, once department planning begins to consider aspects of fire protection and other related operations that will have an impact on external groups, those groups will need to be consulted and incorporated into the planning process. Fire department planning, for example, must consider land-use planning (zoning), water department planning, building code enforcement, emergency management, and possible terrorist activities.

Examples of fire department planning that require the early involvement of other groups are station relocations or closings, building inspection programs, public education programs, and changes in the scheduling of work platoons. These plans, although involving some other groups, are still fairly narrow in scope and usually can be formulated over a relatively short time.

A third type of planning, often called comprehensive, master, or strategic planning, addresses the total community fire protection problem, incorporating both prevention and suppression, and obviously involves many community agencies and organizations and, today, county, state, and federal agencies. Comprehensive planning is a necessity for communities and is aimed at integrating all community efforts at prevention, suppression, disaster response, and improving efficiency and cost-effectiveness of those activities. Improved total community protection is the goal of this planning. Its degree of success must be measured by figures relating to the total cost of fire to the community, and not just in gains for one subsystem. Comprehensive plans often consist of a number of subplans from various agencies that are developed at the same time as part of a larger, total process, and that fit together to make a comprehensive and integrated plan.

Comprehensive plans have clearly stated goals with agreed-on ways of measuring their attainment. These overall goals are reached through overall strategies acceptable to all involved agencies and to the citizens who must pay for the fire protection system. Each goal is composed of some number of subgoals or objectives, and for each objective there are tactics designed to reach that objective. All objectives lead to the accomplishment of the overall strategies. When the objectives and tactics are laid out on a time line, the overall time required to implement the comprehensive plan is then known, and the timing for attaining each objective is apparent.

Fire protection has been largely a local responsibility, and for good reasons it seems destined to remain so.*

Each community has a set of conditions unique to itself. To be adequate, the fire protection system must respond to local conditions and especially to changing conditions. Planning is the key: without local-level planning, the fire protection system is apt to be ill-suited to local needs and unadaptable to the changing needs of the community.

Excellent fire protection (for example, in the form of automatic extinguishing systems such as residential sprinklers or in the form of technically advanced and trained fire-fighting forces) is technically available and certainly can be provided with the resources of most communities. Even with considerable public support, however, this protection may require several years to attain. In the meantime, in every fire jurisdiction (whether a municipality, county, or region), fire protection goals must be set and plans made to achieve those goals. The issues below discuss some of the concepts to be defined in setting these standards.

Goal-Setting Concepts

Adequate Level of Fire Protection. The question of "adequacy" is addressed not only in day-to-day needs but also in major contingencies that can be anticipated for future needs. A definition of "optimal" protection is needed—in contrast to "minimal" protection, which fails to meet contingencies and future needs, and "maximal" protection, which is usually more expensive than a community can afford.

Comprehensive planning must include contingencies drawn from an analysis of community hazards. This process of hazard identification and analysis is crucial to fire department planning.

Reasonable Community Costs. Fire, both as threat and reality, has its costs, including deaths, injuries, property losses, hospital bills, and lost tax revenues, plus the costs of maintaining fire departments, paying fire insurance premiums, and providing built-in fire protection. Each community must decide on an ap-

*Some of the information that follows in this chapter has been extracted in whole and in part from *America Burning*[2] and *America Burning Revisited.*[3]

propriate level of investment in fire protection. Some costs that are beyond the public's willingness to bear may be transferred to the private sector (as when buildings over a certain size or height or with a certain occupancy are required to have automatic extinguishing systems).

Acceptable Risk. A certain level of fire loss must be accepted as tolerable simply because of limited resources of a community. Conditions that endanger the safety of citizens and fire fighters beyond the acceptable risk must be identified as targets for mitigation.

Consideration of these matters helps to determine what functions and emphasis should be assigned to the fire department, other municipal departments, and the private sector both now and in the future. It helps to define new policies, laws, or regulations that may be needed. Most importantly, consideration of these matters makes it clear that fire safety is a responsibility shared by the public and private sectors. Because the fire department cannot prevent all fire losses, formal obligations to have built-in fire protection fall on owners of certain kinds of buildings. For the same reason, private citizens have an obligation to exercise prudence with regard to fire in their daily lives. But prudence also requires education in fire safety, and the obligation to provide that education appropriately falls in the public sector, chiefly the fire department. The public sector (again, chiefly the fire and building code enforcement departments) also has an obligation to see that requirements for built-in protection in the private sector are being met. A fire department, then, has more than one responsibility—and the aforementioned responsibilities are not exhaustive.

Functions of Fire Protection Agencies

The following are significant functions for which fire protection agencies typically have primary or significant roles.

Fire Suppression. Fire fighters need proper training and adequate equipment to save lives, to extinguish fires quickly, and to ensure their own safety.

Specialized Emergency and Disaster Services. These situations include hazardous materials incidents, floods, earthquakes, multiple-vehicle accidents, cave-ins, collapsed buildings, volcanic eruptions, searches for lost persons, attempted suicides, a variety of specialized technical rescue services, weapons of mass destruction training, and so on.

Emergency Medical Services. Capabilities needed during fires and other emergencies include first aid, resuscitation, and possibly advanced life support (paramedical services). (The term *paramedical services* means emergency treatment beyond ordinary first aid, performed by fire service personnel under supervision—through radio communication and preapproved treatment protocols, for example—of a physician.)

Fire Prevention. This prevention includes approval of building plans and actual construction; inspection of buildings, their contents, and their fire protection equipment; and investigation of fire cause and spread to guide future fire prevention priorities and determine when the crime of arson has been committed.

Fire Safety and Dangerous-Situation Education. Fire departments have an obligation to bring fire safety and dangerous-situation education not only into schools and private homes but also into occupancies such as restaurants, hotels, hospitals, and nursing homes that have a greater-than-average fire potential or life safety hazard. These programs may include such topics as swimming pool safety, babysitter training, latchkey child safety, and so on. See Section 5, Chapter 2, "Fire and Life Safety Education Messages."

Deteriorated Building Hazards. In coordination with other municipal departments, fire departments can work to abate serious hazards to health and safety caused by deteriorated structures or abandoned buildings.

Regional Coordination. Major emergencies can exceed the capabilities of a single fire department, and neighboring fire jurisdictions should have detailed plans for coping with such emergencies. But effectiveness may also be improved through sharing of day-to-day operations—such as, for example, an area-wide communication and dispatch network or a joint training facility.

Data Development. Knowledge of fire department performance and how practices should change to improve performance depends on adequate record keeping. Computers and information management systems play a key role in fire protection and emergency management planning. See Section 12, Chapter 5, "Information Management and Computer Technology."

Community Relations. Fire departments are representative of the local community that supports them. The impression they make on citizens affects how citizens view their government. Volunteer departments dependent on private donations must, of course, also be concerned with community relations. Moreover, because fire stations are strategically located throughout the community, they can serve as referral or dispensing agencies for a wide range of municipal services.

As communities set out to improve their fire protection, they must not consider the fire department alone. The police have a role in reporting fires and in handling traffic and crowds during fires. The cooperation of the building department is needed to enforce the fire safety provisions of building codes. The work of the water department in maintaining the water system is vital to fire suppression. In fire safety education, the public schools, the department of recreation, and the public library can augment the work of the fire department. Future community development and planning will influence the location of new fire stations and how they will be equipped.

These nine functions are just the obvious examples of interdependence. Although it may seem trivial, the manner in which house numbers are assigned and posted, for example, can affect the ability of a fire department to respond quickly and effectively to emergencies, as do many other seemingly unrelated topics.

Master Planning

Fire protection is only one of many community services. Not only must it compete for dollars with other municipal needs such as the education system and the police department, but in planning for future growth the fire protection system must account for the changes in progress elsewhere in the community. For example, if a deteriorated area is to be torn down and replaced with high-rise apartment buildings, the fire protection needs of that area will change. Changes in zoning maps will also change the fire protection needs in different parts of the community.

To cope with future growth, local administrators are turning increasingly to the concept of master (comprehensive) planning of municipal functions. Such plans include an examination of existing programs, a projection of future needs of the community, and a determination of methods to fill those needs. They seek the most cost-effective allocations of resources to help ensure that the needs will be met.

A major section of a community's general plan of land use should be a master plan for fire protection, which should be written chiefly by fire department managers. This plan should, first of all, be consistent with and reinforce the goals of a city's overall general plan and its time frame. For example, managers need to plan the deployment of personnel and equipment according to the kind of growth and the specific areas of growth that the community foresees. It is critical that the comprehensive plan determine and set goals and objectives for the fire protection system and the fire department in terms that are understandable to the citizens being protected.

Having established goals, the department officers should use the plan to establish some form of management systematic and quality assurance within the fire department. Management is most effective when each person is aware of how tasks fit into the overall goals and is committed to getting specific jobs done in a specified time.

Because fire departments exist in a real world where a variety of purposes must be served with a limited amount of money, it is important that every dollar be invested for maximum return on investment. The fire protection master plan not only should seek to provide the maximum cost-benefit ratio for fire protection expenditures but also should establish a framework for measuring the effectiveness of these expenditures. Last, the plan must clarify the fire protection responsibility for other groups, both governmental and private, in the community.

Often, as the result of a comprehensive planning effort, a community will formulate a "developmental plan." This document provides a schedule for implementing those changes in the fire protection system deemed appropriate by the community.

Key questions for developmental plans include the following:

- What are the fire protection, rescue, emergency medical, disaster response, and safety education needs?
- What organizational structure and what resources are currently available to meet those needs?
- Is there a disparity between what is available and what is needed?
- What will the community profile be like in 5 to 10 years?
- What will be needed then to provide adequate protection?
- What is and what will be the financial resource base?
- What options are and will be available to enhance protection, or to keep it at an adequate level?
- How can changes be phased in to gain community goals and cost-effectiveness?

Devising a Fire Protection Plan

The following are key questions to be asked by those planning for fire protection:

- Why is planning necessary for us at this time?
- What do we need to start the process, and are the necessary groups committed to the process?
- What are the necessary steps in the planning process?
- How will the plan be financed and implemented?
- Are all aspects of the plan legally possible and enforceable?
- How will the plan be evaluated? Will it be a part of the integrated emergency management plan of the community?
- How will feedback be gathered and the plan modified and updated?

In *Introductory Summary: Fire Prevention and Control Master Planning,* the U.S. Fire Administration[4] underscored the following still very useful set of steps in its overview of the planning process.

Master planning is a participative process that should result in the establishment of a fire prevention and control system that is goal-oriented, long term, and comprehensive; provides known cost/loss performance; and adapts continually to the changing needs of your community. Master planning involves the following:

- Master planning should consider all community elements related to fire prevention and control system elements.
- Master planning involves the participation of all parties interested in the development of a defined cost/loss relationship.
- Master planning allows you to systematically analyze fire prevention and control through commonsense procedures.

Master planning has three phases: preplanning, planning, and implementation. The preplanning phase gets necessary commitments, committees, estimates and schedules, and go-ahead approvals. The planning phase gathers and analyzes data, sets goals and objectives, determines an acceptable level of fire protection service, identifies alternatives, and constructs the plan. The implementation phase never ends, because the plan is ongoing and always being revised and updated.

The following can serve as guidelines to fire department administrators for developing and presenting a master fire protection plan as part of the comprehensive master plan outlined earlier:

Phase I

1. Identify the fire protection problems of the jurisdiction.
2. Identify the best combination of public resources and built-in protection required to manage the fire problem; within acceptable limits:
   a. Specify current capabilities of and future needs for public resources.
   b. Specify current capabilities and future requirements for built-in protection.

3. Develop alternative methods that will result in trade-offs between benefits and risks.
4. Establish a system of goals, programs, and cost estimates to implement the plan:
   a. Develop department goals and programs, including maximum possible participation of fire department personnel of all ranks.
   b. Provide goals and objectives for all divisions, supportive of the overall goals of the department.
   c. Strive to develop management development programs that increase acceptance of authority and responsibility by all fire officers as they strive to accomplish established objectives and programs.

Phase II

1. Develop a definition of the roles of other government agencies in the fire protection process.
2. Present the proposed municipal fire protection system to the city administration for review.
3. Present the proposed system for adoption as the fire protection element of the jurisdiction's general plan. The standard process for development of a general plan provides the fire department administrator an opportunity to inform the community leaders of the fire protection goals and system and to obtain their support.

Phase III

In considering the fire protection element of the general plan, the governing body of the jurisdiction will have to pay special attention to the following:

1. Short- and long-range goals
2. Long-range staffing and capital improvement plans
3. Code revisions required to provide fire loss management

Phase IV

The fire loss management system must be reviewed and updated as budget allocations, capital improvement plans, and code revisions occur. Continuing review of results should concentrate on the following areas:

1. Did fires remain within estimated limits?
2. Should limits be changed?
3. Did losses prove to be acceptable?
4. Could resources be decreased, or should they be increased?

SUMMARY

Public fire protection should consist of a broad range of safeguards, programs, and activities ranging from plan review and code enforcement to provisions for fire suppression and public safety education. Careful consideration of local hazards and demographics, plus analysis of data related to protection and suppression are necessary for the design and maintenance of an effective, cost-effective system. Further, provisions must exist within the plan to promote and assure adequate health and safety levels of its fire fighters. See Section 12, Chapter 7, "Safety, Medical, and Health Issues and Programs." This results in an integrated risk management system.

Local conditions, regulatory orders, and national standards dictate the type and level of prevention and suppression/rescue provisions necessary and appropriate for a community. The time required for response and the number and types of emergency responders and vehicles should match local needs and conform to legal and industry standard requirements. Judgments about the adequacy of local prevention and emergency response provisions can be made by local authorities, Insurance Services Office (ISO) representatives, fire department accreditation teams, or other experts. Fire insurance premiums for residential and commercial property most often reflect periodic assessments of local fire protection provisions.

Municipal planning for fire protection, fire department–based emergency medical services, hazardous materials incident response, and technical rescue services requires a review of past and present data, plus knowledge-based predictions of community change and development. Agreements concerning the level of local emergency service required then lead to decisions concerning the type, size, and deployment of suppression/rescue forces.

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3. United States Fire Academy, *America Burning Revisited,* U.S. Fire Administration, Washington, DC, 1987.
4. National Fire Safety and Research Office, *Introductory Summary: Fire Prevention and Control Master Planning,* U.S. Department of Commerce, National Fire Safety and Research Office, Washington, DC.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on planning public fire-rescue protection discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13E, *Recommended Practice for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems*
NFPA 402, *Guide for Aircraft Rescue and Fire Fighting Operations*
NFPA 403, *Standard for Aircraft Rescue and Fire-Fighting Services at Airports*
NFPA 414, *Standard for Aircraft Rescue and Fire-Fighting Vehicles*
NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents*
NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents*
NFPA 901, *Standard Classifications for Incident Reporting and Fire Protection Data*
NFPA 1001, *Standard for Fire Fighter Professional Qualifications*
NFPA 1002, *Standard for Fire Apparatus Driver/Operator Professional Qualifications*
NFPA 1003, *Standard for Airport Fire Fighter Professional Qualifications*
NFPA 1006, *Standard for Rescue Technician Professional Qualifications*

NFPA 1021, *Standard for Fire Officer Professional Qualifications*
NFPA 1031, *Standard for Professional Qualifications for Fire Inspector and Plan Examiner*
NFPA 1033, *Standard for Professional Qualifications for Fire Investigator*
NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*
NFPA 1041, *Standard for Fire Service Instructor Professional Qualifications*
NFPA 1051, *Standard for Wildland Fire Fighter Professional Qualifications*
NFPA 1061, *Standard for Professional Qualifications for Public Safety Telecommunicator*
NFPA 1071, *Standard for Emergency Vehicle Technician Professional Qualifications*
NFPA 1143, *Standard for Wildland Fire Management*
NFPA 1201, *Standard for Providing Emergency Services to the Public*
NFPA 1221, *Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems*
NFPA 1401, *Recommended Practice for Fire Service Training Reports and Records*
NFPA 1402, *Guide to Building Fire Service Training Centers*
NFPA 1403, *Standard on Live Fire Training Evolutions*
NFPA 1410, *Standard on Training for Initial Emergency Scene Operations*
NFPA 1452, *Guide for Training Fire Service Personnel to Conduct Dwelling Fire Safety Surveys*
NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*
NFPA 1521, *Standard for Fire Department Safety Officer*
NFPA 1670, *Standard on Operations and Training for Technical Search and Rescue Incidents*
NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*
NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments*
NFPA 1901, *Standard for Automotive Fire Apparatus*
NFPA 1911, *Standard for Service Tests of Fire Pump Systems on Fire Apparatus*
NFPA 1932, *Standard on Use, Maintenance, and Service Testing of In-Service Fire Department Ground Ladders*
NFPA 1961, *Standard on Fire Hose*
NFPA 1962, *Standard for the Inspection, Care, and Use of Fire Hose, Couplings, and Nozzles and the Service Testing of Fire Hose*
NFPA 1964, *Standard for Spray Nozzles*
NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*
NFPA 1975, *Standard on Station/Work Uniforms for Fire and Emergency Services*
NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus for Fire and Emergency Services*
NFPA 1982, *Standard on Personal Alert Safety Systems (PASS)*
NFPA 1983, *Standard on Life Safety Rope and Equipment for Emergency Services*
NFPA 1991, *Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies*
NFPA 1992, *Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies*

Reference

Hickey, H., *Fire Suppression Rating Schedule Handbook,* Society of Fire Protection Engineers, Bethesda, MD, 2002.

Chapter 2

Organizational Benchmarking and Performance Evaluation

Dorinda Cline

Chapter Contents

Organizational Acceptance
Performance Management System
Reports and Reporting Cycles
Measurements and Benchmarks

Key Terms

benchmarking, emergency management, evaluating, Government Accounting Standards Board (GASB), performance-based budget, performance management system

Evaluating and benchmarking are not new concepts to fire service professionals. They are inherent in the daily operations of a fire department. From fighting fire to patient care, the actions taken while performing the tasks at hand are measured and judged using a standard of service. Those actions directly and indirectly affect the outcome of the operation.

Evaluating and benchmarking result in quantifying and qualifying organizational performance. *Evaluating* is the process of measuring and judging performance as progress toward a defined standard of service. *Benchmarking* is the process of selecting the appropriate standard of service to use. Combined, evaluating and benchmarking provide information about performance that can be communicated. In this format, performance information can be used to obtain resources necessary to provide services, acknowledge performance success, and improve performance. Effective communication about performance creates the ability to efficiently manage performance on an organizational level.

To elevate performance management from a task level to an organizational level requires a systems approach. The organization is one system with one mission to fulfill. Within that one system are multiple subsystems that interrelate to fulfill a specific role. There are many examples of this concept in everyday life. Our vehicles have brake, electrical, and air bag systems. Our bodies have digestive, respiratory, and nervous systems. These analogies are common and may be useful in referencing this type of management approach. Whichever analogy works for the organization is the one to use; the critical importance resides in the perspective.

This chapter examines organizational benchmarking and performance evaluation from a systems perspective, to include the key elements of success for a fire department performance management system. Steps to implement a new system are discussed in each section. Based on a belief that the key elements already exist in the organization, the implementation is simplified to linking existing responsibilities and processes to communicate performance. With the perspective that a fire department is one system, performance management processes are integrated as a subsystem within the organization.

The first section discusses the factors that affect organizational acceptance of performance management concepts and a formal system. These factors are based on member recognition, education, and participation. The term "member" is used to represent those individuals who have a defined reporting relationship to the organization. It is intended to be inclusive of employees and volunteers, both sworn and civilian.

The second section is focused on the performance management system, as an integrated subsystem within the organization. The overall framework and data flow is charted, with roles and responsibilities defined. The organizational, financial, planning, and operational structures of a working fire department are examined to highlight the existing elements of performance

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management. The benefit to a centralized database is discussed and consideration is given to a performance-based budget development model.

The third section contains a sample performance report template and recommended reporting cycles. Performance reporting is categorized into three "*p*'s": *p*rogram descriptors, *p*erformance information, and *p*lanning objectives.

The fourth and final section examines how measurements begin with a count (a number) and combine with benchmarks to provide meaningful performance information. Included are examples and a list of data categories to consider.

See the following chapters in Section 12 for related topics: Chapter 1, "Planning for Public Fire-Rescue Protection"; Chapter 4, "Managing Fire-Rescue Departments"; Chapter 17, "Pre-Incident Planning for Industrial and Municipal Emergency Response"; and Chapter 18, "Pre-Incident Planning for Emergency Response."

ORGANIZATIONAL ACCEPTANCE

Organizational acceptance is necessary to realize the full potential of performance management concepts. Ways to enhance acceptance are based on member recognition, education, and participation. Recognizing member contributions and connecting them to organizational success is proposed to create a positive connotation to measuring performance. With clear direction and established goals and objectives, a team approach to integrating a system can increase member participation. The use of professional resources and a common language creates an environment in which everyone has a level of understanding and enables each to make a positive contribution.

Contribution Connection

Performance management concepts and words, such as *measuring* and *judging,* often have a negative connotation for the members of an organization. That connotation can be made positive when the standards of service that exist in everyday operations are used to demonstrate a contribution towards performance success for the whole organization. A formal performance management system has the ability to provide that connection and recognition.

Successfully integrating performance measures in an organization begins with recognizing that they already exist in every organization; they are blended into the culture. They exist in the thought processes and everyday actions of those who deliver the services, those who manage the operations, and those who make policy decisions. A performance management system should be designed to provide the connection between individual contributions and the shared mission and goals. In essence, every task is connected to a strategic goal. Every strategic goal is connected to service delivery in the community. The organization becomes one system, with many moving parts, working toward achieving defined standards of service to the customers.

A performance management system provides acknowledgment for the service delivery success that has existed all along. In addition, the measurements create the ability to communicate performance through data-based analysis, which is an excellent catalyst to obtaining resources. For all members, it can create a sense of contribution and connection to the whole system, a sense of belonging to something bigger than themselves, a sense of why and how their work affects the customers. For the customers, it can create a sense of confidence in the quality of service provided.

The integration of performance measures into the management process does not have to have a negative connotation. When combined with intuition, judgment, and experience, performance measures can significantly improve decision making that directly affects the members' ability to successfully perform their work for the customers. Like any other management concept, the key to organizational acceptance is the spirit in which it is presented and used.

Inclusive Participation

Member participation is a key to organizational acceptance. Members will actively participate in management efforts when their contributions are acknowledged as a vital component to success. They are already experts in performing the work associated with delivering services. All they need is the opportunity to understand the concepts and speak the language to make a positive contribution. As they participate, a sense of ownership is created. They are vested in making it work and become champions of success. With their participation, crafting a system to monitor and report performance represents building a useful tool to deliver the best services possible. We all appreciate good tools, like the computer that does the math for us and the vehicle that gets us to our destination. A performance management system has the potential to be a very valuable tool. Just like the computer or vehicle, the amount of appreciation it receives is directly dependent upon the extent to which it supports the members in providing quality services to the customer.

Purpose and Direction

To be a valuable tool, a performance management system must have a purpose, a reason to exist. A purpose is often best illustrated and communicated through established goals and objectives. The progress toward meeting objectives will evaluate the system itself to ensure it is functioning appropriately. Success of the system is critical to ensure the organization reports and acts on credible information. Once everyone understands why a performance management system exists, each member can make that positive contribution to its success. In order for the system to be useful and fulfill its purpose, it must provide information that guides the organization in the right direction. By nature, it must provide accurate and meaningful data that achieves the following:

Direction

- *D*irectly relates to operational and strategic goals
- *I*mproves decision making
- *R*espects professional judgment and technical expertise
- *E*ducates customers
- *C*elebrates accomplishments
- *T*imely reports activities
- *I*mproves processes
- *O*ffers benchmark opportunities with *n*o duplication of effort for the members

Team Approach

A proven method of inclusive participation is through the use of cross-functional project teams. According to Dennis Compton, author of *When in Doubt, Lead!,*[1] teams "enhance a sense of ownership and help foster responsibility and accountability within the organization." In his book, there is a team profile template with helpful guidance to ensure a team's effectiveness.

The cross-functional project team approach has many benefits. All service areas of the organization are represented. The scope of work is well documented and understood. Decisions and activities are communicated throughout the organization as work progresses. Once the team develops a performance management system, its effectiveness is tested and reported prior to implementation. As the first phase of implementation, the responsibility of project team members may include the development and delivery of an educational program or it may be passed on to a training staff. By definition, once the project is completed, this team is disbanded. At the same time, a standing team may be established to periodically test and improve the ongoing functionality of the product of the team's efforts.

Cross-functional teams complement the operational structure of the organization. To develop a performance management system, each operational service area should have at least one representative on the team. In addition, at least one operational manager and one senior manager should serve on the team. These individuals act as liaisons between the team and their respective work groups. The goal is representation for all the services provided by the organization as well as three levels of organizational performance: strategic, operational, and task. Once achieved, the chain of command is inherently represented, which empowers the team to work on behalf of the entire organization. In other words, if the senior manager on the team approves the work, then approval from all the senior managers is implied. This streamlines the effectiveness of the team. At the same time, it places a great deal of responsibility on the team members to effectively communicate the team's actions to the rest of the organization. In addition, team members must ensure the project stays within the defined scope of work, on time, and within budget.

Team members become system experts. They are responsible for selecting the appropriate resources and for designing the overall framework for a system that is useful to the organization. They develop report templates and define reporting cycles to bring consistency within the organization. They become the facilitators within their own service area as measurements and benchmarks are selected. All of these performance management aspects are discussed later in the chapter. It is important to note that these responsibilities are different from the responsibilities of an operational manager. Once the system is developed, as illustrated later in this chapter, it is the operational managers who are responsible for evaluating the performance of services delivered.

One of the most important roles of a team member is to champion the "systems" perspective. The individual services provided by a fire department complement each other or share overlapping objectives toward the shared mission. Many customers receive multiple services from a fire department. One of the worst impressions to leave with a customer is that the right hand does not know what the left hand is doing. If innovative ideas and lessons learned about the performance in each service area are shared on an organizational level, all the service areas will benefit and the customer will see cohesive performance from the organization. The project team members have the opportunity to set the stage for cohesive performance by designing a system that fosters collaborative analysis and centralized oversight for all services.

The potential benefits of this team approach are directly related to the team's profile. The keys to successfully realizing benefits reside in a carefully defined scope of work and appropriate representation from within the organization.

Professional Resources

Professional resources are used for educational purposes and universal recognition. Lessons learned from mature systems are used to avoid pitfalls. National databases and surveys are used to identify service norms. A multitude of agencies provide performance management information, ranging from conceptual models to technical standards. The best professional resources to use are those that match the philosophy, culture, and mission of the organization. Fire departments already interact with many of these agencies, seeking technical guidance and best practices, as well as national perspectives on service-related issues. Commonly referenced agencies include the following:

- National Fire Protection Association (NFPA): Provides consensus-based codes and standards for fire and life safety, as well as research, training, and education.
  http://www.nfpa.org
- Insurance Services Office, Inc. (ISO): Provides a Fire Suppression Rating Schedule that measures the major elements of a community's fire suppression system.
  http://www.iso.com
- Center for Public Safety Excellence: Provides a comprehensive system of fire and emergency service evaluation that can help local governments determine their risks and fire safety needs, evaluate the performance of the organizations involved, and provide a method for continuous improvement.
  http://www.publicsafetyexcellence.org
- International City/County Management Association (IMCA), Center for Performance Measurement (CPM): Assists counties, cities, and towns of all sizes with the collection, analysis, and application of performance information.
  http://www1.icma.org
- Governmental Accounting Standards Board (GASB), Service Efforts and Accomplishments (SEA) research project: Provides research to address the needs of state and local governments trying to develop performance measures.
  http://www.seagov.org

In addition, the experiences of other fire departments serve as useful "lessons learned" in managing performance. Municipalities commonly referenced as progressive in the performance management field are Phoenix, Arizona; Austin, Texas; and Charlotte, North Carolina.

Effective Communication

A common language is essential to communicate effectively about organizational performance. The performance measured and reported may be specific to the fire service. Whether the measurement is an input, output, or outcome, it must have a universal meaning. Many professional resources provide a glossary of performance management terms. A comprehensive example is found in a Government Accounting Standards Board (GASB) special report, *Reporting Performance Information: Suggested Criteria for Effective Communication.*[2]

An advantage to using language published by a national standards agency such as GASB is that the scope of effective communication widens. In addition to the members of the fire department, more customers and partners in performance understand the language. The barriers created by service-specific acronyms are minimized. When the fire department is working with local government services, such as the water or police departments, or is presenting funding requests to elected officials in a public forum, a common language and defined terminology increases the effectiveness of communication. Adoption of a common language is a key step to integrating a new performance management system. To create a common language for this chapter, definitions of the terms used are listed in Table 12.2.1.

PERFORMANCE MANAGEMENT SYSTEM

A successful performance management system is recognized by every member of the organization. It is charted, accessible, and easy to understand. Members know its purpose and use, as well as their roles within the system. These types of system charts are not commonly published, even though key performance measurements are published in most fire department annual reports. For the members of the organization, the visual link between daily operations and published results must exist to connect their contributions to organizational performance. The link improves understanding in how their work affects the customers and becomes an excellent basis for processing improvements.

To integrate a new system, the overall framework and data flow must be charted. An efficient process involves conducting a self-analysis of how the organization currently functions. With the belief that performance evaluation already exists in the organization, it is reasonable to assume the key elements are fragmented within existing operations. In conjunction with reviewing how the organization functions, additional steps can be identified to continue with the process of integrating a new system.

The following series of conceptual charts are derived from organizational charts provided by the Mesa Fire Department,[3] a municipal career department in Arizona. Each chart highlights how the organization functions and how the functions relate to performance management. Included is a transitional model from the organization's operational chart to visually document the integrated performance management system.

The Mesa Fire Department is managed as a system, with three levels of performance. The comprehensive body of work introducing this management concept is *Improving Performance: How to Manage the White Space on the Organization Chart,*[4] by Geary A. Rummler and Alan P. Brache. This book offers charts, checklists, hands-on tools, and case studies to demonstrate implementation of the concept.

Defined Roles and Responsibilities

A successful performance management system has top-down value. Impacts to performance are considered in the decision-making processes at all levels of the organization. Each level of authority has a role and responsibility in organizational performance. A coordinated effort from each level of the organization provides the policy decisions, operational management, and service delivery tasks that contribute to success. A review of the organizational chart shown in Figure 12.2.1 defines these levels of responsibility, with each level of authority having a role and responsibility in organizational performance.

As shown in Figure 12.2.1, the fire department's organizational chart is similar to many organizations. Direct lines of authority are established through a division of labor and reporting relationships. Commonly referred to as the *chain of command,* these lines of authority are primarily used for human resource and fiscal management. Services are not actually delivered through the lines of authority. However, the organizational chart contains key elements to performance success—that is, defined leadership and accountability.

Leaders lead by example. If their actions and language demonstrates that they value performance results, so will the rest of the organization. Holding themselves and others accountable for their role in organizational performance shows top-down value. Performance results should not be punitive. If the results are not quite where they should be, they should serve as a catalyst to ensure resources have been appropriately aligned with service delivery expectations. Processes may need to be improved. New or advanced training may be in order. Equipment may need to be replaced or technology updated. When leaders react with a holistic approach to the factors that contribute to performance success, they demonstrate universal accountability for performance results.

Resources Linked to Performance

Resources used linked to services delivered represent the ins and outs of performance. Resources used represent the inputs to performance. As shown in Figure 12.2.2, a review of the fire department's financial structure reveals the process of documenting the cost of resources used. As expenditures occur, the amount of resources used (inputs) is documented and then summarized on each level of fiscal management.

Typically, a financial structure is an accounting system aligned with the organizational chart. Generally speaking, the budget is developed and financial transactions are captured in a series of revenue and expenditure accounts. In government accounting, fire department revenue and the budget (funding allocated) are not the same. The budget is usually developed by projecting expenditures. Then, actual expenditures are recorded, as they occur, over the course of the fiscal year.

Actual expenditures are the primary focus of a performance management system. As expenditures occur, the amount of resources used (inputs) is documented. These inputs include the following:

TABLE 12.2.1 Common Performance Management System Terms

Common Terms	*Definitions*
Accountability	• Responsibility of one party to another party; in government, responsibility of elected and appointed officials to those who elected or chose them or who provide resources with which services are provided • Being obliged to explain one's actions, to justify what one does; requires government to answer to the citizenry to justify the raising of public resources and explain purposes for which they are used; governmental accountability is based on the belief that the citizenry has a "right to know"
Benchmark	• In the context of outcomes and performance discussion, refers to desired program results • May include a target or standard for the program to achieve • Denotes best practices
Budget	• A quantitative plan of activities and programs expressed in terms of assets, liabilities, revenues, expenses (or expenditures), and in some cases outputs or outcomes • A performance-based budget may express the organizational goals in terms of specific financial and operating objectives
Effectiveness	• Producing a desired result • An ends-oriented concept that measures degree to which predetermined goals and objectives for a particular activity or program are achieved; both intended and unintended results of a program may be included as part of the measurement of effectiveness
Efficiency	• Relationship between efforts (or inputs) to outputs or outcomes; measured by indicators of the resources used or cost per unit of output or outcome • Resource-usage concept, also with a least-cost notion, that is concerned with maximizing outputs or outcomes at a minimal cost or using minimum resources
Explanatory factors	• Includes a variety of information about the environment and other factors that might affect an organization's performance; they can be either factors substantially outside the control of the entity, such as environmental and demographic characteristics, or factors over which the entity has some control, such as staffing patterns
Goal	• Condition or state that one is striving to achieve • Usually long term and may be beyond what might reasonably be expected to be achieved
Input	• Amount of financial and nonfinancial resources (in terms of money, material, etc.) that are applied to producing a product or providing a service (output)
Mission	• Charge, assignment, or purpose of an organization or some part of that organization
Objective	• Statement of the condition one expects to achieve; an objective should be realistic, measurable, generally within the control of the organization, and time constrained
Outcome	• Basic unit of measurement of progress toward achieving an objective; at the least, an outcome may be initial, intermediate, or long term
Output	• Measure of the quantity of a service or product provided (may include a quality component)
Performance measure	• Quantifiable indicator of progress, achievement, and efficiency that includes outcome, output, input, efficiency, and explanatory indicators
Strategy	• Based on goals and objective, a means for transforming inputs into outputs, and ultimately outcomes, through planned use of budgetary and other resources
Target	• Organization's intended results for a program or service

Source: Definitions based on those used in GASB special report, *Reporting Performance Information: Suggested Criteria for Effective Communication.*[2]

- Employee labor and related employer expenses (payroll)
- Services provided by other departments (internal service charges)
- Services provided by outside agencies (invoices/payables)
- Commodities used in service delivery (purchase orders/payables)
- Capital equipment outlay

Linking expenditures to service delivery on an ongoing basis captures meaningful data about performance.

In government accounting, expenditures are typically recorded in cost centers that group like (related) activities. Expenditures, which are initially reported on the cost center level, are compiled into summaries for each level of fiscal management in the organization. These summaries can be useful in connecting

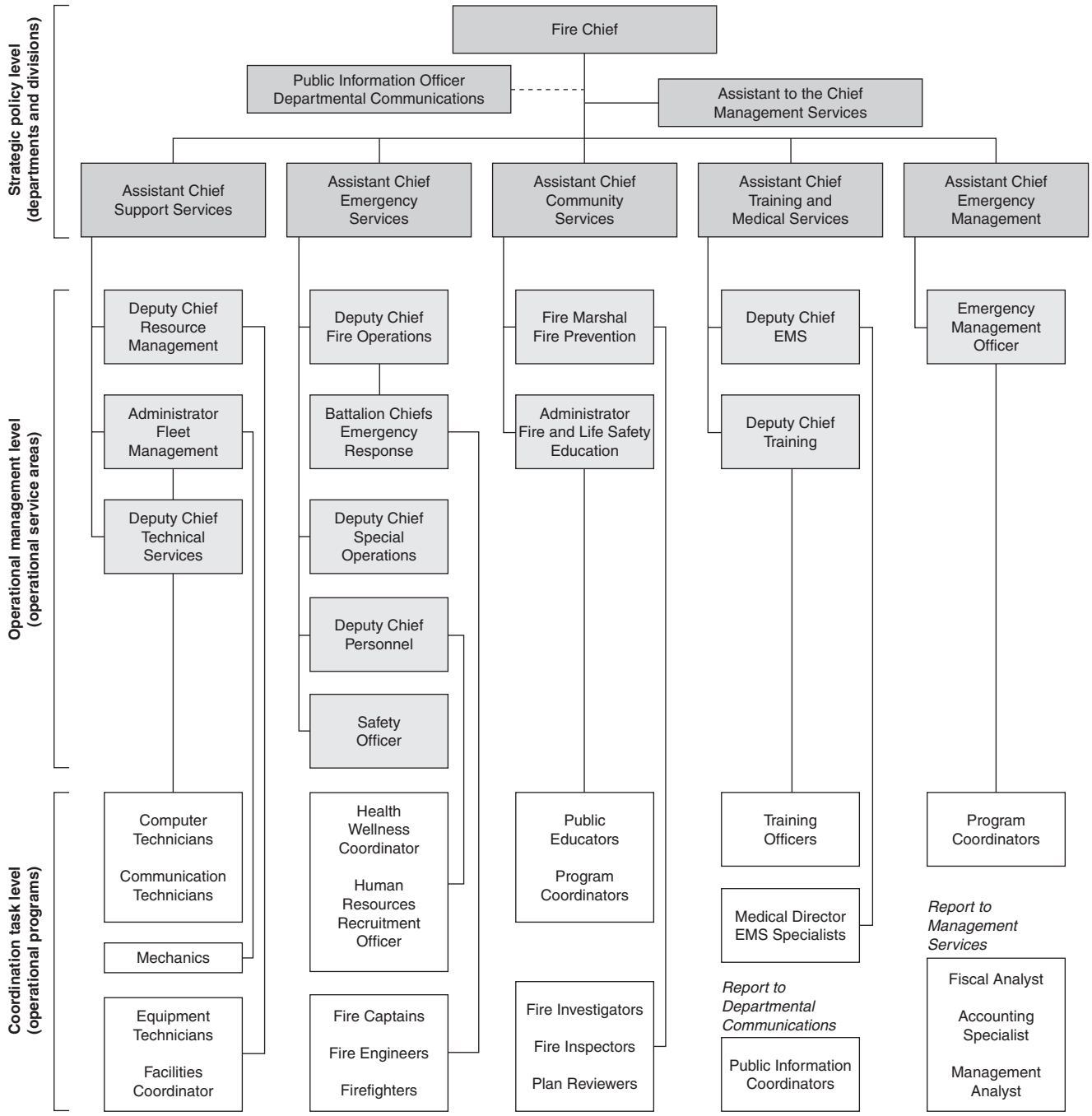

FIGURE 12.2.1 Fire Department Organizational Chart

the resources used (inputs) with the service delivered (outputs). In this type of accounting system, selecting the appropriate level cost centers will increase the usefulness of the summary reports.

One of the most common challenges in selecting the appropriate level to summarize financial data is when recording payroll (time dedicated to service delivery). Since fire department labor is the primary input to performance, this can become a significant challenge. Members may dedicate their time to multiple operational programs. Establishing a cost center for each one may, therefore, create a system that is cumbersome and difficult to use. At the same time, operational managers need detailed information about how much time is dedicated to which services. This information helps determine the efficiency of services, such as turnaround time for customers. In these cases, a cost accounting system embedded in the financial system is the most effective mechanism to use.

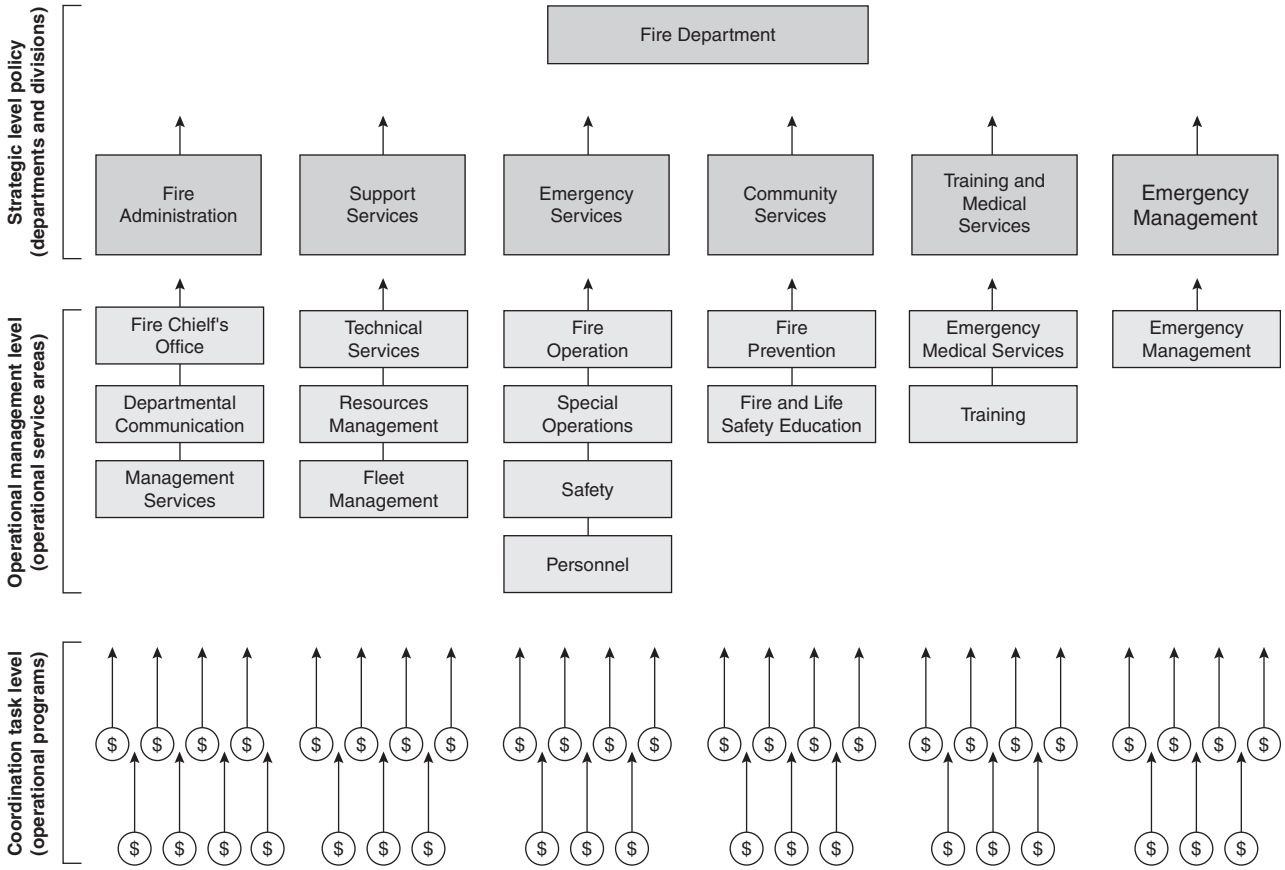

FIGURE 12.2.2 Fire Department Financial Structure

Other challenges may occur when linking an accounting system to a performance management system. A recent survey conducted by researchers at Georgia State University and the Governmental Accounting Standards Board (GASB) specifically addressed this issue with local governments. Results published in *Performance Measurement at the State and Local Levels: A Summary of Survey Results*[5] indicate that most respondents "feel there is an inadequate link between the performance measurement database and the accounting/budget database systems. . . . Nearly 80 percent of respondents from each group indicated that this is somewhat of a problem or is a significant problem."

No matter what financial structure is established or what level of automation is achieved, the key element of performance management remains the accounting of expenditures. The link between expenditures (inputs) and service delivery (outputs) must be established to calculate efficiency measures. Once calculated, they provide meaningful information that is useful to improve performance and justify budget requests.

Direct Relationship to Operational and Strategic Goals

Performance evaluation measures the success toward achieving operational and strategic goals. Planning documents contain a multitude of performance data, such as the strategic and operational goals, activity statistics, and service benchmarks. They represent valuable mediums for communicating a shared vision of performance success.

With an integrated performance management system to collect data, the process of planning is simplified and focused. Operational managers contribute the vast majority or performance data using short-range documents. With the data collected, reporting for multiple uses and to diverse audiences is quicker and easier. A review of the planning and reporting chart (Figure 12.2.3) shows the opportunities to link performance data with planning activities, which is a key step to integrating a new system.

As shown in Figure 12.2.3 the fire department's planning and reporting chart represents an inclusive tiered approach to developing and publishing the organization's mission, vision, goals, and accomplishments. Long-range, strategic-level documents include a 25 year infrastructure plan and a 10 year strategic plan. Shorter-range, management-level documents include a 5 year operating plan, 5 year reaccreditation plan with annual updates, and a 2 year financial (budget) plan. Short-range operational documents include an annual report, 6 month activity plans, program management guides, and project action plans. Operational managers contribute the vast majority of data using short-range documents, which provides the opportunity to link performance data to planning activities.

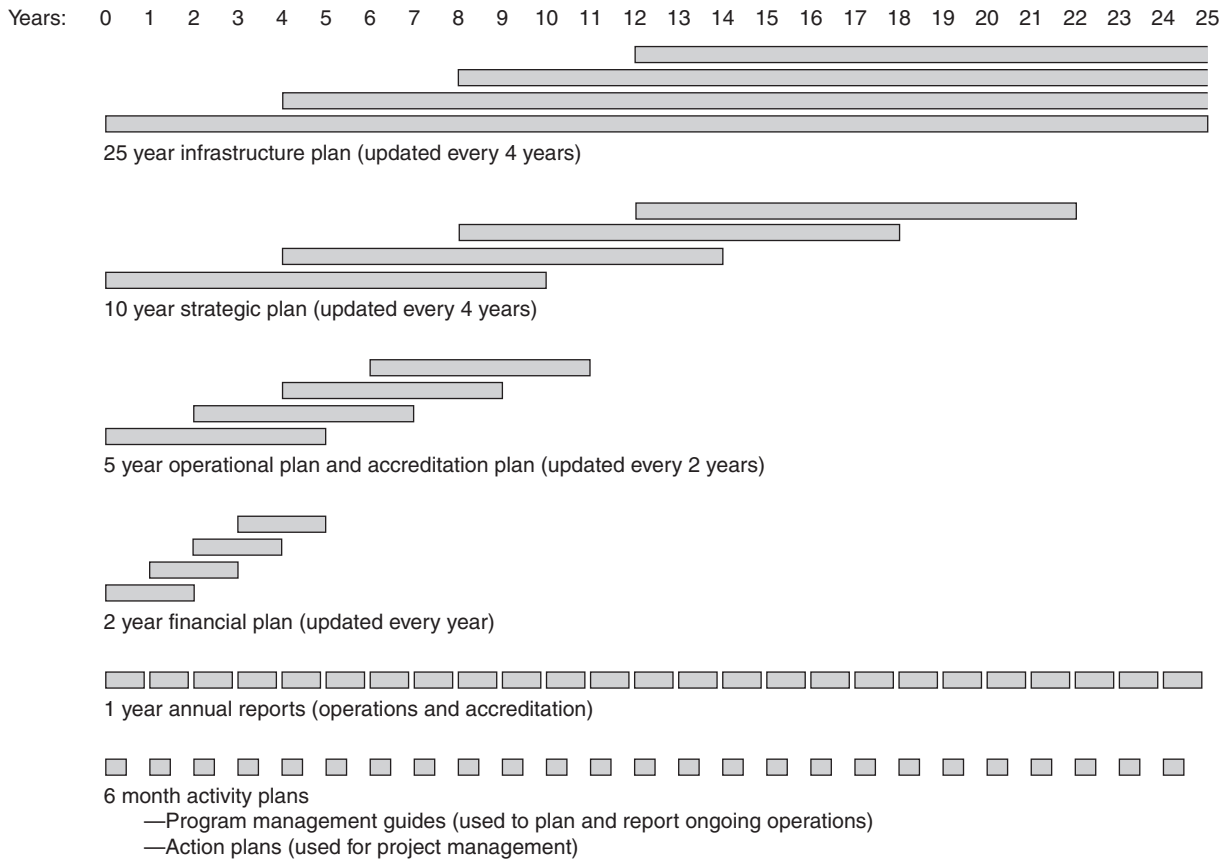

FIGURE 12.2.3 Fire Department Planning and Reporting Chart

Customer Focused Service Delivery

The performance management system quantifies how organizational efforts impact customers. When combined with professional judgment and technical expertise, it guides the organization towards performance success. The fire department's operational chart (see Figure 12.2.4) represents service delivery to the customers. In a circular model, the roles and responsibilities of each service area center around and focus on customers, both internal and external.

As shown in Figure 12.2.4, operational programs are grouped into service areas, which are grouped into divisions based on related roles in the fire department mission. All divisions have a senior manager in the leadership role. The senior managers work as a team, with the fire chief as the team leader, to develop policy and provide consistent cohesive leadership to the organization.

The operational chart is meant to capture the lateral interfaces between operational areas. This cross-functional cooperation is critical in cohesive consistent service delivery to the customers. In contrast, the traditional organizational chart as shown in Figure 12.2.1 captures interfaces vertically, aligned with the chain of command. White space exists between the divisions creating a type of silo effect. If service is delivered by following the traditional chart, a risk of critical components of service falling between the silos into the white space exists. We have all heard the expression of things falling through the cracks in an organization. Creating operational charts that manage lateral interfaces (the white space) minimizes that risk.

According to Rummler and Brache in *Improving Performance: How to Manage the White Space on the Organization Chart,*[4] "the greatest opportunities for performance improvement often lie in the functional interfaces—those points at which the baton is being passed from one department to another." With this in mind, the operational chart is the ideal framework for an integrated performance management system that maintains a focus on customers. Based on performance information, effective and efficient processes that create cross-functional responsibilities can be developed and maintained. In addition, operational managers will be able to respond quickly to customer needs identified in the performance evaluation process.

System Framework

In the transitional model shown in Figure 12.2.5, the operational chart is the starting point of a new performance management flowchart. Performance data must be captured at the point of service delivery. To integrate a performance management system, a linear flowchart was created to represent the transmission of performance data from the point of service delivery. In essence, the organizational chart was turned upside down to create a flow of information from the staff responsible for specific

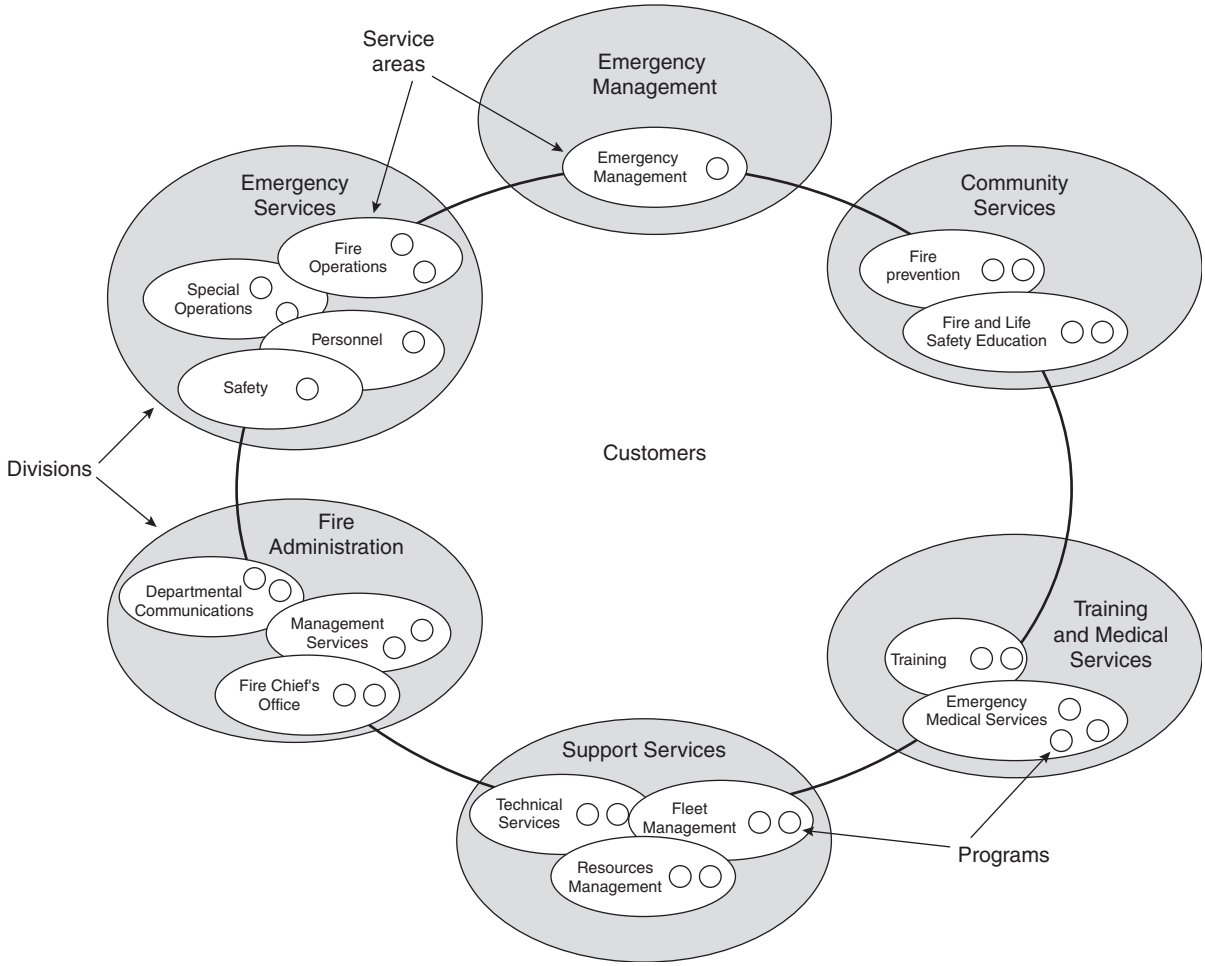

FIGURE 12.2.4 Fire Department Operational Chart

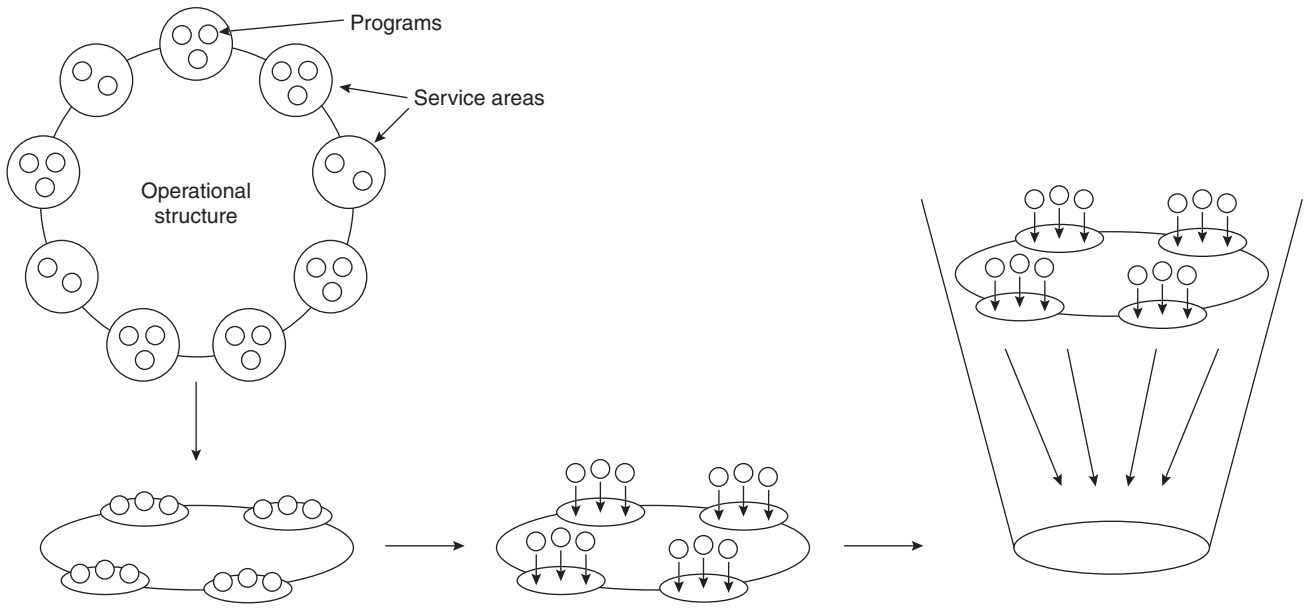

FIGURE 12.2.5 Transitional Model

services to those who manage the organization. The result is a flowchart that resembles the shape of a funnel.

In this model, a collection of individual facts can create a useful context for analysis. For example, a specific measure such as emergency response times may be placed in context with the number of calls for service or population as it flows through the system. In addition, numbers collected from various service areas may be aligned to determine relationships. For example, the number of traffic calming devices installed, media releases on pulling over for fire trucks, or the location of new housing developments may have a relationship with emergency response times. These individual facts might be captured by different service areas but they end up in the same flow of information within a system that compiles and funnels data to an operational and division/department level for analysis.

Following the flow of data through the system (funnel), operational managers are the first to analyze performance data and apply the results to operations. The process of analyzing data includes participation from the coordinators and those who accomplish the tasks related to service delivery. With a direct customer relationship, actions taken at this level will have an immediate effect on customer service.

At the operational service area level, progress toward achieving operational goals is evaluated. An advantage to this process is the ability to apply professional judgment and expertise in the first review of performance data. With the volume of data to be summarized, computer technology is essential. Computer programs will process data consistently in whatever manner they are designed to do. However, data entry is subject to human behavior, which is not quite as consistent.

Whether the technology used is a computer-aided dispatch system, incident reporting system, or spreadsheet software, it is subject to human error. An extra zero here, a dash there, or the push of a button a little differently each time, can skew performance reports. A good operational manager will be able to review data and know when something is just not quite right. Based on the goal of gaining customer confidence, it is very important for all data to be evaluated by those who manage daily operations prior to public release. At the very least, if there is unusual performance data for a given period of time, the operational manager will be prepared to respond to inquiries about the activity. Also, explanatory factors can be documented to accompany the data through the system.

The next level of data flow, moving through the system (down the funnel), is the division/department level. The leader for each area, a senior manager, is responsible to ensure that the performance data is reported appropriately. At this level, the data from individual programs is grouped into operational service areas and compiled to summarize collective progress toward achieving strategic goals. Specific program flowcharts, as shown in Figures 12.2.6 and 12.2.7, may be helpful to visualize the transmission of data through each division.

After the data is processed through the division/department level, it continues to a centralized database moving toward the small central base of the funnel. Figure 12.2.8 illustrates the flow of performance data through the department.

The most important aspect of the performance data flowchart is the evaluation process that occurs as data moves through the organization (down the funnel). By following this path and the associated processes, performance data is converted into performance *information.* Data such as individual facts about specific events, community statistics, and service delivery counts are collectively studied and benchmarked to create messages about how the organization is performing.

Centralized Database

When performance data reaches the centralized database, it has been converted from just numbers into information. Performance information is best centralized within the organization, with a designated custodian. The centralized database should be the sole source of all performance information used or published. One of the quickest ways to lose customer confidence is to publish conflicting information about service delivery. If

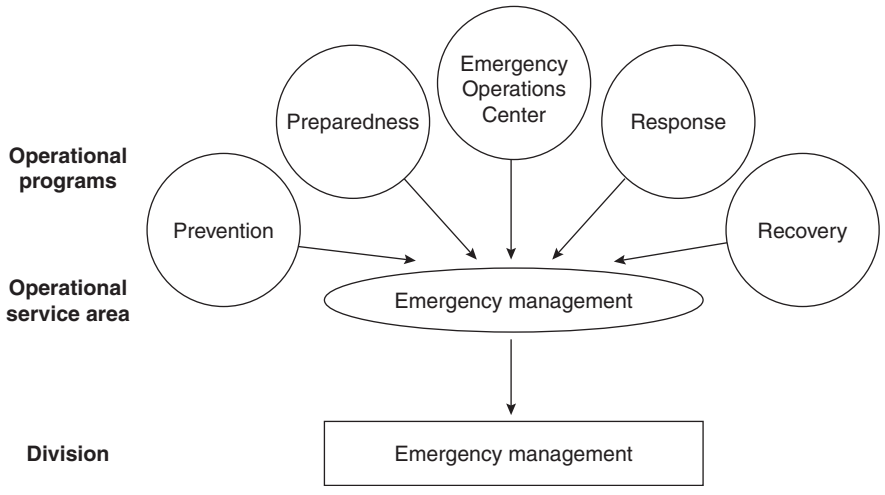

FIGURE 12.2.6 Flowchart for Emergency Management Programs

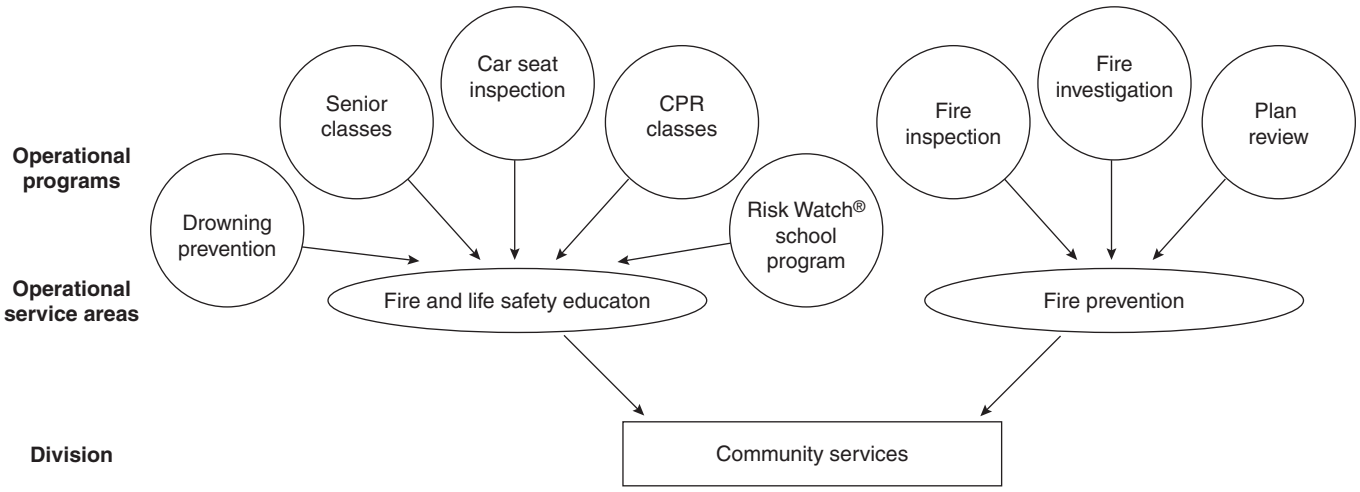

FIGURE 12.2.7 Flowchart for Community Services Programs

an existing system is not producing the information needed to manage operations, then the system should be changed. The alternative of creating multiple sources of information is not a viable option for success. A service measure as simple as the number of fire fighters on duty can vary. For example, one area may publish the people count and another area may publish the position count (to include vacancies). If an organization cannot publish consistent numbers about how many fire fighters are on duty, the credibility of more complex measures is compromised.

The ideal location for the centralized database within the organization varies. The decision depends on the staffing available and the organization's commitments to report performance. The key to successfully selecting the appropriate location is to match the custodianship with similar internal services. Planning and research, technical services, or management services

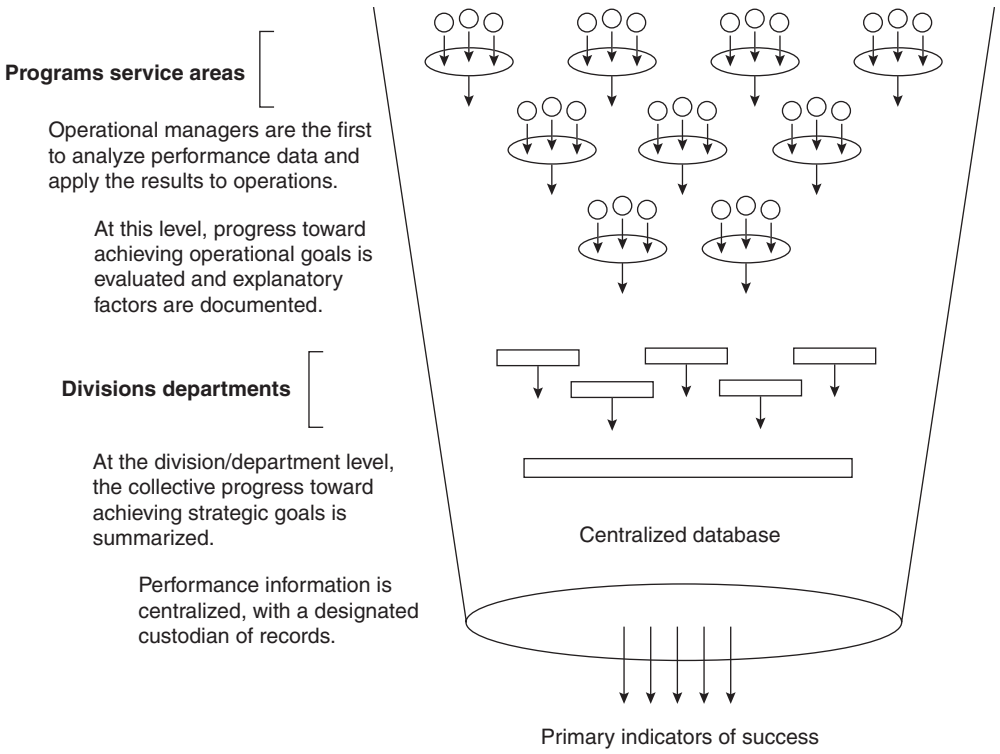

FIGURE 12.2.8 Fire Department Performance Management Flowchart

are excellent candidates. These areas may already coordinate department-wide, data-based programs, such as strategic planning, accreditation, and budget development. These internal service areas may also provide historical statistical information for process improvements and management reports. The opportunity to eliminate duplication of efforts and streamline processes resides in the selection of the centralized database location. This selection represents another step to integrating a new system.

Performance-Based Budget

Many local governments require budget documents to include performance measurements. Funding allocations are quantified to show the impact of service delivery to the community. (If operational programs are not fully funded, they will not be able to meet performance expectations). For government and community leaders, this adds value to their decision-making process. For publicly funded fire departments, accounting for resources becomes critical to maintaining funding for services. The process of budget adoption is open to the public and is participative, which provides an excellent forum for educating customers. In this environment, integrating the centralized performance database with fiscal management maximizes the opportunities to obtain resources and gain customer confidence.

Fiscal management typically resides in an administrative area, such as management services. Common fiscal management includes developing and monitoring the budget. When integrated with administrative information from multiple stakeholders and sources, such as policies, surveys, and planning documents, budget development becomes an inclusive participative process in which financial resource needs are applied to performance expectations (Figure 12.2.9). This process is commonly referred to as performance-based budgeting.

REPORTS AND REPORTING CYCLES

A standard report template streamlines the process of compiling, analyzing, and reporting data. An electronic format streamlines the transmission of data, as well as the ability to index and sort the data for multiple purposes. A fully integrated system connects service levels (outputs) with operational goals (targets), strategic goals (outcomes), and resources used (inputs). Using a report format, programs are set up by operational managers, who populate program descriptions, targets, and outcomes. The report is populated with outputs and inputs by selected criteria from other technological databases on a routine cycle.

Operational managers evaluate performance data in short-range cycles. A monthly cycle is optimal for reviewing service levels and resources used. This frequency coincides with the monthly reporting cycle of an accounting system, which allows the manager to monitor funding levels at the same time. Significant variances between the budget and expenditures are identified quickly. Remedial actions by operational managers keep

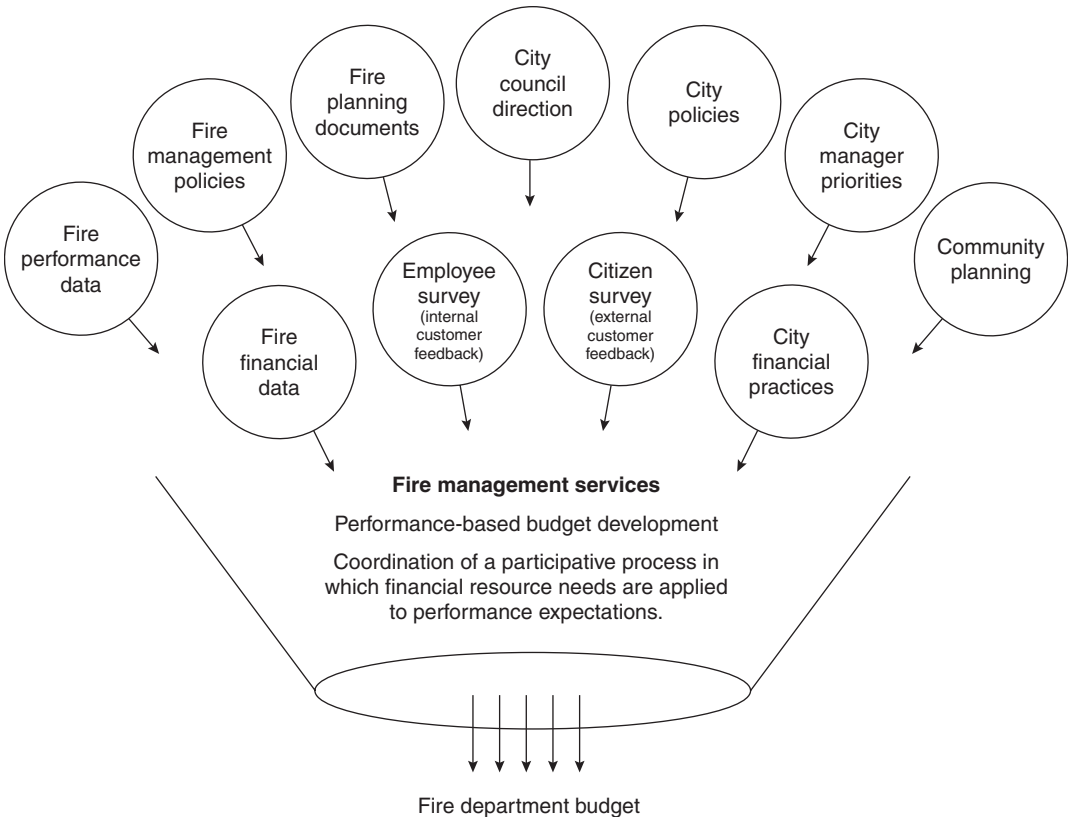

FIGURE 12.2.9 Performance-Based Budget Development

programs on track and funded, over the course of a fiscal year. A monthly cycle identifies service level trends in the early stages, as well. Operational managers are alerted to the possibility that resources may need to be realigned to meet shifts in service level demands. Early detection increases the organization's responsiveness to meet customer needs.

Senior managers evaluate performance data in longer-range cycles. A 6 month cycle is sufficient to support planning activities and budget development. For policy development, related performance data can be produced, as needed.

To integrate a new system, creating a standard report template and establishing the reporting frequencies are key steps. The sophistication of a fully integrated system may not be possible to obtain with initial implementation. In this case, the service levels (outputs), operational goals (targets), strategic goals (outcomes), and resources used (inputs) may have to be provided to operational managers on separate reports. As long as the data is linked, manually or through the use of technology, a thorough evaluation of organizational performance can be conducted.

The key elements of a performance report are summarized in Table 12.2.2 with three "*p*'s": program descriptors, performance information, and planning objectives. Included are proposed characteristics of each and a fictional program example.

MEASUREMENTS AND BENCHMARKS

Measurements and Benchmarks Defined

Measurements and benchmarks provide information. They are the mechanisms to quantify and qualify organizational performance. Using GASB definitions listed earlier in this chapter, measurements come in five major categories: inputs, outputs, outcomes, efficiency and effectiveness. The term *benchmark* has a dual meaning. In one context, it represents the standard to which we measure. In the other, it denotes the search for best practices. The common denominator of measurements and benchmarks is the provision of information about organizational performance.

Measurements linked to benchmarks create a context that increases the value of the information provided. In a numeric format, measurements quantify performance. Measurements linked to a benchmark qualify progress. The measurement is the count and the benchmark is the yardstick to which we measure the count.

The process of measuring organizational performance begins with a count (a number). The number of commercial buildings inspected is a count. The count may be stated as a percentage of a whole. The number of commercial buildings inspected as compared to the total number of commercial buildings in the community is a percentage of a whole. The number may be qualified to represent performance progress. The percent of commercial buildings inspected this year is *X* percent, compared to last year's *Y* percent. In this example, the performance benchmark is the prior year. The value of information increased when the numeric value of the measurement was linked to a benchmark to create a context.

The context of a measurement creates meaning to those who evaluate performance. As an evaluator of performance, we need more than just a number to convert data into information. As an example, a 7 digit number in itself doesn't provide information. If the 7 digit number is the odometer reading in our car, linked to a southern direction, it provides us with information about our driving progress. From our initial reading, we can calculate how far we have traveled and how much further we need to go to reach our destination. From our initial fuel level, we can calculate our miles per gallon and project the amount of fuel we will need to make it to the next gas station. Then we can benchmark our driving progress in many different ways.

Benchmarks vary and are based on the context that provides the most meaningful information to us. They may be based on technical standards, build on historical data, be comparables from like organizations, or be specific to organizational priorities. A benchmark can be the target itself.

Continuing with the example used for measurement context, we drove 600 miles today. To measure our progress, we can compare our measurement to several different benchmarks. We can compare our mileage to a technical standard. For example, our car insurance company has studied safe driving and recommends an average of 500 miles a day. We can compare it to yesterday. We drove 500 miles yesterday and set a goal of driving 500 more miles today. We can compare it to other drivers traveling the same highways. They drive an average of 700 miles per day. We can compare it to our destination. We are halfway to our destination. We can simply plan our trip based on our resources and our priorities at driving 600 miles each day.

An important note about the driving example is that the unit of measure created more opportunities to benchmark. Had we measured our progress in kilometers, it would have been difficult and time consuming to compare with external benchmarks that use miles as the norm. Due to service norms, sometimes the benchmark is selected prior to the units of measure to ensure comparability with external agencies.

Benchmarks as Best Practices

Not all things counted are measurements of performance. Many fire service professionals propose that a count such as fire fighters per capita represents a service norm as opposed to a performance measure. As discussed in *Municipal Benchmarks: Assessing Local Performance and Establishing Community Standards*[6] by David N. Ammons, "national or regional norms . . . can tell officials whether local practices and characteristics lie within or outside normal bounds, but they do not address performance."

Not all things benchmarked are measurements of performance. The term *benchmark* is also used to denote best practices. In *Managing Fire and Rescue Services,*[7] David T. Endicott examines benchmarking as a process of searching for and identifying best practices. The process involves comparing similar services provided by outside agencies in an effort to discover new and innovative practices that lead to improved performance.

Most fire departments benchmark to other fire departments. For those in major metropolitan areas, specific attention is given to neighboring communities with shared borders. This process

TABLE 12.2.2 Key Elements of a Performance Report

Key Element	*Characteristics*	*Example*
Program Descriptors		
Program title	Concise and recognizable	Emergency response
Program scope	Short description of services provided	Rapid response to emergencies dispatched through the 9-1-1 system
Program customers	Group(s) of people to whom services are provided (may be internal or external to the organization)	Residents, businesses, and visitors to the community
Program manager	Primary manager of services provided (operational level)	Deputy chief of fire operations
Strategic goal	Supports mission and directly linked to planning documents	To protect life and preserve property within the community
Operational goal	Supports strategic goal and directly linked to planning documents	Response time of 4 minutes or less, 90 percent of the time
Performance Information		
Reporting period	Date-bound reporting cycle	July 2007–December 2007
Service levels	Measurement of service provided during the reporting period, in the same units of measure as the operational goal	• Average response time: 3 minutes, 52 seconds • Response time within 4 minutes: 69 percent
Service efforts	Measurement of resources used to provide services during the reporting period, stated in format that is meaningful to the organization (may be hours, dollars, percentage of dollars, etc.)	• Regular time staffing budget: 49 percent expended, 50 percent through the fiscal year • Overtime staffing budget: 40 percent expended, 50 percent through the fiscal year
Explanatory factors	Significant factors that affected service delivery during the reporting period	Due to freeway expansion, 20 percent of major traffic corridors in the northeast section of the community have detours, causing emergency response units to use alternate routes
Major objectives	Major activity planned during the reporting period, to support operational goal; may be more than one	• Work with the transportation department to develop an electronic notification system for road construction schedules • Implement by November 30, 2007
Major accomplishments	Result of the major objective planned; may be in progress or completed; may be more than one.	New system implemented on September 18, 2007. Initial results of new system: • 100 percent of emergency response crews were notified, a minimum of 7 days prior to road construction via an e-mail distribution list. • 80 percent of crews reported the process is having a positive effect on their ability to identify the quickest route to an emergency.
Planning Objectives		
Major objectives	Major activity planned during the next reporting period to support operational goal; may be more than one	Research and recommend a digital display monitor for dispatch at multicompany stations by February 8, 2008
Projected outcome	If accomplished, how this activity will support the operational goal	The ability for emergency response crews to see the unit dispatched is projected to have a positive effect on turnout time (a component of overall response time to emergencies).

provides a wealth of useful information. At the same time, great care must be taken when selecting benchmark communities.

Prince William County, Virginia, has performed a process called Service, Efforts, and Accomplishments that selects similar municipal agencies to compare like measurements. They have run into some challenges with truly "like measures." Even though the comparison is made to other combination departments, there are organizational and cultural differences that sometimes equate to comparing apples to oranges or at best to a different type of apple.

Variables in the demographics and service dimensions of every community and region have the potential to skew measurements. An example is found in the measurement of fire fighters per capita. The variable is the scheduled workweek for fire fighters. In some regions of the United States, it is 40 hours per week. In others, it is 56 hours per week. In two communities with different workweeks, the numbers of fire fighters on duty may be the same each day but the number of fire fighters employed to fill the on-duty assignments may be significantly different. In turn, the number of fire fighters employed can skew the measurement of fire fighters per capita. Identifying these types of variables when compiling a profile of benchmark communities will increase the value of comparisons. If a true apples-to-apples comparison cannot be obtained, at least the variables that affect the measurement can be noted and considered in the evaluation process.

The decision about how to use benchmarking goes back to the practice that best matches the philosophy, culture, and mission of the organization. There is an abundance of things to measure and benchmark in a fire department. The key to providing information and not just numbers lies in the selection of what to count and which yardstick to use to create a context that has meaning.

Meaningful Measures

An example of an evaluation process to select meaningful measures is found in Figures 12.2.10 through 12.2.13. Developed by the Ontario Fire Marshal's Office as part of its "Performance Measurement and Benchmarking Project," they provide an evaluation tool to help municipalities measure all the components of community fire protection planning. (The full model is a product of work that is available by contacting the Ontario Fire Marshal's Office.)

In addition to reviewing the Ontario model, the following list of data categories may be useful in the selection of meaningful measures (many were derived from measurements used by Prince William County, Virginia, and Scottsdale, Arizona, and they appear in no particular order of importance):

Emergency Services

- Number of calls for emergency services, total and by type
  - Fire
  - Medical
  - Hazmat
  - Technical rescue
  - Aircraft rescue and fire fighting
  - Other
- Number of units dispatched, total and by type
- Response times to emergency calls, actual and average
  - Percent of responses made in under X minutes
  - Dispatch time
  - Turnout time
  - Travel time
- EMS transports (patients transported)
- EMS quality assurance review results
- AED use, deployment statistics, and usage rates
- Training hours, total and average per member, by type
- Members certified to minimum standards of services provided, by type
  - ALS (paramedic)
  - BLS (EMT)
  - Special operations
- Training participation
  - Promotional processes rates
  - Succession planning rates
  - Recruit retention rates
- Health and wellness participation
  - Exposure rates
  - Fitness rates
  - Health screening participation rates
  - SCBA fit test rates
  - Workers compensation claims, hours lost to injuries

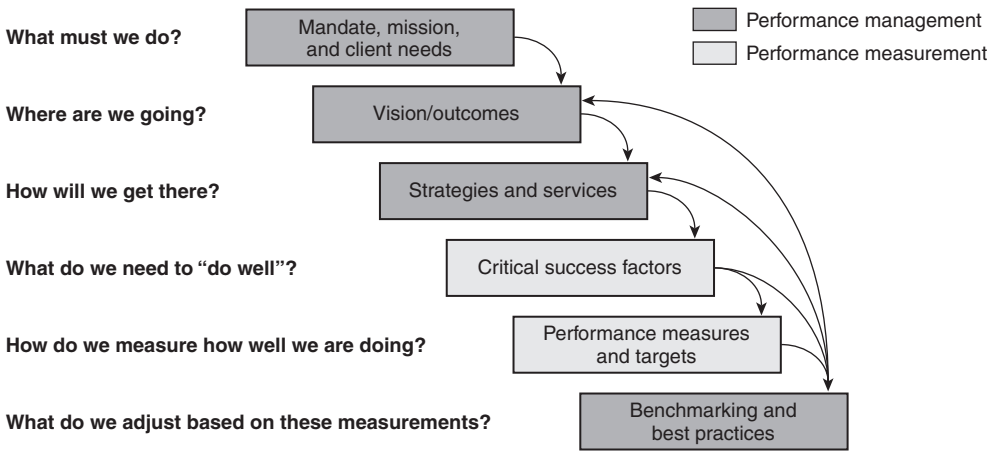

FIGURE 12.2.10 Performance Management Framework (Source: "Ontario Fire Service Performance Measurement and Benchmarking Partnership Project," Office of the Fire Marshal, Province of Ontario, Canada)

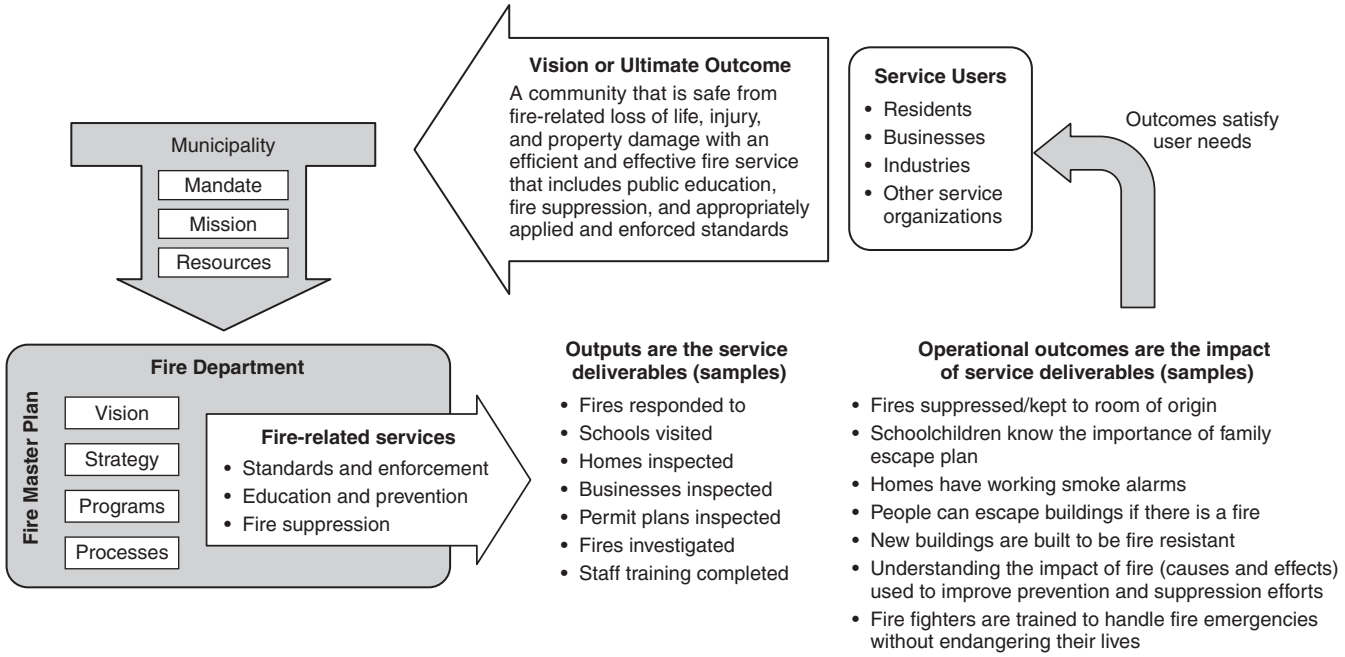

FIGURE 12.2.11 Fire Services Delivery Model (Source: "Ontario Fire Service Performance Measurement and Benchmarking Partnership Project," Office of the Fire Marshal, Province of Ontario, Canada)

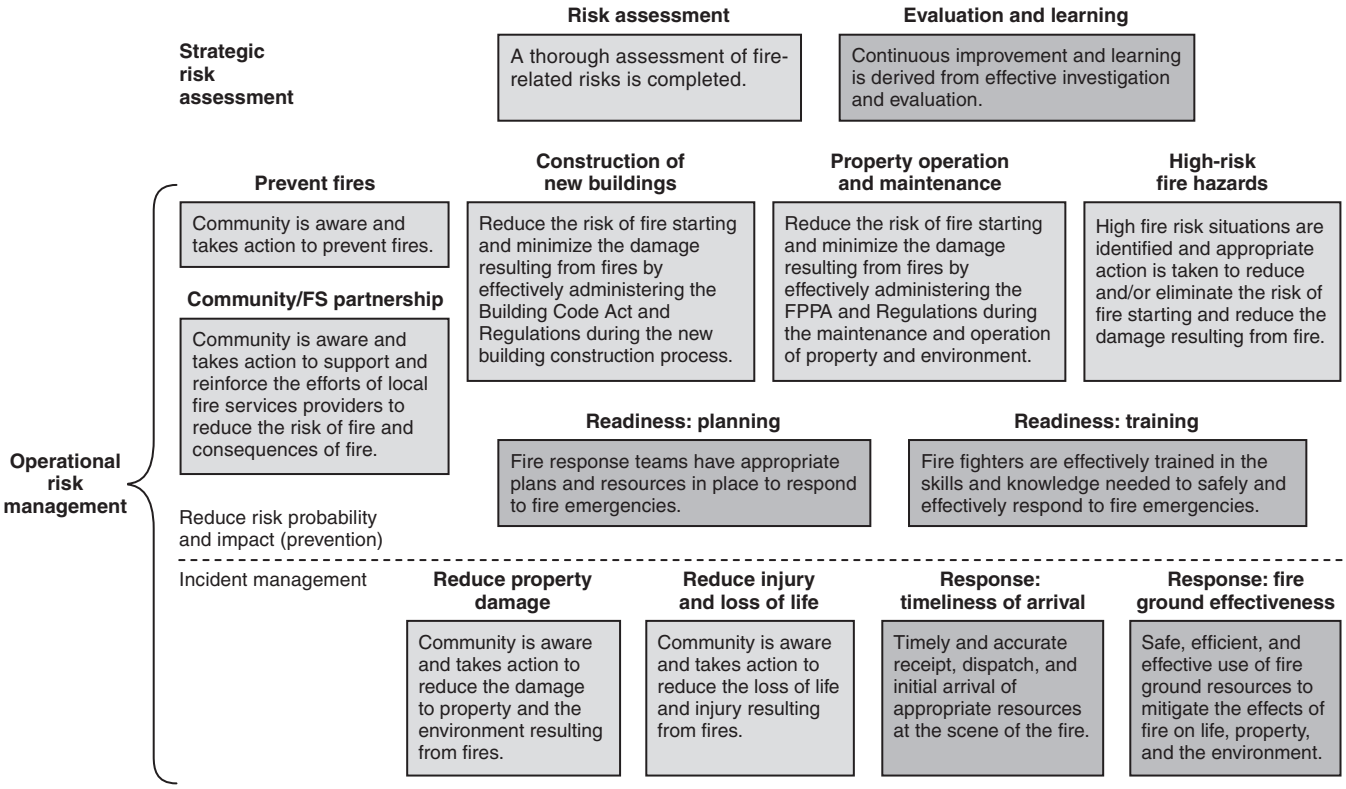

FIGURE 12.2.12 Fire Protection Outcomes (Source: "Ontario Fire Service Performance Measurement and Benchmarking Partnership Project," Office of the Fire Marshal, Province of Ontario, Canada)

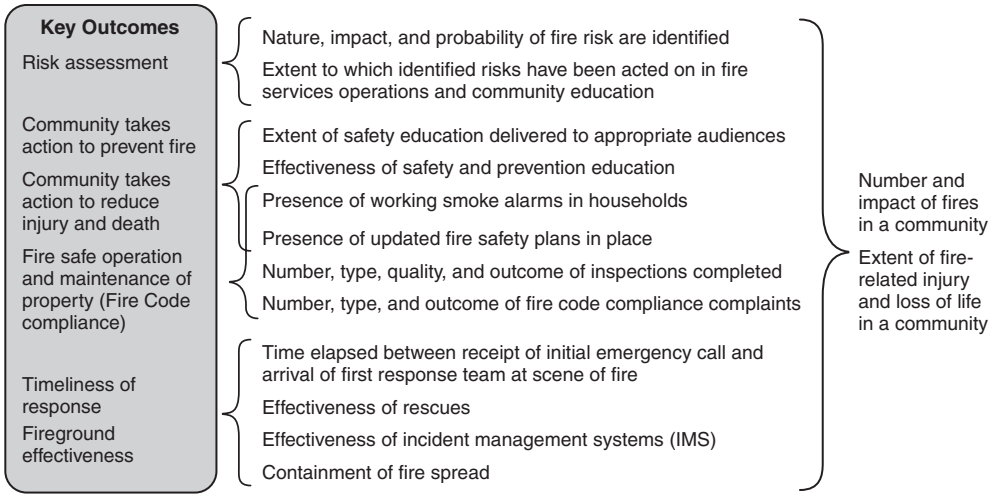

FIGURE 12.2.13 Key Performance Indicators (Source: "Ontario Fire Service Performance Measurement and Benchmarking Partnership Project," Office of the Fire Marshal, Province of Ontario, Canada)

Fire Prevention

- Inspections, numbers conducted, and turnaround time
- Number of occupancies in the community, by type
- Structure fires of the various occupancies
  - Fires contained to room of origin, unit of origin, building of origin
  - Fires contained to the level of involvement on arrival of first fire unit
- Number of false alarms
- Fire loss
- Civilian injury and death rates
- Fire investigations, number conducted
  - Cause and origin determination rates
  - Arson rates, conviction rates
- Plans reviewed, number conducted
  - Customer turnaround time
  - First review approval rates
- Complaints investigated
- Community access rates, use of technology
- Built-in protection
  - Number of residents with smoke detectors
  - Number of residents with fire sprinkler systems

Fire and Life Safety Education

- School programs, by grade level: class hours and students contacted
- Community events, participation rates, by type
  - Car seat inspections
  - Senior events
  - CPR classes
  - Drowning prevention
- Educational literature distributed, by type

Administrative and Support Services

- Citizen satisfaction survey results, by service provided
- Employee satisfaction survey results
- Employee turnover rates
- Emergency operations center (EOC) activations and drills, participation rates
- Community emergency response team (CERT) volunteers, participation rates
- Media releases provided
- Public service announcements produced
- Lawsuits filed
- Vehicle accident rates
- Number of intersections with traffic pre-emption devices
- Mapping update and distribution rates
- Incident records, processing and turnaround times
- Apparatus statistics: in service, by type; out of service, by cause
- Equipment inventory rates: out of service, by cause; lost, by type
- Personal protective equipment statistics
- Supply inventory and usage statistics

Service Dimensions

- Population
- Service area, square miles served
- Total fire department personnel, number of civilians in department, and number of sworn personnel
- Total fire department operating budget by expenditure type, dollars, and labor hours
- Total fire department capital improvement budget, by project
- Number of fire stations
- Number of on-duty personnel, per day
- Per unit staffing, minimum staffing criteria

SUMMARY

A systems approach to organizational benchmarking and performance evaluation captures the key information necessary to communicate performance expectations and success. Effective communication combined with member participation leads to organizational acceptance and accountability for performance results. An environment of universal accountability fosters process improvements and the efficient use of resources. When resources are linked to service delivery, value is added to decision-making processes and customer confidence increases.

An organization with an integrated performance management system has the ability to capture and convert data into information. Data captured on an operational level, when combined with professional judgment and expertise and centralized, provides accurate information. Performance information that is customer focused and has a direct relationship to operational and strategic goals is meaningful. Accurate and meaningful information about an organization's performance leads to excellence in service delivery for customers.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on organizational benchmarking and performance evaluation discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 901, *Standard Classifications for Incident Reporting and Fire Protection Data*

NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*

NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments*

Chapter 3

Needs Assessment and Hazard Analysis

William F. Jenaway

Chapter Contents

Overview of Assessment Components and Resources
General Plans
Assessment Processes and Tools
Stakeholders and Assessment Information Resources

Key Terms

accreditation, community risk assessment, emergency planning, hazard analysis, hazard assessment, Insurance Services Office (ISO), master plan, needs assessment, risk assessment, standard of response cover, strategic plan, water supply

Fire officials, fire departments, and emergency service organizations often do not perform an adequate needs assessment and hazard analysis in their area for use in their planning processes. A needs assessment and hazard analysis is fundamental to determining necessary resources to operate a department and ensure performance of its assigned functions. Knowing what resources a department or organization will need can only be determined by understanding the hazards it faces. However, time, funding, and other priorities continually prevent fire officials from effectively analyzing needs and incorporating appropriate resources into organizational operations.

The purpose of this chapter is to demonstrate the interrelationship of numerous routine or special activities that can be conducted as components of a comprehensive needs assessment and hazard analysis—that is, the identification of the challenges faced and the resources needed to manage these challenges.

For related information see the following chapters in Section 12: Chapter 1, "Planning for Public Fire-Rescue Protection"; Chapter 2, "Organizational Benchmarking and Performance Evaluation"; Chapter 12, "Disaster Planning and Response Services"; Chapter 17, "Pre-Incident Planning for Industrial and Municipal Emergency Response"; Chapter 18, " Pre-Incident Planning for Emergency Response"; and Chapter 19, "Community Risk Reduction."

OVERVIEW OF ASSESSMENT COMPONENTS AND RESOURCES

Components of the Assessment Process

Any process to assess needs and analyze hazards must utilize a fundamental decision-making process. There are several such models; however, regardless of the one chosen, the basic components of the process remain the same and include the following:

- Developing the analytical data
- Evaluating the data developed
- Deciding on the data to use or course of action to take
- Implementing the chosen data
- Monitoring and modifying the information implemented

This decision-making process will assist decision makers in understanding what hazards exist, what actions are needed to manage those hazards, and how to fulfill the identified needs. The decision-making activity becomes a path to matching hazards and needs. For reference in this decision-making process, see related chapters in Section 12 for additional information.

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Needs Assessment Study

A cooperative study, authorized by U.S. Public Law 106-398, required that the director of the Federal Emergency Management Agency (FEMA) conduct a national study in conjunction with the National Fire Protection Association (NFPA) to accomplish the following:

- Define the current role and activities associated with the fire service
- Determine the adequacy of the current levels of funding
- Provide a needs assessment to identify shortfalls[1]

Evaluation Areas of Study. This initiative focused on six areas. The details of the findings of the report appear throughout this chapter; however, it is important to understand what the study evaluated and its related limitations in overall needs assessment and hazard analysis. The study evaluation areas included the following:

- Services provided
- Personnel and their capabilities
- Fire prevention and code enforcement
- Facilities, apparatus, and equipment
- Communications and communication equipment
- Ability to handle unusually challenging incidents
- New and emerging technology

Although these are all valid considerations, before needs can be defined, the expectations of the public, an understanding of the risks posed within the community, and the expectations of everyone receiving and providing the service must be identified.

Resource Categories. To properly determine how the fire department will do its job, a needs assessment and a hazard analysis are integral to the process. For example, the needs assessment study completed as a result of U.S. Public Law 106-398 identifies several categories of resources, including the following:

- Fire-fighting personnel
- Training for fire-fighting personnel
- Rapid intervention teams
- Certification for fire inspectors
- Wellness and fitness programs for fire-fighting personnel
- Emergency medical service programs provided by fire departments
- Fire-fighting vehicles
- Fire-fighting equipment, including communications and monitoring
- Personal protective equipment for fire-fighting personnel
- Modifications to stations and facilities for reasons of fire fighter health and safety
- Enforcement of fire codes
- Fire prevention programs
- Education of the public about arson prevention and detection
- Recruitment and retention initiatives for volunteer fire fighters in fire departments.[1]

Although these resources were quantified to better understand the magnitude and nature of fire department needs, it must be recognized that specific needs will be driven locally and based significantly on the local hazards faced, without going below the minimum requirements defined in the standards. The study provides insight into key areas of concern at issue nationwide, but its applicability in a specific community is determined by what that community has completed in terms of coordinating hazard analysis with needs assessment.

Study Findings. The FEMA/NFPA study provided findings in the areas of revenues and budget; personnel; fire prevention and code enforcement; facilities, apparatus, and equipment; communications and communications equipment; ability to handle unusually challenging incidents; and new and emerging technology. In the updated needs assessment study of the U.S. fire service created by the U.S. Department of Homeland Security/U.S. Fire Administration and the National Fire Protection Association four years later,[2] the following were noted:

- Taxes provide at least three-fifths of the revenue for all-volunteer or mostly volunteer fire departments in the United States. Taxes plus other government payments, including per-call reimbursements, raise the total percent of revenue coming from government to at least three-fourths (77%). Fund raising provides at most 19 percent, which is the fund-raising share for rural communities of less than 2500 population.
- Converted vehicles account for 14 percent of apparatus used in communities under 2500 population and 10 percent of apparatus in communities of 2500 to 4999 population.
- Many fire departments fail to deliver a first-arriving complement of at least 4 fire fighters to a structure fire, the minimum complement needed to safely initiate an interior attack.
- An estimated 53 percent of departments are involved in structural fire fighting but have not formally trained all involved fire fighters in those duties. The corresponding percentage is 36 percent for emergency medical services, 36 percent for hazardous material response, 63 percent for wildland fire fighting, and 50 percent for technical rescue. Except for technical rescue, the percentages of departments needing more training are always higher for rural communities (less than 2500 population), in which nearly all departments are all-volunteer.
- One-quarter of the population are protected by fire departments that do not provide plan review and nearly half are protected by fire departments that do not provide permit approval or routine testing of fire protection systems. An estimated 7 percent of the population live in communities where no one conducts fire code inspections, and two-fifths of this unprotected population live in rural communities.
- Similarly, one-third of the population live in communities where there is no fire department program for free distribution of home smoke alarms, and two-fifths of the population are protected by fire departments with no juvenile firesetter program.
- An estimated 36 percent of fire stations are at least 40 years old, 54 percent do not have backup power systems, and 72 percent are not equipped for exhaust emission control.
- Half (49%) of all fire apparatus are at least 15 years old.
- An estimated 65 percent of fire departments do not have enough portable radios to equip all emergency responders on a shift. An estimated 60 percent do not have enough self-contained breathing apparatus (SCBA) and an estimated 48 percent do not

have enough personal alert safety system (PASS) devices to equip all emergency responders on a shift. An estimated 8 percent do not have enough personal protective clothing to equip all fire fighters, most of them being departments in rural communities.

- About three-fourths of departments say they cannot communicate with all their federal, state, and local partners at incident scenes, and one-fourth to one-third say they cannot communicate with any of their partners. Roughly half of all departments have no map coordinate system, and almost none use the U.S. National Grid System, which has been adopted by the Federal Geographic Committee as the system best suited for eventual national standardization.
- Written agreements to direct use of nonlocal resources are lacking for 74 percent of departments with regard to technical rescue and EMS at a defined structural collapse and 70 percent of departments with regard to hazmat and EMS at a defined chemical/biological agent incident. Written agreements are also lacking for major floods and wildland/urban interface fires. On the positive side, the percentage of departments with written agreements increased between the 2001 and 2005 needs assessments.
- Finally, the majority of departments (55%) now have thermal imaging cameras, up from only 24 percent in the 2001 survey.

Each of these situations identified by the needs assessment study pinpoints a fire department need that poses a challenge to be resolved before the hazards identified can be managed.

Terms Defined

In this text the terms *hazard, risk, needs assessment,* and *hazard analysis* are defined as follows:

Hazard: Level of harm associated with exposure to a fire or its effluent.
Risk: Expected loss from a fire of a given severity.
Needs Assessment: An analysis to determine the shortfall between expected performance and current performance.
Hazard Analysis: An analysis to determine the potential impact of a fire scenario when the hazard is involved in fire.

GENERAL PLANS

Over the years a variety of planning processes have been developed and introduced to the fire community. Each process establishes and accomplishes different objectives. The following section defines the processes involved with strategic plans, master plans, community risk assessments, pre-emergency planning, and disaster plans, and discusses what to expect from each of these processes when they are completed.

Strategic Plan

The strategic planning process serves as a single point of collection to coordinate various data points, administrative processes, and planning considerations. This integration of benchmark performance, budgetary commitments, mission statements, emergency service organization activities assessment, and so on serves the management team with a summary report of the efficiency and effectiveness of the organization.

Purpose of Strategic Focus. *Strategic planning* or *strategic focus* has been described as a set of concepts, procedures, and tools designed to assist leaders and managers in exercising control, coping with change, and developing a basis for decision making.[3] The strategic focus process can help answer such questions as these:

- What are the fire department's objectives for the next five years?
- Where will the organization be in seven years?
- What are the fire department's capital purchasing plans for the next ten years?
- What is the fire department's standard of response cover?

In recent years there have been several approaches to performance enhancement in both profit and nonprofit organizations. The terminology may vary; however, as long as managers are driving the organization to future decision and action to ensure organizational success, they are strategically focused and participating in strategic planning.

Strategic Focus Model. Creating and implementing a strategic focus helps the organization understand its resources, capabilities, and needs. In order to develop such a plan successfully, an appropriate planning model is necessary. To enable resources to meet expectations, the strategic focus model (Figure 12.3.1) employs three essential concepts:

- Organization resource assessment
- Defined service expectation
- Priority planning

With these concepts incorporated into the strategic plan, a basic decision and action process is created that helps structure the emergency service organization and spells out what it does and why it does it. In essence the process defines the future of the emergency service organization.

Basic Activities. The following are five basic activities identified in the strategic focus model:

1. Identifying, developing, creating, and analyzing key issues:
   - Mission and vision
   - Standard of response cover
   - Roles and responsibilities
   - Goals and objectives
   - SWOT (strengths, weaknesses opportunities, and threats)
   - Strategic alliances
2. Obtaining direction from key sources of input:
   - Organizational members
   - Community leaders
   - The citizenry
   - The business community
   - Mutual aid agencies

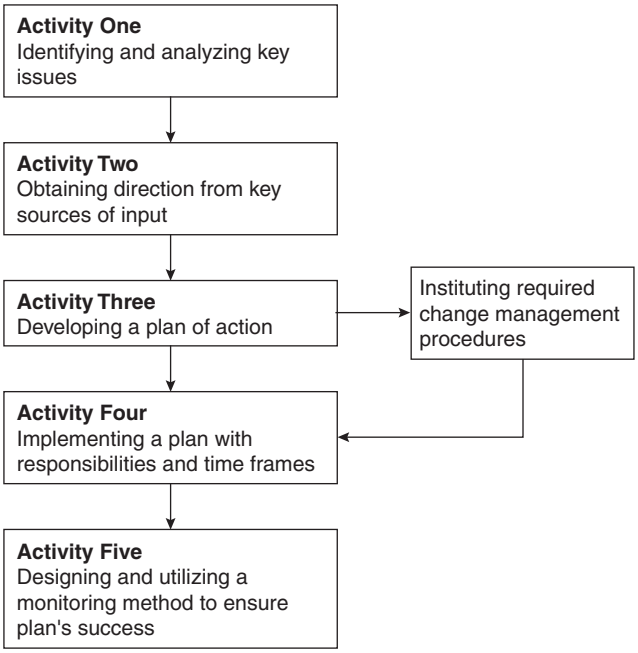

FIGURE 12.3.1 Strategic Focus Model

3. Developing a plan for implementation over a defined time period:
   - Immediate action steps to achieve goals and objectives
   - Long-term plan for implementation
4. Implementing a plan with responsibilities and time frames involving:
   - Finance
   - Personnel
   - Apparatus
   - Equipment
   - Facilities
   - Processes and procedures
5. Designing and utilizing a monitoring method to ensure plan success

Change Management Practices. Identifying and acting on the issues previously described can increase the efficiency of the emergency service organization and can help to plan for future contingencies. The result of any strategic focus initiative is change. Therefore, any such process must be undertaken by an organization that is ready for change. If the organization is not ready for change, then conflict can and will exist. As a result, change management practices must be identified and catalogued for reference as the planning process moves forward.

Identifying and prioritizing the initiatives critical to an organization's performance ensures long-term health and growth of the emergency service organization. The output from this process establishes coordinated goals, objectives, and, in some cases, action steps dealing with the following aspects of the organization:

- Finances
- Personnel
- Facilities
- Apparatus
- Equipment
- Procedures/processes

These are consolidated into planning documents, including identified costs, time frames for completion, and responsibilities for completion. The process then identifies different sets of objectives for organizational action.

In conclusion, although we may want it to be "the same old fire service as the glory years of the 60s," it isn't. Today, emergency service organizations are complex and dynamic and they must identify what they are doing, why they are doing it, and incorporate mechanisms for change if current initiatives are ineffective or problematic. The strategic focus process helps an organization develop the vision of where it wants/needs to be and how to get there.

A strategic plan establishes a "vision" and deals with more than just fire protection. To give an analogy, a strategic plan is a road map, whereas a master plan provides details on the streets, buildings, and related details encountered along the way.

Master Plan

Over the years, the term "master plan" has had several definitions and applications. In fact, some may say it is the same as a need assessment and hazard analysis. A master plan may be best characterized as a plan that helps to zero in on priorities and levels of service provided in specific operational areas. The master plan can assist in addressing adequacy and performance and align specific divisional needs with organizational expectations and the strategic plan.[4] Therefore, its development can serve as a component of comprehensive needs assessment and hazard analysis.

As noted above, a master plan differs from a strategic plan in that a master plan typically determines how much risk a community is willing to assume specifically relating to fire protection.

Community Risk Assessment

Community risk assessment, a fundamental assessment and planning process to assist in defining goals, is used to identify the community's fire protection and other emergency service needs in order to determine potential goals and objectives. Emergency service organizations must expand their use of this planning process to ensure they can meet future demands. All agencies should have a basic source of data and information in order to logically and rationally define the organization's mission. The end result of the process is to establish a long-range general strategy for the operation of the system. Emergency service organizations can achieve this goal by taking the following steps:

1. Documenting area characteristics by collecting historical data and instituting a process by which hazards are de-

fined and potential organizational goals and objectives are established.
2. Assessing the nature and magnitude of the hazards within its jurisdiction by categorizing and listing significant events to allow for future analysis and study in determining standards of coverage and related services.
3. Assessing the nature and magnitude of other hazards and risks within its jurisdiction and identifying appropriate strategies, methods of operation, and resource allocation required to mitigate potential emergencies.
4. Creating a "strategic" or other form of long-term (typically three to five years into the future) planning process that, along with a budget, guides the activities of the organization.
5. Submitting the plan to the appropriate authority having jurisdiction for review and implementation.

The coordination of these actions results in a plan to manage a community's emergency response. This plan, based on facts, will help the community better understand the emergency service organization's goals and help the organization to work toward these goals.

Pre-Emergency Planning

As personnel within the department gain particular information about a risk, they should categorize and develop this information into a database for use when needed and for training—both of which serve the function of hazard analysis and need assessment.

Figure 12.3.2 illustrates how the pre-emergency planning process works, but if data is not documented, communicated (in training and in routine communication), used to access appropriate resources, and formatted to be accessible when needed, the value in its relationship to hazard analysis and needs assessment is lost.

Disaster Plan

One need only look at emergency response information to realize that the emergency service organization responds to more than fires and thus must be prepared for each risk. In fact, in many communities today, the reality is that fires demand fewer responses but larger response capabilities. This can only be defined by a comprehensive threat/risk review and a determination

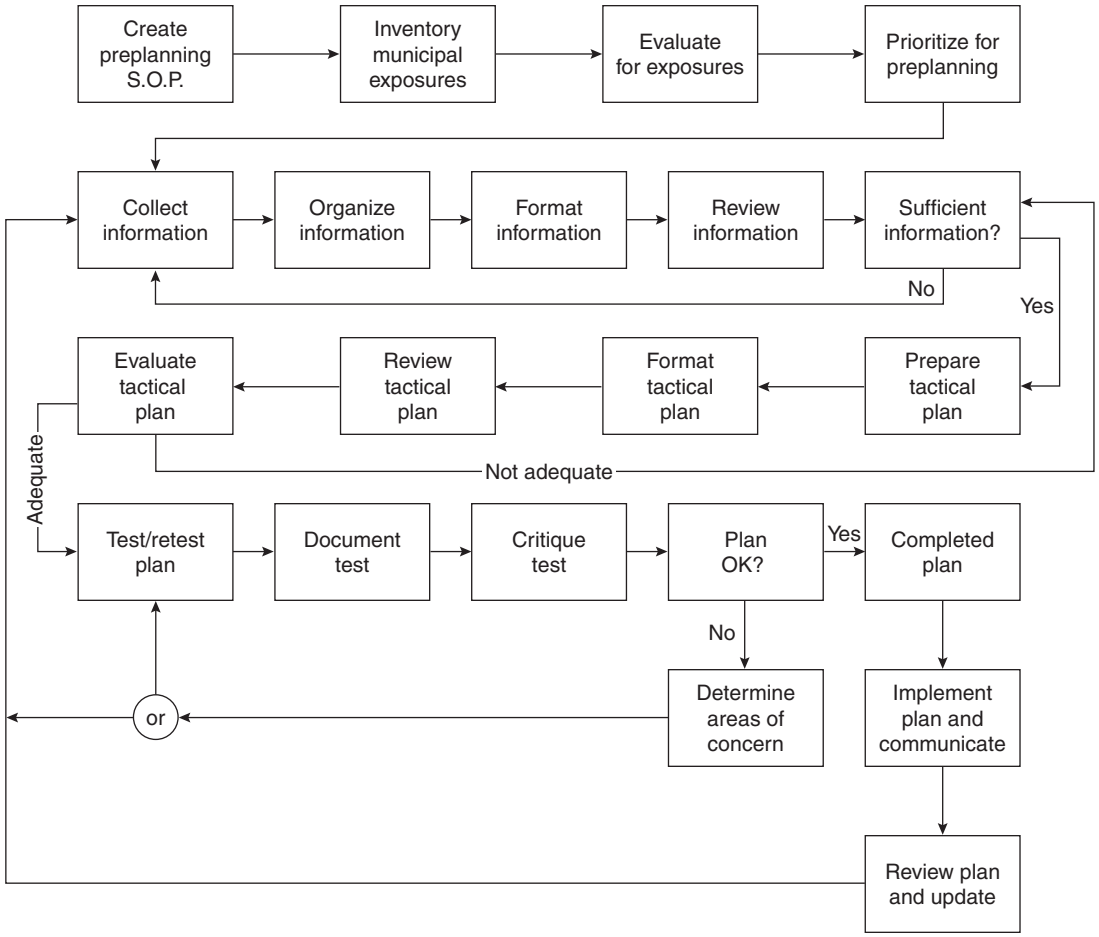

FIGURE 12.3.2 Pre-Emergency Planning Process (Source: W. F. Jenaway, *Pre-Emergency Planning,* ISFSI, Pleasant View, TN, 1996)

of how these risks must be managed. See Section 12, Chapter 12, "Disaster Planning and Response Services," for information on planning for more than fire risk.

ASSESSMENT PROCESSES AND TOOLS

Several assessment processes and tools are available to help in the analysis of hazards and determination of needs. Figure 12.3.3 illustrates related activities that fit into the assessment process, including plans (discussed in the preceding section), processes and tools, and the various stakeholders and assessment information sources.

Accreditation

One such assessment tool is accreditation. The accreditation program managed by the Commission on Fire Accreditation International provides an analytical self-assessment process to evaluate ten categories. Integrated within the ten categories is an expectation for the community to analyze itself by planning zones and for each planning zone to identify the hazards posed, ranking them by potential severity, and, as discussed in a later section, to ensure that the appropriate resources are available to manage the hazards. The accreditation self-assessment process is extremely helpful in determining needs and analyzing risks, even if the emergency service organization does not seek formal accreditation. Once the hazard is evaluated, the resources to manage the hazard can be defined, and an expected service delivery capability—that is, the standard of response cover—can be established.

Standard of Response Cover

The Commission on Fire Accreditation International defines *standard of response cover* as being "those adopted, written policies and procedures that determine the distribution, concentration, and reliability of fixed and mobile response forces for fire fighting, emergency medical service, hazardous materials and other forces of technical response."[5]

The standard of response cover can be considered a tool to accomplish several objectives, including the following:

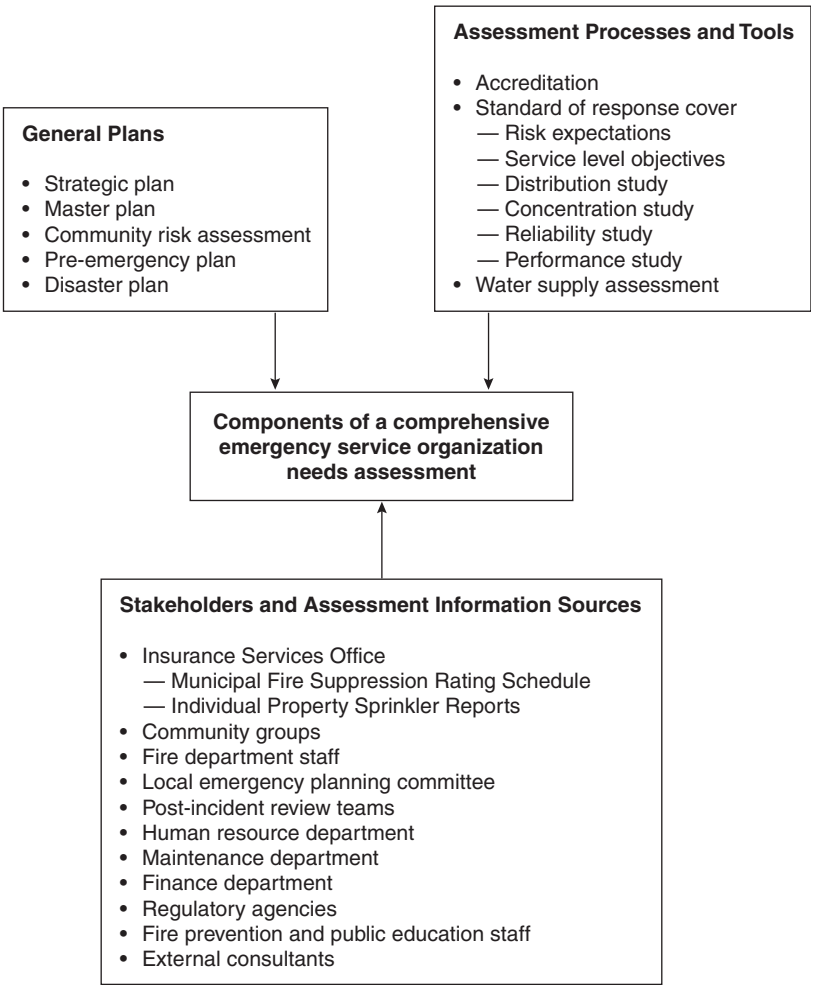

FIGURE 12.3.3 Components of a Comprehensive Emergency Services Organization Needs Assessment

- Evaluating and defining an agency's baseline of operations
- Identifying benchmarks for achieving an agency's goals and objectives
- Determining levels of service for all portions of a community
- Measuring an agency's performance over different budget operational years

Developing a standard of response cover is not quick or easy, but it is valuable to the progressive emergency service organization and should already be in place. The standard of response cover process includes an evaluation of the following eight components, all of which are integrated into a final methodology for standard of response cover (SORC) development:

1. Existing deployment
2. Risk assessment
3. Risk expectations
4. Service level objectives
5. Distribution study
6. Concentration study
7. Reliability study
8. Performance study

Existing Deployment. An evaluation of this component requires the fire department to map, measure, and understand its existing deployment, regardless of how it originated (e.g., insurance services office requirements, community growth, etc.). This will help clarify the department's total reflex and coverage capability.

Risk Assessment. Risk assessment requires the fire department to understand fire flow demand and capability, the probability of an emergency, the consequences to life safety and economic impact, and the estimation and evaluation of risk.

Risk Expectations. Evaluating risk expectations requires the fire department to identify what the community and the emergency service organization want in the form of service, what the outcomes should be, and whether the desired outcomes can be justified. These will assist in establishing critical tasking measures, shown in the following examples:

> *Structure Fire Performance Objective:*
> To stop the development of a moderate fire risk when encountered, conducting search and rescue as required, confining damage to as close to the room of origin as possible, limiting the expansion of heat and smoke damage.
>
> *EMS Risk Objectives:*
> To effectively provide a basic level of medical care at the basic life support level.
> To be on-scene in a timely fashion to:
>
> - Assess and prioritize patient situations
> - Minimize death and disability
> - Stabilize patients to the level of training of responders
> - Intervene successfully in life-threatening situations

Service Level Objectives. Service level objectives require the fire department to assemble and evaluate fire growth and flashover, EMS response needs, special service response needs, reflex and response times of on-scene operations, problem-solving critical tasks, and determining an effective response force. Examples of service level objectives as defined by the Commission on Fire Accreditation International are the following:

> *Service Level Objective:*
> For 90% of all incidents, the first arriving unit shall arrive within five minutes total reflex time (or travel time).
>
> *Service Level Objective:*
> The first arriving unit shall be capable of advancing the first line for fire control or starting rescue or providing basic life support for medical incidents.

Or the service level objective can be even more specific.

Distribution Study. The distribution study component requires the fire department to geographically analyze first-due resources for initial incident intervention to ensure quick deployment in order to minimize and terminate the hazards of average, routine emergencies. The distribution measures are up to the department, but might include percentage of square miles, percentage of equally sized analysis areas, percentage of total road miles in jurisdiction, or some similar measure.

Concentration Study. The concentration study component requires the fire department to look at the arrangement of multiple resource spacing (close enough together) so that an initial "effective response force" can be assembled at the scene within the adopted public policy time frames. The initial effective response force is one that should be able to stop the escalation of the emergency for the risk posed. Concentration measures can be similar to distribution measures.

Reliability Study. The reliability study component requires the fire department to determine the ability to meet performance expectations even if resources are committed on an existing call. This necessitates a historical measure of performance, resource exhaustion, relocation practice, and expectations.

Performance Study. The performance study component requires the fire department to evaluate information and data available, such as the following:

- Existing standards of cover documents
- Risk assessments
- Historical performance
- Cost-benefit evaluations

The information gleaned from evaluating these eight components is then used to develop the standard of response cover.

Water Supply Assessment

The water supply of the community must be known for two basic reasons. For locations subject to fire, knowledge of water supplies is necessary to determine surplus or need. The Insurance

Services Office (ISO) Municipal Fire Suppression Rating Schedule will also provide guidance on the location of hydrants tested during its analysis of water supply needed versus water supply available, indicating if a surplus or need exists for specific locations in the event of fire. (This water supply need can also be determined by the fire department during pre-emergency planning.) If water is needed, the hazard analysis component can be used to then determine where it can be obtained—whether from a static source, from a flowing stream, brought to the scene by a water tender or other means, or obtained from another water supply system—or whether a do-not-fight-the-fire scenario is the reality.

Second, it is important to know the water supply available for individuals providing sprinkler plans for review. It is important to ensure that the available water supply can meet the demand of the sprinkler system being installed, and, if not, how much water is needed and how it will be obtained. The Insurance Services Office (ISO) reports on sprinklered structures, in which the ISO has evaluated individual properties to determine the risk posed and the availability of an adequate water supply, can help provide this information.

In both of the preceding situations, understanding the hazard posed, the amount of water needed, and the amount of water available assists the fire department in hazard analysis and needs assessment.

STAKEHOLDERS AND ASSESSMENT INFORMATION RESOURCES

Insurance Services Office

The Insurance Services Office (ISO) serves the insurance marketplace with statistical, actuarial, underwriting, and claims data; policy language; information about specific locations; fraud-identification tools; consulting services; and information for marketing, loss control, and premium audit. Through its Public Protection Classification (PPC) Program, ISO evaluates municipal fire protection efforts in communities throughout the United States.[6]

ISO provides two primary support roles to the fire department in the area of hazard analysis and needs assessment: the Municipal Fire Suppression Rating Schedule and individual property sprinkler reports (as discussed earlier).

Municipal Fire Suppression Rating Schedule. The municipal fire suppression rating schedule evaluates the following three major areas:

1. The fire department
2. The water supply
3. Receiving and handling of fire alarms

When completed, the process provides an assessment of each area, complete with ratings that are translated into an insurance rate for the community. The process also facilitates the development of "improvement statements," indicating deficiencies and needed improvement in the area of staffing, water supply, equipment, apparatus, pumping capacity, aerial capacity, and so on.

Individual Property Sprinkler Reports. Similarly, ISO will conduct evaluations of structures that contain automatic sprinkler systems (as discussed earlier). These evaluations will determine whether the system is adequate for the hazard it is designed to protect and whether there is sufficient water supply to support the system if it activates. ISO's assessment identifies needs.

Community Groups

One of the most significant sources of input is the community. Not only will individuals in the community communicate their satisfaction, concerns, and expectations, they will be brutally honest. Even if the fire department is providing the best service it believes possible, the "customer" may agree or disagree. For the department to not capitalize on regular communication with the public and build its plan accordingly would be to do without the input of its most important customer. Civic groups, homeowner associations, neighborhood groups, church groups, fraternal organizations, the Rotary Club, the Chamber of Commerce, the Jaycees, and so on can be valuable resources for communication with the community.

Fire Department Staff

Similarly, to not periodically request information on planning from the fire department staff would be a mistake. These individuals know the level of service they are delivering and the hazards they are facing. Seeing the "streets" daily, they have the perspective of knowing what is out there and what is needed to deal with it.

Local Emergency Planning Committee (LEPC)

In many communities, the true hazards are found in the industrial operations of the town. Industrial facilities, often loaded with hazardous materials, pose a significant hazard to the community at large if the hazardous materials are not managed in routine operations, let alone a fire. The local emergency planning committee (LEPC) is charged with obtaining and appropriately distributing information regarding hazardous materials stored and used at various sites. The information the LEPC distributes—be it the chemical name of the hazardous material or the material safety data sheet (MSDS)—provides the critical information needed, including the product name, its hazards, and the control methods during both routine and emergency situations. As it pertains to assessing needs, it may be determined, based on this information, that large quantities of foam concentrate are needed; that extensive spill control or diking equipment should be maintained; or that specialized personal protective equipment is needed. Whatever the need is, it is identified based on the hazard analysis.

Postincident Review Teams

Each incident responded to provides a postincident analysis opportunity to learn about hazards and what is needed to manage incidents involving specific hazards. As each incident recap occurs, the team involved in the response can identify whether it had enough staff to handle the problem, the equipment was

adequate, specialized resources were available to meet the need, and so on. In each instance, based on the hazard posed by the incident responded to, the team can determine whether adequate or inadequate resources were at hand to handle the problem.

Human Resource Department

When looking to determine adequate staffing, adequate deployment, and the probability of hazardous situations resulting in accidents or injuries, the fire department needs to look no further than the human resource department. The human resource department can provide input on whether there is sufficient staffing and whether shortfalls exist because department members are unable to respond due to illness, injury, vacation, or some other factor. Because the human resource department probably has some responsibility for the safety function of the fire department, it can provide valuable information regarding the types of injuries incurred by members and the causes of those injuries. The hazard information can be used to redefine job tasks, procure personal protective equipment, or prohibit doing certain tasks to meet organizational needs.

Maintenance Department

Maintenance personnel for the department, whether building maintenance staff or apparatus maintenance personnel, provide valuable input into the condition of apparatus and facilities and thus any hazards posed by working in the stations and with the apparatus. The input of maintenance personnel is critical in determining when repairs, upgrades, rebuilds, or new acquisitions must be made, based on their educated assessment of the hazards at hand in the stations and on the vehicles.

Finance Department

Similar to the human resource department's input, the finance department provides valuable input on the rate at which funds are being spent and the manner in which spending must be managed to meet needs. If budgeted amounts are being encroached on, overtime may need to be better managed and staff may need to be reduced or redeployed, thereby requiring mutual-aid arrangements to meet the need for adequate staffing at an emergency. The same scenario exists for equipment purchasing and helps determine the input for replacement apparatus purchasing.

Regulatory Agencies

A number of regulatory agencies assist the fire department in the identification and analysis processes so needs can be determined. The Occupational Health and Safety Administration (OSHA) has assisted the fire service through the determination of workplace hazards and the actions necessary to manage them. Similarly, the Environmental Protection Agency (EPA) has established guidelines and provided staff to evaluate hazards and determine needs to be addressed. The Resource Conservation and Recovery Act (RCRA) has provided a similar capability, and many others can be found in the workplace today. In each case, the regulations provide a benchmark of safe operation based on the hazard posed, from which the personnel, equipment, materials, and the like to manage the situation at hand can be determined. The procurement or accessing of those items can then be made.

Fire Prevention and Public Education Staff

Staff performing fire prevention and public education functions provide yet another form of input similar to staff performing fire investigations, inspections, code enforcement activities, and so on. Their ability to evaluate risk in the community and create fire prevention and public education programs solves immediate needs in the community. Whether these individuals are addressing the evacuation capability of a high-rise building and educating residents on how to escape, targeting smoking as a fire hazard based on smoking materials causing fires, focusing attention on the lack of smoke detectors in residences, or addressing some other scenario, they are analyzing hazards, solving problems, and meeting the needs of the customer.

External Consultants

The external consultant plays a prominent role in today's fire protection system. Rarely used until the 1990s, consultants now are involved in several aspects of hazard analysis and needs assessment. Not only have consultants designed a number of the risk analysis systems currently in use in the fire service today, they are responsible for the implementation of these same systems in many communities.

External consultants are often called in because local communities are unable to come to a resolution on a situation. These consultants become the solution to determine where a fire station will be placed, to analyze what types of hazards exist in a community, to provide pre-emergency plans, to evaluate workload, to determine what types of apparatus will be purchased and where it will be placed, and so on. The consultants answer the tough questions that local communities cannot answer, most of which involve some type of analysis of hazards and determination of needs. However, caution must be exercised with the use of consultants. A specific "scope of work" must be developed to ensure that the consultant performs work to meet the objectives of the organization and project, with defined timelines, deliverables, and related costs. In addition, consultants should have expertise in performing the tasks defined in the scope of work and utilize staff experienced in the issue and type of community being analyzed.

SUMMARY

The FEMA/NFPA needs assessment study provides a backdrop of identified nationwide needs and serves as an excellent educational and planning tool. However, a fire department's local needs should be driven by the findings from a comprehensive local hazard analysis in which the department's needs are compared with the results of the assessment study to see if there are gaps or unidentified areas, followed by the development of an action plan. Knowing what resources the department will need can only be determined by understanding the hazards it faces.

Once the hazard type is identified, the number of personnel needed to provide the mitigation services can be determined. The number of personnel responding is also defined by the number and types of vehicles carrying these individuals to the incident, with the final variable being the response time established to achieve the response/performance objective to manage the hazard identified. The emergency services community knows that if needed resources (personnel and equipment) do not arrive in time, the nature of the emergency will grow beyond the ability of the resources to manage the problem. The objective of the hazard analysis and needs assessment is, therefore, to develop the knowledge of the hazards being faced, the nature and amount of resources needed to manage the hazard, and the assurance that the resources can be deployed efficiently and effectively. This chapter provided a look at the components of a comprehensive emergency service organization needs analysis, including various planning processes, assessment and planning tools, and the stakeholders and assessment information sources.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on needs assessment and hazard analysis discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 551, *Guide for the Evaluation of Fire Risk Assessments*
NFPA 1201, *Standard for Providing Emergency Services to the Public*
NFPA 1250, *Recommended Practice in Emergency Service Organization Risk Management*
NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*
NFPA 1620, *Recommended Practice for Pre-Incident Planning*
NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*
NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments*

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Chapter 4

Managing Fire-Rescue Departments

Rebecca F. Denlinger

Chapter Contents

Early Fire Suppression and Fire Regulations
Types of Fire Departments
Organizing Fire Service Agencies
Organizing Fire-Rescue Departments
Department Structure
Organizing for Emergency Response
Mutual Aid and Major Emergencies
Communications
Management and Budgeting
Staffing Practices
Procuring Equipment and Supplies
Governmental Relations

Key Terms

call fire fighter, career fire department, city fire department, code enforcement, combination fire department, county fire department, emergency medical services, fire bureau, fire district, fire investigation, fire prevention, fire protection district, fire service, fire suppression, mutual aid, professional qualifications, public fire and life safety education, public fire department, volunteer fire company, volunteer fire department

This chapter provides an overview of the elements involved in organizing, administering, and managing agencies that provide fire and rescue response services.

Today's fire protection agencies have their roots in centuries of community efforts that attempted to prevent hostile fire and limit the damage it caused. From the start of night watches and bucket brigades through the first organized fire-fighting forces, those efforts have evolved into the amalgam of fire departments and other fire-fighting agencies that serve the United States and Canada today.

Fire protection in the United States is provided by more than 26,000 fire departments that are organized in different ways to meet their communities' specific needs.[1] Most often, public fire protection is a function of local government, although state, provincial, and federal authorities have also organized fire agencies, primarily to provide wildland fire protection on public lands or structural fire protection for government property. Similarly, large industries often organize or contract with private fire departments at their industrial complexes. The organization and objectives of fire departments vary according to available resources, ranging from simple to complex.

Most fire departments were administered by clearly defined organizational structures and systems before such techniques were widely applied to industry and business with the advent of the industrial age. Fire departments developed systems that broke down responsibilities at a fire into tasks that were assigned to engine and ladder crews. Each person on an apparatus was responsible for performing certain functions in a designated sequence so that each team operated as a coordinated unit, effort was not duplicated, and the common goal—usually to rescue trapped occupants and extinguish the fire—was achieved.

Most public fire departments are structured around the traditional mission of fire suppression. Many now also emphasize fire prevention and public education as more effective ways to protect life and property. Most have taken on other roles in their communities as well, particularly emergency medical and technical rescue services. They may also provide hazardous materials response, building and facility plans review, fire cause determination, and fire code inspection and enforcement.

Fire departments must be organized according to a comprehensive and coordinated plan if they are to operate efficiently and effectively. The organizational plan should clearly outline the roles and responsibilities of all line and staff personnel, their interactions with each other, and their relationship to the total organization.

Emergency response services are usually provided through a decentralized system of fire stations that are strategically located throughout the community and house a range of engine, ladder, rescue, and other companies as local needs demand and resources permit. Fire departments may be staffed by career, part-time, or volunteer personnel, or any combination of these, according to the manner in which the department has developed.

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Neighboring fire departments traditionally help each other when major emergencies or simultaneous events overwhelm one department's response capacity. To be effective, mutual-aid agreements should be carefully drafted and agreed on by all parties involved, and should take into consideration all factors that affect the agencies' ability to function in a joint effort. Mutual aid may extend beyond emergency response into the realms of training facilities, apparatus purchase, and long-range planning.

No fire department can operate well without an effective communications system that receives alarms from the public, dispatches units to the scene and coordinates their activities, and also provides for nonemergency communications for the department. The size and configuration of this system, the personnel staffing it, and the technology used, will vary considerably depending on the size of the agency and the number of emergency responses it makes.

Fire departments may depend on career, call, or volunteer personnel, or any combination of these. The type of personnel a department uses depends on financial resources, the availability of call or volunteer fire fighters, the number of emergency calls received, the range of services the department provides, and any preferences expressed by the community as to the type of fire department it wishes to have. Staffing levels and scheduling must be arranged to comply with budgetary constraints and provide 24-hour coverage with maximum efficiency.

Effective fire department management requires decisions that are suited to meet the needs of the particular community through the efficient practice of organizing, planning, directing, controlling, and analyzing.[2] One key responsibility of management is preparing, submitting, and adhering to the budget for the fire department. Fire department managers must fully understand the budgeting process used by their jurisdiction and be able to develop a budget that is fiscally manageable for the jurisdiction while at the same time allowing the fire department to perform the roles expected of it. The responsibility for personnel management and for achieving cooperation among government agencies and political bodies requires a collaborative management style and a diplomatic temperament.

Fire department equipment and supplies, procured through the jurisdiction's purchasing department, may either be requisitioned from the purchasing agency or, for specialized items, purchased through a bid process. Fire department managers must be knowledgeable about preparing purchasing specifications and interpreting the bids received.

A fire department will be most effective if it develops and maintains good working relationships with other local, state, and federal agencies whose mission overlaps or supports its own. This interaction includes local police and other law enforcement agencies, the building and water departments, and many other agencies of local government. State and federal agencies concerned with transportation, domestic preparedness, and emergency management are also key partners and allies for fire departments of all sizes and types.

For related topics see the following chapters in Section 12: Chapter 1, "Planning for Public Fire-Rescue Protection"; Chapter 2, "Organizational Benchmarking and Performance Evaluation"; Chapter 3, "Needs Assessment and Hazards Analysis"; Chapter 5, "Information Management and Computer Technology"; Chapter 10, "Training Programs for Fire and Emergency Service Personnel"; Chapter 12, "Disaster Planning and Response Services"; Chapter 14, "Fire Rescue Stations and Fire Service Training Centers"; Chapter 15, "Public Emergency Services Alarm, Dispatch, and Communications Systems"; Chapter 16, "Fire Department Apparatus and Equipment"; and Chapter 17, "Pre-Incident Planning for Industrial and Municipal Emergency Response."

EARLY FIRE SUPPRESSION AND FIRE REGULATIONS

Today's public fire departments evolved from groups of citizens who banded together to warn of and limit the spread of a threatening fire. To provide a visual context for this section, Figure 12.4.1 sketches a time line for the history of modern fire protection in the United Kingdom and the United States. The earliest efforts involved the organization of night watches. Next to develop were fire prevention regulations and the appointment of individuals charged with enforcing those regulations. In cities and towns, groups organized to salvage belongings during or after a fire. These groups were followed by volunteer fire-fighting companies, who banded together to operate pumps to extinguish fires. Eventually, fire fighters and officers were appointed and paid to operate full-time fire departments.

One of the earliest accounts of an organized effort to provide fire protection is from 24 B.C., when a "vigil," or watch service, was created in Rome during the reign of Augustus. Regulations for monitoring and preventing fires were issued, giving the vigils duties similar to today's fire marshal's office or fire prevention bureau. The vigils were also provided with fire-fighting tools and equipment, such as buckets and axes.

Another early fire protection regulation dates to A.D. 872, in Oxford, England, when a curfew was adopted requiring hearth fires to be extinguished at a specified time. After 1066, William the Conqueror established a general curfew law for England that was apparently aimed not only at fire prevention but also at preventing revolt.

Fire Brigades in the United Kingdom

Prior to 1830, night watches and other services that used fire apparatus operated without any legal authority. *The History of the British Fire Service*[3] mentions an early exception: in 1643, during the English Civil War, a company of 50 women was organized to patrol the town of Nottingham at night and raise the alarm in case of fire.

Following the devastation caused by the Great Fire of London in 1666, several insurance companies created fire insurance brigades. Each brigade fought fires only in properties insured by its company and had no lifesaving responsibilities. The brigades operated without statutory authority or obligation, and it was the insurance offices, not government agencies, who decided where the brigades would be located. In London, the insurance company fire brigades in 1833 were consolidated into the London Fire Engine Establishment, which was taken over by the Metropolitan Fire Brigade in 1865.

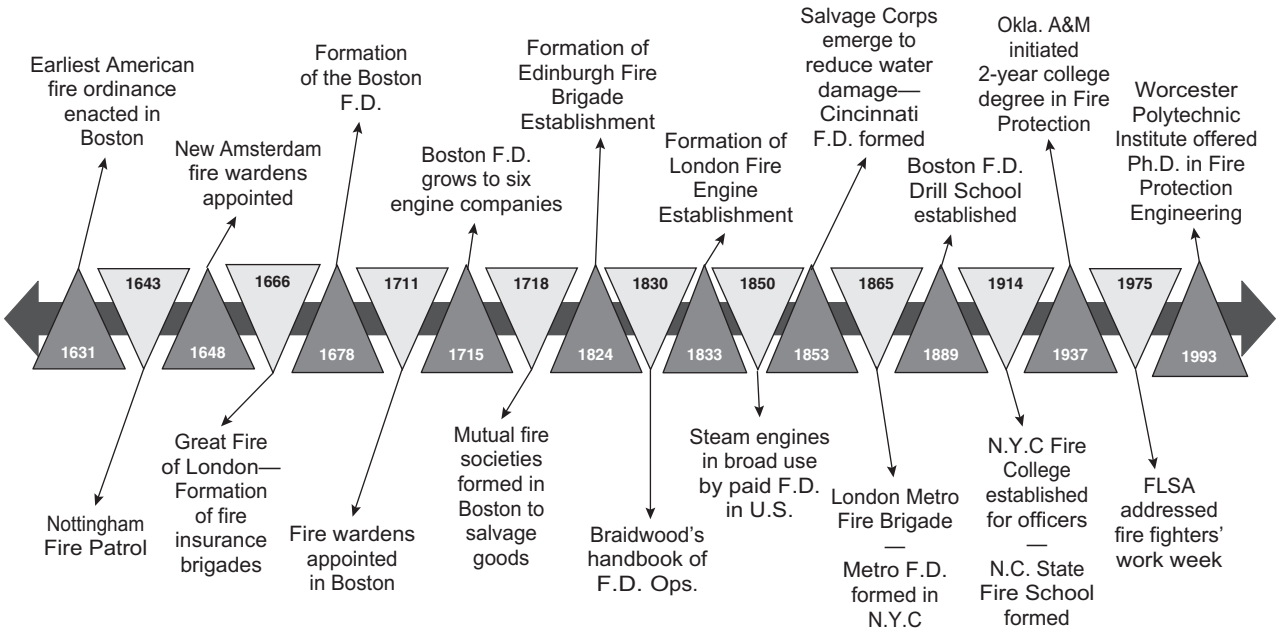

FIGURE 12.4.1 Time Line of the History of Modern Fire Protection in the United Kingdom and the United States (Courtesy of Stuart Shannonhouse, Resource Officer, Cobb County [Georgia] Fire and Emergency Services)

Edinburgh's Fire Brigade Establishment was the first public fire service to develop modern standards of operation. A surveyor named James Braidwood was appointed chief of the brigade. He chose 80 part-time aides between the ages of 17 and 25 and required them to participate in regular drills, including night training. In 1830, he wrote the first comprehensive handbook on fire department operations, which included 396 standards and set forth for the first time the kind of service a good fire department should deliver.

Fire Protection in Early America

The first fire ordinance in the New World was adopted in Boston, Massachusetts, following a disastrous fire in 1631. The ordinance prohibited thatched roofs and wooden chimneys, and was enforced by the colonial city's board of selectmen. In 1648, New Amsterdam (now New York City) appointed five municipal fire wardens with fire prevention responsibilities. This is often considered to be the origin of the first public fire department in North America.

After another conflagration in Boston, which occurred in 1679, destroyed 155 major buildings and a number of ships, laws were adopted requiring stone or brick walls for buildings and slate or tile roofs for houses. That fire also led to the establishment of the first paid municipal fire department in North America, if not the world, in 1678. The town imported a "fire engine" from England—essentially a small wooden box with carrying handles, a pump, and a small hose—and employed 12 fire fighters and a fire chief, Thomas Atkins.[4] From the start, jurisdictions in Massachusetts used paid fire fighters on an on-call basis, as contrasted with the unpaid volunteer fire companies that later were organized in other colonies.

Colonial communities required each household to keep two fire buckets at hand, and when the church bells rang an alarm, to report to the fire to form lines for passing water from wells, springs, or other water sources. As late as 1810, Boston citizens were subject to a $10 fine for failure to respond to alarms with their buckets. When hand-pumped fire engines were first obtained in the 1830s, teams of citizens were organized to operate them, and the bucket brigade supplied the pump's tank. The laws in a number of states and provinces still impose penalties on citizens who refuse to assist in fire-fighting operations upon orders from fire officers. For example, in Toronto, Ontario, the Municipal Fire Code, § 79-15 Refusal to Assist reads:

> If required to do so by the fire department, no person present at a fire shall refuse to assist in:
>
> A. Extinguishing fires;
> B. Pulling down or demolishing buildings or structures to prevent the spread of fires;
> C. Crowd and traffic control; or
> D. Other reasonable ways.
>
> [Amended 2000-10-05 by By-law No. 869-2000]

Fire wardens, who responded with their staff members to fires and supervised bucket brigades, were appointed in Boston in 1711. By 1715, Boston had six fire companies with British-made engines.

Mutual Fire Societies. According to many accounts, these companies were the forerunners of salvage corps. The first mutual fire societies were formed in Boston in 1718 when a group of affluent Bostonians organized to assist each other in salvaging goods from their homes and businesses affected by

fire. Each person's equipment included a bag in which to collect valuables, a screwdriver, and a bed key to disassemble and remove beds from burning buildings. (At the time, beds were prized and valuable possessions, not commonly owned.) These societies were active for about a century, until fire insurance became generally affordable.

Salvage Corps. By about 1850, the major cities of the United States had organized paid fire departments equipped with steam engines. Insurance interests in nineteen of these cities formed salvage corps whose job was to reduce water damage at fires. Over time, the increasing cost of operating these corps, combined with improved fire-fighting procedures, made them obsolete, and they were disbanded. Today, public fire departments carry out the function of salvage operations at fires.

Growth of Paid Fire Departments. A lack of discipline within volunteer fire brigades, coupled with their resistance to using fire pumps and steam engines, led to the organization of paid fire departments. Following disorder and occasional violent confrontations between members of competing volunteer fire companies at fire scenes, a paid fire department with horse-drawn steam engines was placed in service in Cincinnati, Ohio, on April 1, 1853. In 1855, two steam pumpers were delivered to New York City, but the volunteer fire fighters refused to use them. Ten years later, the Metropolitan Fire Department, using steamers, replaced New York City's volunteers.

Duty Systems. Until World War I, paid fire fighters worked a continuous-duty system with limited off-duty time. By World War II, most paid fire departments had adopted a two-platoon system, which allowed additional days off and reduced the fire fighter's average number of hours worked per week. Hours worked per week have continued to decline for U.S. fire fighters, although in most jurisdictions they continue to work more hours per week than other public or private workers. Many fire fighters remain on a 24-hour-duty work shift. The 1975 Fair Labor Standards Act reduced to 53 the maximum hours of work per week for a fire fighter: hours worked in excess of the maximum must be paid at a higher wage rate. Additional discussion of many of the numerous duty systems used by fire departments appears later in this chapter.

Training. In 1889, the Boston Fire Department established the first fire fighter drill school, delivering basic training to its members. Uniform company drills were also performed, promoting the task allocation system that remains in use in well-organized fire departments. Most fire departments now provide some form of basic training to their members, and many have sophisticated training divisions that develop individual and company skills in fire suppression, emergency medical services, and technically specialized areas such as hazardous materials response; trench, high angle rope, confined space, and structural collapse. The incident command system, a staple of fire service training for decades, has been adapted to meet the command and control demands of all emergency events and is incorporated into the National Incident Management System (NIMS). NIMS is taught across the United States as part of local, state, and national fire training curricula.

The first fire officer training institution was established in New York City in 1914, when the FDNY Fire College began providing advanced training to its fire officer corps. Today, officer training is a high priority in many career and volunteer fire departments. Quality officer training is available through commercially available computer-based products, consulting companies that deliver training on site, Internet programs provided by the U.S. Fire Administration, and at private, local, state, and federal training institutions around the country.

Also in 1914, the first state fire school was organized in North Carolina. The first state fire schools for volunteer fire fighters were started in Illinois and Iowa in 1925. Today, every state reports offering some level of training service to its fire fighters.[5] Funding for training programs related to weapons of mass destruction and other large-scale events has grown since the first courses that were funded by the Nunn-Lugar-Domenici Act in the 1990s. Such funding is commonly allocated to state or regional initiatives in order to prepare local responders, including fire fighters, to respond to disasters.

College degree programs related to the fire service first appeared in the United States in 1937, when Oklahoma A&M (now Oklahoma State University) initiated its two-year (later four-year) fire protection degree. More than 200 institutions in the United States now offer two-year degrees in fire protection through a variety of methods, including online and other distance learning options as well as resident programs. Several colleges offer four-year programs of study leading to degrees in fire technology or fire service management, and the Worcester Polytechnic Institute and the University of Maryland at College Park offer masters degrees in fire protection engineering. Worcester Polytechnic Institute has also offered a doctoral degree in fire protection engineering since 1993.

TYPES OF FIRE DEPARTMENTS

Career Versus Volunteer Fire-Fighting Personnel

As of 2006, an estimated 313,300 career fire-fighting personnel and frontline supervisors and 823,650 on-call or volunteer fire-fighting personnel served in the United States.[6] The principal distinction between the two is that career personnel are assigned regular periods of duty and are compensated on a regular basis, whereas on-call or volunteer personnel are not normally required to be available except for meetings, training sessions, and emergency responses. They may or may not receive compensation for their services.

Most towns of 25,000 or more employ career personnel and many use auxiliary personnel or volunteers to supplement their regular forces. Other cities and towns use combinations of career, on-call, and volunteer personnel. Some communities have a career fire chief, officers, and/or apparatus operators but rely on on-call or volunteer personnel for the rest of their staffing. Other communities use career personnel only during the daytime and rely on on-call or volunteer personnel at night.

Many fire departments—career, combination, and volunteer—provide an acceptable level of service to their respective communities. The success of their operation does not depend on

whether the personnel are paid or unpaid but on their individual and collective ability to perform and to accomplish department objectives. There are no simple guidelines that mandate the type of personnel a fire department should use. The decision must be made at the local level after carefully analyzing all pertinent factors.

Factors Influencing a Fire Department's Personnel

When a community decides to start providing fire protection, several factors influence the type of personnel the new fire department will use. These factors are (1) the financial resources of the community, (2) the availability of on-call or volunteer personnel, (3) the frequency of fire incidents, (4) the range of services expected from the department, and (5) the type of department preferred by the community.

The Community's Financial Resources. The financial resources of smaller communities will often dictate that the department be composed entirely of volunteer personnel. Salaries normally consume a large percentage of a fire department's budget, and the community may have only enough money available to purchase and maintain apparatus and equipment.

On-Call or Volunteer Personnel Availability. Some communities may find they do not have enough people willing and able to serve as volunteer fire fighters, and that the fire department must be staffed fully or partially by career personnel. This situation happens most often in rapidly growing suburbs near major cities. Originally these outlying areas were composed of small communities that provided a climate suitable for volunteer departments. As times changed, however, more and more residents became employed outside the community and were thus unavailable for emergency response in the daytime, or even to participate in the fire department at all. At the same time, rapid suburban growth increased the demand for fire protection and rescue services. As a result, many of these once-volunteer fire departments have added the services of career personnel.

Effect of Incident Frequency. Call volume, or the frequency of emergency response, will often determine the type of personnel chosen to staff a fire department. Densely populated, congested areas, especially those with extensive commercial or industrial development, will usually need fire and rescue services more often than more sparsely settled, largely residential areas. A high level of incident frequency will tend to overwhelm a volunteer operation unless the department has a large membership and the workload can be apportioned to reduce the commitment required of each individual.

In order to track the effects of call volume and the efficiency of volunteer response, the fire department should keep accurate statistics that include the number of volunteers responding per call and the length of time it takes them to respond. Weekends and weekdays should be tracked separately. Monitoring this data will help a community decide when it needs to hire career personnel in order to maintain the level of service desired.

Range of Department Services. The variety and frequency of incidents that occur in the community will determine the range of services the fire department provides. Most departments offer some level of rescue service, as extrication and emergency medical response are universal needs. The extent and type of development in a locality, and the existence of any natural hazards, also influence the scope of services offered by a fire department. In addition, the presence of a target hazard or particular critical infrastructure may also affect the range of services expected of a department.

Type of Department Personnel Preferred by the Community. Communities often have preferences for the type of personnel who staff their fire departments. In some instances, the volunteer fire department serves as a focal point of community activity, and the community is satisfied with the level of service provided by volunteer staff. In others, the career department is a well integrated part of the community. In every case, fire department personnel should be selected, trained, and equipped to provide the best possible service for the community.

ORGANIZING FIRE SERVICE AGENCIES

Most public fire service organizations in North America are established by local governments or by independent local entities created to provide public fire protection. Local government is responsible for organizing fire protection for the vast majority of people in North America. These fire protection services vary widely in character, from volunteer departments with little revenue to full-service agencies that employ career fire fighters and civilian staff. They also differ widely in their source of jurisdictional authority.

One of the most common types of fire protection agencies is the *city fire department,* a department of municipal government. The head of the department is responsible to the chief administrative officer of the municipality, typically the city manager or the mayor, or in some cases to a fire commission. Most large municipalities, as well as many small communities, operate this type of organization.

Less common is a *fire bureau,* which is usually a division of a department of public safety. In this type of organization, the public safety department head manages the administration of several important operations, including fire, police, and 9-1-1 communications center services. Since September 11, 2001, the public safety agency concept is growing in acceptance and use, as communities recognize the value of leveraging expertise of the various public safety disciplines to better effect.

The *county fire department* is gaining acceptance in many areas. In this type of organization, suburban municipalities join together to enjoy the benefits of a large, professionally administered public fire department with staff and service facilities that they could not afford individually. The transition to a county fire department often begins when a county fire prevention office and fire communications system are put in place; fire departments (often staffed by volunteers) initially remain autonomous for fire suppression purposes. Gradually, more functions are assumed by the county organization as the cost effectiveness and organizational expedience win attention and favor.

Another type of public fire protection is the *fire district,* which is organized under provisions of state or provincial law. It is, in effect, a separate, independent unit of government with its own governing body composed of commissioner, trustees, or other officials, and is commonly supported by a tax levied throughout the district. A fire district is usually organized following a vote of residents in the proposed district. The fire district may include portions of one or more political subdivisions, such as townships.

A fifth common type of fire protection authority is the *fire protection district,* which in some states is a legally established, tax-supported unit that contracts for fire protection from a nearby career (or in some instances volunteer) fire department. This arrangement provides timely fire protection for rural or suburban areas that might otherwise find it difficult to maintain effective and experienced fire-fighting forces. Contracts with a fire protection district can be a valuable source of financial support to the small municipal fire departments that participate, as well as providing fire apparatus for use in rural areas.

Another type of public fire service organization is the *volunteer fire company* or *association* that raises a portion of its funds through public activities and sometimes, subscriptions. Tax dollars comprise the majority of the funding available to volunteer fire agencies, and most of the tax dollars come from local tax sources.[1] Donations of equipment may also be received from interested units of government. Many volunteer fire associations maintain excellent equipment and facilities and also provide a location for various community activities. Certain volunteer fire companies prefer to retain independence from government, especially when purchasing equipment. It is common, however, to find independent fire organizations that are coordinated through special governmental advisory boards.

ORGANIZING FIRE-RESCUE DEPARTMENTS

In recent years, the role of the fire service in many communities has expanded far beyond its original mission of fire suppression. The term *fire department* does not begin to cover the many services progressive organizations now provide to their communities: a far broader public safety role has become the "business" of the modern fire department. Twenty-first-century fire services increasingly emphasize such proactive elements as fire prevention, code enforcement, public education, pre-incident planning, and interagency training and coordination. Citizens depend on the fire department to protect them from any emergency: fire, entrapment, explosion, building collapse, and natural disasters and other incidents that can result in mass casualties, such as biological, chemical, and radiological events. Fire departments respond to these demands with a growing range of capabilities, such as hazardous materials, technical rescue, and emergency medical services. In addition, fire-rescue departments typically are now involved in planning and training for response to disasters that exceed the capabilities of public safety agencies in the areas in which they occur.

Each community establishes the array and level of services it expects of its fire-rescue department, and these expectations will change over time. In this dynamic environment, a successful department is one that can effectively and efficiently satisfy these changing community needs. The leadership challenge for the fire service is to determine how the department should deliver needed services and to develop an organization that can manage and administer its operations. Fire chiefs must be prepared to implement changes in their department's service delivery mission that are dictated by governing boards. Fire fighters must be ready to train for and deliver those services.

Some communities have choices in selecting from companies and departments that can deliver the desired services. In such situations, the competitive edge goes to the agency best organized to deliver a range of effective services most efficiently.

Fire Prevention and Code Enforcement

Fire prevention and code enforcement are major areas of responsibility for the fire service. As fire departments have professionalized, they have tended to develop their fire suppression capacities to a much greater extent than their fire prevention abilities. Because emergencies cannot be eliminated or predicted, community protection depends on a reliable and effective response force. As a result, most of a fire department's resources are dedicated to responding to emergencies after the fact; typically, only a small percentage of resources are dedicated to preventing those emergencies. As technologies to improve the prevention, early detection, and automatic suppression of fires develop, more emphasis on proactive prevention, enforcement, and education programs within fire departments will better position communities for a safer future.

Adoption of Building Codes. The local fire department should lead the way in urging the community to adopt a complete nationally recognized fire and building code. Most fire departments have adopted one of the model codes developed by regional and national standard development organizations. These model codes can be amended to adjust for local concerns and needs. Working closely with community building and development officials, fire service leaders can tailor codes and permitting processes to support requirements for delivery of fire and emergency services. Particularly in areas that experience "build out" and consequent in-fill and redevelopment, codes should address the specific issues of street width, turnaround space for apparatus, distance to hydrants, and factors that affect service delivery.

Ideally, fire departments should assign full-time personnel to review plans and inspect buildings and fire protection systems. The widespread adoption of performance-based codes requires professionals, preferably fire protection specialists or engineers, who are trained to evaluate systems plans for adequate performance during the permitting process.

In the past, most fire prevention activities were carried out by a small nucleus of full-time specialists. The size of the fire department and the community determine the need for, and feasibility of, full-time prevention personnel. The prevention responsibilities of the fire department, however, go far beyond what a small cadre of specialists can perform. Many departments now involve fire fighters in inspections and code enforcement. All fire department personnel must recognize that fire safety

education and fire prevention are major parts of a fire fighter's responsibilities.

Pre-Incident Planning. Pre-incident planning is a necessary adjunct to tactical operations and should aid in efficiency, reduce fire loss, and help provide an optimum level of emergency service. Pre-incident plans are desirable for all target hazards, for special risks, and for large complexes. (Standard operating procedures are usually sufficient for single-family dwellings and smaller occupancies, as well as routine multidiscipline events.) The planning process must involve all fire suppression personnel on a continuing basis. Pre-incident plans should complement standard operating procedures by familiarizing personnel with unusual buildings and facilities, and with processes and products that pose unusual hazards.

Pre-incident plan information should be presented in a standard format and made available to help the incident commander manage fires or other emergencies at the site. (For an example, see the *Fire Protection Handbook,* Section 12, Chapter 17, "Pre-Incident Planning for Industrial and Municipal Emergency Response" and NFPA 1620, *Recommended Practice for Pre-Incident Planning.*) Plans should be sufficiently flexible to allow for varying conditions and should use the framework of the department's standard operating procedures as a basis. Plans that are too rigid or complex may handicap an operation more than they help it.

Fire chiefs and department staff should encourage and support multidisciplinary planning. Local response partners such as law enforcement, EMS, and public health, should be involved in the process of developing plans for large-scale emergencies. This cooperation will enhance both the quality of the plans and the preparedness of the public safety community. In situations that require unified or area command, incident management will be more effective if the incident commander is familiar with the roles and responsibilities of allied agencies. During the planning process, all relevant response agencies, including utility providers and environmental agencies, should be involved in identifying and targeting critical infrastructure in the community. Planning for response to incidents involving weapons of mass destruction should be done by a group that includes planners from all response agencies. Personnel from all such agencies should become familiar with, and have access to, the resulting plans.

The following steps are part of the pre-incident planning process:

1. *Information gathering.* Pertinent information, such as building construction features, avenues of egress, occupancy, exposures, utility disconnects, fire hydrant locations, and water main sizes, which might significantly affect fire fighting or allied agency operations, must be collected at the selected site.

2. *Information analysis.* The information gathered must be analyzed for what is pertinent and vital to fire suppression operations, so that a plan can be documented in a format that can be used during the incident. A pre-incident plan usually includes a site plan or map; floor plans and diagrams identifying pertinent features, including vertical avenues of fire travel in multistory buildings; hazards and fire control equipment; area maps indicating various staging and rally points; and additional text outlining special problems, specific tactics, hazardous contents, and information on parties responsible for specific areas.

3. *Information dissemination.* Pre-incident plans should be assembled and distributed in a standard format for easy use on the emergency scene. Plans may be maintained on paper and carried in fire apparatus, microfilmed and used with viewers in command vehicles, or stored in computer systems accessed by mobile data terminals or fax machines. Plans should be clearly dated and revised periodically, with revised plans disseminated on a systematic basis.

4. *Class review and drill.* Any fire company that might respond to an incident at a site that has a pre-incident plan should review the plan on a regular schedule. If possible, periodic drills and familiarization tours with all the companies involved should be scheduled on the property. All concerned agencies should periodically review pre-incident plans.

Fire Investigation

Competent fire investigations, performed to determine fire cause as well as to detect criminal activity, can identify factors that can lessen the number and severity of fires in the future. Information gained through investigations is a valuable tool in improving fire prevention by pointing out needed code revisions, updating public education program content, and planning for future fire protection and response needs. In addition, a thorough investigation of all incendiary or suspicious fires is a powerful arson deterrent. Adequately trained and equipped personnel should be available to investigate all fires of unknown or suspicious cause.

Community-Based Safety Education

Fire departments inevitably respond to tragedies. The challenge is to prevent these tragedies from happening in the future, and the most effective place to do this is at the community level. Fire stations have always had a community profile, yet they often have a great deal of unrealized potential. The neighborhood fire station can be a key delivery point for fire and emergency prevention efforts, and fire fighters in the stations can effectively deliver community fire prevention programs. By effectively using demographic and fire experience data, a department can customize prevention education to the needs of individual response territories. The central public education staff can then focus on delivering programs in schools, senior centers, and other facilities where at-risk populations congregate. This staff can also coordinate the prevention initiatives of the fire stations.

Although community fire education has been a part of the fire service for many years, it has only recently emerged as a major component in fire protection. National conferences that champion the public education effort have been introduced in Oklahoma and Texas. The National Fire Protection Association's (NFPA) *Learn Not to Burn*® program is one component that has been successful in reaching and educating schoolchildren on fire safety issues. "Fire safety houses," portable model homes transported on trailers, have proven to be valuable teaching tools in many communities.

To complement the fire service's expansion into emergency medical services, many fire safety education programs are now successfully incorporating NFPA's *Risk Watch*® program. This curriculum goes beyond traditional fire prevention to include accident and injury prevention. In Canada and some areas of the United States, the *community safety village* concept has been developed as a tool for delivering a full menu of public safety education programs to the community. Fire safety programs are integrated into the curriculum of these learning and education centers.

Public Relations and Community Partnerships

Fire departments supported by public funds need public support and interaction to be effective. Only with the public's interest and cooperation can fire protection and prevention programs be fully effective and the fire department operate successfully within its particular political environment. Without community support, it can be difficult for the department to obtain the needed funds to operate at the required level. Accordingly, public information and community service programs, or public relations, are an important fire department management activity.

Good public relations programs keep the public informed of departmental activities. Relations with the news media should be cordial, and the fire department needs to cooperate with representatives of the media, who can be of invaluable assistance in pushing out messages to the public. This is not always easy, because suburban fire departments are often located in communities that depend largely on a metropolitan press, and items that might be of interest to local citizens may not be newsworthy for the entire region. It may be effective to explore options, such as local weekly papers or local-area editions of metropolitan papers that do have local correspondents.

The amount of publicity fire departments get seems to vary greatly among geographic areas. In some areas, citizens are traditionally interested and involved in local governments and their fire departments, whereas in other areas, fire departments are not considered newsworthy. The latter situation obviously requires a greater effort in order to get fire-related information to the public. In general, communities whose citizens regularly participate in town affairs seem to give fire departments better support. Communities with substantial numbers of low-income residents subject to fire dangers are often most concerned with the adequacy of fire department services.

Public education information can be passed through local government publications and regional periodicals, as well as through inserts in utility bills and department newsletters. Fire departments should develop safety and awareness campaigns to target specific communities. Resourceful and energetic public relations officers will find numerous avenues for spreading public information.

News personnel should be given accurate information promptly at incident scenes. Most fire departments specify that only the incident commander or a designated public information officer (PIO) should give out information. This practice should prevent the release of conflicting, inaccurate, or ill-advised statements that might be misleading or could compromise fire investigations. The PIO position is a designated function in an effective incident command system.

Some large fire departments have a designated PIO who also functions as a public relations officer, giving the press all possible cooperation and information regarding the department's activities. In smaller fire departments, the fire chief may perform this function. Staff public relations officers often report directly to the fire chief because of the need for regular communication between the two. The public relations officer may act as a communications or media adviser to the chief, and the chief should keep the public relations officer apprised of all potentially newsworthy department decisions and activities.

Emergency Medical Services Delivery

Emergency medical service (EMS) has become an important function of many fire departments. Although fire departments have operated ambulance services for decades, the major growth in this area has occurred since 1970, stimulated by higher standards for patient care, training, and associated equipment. Increased public, medical community, and local government interest in delivery of emergency medical service has prompted many fire departments to increase their participation in EMS; consequently, the quality of EMS delivery has improved greatly.

In most fire service organizations that provide first-responder or transport EMS services, EMS runs account for 60 to 75 percent of their emergency call volume. This growing service demand has changed the business definition of fire departments throughout the country. Many fire department managers and organized labor groups link the competitiveness of their organizations with emergency medical service delivery.

The addition of the EMS mission to a fire department is a natural extension of responsibilities and can be managed so as to increase organizational productivity without a negative impact on fire protection. Fire service personnel are already oriented toward delivering emergency service and assisting citizens. Fire personnel and apparatus are housed in fire stations that are decentralized to provide rapid response to all areas, served by communications systems that receive emergency requests from the public and dispatch assistance without delay. These two elements provide the foundation of effective EMS delivery.

Increasingly, the emergency medical services delivery system may be solely the responsibility of the fire department, from first responder providing basic life support to advanced life support with paramedic-level care, including transport (Figure 12.4.2).

Nationwide, fire department emergency medical service calls outnumber fire alarms by more than six to one. Even though responding to EMS calls places an increased workload on fire companies, the combination of the two missions has proven very efficient in many jurisdictions. Providing basic EMS equipment on engine and ladder companies with emergency medical technician (EMT)–certified fire fighters enables these units to handle most life-threatening situations. In most communities, the fire department is also the lone provider of extrication and rescue services, provided via the same apparatus and personnel. Paramedics responding on ambulances or rescue

FIGURE 12.4.2 Emergency Personnel Loading a Patient into an Emergency Care Helicopter

vehicles generally back up first responders and EMTs. In some fire departments, all personnel are trained and certified at the EMT or EMT-Intermediate level, and dual-role paramedics are assigned to engine and ladder companies.

Hazardous Materials

Storing, using, transporting, and disposing of hazardous materials and hazardous waste create significant safety risks. Changing federal regulations, along with increased sensitivity to environmental protection, have created a new service demand in many communities. In many cases, the fire department is the lead agency in responding to hazardous materials incidents.

Many fire departments find they have neither the trained personnel nor the funds to support a full hazardous materials emergency response team. Regional hazardous materials response teams have been organized within counties and parishes, and in some cases across greater areas, in order to combine available resources and personnel to best effect.

Fire departments should either lead or participate in the process of gathering and organizing information, identifying risks, and planning for hazardous materials emergencies, as well as in regulating the storage, use, transportation, and disposal of hazardous materials and hazardous wastes. Federal law commonly known as the "Community Right-to-Know" provisions (the Emergency Planning and Community Reporting Act: Title III of the 1986 Superfund Amendments and Reauthorization Act) requires that facilities that hold chemicals above certain quantities report what they have on the premises to the local fire department. Fire departments should receive these reports and use them to inform effective pre-incident plans and to budget for appropriate equipment.

Rescue Services

The level and sophistication of rescue services offered by fire-rescue departments has expanded significantly in recent years. In many communities the local fire-rescue department is the lone provider of extrication services. Heavy rescue and structural collapse services are also increasingly available via the local department. More technically complex forms, such as trench (Figure 12.4.3), confined space, and high angle rope rescue, are also more common. The amount and type of equipment that has been procured through federal Homeland Security funds has made these various rescue services more prevalent than ever before. Fire departments should evaluate the potential for the need for rescue services and pursue the equipment, the training, and, if necessary, the staff to make possible the provision of the appropriate programs to the community.

Management Improvement Systems

A number of systems have been developed to improve management decision making through teamwork and enhanced working relationships. Such systems include organizational development, quality circles, and quality assurance and service improvement programs. Although these have been developed primarily for the private sector, they can also improve how public sector organizations are managed.

Progressive organizations have augmented the traditional, authoritative, fireground chain-of-command management style with private industry processes that focus on quality management. Quality management stresses a total organizational approach that makes the quality of service, as perceived by the customer, the driving force for the organization. The purpose is to improve the quality of service, productivity, and (increase) cost effectiveness through clearly stated, well-developed goals and measurable objectives. These goals and objectives are identified and accomplished by increasing the participation of both managers and workers in the organization's planning and decision making.

Every fire department should have a *mission statement* regarding the scope of services it provides. The mission of fire departments—the menu of services provided to the community—may be very similar from one part of the country to another. Many progressive organizations develop their mission statements by first creating a *vision* that states where they are headed and where they believe the future lies for their

FIGURE 12.4.3 Rescue Effort at Legacy Park, Lawrenceville, Georgia (Source: Courtesy of Cobb County Fire and Emergency Services)

organization. Many fire departments also develop a set of *values*. Values say something very individual about an organization and may reveal what is most important to the department and to the community. In addition, *goals* should be established for the department, along with measurable objectives for each level of the organization.

Information Management Systems

The information generated by a fire department—particularly in the areas of fire protection, EMS delivery, personnel, and fiscal management—should be systematically collected in an information or records management system (RMS). An effective RMS can then be used to analyze the data collected in ways that are useful to department managers. Data analysis is a powerful tool for monitoring the effectiveness of programs and services and for guiding planning. The information can be displayed in a variety of ways, including charts, graphs, maps, and reports.

Information management systems for use by fire departments are available commercially in off-the-shelf and custom formats, or can be developed locally. Sophisticated systems can interface with other computer applications, such as computer-aided dispatch and geographical information systems. Making use of the data captured in such systems requires trained personnel who have sufficient time to analyze, collate, and prepare data for management to interpret.

Some systems collect data regionally and nationally; for example, NFPA analyzes and prepares statistical reports from a national system of data collection. Many standard reports (such as *U.S. Fire Fighter Deaths*) and "customized analysis" are available from the NFPA Fire Analysis and Research Division. This information is available for use by individual departments.

Occupational Safety and Health

Fire fighting has been recognized for many years as one of the most dangerous professions. In each year between 1996 and 2005, an average of 135 fire fighters per year lost their lives[7] and roughly 58,000 were injured.[8] To address this unenviable record, NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program,* was established to guide fire departments in developing fire service health and safety programs. The standard is dedicated to making the fire service less dangerous by reducing the risk of accident, injury, and death during line-of-duty activities and to make fire fighters healthier and more physically fit.

NFPA 1500 addresses the elements of a fire department occupational safety and health program. It was developed by the fire service, for the fire service, and supports the requirements of the federal Occupational Safety and Health Administration (OSHA) fire brigade standard developed for private sector and public fire suppression organizations.

NFPA 1500 addresses health and safety as an overall program to reduce the risks to members of the fire department. The standard applies to all members of the department and specifically identifies management as a provider of the safest possible work environment, given the hazardous nature of the work. Fire service management thus must take the lead in establishing rules and procedures that support an effective health and safety program.

Entering into a comprehensive health and safety program can be difficult, as it involves a number of complex issues as well as inevitable budgetary impact. It may be easiest to implement the program on a phased basis, tailored to the specific needs of the fire department. (See NFPA 1500, Section 1.5, "Adoption Requirements.") Developing a comprehensive implementation plan will require the fire department to assess its strengths and weaknesses, determine what would be required to meet the standard, and then prioritize the steps that will be taken to reach this goal. The implementation plan should address vehicles and equipment, training and education requirements, protective clothing and protective equipment, incident command procedures and safety officer programs, facility safety, health and fitness standards, risk management procedures, and employee assistance programs.

Nearly 80 percent of active fire fighters in the United States are estimated to serve in departments with no fitness and health program.[1] A number of information sources are available on the Internet for departments interested in monitoring fire fighter health and safety issues, including the website sponsored by partnering agencies interested in preventing fire fighter deaths and injuries, http://www.firefighternearmiss.com. The International Association of Fire Chiefs' Safety, Health, and Survival Section and the International Association of Firefighters provide numerous resources for departmental health and safety programs.

DEPARTMENT STRUCTURE

Fire departments, like other organizations, are composed of people working together in a coordinated effort to achieve a common set of objectives. This coordination is achieved through organizational principles that determine how work is divided and coordinated, and through organizational plans that show the relationship of each operating division to the total organization.

Principles of Organization

One basic organizational principle is that work should be divided among individuals and operating units according to a plan. The plan should be based on the functions that must be performed, such as fire prevention, training, and communications.

A second important principle is that, as a department increases in size and complexity, the need for coordination also increases. Small departments allow frequent personal contact among individuals, reducing the need for planned, formal coordination. As departments increase in size and complexity, however, operating units must be coordinated more systematically in order to achieve their objectives. The logical grouping of similar functions and tasks will help to promote interaction that is necessary to successful management.

The most successful organizations operate as a team. Department leaders are organized as a system, in which all divisions and sections are equally important in achieving the desired objective: service to the community. Most fire departments retain a linear organizational structure, but many are recognizing the utility of creating work groups to address many management tasks. For example, the Department Information Systems manager may be responsible for specifying and recommending

a new records management system, and may seek the support of a focus group of interested employees in the process. Once the process is completed, the IS manager takes responsibility for the recommendation and moves it up the organization for further action. This team approach to accomplishing organizational goals helps limit the distancing effect that can occur in departments large enough to fund specialized staff positions.

The span of control for each manager and supervisor in an organization should also be considered. Generally, five to seven subordinates per supervisor are considered to be the ideal number for a manageable span of control. However, the complexity, importance, and sheer volume of work involved in the tasks being managed, as well as the manager's level of responsibility, should be taken into account.

Coordinating the systems within a department is an overarching function of the fire chief. This means the chief is responsible for organizing, planning, directing, controlling, and analyzing the work of the department. Activities that monitor, track, review, and revise systems as necessary will help establish and maintain an effective and efficient department that continually meets the needs of the community.

Line Functions

Line functions in fire departments normally refer to activities directly involved with delivering service to the department's customers. Fire suppression officers are considered to be line officers. This does not mean, however, that they do not have other functions. As these officers are promoted within the department they often acquire staff responsibilities as well. At the highest officer levels within the department, line responsibilities diminish and staff responsibilities increase. Line functions may include the following:

Emergency response. Fire suppression, emergency medical services, rescue operations, hazardous materials response, and other emergency services

Fire prevention. Inspection of construction and of existing properties for compliance with codes and ordinances; reviewing plans for new construction, major renovation, or installation of fire protection systems; operation of a public education program; and investigation of fires to determine the reasons fires start and spread

Staff Functions

Staff functions are activities that involve administering to or managing the needs of the department's service units and divisions, rather than dealing with day-to-day emergency incidents. Staff functions may include the following activities:

Training. Training of all personnel in their job skills; administering continuing education programs in special subject areas; administering the fire department safety program; and organizing and administering pre-incident planning

Maintenance. Maintaining apparatus, equipment, and physical facilities; recommending replacement programs for apparatus and equipment; and developing specifications for the purchase of apparatus and equipment

Communications. Providing and maintaining adequate facilities for the receipt of alarms from the public and communication with fire companies both in quarters and by radio in the field; also includes functions of developing and maintaining dispatch policy and response requirements

Research and planning. Creating the new knowledge the fire department needs to provide better service; forecasting long-range department goals; and performing the types of analyses necessary for other department functions to assess program effectiveness

Public information and relations. Maintaining contact with the public and the news media to tell the fire department's story; in larger departments, this function may also be responsible for internal communications

Financial management. Preparing a budget; monitoring expenses against the budget planning for capital expenditures; and supervising the purchase and inventory of needed materials

Personnel management. Supervising the recruitment, selection, and promotion of personnel; administering the retirement system and the benefits program; and supervising the administration of discipline within the department

Fire protection engineering. Developing proposals for code changes; and assisting in the technical aspects of plan review, code enforcement and fire investigations; also used in the research and planning functions

In large fire departments, a staff officer normally supervises each of these functions; these officers are not normally involved in line functions. The number of personnel assigned to a staff officer will vary with the size of the department and the importance of the function. In small departments, line officers may also be assigned staff functions, or a single officer may supervise more than one staff function. In the smallest of departments, the fire chief or assistant chief may directly assume many of the functions.

Organizational Plans

A department that functions effectively will have an organizational plan that shows the relationship between the operating divisions and the total organization, and allows the department to be managed effectively. (Organizational charts with typical structures of small, medium, and large fire departments are shown in Figures 12.4.4, 12.4.5, and 12.4.6, respectively.) A good organizational plan that reflects the current status of the department is essentially a blueprint of the organization.

A list of responsibilities or a job description for each position should accompany the organizational plan. In small departments, a single individual may be responsible for more than one function. For example, a single officer may be responsible for both training and maintenance. This should be detailed in the job description. The organizational chart must show how functions that may demand time and support from other personnel or groups will be coordinated within the department. The organizational plan and chart should reflect, to both fire department personnel and the public, a clear, coordinated effort to provide service to the community.

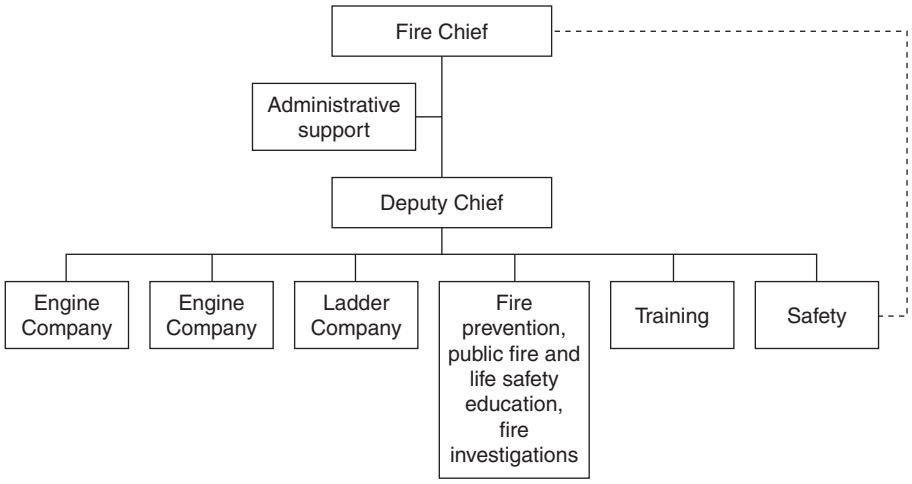

FIGURE 12.4.4 Organizational Chart for a Small Fire Department

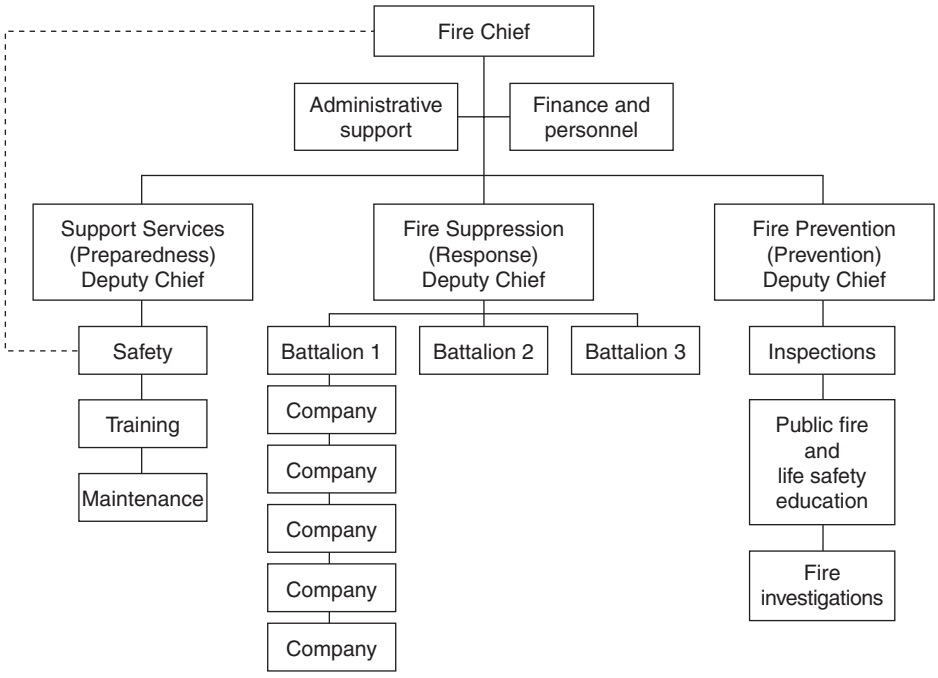

FIGURE 12.4.5 Organizational Chart for a Medium-Sized Fire Department

Rules, Regulations, Procedures, and Guidelines

As with any organization, fire departments need directives to govern operations, set performance standards, and outline expectations of behavior. Every fire department should have a set of rules and regulations, including a code of conduct, and standard operating procedures and guidelines. Operating procedures and guidelines are especially important in the fire service because the hazardous activities that are undertaken require a clear understanding of expected performance to ensure safety.

Chief officers may also issue orders when special circumstances and events require immediate or short-lived directives. Management should also create directives that specify disciplinary procedures for poor performance or for failure to follow regulations.

All directives should be written and distributed in such a manner as to ensure that they are known and accessible to all department members.

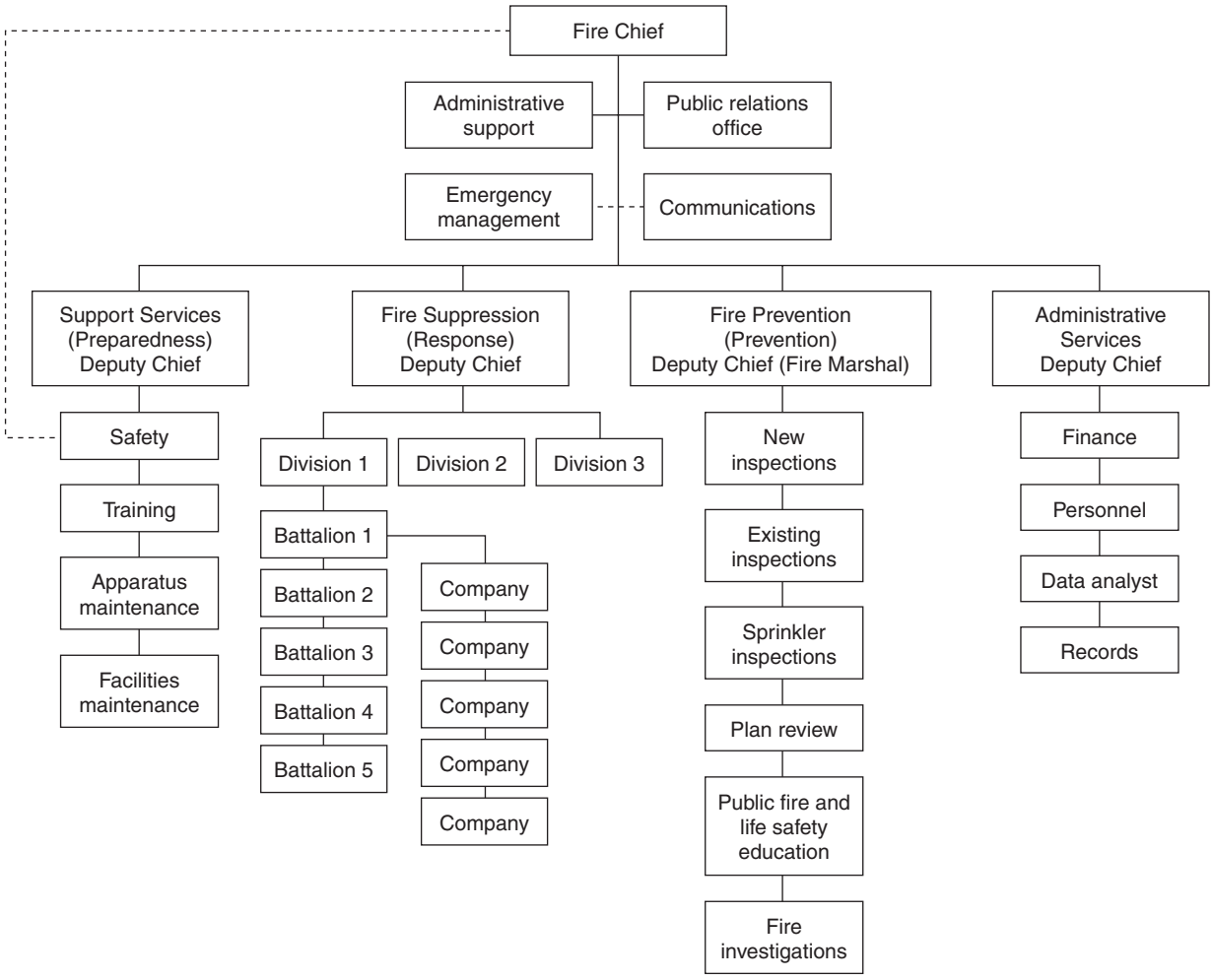

FIGURE 12.4.6 Organizational Chart for a Large Fire Department

ORGANIZING FOR EMERGENCY RESPONSE

Fire Suppression

Fire department structure is usually organized around providing fire suppression. The complexity of the response services section of the department is directly related to the size of the department. In many small fire departments, the fire chief supervises field operations. In larger departments, companies are organized into battalions or districts supervised by intermediate-level command officers (Figure 12.4.7).

The basic tactical unit of the fire department is the company, a group of personnel operating one or more pieces of apparatus under the supervision of a company officer. Several companies may operate from a single fire station. Engine and ladder companies are the most common; others are often provided to perform combined or specialized functions. These companies include rescue squads and companies that operate special tactical or support-function apparatus. In some fire departments, several companies operating from the same station are organized as task forces.

Engine Company. The most common type of company in a fire department is the engine company. The basic unit of apparatus is the engine or pumper, which carries hose, nozzles, a water tank, a pump, ground ladders, and assorted equipment, appliances, and tools. The engine company's basic tactical role in fireground operations is to deliver water through hose lines to control fires. Most engine companies also carry equipment to provide emergency medical services. In most cases, at least one engine company is based at each fire station in order to respond quickly and begin operations at a fire scene.

Ladder Company. The basic ladder company (or "truck company") apparatus is an aerial ladder or elevating platform that provides access above ground level or to rooftops, and can be used to direct elevated master streams onto fires.

Ladder trucks carry a complement of ground ladders and a selection of hand and power tools. On the fireground, ladder

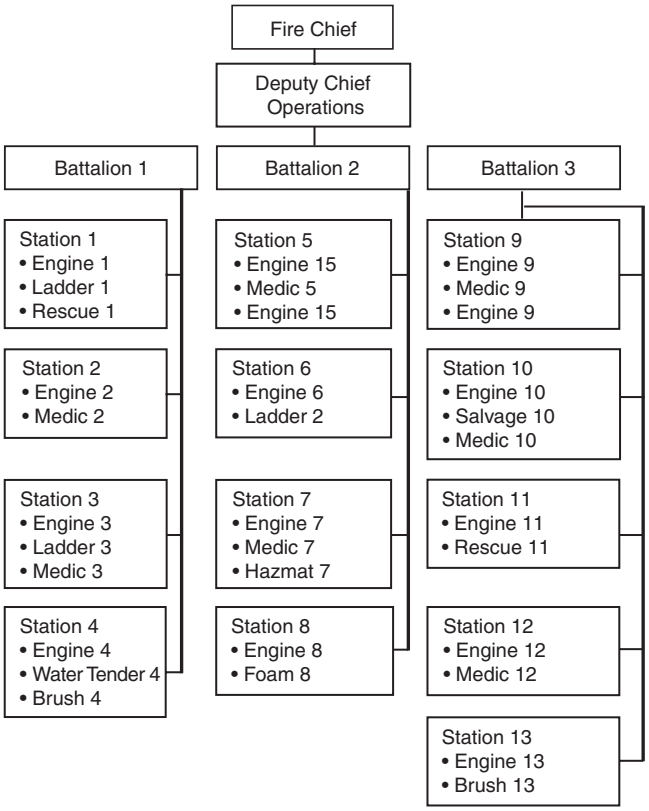

FIGURE 12.4.7 Organizational Chart for Operations Division of a Large-Sized Fire Department

companies perform search and rescue, forcible entry, ventilation, salvage, and overhaul. They also use ladders to gain access to fires and rescue persons trapped above ground level. Many departments operate ladder companies whose apparatus, called a "quint," are also equipped with hose, a water tank, and a pump. This type of ladder company can also apply water to fires through its hose lines.

The need for ladder companies, the design of ladder trucks, and the way ladder trucks are equipped, all depend on the community's needs. In a densely developed city, one ladder company may be provided for every two or three engine companies. In suburban jurisdictions that cover large response areas, the quint concept is particularly prevalent, because engine companies may have farther to travel and a choice of tactical options is desired. In rural and sparsely populated suburban areas, the functions normally performed by ladder companies are often assigned to engine companies carrying additional equipment.

Rescue Company. Many fire departments use separate rescue companies for both fire fighting and non-fire-related incidents. Rescue companies specialize in technical rescue, such as extricating victims from vehicles involved in accidents, removing injured persons from perilous locations, and assisting victims of industrial accidents (Figure 12.4.8).

On the fireground, rescue companies are usually assigned primarily to search and rescue, and to deliver medical treatment

FIGURE 12.4.8 Rescue Personnel Training for High-Angle Rescues

to civilians and responders. They may also take on some ladder company functions, particularly forcible entry, ventilation, and the use of power tools. Rescue companies may also be assigned as rapid intervention teams, with a focus on reducing injury and death to fire fighters operating at fires.

Special Apparatus. Fire departments often use specialized vehicles, such as off-road vehicles for brush fires, water tenders, hose wagons, foam pumpers, hazardous materials units, lighting trucks, breathing-air-supply trucks, and command vehicles. These may be organized as separate companies, or the role may be assigned as a second function to regular companies, with one company of fire fighters responding to an incident on either of two apparatus, depending on the nature of the incident. Some fire departments operate special companies with vehicles designed to carry little equipment other than the protective clothing and breathing apparatus used by the crew. These "flying squads" are intended to provide additional staff in a hurry to task-intensive incidents.

Fire apparatus may be purchased with a variety of options and configurations to suit the needs of the community or fire department. These options include aerial devices, water towers, and foam systems on engine-company apparatus; high-volume pumps and remotely controlled nozzles on ladder trucks; and large electrical generators and air-supply systems. The current trend is to purchase apparatus with multiple capabilities and to equip companies to perform multiple functions.

In many jurisdictions, the fire service has expanded its scope to embrace certain domestic preparedness functions. These departments have acquired specialized apparatus and vehicles for uses such as mobile decontamination trailers, incident communications centers, command and control vehicles, medical operations units, mobile radiological detection and monitoring stations, and multidiscipline response units.

The National Fire Protection Association publishes a series of standards for the design and construction of fire apparatus. Refer to Section 12, Chapter 16, "Fire Department Apparatus and Equipment," for a detailed discussion of fire apparatus.

MUTUAL AID AND MAJOR EMERGENCIES

Fire department managers should always be aware that a fire, natural disaster, disease outbreak, or terrorist attack could overwhelm the local emergency services. For this reason, most fire departments traditionally have rendered assistance to each other in times of need. Mutual-aid plans establish procedures for requesting and dispatching help between fire departments so that each party will know what is expected.

Mutual-aid plans may include immediate joint response of several fire departments to high-risk properties; joint response to alarms near the boundaries between fire department areas; coverage by outside departments when the resources of the local department are engaged; provision of additional units to assist at major fires that are too large for the local department to handle; and provision of specialized types of fire-fighting equipment not available locally in adequate quantity for the particular incident.

Mutual-aid plans also should specify that the National Incident Management System (NIMS) and ICS will be used during all incidents, and include provisions for standard operating procedures, interdepartmental communications, maps, adaptors, and other considerations that directly affect the ability of departments to operate together effectively. Command responsibility, jurisdictional questions, insurance coverage, and legal constraints should be covered in written agreements and supported by enabling legislation to establish effective mutual-aid systems.

Some communities have adopted automatic reciprocal aid agreements under which two or more fire departments are dispatched through one 9-1-1 communications center as though they were a single department. This "total boundary drop" that considers all concerned jurisdictions as one, optimizes emergency response for the citizens in the affected area. It usually results in a savings for the taxpayers as well, because it eliminates the need for multiple communications centers.

Some jurisdictions have extended the automatic-aid concept to the extent that fire department resources are pooled or merged into an integrated system with standardized training procedures. These networks may include shared facilities, joint purchases of specialized apparatus and equipment, and a coordinated approach to long-range planning.

True mutual aid is a relationship in which each member is prepared to assist the other parties to the agreement. In most areas of the country, larger fire departments are willing to assist smaller jurisdictions when requested at major incidents that exceed local capabilities. In many places, communities or individual properties known to be deficient in fire-fighting resources contract in advance to pay another jurisdiction for certain fire-fighting assistance. These programs are known as outside aid programs. In some instances, the contract covers basic first-alarm response; in other cases, additional assistance is provided for fighting major fires.

In all cases of mutual aid and outside aid, carefully worded agreements should be made in advance according to the legal requirements governing fire department operations outside normal jurisdictional areas. Local departments may have different operating methods and types of equipment, and this could hamper effective coordination of resources if a well-constructed agreement is not in place. The parties to the plan may choose to render assistance only to the extent that they feel they can do so without seriously reducing local protection; thus the plan should identify and address any coverage weaknesses.

The ideal plan is an extensive, region-wide agreement that maintains and optimizes coverage for all jurisdictions involved. As experience with natural disasters and other large-scale incidents has shown, effective plans and organizational procedures are crucial in systematically mobilizing fire forces. Most states and provinces have established large-area disaster plans involving all emergency services, coordinated under the NIMS. Such plans must integrate with the normal organizational and command procedures used by fire departments. These large-scale mutual-aid networks form a natural basis for smaller scale, more routine mutual assistance plans.

The amount of work involved in establishing and maintaining the mutual-aid agreements necessary for each jurisdiction can be a significant administrative burden. State legislation that provides mutual-aid agreement between all jurisdictions and emergency service agencies within the state can help to alleviate this burden. Such legislation can be written to allow individual communities or agencies to opt out of the agreement. This approach promotes regional planning and cooperation among all emergency responders and services, which is the cornerstone to successful response to and recovery from disaster. Similarly, interstate mutual aid agreements should be considered. Widespread effects of certain disasters can require the response of resources from states near and far. Interstate mutual-aid agreements should be examined to ensure that they provide for the release of resources for emergency response within hours of requests for assistance.

COMMUNICATIONS

An effective communications system is a key factor in fire department operations. The communications system is responsible for receiving notification of emergencies from the public; alerting and dispatching personnel and equipment; coordinating the activities of the units engaged in emergency incidents; and providing nonemergency communications to coordinate units.

Receiving Alarms

The first fire alarm telegraph system was created in Boston, transmitting the first fire alarm in 1852.[4] Although in many urban areas, municipal alarm systems remain in widespread use, today most alarms are received over landline or cellular telephone systems. Small departments with low activity levels may receive alarms through a variety of systems that provide 24 hour coverage.

In most areas, combined emergency service answering centers called public safety answering points receive calls for police, fire, and emergency medical services through a 9-1-1 emergency number; fire departments in other jurisdictions receive calls at a separate communications office. Enhanced 9-1-1 systems can identify the telephone number and location from which a call made from a landline phone originates. Other sophisticated tracing equipment enables public safety answering

points to determine the location of the cell tower closest to the origination of a call made from a cell phone.

As a result of high false alarm rates, many cities have removed municipal alarm systems or converted from telegraph to systems providing voice contact between the dispatcher and the caller. For more information, see NFPA 1221, *Standard for the Installation, Maintenance, and Use of Emergency Services Communication Systems.* Additional information is provided in Section 12, Chapter 15, "Public Emergency Services Alarm, Dispatch, and Communications Systems."

The communications center should provide recording equipment for all telephone lines and radio channels to provide immediate playback capability to verify information and to provide a complete record of all activity. In addition to telephones and municipal alarm systems, many fire departments receive automatic fire alarms from systems installed in buildings in their jurisdiction; these systems are connected directly to the fire department or relayed through a private alarm company.

Dispatching Procedures

Once an alarm has been received, personnel must be alerted and equipment must be dispatched. The complexity of this process varies with the size and population of the area served and the number of units under the alarm center's control.

The dispatcher must identify the units that are to respond to an incident based on the geographic location and type of situation, as well as the current availability of the units. The selection criteria for response units is determined in advance based on distance from, or response time to, the reported location. The type and number of units due to respond to each type of incident, often called the response array, should also be determined in advance based on risk criteria and unit capabilities.

The dispatcher must know the status of each unit in the system and be able to contact immediately all units that are available to respond to an incident. Global positioning systems (GPS) may be installed on response vehicles that enable the dispatcher to consider a unit that is closer than the recommended unit. If regularly assigned units are engaged at another incident or are otherwise unavailable, the system should identify the next units to substitute. This information is also needed if the dispatched units request additional assistance. Many communications centers and public safety answering points have computer-aided dispatch systems (CADS) that automate these functions. Printouts of automated dispatch systems are kept on hand as a backup system. Smaller systems often rely on printed "running cards" or policies to provide the dispatcher with response information for each zone.

The units assigned to respond to an incident may be alerted by radio, microwave, telephone, telegraph, other wired systems, or a combination of these. In some areas, individual pagers, outside sirens, or horns are used to alert volunteer or call personnel. Most departments use a voice message from the dispatcher to the responding unit, carried over the radio or wired circuits to the fire station. The alarm center should have at least two separate means of communication with each fire station, in case of equipment failure. In addition to voice messages, some fire departments use printers or telegraph systems as a backup. Units out of quarters are normally alerted by radio.

Radio Communications

Every fire department vehicle should be equipped with a two-way radio. Units responding to or engaged at incidents should be in radio contact with other units and with the alarm center. For larger departments, this may require several radio channels to provide sufficient communications capacity. The alarm center must be able to contact responding units en route, in order to provide additional information or directions, and units at the scene must be able to request or return additional resources. Mobile data terminals on the responding units provide the responders a view of the best information available to the dispatcher. This equipment saves time that would otherwise be spent gathering this information over the air.

The incident commander should be able to contact the alarm center at all times, providing progress reports, advising on the need for assistance, or releasing units from the scene. A dedicated fireground channel should provide communications between the incident commander and the units operating at the scene. Complex incidents may require multiple for communications within various sectors of the incident management system.

At a minimum, each company officer and sector officer should have a portable two-way radio on a fireground channel. As an essential element of safety, every member operating in a hazardous environment should have a portable radio. Units released from an incident by the incident commander should advise the alarm center when they are available to respond to other incidents.

As fire departments have become more mobile and active, with units spending less time in quarters, radio communications have become more important. The radio system must reach all units and be able to handle the volume of communications a major emergency generates. Regional communications plans are essential to coordinate activities involving units from multiple jurisdictions. Such plans may specify dedicated frequencies, specialized equipment that enables different systems to communicate, or other predetermined methods for providing a communications platform.

Communications Center Staffing

Fire communications centers require trained operators who are familiar with fire department operations and equipment. In very small communities, the fire department telephone number may be arranged to ring in a number of locations where appropriate action can be taken to dispatch fire apparatus. Dispatching may also be handled by the police department, a town office, or other locations that provide 24 hour coverage. Increasingly, small fire departments are being served by regional fire communication centers that are properly equipped and staffed.

Larger communities and regional communication centers require adequate numbers of trained, capable personnel to be on duty at all times. Enough operators must be on duty to handle the volume of communications during busy activity periods and working incidents. Procedures should be in place

to call in off-duty personnel or additional trained dispatchers, or otherwise increase capacity when major emergencies and high-activity situations exceed the effective capabilities of on-duty staff.

System maintenance and repair personnel should be on duty or on call at all times. All equipment must be maintained properly and tested for maximum reliability, and backup equipment or systems should be provided in case any key component fails. Every fire department should have a backup facility to which basic communication capability can be transferred if the primary center becomes unusable. In addition, 9-1-1 communications centers should have an agreement with a comparable center to allow for the redirection of 9-1-1 calls and dispatch of units in the event of a local phone system failure.

Information Retrieval and Storage

The communications center should have immediate access to essential information that may be needed in dispatching units to fires and emergencies. The data files must include a complete geofile index of all streets, intersections, and related numbering systems in the area. The geofile should also include all target hazards such as schools, hospitals, critical infrastructure, and large buildings. The system must allow the dispatcher to determine the appropriate response zone and map location for any reported emergency so that the proper units can be dispatched. Maintaining and updating these files is an important ongoing function, whether the information is kept in hard-copy form on cards or index systems or in a computer system. The same approach is necessary to keep pre-incident plan information and maps up to date in the communications center, as well as on fire apparatus.

Communications center data files should also include telephone numbers for responsible parties for target hazards, utility companies, and other agencies to contact during emergencies, as well as other individuals who may have to be notified of, or asked to respond to, certain incidents.

Electronic data processing equipment enhances information storage and speeds its retrieval. Information available on a particular location within a CAD system may include data on building arrangements, construction, hazards, code-inspection access, water supplies, and even prior fire experience. The system may provide for direct transmission of this information to terminals in responding vehicles or for storage in portable computers or microfiche systems carried in command vehicles.

Station/Personnel Alerting Systems

Some fire departments maintain a 24 hour watch at a console or control room in each fire station. The person on watch is responsible for receiving dispatch messages and controlling alerting devices within the station. Instead of maintaining a watch, other departments rely on the communications center to operate audible alerting devices in the stations.

Controls for lights, electrically operated doors, traffic-control devices, and similar equipment are usually located at the watch desk. Other fire departments control some or all of these devices from the communications center via radio signals or hardwired circuits.

In those stations that are staffed entirely by volunteer or on-call personnel, the communications center may alert personnel by activating sirens or horns or by tone activation of radio pagers carried by personnel or kept in their homes.

Communications center managers should carefully evaluate and anticipate the need for additional channels and frequencies and include strategies for funding the addition of these and other needed equipment in their planning. Radio systems, computer equipment, global positioning systems, software interfaces to coordinate these systems, and other communications tools are complex, expensive, and often little understood by the authorities who must agree to fund them.

Communications center managers should plan and train for the coordination of operations among public safety agencies during a disaster. Fire-rescue departments that operate a separate communications center, in particular, should prepare the communications staff for effective interagency operations.

MANAGEMENT AND BUDGETING

The operation of a fire department is normally a function of local government—in the case of a fire district, possibly the only function—that supports the service and is responsible for the level of service rendered. As with any governmental or business operation, this function involves three major areas of responsibility: (1) fiscal management, (2) personnel management, and (3) productivity. Other areas of responsibility include planning, research, and record keeping.

Fiscal Management and Budgeting

In general, fiscal management practices follow those used by the government agency supporting the department. These practices involve budgeting, cost accounting, personnel costs including payroll, and purchasing or procurement costs. The degree to which these factors are a direct responsibility of fire department management varies, depending on the practices of local government.

Fire department budgets are generally prepared and submitted by the fire chief, directly or through management structure, to the elected body that administers the community or district operations. A typical budget consists of operating, personal services, capital replacement, and capital improvement segments. Personnel costs are generally the most significant segment of a fire department's budget, accounting for approximately 85 to 90 percent of the total expenditures of a fully paid fire department.

Fire department managers must thoroughly understand their jurisdiction's budgeting system. Inadequately prepared budgets can lead to serious monetary shortfalls at the end of the fiscal year. Costs must be estimated realistically and expenditures must be monitored on an ongoing basis.

Long-range plans should be created that will project capital replacement costs for items such as staff vehicles, fire apparatus, fire stations, and other major pieces of equipment. Fire apparatus costs normally run from 2 to 3 percent of payroll costs. (Some fire departments include an apparatus replacement allowance in their operating budgets, but this item is regularly reduced or

eliminated, with the result that apparatus replacement may be included in a capital expenditures budget. Although this reduces the fire department's annual budget, it may ultimately result in higher taxes due to interest costs. However, such decisions are generally made above the level of the fire department administration.) New fire stations and new service programs are usually included in a capital improvement budget separate from the fire department budget.

Large fire departments may have separate budget accounts for staff divisions, such as fire prevention, maintenance, and training. Expenditures are charged against specific items in the line budget, and the remaining balance is shown after each expense deduction. Usually, the department head or staff division supervisors have the authority to make emergency transfers of funds between line categories, whereas transfers between major categories must be authorized by the municipal manager, finance officer, or other governing body. Purchases and procurement procedures must be executed within the policies of the governing authority.

Budget Submission

Fire department administrators are required to submit their budget estimates by a specified date for the coming fiscal year (or years, in jurisdictions that employ a biennial budget). Budgets are usually submitted to a finance officer or committee, and department heads are then asked to justify specific items. Salary totals may be governed by contract with the employees, but estimates must cover all ranks, overtime costs, and anticipated hiring and retirements. Because salary increases are not always determined before the budget is submitted, it may be necessary to incorporate a projection based on reasonable assumptions.

After a departmental budget has been approved by the governing administration, it must be approved by the city council or other governing body. In some communities, this requires a public hearing. With some municipal charters, the council can reduce but not increase the budget in order to guard against political pressure on the administration. Once approved, the budget takes effect at the beginning of the fiscal year. If not approved in time, it is customary to permit ongoing expenditures at the same rate as the previous year.

The governing authority should clearly define who is responsible for managing each area of the budget. Responsibility for keeping the department within its authorized budget most often rests with the chief of the department.

Personnel Management

A fire department is only as good as the people who work for it. Choosing new fire fighters, and promoting them to officer or other ranks, is to a great extent the job of the fire chief or other upper department management, although human relations departments take over much of this role in many jurisdictions. Hiring and promotional processes are also subject to legal constraints as well as, often, to civil service rules and local government policies. Fire department management is also responsible for assigning employees to positions within the organization (subject in some cases to the work contract agreement) and for supervising them and evaluating their performance.

Recruiting. Fire departments are often very involved in recruiting efforts to fill vacancies in their ranks. A common arrangement is to conduct recruiting efforts jointly with the local government human resources or personnel agency. (Because of their makeup, most fire districts and volunteer departments recruit their own members.) Many large fire departments have recruitment sections. Some departments coordinate recruitment efforts with other allied agencies, such as other fire-rescue departments in the region.

Fire department management has three recruitment responsibilities. The first is to develop and employ appropriate hiring standards. The second is to provide the basic training new recruits need in order to perform their assigned duties properly. The third is to certify that the newly trained fire fighters are ready for appointment as permanent fire fighters or, when individuals prove unable to perform satisfactorily, to recommend that their services be terminated.

Personnel selection must comply with local, state, and federal laws. U.S. courts have ruled that there can be no discrimination in hiring practices based on race, gender, national origin, religion, age, or marital status. State or local law may further define employment practices, expanding the list of nondiscriminatory practices or setting criminal history disqualifiers, for instance. Many communities have identified diversity in the public sector as a value and have established a goal that personnel reflect the diversity of the community they serve. Many departments thus administer comprehensive recruitment, pretraining, and mentoring programs designed to increase the representation of women and people of color within their organizations.

Periodic review of the selection, hiring, and retention practices of the department is a wise practice. Selection practices are a sensitive issue, and knowledgeable counsel should be sought when developing hiring standards in order to ensure a sound legal foundation. For example, some rulings prohibit residence requirements for recruits, although fire department rules of employment may stipulate that, because of the emergency nature of the work, employees must reside within a reasonable distance of the community. One court decision has prohibited entrance examinations that require prior knowledge of fire department practices and equipment.

In most jurisdictions, applications for employment as a fire fighter are obtained from local government personnel offices or the civil service agency. In at least two states, recruitment is handled by a state civil service commission. Age requirements for entry-level appointments vary and have been affected by recent federal regulations.

Qualifications. All fire service personnel must be fully qualified and capable of efficiently performing the wide range of functions necessary to protect life and property. Many states have established commissions on fire fighter standards that require that all personnel employed by fire departments satisfactorily complete basic training before they are given permanent employment. Many states have also adopted, or are in the process of adopting minimum fire fighter qualifications standards.

In 1971, the Joint Council of National Fire Service Organizations (JCNFSO) created the National Professional Qualifications Board for the Fire Service (NPQB) to facilitate the development

of nationally applicable performance standards for various levels of responsibility within the uniformed fire service. On December 14, 1972, the board established four technical committees to develop those standards using the NFPA standards-making system. The initial committees addressed the fire fighter, fire officer, fire service instructor, and fire inspector and investigator.

The original concept of the professional qualification standards, as directed by the JCNFSO and NPQB, was to develop an interrelated set of performance standards specifically for the fire service. The various levels of achievement in the standards were to build on each other. In the late 1980s, the standards were changed to recognize that the documents should stand on their own merits in terms of job performance requirements for a given field. Accordingly, the strict career ladder concept was abandoned, except for the progression from fire fighter to fire officer. The later revisions facilitated the use of the documents by other than the uniformed fire services.

In 1990, the NFPA assumed the total responsibility for the appointment of professional qualifications committees and the development of the professional qualifications standards. The NFPA Standards Council appointed the Correlating Committee for Professional Qualifications Standards in 1990, which assumed the responsibility for coordinating the requirements of all of the professional qualifications documents. The chair of each technical committee sits on this committee.

Currently, technical committees are working on the following projects:

- NFPA 1000, *Standard for Fire Service Professional Qualifications Accreditation and Certification Systems*
- NFPA 1001, *Standard for Fire Fighter Professional Qualifications*
- NFPA 1002, *Standard for Fire Apparatus Driver/Operator Professional Qualifications*
- NFPA 1003, *Standard for Airport Fire Fighter Professional Qualifications*
- NFPA 1005, *Standard on Professional Qualifications for Marine Fire Fighting for Land-Based Fire Fighters*
- NFPA 1006, *Standard for Rescue Technician Professional Qualifications*
- NFPA 1021, *Standard for Fire Officer Professional Qualifications*
- NFPA 1031, *Standard for Professional Qualifications for Fire Inspector and Plan Examiner*
- NFPA 1033, *Standard for Professional Qualifications for Fire Investigator*
- NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*
- NFPA 1037, *Standard for Professional Qualifications for Fire Marshals*
- NFPA 1041, *Standard for Fire Service Instructor Professional Qualifications*
- NFPA 1051, *Standard for Wildland Fire Fighter Professional Qualifications*
- NFPA 1061, *Standard for Professional Qualifications for Public Safety Telecommunicator*

Each of these standards defines the levels of progression within the specified job. The job performance requirements defined for each level of progression are considered the minimum requirements for individuals at that level. The intent of the committees is to develop clear and concise job performance requirements that can be used to determine whether individuals possess the skills and knowledge necessary to perform the related duties and tasks of the job. These job performance requirements can be used by any fire department in any city, town, or private fire service organization.

Under the new leadership of the National Board on Fire Service Professional Qualifications, the NPQB has assumed the role of third-party accreditor of fire service certification programs and developer of a national registry of those certified.

Certification in the fire service is based primarily on the NFPA professional qualifications standards. The Fire Service Accreditation Congress at Oklahoma State University has also been established as an accreditation agency for the fire service. The Center for Public Safety Excellence offers accreditation to qualified fire service agencies and chief fire officers.

The establishment of standards and testing procedures does not in itself ensure that all personnel will achieve the required level of competency; NFPA 1001, *Standard for Fire Fighter Professional Qualifications,* is a professional qualifications standard, not a training standard. Training programs are necessary to prepare members of the fire service to acquire the skills and knowledge necessary to meet the job performance requirements set forth for each grade. However, training should not be random. It must be organized to prepare trainees to meet the specified levels of performance demonstrated by the performance testing described in NFPA 1001.

Courts have ruled that height and other arbitrary requirements are discriminatory and may not be part of hiring criteria. Discrimination against individuals with a disability is also a violation of federal law, but candidates may be required to demonstrate their ability to perform the bona fide duties of a job. Fire departments must evaluate their hiring processes, defining and validating the "essential functions" for fire department positions.

Testing. Fire fighting requires physical endurance and strength, and fire fighters depend on each other in fire suppression and rescue operations. In some jurisdictions, the fire department's training division or other personnel may be used to test candidates for fire fighter positions. Regardless of who provides entry-level testing, recognized standards and all applicable laws and guidelines must be followed carefully. The goal of the testing process should be to select those candidates who, with training, will be capable of carrying out the functions of the job proficiently, without making the results subject to charges of discrimination.

Promotional Practices. In the vast majority of fire departments, officer ranks are filled from the pool of personnel serving in the next lower rank or ranks, although fire departments are increasingly recognizing the potential benefits of allowing qualified personnel from other areas and departments to compete for positions above the entry level. Promotional procedures are designed to take into account technical qualifications for the particular rank, as well as fire department or other relevant

experience. Examination procedures in the civil service must be competitive and nondiscriminatory.

Promotional procedures are generally administered by personnel departments or by state or local civil service authorities with the assistance of experienced persons who are knowledgeable about the particular job classification. Such subject matter experts include fire chiefs, fire fighter organizations, department personnel, and technical consultants. Their assistance may include guidance as to the relative weight to be given to experience and to the result of written examinations covering the technical qualifications of the position.

In many systems, however, the testing process is rigidly defined by civil service law or contract. In some systems, performance ratings may be included. Some supervisors tend to be much more demanding than others when rating performance; and their subordinates often have less favorable performance grades than other employees, who may actually be less qualified. Because of the question of their uniform application, subjective performance ratings are now used less frequently in the promotional process.

Some promotional processes include an oral review. Although oral reviews provide an opportunity to evaluate important attributes that are difficult to quantify and test, they can also be very subjective. Few oral interviews are scientifically designed or professionally administered, and they may reflect the interviewer's bias or be subject to a challenge of bias. As a result, more emphasis is given to written examinations that test technical knowledge exclusively.

Where permitted by law, more fire departments are now commonly relying on assessment centers as a means of selecting candidates for promotion. Assessment centers, which have long been used by private industry, require a candidate to demonstrate certain abilities through the use of problem-solving exercises, role playing, prioritization of a list of tasks, incident simulation, and other exercises. Each candidate is observed by a trained assessment team and scored according to performance. Many experts in the field of human resource management agree that the assessment center is the most realistic means of determining a candidate's suitability for a promoted position.

NFPA 1021, *Standard for Fire Officer Professional Qualifications,* specifies the levels of performance for fire officers. Written in performance terms, this standard requires an individual to demonstrate competence by knowledge and performance.

Many fire departments include educational requirements for officers, such as community college fire science certificates or bachelor's degrees for chief officers. It is not uncommon to find fire departments that seek individuals with graduate-level degrees in public administration or management for the position of fire chief. Many jurisdictions specify completion of the National Fire Academy's Executive Fire Officer program in their job qualifications for chief executive officer.

The fire department administration, as an arm of the municipal administration, has an important role to play in the promotional process. First, it must advise the personnel agency of the qualifications required in any job or rank to be filled, for those instances in which such qualifications have not been previously listed. Second, when a list of successful candidates is received from the personnel agency, the administration must normally advise the promoting authority of the promotions to be made. The usual practice is to fill vacancies from the top of the promotional list, except where the head of the fire department specifies in writing valid reasons for rejecting or passing over an individual.

Such reasons might include a record of serious disciplinary problems, including disobedience of written orders; frequent bad judgment when performing assigned duties; or a record of conflicts with other employees. Personnel records should be available to substantiate such rationale. These problems should be relatively current and not relate to behavior that occurred years ago that the individual has corrected.

Personnel Records. The fire department should maintain a careful and complete personnel record for each member. Such records cover all the pertinent facts of the person's fire service career, from probationary appointment through retirement, and include the original application for employment, all assignments, transfers, promotions, commendations, and records of disciplinary action. The record should also contain information on any special skills an individual possesses that may be useful to the department, as well as the individual's educational background.

In addition to the general record of an individual's service, a training file should be maintained, as covered in NFPA 1401, *Recommended Practice for Fire Service Training Reports and Records.* The file will show training periods and subjects in which the individual has received instruction, such as apparatus operation, emergency medical service, and fire inspection.

A medical history must be kept for each member, showing absences due to sickness and service-related injuries. A new addition to the personnel file is a record of exposure to hazardous materials and infectious diseases. This information provides a historical record of the fire fighter's known exposure to toxic materials or to infectious communicable diseases during his or her employment, as well as any appropriate inoculations he or she has received.

Productivity

Effectiveness in the fire service is difficult to measure. The basic objective of the fire service is the protection of life, property, and the environment. Modern fire service practice involves two major activities: controlling hazards to minimize fire losses and to prevent fires, and dealing with actual fires and emergencies to minimize suffering and losses. It is difficult to assess the number of fires and the amount of suffering or loss fire department activities have prevented. Experience demonstrates, however, that a lack of effective fire prevention and control measures invites disaster.

Likewise, the fact that most fires are suppressed with minimal losses and injuries does not indicate conclusively that an adequate level of fire department service has been provided. Experience shows that major fires and emergencies often arise from a combination of circumstances that are beyond the immediate control of fire department management but that must be dealt with effectively by the department to protect the public.

The fact that most fires are suppressed with minimal losses and injuries does not indicate conclusively that an adequate

level of fire department service has been provided. Nor does the occurrence of a large-loss fire necessarily mean that the fire department is inadequate. Major fires and emergencies often arise from a combination of circumstances that are beyond the immediate control of the fire department, yet it is left to the department to manage the results.

Because local fire losses do not necessarily reflect fire department performance, fire department management must rely on regional and national fire loss experience to help them develop standards for the department. Frequent training and assessment of company effectiveness can also help provide benchmarks for performance on the fireground.

EMS services provided by fire departments range from first responders assisting ambulance crews to actually providing paramedic engine and ladder companies and an ambulance service. Fire departments involved in this aspect of public safety have seen significant increases in the use of personnel and equipment and in community support.

Increased emphasis on domestic preparedness and large-scale disaster response has caused increasing numbers of fire departments to develop hazardous materials teams. Many metropolitan-area fire service agencies are also active in a federal, state, or regional search-and-rescue team with structural collapse rescue capability. Until a large-scale emergency occurs and the value of their services is realized, the productivity of these specialized programs often is measured in training hours, equipment procured, and exercises completed.

Planning

Planning for the future needs of a fire department is the most important job of fire department managers. Without adequate planning, an administrator will find he or she is handling one crisis after another and can never seem to get ahead. Long-range planning has often been neglected by fire department managers, but with budget constraints, it is absolutely essential. The U.S. Fire Administration (USFA) has developed a master planning process, available to local communities, that outlines the steps a community may take to determine long-range goals for its fire department and explains how these goals can be achieved. The NFA Technical Support Program will assist local governments in developing a master planning process.

All departments, small and large, should develop short- and long-range strategic plans. Short-range plans are generally considered to encompass the next five years; long-range plans cover ten or more years. These plans must be flexible and should be continually updated to reflect changes in the community as well as developments within the fire service. The plans should also be known to department membership and the governing authority. Goals drawn from these plans should guide department budgeting, program development, and decision making. (See Section 12, Chapter 5, "Information Management and Computer Technology," for more information on this topic.)

Research

The term *research* is commonly heard in the fire service, yet few fire departments are staffed or financed to support any significant research activity. Most fire departments are relatively small organizations that do not have sufficient personnel to meet their ongoing fire protection obligations, let alone undertake real research into efficient equipment design.

The development of the Internet and the host of resources available online have made research easier. Websites have emerged that are useful to fire-rescue managers, such as the Lessons Learned Information Sharing site, http://www.llis.gov, maintained by the federal government. The Homeland Security Information Network–Emergency Management site, or HSIN-EM, provides a communication conduit for fire service leaders and managers across the country free of cost. It is intended to facilitate planning and operations activities within the fire community of the emergency services sector, according to the National Infrastructure Protection Plan. Countless other information and research sites are available through the Internet. Fire departments without routine, affordable access to the Internet should seek funding to make this critical connection to the greater fire service community and the world.

Few fire departments have been able to do true research into efficient equipment design. The same is true of most fire equipment suppliers. As competitive, small-volume businesses, they do not often generate a profit margin large enough to fund research and development. Fire apparatus builders have focused much of their engineering effort on meeting the increasingly exacting vehicle safety standards of the U.S. Department of Transportation (DOT). NFPA 1901, *Standard for Automotive Fire Apparatus,* updated every four years, also affects fire apparatus design and development.

One area in which fire department research can readily show returns is in fire record analysis, using programs such as the National Fire Incident Reporting System (NFIRS), which collects data from fire departments around the country. This information yields insights regarding hazards and trends, which allow prevention efforts to be targeted more effectively.

Well-analyzed data can be an informational gold mine, as long as the information is collected in a manner that supports analysis. Commercially produced software is available that will analyze a department's dispatch data. The results can help identify problems in response patterns, such as neighborhoods that receive subpar service delivery. Other applications can model or predict the value a new fire station or company could provide, recommend response arrays, and evaluate effective response times. With the proper tools and training, staff can also analyze data and return useful information.

Fire service managers seeking research expertise and resources can call on a range of fire service allies for help. The NFPA conducts research designed to help fire departments and makes this information available to interested parties around the world. The International Association of Fire Fighters (IAFF) Research Department is available on request to assist its local affiliates with problems. The USFA conducts and sponsors research relating to fire service needs.

Management Records and Reports

The fire chief and other administrative officers should have access to a records system that gives them data indicating how

effective the department is at preventing and fighting fires. Complete records of all fires and inspections must be maintained and made available to government officials and the public. All records should be examined in light of their usefulness. A records retention and disposal system should be employed, and a careful review should be made to ensure that the records system meets all legal requirements. (See Section 12, Chapter 5, "Information Management and Computer Technology," for more information on this topic.)

STAFFING PRACTICES

The principal resource of a fire-rescue department is its personnel. In most fire departments, the vast majority of personnel are assigned to the emergency response division. Resource allocation will thus be most effective if all personnel—and particularly those assigned to fire fighting and rescue—are assigned for maximum use. This can be accomplished through careful time-utilization schedules, assigning appropriate portions of work periods to apparatus and equipment maintenance, training, inspections, and other duties expected of the response division. Careful coordination and planning can help create the most effective emergency service delivery program possible.

In some fire departments, a small percentage of personnel are assigned full-time to fire prevention. Typically, these personnel undertake plan review, code enforcement, fire cause determination, public fire education, and similar prevention and enforcement activities. Departments with adequate funding may also assign full-time personnel to perform new and existing code inspections.

Personnel may also be assigned to perform functions that support the operations of the response and prevention divisions. Such functions, which may be grouped together as preparedness activities for the operations of line personnel, include training, equipment and apparatus maintenance, and facilities management. Like fire prevention, the preparedness division also usually comprises a small percentage of a department's personnel.

Factors Affecting Staffing Levels

Staffing levels for fire departments vary considerably and are influenced by such things as the size or risk characteristic of the population protected, population density, fire fighters' work hours per week, response distances, community risk profile, and fire fighter safety. Most fire departments use a three- or four- platoon system that will accommodate a 56 to 42 hour workweek, respectively. A four-platoon system requires about a third more personnel than a three-platoon system. Staffing levels for cities of 250,000 or more population range from 0.5 to 2.9 fire fighters per thousand population, with a median of 1.1 to 1.5 per thousand. Cities in northeastern United States generally have a higher staffing ratio than do cities in the central northern and southern United States, which in turn tend to have higher staffing ratios than cities in the western United States. Communities must assess their needs to determine the level of staffing that meets their requirements. A study conducted with the Dallas, Texas, Fire Department, however, suggests that when staffing falls below four fire fighters per company, fireground effectiveness may be compromised, overtaxing available forces and contributing to higher losses.[9]

Certain fire-rescue service functions place additional requirements on department staffing. Fire departments operating emergency medical service transports need additional personnel, as time spent delivering patients to hospitals could otherwise erode effective fire company strength. In smaller communities, the staffing ratio per population protected may be relatively high because of the need for sufficient on-duty personnel for effective initial attack and rescue operations. This personnel need is especially true in "bedroom communities" where call personnel are not readily available during the workday. Similarly, fire departments in many core metropolitan cities protect more lives and property than population figures reflect. A city of 80,000 may be the business center for an area of 200,000 persons and house a high percentage of low-income groups. The number of high-rise buildings and structures with unusually high square footage to be protected and the frequency of alarms for fires and emergencies should be considered in determining on-duty fire department staffing.

Some very large fire departments may operate with a lower relative strength per thousand population than those in cities of a more moderate size because, with high population densities, these departments have sufficient companies to provide needed coverage while handling working fires. For example, a large city fire department may operate one engine company per 15,000 to 20,000 population and still have a large number of well-distributed fire companies, whereas a city of 30,000 might not be able to muster an effective fire-fighting force with only two engine companies.

Mutual aid plays an important role in providing additional resources. Even the largest jurisdictions rely to some extent on mutual aid from surrounding areas to provide fire-fighting resources on a routine or major emergency basis. Some departments use automatic mutual aid on initial response. Even large cities are making increased use of both regularly assigned and automatic mutual aid. This use is practical especially when companies from neighboring fire departments may be much nearer to an incident than the city's fire companies, and vice versa.

It is frequently impossible for small cities to fully staff all of the fire companies they need to handle working fires throughout the community. In many cases, the population density and the values protected per square mile are relatively low. In such communities, some engine companies may respond with only three persons on duty and ladder trucks with only two. Such low levels of staffing should be reinforced promptly by off-shift or call personnel or by multiple alarm response to ensure adequate operating forces. In some cases, additional apparatus may be assigned to respond, offsetting deficient company strength. In communities with large geographic areas and relatively low concentrations of value, this may be an acceptable arrangement. To promote fire fighter safety, NFPA 1500 recommends that interior fire fighting and rescue operations begin only when four personnel are on the scene. This is a requirement of OSHA as well, with limited exception. In general, each engine company should have a minimum of four fire fighters on duty, including an officer.

Staffing Career Fire Departments

The number and type of fire department emergency response personnel a jurisdiction needs is determined in part by the factors discussed previously in "Types of Fire Departments," such as (1) the financial resources of the community, (2) the availability of on-call or volunteer personnel, (3) the frequency of emergency incidents, (4) the range of services expected from the department, and (5) the type of department preferred by the community.

Other factors, which are elements of a department's Standards of Response Coverage and also influence required staffing, are (1) on-scene operations, which includes fire flow tasks and life safety tasks; (2) critical tasks, which must be conducted in a timely and safe manner to control a fire prior to flashover or to extinguish a fire; (3) the establishment of an adequate effective response force (ERF), which is the minimum staffing and equipment needed to perform the critical tasks; and (4) the ability to reach an emergency scene within a maximum total reflex time, which is the time elapsed from the call receipt to the time the units arrive on-scene.

The primary goal of every fire department should be to arrive at an emergency scene with an adequate number of well-trained and fully-equipped personnel, within the time allotted by a department's response time standard, and in a manner that meets the expectations of the community. This goal is the starting point for determining adequate staffing for a career fire department.

Tours of Duty. Fire departments are traditionally staffed 24 hours a day. The next step in determining adequate staffing is to identify the number of positions that must be covered 24 hours a day throughout the year, plus the number of duty tours, or employee shifts, required for each 24 hour period. If 24-hour shifts are used, there is one duty tour per position per day. With 10 to 14 hour or similar tours of duty, there are 2 per day or 730 per year.

As an example, take a community that has determined that at least 58 officers and fire fighters should be on duty at all times. With a 42-hour-average workweek, including day and night shifts, each shift or group is on duty 182.5 times during a 365 day year. With 58 persons on duty, this requires 42,340 individual tours of duty per year.

This fire department's records show that with vacation, sick and injured leave, and other absences, its fire fighters actually average not 182.5 but 146.5 tours of duty per year. The required 42,340 tours of duty, divided by 146.5 tours worked per person, show that instead of 212 officers and fire fighters, 289 are actually needed to provide a minimum of 58 personnel on duty and cover the anticipated absences. The additional personnel would be distributed among the companies in the district. Even when vacations are carefully scheduled so that only one person from each shift of each company is absent at any given time, off-duty personnel may sometimes have to be used on an overtime basis due to sickness or injury. The budget should allow for contingency overtime as needed to call back members to cover staffing shortfalls as well as major fires and emergencies.

Defining Minimum Staffing. In many fire departments, when an unusually high number of absences occur, stations housing more than one company may be allowed to operate one person below the desired minimum rather than pay overtime, unless the company minimum strength is specified by contract or city ordinance. Other jurisdictions with a defined minimum staffing level may be forced to take units out of service if the funding level cannot support overtime.

Generally, a 42 hour workweek requires not four but five persons per position. Thus, a 20 person company is needed to maintain an average of four on duty. Because this does not allow two members to be away from their shifts at one time, overtime or personnel swaps between companies may occasionally be needed.

With a fire department operating on a three-platoon system with 24-hour duty tours, each platoon covers 122 tours in 366 days (a leap year). It requires 21,208 tours to have 58 officers and fire fighters on duty. The records in this example indicate that the average member works 98 tours per year. Thus, 21,208 divided by 98 requires 216 fire fighters or 72 for each of the three platoons. With a 53-hour maximum workweek permitted under federal labor law (FLSA), however, each member working more than 53 hours in each 28 day work period would exceed the allowable maximum by 3 hours and would be eligible for extra compensation, except possibly when the work cycle is broken by absences.

When minimum company strength of five persons is desired for a 42 hour workweek, most fire companies have 24 persons assigned to the four duty shifts and 28 assigned for approximately every fourth company. In some fire departments where more vacations are scheduled in the summer months, a 4 person minimum may be maintained in the summer and a 5 person minimum maintained in the winter. However, most fire departments prefer to maintain minimum staffing year round rather than attempt to adjust for seasonal trends. If additional personnel are needed during severe winter storms, they are provided on a temporary overtime basis and are paid from the overtime account.

It was customary in the past to allow 10 percent for absences from assigned shifts due to vacations and sickness. Now the figure commonly is 20 percent or more. Vacations have been increased, and employee benefit programs or work contracts often provide for various other compensated absences from duty.

Meeting Minimum Staffing Requirements. The practice of establishing minimum staffing levels for each fire company or duty shift has become widespread in recent decades. It is a policy in many fire departments not to operate engine or ladder companies with fewer than four fire fighters, including an officer, on duty. In rare cases, because of the workload and the population and values protected per company, the minimum is five persons on duty per company. When a company member is sick or injured while another member is on vacation and no on-duty fire fighter is available to cover the absence, the department employs an off-duty fire fighter on an overtime basis to maintain minimum strength.

Labor boards and at least one court have found that minimum staffing agreements or ordinances are reasonable requirements for the protection of the public and personnel. A number of small fire departments that do not attempt to maintain minimum on-duty company strength have established a minimum for the duty shift while employing off-duty personnel to maintain the predetermined minimum effective strength. Such a plan should account for apparatus that must be operated from several fire stations before off-shift or call fire fighters can arrive to assist. In order to meet minimum staffing goals, it is helpful to have a policy that regulates the number of vacancies permitted due to discretionary absences.

As noted above, off-duty personnel may sometimes be used on an overtime basis when unscheduled absences reduce staffing below the minimum level. This use is usually more economical than maintaining a roster that is large enough to prevent these occasions from ever occurring, but if the roster is too small, overtime may cost more than hiring more members. The calculation of staffing levels should thus be made carefully, considering not only scheduled absences but also typical levels of sick, injured, and military leave, temporary reassignment of emergency response personnel to nonemergency functions, and any other factors that can reduce the number of on-duty personnel.

Work Schedules. Most fire fighters who work an average of more than 50 hours per week use a 24 hour tour of duty. Most fire fighters who work 48 or fewer hours per week have day and night shifts; the most common is a 10 hour day shift and 14 hour night shift. When the law states that anyone working more than 40 hours per week will be paid overtime, many fire departments work a 42-hour, four-platoon schedule by paying 2 hours of overtime. Often, this is considerably less expensive than hiring additional personnel, and better teamwork is maintained by keeping crews together on a regular four-shift basis. (The Department of Labor Issues and Collective Bargaining of the International Association of Firefighters has published "The Hours/Schedules Kit," a compendium of various duty shifts and schedules that have been employed by fire departments.)

Occasionally, municipal administrators have suggested that fire fighters be assigned to an 8-hour-day/40-hour-week work schedule similar to police schedules. This schedule has not proven to be practical or desirable. On-duty police staffing properly varies with the time of day and day of the week, as required by demands for traffic control, patrolling, details, and so on. The work involved in fire fighting and rescue requires a team effort, and the team includes platoon chief officers, company officers, apparatus operators, and fire fighters working together on a regular basis. Serious fires and accidents occur at every hour of the day and night and on every day of the week. Thus, the uniform staffing provided by three- and four-platoon systems is essential to effective, timely operations. Work shifts are readily scheduled in seven 24-hour tours of duty per week on a 56-hour average workweek, or fourteen 10- and 14-hour tours of duty per week on a 42-hour average workweek. When the 168-hour calendar week is divided by 8 hour tours, 21 work shifts are required, a number that cannot be used to schedule evenly staffed platoons around the clock.

In most instances where the 8 hour schedule has been proposed, it has been rejected. Very few fire-rescue departments in the entire United States use an 8 hour work shift. The choice between having fire fighters on 24 hour shifts, or reducing staffing or resources by 40 percent to accommodate 8 hour work shifts, means most municipal fire departments can not seriously consider the latter. As the fire service becomes more adept at computerized analysis of emergency incidents and develops a good base of response data, staffing arrangements similar to police staffing may be possible in the future, particularly for EMS personnel. Demand analysis may demonstrate predictable patterns that can be addressed through more flexible staffing levels.

The requirement for overtime has resulted in improved mutual-aid arrangements, as on-duty companies from nearby departments can respond much faster than can off-duty local personnel called back in. Relying on mutual aid in this way also keeps overtime costs down. However, many small fire departments rely heavily on off-duty response on an overtime basis. Usually a minimum of 2- and 4-hour overtime pay is guaranteed for each response. When alarms for structure fires are infrequent, it may be much more economical for a small municipality to contract for overtime response than to provide a fully staffed fire company around the clock. One major drawback to this scheme is increased response times that will adversely affect fire losses.

Staffing Combination and Volunteer Fire Departments

Significant portions of the populations of the United States and Canada live in communities that cannot support career fire-fighting personnel. According to a 2002 study, whereas 40 percent of the U.S. population is served by career-level fire departments, 26 percent of U.S. citizens live in communities or rural areas whose fire departments are staffed entirely by volunteers.[1]

In most small communities, volunteer fire departments are based on a "neighbor helping neighbor" philosophy in which members receive no compensation other than possibly some reimbursement for personal expenses and uniforms. It is estimated that 84 percent of communities with populations ranging from 2500 to 4999, and 96 percent of those under 2500 are served by all-volunteer fire departments.[1] Various states have recognized the contribution made by their volunteer fire fighters by enacting protective legislation and providing statewide training programs, facilities, retirement systems, tax relief, and similar supportive measures.

Volunteers. When they receive an alarm, members of many volunteer fire departments report to assigned fire stations from which they respond with apparatus; other departments allow members to respond directly to the incident. To guarantee an effective working crew, many departments require the first piece of apparatus to respond with at least three members. NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments,* states that volunteer fire companies should not conduct interior fire-

fighting operations unless at least four trained members are on the scene.

Fire department administrators should periodically review response records to make sure enough members are responding to emergencies at all times and, if this is not the case, should recruit and train new personnel. In an all-volunteer fire department, staff positions are filled by volunteer officers. In other systems, career personnel may be hired to fill fire prevention, training, and/or communications functions.

Career Staff. Employing career fire fighters means a faster response time and greater efficiency. The fire fighters on duty take the apparatus to the fire, and the volunteers go directly to the fire when notified, thus saving an average of about 3 minutes in arrival time. The career apparatus operator normally is in charge of the apparatus and of the fire station, but volunteer officers may direct the fire fighting. One difficulty with this arrangement is that there are few, if any, opportunities for advancement for career personnel.

An arrangement that works successfully is to have the first responding pumper staffed by a career officer, an apparatus operator, and, when staffing permits, an additional fire fighter. This force is supplemented by additional personnel assigned to respond on call. The second-due engine may be staffed by volunteers or paid call personnel, or it may have a career apparatus operator to take the apparatus to the fire, where it is joined by the volunteer or paid call fire fighters. The ladder truck has a career apparatus operator assigned but is staffed at the fire by volunteer or paid call fire fighters. This arrangement permits a reasonably effective initial fire attack that is quickly backed by volunteer or paid call members. In all cases, there should be just one fire department in any jurisdiction, operating under a clearly defined and unified chain of command that is known to all department members.

Teams of Volunteer and Career Staff. In a number of combination fire departments, career fire fighters have complained about being commanded by volunteer officers whom they felt lacked the needed experience and qualifications. All fire officers should meet the appropriate NFPA qualifications for their rank, as many volunteer officers do. When a career apparatus operator is assigned to operate volunteer fire company apparatus, he or she should work under the orders of the volunteer officer of that company on the fireground. It is important that administrators make clear the respective roles and duties of all members, career and volunteer.

As the principal fire protection officer of a community, the chief of the department should be appointed on the basis of qualifications and experience. The increasing legal and technical responsibilities of the job strongly suggest that communities should consider adopting NFPA standards for fire officers and fire fighters as minimum requirements.

Call Fire Fighters

Many fire departments in small communities employ fire fighters who have no regular duty shift in the stations but are paid by the hour or by the incident for response to alarms and drills. Such members are sometimes loosely termed "volunteers," but under federal labor rules they are considered paid employees of the fire department and, as such, are subject to federal wage and hour regulations.

Compensation. In most cases, call fire fighters are local businesspeople and tradespeople who are willing to be part-time fire fighters. The paid on-call members may also be employed by another agency of the jurisdiction, in which case the time they spend on fire department duty may affect their overtime status. Call fire fighters are expected to meet the same standards of performance as career members of the same rank, although they may not be assigned as apparatus operators when there are sufficient career operators on shift duty.

A call fire fighter's service time is based on attendance at fires and training sessions, with a minimum hourly rate specified for response to alarms. Often, on reaching mandatory retirement age, they also receive a prorated pension, based on their years of service and hours of duty. Various methods are used to determine compensation for paid call fire fighters. In many departments, they receive the same hourly wage for their rank as employees who work regular duty shifts.

Another method of compensation is a fixed annual salary based on rank, from which deductions are made for excessive numbers of unexcused failures to respond or train with the assigned companies. Many fire chiefs arrange to excuse members known to be at their regular employment, except in the case of multiple alarm fires. Chiefs should have the authority to dismiss members who frequently fail to respond to fires or to complete required training sessions.

Still another method of compensation is to make an annual appropriation for call fire service, based on past experience, designed to approximate the hourly wage rate for fire fighters. This amount is divided on a regular basis among the call members as determined by individual attendance at fires and training sessions, so that members responding most faithfully receive the largest compensation. Whatever the compensation method used, the fire department should pay for members' insurance, workers' compensation, training, and all protective equipment.

Service Records. Accurate individual service records should be kept in the personnel files of all fire fighters, both career and volunteer. Response and attendance records are also essential, and members who are habitually late in responding should be replaced. Accurate response records can help identify staffing deficiencies and justify hiring additional career personnel. Municipal officials have often believed that because several hundred volunteers' names were on the roster, the fire department had ample strength, when actually most of those listed were no longer active. This type of situation has resulted in serious delays and in the extension of fires that should have been readily controlled.

Senior fire fighters who cannot respond regularly to first alarms may be assigned to operate reserve apparatus or to guide mutual-aid fire companies when serious fires occur. Other senior call members may be assigned to cover the alarm desk when paid apparatus operators are out of quarters.

PROCURING EQUIPMENT AND SUPPLIES

In most municipalities, fire department equipment and supplies are procured through purchasing departments. Items such as office supplies that are common to all departments may be requisitioned from the purchasing agency and charged to the appropriate fire department account. When items are of a specialized nature, such as fire apparatus or fire-fighting tools and equipment, purchasing specifications must be prepared by the fire department, approved by the purchasing department, and advertised for bids. In preparing specifications for such items as fire apparatus and fire hose, current NFPA standards should be followed.

The fire chief, with advice from the apparatus equipment supervisor, should determine whether proposals submitted by bidders meet specifications. In larger jurisdictions, the law requires that a contract be awarded to the lowest responsible bidder. However, bidders frequently take exception to various details in the specifications or offer substitutes. This situation requires that a fire chief determine whether such proposals meet the intentions of the specifications. If they do not, the bids should be rejected. If, however, the proposals conform to the specifications and are within the appropriation, the contract should be awarded. On delivery, new equipment should be tested in accordance with appropriate NFPA standards.

When emergency purchases must be made, it is customary to require bids from several suppliers. If the amount involved is small and funds are available in the appropriate budget item, the fire chief can authorize the expenditure. If funds are not available in the fire department budget, authorization and funds must be obtained from the municipal management or finance officer.

GOVERNMENTAL RELATIONS

Fire departments are but one agency of local government, and much of their success depends on cooperative working relationships with other local, state, and federal agencies. Some of the more important intergovernmental contacts are discussed here.

Building Department

The proper construction and arrangement of buildings is essential to a sound fire protection program. A community's building department is a key component in ensuring quality control in building construction and compliance with the fire protection features of local building codes.

State laws and local ordinances or agreements between fire and building departments increasingly require the head of the fire department to give written approval of specified fire protection features before building and occupancy permits can be issued. Close cooperation is also needed between these departments to control serious fire hazards that commonly are present while buildings are under construction, before the required fire resistance or protection features have been installed. In small communities, the fire chief generally must handle these duties, but in many fire departments, they are some of the responsibilities delegated to the fire prevention bureau.

Law Enforcement Department

Cooperation between the fire department and law enforcement officials is essential. Regular law enforcement response to fire alarms and other emergency scenes is necessary to control traffic and crowds and otherwise support operations. Similarly, fire-rescue departments are frequently called on to respond in support of law enforcement in investigating criminal matters. Such support can include initiating patient care, extricating victims from vehicles, and providing access to roofs. Fire and law enforcement agencies must develop coordinated plans for managing incidents that require the evacuation or closure of areas.

Law enforcement and fire officials must also develop working relationships to deal effectively with criminal investigations of fires. Many areas use fire investigation teams made up of both fire and law enforcement personnel. Many other fire departments employ fire investigators who have received the necessary law enforcement training to obtain "police powers." These personnel undertake the complete investigation to determine fire cause and origin. In these cases, both agencies work together, combining their areas of special expertise in a coordinated effort when arson is suspected.

As partner agencies in public safety, fire and law enforcement agencies must plan and train together. The scope of incidents that require coordination and unified command to be managed successfully is very broad. Heads of public safety agencies should establish mutual goals and plans that can be relied on in any incident, minor or disastrous.

Water Department

Adequate water supplies, including hydrant service, are essential for fire fighting and are the responsibility of the water department. All too often, water authorities have little knowledge of the waterflow requirements of the fire department for various areas and types of property. Thousands of fire hydrants have been set up improperly because water department crews did not understand the proper location and setting of hydrants required for efficient fire fighting. To prevent this, a knowledgeable fire officer should be assigned as liaison with the water authority. In some communities, the fire department is responsible, by ordinance, for determining the location and setting of hydrants.

All hydrants must be serviced regularly and after use, especially in cold weather. After each incident, the fire department should report all hydrants used to the water department promptly. Alert fire departments maintain a list of hydrants in each fire company inspection district with flow data on each hydrant. (In areas where the water distribution system produces fluctuating flows, however, hydrants should not be marked with flow data.) Hydrants should be marked for nighttime visibility. In many communities the development of geographical information systems (GIS) maps has included a layer that shows the location of every hydrant in the jurisdiction. GIS maps available electronically, and those that identify the global positioning system (GPS) location of the hydrants are increasingly common.

Water departments should operate according to nationally recognized standards, such as those published by the Insurance Services Organization (ISO) and the American Water Works Association (AWWA). The fire department liaison officer should

be familiar with the standards and guidance used by the water department. The fire department should work closely with the water department to identify areas of responsibility and authority for matters such as private hydrant maintenance (in shopping centers, etc.), records management, and development planning and zoning issues.

Public Health Department

Local public health agencies are key partners in community risk management. Fire-rescue department officials should be familiar with local public health officials and coordinate disaster preparedness, response, and recovery planning. A department liaison officer should identify a point of contact within the local public health agency with which regular contact can be maintained. The local health agency is also a conduit to state and federal public health authorities. Public health planners can share guidance with department members for handling emerging diseases and other biohazards, as well as information that has been prepared to inform the public of these issues.

Transportation Department

The local department of transportation is responsible for building and maintaining local roads and streets, and is in constant contact with regional, state, and federal department of transportation agencies. Fire-rescue departments should establish and maintain a good working relationship with the local department of transportation, including staying abreast of its short- and long-term plans for the area. During transportation emergencies, the department of transportation is an invaluable resource and should be part of the unified command structure.

Many metropolitan areas have a regional transportation authority that acts as the long-term planning body for the region. The plans developed often include light rail, rail, and bus systems. Understanding in advance what new modes of transportation and vehicles of conveyance will be brought into the area can be important to fire-rescue planners. A liaison to the regional transportation authority can assist in setting realistic objectives in long-term planning.

Domestic Preparedness Department

Since the federal Department of Homeland Security was created in 2002, state and local government offices have also been organized to address domestic preparedness concerns. The primary goal of these offices is to prevent acts of terrorism, but they also prepare for, respond to, and lead recovery efforts following such acts. Fire-rescue departments should be aware of and in conversation with any homeland security office with standing in their jurisdiction. If an information sharing and analysis center (ISAC) has been created, the department should ensure that fire-rescue personnel participate in its activities and receive relevant information as it is developed. The resilience of a community and its ability to rebound following a terrorist attack will likely hinge on the degree to which comprehensive planning and networking occurred prior to the attack. Fire-rescue officials should insert themselves into local and regional antiterrorism preparedness efforts, along with their allied planning partners.

Emergency Management Agency

Many fire departments are organized to operate the local emergency management agency (EMA) as well. As EMAs have become larger and taken on a wider range of services, however, independently organized EMAs have sprung up within local government. Fire-rescue departments should position themselves as a main support agency to the local EMA. Planning and preparedness for natural disasters is often the primary focus of the EMA and fire-rescue planners have experience, equipment, and trained, geographically distributed staff to offer the community when disaster strikes.

Public Education Department

In the realm of fire safety education, the local public and private school systems, the parks and recreation department, and the public library system can augment and support the local fire department's educational activities. If public fire safety educational activities are to be successful, the local fire department must be able to serve as a focal point for other community resources and be able to build partnerships across a wide variety of public and private organizations. The *Learn Not to Burn*® program is one of the NFPA's excellent fire safety education programs with proven results.

The community safety village is a successful concept originally developed in Canada and now becoming more common in the United States. These villages offer a delivery point in the community for programs of safety education and can include a wide range of education programs, including fire, bicycle, pool, pedestrian, driver, and gun safety. The typical village incorporates classroom space and a kid-sized town into a campus that is used as a training ground for practical elements of the safety lessons. The safety village thus allows a range of organizations to collaborate in managing risk and improving community safety.

Human Resources Department

Members of career fire departments are public employees, and, as such, their recruitment and promotion may involve cooperation with the human resources agency, which, in some jurisdictions, is responsible for conducting entrance and promotional examinations. Fire department management should work closely with the human resources or personnel office, which usually manages compensation and benefits programs for the employing authority.

Finance Department

Fire departments should work closely with finance officials when developing and administering budgets. Budgeting is generally very complex, and fire budget documents must be well prepared. After budgets have been prepared and adopted, proper records of expenditures must be maintained and spending must be kept within the adopted budget. Although some fire departments may have a finance officer, liaison with the finance department may be handled by designated staff officers.

Purchasing Department

All purchases exceeding stipulated amounts must be made according to specifications, usually with competitive bidding conducted by the purchasing department. Close liaison is necessary to ensure that specifications are drawn properly and meet fire department needs and that, when bids are opened, any proposals that deviate from specifications are rejected.

Data Processing Department

Increasingly, fire departments are using electronic data processing to keep fire records and payroll records for statistical analysis. Each fire department should have persons knowledgeable in data processing. It may be desirable to appoint one officer to coordinate this activity and to be involved in administrative planning for the department.

Planning Department

Fire departments, particularly those in rapidly growing areas, should maintain a close working relationship with local and regional planning groups, such as the local emergency planning council (LEPC) and the regional transportation authority. These agencies can provide valuable information on growth patterns that will affect the resources of the department and demands on those resources. The plans, studies, and reports prepared by the planning agencies can be used to determine whether more personnel, equipment, or station facilities are needed.

A variety of other sources of information are also available to fire department planners. Local academic institutions may provide resources that can aid in strategic planning. Coalitions of government that act to coordinate local government agencies actions in regional emergencies often develop sector-specific committees that can serve as referent information sources to planners. Recently, regional planning bodies that convene to address domestic preparedness issues, such as urban area security initiatives, have also become available as a planning resource. Astute fire-rescue planners will avail themselves of the entire planning and information community.

SUMMARY

Fire departments have evolved into organizations that provide a wide array of services. Although fire prevention and emergency response continue to form the basis of the service, most departments now provide some level of emergency medical service, and others provide specialized rescue and hazardous materials response. The growing threat of terrorism presents a new challenge to the changing fire service.

There are many common denominators that define a successful fire service organization. The most successful ones, however, have developed and have adjusted to meet the changing needs of their local communities. Although regional differences result in a significant diversity in structure and staffing, volunteer, paid, and combination departments all function in an environment in which their effectiveness depends on successful intergovernmental relationships with many agencies that interact to achieve public safety.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the management of fire-rescue departments discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of the current editions of the following documents.)*

NFPA 1001, *Standard for Fire Fighter Professional Qualifications*
NFPA 1021, *Standard for Fire Officer Professional Qualifications*
NFPA 1221, *Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems*
NFPA 1401, *Recommended Practice for Fire Service Training Reports and Records*
NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*
NFPA 1620, *Recommended Practice for Pre-Incident Planning*
NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments*
NFPA 1901, *Standard for Automotive Fire Apparatus*

Chapter 5

Information Management and Computer Technology

Brian P. Duggan

Chapter Contents

Information Technology Networks
Management Applications
Emergency Response and Operational Applications
Internal and Public Communication Applications
Planning, Training, and Research
Integration of Systems

Key Terms

computer-aided dispatch, enhanced 9-1-1, geographic information system (GIS), incident reporting system, information management, information technology, interoperable communications, Learning Resource Center (LRC), local area network (LAN), mobile data terminal, office automation, personnel accountability system, thermal imaging, wide area network (WAN)

As the fire service enters a new age of expanded information, technology continues to evolve rapidly. This digital revolution has produced an unprecedented external force that requires fire service organizations to change and adapt in an environment increasingly focused on the instantaneous exchange of information. Information-based technology continues to expand at an exponential rate. Often technology is initially developed for the military, space program, or the business community and then adapted to benefit the fire service. The trend toward expanding information applications, integration, and mobile connectivity should be anticipated, and new fire service applications that extend beyond those mentioned here should be expected. Examples of developing applications include intelligent transportation systems that will provide responding units with incident-related information and voice integration that will allow computers to recognize and respond to an individual's voice.

Information technology can enhance organizational effectiveness and efficiency by providing rapid access to high-quality information and empower fire department personnel to offer a higher level of service. Information technology has become an organizational necessity and provides a means for the fire service to innovate and adapt in an increasingly digital world. Although it is clear that the fire service needs to learn new technologies, its mission must be to harness and drive the technology as opposed to allowing technology to drive the fire service.

For related information, see Section 3, Chapter 3, "Fire Data Collection and Databases"; Section 3, Chapter 4, "Use of Fire Incident Data and Statistics"; and Section 12, Chapter 13, "GIS for Fire Station Locations and Response Protocols."

INFORMATION TECHNOLOGY NETWORKS

The availability of low-cost personal computers, widespread Internet access, and wireless connectivity provides even the smallest fire service organizations with the ability to utilize many of the applications discussed in this chapter. As price points continue to decline, a wider range of technology will become more available. In some cases this technology will become single-use disposable items that are critical to operational success. Technology has become evident in most aspects of our culture and can complement the mission of the fire service. These applications range from the dispatch of apparatus to training personnel and providing public education and information services to target populations. Figure 12.5.1 shows an example of fire service specific handheld technology. This rugged unit provides mobile wireless computing for a wide range of fire service applications including personnel accountability and building inspection.

As with many public sector agencies, the fire service is facing the reality of increased competition and diminished resources. Like all government units, the fire service has been asked to maintain, and even increase, service levels. Information technology can facilitate new levels of communication and can help integrate services that provide a foundation for quality service delivery

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FIGURE 12.5.1 Handheld Technology Specific to Fire Service (Photo provided courtesy of Tripod Data Systems, Inc.)

and innovation. The contradiction of "doing more with less" can be resolved only with improved management practices that result in higher levels of organizational productivity. Information technology can assist the fire service in meeting the increasing challenges of the twenty-first century. Specifically, information technology is being used to support and complement the following fire service functions:

- Administration and office automation
- Emergency management
- Emergency response, operations, and safety
- Enhanced internal and external communication
- Fire prevention public education and community outreach
- Hazard detection
- Research activity reporting
- Resource control and deployment
- Training

Although the extent of automation varies, the development of information technology has become a specialized niche and many larger organizations have hired information managers and Internet specialists to maximize the organization's ability to successfully apply and benefit from information technology. Information technology has produced a focus on enhancing the effectiveness of both internal and external communication. As such, the development of a sound information technology plan that collaborates and coordinates with other agencies is critical to success.

Local Area Networks (LAN) and Wide Area Networks (WAN)

Connectivity and mobile information applications deserve special attention based on the potential of these applications to benefit the fire service. First, internal connectivity provides the ability to rapidly integrate and share information through the use of local area networks (LAN) and intranets by providing a consistent source of enhanced internal organizational communication. Second, connectivity frequently extends beyond a single agency through the use of a wide area network (WAN). For example, every department in a city may be connected and allowed to rapidly share information and communicate through the use of a single WAN. Networks once fed through miles of wire are quickly becoming wireless and as such more versatile.

The Internet

Connectivity can be further extended through the use of the Internet. The Internet—the organized part of which is called the World Wide Web—provides a means of external connection that can facilitate almost instantaneous communication, data transfer, and information exchange across the globe. The Internet is becoming the most frequent portal of organizational contact with the public. At present, most public sector agencies and private companies maintain an easily accessed informational or commerce-based website. NFPA, for example, maintains a home page on the World Wide Web at http://www.nfpa.org. The Internet provides sources of information on any subject. Some of this information can have relevance in supporting programs, establishing contacts with other persons dealing with the same issues, or developing information for research.

As the Internet has expanded it has become a resource that in many ways has replaced text-based reference sources and printed materials. In essence the Internet has become a library of information and as such an indispensable resource. An example of the vast amount of fire service data available through the Internet can be found through the Learning Resource Center (LRC), which is a virtual fire service specific library maintained by the United States Fire Administration. The LRC provides instant access to an extensive quantity of fire service research and publications. This resource can be found on the Internet at http://www.usfa.fema.gov/training/lrc. Those using information from the Internet are cautioned to verify the source and validity of that information because there is no professional oversight as to what is posted other than information posted by technical organizations.

Fire service agencies can use the Internet successfully for an ever-broadening range of communication needs. One example of how the Internet can benefit the fire service is by providing instant access to the current *National Fire Codes*®, which is an option available through a secure portion of the NFPA website. Through this service, the subscriber is ensured access to updated codes. Previously, updates of *National Fire Codes* were mailed out in printed form or on CD-ROM on a regular basis. This use of technology decreases publication costs, enhances the use of current standards, and increases the effectiveness and efficiency of the subscriber.

Other Internet applications include information research, electronic transactions, purchasing, public outreach, voice communication, video transmission, data transmission, and distance learning. The Internet also provides a tremendous potential for the future as technology continues to evolve.

Although the Internet is full of useful information and has become a primary research tool, it also contains hazards. As technology has developed, viruses, unwanted junk e-mail, and unauthorized intrusion into organizational networks have become all too common. Organizations need to be mindful of

these threats and provide appropriate protection through the use of firewalls, secure software, and diligent data backup.

Wireless Connectivity and Mobile Data

Wireless connectivity has become commonplace, and this technology can be utilized to further extend fire service capabilities. Mobile data allow responding units and command personnel to have rapid access to critical address-based information (Figure 12.5.2). Mobile data also enhance the effectiveness and efficiency of event reporting, allowing fire, medical, and inspection reports to be completed in the field and uploaded to a secure server. Clearly this provides a more rapid means of data collection and reduces the time personnel previously dedicated to these administrative functions on their return from an incident or fire prevention activity.

The advantages of mobile data and wireless connectivity are evident both at the incident scene and through the application of technology developed for the business world. Fire service agencies can also use wireless technology to dramatically enhance communication and coordination of nonresponse functions. Examples of this include electronic mail, remote retrieval of department records, and scheduling applications.

The information age has also provided additional tools that can be used to enhance both safety and operational effectiveness. Examples include computer-driven infrared imagery, electronic personnel accountability systems, and command management software.

Many fire departments have automated a wide variety of functions. Integration of several applications allows for the sharing and retrieval of information among previously distant platforms. Fire service information can be shared among databases and linked through the common thread of address-, person-, or resource-based information fields. (For related information, see Section 3, Chapter 3, "Fire Data Collection and Databases," and Section 3, Chapter 4, "Use of Fire Incident Data and Statistics.")

FIGURE 12.5.2 Command Officer Using a Mobile Data Terminal (Photo provided courtesy of Livermore-Pleasanton Fire Department)

MANAGEMENT APPLICATIONS

Information Management

The successful functioning of a fire department's *information technology*—a term that is used here to include computers, software, data, applications, connectivity, and personnel—depends on how that technology is organized, managed, and incorporated into the organization. Because every organization is unique and because technology continues to provide expanded application opportunities, there is no single best way to develop information technology. A critical step that is often overlooked, however, is the development and training of personnel. Organizations often fail to invest in training personnel how to use and benefit from technology. Without the appropriate development and training of personnel, their resistance to the new technology that often impedes the effective deployment of applications should be anticipated.

Information management within an organization is critical to an organization's overall success. Consequently, information systems are valuable organizational components that must be well managed. Many fire departments now have senior staff members who are responsible for the management of information systems.

Organizational Needs vis-à-vis Information Systems

A well-developed information system fulfills a variety of organizational needs:

- Strategic planning
- Resource optimization
- Support of daily operations
- Public outreach and communications
- Internal communication and documentation

Strategic Planning. Strategic planning is the process by which fire service leaders decide how future resources will be allocated or deployed in the delivery of services—for example, how and where facilities, emergency equipment, and personnel will be distributed. Some fire departments have developed sophisticated computer-based models for the development of strategic plans; others have contracted outside resource groups to provide such analyses. Although modeling applications are becoming cost-effective and widely available, most fire departments depend on the statistical information from fire incident and emergency medical reporting systems as a basis for decision making.

Resource Optimization. Resource optimization is the process of maximizing the output or service provided by resources. Therefore, by optimizing resources we can ensure a high level of effectiveness and efficiency. Resource optimization begins with implementation of strategic choices identified through strategic planning. It continues with the use of control information to make tactical and operational decisions consistent with the organization's strategy and oversight that all decisions are being

implemented as intended. Administrative control and automation are necessary in several areas: (1) finance, (2) personnel, (3) fire prevention, (4) fire investigation, (5) fire suppression, and (6) facility management. Control information is often provided as an additional output of systems designed to support administrative operations. In other words, many applications were initiated for administrative utilization. As an additional benefit, this information can often be used to optimize control of resources such as personnel and equipment. For example, a personnel information system developed to increase the efficiency of collecting and tracking data on individual personnel is likely to permit easy tracking of secondary data useful as controls on the entire workforce (e.g., scheduling of needed training). Applications such as a personnel information-gathering system are often adapted from programs originally developed to meet the needs of the business world.

Support of Daily Operations. The majority of fire service applications and information systems are designed to support day-to-day operations. The most common examples of this type of system are computer-aided dispatch (CAD) and enhanced 9-1-1 (E9-1-1). These systems attempt to optimize response by combining the most accurate data about both the emergency situation and resource availability. Other systems support financial management, fire investigation, equipment inventory and maintenance, inspections, permits, and organizational communications.

Public Outreach and Communications. The ability to provide information to the customer is critical to the future success of the fire service. Websites, e-mail, and distance learning provide an electronic means of enhancing outreach and communication within the community. This form of communication engages the community and provides a previously unheard of level of public contact and customer support. Departments often utilize this conduit to provide information about both the organization and life safety.

Internal Communication and Documentation. The systems applications cited earlier operate as systems of information flow and processing. Each requires certain forms of internal communication and documentation. Strategic planning and resource optimization depend on internal communication of goals, objectives, alternative choices and decisions, and documented field experience, activities, and inventories. Operations support requires internal communications of situation-specific facts and decisions based on the interpretation of principles and procedures in light of these facts. Through integration, systems are often packaged as a function of priorities based on systems planning, organizational needs, and these types of situational factors. There are, however, certain recurring patterns to the way information systems are developed and used within fire service organizations. The following are widely used applications of fire department information systems:

- Word processing
- Electronic mail
- Personnel and facilities scheduling
- Spreadsheet and database programs

Resource Control and Deployment

Program and Organizational Performance Evaluation. Program evaluation is the mechanism by which fire service agencies use facts to make choices about actions that will best achieve their goals. Information technology can be utilized to evaluate an individual program or an entire organization's performance. Points of evaluation must be based on a comparative analysis with other similar service-based agencies. The quality of annual performance and service-level reporting often contributes to resource-level determination. Presenting a compelling case to enhance resource levels is based on the ability to extract and present quality data. This analysis can be used to develop benchmarks that identify both the best practices and the average performance. The benchmarking process can provide a tangible performance analysis of often intangible services. For example, through analysis of trends in fire death and injury statistics, an organization can gauge the overall performance or output of its fire prevention and public education programs. Evaluation can also provide information relating to performance-based criteria, such as the evaluation of response times, or to the need for specialized services, such as advanced life support (ALS), hazardous materials response, or technical rescue.

Fleet Management. Vehicles and equipment represent a significant capital investment, provide safety to fire service personnel, and enable the delivery of high-quality emergency services to the community. Fleet management systems provide the information needed for budgeting and controlling these expenditures, as well as for ensuring that the fleet is maintained in a high state of readiness. The need for information about the fire department fleet exists at all levels: strategic, managerial, and operational. To meet this data-intensive need, fleet management systems involve several components, including fleet inventory, equipment inventory, maintenance records, vehicle replacement schedules, fuel consumption, internal billing for vehicle use (e.g., in the case of citywide carpools), repair cost projection, and performance analysis. Most of these components have become common in the majority of fleet management systems.

At the strategic level, information about the existing fleet is needed to plan and budget for vehicle acquisition and replacement. To make sound replacement decisions, accurate information on maintenance frequency, operating costs, age, and so on for each major piece of equipment is needed. Indeed, those decisions are often so complicated and have such significant political overtones that decision-support software (i.e., operations research models) is needed to help analyze and organize these data.

At the managerial control level, fleet managers need computer support to control preventive maintenance intervals, prioritize work in progress, track fuel consumption, and plan for the appropriate staffing of the maintenance facility. If the maintenance staff members are to be effective, they require immediate access to information, such as vehicle performance, repair records, parts inventory, interchangeable parts data, equipment

manuals, and standard repair times. Likewise, administrative services managers need financial data on expenses for budgetary forecasting and control.

Personnel at the operational or task level also need information from a fleet management system. Most important, of course, is the ability to have information on vehicle condition and availability. Although this information is not always provided by the fleet management system per se, dispatchers need to know what equipment is in service and available to respond to a given type of emergency.

Few fire departments develop their own fleet management systems. They either use a commercially available system or a citywide fleet management system. Commercial systems may be difficult to interface directly with other department or city systems. Also, added capabilities, such as vehicle replacement models, may not easily integrate with these systems. Yet, this internal approach can be implemented easily and is cost-effective, especially for fire departments that do not have highly integrated systems.

The citywide approach also suffers from some of the same deficiencies. Since citywide systems are typically designed for standard street vehicles, they may ignore certain features that would be common to fire apparatus and emergency response vehicles. For example, the city system may not have a provision for capturing and maintaining special data on apparatus components, or it may not provide for maintenance records of special equipment unique to the fire service. If these deficiencies are to be eliminated, the fire personnel must actively participate in defining information requirements. When these requirements have been defined, the citywide approach can be worthwhile. As fire service integration advances, fleet management systems that are customized to the specific needs of the fire service are becoming a common part of most fire department records management systems.

Capital Asset and Personnel Planning. The ability to develop and support a capital plan that anticipates service demand has become an extremely technical process that involves several aspects of information technology. This process includes the evaluation of incident type, location history, response time analysis, and the evaluation of resource availability. This information can be used to model station locations, set performance-based goals, determine peak service demand hours, identify service gaps, and forecast personnel, facility, and equipment needs.

EMERGENCY RESPONSE AND OPERATIONAL APPLICATIONS

Computer-Aided Dispatch

Computer-aided dispatch (CAD) is an address- or occupancy-based information application that is oriented toward operations. CAD monitors resource status and optimizes emergency response by rapidly assigning the closest appropriate and available units (Figure 12.5.3). Through integrated CAD systems, resources are tracked, alarms are received, fire stations are alerted,

FIGURE 12.5.3 Dispatcher Using a Multiscreen CAD System (Photo provided courtesy of Geac Public Safety)

information on hazards can be transmitted, and situations are managed. The system's purpose is to support current activity rather than provide managerial control or strategic planning information. However, the functions of CAD systems often go beyond operational support. In an integrated information systems environment, the CAD system may produce nonoperational information in support of other administrative and planning functions.

CAD systems support a multitude of fire service dispatch functions:

- Alarm receipt, fire alarm signal decoding, central station communications management, and so on
- Communications and signaling management: alerting unit/station, two-way exchange of data, paging, electronic mail, radio frequency selection, and coordination
- Emergency medical dispatch (EMD) and other situation-based emergency instruction
- Status maintenance: monitor resources, equipment, personnel, and system supervisor
- Response assignment: dynamic assignment based on current availability and relative location of emergency response resources to incident

Although CAD is usually credited with reducing response time, the payoff is not necessarily in this area. Some departments even report an increase in response time after implementing a CAD system. The real benefits of CAD occur in the coordination of emergency response activity. Thus, rapid recall of information, such as apparatus status and occupancy data, is at least as important as response time.

Implementing a CAD System. Choosing a correct approach to implementing a CAD system is a multifaceted problem. The first facet of the problem is related to policy. In some cases, dispatching is a shared public safety responsibility. In others, regional dispatch centers serve multiple jurisdictions. The organizational situation can have an important influence on other aspects of the approach, as well as on the ultimate usefulness of the system.

Determining the System Scope. A major starting point in CAD development is a decision on the scope of the system—that is, whether the system is to be developed only for CAD or whether it will include other applications. Most departments elect to develop a stand-alone CAD system with the necessary interfaces to other applications, for example, the fire incident reporting system. Others may elect to more closely integrate their CAD system with other computerized record management systems (RMS) in the department. Regardless of how many applications may be bundled together, the CAD operation is the top priority and it is designed to continue to operate even if some of the other applications are temporarily unavailable.

Closely related to the issue of scope is the degree of modularity built into the system. A highly modular system permits the system to be expanded to include enhanced CAD functions, such as alarm system interface and alphanumeric paging, as well as other peripheral applications. It also allows new software to be tested in an off-line mode and operators to be trained without interfering with operations. Modularity is important in all applications, but it is especially critical in CAD systems because the systems are subject to almost constant change.

Using Outside Contractors. An outside contractor is often used to develop a department's CAD system, although internal teams have developed effective systems. If an outside contractor is used, both operations and communications personnel must be extensively involved in developing the system requirements and specifications to ensure that the final system meets their needs. Likewise, when the system is installed, all staff members must be involved so they understand the system design and are properly trained to maintain and operate the system. The importance of properly involving and training personnel cannot be overstated.

Interoperable Communications. Communications is another aspect in selecting an approach. Standard telephone service has typically been used for communications between the dispatch center and the fire stations. Increasingly, other ways are being found to transmit data. The 800 MHz radio frequencies have been used successfully, as have microwave links and dedicated data lines. Alphanumeric pagers, computer terminals in fire apparatus with both paper printouts and liquid crystal display (LCD) readouts, fax machines, voice-over Internet, and cellular telephones are also becoming increasingly popular for dispatching apparatus and communicating with company officers and incident commanders.

The ability to operate on multiple frequencies and coordinate operations between agencies has become increasingly complex. Often agencies even with the same jurisdiction operate on different frequencies. The inability to create seamless controlled interoperable communications is an ongoing challenge within public safety agencies. Technology has expanded to provide the ability to bridge frequencies. These efforts, however, must be planned and managed through a communications plan because this technology can quickly create a dysfunctional situation. Interoperability equipment includes both a computer-based patching capability (Figure 12.5.4) and banks of radios (Figure 12.5.5).

Incident Management Support

The effective and efficient management of significant incidents can tax even the largest fire service organizations. The use of technology to coordinate and manage operations during large-scale events has increased, and many jurisdictions have developed mobile technology platforms that are designed to optimize deployment, coordinate activity between multiple agencies, and provide general incident support services. Figure 12.5.6 shows an incident in which a technology platform provided incident support at a large warehouse fire.

FIGURE 12.5.4 Computer-Based Patching (Photo provided courtesy of the Massachusetts Department of Fire Services)

FIGURE 12.5.5 Banks of Radios (Photo provided courtesy of the Massachusetts Department of Fire Services)

FIGURE 12.5.6 ISU Fire Response (Photo provided courtesy of the Massachusetts Department of Fire Services)

Although some of these platforms, such as the mobile technology platform pictured in Figure 12.5.7, were designed and deployed prior to the tragic events of September 11, 2001, the development of these vehicles, which often serve a large region or multiple agencies, has become commonplace.

The mobile technology platform pictured in Figure 12.5.7 can effectively be utilized to support operations and assist the incident commander. Examples of the technology provided by the mobile platform often include the following:

- Additional communication resources
- Cellular and satellite-based telecommunications
- Coordination of emergency response mobilizations
- Cross-band and multi-agency communications management
- Download of audio and video signals

FIGURE 12.5.7 Mobile Technology Platform Used to Support Large-Scale Operations (Photo provided courtesy of the Massachusetts Department of Fire Services)

- Equipment tracking
- Event logging
- Geographic information systems
- Interface with other agencies and units
- Internet and paging access
- Interoperable communications planning and management
- Scheduling and long-term planning
- Thermal video imaging and projection
- Weather monitoring

Many communities replicate some of the foregoing resources within an emergency operations center (EOC), and these mobile technology platforms offer the unique ability to operate at an incident scene. Because this equipment is complex, it is essential to have a trained overhead team that works with this technology on a regular basis.

Emergency Access Systems

Enhanced 9-1-1 System. Enhanced 9-1-1, or E9-1-1, is a highly reliable emergency phone system that displays the caller's telephone number, address, response district, and other important information automatically on the dispatcher's computer screen, along with dispatch information for fire, police, emergency medical service (EMS), or other emergency responders. This system is invaluable, especially in those cases where the caller is unable to give information fully or clearly because of language barriers, incapacitation, confusion, or excitement caused by the incident, age, or even lack of knowledge of the area. E9-1-1 can have a dramatic effect on reducing response times. Because it identifies the actual telephone location from where the call is placed, it also helps reduce false alarms.

This system has been widely installed throughout the United States. Even more sophisticated systems can provide information concerning previous calls to the same address, hazardous materials stored on site, day care or other life-safety–intensive operations at the address, and other information pertaining to a caller's disability or medical condition that is useful to the responding units.

As E9-1-1 continues to develop, cellular triangulation that maps and identifies the relative position of a caller will be implemented. The development of a caller's location can be accomplished through the use of signal triangulation from multiple cellular towers and integration with geographic positioning systems (GPS). This technology is common within the majority of enhanced 9-1-1 systems and has the potential to provide information that will assist in locating an incident, therefore saving both time and lives. As 9-1-1 systems have become accepted by society, they often become overburdened with less than true emergency calls. In an effort to properly channel these informational calls, over two dozen U.S. cities have developed alternative informational numbers such as 3-1-1 to divert call volume and match the callers to the best resource to address their needs.

Although the Internet and other modern technologies are being used globally, the application of these technologies varies widely. Of more specific interest here is whether and what kind of enhanced emergency access systems are found in countries outside the United States. Australia has a system similar to the

enhanced 9-1-1 system found in the United States. A call (made to 000, the Australian emergency call number) is received by the national telephone company and passed on to the CAD system covering that area, at which point enhancement kicks in with call line identification and cell phone general area information. The system then captures the information for the incident reports. Utilizing the triangulation of cellular signals in concert with geographic positioning systems, the vast majority of enhanced 9-1-1 systems can rapidly determine the geographic location of a caller.

Across Pacific Asia, enhanced emergency access systems range from very sophisticated systems in Singapore and Hong Kong to very basic systems in other parts of Asia. Of significance to the development of such systems are issues pertaining to the infrastructure currently available, especially within relatively underdeveloped countries.

Geographic Information and Positioning Systems

The integration of digital imagery and mapping technology provides a foundation for the development of location-based applications that combine to form a geographic information system (GIS). This address-based information system serves as a valuable tool to many municipal agencies and can provide a central information link between departments if GIS has been developed, integrated, and networked properly. For example, when a new subdivision is proposed, information relative to the water system would be of interest to the building, fire, planning, and water departments. Information on a structure at a given location is of value both to units responding to an emergency and to the community's tax assessor. Consult Section 12, Chapter 13, "GIS for Fire Station Locations and Response Protocols," for more information on GIS.

GIS represents a mapping application that provides several selectable layers of information. Each layer can be included or excluded depending on the specific need—for example, the zoning information layer would not be of value when configuring GIS to provide a map to be used to search for a missing person. GIS offers a previously unknown ability to consolidate information by address. Specific to the fire service, information pertaining to hazards, permits, structure history, water supply, navigation, and topographical land features are routinely utilized.

GIS can also be used to support fire service planning needs, ranging from response time evaluation to station location analysis. Operationally, GIS can be used to support fire service activity at a variety of emergency situations, including hazardous materials situations, wildfires, and weather-related events. Capitalizing on the ability to integrate multiple applications, officials can now anticipate the track of a severe storm or chemical plume and automatically warn residents within the projected path. Through this technology, evacuations can be expedited and residents can be advised to take appropriate action. Previously, these notifications would take hours and consume vast amounts of resources.

Geographic positioning system (GPS) integrates the mapping of GIS with the ability to determine current location (Figure 12.5.8). This technology, originally developed by the military, can provide accurate location information for aircraft or other responding resources. In addition, GPS can aid navigation by providing directions, inclusive of verbal instructions, to a destination. GPS can be updated to provide optimal routing, given changing traffic conditions. These systems have become popular options in many passenger vehicles, and as they become more affordable, they will continue to gain popularity. In the future, GPS will likely be integrated with intelligent transportation systems and provide an automated reflection of current conditions.

Automatic vehicle location (AVL) further links GPS to GIS. AVL provides the dispatch center with the ability to visually monitor a real-time map that shows resource status, speed, and location. As a result, available units that are closest to a situation can be dispatched. AVL enhances resource control and dramatically reduces response time to emergency situations. This technology truly saves lives, reduces loss, optimizes resource deployment, and complements the fire service mission.

Mobile Data

The ability to provide critical information to responding units can be accomplished through the use of wireless computer technology. Through mobile data systems, responding units can obtain situation updates, directions, prefire plans, digital imaging, structure information, hazard information, water-supply configuration, and hydrant locations (Figure 12.5.9).

In addition, the ability to communicate remotely provides rapid access to reliable data and improves the decision-making process. Mobile data can be transmitted through radio systems or cellular technology; at present, the most popular transmission medium is either the use of secure wireless Internet connection or data bursts sent through cellular digital packet technology (CDPD). As communications networks evolve, mobile data communication will increase in speed and will most likely include the use of both satellites and the Internet.

FIGURE 12.5.8 Mobile Geographic Positioning and Mapping Information (Photo provided courtesy of Livermore-Pleasanton Fire Department)

FIGURE 12.5.9 Responding Engine Company Using a Mobile Data Unit (Graphic image provided courtesy of ESRI. Copyright © 1999, 2000 ESRI)

Thermal Imaging

An infrared thermal imagery unit, which detects temperature variations, can penetrate smoke, structural features, and darkness and provide fire fighters with a visual image of reflected temperature (Figure 12.5.10). Light changes indicate temperature variations. This computer-based tool can be harnessed to increase both the ability and safety of fire service personnel. Thermal imagery, the projection of heat images, has several fire service applications, including the following:

- Searching for fire victims
- Searching for hidden fire (in concealed spaces)
- Searching for missing persons
- Identifying malfunctioning equipment
- Identifying fire location
- Providing assistance to other agencies, municipal agencies, and industry

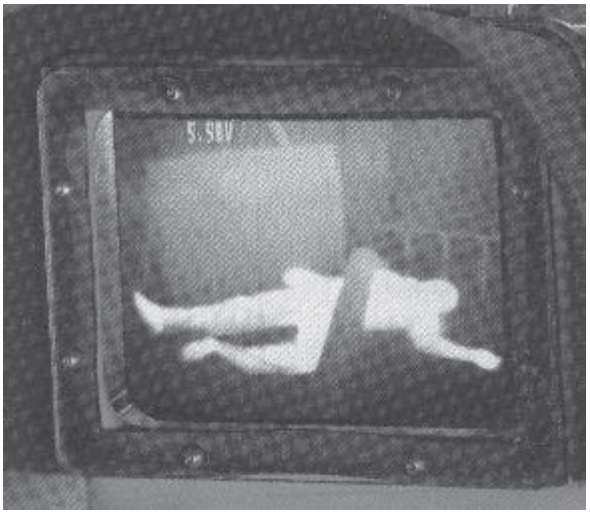
Thermal images can also be transmitted to provide command personnel with improved reconnaissance as they manage a situation from a remote location. The size of thermal imagers continues to decrease and additional technological advances should be expected. Currently thermal imaging has become an affordable technology that continues to evolve. Future enhancements will include the integration of imagers into a fire fighters' turnout gear, color display, levels of warning, and pattern recognition.

Personnel Accountability/Fire Fighter Tracking Systems

The need to track personnel operating at an emergency scene is a basic principle of safe operations. Technology that uses bar code scanning, coded data chips, radio signal transmissions, and personal digital assistant databases assists command and safety personnel with the management of this complex function in less than optimal environments. Currently, automated personnel accountability systems can track personnel assignments, duration of entry, and project air consumption (Figure 12.5.11). These units automatically prompt and record periodic personnel accountability reports. Other systems can be utilized to direct rescue crews toward the location of a lost or injured fire fighter. Although many systems are complex, this emerging technology is becoming easier to use and more cost-effective. The challenge will be to utilize this technology to provide a timely and accurate reflection of operations.

Locating an injured or unresponsive fire fighter has been a difficult task. Automated location systems that provide a directional pointer to the location of a fire fighter in distress can assist a rapid intervention team. Although this technology is currently useful, it should be expected that systems of this type will be enhanced to provide more detailed information.

(a)



(b)

FIGURE 12.5.10 (a) Thermal Imaging Unit (b) Thermal Image (Photos provided courtesy of Bullard®)

FIGURE 12.5.11 Automated Handheld Personnel Accountability Device (Photo provided courtesy of XTrack.com)

Hazardous Materials Detection

The ability to detect hazardous conditions is firmly based within technology. As the need to handle hazardous materials has increased, the need to detect chemical, biological, radiological, and nuclear threats has developed a wide array of computer-driven metering systems. As this technology matures, these metering devices are becoming increasingly reliable, more compact, and easier to use.

Digital Documentation

In a litigious society the need to document conditions and actions at the incident scene has dramatically increased. Information technology has facilitated this documentation. Most fire service radio traffic and telecommunications are digitally recorded and time/date stamped. This audio recording of voice communication provides a foundation for event documentation.

Digital Imagery

Both still photographs and video expand the ability to provide professional documentation. These images can enhance post-operational review and serve as a training and evaluation tool. Images can also communicate and market the organization's role and mission and can be used as a tool in public education efforts. Documentation is essential to an effective fire investigation program.

Emergency Medical Services

Most fire departments now provide emergency medical service (EMS). Fire equipment and fire fighters are generally dispatched to perform or support EMS activities. The fire department may or may not be involved in the actual patient transport. Ambulances, whether operated by the fire department, another city agency, or the private sector, are often dispatched by the fire department or public safety dispatch center.

Technology has gained an expanding role within emergency medical services over the last 5 years (Figure 12.5.12). Examples of the utilization of technology range from defibrillators that can correct an improper electrical rhythm within the heart to a pulse oximeter that monitors a patient's oxygen level.

In many jurisdictions, the cost of emergency medical service is billed to the patient. Since this practice represents a substantial revenue source for the city or county, the billing process is the most intensive information system within most EMS systems. Other components of an EMS data system include the following:

- Patient care information
- Treatment protocol and reference material
- Response needs and resource allocation
- Training material

The statistics generated from EMS systems are used in both long-range plans and operational planning and control. Response times, locations of incidents, and unit staffing and deployment patterns are required to plan and budget for resources and determine if the units, personnel, and facilities are being configured appropriately.

In some fire departments, separate systems have been designed to handle both the EMS billing system and the EMS incident records. In other departments, data from the billing system are transferred to the fire incident reporting system from which operational statistics are generated. Having all incident data in-

FIGURE 12.5.12 Wireless Reporting System for Patient Care (Photo provided courtesy of Zoll Data Systems, Inc.)

tegrated into the same database is helpful in studying fire department emergency activity.

A basic EMS report form can be used by fire departments to keep track of their EMS activities and can be amended to reflect their specific EMS reporting needs. Mobile EMS reporting has enabled EMS personnel to quickly access and update patient care records while treating a patient. Many of these systems automatically upload and synchronize billing and patient care records.

Technology and information systems facilitate communication between ambulances and hospitals for the transmission of medical directions and telemetry data for physician evaluation. Mobile incident reporting has also become an accurate means of documentation because the report is completed rapidly. In addition, this technology can reduce the time that personnel dedicate to documentation and administrative tasks because reports are completed prior to returning to a fixed facility. As the use of the Internet and mobile data expands, the development of information technology that can transmit medical images and video to a treating physician should be expected. Technology currently in use concentrates on telemetry (sending heart rhythms and other critical patient care information over radio signals) and EMS incident reporting.

INTERNAL AND PUBLIC COMMUNICATION APPLICATIONS

Easy access to computer technology and the widespread acceptance of advancing technology have propelled the use of electronic communication. This shift in communication methodology provides the fire service with a tremendous opportunity to enhance both internal and external communications. Internally, electronic mail allows consistent and rapid communication to all personnel within the organization. Regular communication with shift personnel is increased with e-mail. A LAN, or intranet, which serves as an internal information network, can store reference material and share organizational information, such as policies and standard operating guidelines.

Externally, e-mail and Internet webpages permit the positive projection of an organization. Through increased communication, an organization can strengthen both community outreach and customer service. A webpage often becomes the most accessible public portal, and fire service agencies should recognize the importance of an Internet presence and develop a website that is reflective of the quality of the organization. The Internet, which has become a conduit for public information, allows the rapid dissemination of information. In its attempt to meet the needs of its customers, effective fire services will seize on this communication medium as a tool to educate and become more responsive to the community.

Public presentations often influence both resource allocation and programmatic success. Although a presentation reflects the ability of the speaker, information technology can add professionalism and provide a technological means to make presentations more effective. By using presentation software such as Microsoft PowerPoint and liquid crystal display (LCD) projection, speakers can augment and customize their presentations with audio, digital imagery, and video enhancements. They can then electronically transfer these presentations via the Internet to create a base for distance-learning applications. For example, a fire service agency may post an automated training program specific to fire safety for the elderly on its website and allow the public to download and view this material.

Administration and Office Automation

The term *office automation* refers to a group of applications that support clerical and managerial activities. These applications include word processing, spreadsheets for financial and numeric data, database development for various record-keeping applications, e-mail, "tickler" systems, teleconferencing and videoconferencing, and personal calendar management.

The purpose of these applications is to make the executive and the clerical worker more effective. Although the same may be said about traditional information systems, the focus here is different. Traditional information system applications are process oriented; office automation, in contrast, is more people oriented. The objective is to make office personnel more productive by allowing them to use computers and other technology as a natural extension of their minds and bodies.

Executives and clerical workers need office automation to cope with the complexities and increased demands of today's office environment. Fire agencies must contend with an explosion of information in the form of reports, forms, memoranda, and computer files. The efficient development and effective management of this information resource strain even the most dedicated staff. The computer, through automation applications, extends human intellectual capabilities and allows office staff to do more. Personnel development is essential to harness the abilities of office automation software suites. As office automation is developed, employee input must be considered. Through focus groups and internal training, consistent ways to maximize the potential benefit of this technology can be developed.

Mobile Connectivity

Mobile connectivity extends beyond prefire planning, reporting, and emergency operations. Remote communication through wireless technology, mobile data terminals, personal digital assistants, and cellular technology is growing in popularity (Figure 12.5.13). For example, through wireless integration, a fire inspector can adjust his or her schedule, retrieve technical data, update prefire plans, review facility history, and document activity without devoting administrative time at the office to perform these tasks. Therefore, through this technology the inspector's effectiveness and efficiency have been dramatically increased. Based on technology, the inspector can recall records, spend more time in the field, and be instantly updated.

Networking

To provide the needed integration while retaining the flexibility for stand-alone units, most fire service organizations are developing network-based systems. These are full-fledged computer systems specifically designed (both in terms of hardware and software) to handle office automation and interface with other public safety technology. The individual office computer is connected to a central server that manages data storage and

FIGURE 12.5.13 Wireless Personal Digital Assistant (Photo provided courtesy of Livermore-Pleasanton Fire Department)

communication. This setup allows the user to have a stand-alone workstation on a desktop that can perform all the office automation functions and still have access to the databases retained on the central network server (Figure 12.5.14).

There are several variations on network design. Depending on how data are captured and utilized throughout the network, various functions can be performed either by the desktop computers, network servers, or a central microcomputer. For example, a desktop computer might be used for word processing as a stand-alone task but be tied to a network system to transmit electronic mail, link to other computers, and make inquiries into CAD databases on a central computer. The network provides the mechanism to integrate all these activities. Based on the risk posed by mechanical failure, file corruption and virus infection-critical data should be backed up on a frequent basis. At least one full system backup should be stored at a remote location to avoid a potential catastrophic data loss if disaster strikes.

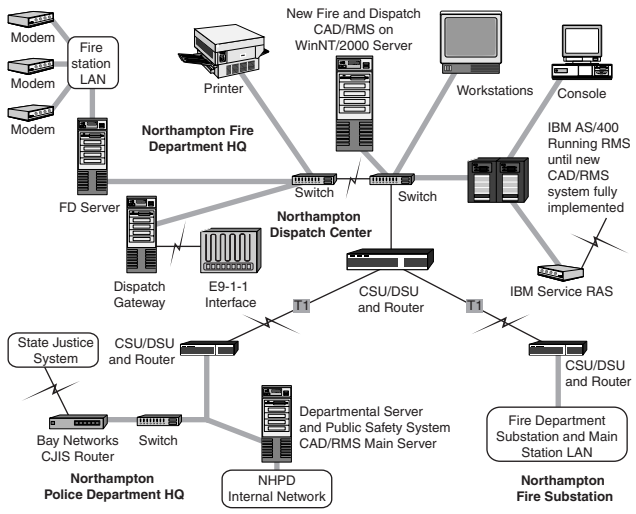


FIGURE 12.5.14 Sample Design for Public Safety Network (Image provided courtesy of Corporation for Public Technology)

Internal Databases

With the advent of desktop and laptop computers, commercial database packages that can develop customized files are becoming the accepted way of gathering information for a fire department. Relational databases not only accomplish one-dimensional tasks but also go much further in their usefulness. The term *relational* means information can be compared in relation to other information; for example, "what if" questions are easily and rapidly answered when data are gathered using a relational database. If a fire chief is asked to cut the budget and the only way to do so is to close a station for some period of time or send fewer engines, he or she can quickly determine the time period when such an action will have the least impact on service to the community. A relational database can analyze incident data to show the best time to close down a station, based on number of alarms, severity of fires, or other criteria the fire chief may want to use to determine the best alternative.

Relational databases, even though created for use on desktop computers, are extremely powerful, highly useful programs. The ease of learning and using these programs has improved dramatically over the past several years, such that most departments, no matter how large or small, would find them valuable tools for all types of information management.

External Databases

Much of the technical and legal information needed by fire departments exists on commercial or governmental databases. These databases are created for general use, and users are charged for access on the basis of either a subscription or a flat hourly rate based on time actually used.

In a very real sense, commercial and governmental databases are a public utility. The source for the information stored in these databases is primarily current technical literature and legal materials. In some databases, abstracts of documents and books are stored; in others, the complete text is stored. For example, *National Fire Codes* is currently available to subscribers through protected electronic access. Numerous firms provide databases. Literally over a million databases, covering various fields, are available today through most technical companies and public communications entities.

The databases of greatest use to the fire service are those dealing with hazardous materials, codes, standards, and legal information. Chemical and hazardous materials databases allow a user to search for a hazardous material by chemical structure, trade name, generic name, CAS registry number, chemical or physical properties, and textual description. These databases can be powerful tools in handling chemical spills, fires involving hazardous materials, and some emergency medical situations.

During the next few years, electronic reference material will become dominant over printed reference material. This growing popularity is based on the increasing ability to rapidly search a large volume of current information.

Fire Service Specific Applications

A variety of programs developed specifically for the fire service exist. Although some perform only one function such as

incident reporting, others provide an entire suite of fire service management applications that can assist with fire prevention, training, budgeting, internal communication, and other functions. As software is selected it should be carefully assessed and matched to the needs of an organization.

One advantage to a comprehensive fire service specific software system is that as data are populated in one area, they are shared throughout the other applications, thus reducing the need for redundant data entry. However, these fire service specific systems often fail to have the capability of easily sharing data with other non–fire service municipal applications. Therefore, many communities have selected separate software packages that can be utilized by several municipal departments that need to share data on a frequent basis.

Financial Applications

Financial applications include those systems that support budgeting, fiscal control, general ledger, accounts payable, and billing. Payroll is sometimes included, although more often it is a part of the personnel system. Billing may also be included in specific systems—for example, billing patients for emergency medical services and billing property owners for removal of illegal brush. (Many high-fire-risk states have ordinances requiring clearing of underbrush to reduce fire intensity and the chance of building involvement.)

The implementation of financial systems in fire departments has been slow, partly because the support of staff functions, such as finance, has been secondary to the support of line activities. In addition, municipality-wide financial systems often preempt those in the individual departments.

Perhaps the most critical need for financial information in the fire department occurs during the yearly budget cycle. The arduous and sometimes politically risky process of allocating resources requires considerable analysis. Decisions must be supported and justified by the kinds of facts best stored and manipulated by a fire service information technology system.

Budget control is also a high priority for fire agencies. Management needs to forecast expenditures to determine if the department is staying within budget. Even if central systems are available for this purpose, they may not provide data in sufficient detail or in a form that is useful to the fire department.

The remaining needs addressed by financial systems are primarily operation oriented: general ledger, billing, accounts payable, and payroll. The last three requirements more often than not are a part of associated applications (e.g., payroll in the personnel system, billing in the emergency medical system, and accounts payable in the procurement system). Manual or automated "bridges" are then provided to integrate general ledger and budgeting systems. The most common design approach to financial systems is a strongly centralized one. This is not surprising in view of the fiduciary responsibility of the chief financial officer in the public sector.

Human Resource Functions

Personnel systems are among the most complex and data intensive of all fire department applications. They may be part of a communitywide personnel system or may be specific to the fire department. Consisting of a number of subapplications, these systems are important in large departments to support the multiple functions of personnel administration, such as basic personnel records management, certification tracking, time and attendance reporting, payroll (sometimes part of financial management), duty schedules, physical fitness and medical records, employee evaluation, training records, position control, badge history and control, and disability/injury analysis. Without computer support for the personnel administration functions, large fire departments would find it difficult, if not impossible, to maintain all the necessary information, and little or no analysis of the collected data would be available.

The operational benefits are obvious. In a 1000 person fire department, a large volume of information is needed to carry out standard personnel functions. Fire fighters must be scheduled and personnel assignments must be balanced daily. Detailed training records are required for each department member. Time and attendance records are necessary for payroll. Employee records must be evaluated and considered for promotion. Overtime hours must be monitored and analyzed. These functions require an efficient way of storing, retrieving, sorting, and evaluating information.

The information that is useful for day-to-day operations also has residual value for strategic planning and managerial control. For example, the roster data may be aggregated in such a way that this information becomes useful for position control or personnel resource planning—that is, controlling the number and rank of personnel assigned to ensure that appropriate staffing patterns are employed. Management may use routine, periodic reports to review time and attendance data in an effort to control excessive sick leave or overtime. However, information required for strategic planning and managerial control typically cannot be fully defined prior to the time it is needed. Therefore, it is useful to have the facility for designing ad hoc inquiries using the operational database to provide information properly tailored to the nonroutine strategic or control application.

At the highest level of design, the approach taken will depend on the relationship of fire department personnel functions to city (or county) personnel functions. For example, the payroll may be prepared by the city from prescribed time and attendance records. In such a case, the fire department may have difficulty developing some of the components of a personnel system.

Another aspect of the design approach is the degree to which the components of the personnel system are integrated. In most cases, the personnel system has been built over several years, with one component implemented at a time, with no overall design providing for integration of files and input. A comprehensively planned system provides for integration, even if the components are implemented separately.

Facility Management

As fire facilities become more complex, technology can be employed to monitor critical aspects of operation. Systems that can be controlled through the use of technology include life safety, backup power, communications, access control, and energy management.

The need for security has increased as fire services have evolved. Ranging from basic facility security to controlled access to narcotics and other medications, controlled access is essential to operations. As such, several access technologies have been developed. Commonly, user name and password combinations will protect information system access, and fingerprint or magnetic card readers can provide access and monitor utilization of facilities and critical equipment.

Energy management systems provide information for control of energy costs, including information about the consumption of electric power, natural gas, and heating oil. In some cases, the use of motor vehicle fuel may be monitored, although this function is more properly a function of fleet management systems. The typical approach to the design of energy management systems is to capture energy billing data, update master files, and make various reports available to administrators. This energy conservation strategy can be maximized through the use of either a relational database or a spreadsheet. More sophisticated approaches include real-time monitoring systems and even real-time energy control. Computer-based evaluation models are also used to assess the impact of conservation measures. The cost of implementing a computerized energy management system can be recovered quickly through increased energy resource efficiency. This technology can control multiple systems to ensure comfort and efficiency and can identify problem areas.

Fire Prevention Applications, Inspection, and Permit Tracking

Fire prevention management information systems are address-based tracking systems for storing fire protection–related information on a community's buildings. The heart of a fire prevention system is a flexible file of properties. The application is useful in planning and managing fire prevention activities, controlling hazardous contents, and prefire planning for fire suppression.

Fire prevention records in many communities still consist of long, often handwritten, forms and narratives filed in individual folders, one for each property. This lack of electronic automation makes it virtually impossible to manipulate data and develop any information on patterns of hazards or violations across the community or for particular property classes.

Even within a file on a single property, it can be difficult to ascertain whether the fire department has been providing the kind of frequency of contact called for by the department's policies, community ordinances, and other state and federal laws and regulations. This difficulty exists because such files are often dumping grounds for any and all papers bearing the property's address. Minor, unofficial correspondence and news clippings may share space with inspection reports, violation notices, and detailed construction plans. Files on properties not covered by the fire prevention code (such as single-family dwellings), on fire education contacts, and on contacts by other agencies (such as the building and housing departments) are generally nonexistent or wholly separate and incompatible with the fire inspection files. Fire incident records are rarely tied to files on the violation and hazard histories that may have caused the fires. In fact, it would be difficult to identify any aspect of a fire department's record keeping that is more in need of refinement and automation than fire prevention. Handheld computers serve as tools to make the fire inspection process more effective and efficient. For example, the TDS Ranger pictured in Figure 12.5.15 makes available applications on fire prevention inspection and records management.

As fire prevention activities are address based, utilizing handheld computers that can retrieve, update, and input property-based information can add to an organization's capabilities. Many of these systems can provide an inspector with a complete history of a property and prevent the need to duplicate data entry. In addition, most of these devices synchronize with a network system and create a database that can be shared with other code compliance agencies.

The first requirement for an adequate fire prevention system is a comprehensive address-based inventory of all properties in the jurisdiction. Such a file is difficult to create. Past studies have shown that, despite conscious efforts, fires are reported in properties that should have been subject to fire inspections but did not appear in the inspection records. These were not new businesses or businesses operating illegally out of homes; they were legitimate businesses of some years' standing that simply had been overlooked.

Although file completeness cannot be guaranteed, it can be improved. Address files should be linked to the fire incident records, preferably through a link to the communities' GIS and CAD systems, so that emergency runs or municipal records to corresponding unlisted addresses will lead to the creation of an inspection file.

Sources for both the initial building inventory and periodic updates are the city's tax records, E9-1-1 database, the build-

FIGURE 12.5.15 Fire Fighter with a TDS Ranger (Photo provided courtesy of Tripod Data Systems, Inc.)

ing department, any inspection agency, and city-owned utilities, such as the water, sewer, and electric departments. Some lists (e.g., the telephone company's Yellow Pages, cross-indexes, and mail carrier routes) tend to be unwieldy or poor sources for finding missing addresses.

The physical fire inspection procedure itself can be a source of effective property list updates. Inspections conducted on a sequential basis allow inspectors to see properties they might miss if they were to organize their routes with strict attention to those properties identified only by the computer.

Once the file is created, it can be used as a basis for organizing and scheduling inspections. The system can be set to print inspection reports for properties scheduled for inspection in any given time period (weekly, biweekly, or monthly), thereby allowing inspectors to plan their work. Likewise, the need for reinspections to check that hazards are abated or other violations corrected can be easily tracked, and missed inspections can be identified. Inspector workloads can be balanced either by the number of inspections or by the total time spent on inspections if statistics are kept on the typical duration of inspections by type and size of property.

Accuracy is important when automating data on buildings in a community. Although the occupants of a building change from time to time, the building itself usually doesn't change much. Some jurisdictions use the Basic Structure Report, Form 903SR, to gather basic information about structures. This form is an excellent way to capture data about buildings that need to be inspected periodically. Furthermore, the information gathered is extremely valuable for prefire planning efforts at that structure.

For all buildings, especially those that contain more than one occupancy, a basic occupancy report provides a way to gather information (e.g., who is using the building) for both inspection and training functions. The best asset of such an information-gathering system is that the data are classified in a uniform manner, based on NFPA 901, *Standard Classifications for Incident Reporting and Fire Protection Data.* With the data classified, it is easy to analyze the data, assess the severity of hazards being reported, and retrieve records for properties that have similar characteristics. This allows a supervisor to prioritize a fire department's inspection functions, based on the hazards present and the severity of the potential fire problem, especially when that department may not have sufficient resources to inspect every building as often as might be desired.

Incident Reporting and Analysis

Incident reporting systems are used to outline operations, document situations, and maintain statistics on fire, medical emergencies, and other emergencies to which a fire department responds. This application is one of the most common uses of information technology.

The methods of capturing data are rapidly changing. Batch data entry, in which a form or forms are completed after each incident and someone other than the person completing the form inputs the data in batches at a computer, has given way to the fire officer entering the data directly at a computer terminal in the fire station or remotely through wireless and mobile data systems.

Departments with a CAD system usually collect at least some of the incident data as a by-product of a CAD operation. These data can then be displayed on a networked computer or on a terminal where data collected at the incident scene can be added by the company officer or officer in charge. Allowing the officer in charge to enter the data directly has the advantage of ensuring completeness and correctness, because the data can be edited as they are entered and mistakes corrected immediately.

Casualty reporting systems are generally subsets of incident reporting systems. As such, they are linked to the incident record so that cause-and-effect studies can be done. Typically, records on fire fighter casualties and civilian casualties are maintained separately, because the information desired or the level of detail is different for the two.

Data on civilians injured at fires are useful for supporting injury reduction programs. These programs can be educational in nature to correct inappropriate behavior or may be focused at either getting unsafe products off the market or redesigned to make them safer. Code and standards developers can use the data from injury reporting to make prudent decisions based on past history. The criteria outlined in codes and standards can help to reduce injuries.

Fire fighters experience a high number of injuries while doing their jobs. Tracking those injuries is important and may involve more than one part of the fire department's information system. Data about the cause and circumstances of the injury can assist in making decisions for additional training, equipment redesign, or operational changes. For example, data collection has revealed that most fatal fire fighter injuries involve a heart attack or vehicle collision and that fire fighters suffer a higher rate of nonfatal injuries per hundred fires at fires that involve abandoned structures than in other properties.

Medical data about the injury are often important for workers' compensation claims. Data on potential time lost are needed to schedule other fire fighters to fill the shift and could affect the overtime budget.

A basic casualty report provides a method of uniformly gathering casualty data for both civilians and fire fighters. This report provides for the classification of much of the collected data so they can be easily summarized and analyzed to support injury reduction programs. This form is not designed to be a medical form for reporting to workers' compensation, although some of the basic data might be applicable to both needs.

Fire Investigation

The investigation of fire incidents needs to be a well-documented and methodical process. Technology such as digital imaging and prefire planning and fire inspection database systems can be a help in investigations. In addition, through GIS, all municipal information on a fire property, on the owner, and on the structure's history can be easily developed.

A number of computer-based data systems have been developed to profile the properties in the neighborhood and assist in identifying arson-prone buildings. The community group or public officials are then able to implement intervention strategies

appropriate for the situation. Much of the early work sponsored by the Federal Emergency Management Agency (FEMA) has led to a developed and tested microcomputer-based arson information management system (AIMS). The system provides both identification of arson-prone buildings and a case management system for fire investigators.

There are many municipal and private databases or record systems that are typically used to support a fire investigation. These sources include data from the fire department incident-reporting system and code-enforcement program, the building department, the assessor's office, the police department crime-reporting system, the prosecutor's office, the tax collector's office, the registry of deeds, mortgage companies, and the insurance industry. Many jurisdictions are choosing to computerize the incident follow-up report in order to increase the information available on significant fires within a jurisdiction. Analysis of this data may reveal patterns showing types of fires that could point to deliberately set fires and other criminal activity.

PLANNING, TRAINING, AND RESEARCH

Emergency Planning

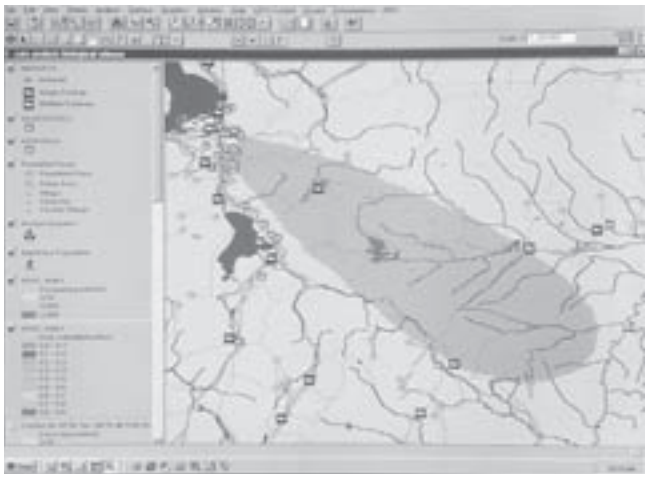
Through GIS and other information technology, emergency personnel can plan for a variety of situations that could affect large portions of a community. Ranging from hazardous materials releases to weather-related events, emergency management systems must be ready to respond to the unforeseen. Most community emergency management plans are currently developed in electronic format and can benefit from integration with other community-based data. Technology allows for hazards to be identified and, through modeling applications and automation, plans can be developed to ensure an appropriate response to a multitude of potential situations (Figures 12.5.16a, b, c). The purpose of such an automated display is for automated notification and evacuation planning.

GIS files can be expanded to include information essential to the emergency management function. Examples of this information include the type, quantity, and location of hazardous materials and the type, frequency, and location of other hazardous activities. The prime difficulty in making a hazard assessment system work is that the situation is dynamic. Types, quantities, and locations of materials may fluctuate widely according to the demands of the business. Annual or even semiannual updating of a central file may be insufficient to give a picture of the community's true hazardous materials profile.

Ownership information on properties can be among the most difficult to obtain. Current ownership is probably not needed until legal proceedings have to be instituted. It is easier and more reliable to check legal ownership in those relatively few cases as they occur than to try to develop and maintain a file on legal ownership for all properties. Knowing who is responsible for the property, however, is important, so that contact can be made in the event of an emergency or to schedule inspections.

Information technology through both the Internet and satellite communication allows the radar monitoring of weather conditions and the projection of the track of events such as tornadoes, flash floods, and blizzards. This technology has saved countless lives by warning the public of a dangerous weather event.

(a)



(b)

(c)

FIGURE 12.5.16 (a) Automated Display of an Evacuation Area Surrounding a Hazardous Materials Incident (b) Automated Modeling and Mapping of a Plume Secondary to a Release of Hazardous Material (c) Automated Path Projection of a Tornado or Other Severe Weather System (Photos provided courtesy of Bradshaw Consulting Services, Inc.)

When weather tracking and other emergency management applications are integrated with automated warning applications, residents can be contacted and given information on the situation. This information may be instructions on whether to seek shelter in place or to evacuate the area.

Through the use of subscription-based Internet calling centers that can quickly distribute thousands of customized voice messages to a targeted population, versatile systems can distribute messages ranging from safety-related messages to instructions on how to shelter in place during an emergency event.

Training and Research

Information technology can provide an exceptional level of support to training, educational, and research activities. Many texts have transitioned to provide CD-ROM study guides, tutorials, and self-paced learning programs. These programs, which focus on the needs of the adult learner, ensure comprehension by requiring students to master lower-level principles before allowing them to proceed to more advanced topics. Therefore, a solid foundation of knowledge is built. The International Fire Service Training Association (IFSTA), for example, offers computer-based and tutorial training for the development of basic fire fighter skills, in accordance with NFPA 1001, *Standard for Fire Fighter Professional Qualifications.* Aircraft orientation and emergency procedures, which crash fire rescue organizations now provide in the form of interactive computer-based training aids, are another example.

These applications are of benefit to fire service personnel because they are a complement to formal training programs. Interactive individual learning can be extended to the evaluation of a student's knowledge, skill, and abilities. Technology has developed realistic incident simulations used to gauge performance or develop a fire officer's confidence and skill (Figure 12.5.17).

Testing and performance during incident simulations and computer-based examinations can be recorded either locally or through secure Internet sites. A fire fighter required to attain a specified performance level can be periodically tested and evaluated through an Internet-based examination. Although this type of testing raises some security issues, these obstacles are being overcome.

FIGURE 12.5.17 Digital Incident Simulation Screen (Image provided courtesy of Digital Combustion, Inc.)

The complexity and specialization of the fire service create the need to use resources outside the organization. Remote locations or entire satellite networks can be reached through distance learning. The Federal Emergency Management Agency (FEMA) and the United States Fire Administration (USFA), for example, have offered online courses of benefit to the fire service.

Through the Internet, new learning opportunities and training materials have become accessible. At present, several fire service websites allow training presentations and materials to be downloaded. The availability of these materials promotes consistency and reduces the program development demands common to local training personnel.

Distance learning is well accepted in the academic environment. Many colleges provide interactive distance learning to enhance the quality of what can be affordably delivered to a remote location, to deliver instruction to smaller audiences, and to increase economy of scale. This interactive instruction is followed by electronic completion of assignments. Several colleges have become paperless institutions with students able to obtain all required materials electronically.

INTEGRATION OF SYSTEMS

Many organizations do not have a systematic approach to the development of information systems. Their approach is piecemeal without an overall plan for the integration of systems. By analogy, an airplane designed in a piecemeal fashion might have three wings, an engine with insufficient power for takeoff, and a fuel tank where there should be cargo or passengers. In short, although each subsystem might fulfill its intended function, the overall system is a failure.

The solution to this problem is information technology planning. As is the case with other organizations, the fire department needs an overall plan for integrating the various component subsystems. All components do not have to be implemented at one time to have a workable system, but a strategic plan for eventual integration and an action plan on how to achieve it are required.

Levels of Integration

Normally, two levels of integration are to be considered. The first is the integration of fire department systems with citywide systems. Considerable benefit can arise from, for example, having a GIS database of occupancy data that can be used by the assessor, tax department, and fire department. In general, however, information resource managers in the fire service should be wary of databases over which they have no control. Nevertheless, the potential benefits are worth the necessary effort in working toward a well-developed multiagency plan. At a minimum, the fire department should think through potential interfaces with city systems and provide the connectivity for future system development. The second level of integration is within the fire department itself where there is significant opportunity for controlling the design of systems, databases, and their interfaces.

Planning Techniques

An organization uses information systems to support strategic planning, managerial control, and operational activities. These activities may be classified into a number of business functions (e.g., scheduling personnel, dispatching, and budgeting). In turn, each function requires a certain subset of the organizational data. Obviously, different functions may require overlapping data subsets. This type of analysis suggests two ways to integrate systems.

Packaging Approach. The first approach to integrating systems is related to the way fire service functions are "packaged" into application systems. For example, a typical entry-level application in a fire department is CAD. In most cases, CAD is implemented on a stand-alone minicomputer. However, the boundary of the system could be expanded to include other records management functions, such as inspections and incident reporting. In the case of inspections, the staff needs information about hazardous materials, occupancy, guard dogs on premises, and so on. In the case of incident data, CAD collects much of the data needed to report fire incident documentation.

Thus, although the focus is still on CAD, the system's boundary would be enlarged to include "subordinate" or supporting functions. The links to supporting functions would be developed as subsystems with their own databases (or files) and have automatic data sharing provided to tie them together.

Data Model Approach. The other approach is based on a data model of the organization. The focus here is on the data and their interrelationships. Whereas the data traditionally have been owned by the application, now the application has become almost insignificant, replaced by transaction sets that update and query the public safety database. In reality, single physical databases are not defined; rather, they are grouped according to some coherent scheme. (Relational databases are appropriate.) Such a scheme should ensure that like entities are grouped together. Although other arrangements are possible, this line of thinking suggests the following groupings:

1. *Personnel database.* Includes data on scheduling of personnel, training, payroll (if not part of the financial system), accidents, assignments
2. *Financial database.* Likely to be citywide in scope; includes data on budgets, flow of funds
3. *Incidents database.* Includes historical data on closed fire and emergency medical incidents
4. *Fire prevention database.* Includes a building inventory and data on occupancy, ownership, hazardous materials; may include arson data
5. *Operational database.* Includes data about incidents in progress; data maintained for relatively short durations; may be moved to incidents database at close of incident or periodically to prevent overloading real-time CAD system with non-real-time data
6. *Supplies and equipment database.* Typically a citywide database; includes supplies inventory and equipment inventory and may include fleet management

SUMMARY

In view of the complexity of information applications, hardware, software, connectivity, and integration, this chapter does not purport to be a complete presentation on fire department information systems and technology. It does, however, attempt to balance technical information with a description of how information technology can be successfully applied to the fire service. Technology continues to evolve at an unprecedented rate; therefore, new applications and innovations beyond those detailed in this chapter should be expected. As new applications develop, they should be evaluated in terms of both reliability and benefit to the fire service.

Technology's increasing interactivity will extend an organization's capabilities. In the fire service, situations are often unforgiving; thus, the reliability of applications is critical. To meet the challenge, organizations should proceed slowly. They should place emphasis on training personnel, evaluating information technology products, and creating a comprehensive technology plan that involves staff members and includes the pilot testing of any new technology. Through this evaluation process, department personnel can ensure that the benefits outweigh the cost and that the best possible applications are selected for the organization.

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NFPA 901, *Standard Classifications for Incident Reporting and Fire Protection Data*
NFPA 1001, *Standard for Fire Fighter Professional Qualifications*

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Chapter 6

Liability of Fire Service Organizations for Negligent Fire Fighting

Maureen Brodoff

Chapter Contents

Negligence in the Fire-Fighting Context
The Fire Service and the Doctrine of Governmental Immunity
Legal Protections for the Fire Service Today
Public Duty Rule as an Added Protection for the Fire Service

Key Terms

discretionary functions immunity, governmental immunity, liability, limited damages, negligence, public duty rule, punitive damages, tort claims act

In 1955 a large quantity of gasoline was spilled onto a city street in Lawrence, Kansas, during the removal of gasoline storage tanks from a gas station. The local fire department was notified and quickly arrived at the scene. In order to determine the extent of the problem, the fire chief who was supervising the scene instructed a fire fighter to touch a cigarette lighter to the ground. Not surprisingly, a conflagration ensued that destroyed several automobiles. In the lawsuit that followed, the court refused to hold the town liable for the foolhardy tactic of its fire chief.*

This case and many others from the period reflect the traditional view that local governments were not liable for their failure to provide effective fire protection. Indeed, even extreme carelessness in fighting fires would not give rise to liability. Today, however, in the field of fire fighting, as with most modern-day endeavors, the historical limitations on legal liability are eroding, and theories of liability are expanding. Fire service legal liability must now, of necessity, be a concern to the fire service.

This chapter describes the general legal principles that are used in analyzing the legal liability of fire service organizations for negligence in conducting fire-fighting activities.† It should be remembered that the law in this area is not uniform but is governed largely by state and local laws and, therefore, varies from jurisdiction to jurisdiction. The liabilities of individual fire service organizations can only be determined by reference to the specific law in its jurisdiction.‡

For related topics, see Section 1, Chapter 4, "Legal Issues for the Designer and Enforcer."

**Perkins v. Lawrence,* 281 P.2d 1077 (Kan. 1955).

†There are many potential types of legal liabilities encountered in the modern fire service. This chapter treats only one—liability for negligent fire-fighting activities—and is intended only as a general introduction to the subject. It does not deal with other types of liability a fire department could owe to members of the public, such as for negligent inspection or automobile negligence. It also does not deal with employment law issues, such as workers' compensation, wrongful termination of employment, and the expanding field of antidiscrimination law, which has had a widening impact on the fire service in recent years. For the interested reader, there are several works designed for the layperson on these and other legal issues relating to the fire service. See, for example, Callahan, T., *Fire Service and the Law,* 2nd edition (National Fire Protection Association, 1987); Hogan, L. J., *Legal Aspects of the Fire Service,* 3rd edition (Amlex, 2000); Schneid, T. D., *Fire Law: The Liabilities and Rights of the Fire Service* (Wiley, 1995); and Grant, N. K., and Hoover, D., *Fire Service Administration* (National Fire Protection Association, 1993).

‡For convenience, this chapter will generally use the terms "fire service organization" or "municipality" in referring to the entity that may bear liability for negligent fire fighting. The reader, however, should be aware that the actual party that is named in a lawsuit alleging negligent fire fighting will vary depending on how the fire service is organized in a particular locale. Most frequently, fire departments are branches of municipal government and, when a lawsuit is brought, it is the city or town that is named in the suit and that is responsible to pay any judgment. In other cases, it may be an independent fire district or a county that is the responsible party. Sometimes individual fire fighters may be named in such suits. Although such individual liability is beyond the scope of this chapter, protections similar to those described here relating to fire service organizations will frequently protect fire fighters from individual liability for simple negligence. See, e.g., *Love v. Detroit,* 2006 WL 964721 (Mich. Apr. 13, 2006); *Willis v. Beaufort,* 143 N.C. App. 106, 544 S. E.2d 600 (N.C. Ct. App. 2001).

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NEGLIGENCE IN THE FIRE-FIGHTING CONTEXT

As with any other endeavor, particularly one as fraught with danger and uncertainty as fire fighting, things can go wrong. Fires sometimes cause deaths and injury in spite of the best efforts of the fire service. Property damage may result, not only from the effects of fire but also frequently from the activity of fire fighting itself. A tactical decision made in the midst of impending disaster may, in hindsight, turn out to have been terribly wrong. Bad outcomes alone, however, do not make the fire service liable.

The Elements of a Negligence Case

The principal theory of liability used in lawsuits for personal injury and property damage is what is known in the law as negligence.* The law of negligence does not hold a person liable for *any* damage that results from his or her actions, only damage that results from some act of carelessness in circumstances where the actor had some duty to act with reasonable care. This principle can be understood by way of an illustration drawn from an actual case involving allegations of negligent fire fighting.

In 1978 in the city of Lowell, Massachusetts, a fire occurred in and destroyed five brick buildings.† The fire started on the sixth floor of an unoccupied building. This building had a working sprinkler system and, indeed, the system worked properly in the initial stages of the fire. The fire fighters who responded to the fire, however, chose to use the available water source to operate hoses. This reduced water pressure in the sprinkler system, in effect turning it off. There was evidence that good fire-fighting practice would have been to rely on the building's sprinkler system to fight the fire rather than to have diverted the water from the system to fight the fire with hoses. There was also evidence that the sprinkler system, if allowed to operate, would have put out the fire or contained it until it could have been put out by manual means. Instead, because of the choice of the fire fighters to effectively shut off the sprinkler system, the fire eventually engulfed and destroyed five buildings.

In this case, one can see all of the essential elements of a fire-fighting negligence case. First, under the law, all persons generally have a duty, once they undertake to act, to do so with reasonable care. As explained later in this chapter in the discussion of the "public duty" rule, there is some controversy whether fire fighters owe such a duty of care. In this case, however, it was conceded that once the fire fighters undertook to fight the fire, they had a duty to fight the fire with reasonable care.

Second, the fire fighters breached their duty to act with reasonable care. In lay terms, this simply means that they acted carelessly in fulfilling their duty to fight the fire. Reasonable care, in the context of fire fighting, means that level of care that the reasonably prudent fire fighter would use in similar circumstances. Since the evidence in the case showed that proper fire-fighting practice would have been to leave the sprinklers on, turning them off was viewed in the eyes of the law as negligent.

Third, the fire fighters' breach of their duty to reasonably fight the fire caused the destruction of the buildings. From the evidence, if the sprinklers had been allowed to function, the fire would have been contained. In other words, the fire fighters were the legal cause of the destruction of the buildings, because the destruction of the buildings would not have occurred had the sprinkler system been left on, and the consequences of shutting off the system were reasonably forseeable.

Finally, the fire fighters' negligence resulted in damages. In this case, the damages roughly equaled the value of the destroyed buildings and their contents.

Fire Service Negligence in the Caselaw

This case of the turned-off sprinkler system is a good example of what any case of negligence will have to prove in order to be successful; that is, the existence of a duty of care, the breach of that duty, causation, and damages. It is important to remember, however, that this is but one example of what can be alleged as negligent fire fighting. The types of negligence that can be alleged in the fire-fighting context are infinite. Areas of potential liability include fire suppression activities, tactics and strategies, emergency response system failures, operation of fire service vehicles,* hydrant and water supply maintenance, and maintenance of fire-fighting equipment.

Actual cases that have been brought illustrate the variety of claims that creative lawyers can allege. In an Indiana case, for example, it was alleged that a fire service organization was negligent in failing to maintain a sufficient number of fire fighters for the equipment intended to be used.† In the same case, it was also alleged that there was negligence in the service's failure to supervise and train its fire fighters in controlling and extinguishing fires under the conditions encountered in a particular fire. In an Alabama case, negligence was claimed in the failure of a fire department to respond to a house fire because the apparatus operator had gone home sick.‡ In a Maryland case, negligence was alleged in the failure to properly control and extinguish a brush fire that eventually reignited, causing a second fire in which a

*Sometimes other theories of liability are used in suits against the fire service. For example, lawsuits have been brought under a federal law permitting lawsuits for injuries resulting from the deprivation of some civil right. (See 42 U.S.C. § 1983.) These lawsuits require more than allegations of negligence. Typically, they allege some discriminatory action, such as the withholding of adequate fire protection from a minority neighborhood. Lawsuits also sometimes allege deliberate misconduct as opposed to mere negligence. A full discussion of these other theories is beyond the scope of this chapter.

†The fact pattern used for this illustration is drawn from the Massachusetts case of *Harry Stoller & Co. v. Lowell,* 412 Mass. 139 (1992).

*The laws involving the operation of fire service vehicles present something of a special case, since many states have laws aimed specifically at limiting liability for the operation of emergency and fire service vehicles. These statutes vary from state to state. Indiana, for example, provides immunity for the operation of fire service vehicles only when the operator of the vehicle is an employee of the fire service organization and only in the case of authorized emergency vehicles. [See *Indiana Code* § 9-4-1(d).] Other states have additional requirements, such as that emergency sirens or lights be activated.

†See *Hammond v. Cataldi,* 449 N.2d 1184 (Ind. App. 3d Dist. 1983).

‡See *Williams v. Tuscumbia,* 426 So.2d 824 (Ala. 1983).

warehouse was destroyed.* And in a Massachusetts case, it was alleged that fire fighters were negligent in fighting a fire burning at the rear of a house by spraying water on the front of the house where there was no fire.†

In one particularly dramatic case in Alaska, liability was alleged and found for negligent failure to rescue a person stranded in an upper floor of a burning building during a fire. The rescue failed because the ladder used in the attempt was too short to reach the victim's window. Although the court said this fact alone did not constitute negligence, the fire fighters failed to use other commonsense methods of rescue that were available as an alternative. In particular, the court was deeply disturbed that some spectators who had obtained an extension ladder of sufficient length to reach the victim, and who had raised the ladder and started to extend it, were ordered by a fire official to get away from the building and, when they refused to obey, were driven off by fire hoses.‡

Limits on Fire Service Liability

These illustrations would seem to indicate that liability exists around every corner. Although allegations of negligence are easily made, however, not all negligence claims result in a finding that the fire service was liable. There are two broad reasons tending against findings of fire service liability for negligent fire fighting.

The first reason is that allegations of negligent fire fighting are generally more difficult to prove than in the typical negligence case. In a typical negligence case, a party is accused of creating a dangerous situation that resulted in injury. In the typical fire fighter negligence case, the dangerous situation, that is, the fire, already exists when fire fighters enter the picture. A plaintiff, therefore, is usually in a position of having to prove that the fire fighters either made worse or failed to mitigate a harm that they did not cause. This is a difficult task, especially since the unpredictability and destructive power of fire in general often make it difficult to say with any assurance that some other course of action not taken by the fire fighters would have yielded a better result. Thus, as the Alaska case described previously vividly shows, liability is most often found in the extreme case where the conduct of the fire fighters is viewed as foolhardy or outrageous.

The second reason requires some explaining, but it has even greater impact on fire service liability. As discussed earlier, a case of negligence is built by proving that an individual or group by their careless actions violated a duty to act with reasonable care and, thereby, caused damage. If fire fighting were strictly a private enterprise, carried out by and for the benefit of private parties, such proof would be all that was required to entitle the injured party to hold the fire service organization liable to pay for all damages.

Fire fighting, however, is not a private enterprise. It is generally a governmental function carried out by cities, towns, and other governmental units for the benefit of the public. Because of this, the fire service is the beneficiary of an elaborate body of law that has been developed to shield the government from liability, even when it has acted negligently. This law of "governmental immunity" greatly complicates the question of whether and when a fire service organization can be held liable for damages caused by negligent fire fighting.

THE FIRE SERVICE AND THE DOCTRINE OF GOVERNMENTAL IMMUNITY

Until the last 30 or so years, the doctrine of governmental immunity fully protected governments from lawsuits aimed at governmental functions. Under this doctrine, the government as "sovereign" could do no wrong and could not be sued. In the case of fire-fighting activities, it meant that no matter how negligent a fire department might be or how much damage to life or property that negligence might cause, the municipality whose fire fighting had caused the damage could not be sued.

The doctrine of governmental immunity left no remedy to individuals who had suffered grievous injuries as a result of negligent fire fighting or other governmental negligence. As might be expected, the injustice that the doctrine often seemed to impose led to much criticism of the doctrine and calls for reform.

Beginning in the 1970s, the federal government and the states began, either through court decisions or, more often, through the passage of legislation, to severely limit the absolute governmental immunity that governmental entities had enjoyed. The most common type of legislation, now in existence in some form in most states as well as the federal government, is commonly known as a "tort claims act." Each state act is different but, generally speaking, the acts provide that government entities are liable for injury caused by their negligence in the same manner and to the same extent as a private entity. There are important qualifications, however, that provide the fire service with significant protection against liability.

LEGAL PROTECTIONS FOR THE FIRE SERVICE TODAY

Limits on Amount of Damages

Probably the most important protections for the fire service provided by the various state tort claims acts are the limitations they impose on the amount of damages. Thus, although government entities can now be held liable for their negligence just as can a private individual, the amount they can be required to pay has been limited. In Massachusetts, for example, the amount of liability that a municipality can be required to pay if found negligent is limited to $100,000 per claimant. Frequently, there is an overall cap so that, no matter the number of claimants, the total damages awardable for fire department negligence in any one incident cannot exceed a given amount. Vermont, for example, has a limit of $250,000 per claimant with a maximum aggregate liability of $1,000,000 to all claimants arising out of any given occurrence; Maryland has a limit of $200,000 per claimant with

*See *Utica Mut. v. Gaithersburg-Washington Grove,* 455 A.2d 987 (Md. App. 1983).

†See *Cryan v. Ware,* 413 Mass. 452, 469 (1992).

‡See *Fairbanks v. Schaible,* 375 P.2d 201, 206 (Alaska 1962).

an overall cap of $500,000 per occurrence.* A few states provide lower maximum compensation for property damage than for personal injury.† And in North Carolina municipalities are held to have waived their immunity by purchasing liability insurance and can be held liable up to the amount of the purchased coverage.‡ Finally, punitive damages, that is, damages designed to punish the wrongdoer rather than compensate the injured party, are generally forbidden.§

These various limits on liability are highly significant protections for fire service organizations, since they cap damages at an amount that may frequently represent only a small fraction of the damages actually awarded by a jury. Particularly in the area of fire suppression, where mistakes can result in millions of dollars of personal injury and property damage, the tort claims acts provide a great deal of protection against potentially huge damage awards.

Exceptions Specifically Aimed at Fire-Fighting and Related Activities

Several state tort claims acts have exceptions that specifically retain governmental immunity for fire-fighting and related activities. North Dakota, for example, retains governmental immunity for failure to provide adequate fire prevention personnel or equipment, except if gross negligence can be proved.# Illinois retains governmental immunity for any injury caused by the failure to suppress or contain a fire or while fighting a fire.** Kansas, California, South Carolina, and Texas, by statute, and Indiana, by judicial decision, retain immunity for the failure to provide, or the inadequate provision of, fire protection.††

There are other types of specific exceptions that relate to the fire service, as well. Alaska specifically retains governmental immunity for the performance of duties "in connection with an enhanced 9-1-1 emergency system," and for the performance of duties upon the request of or by agreement with the state "to meet emergency public safety requirements."‡‡ Some states retain immunity for claims relating to the provision of or failure to provide emergency services.§§ Also, many states specifically retain immunity for the failure to make an inspection or the making of an inadequate or negligent inspection.* Finally, some states retain such broad general immunity for governmental functions that fire-fighting activities are more or less categorically immune from liability.†

"Discretionary Functions" Immunity

In addition to the exceptions in some states expressly relating to fire-fighting and related activities, there exists in most state tort claims acts another type of exception that provides significant protection for the fire service. This is known as the "discretionary function" exception, and it requires some explanation.

Although, in passing tort claims acts, the lawmakers of the various states wished to make it possible for citizens to obtain compensation for injuries caused by governmental entities, they were reluctant to abolish immunity for all governmental activities. They were concerned that lawsuits might be used to second guess every governmental policy decision and that the constant fear of lawsuits could severely hamper the ability of municipal officials to govern and to freely exercise the discretion of their office. In order to address these concerns, lawmakers created an exception in the tort claims acts that preserved governmental immunity for "discretionary functions."

The typical discretionary functions exception merely states that the tort claims act, and the governmental immunity that it abolishes, simply does not apply to any claim based on a public employee's performance or failure to perform a "discretionary function."‡ What is a "discretionary function," however, and what does it mean in the context of fire fighting? Many legal battles have been fought over the meaning of this exception.

The main problem has been in determining the breadth of the discretionary function exception that, read literally, could be quite broad indeed. The word "discretion" implies, in its essence, the exercise of judgment, and, therefore, a literal interpretation of the discretionary function exception might lead to the conclusion that all conduct involving the exercise of judgment is immune from negligence liability. In addition, since virtually all fire-fighting activities involve the exercise of judgment, even if only concerning minor details, one might conclude that all fire-fighting activities are immune from suit. This, however, is not the case.

Purpose of Discretionary Function Exemption

Courts have generally rejected a too literal reading of the term "discretionary function." They have felt that granting immunity to all acts that involve some exercise of judgment would, in effect, immunize all governmental activity and, therefore, defeat the whole purpose of the tort claims acts, which was, after all, intended to abolish complete immunity. Courts, therefore, have looked to the purpose of the discretionary function exception. It was only intended to protect conduct involving the kinds of broad public policy and planning judgments that governmental

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*See Vt. Stat. Ann. tit. 12, § 5601(b); Md. Cts. & Jud. Proc., § 5-403(a).

†See, e.g., Or. Rev. Stat., § 30.270; N.M. Stat. Ann., § 41-4-19.

‡*Willis v. Beaufort, supra,* 143 N.C. App. at 110; see also N.C. Gen. Stat. §160A-485.

§See, e.g., Mass. Gen. Laws ch. 258, § 2; Minn. Stat. Ann., § 466.04.

#See N.D. Cent. Code, § 32-12.1-03(3).

**See Ill. Rev. Stat. ch. 85, §§ 5-102, 5-103.

††See Kan. Stat. Ann., § 75-6104(n); West's Ann. Cal. Gov. Code § 850.4; S.C. Code Ann. § 15-78-6(6); Tex. Civ. Prac. & Rem. Code Ann., 101.055(3) ; *O'Connell v. Schererville,* 779 N.E.2d 16 (Ind. Ct. Ap. 2002). See also *California v. Superior Court,* 87 Cal. App. 4th 1409, 1412-1415; *Wells v. Lynchburg,* 331 S.C. 296, 501 S.E.2d 746 (1998).

‡‡See Alaska Stat., §§ 09.65.070(d)(6), and (d)(5).

§§See, e.g., Iowa Code, § 613A.4; Tex. Civ. Prac. & Rem. Code Ann., § 101.055(2).

*See, e.g., Kan. Stat. Ann., § 75-6104(k).

†See, e.g., *Davis v. Detroit* 2005 WL 3179537 (Mich App. Nov. 29, 2005).

‡See, e.g., Mass. Gen. Laws ch. 258, § 10(b).

actors need to be able to perform without the constant threat of being sued. In keeping with this purpose, most courts have tended to find immunity, not for all discretionary conduct, but only for conduct that involves "policy making or planning."*

In the context of fire fighting, what does this mean? The legal decisions are far from clear and vary widely in how they treat particular fire service activities. Nevertheless, certain themes emerge.

Administrative Policy Decisions

First, there are aspects of fire service decision making that have an obvious planning or policy basis. These are administrative policy decisions involving the overall structure and makeup of the fire department, the training and equipping of fire fighters, and the allocation of limited fire-fighting resources within the community. They include decisions about the number and location of fire stations, the amount and type of equipment to purchase, the size of the fire-fighting staff, the type and extent of fire fighter training, the number and location of hydrants, or the adequacy of the water supply.†

When lawsuits blame these types of administrative policy decisions for bringing about injury or death, they are frequently dismissed based on the discretionary function exception. For example, a claim that fire fighters were unable to suppress a fire because the nearest fire station was too far away to make timely fire fighting possible would generally fail because decisions about where to locate a fire station are, even if patently unreasonable, protected from liability under the discretionary function exception.

Of course, some courts are more stringent in applying the exception than others. Many courts, for example, will view any broad administrative-level policy decision as categorically immune from liability, without any inquiry into the thought processes of the decision makers. Other courts, however, will require that the fire service organization, in order to claim immunity, present evidence showing that the decision makers actually went through a weighing of policy choices. In a case alleging that fire fighters were not supplied with a particular type of rescue equipment that would have prevented an injury, such a court would, for example, require that the fire service organization show that its failure to provide such equipment was the result of a conscious policy-making decision involving the balancing of competing interests, rather than the result of a simple failure to consider the question whether the equipment was needed.‡

It is clear, therefore, that administrative decisions are generally covered and immune from suit, at least where the decisions involve a conscious weighing of policy considerations. What about operational decisions made in the course of fighting a particular fire? Some have argued, for example, that the initial decision to fight a fire is discretionary, but that all of the subsequent actions in actually fighting the fire are not. Under this view, almost all actual fire suppression activities on the fireground would fall outside the "discretionary function exception" and would, therefore, be subject to potential liability.

This point of view, however, has mostly been rejected. Some courts go so far as to say that all tactical fireground decisions are immune from liability as "discretionary functions."* Most courts, however, have been more selective and have found that, while many decisions taken in the course of fire fighting do not involve policy or planning considerations, some decisions made on the fireground do involve broad public policy choices protected by discretionary function immunity.

Entitlement to Discretionary Function Immunity

How do courts decide whether a fireground decision is entitled to discretionary function immunity? In one recent case, the court looked to whether allegedly negligent fire-fighting decisions were dictated by a statute, regulation, or fire department policy. The case involved a warehouse fire during the course of which the fire department ordered all power to the building turned off. After the fire was extinguished, the fire fighters ordered the power restored, but did so without first either having the electrical system checked or obtaining a permit. The restoration of power resulted in a rekindling of the fire, which then entirely destroyed the building. The municipality argued that the decision to restore the power, even if negligent, was entitled to discretionary function immunity. The court disagreed, however, because there was evidence that the building code as well as fire department policy prohibited restoring power to the building in the way that the fire fighters had done. The court reasoned that, where procedure for the restoration of electrical power was dictated by specific regulations and policies, the decision to restore power was not a matter of discretion and was not, therefore, immune from liability.†

Usually, though, particular fireground decisions are not dictated by a specific rule or regulation. To determine, in these cases, whether a particular operational decision constitutes a discretionary function, courts generally look not at the particular action but at the reasons for fire fighter actions.

To illustrate, consider the case, described earlier in this chapter, of the fire fighters who turned off an operating sprinkler system in an unoccupied building because they wanted to fight the fire with hoses. Their decision to turn off the sprinkler system was clearly negligent, in that good fire-fighting practice would, in the circumstances, have dictated using the sprinkler system to extinguish the fire. The decision to shut off the sprinkler system also did not involve any policy or planning considerations, since the fire fighters simply made a careless decision about how to best fight the fire.

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*See, e.g., *King v. Seattle,* 84 Wash.2d 239, 525 P.2d 228, 233 (1974); *Keopf v. County of York,* 198 Neb. 67, 251 N.W.2d 866, 870 (1977); *Johnson v. State,* 69 Cal.2d 782, 788, 447 P.2d 352 (1968); and *Harry Stoller & Co. v. Lowell,* 412 Mass. 139 (1992).

†See, e.g., *Adams v. Tenakee Springs,* 963 P.2d 1047 (Ala. 1998).

‡As examples of the differing approaches used by courts, see and compare *Hammond v. Cataldi,* 449 N.E.2d 1184 (Ind. App. 3 Dist. 1993); and *Waldorf v. Shuta,* 896 F.2d 723, 728-730 (3d Cir. 1990).

*See *Jimenez v. LMA Intern, Ltd.,* 2002 WL 31553547 (N.Y. Sup. October 15, 2002).

†See *Commerce and Industry Ins. Co. v. Grinnell Corp.,* 280 F.3d 566 (5th Cir. 2002).

In slightly different circumstances, however, the decision to shut off a sprinkler system could easily involve a significant policy choice. Suppose, for example, that the fire fighters had decided to shut off the sprinkler system in the unoccupied buildings, not merely to deploy hoses, but to divert the water supplying the sprinkler to fight a fire in a neighboring building that was occupied. The decision to sacrifice the unoccupied buildings in order to devote limited fire-fighting resources to saving lives next door clearly involves policy choices about the relative value of property and human life. Thus, even if the decision to shut off the sprinkler system was ultimately shown to be negligent in that the occupied building could have been saved without diverting water from the sprinkler system, the decision was grounded in an important policy choice, and many courts would rule that it was immune from liability under the discretionary function exception.*

In summary, although the court decisions in this area vary widely from jurisdiction to jurisdiction, it can be said that the discretionary function exception provides immunity to the fire service from liability for most broad administrative-level decision making and for many operational-level decisions as well. Though far from comprehensive, and less than certain in any individual case, the discretionary function exception still provides the fire service with substantial protection from liability.

PUBLIC DUTY RULE AS AN ADDED PROTECTION FOR THE FIRE SERVICE

So far, the liability for negligent fire fighting, although complicated, can be summarized quite simply. Initially, the doctrine of governmental immunity completely protected fire-fighting operations from liability, even if a fire was fought negligently. Today, however, fire service organizations can, in some circumstances, be successfully sued for negligence. The extent to which they can be sued is limited in most jurisdictions by the tort claims acts and the court decisions that interpret them. In general, those acts will, through the discretionary functions exception and other exceptions aimed at protecting fire and emergency services, immunize fire service organizations entirely for some activities. Where immunity is abolished, however, the acts will still provide a cap on damages that can be won against a fire service organization.

Immunity Through Public Duty Rule

If the law preferred simplicity, even of a relative kind, the issue might end here. There is, however, one more important twist: "the public duty rule."

Even though state legislatures have abolished governmental immunity and permitted local governments to be sued in many situations, courts have continued to be sympathetic to the problems of cities and towns and their difficulty in paying even the limited awards permitted by the tort claims acts. Particularly in the area of fire and other public protective services, some courts have expressed the fear that imposing even limited liability for negligence could pose a crushing burden on municipalities, particulary in busy urban areas. As one judge pointed out, in extreme circumstances, such as the Los Angeles riots where there were hundreds of fires and severe obstacles to effective fire fighting, the potential costs of liability could be catastrophic.* This fear has led some courts to develop a judge-made rule to shield the fire service and other public protective services, such as police and inspection. The "public duty" rule offers immunity from negligence liability that goes far beyond the limited immunity retained in the tort claims acts.

Under the public duty rule, fire fighting and other public protective services are viewed as an obligation that governments owe, not to any particular individual, but to the general public as a whole. Based on this view, the public duty rule holds, somewhat paradoxically, that, because fire fighting is for the benefit of all, it is, in effect, for the benefit of no one in particular. Under the rule, therefore, no individual can seek damages for injuries caused by negligent fire fighting because, in essence, the fire service owes no duty to any particular individual to act reasonably.

What is the effect of the public duty rule? Its greatest impact is at the operational level of fire fighting. The immunity offered by most state tort claims acts under the discretionary function exception is quite limited, and most decisions made on the fireground can give rise to potential liability, unless they can be said to involve public policy choices. In states that follow the public duty rule, however, such decisions become largely immune, and any fire-fighting activity, even if negligent and even if devoid of public policy implications, cannot give rise to liability.

Limitations to Public Duty Rule

It would seem that fire service organizations in states following the public duty rule have nothing to fear from lawsuits claiming negligent fire fighting. This is largely true. However, in the law every rule has its limitations and exceptions, and so does the public duty rule.

First, courts that follow the public duty rule limit its protection to the suppression of fires not caused by the fire department itself. Thus, if a fire department negligently caused a fire during a fire training exercise or some other non-fire-suppression-related activity, the public duty rule would offer no protection. Also, a few courts would not apply the public duty rule to protect fire fighters in cases where they aggravated an existing fire as opposed to merely failing to suppress it.† These courts, for example, would provide complete immunity where fire fighters negligently failed to put out an existing fire, because they negligently aimed hoses on the wrong part of the building. They would, however, permit liability where fire fighters took some action that actively made matters worse, as, for example, turning off an operating sprinkler system that, left alone, would have contained the fire.

*See, e.g., *Dahlheimer v. Dayton,* 441 N.W.2d 534, 538–539 (Minn. 1989).

*See *Cryan v. Ware,* 413 Mass. 452, 455 (1992).

†See *Cryan v. Ware, supra,* 413 Mass. 452 (1992).

"Special Relationship" Exception

Second, there is an exception to the public duty rule known as the "special relationship" exception. It holds that, even though fire fighting and other protective services are viewed in general as an obligation owed only to the public at large, a fire or other protective service organization can, by words or actions in a particular case, create a special duty to particular private parties.

How does a fire service organization create for itself this "special relationship," where liability may occur? The special relationship exception has been complicated and often inconsistent in application, and, in practice, courts have been reluctant to apply it to hold the fire service liable.* It seems clear that a fire department does not create a special relationship to an individual property owner merely by responding to the owner's call for assistance and fighting the fire on the property.†

Similarly, the fact that a municipality regularly inspected a factory would usually not, by itself, create a special relationship sufficient to expose the municipality to liability for negligent fire-fighting operations later conducted at the site.‡

Generally speaking, in order to demonstrate a special relationship that could expose a municipality to liability, courts have required a showing that the municipality's fire fighters (or other agents) assumed an affirmative duty to provide a service beyond that generally owed to the public, that the fire fighters knew that failure to perform the duty could cause harm, that the duty was established through direct communication or contact between the fire fighters and the injured party, and that the injured party justifiably relied, to his or her detriment, on the fire fighters to perform the duty they had undertaken.§

Examples of "Special Relationship" Exception

The situations that lend themselves to a finding of a special relationship are best understood by looking at some illustrative cases. In one case, for example, involving a factory fire, factory representatives approached fire fighters at the fire scene and warned them that there were metallic chemical elements stored in the building that were not amenable to water suppression methods. The court found that the warning made directly to fire fighters at the scene created a reasonable reliance on the part of the factory owners that the fire fighters would correctly fight the fire. As a result, a "special relationship" was created, and the municipality could be found liable for the damages that resulted when its fire fighters ignored the warnings, as well as the relevant fire codes, and doused the fire with water.#

Another case involved an inn fire in which a husband who had managed to awaken and escape from the inn desperately tried to return and save his wife when he realized that she had not likewise escaped. As fire fighters arrived at the scene, he began yelling at them to rescue his wife, who could be heard screaming through a wall that the husband had been trying to break through. The fire fighters, however, allegedly did not respond to his pleas, and when he tried to continue the rescue on his own, fire fighters physically restrained him. It was not until 15 minutes following the restraint of the husband that fire fighters began an attempt to rescue the wife. By then it was too late, and the wife perished. Based on these "extraordinary" facts, the court had little difficulty concluding that, when the fire fighters affirmatively prevented the husband from rescuing his wife, they made an implied promise to rescue her themselves, upon which he was forced to rely. A special relationship was thereby created and the municipality could not claim immunity from liability for any negligence of the fire fighters in failing to rescue the wife.*

As the preceding examples illustrate, the public duty rule does not provide complete immunity for fire service organizations. But even apart from the potential liability opened up by the "special relationship" exception and other limitations on the public duty rule, there is yet another reason why fire service organizations in states that observe the public duty rule should not rest with complete ease. The public duty rule has been widely criticized as fundamentally inconsistent with the tort claims acts, because the rule creates immunity where legislatures have sought to remove it. For a time, therefore, a trend appeared to be taking shape to abolish the rule and many states did so.†

The trend stalled, however, and the majority of states that have considered the issue still recognize the public duty rule.‡

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*Contrast, e.g., the markedly different treatment the court gave police and fire fighters, respectively, in *Cryan v. Ware, supra,* 413 Mass. 452 (1992); and *Irwin v. Ware,* 392 Mass. 745 (1993).

†See, e.g., *Commerce & Indus. Ins. Co. v. Toledo,* 543 N.E.2d 1188 (Ohio 1989).

‡See *State Automobile Mutual Ins. Co. v. Titanium Metals Corp.,* 159 Ohio App. 3d 338, 344, 823 NE2d 934 (Ohio Ct. App. 2004).

§See *State Automobile Mutual Ins. Co., supra,* 159 Ohio App. 3d 343. *See also Babcock v. Mason County Fire Dist. No. 6,* 144 Wash.2d 774, 30 P.2d 1261 (Wash. 2001).

#See *State Automobile Mutual Ins. Co., supra,* 159 Ohio App. 3d 338.

*See *Stata v. Waterford,* 225 A. D.2d 163, 649 N.Y.S.2d 232 (N.Y.A.D. 3 Dept. 1996).

†See *Adams v. State,* 555 P.2d 235 (Alaska 1976); *Leake v. Cain,* 720 P.2d 152, 158-159 (Colo. 1986); *Adam v. State,* 380 N.W.2d 716, 724 (Iowa 1986); *Maple v. Omaha,* 222 Neb. 293, 301 (1986); *Schear v. County Comm'rs,* 101 N.M. 671 (1984); *Coffey v. Milwaukee,* 74 Wis.2d 526 (1976); *DeWald v. State,* 719 P.2d 643, 653 (Wyo. 1986); *Ryan v. State,* 134 Ariz. 308, 310 (1982); *Commercial Carrier Corp. v. Indian River County,* 371 So.2d 1010, 1015-1016 (Fla. 1979); and *Brennen v. Eugene,* 285 Or. 401, 407 (1979). See also *Hollis v. Brighton,* 885 So.2d 135 (Ala. 2004) and *Ziegler v. Millbrook,* 513 So. 2d 1275 (Ala. 1987) (applying public duty rule to volunteer but not to professional fire departments). See also *Dean v. Childs,* 262 Mich. App. 48, 58–59, 684 N.W. 2d 307 (2004) and *Willis v. Beaufort, supra,* 143 N.C. App. at 108–109 (applying public duty rule to police but not to fire protection services).

‡See, e.g., *Yates v. Mansfield Bd. of Edn.*, 102 Ohio St.3d 205, 808 N.E.2d 861 (Ohio 2004); *Babcock v. Mason County Fire Dist. No. 6,* 144 Wash.2d 774, 30 P.2d 1261 (Wash. 2001); *Stata v. Waterford, supra,* 225 A.D.2d 163. *Shore v. Stonington,* 187 Conn. 147 (1982); *Randall v. Fairmont City Police Dep't,* 186 W. Va. 336 (1991). As many as 21 states and the District of Columbia have been cited as following the traditional public duty rule. Excluding Michigan, which, as indicated in the previous note, no longer recognizes the public duty rule for fire-fighting activities, these states include California, Connecticut, Hawaii, Illinois, Indiana, Kansas, Maryland, Minnesota, Missouri, Nevada, New Hampshire, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, Utah, Washington, and West Virginia. See *Jean v. Commonwealth,* 414 Mass. 496, 518 n.1 (1993) (O'Connor, J., concurring).

And at least one state, Massachusetts, has, following court abolition of the rule, revived it by incorporating it into the state tort claims act.* It is safe to say, therefore, that the public duty rule, in many states, still offers fire service organizations a large measure of immunity.

SUMMARY

The degree to which the fire service may be exposed to liability for negligent fire fighting depends, to a large degree, on the law of the state in which the fire service organization is located. Although all states have abolished to one degree or another the total governmental immunity from negligence lawsuits, the amount of protection that remains varies among jurisdictions. In all states, however, it is important to remember that, even in the absence of complete immunity, there are still significant protections offered the fire service. Although the principles defy easy summarization, the following, in general, can be said.

1. In virtually all states, fire service organizations will be protected from suits criticizing broad administrative policy decisions of fire department and municipal administrators. Thus, suits claiming injuries resulting from bad policy decisions about the placement or number of fire stations, the size of fire department staffs, and the adequacy of funding for fire department activities will generally be prohibited under the "discretionary functions" exception or similar legal principles contained in the torts claims acts or caselaw of most states.
2. In the majority of states, fire service organizations will generally be liable for injuries for negligent fire fighting when the claims are based on bad operational decisions made on the fireground about how to fight a particular fire. Even operational decisions, however, will sometimes be protected under the "discretionary functions" exception, particularly where those decisions involve public policy choices.
3. In the minority of the many states that still follow the "public duty" rule, fire service organizations will be protected from negligence suits, even those involving operational decisions, unless the department or its employees have by words or deed created a "special relationship" with an injured party, thus creating a duty beyond that owed to the public as a whole.

The trend of recent years has been to hold fire service organizations liable when fire fighters have acted negligently. This trend, however, is far from complete. As the preceding discussion shows, limited immunity still exists both in the discretionary function exception and in the persistence of the public duty rule, which, despite much criticism, continues to show vitality in many statews. In addition, the caps on damages that exist in all states will continue to serve to soften the impact of negligence cases on the fire service. The explosion of liability that has occurred in all areas of the law in recent years has had only mixed results when it comes to the fire service.

*See Massachusetts General Laws, ch. 258, § 10, as amended by 1993 Stat. Ch. 495, § 57.

Chapter 7

Safety, Medical, and Health Issues and Programs

Revised by
Murrey E. Loflin

Chapter Contents

Evolution of Safety and Health Legislation
NFPA Standards
Definition of Safety Officer Roles
Risk Management
Risk Management Model
Incident Command System (ICS)
Blending Incident Command Systems
Communication Issues
Incident Scene Rehabilitation

Key Terms

fire fighter safety, incident command system, industrial fire brigade, infection control, occupational safety and health, rehabilitation, risk management, safety officer

Over the past 35 years, positive changes have emerged in fire service, as fire fighters have increasingly applied occupational safety and health concepts to the practice of our profession. Vast improvements with protective clothing and protective equipment, apparatus and vehicles, command and control of emergency operations, health maintenance, and numerous other components have improved fire fighter safety and health. One method for gauging the effectiveness of a national fire fighter occupational safety and health program is fire fighter fatality and injury statistics, and those numbers are beginning to move downward. This trend indicates that an emphasis on occupational safety and health is becoming a standard part of fire department operations and activities. However, there is still an incredible amount of work ahead for the fire service regarding occupational safety and health. In years past, the fire service had the distinction of being the most hazardous occupation in the country. Slowly, the fire service is losing this pronounced title and taking pride in conducting safe and effective operations. The number of fire fighter fatalities has averaged approximately 100 per year for the past 15 to 20 years. Since 1977 when fire fighter fatality statistics began to be tracked by the National Fire Protection Association (NFPA), the number reached a high of 173 fatalities in 1978 and a low of 75 in 1992 (Table 12.7.1). Progress has been made in the fire fighter safety and health arena, but there is still opportunity for improvement.

The fire service is beginning to understand the necessity and rationale for developing, implementing, and maintaining a proactive, comprehensive occupational safety and health program. However, many fire service personnel still do not subscribe to the safety and health philosophy. Tradition plays a major role in this lack of understanding of fire fighter safety and health. Although the struggle is far from over, the fire service is learning the lesson that safety is good business.

This chapter outlines the history of safety and health legislation as it applies to fire departments and describes relevant NFPA standards and requirements within the context of that history. The chapter concludes with a description of the risk management program that is detailed in NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program.*

For related topics, see Section 12, Chapter 1, "Planning for Public Fire-Rescue Protection"; Section 12, Chapter 8, "Effect of Building Construction and Fire Protection Systems on Fire Fighter Safety"; and Section 12, Chapter 9, "Fire and Emergency Services Protective Clothing and Protective Equipment."

EVOLUTION OF SAFETY AND HEALTH LEGISLATION

On December 29, 1970, the Occupational Safety and Health Act of 1970 (Public Law No. 91-596) was signed into law by President Richard M. Nixon. The Occupational Safety and Health Act had an effective date of April 28, 1971. Coauthored by Senator Harrison A. Williams (D-NJ) and

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TABLE 12.7.1 Fire Fighter Fatalities and Injuries, 1977–2006

Year	*Total Fatalities*	*Career*	*Volunteer*	*Injuries*
1977	157	70	82	NA
1978	173	64	101	NA
1979	125	58	57	NA
1980	138	61	69	NA
1981	136	58	65	103,340
1982	128	51	67	98,150
1983	113	54	51	103,150
1984	119	43	59	102,300
1985	128	55	66	100,900
1986	119	50	55	96,450
1987	132	49	68	102,600
1988	136	43	81	102,900
1989	118	43	65	100,700
1990	107	26	62	100,300
1991	108	36	66	103,300
1992	75	24	44	97,700
1993	79	21	55	101,500
1994	105	34	38	95,400
1995	98	30	59	94,500
1996	96	27	65	87,150
1997	99	31	59	85,400
1998	91	33	49	87,500
1999	112	37	71	88,500
2000	103	28	58	84,550
2001	103/443	25/365	66	82,250
2002	97	29	50	80,800
2003	106	26	58	78,750
2004	105	29	65	75,840
2005	87	25	54	80,100
2006	89	23	46	83,400

Note: 9/11 fatalities are listed separately for 2001.
Source: NFPA, August 2006.

Congressman William Steiger (R-Wis), the Occupational Safety and Health Act is referred to as the Williams-Steiger Act or the Williams-Steiger Occupational Safety and Health Act. Prior to the passage of the Occupational Safety and Health Act, legislation for general industry was intermittent and grossly inadequate. Most states had little or no safety and health legislation, inadequate safety and health standards, insufficient staffing, and inadequate enforcement procedures. Budgets were poorly funded. In turn, the occupational fatality rate was greater than 14,000 employees killed and 2.2 million suffering work-related injuries annually in the late 1960s. Prior to 1970, the federal legislation for occupational safety and health was erratic. Efforts were directed more toward specific interests than the widespread coverage, as designated in the Occupational Safety and Health Act.

When the Occupational Safety and Health Act of 1970 was enacted, each state was given the opportunity to develop its own safety and health plan. Under the Occupational Safety and Health Act of 1970, the federal Occupational Safety and Health Administration (OSHA) has no direct enforcement to ensure that state and local governments comply with safety and health standards, such as the OSHA Bloodborne Pathogens standard for public employees.

State Plans and Programs

Twenty-four states and two territories have established and maintain an effective and comprehensive occupational safety and health program for public employees. These state plans must meet or exceed the requirements of federal OSHA. OSHA gives each state 6 months from the publication date of any new federal final standard to adopt a similar state standard. All fire departments, whether state, county, or municipal, in any of the 24 states or two territories that have an OSHA plan agreement in effect have the protection of the minimal acceptable safety and health standards mandated by federal OSHA.

The following 24 states and two territories have state OSHA plans that cover public employees:

Alaska	Michigan	South Carolina
Arizona	Minnesota	Tennessee
California	Nevada	Utah
Connecticut	New Jersey	Vermont
Hawaii	New Mexico	Virgin Islands
Indiana	New York	Virginia
Iowa	North Carolina	Washington
Kentucky	Oregon	Wyoming
Maryland	Puerto Rico	

Section 18 of the Occupational Safety and Health Act of 1970 encourages states to develop and operate their own job safety and health programs. OSHA approves and monitors state plans and provides up to 50 percent of an approved plan's operating costs.

There are currently 24 states and jurisdictions operating complete state plans (covering both the private sector and state and local government employees) and 4—Connecticut, New Jersey, New York, and the Virgin Islands—covering public employees only. Eight other states were approved at one time but subsequently withdrew their programs. States must set job safety and health standards that are "at least as effective as" comparable federal standards, though most states adopt standards identical to federal standards. States have the option to promulgate standards covering hazards not addressed by federal standards.

Inspection and Consultation. A state must conduct inspections to enforce its standards, cover public (state and local government) employees, and operate occupational safety and health training and education programs. In addition, most states provide free on-site consultation to help employers identify and correct workplace hazards. Such consultation may be provided either under the plan or through a special agreement under Section 21(d) of the act.

Awareness of Laws and Standards. Regardless of whether a department is mandated to comply with the requirements under the Occupational Safety and Health Act or not, it is a good practice to do so for the protection and welfare of personnel. With

more emphasis being placed on health and safety, fire and EMS agencies are now more aware of pertinent laws and standards.

Laws and standards are a critical and significant part of the operations of any emergency services organization. Administrators must remain knowledgeable and compliant with current safety and health regulations. As managers responsible for the delivery of customer services, we must have a thorough understanding of the laws, standards, and regulations that govern the safety and health of members relating to response and actions at the emergency scene.

Regulations for Fire Brigades

With the development of occupational safety and health standards for general industry, there were applicable requirements for the fire service in 29 Code of Federal Regulations (CFR) 1910.156, Industrial Fire Brigades. This standard contains requirements for personal protective equipment, training, respiratory protection, and the use of fire-fighting equipment. Basically, this was the fire service's introduction to safety and health requirements. Attitudes toward safety and health in the fire service have been gradually changing as occupational safety and health requirements have improved over the past 20 years.

Fire Service Processes for Occupational Safety and Health

Federal and/or state laws now regulate components of the fire service occupational safety and health process, which include the following:

- Development of an occupational safety and health program
- Facility safety
- Training and education
- Protective clothing and protective equipment
- Respiratory protection
- Infection control
- Health maintenance

The risk management process must be recognized as a vital component of ensuring the success of the fire department's occupational safety and health program (see the section entitled "Risk Management"). Before dealing with specific risk management programs, it is important to understand the requirements of relevant NFPA codes.

NFPA STANDARDS

NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program,* and Related Standards

This document was intended to function as an umbrella for future standards developed by the Fire Service Occupational Safety and Health Technical Committee. The true advancement of fire fighter safety and health can be tied to the development of NFPA 1500, which was passed at the NFPA Annual Meeting in 1987. The standard was approved at the Standards Council Meeting in July 1987 and was published with an effective date of August 1987. Prior to the comment period of NFPA 1500, no standard had generated this many public comments (1200). NFPA 1403, *Standard on Live Fire Training Evolutions,* generated approximately 1000 comments during the Report on Comments in 1985.

After the initial passage of the standard in May 1987, issues that surfaced focused on incident management, infection control, and health maintenance. Task groups were appointed and work was initiated to begin development of the following standards: NFPA 1561, *Standard on Emergency Services Incident Management System;* NFPA 1581, *Standard on Fire Department Infection Control Program;* and NFPA 1582, *Standard on Comprehensive Occupational Medical Program for Fire Departments.* Also a complete rewrite of NFPA 1501, *Standard for Fire Department Safety Officer* (renumbered to NFPA 1521 during the 1992 revision cycle) was initiated as the requirements of this document had not changed significantly since its inception in 1977. Additionally, the technical committee addressed the continued development of NFPA 1500 to improve on the initial requirements addressed in the 1987 edition of the document. Two additional standards developed were NFPA 1583, *Standard on Health-Related Fitness Programs for Fire Fighters,* and NFPA 1584, *Recommended Practice on the Rehabilitation of Members Operating at Incident Scene Operations and Training Exercises.*

NFPA 1501, *Standard for Fire Department Safety Officer* (now NFPA 1521)

The initial standard that promoted health and safety for fire fighters was NFPA 1501, approved in 1977. The technical committee responsible for the development of NFPA 1501 was dissolved by the NFPA Standards Council and a new technical committee was officially formed in 1983. The scope of the Fire Service Occupational Safety and Health Technical Committee was to address the development of a comprehensive fire service occupational safety and health program.

Evolution of Standards in the 1990s

The issues that surfaced during the public proposal period of NFPA 1500 included the need to identify methods for achieving competencies for fire fighter, driver/operator, fire officer, and safety officer job functions and the need to establish training and education mandates for achieving and maintaining certifications.

Staffing for fire apparatus was also an issue. During the Report on Comment Period, a public comment was submitted to identify the minimum staffing on fire apparatus. The public comment led to a vote at the NFPA Annual Meeting in May 1992 in New Orleans. The issue was taken to the Standards Council for consideration. The staffing requirements remained in the annex under emergency operations.

During the 1997 revision cycle, additions to NFPA 1500 included recommendations on administrative and operational risk management and on conducting fire fighting operations during the incipient stages of an incident (for the initial rapid intervention crew). This crew required sufficient personnel to

conduct an "initial operation" in an atmosphere that was either potentially or actually immediately dangerous to life and health (IDLH).

The Occupational Safety and Health Administration defines an IDLH atmosphere as one that poses an immediate hazard to life or produces immediate irreversible debilitating effects on health. This issue, which was discussed and debated during the subsequent revision to NFPA 1500, coincided with OSHA's public review process of 29 CFR 1910.134, Respiratory Protection, which contained the mandates for the "Two in/Two out" requirements. The citing of fire departments caused a great deal of confusion and resistance among the fire service leaders and the governing bodies they reported to. Not until the revised NFPA 1500 was passed in May 1997, and OSHA issued its rules in January 1998, was the inconsistency resolved. The 1997 edition of NFPA 1500 included material that provided a comparison of the requirements 29 CFR 1910.134, Respiratory Protection, and those included in NFPA 1500 including the medical requirements.

FIGURE 12.7.1 Assessing Risk as Part of the Incident Management System (Photo courtesy of Fairfax County Fire and Rescue Department, Fairfax, Virginia)

Developments in the Twenty-First Century

Evolution of NFPA 1500. The fourth edition of NFPA 1500 was approved at the NFPA 2001 fall meeting and was issued by the Standards Council with an effective date of January 31, 2002. Changes were made based on input from NFPA Data Analysis and Research Division, NFPA fire investigation reports, and the National Institute on Occupational Safety and Health (NIOSH) Fire Fighter Fatality Investigation reports. The changes were made to the standard relating to personal protective clothing and equipment, fire apparatus, training requirements, medical requirements, and several other areas. The Fire Service Occupational Safety and Health Technical Committee working with several other NFPA technical committees developed a complete section that outlines the requirements for a fire department respiratory protection program. The standard provides the user and the enforcer one source in which to develop and implement a comprehensive respiratory protection program.

The 2007 edition of NFPA 1500 was approved at the annual meeting in Orlando, Florida, in June 2006 with an effective date of August 17, 2006. The 2007 edition is a complete revision of the standard, which includes a change in chapter titles, revisions to each chapter based on fire fighter fatality data analysis and reports, and requirements in the chapters addressing the operations of fire apparatus, protective clothing and protective equipment, and emergency operations. Annex material for each chapter was completely reviewed with necessary changes made.

NFPA 1561, *Standard on Emergency Services Incident Management System.* The 2005 edition of NFPA 1561 was prepared by the Technical Committee on Fire Service Occupational Safety and Health, acted on at the NFPA 2004 Fall Meeting, and issued by the Standards Council.

The first edition of this document was issued in 1990 to support requirements in NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program,* requiring fire departments to conduct emergency operations within an effective incident management system (Figure 12.7.1). The committee realized that the safety aspects of an effective and efficient command and control were as important as the operational coordination and effectiveness of the system. In developing this document, the committee examined several incident management systems and variations thereon that were in use in different fire departments and related organizations. The committee determined that, in addition to requiring the use of an incident management system, there should be performance criteria for the components of a system that contribute directly toward safety and health objectives and developed the standard to specifically address those concerns.

The 1995 edition expanded the areas of accountability, use of rapid intervention crews (RIC) for rescue of members, and interagency cooperation and recognized that incident management includes more than fireground operations. The 2000 edition expanded the document to reflect the mainstream utilization of incident management systems. The title of the document was changed to *Standard on Emergency Services Incident Management System* to reflect the fact that all emergency service organizations should use an incident management system. In the 2002 edition, the committee focused on areas of risk management, communications, roles and responsibilities of the Incident safety officer (ISO), rapid intervention crews, and defined command structures. In addition, new annex material was added to assist the users of the standard.

Following the issuance of the 2002 edition, a Tentative Interim Amendment (TIA) was issued to add annex material on position descriptions and roles, responsibilities of command, and general staff positions within an incident management system. This edition expands the TIA and incorporates it into the body of the standard. The response and operational capabilities of the emergency response community are required to be managed through an incident command system. The revisions in the 2005 edition of the standard address specific issues such as incident management teams, unified command, the roles and responsibilities of the incident commander (IC), and command and general staff functions.

DEFINITION OF SAFETY OFFICER ROLES

As previously stated, NFPA 1501, *Standard for Fire Department Safety Officer,* was the association's first fire service safety document. Although other standards dealt with protective clothing, fire apparatus, and other issues related to the fire service, NFPA 1501 was the first to specifically address fire fighter safety and health. The first two editions (1977 and 1982) of this standard addressed areas dealing primarily with the roles and responsibilities of a fire department safety officer. These roles were vague and were interpreted differently from user to user. The committee struggled to make this document a useful tool for the fire department and to make it play a more significant role in fire fighter safety.

Expanding Roles of the Safety Officer

With the appointment of the Fire Service Occupational Safety and Health Technical Committee in 1983, NFPA 1501 was assigned to this new technical committee. During the revision between the 1987 and 1992 editions, a movement began within the fire service to expand the roles and responsibilities of the safety officer. With the revision of the 1992 edition of the standard came a change in the numbering of the standard. This was done to be consistent with other standards developed by the technical committee. The role of the fire department safety officer was divided into two distinct positions—the incident safety officer (ISO) and the health and safety officer (HSO). Note that with the advent of the national incident management system, the term *safety officer* is the correct title for this position on the command staff. NFPA 1521 uses the term *incident safety officer* to distinguish the positions.

Training of Safety Officers

While the technical committee was revising and expanding NFPA 1521, fire service subject matter experts and curriculum developers at the National Fire Academy in Emmitsburg, Maryland, were developing two new courses based on these two distinct roles of the safety officer. These two 16-hour courses, Incident Safety Officer and Health and Safety Officer, outlined the basic requirements and roles and responsibilities of each position. The course included activities that emphasized the decision-making processes each position requires and provided instruction on how to read and utilize NFPA standards, federal laws, and rules and regulations. These two courses were offered to the fire service beginning in early 1996 and were updated in 2003.

These two courses continue to be two of the National Fire Academy's most popular courses. The specific roles for the incident safety officer and health and safety officer within a fire department's occupational safety and health program are a critical component in making the health and safety programs work. In some small or medium-sized departments, one person may be assigned the responsibilities of both positions, which usually leads either to that individual being overworked and frustrated or to the program not being implemented at all.

Roles and Responsibilities of the Health and Safety Officer

Health and safety officers must have a knowledge and understanding of pertinent laws, codes, and standards. Their responsibilities and functions include the following:

- Ensure that training and education programs relating to fire department operations are conducted
- Manage an accident prevention program
- Develop procedures for accident investigation and review
- Maintain records and conduct data analysis pertaining to fire fighter fatalities, injuries, occupational illnesses, health exposures, and accidents
- Review apparatus and equipment specification
- Conduct facility inspections to ensure compliance with applicable codes and standards
- Manage the health maintenance program to ensure compliance with NFPA 1582, *Standard on Comprehensive Occupational Medical Program for Fire Departments*
- Serve as liaison to various internal and external committees that influence the department's occupational safety and health program
- Serve as a member of the department's Occupational Safety and Health Committee
- Serve as the department's infection control officer or maintain a liaison with the infection control officer
- Ensure that the department has a critical incident stress management program
- Ensure that fire fighter safety and health issues are addressed during the post-incident analysis process

Roles and Responsibilities of the Incident Safety Officer

Standard operating procedures define criteria for the response or appointment of an incident safety officer position. The functions of the incident safety officer include the following:

- Serve as the safety officer of the command staff
- Monitor conditions, activities, and operations to determine whether they fall within the criteria as defined in the fire department's risk management plan
- Ensure that the incident commander establishes an incident scene rehabilitation tactical-level management unit during emergency operations
- Monitor the scene and report the status of conditions, hazards, and risks to the incident commander
- Ensure that the fire department's personnel accountability system is being utilized
- After receiving the incident action plan from the incident commander, provide the incident commander with a risk assessment of incident scene operations
- Ensure that established safety zones, collapse zones, hot zone, and other designated hazard areas are communicated to all members present on scene
- Evaluate motor vehicle scene traffic hazards and apparatus placement and take appropriate actions to mitigate hazards

- Communicate to the incident commander the need for assistant incident safety officers due to the need, size, complexity, or duration of the incident
- Ensure that a rapid intervention crew meeting the criteria in Chapter 8 of NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program,* is available and ready for deployment
- Where a fire has involved a building or buildings, advise the incident commander of hazards, collapse potential, and any fire extension in such building(s)
- Evaluate visible smoke and fire conditions and advise the incident commander, tactical-level management units officers, and company officers on the potential for flashover, backdraft, blowup, or other fire events that could pose a threat to operating teams
- Monitor the accessibility of entry and egress of structures and the effect they have on the safety of members conducting interior operations
- Ensure compliance with the department's infection control plan and NFPA 1581, *Standard on Fire Department Infection Control Program,* during emergency medical operations
- Ensure that incident scene rehabilitation and critical incident stress management are established as needed at emergency medical operations, especially mass casualty incidents

Roles and Responsibilities of the Hazardous Materials Incident Safety Officer

The hazardous materials incident safety officer should meet the requirements of NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents.* The functions of the hazardous materials incident safety officer include the following:

- Attend strategic and tactical planning sessions and provide input on risk assessment and member safety
- Ensure that a safety briefing, including an incident action plan and an incident safety plan, is developed and made available to all members on the scene
- Ensure that hot, warm, decontamination, and other zone designations are clearly marked and communicated to all members
- Meet with the incident commander to determine rehabilitation, accountability, or rapid intervention needs; for long-term operations, the hazardous materials incident safety officer should ensure that food, hygiene facilities, and any other special needs are provided for members

Roles and Responsibilities of the Incident Safety Officer for Special Operations Incidents

The individual who serves as the incident safety officer for special operations incidents should have the appropriate education, training, and experience in special operations. The functions of the incident safety officer for special operations incidents include the following:

- Upon notification of a member injury, illness, or exposure, immediately communicate this information to the incident commander to ensure that emergency medical care is provided
- In the event of a serious injury, fatality, or other potentially harmful occurrence, request assistance from the health and safety officer
- Prepare a written report for the post-incident analysis that includes pertinent information about the incident relating to safety and health issues; the incident safety officer for special operations incidents participates in the post-incident analysis
- Include information about issues relating to the use of protective clothing and equipment, personnel accountability system, rapid intervention crews, rehabilitation operations, and other issues affecting the safety and welfare of members at the incident scene

RISK MANAGEMENT

Risk Management During Emergency Operations

According to NFPA 1500, the management of risk during emergency operations is a critical factor for ensuring the safety and health of fire fighters. In order to have effective operational risk management, the following components need to be part of the incident command system:

- Routine evaluation of risk in all situations
- Well-defined strategic options
- Standard operating procedures
- Effective training
- Full protective clothing and protective equipment
- Effective incident management and communications
- Safety procedures and the use of an incident safety officer
- Rapid intervention crew(s)
- Adequate resources
- Incident scene rest and rehabilitation
- Regular re-evaluation of conditions
- Pessimistic evaluation of changing conditions
- Experience based on previous incidents and critiques

Using Risk Management Principles

The incident command system starts with the arrival of the first department company. The first company to arrive integrates risk management into the routine functions of incident command. As indicated in NFPA 1500, the concept of risk management should be utilized on the basis of the following principles:

- Activities that present a significant risk to safety of members should be limited to situations in which there is the potential to save endangered lives.
- Activities that are routinely employed to protect property should be recognized as inherent risks to the safety of members, and actions should be taken to reduce or avoid these risks.
- No risk to the safety of members should be acceptable when there is no possibility to save lives or property.

As indicated in the second item just listed, "actions should be taken to reduce or avoid these risks." Identifying potential safety concerns to members and taking actions to reduce risks to fire fighters are without a doubt two of the most important things that can be accomplished.

Reducing Risks. The following are just some of the ways to reduce the overall risks to members operating at the scene of emergency incidents:

- Written guidelines should be established and used that provide for the tracking and inventory of all members operating an emergency incident.
- All members operating in an emergency are responsible to actively participate in the department's personnel accountability system.
- The incident commander should be responsible for the overall responder accountability for the incident. The incident commander should initiate an accountability worksheet at the beginning of the incident and maintain the system throughout the operation.
- The incident commander should maintain an awareness of the location and function of all companies assigned to an incident.
- The incident commander should implement branch directors and division, group, or sector supervisors when needed to reduce the span of control for the incident commander.
- Branch directors and division and group supervisors should directly supervise and account for companies operating under their command.
- Company officers are accountable for all company members, and company members are responsible to remain under the supervision of their assigned company officer. Members should be responsible for following the personnel accountability system procedures, which should be used at all incidents.
- The incident command system should provide for additional accountability responders based on the size, complexity, or needs of an incident. The implementation of division, group, or sector supervisors can assist the incident commander in this area by reducing the span of control.
- The incident commander should provide for control of access to the incident scene.
- A department should adopt and routinely use a standard responder identification system to maintain accountability for each member assigned to an incident. There are several accountability systems used during structural fire fighting.
- The personnel accountability system should provide an accounting of those members actually responding to the scene on each company or apparatus.
- The incident command system should include standard operating guidelines that use emergency traffic communication to evacuate responders from an area where imminent hazard is found to exist and to account for their safety.

Emergency Traffic. The fire department standard operating procedure provides direction in the use of clear text radio messages for emergency incidents. The standard operating procedure should use emergency traffic as the designator to clear the radio traffic. "Emergency traffic" can be declared by the incident commander, division or group supervisor, or member in trouble or subject to emergency conditions. Clear text should be used to describe the emergency conditions present. Examples of emergency conditions that could occur include the following:

1. "Fire fighter down"
2. "Fire fighter missing"
3. "Fire fighter trapped"
4. Serious conditions—"all members evacuate the building"
5. Change in conditions—"wind changed direction from north to south"
6. Hazard identification—"power line has energized a fence to metal roof"
7. Change in tactics—"change from offensive to defensive"

When a member has declared "emergency traffic," that person should use clear text to identify the type of emergency, change in conditions, or tactical operations. The member who has declared the "emergency traffic" should conclude the condition by transmitting "all clear, resume radio traffic" to end the emergency situation or to reopen the radio channels for communication after announcing the emergency message.

Retreat Policy. A fire department should have an operational retreat policy. In addition to an emergency traffic radio message, fire departments could use an additional signal, such as an apparatus air horn, to cause an evacuation of responders. Some departments have incorporated a series of three 10-second short blasts on an air horn with a 10-second silence between each series of blasts of an air horn. For fire departments that adopt this system, it is very important for the incident commander to select apparatus away from the command post to reduce the possibility of missing radio messages while the air horns are sounding.

Personnel Accountability Report. The incident commander should conduct a personnel accountability report (PAR) from each division or group supervisor whenever there has been an announcement of a change in conditions that could create an unsafe operation. When a division or group supervisor is requested to conduct a PAR, this supervisor is responsible for reporting on the accountability of all companies or members working within his or her area of responsibility. (A position description that addresses fire fighter Incident Safety and Accountability Guideline is available from FIRESCOPE and is published in the ICS 910 publication.)

Officer Responsibilities

An incident safety officer should be designated by the incident commander whenever the incident commander cannot perform this vital function due to the size or complexity of the incident. At an emergency incident where activities are determined by the incident safety officer to be unsafe or to involve an imminent hazard, the incident safety officer should have the authority to alter, suspend, or terminate those activities. The incident safety officer should immediately inform the incident commander of any actions taken to correct imminent hazards at the emergency scene. At an emergency incident where an incident safety officer identifies unsafe conditions, operation, or hazards that do not

present an imminent danger, the incident safety officer should take appropriate action through the incident commander to mitigate or eliminate the unsafe condition, operation, or hazard at the incident scene.

The incident safety officer should be designated by the incident commander and be integrated with the incident management system as a command staff member. The incident safety officer should survey and monitor the scene and report the status of conditions, hazards, and risks to the incident commander. The incident safety officer can have designated assistant safety officers based on the need, size, complexity, or duration of the incident.

The incident commander should be provided with reports of elapsed time-on-scene at emergency incidents in 15-minute intervals from the emergency service organization communication center until reports are terminated by the incident commander. Members operating in hazardous areas at emergency incidents should operate in crews of two or more.

Deployment

Initial Crew. In the initial stages of an incident where only one crew is operating in the hazardous area at a working structure fire, a minimum of four individuals is required, consisting of two individuals working as a crew in the hazard area and two individuals present outside this hazard area who are available for assistance or rescue at emergency operations where entry into the danger area is required. The standby members should be responsible for maintaining a constant awareness of the number and identity of members operating in the hazardous area, their location and function, and time of entry. The standby members should remain in radio, visual, voice, or signal line communications with the crew. The initial stages of an incident should encompass the tasks undertaken by the first arriving company with only one crew assigned or operating in the hazardous area.

The following examples from NFPA 1500 indicate how a fire department could deploy a team of four members initially at the scene of a structure fire:

- The team leader and one fire fighter could advance a fire-fighting hoseline into the IDLH atmosphere, and one fire fighter and the pump operator become the standby members.
- The team leader could designate the pump operator to be the incident commander. The team leader and one fire fighter enter the IDLH atmosphere, and one fire fighter and pump operator remain outside as the standby members.
- The two fire fighters could advance the hoseline in the IDLH atmosphere, and the team leader and pump operator remain outside as standby members.

Assignment of Additional Resources. Once a second crew is assigned or operating in the hazardous area, the incident should no longer be considered in the initial stages, and at least one rapid intervention crew/company should comply with the following requirements: (1) on-scene members designated and dedicated as rapid intervention crew/company, and (2) on-scene members performing other functions but ready to redeploy to perform rapid intervention crew/company functions.

The assignment of any responders as members of the rapid intervention crew/company should not be permitted if abandoning their critical task(s) to perform rescue clearly jeopardizes the safety and health of any member operating at the incident. As the incident expands in size or complexity, which includes an incident commander's requests for additional resources beyond the fire department's initial attack assignment, the dedicated rapid intervention crew/company (RIC) should on arrival of these additional resources be either one of the following: (1) on-scene members designated and dedicated as rapid intervention crew/company, and (2) on-scene crew/company or crews/companies located for rapid deployment and dedicated as rapid intervention crews.

During fire fighter rescue operations, each company should remain intact. At least one dedicated rapid intervention company should be in the standby mode with equipment to provide for the rescue of members who are performing special operations or for members who are in positions that present an immediate danger of injury in the event of equipment failure or collapse.

When more than one rapid intervention crew is deployed, consider implementing a rescue group supervisor to manage the multiple rapid intervention companies and to coordinate any rescue attempts when in the deployment mode. Whenever a rapid intervention crew is deployed, the incident commander should designate another rapid intervention crew in the standby mode to provide for fire fighter safety.

Additional areas that are also very important in reducing risks to members include the following: effective training, rest and rehabilitation, continuous evaluation of changing conditions, and past experience.

NFPA 1581, *Standard on Fire Department Infection Control Program*

Emergency Medical Services. As the fire service has expanded its role, the fastest-growing service it provides is that of emergency medical services (EMS). For fire departments that provide a level of emergency medical service, that service constitutes more than 60 to 70 percent of their responses. The fire service provides different models and levels of this service. Included are the basic first responder level, as outlined by the medical regulatory agency; the basic emergency medical technician level (EMT-B); the intermediate level (EMT-I); and the paramedic level (EMT-P). At both the intermediate and paramedic levels, regulatory agencies may allow certain procedures based on need, training, and local medical protocol. The models of service delivery may include treatment and transport at all levels; treatment at all levels with a combination of public, private, or third-party transport; and treatment with only private transport.

In any of these models, the fire service uses largely dual-trained cross-role fire fighters. Many departments now require members to have some level of emergency medical training and certification before they apply for a position within the department.

Exposure to Disease. With these increased roles and services come increased risks. The risks within this context include com-

municable and infectious disease. The fire service members providing patient care place themselves at risk at an incident scene, but some of these same risks are found in the facilities in which they live and work. NFPA 1581, 1992 edition, was part of the plan of developing standards that could have a significant and immediate impact on fire fighter health and safety. The standard outlined a program that would afford fire fighters a level of protection if they complied with documented practices regarding the following:

- Wearing protective clothing
- Being immunized and vaccinated
- Adhering to an exposure reporting system
- Cleaning and disinfecting clothing and equipment
- Acquiring needed training

Important to note is the fact that when the standard was being issued, there was an outbreak of the AIDS virus, the initial hepatitis B vaccines were being developed, and the fear of fire fighters becoming infected and possibly dying was ongoing. The federal government moved quickly, under the auspices of the Centers of Disease Control and Prevention (CDC), and OSHA developed regulations on protecting emergency response personnel and health care workers (Figure 12.7.2). The Ryan White Act spelled out protection, notification, and confidentiality issues regarding communicable and infectious diseases.

Cleanup. One important aspect of infection control is the cleaning and disinfecting of protective clothing and protective equipment. This cleanup includes the proper cleaning and disinfecting of protective clothing and equipment, a separate room and laundry facilities to accomplish that, a clean work area in the kitchen to wash and prepare meals, and clean and properly spaced living quarters. The 1992 edition of NFPA 1581 provided the initial requirements. The 1995 edition contained those additional requirements and updates on vaccinations and immunizations, facility safety, and worker protection. The 2000 edition has continued along those same avenues and expanded into other areas, including updating the CDC regulations, updating the immunization and vaccination list, expanding the list of infectious and communicable diseases, and developing requirements for cleaning and disinfecting apparatus and vehicles. This standard, along with NFPA 1999, *Standard on Protective Clothing for Emergency Medical Operations,* is an asset to being better educated regarding the hazards of infectious and communicable diseases. The fire service needed an educational venue to explain to fire fighters that the protective clothing they wore at an incident scene contained contaminants that might be harmful. The possibility for such cross-contamination is real and the fire service needs the education component. Even if the station does not have in-house cleaning capabilities, the fire department is required to clean the fire fighters' protective clothing every 6 months at a minimum. The issue is for fire fighters to protect themselves so that they can continue to provide service to the citizens we serve.

NFPA 1582, *Standard on Comprehensive Occupational Medical Program for Fire Departments*

Fire fighter medical requirements were originally included as a component of NFPA 1001, *Standard for Fire Fighter Professional Qualifications.* In 1988 the Occupational Safety and

FIGURE 12.7.2 Emergency Response Personnel Protecting Himself While Providing Patient Care (Photo courtesy of Fairfax County Fire and Rescue Department, Fairfax, Virginia)

Health Technical Committee and the Professional Qualifications Technical Committee formed a working subcommittee whose mission was to write a medical requirements standard for both candidate and incumbent fire fighters. This committee, which was composed of occupational medical physicians, fire service personnel at all levels, fire service instructors, and representative fire service organizations, realized early in the process that medical evaluations for fire fighters are an important component of an overall occupational medical program.

Medical Condition of Fire Fighters. The first edition of the standard, issued in 1992, outlined medical requirements that were categorized into A and B conditions. Category A conditions would preclude someone from either becoming a fire fighter or from continuing in a position that included primarily fire suppression. This decision caused difficulty because most fire departments had only one entry portal into the service and that was as a fire suppression fire fighter. An additional complication emerged as fire departments created "light-duty positions" or moved personnel into other positions that had no job description.

Fire department physicians or those hired to perform medical evaluations had no fire fighter job description or task analysis on which to base the medical evaluation and, thus, determine the medical condition necessary to be a fire fighter. Consequently, this raised questions on who was being "accommodated" in order to maintain his or her status as a fire fighter. Although some departments made this practice part of a labor agreement, other departments considered it part of the routine procedure. This issue led to some problems while the 1997 edition of the standard was being written. The technical committee physicians realized that when they examined fire fighters, certain areas within the standard were critical, based on how the 1992 edition was being interpreted.

They identified the following areas as ones that needed greater emphasis and clarification: cardiovascular, neurological, vision, hearing, and metabolic processes. Thus, the committee sought out specialists in those areas to assist them in rewriting the standard.

Americans with Disabilities Act. Concurrently, litigation, citing NFPA 1582, was brought forward regarding the use and interpretation of the Americans with Disabilities Act (ADA). The implementation and interpretation of the ADA law created confusion on how this law impacted employment factors of hiring and promoting within the fire service. The committee worked toward revising the standard and further defining areas by developing a sample job task analysis, a sample job description, an annex that included discussion regarding ADA, and a sample physician's checklist. In the 1997 edition, all these changes were made and the medical requirements were updated. Medical technology changes constantly; the standards-making process, however, cannot keep up with these changes.

The committee members, along with outside physicians, worked within the confines of a short revision cycle to continue to refine the five identified areas in the 1997 edition. Additionally, the committee realized that the work being done by the National Institute for Occupational Safety and Health (NIOSH) in its fire fighter fatality investigations as well as documentation from NFPA Fire Analysis and Research Division would assist it in the future as revisions to NFPA 1582 were being made. The 2000 edition of the standard, therefore, reflects some of those revisions, especially in the areas of diabetes, hearing, and cardiovascular disease.

Common Medical Problems. Statistics tell us that almost 50 percent of fire fighter fatalities are cardiac related and almost 50 percent of those had previous cardiac-related problems. The commonsense approach would be to medically evaluate these personnel annually and try to diagnose these conditions in the early stages and treat them before they occur. Recall that the purpose of an occupational safety and health program is for the fire fighter to leave the profession in the same condition as when he or she entered it. Fire fighting is a hazardous occupation.

In addition to cardiac-related problems, other medical problems are also characteristic of the profession, including a high incidence of cancer, especially of the liver, kidney, colon, prostate, and lung. Screening for these and other occupationally related diseases is a component of an occupational medical program and is included as part of the medical evaluation program.

Role of the Fire Department Physician. The fire department physician plays a significant role in managing the fire department's occupational medical program. Many fire departments that cannot afford their own physicians have grouped together to contract with either a physician or local HMO. Some smaller departments may utilize the physician as a regular member of their fire-fighting force. In any case, the physician oversees the program, reviews medical exams and evaluations, recommends follow-up or specialist exams, and works in conjunction with the health safety officer and the health fitness coordinator.

The 2003 edition addressed the issues of medical care and evaluation of both candidates and incumbents within a fire department; these issues have been discussed in numerous NFPA standards. The initial discussion and mandatory medical requirements were contained in NFPA 1001. Members of both committees have broken significant ground in providing a standard that the user—the fire department physician—can understand. The physicians on the committee have developed a physician guidance text that provides a link between the essential job tasks of a fire fighter doing manual fire suppression and the medical requirements in the standard. This will assist the user in determining, based on medical evaluations, if someone can do the essential job tasks.

Occupational Medical Program. In addition, the standard has delineated the document to address those medical issues of a candidate seeking to become a fire fighter and those incumbents currently performing the tasks of fire fighting. This standard does not differentiate among volunteer, paid-on-call, part-time, and career fire fighters—the tasks are the same. Since the committee has changed the title of the standard to reflect a comprehensive occupational medical program, it has included references to the IAFC-IAFF Joint Wellness Initiative and to NFPA 1583. These two documents outline a health-related fit-

ness program that is medically validated against this edition of NFPA 1582. Although the cost of medical exams continually increases, the organization must weigh the initial costs versus long-term job related illnesses, injuries, and fatality costs. Fire departments spend a lot of money on preventive maintenance of apparatus and equipment; however, that is an inefficient use of resources if they do not have medically qualified personnel to operate them and to respond to emergency incidents.

NFPA 1583, *Standard on Health-Related Fitness Programs for Fire Fighters*

As part of a fire department occupational health and safety program, NFPA 1500 includes text requiring a physical performance program as well as a fitness program. The committee struggled to provide a standard on physical performance requirements that would be required for both candidates and incumbents alike. This standard was doomed from the outset. There was considerable discussion among the technical committee members, as well as litigation within the United States, regarding the validity and content of physical performance testing. Trying to develop a set of physical test skills related by task analysis to the profession of fire fighting and then to validate that test was difficult at best.

The committee skipped a cycle and with a great deal of angst reached consensus on a document that was passed by the NFPA membership and then subsequently appealed to the association's Standards Council. It was returned to the technical committee by the Standards Council and withdrawn from the system after a unanimous vote from the committee members in 1997. The technical committee initiated a new document in the summer of 1997.

Joint Fire Service Wellness Program. As this proposed NFPA standard was withdrawn, a group of 10 cities within North America began work on a joint fire service wellness program. This program, supported and endorsed by the International Association of Fire Fighters (IAFF) and the International Association of Fire Chiefs (IAFC), included Phoenix, Arizona; New York, New York; Los Angeles County, California; Seattle, Washington; Calgary, Alberta, Canada; Austin, Texas; Charlotte, North Carolina; Indianapolis, Indiana; Fairfax County, Virginia; and Metro-Dade County, Florida. IAFF officials from each local, fire chiefs from each city, and fire department physicians worked on this program, which was introduced at both Fire Rescue International and the IAFF Redmond Symposium in 1999. This program has been used successfully by these 10 departments, as well as others across the world. It is a great example of a joint labor-management initiative that benefits all of the fire service.

The Fire Service Occupational Medical and Health Technical Committee began work on a health-related fitness program for the fire service, which initially did not have widespread support from the fire service. Many saw this effort as a revisit of the physical performance test versus what it really was—namely, a standard containing the components of an overall health-related fitness program for the fire service. Managed by both the fire department physician and the health fitness coordinator, this standard has nutrition, wellness, and fitness components that may be accomplished in a number of different ways. The program, as outlined in the standard, is similar to the program developed by the IAFF/IAFC Joint Labor/Management Wellness Initiative.

Fitness Testing. The 10 cities in the initiative then began work on a physical performance component that would be used to test candidates wishing to seek employment in the fire service profession. The testing process was developed with the assistance of the U.S. Department of Justice. The job tasks were validated for the 10 cities, the testing mechanism and props were developed, and then the test was run using incumbents from each department. This test, called the Candidate Performance Agility Test (CPAT), was introduced at both Fire Rescue International and the IAFF Redmond Symposium in 1999. The validity developed within the 10 cities required each to provide a job task analysis and a job description based on that analysis in order to validate the CPAT test for their municipality. The validation process is not a "one size fits all" for those who choose to utilize it. Municipalities must go through the same process as did the 10 cities and validate the CPAT individually. The IAFF has developed a Peer Fitness Training Program that assists those municipalities that wish to use the CPAT.

NFPA 1584, *Recommended Practice on Rehabilitation of Members Operating at Incident Scene Operations and Training Exercises*

The 2003 edition of NFPA 1584 was prepared by the Technical Committee on Fire Service Occupational Medical and Health and acted on by NFPA at its November Association Technical Meeting held November 16–20, 2002, in Atlanta, Georgia. It was issued by the Standards Council on January 17, 2003, with an effective date of February 6, 2003.

The Technical Committee on Fire Service Occupational Medical and Health has responsibility for this document. The members of the committee have developed standards in areas of incident management, occupational medical programs, fitness evaluation, fire department safety officer, and infectious disease control programs. These standards fall under the umbrella of NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program,* 2002 edition. An integral component of both an occupational safety and health program and incident scene management is an organized approach for fire department members' rehabilitation at incident scene operations.

The concept of incident scene rehabilitation has been discussed and utilized throughout the fire service in various sizes and configurations. Many departments have utilized material from the United States Fire Administration, as well as material from emergency medical services. Progressive departments have shared their "lessons learned" in the development of this document. This recommended practice establishes the minimum level of criteria for developing and implementing a rehabilitation process for fire department members at incident scene operations and training exercises. This recommended practice provides for the rehabilitation of members operating within an

incident management system rehabilitation component, including but not limited to, the following:

- Medical evaluation and treatment
- Food and fluid replenishment
- Relief from climatic conditions
- Rest and recovery
- Member accountability

RISK MANAGEMENT MODEL

NFPA 1500 requires the development, implementation, and use of a written risk management plan. This plan must consider all fire department activities, operations, and standard operating procedures to ensure that a comprehensive approach is the focus. The health and safety officer is the primary person responsible for this document but must seek assistance as this plan covers all aspects of the fire department.

The risk management model presents a systematic approach for identifying and planning for the control of risks. This methodical process for making decisions can be utilized not only for the nonemergency risks that all organizations must address but also for the risks associated with the response to and mitigation of an emergency incident. The factors at each incident will always vary, but as we have known for years, continual training in all aspects of the approach will yield the best, most consistent results possible.

Five Steps

The model has five primary components, or steps, which serve as a foundation for this process. Each one depends on information generated by the previous step, so it is important to evaluate each one before moving on to the next. The following five steps are discussed in detail in the next sections:

1. Identifying risk
2. Evaluating risk
3. Establishing priorities or prioritization
4. Establishing risk control techniques
5. Monitoring

For each step in the process, it is important to record performance criteria, suggestions, and recommendations. These data will provide the elements that formulate a written risk management plan. The number of pages in the plan has no impact on the plan's effectiveness. Once created, the plan should be periodically updated (at least annually). Consider it a dynamic process, not a static event with a single written record. Keep the plan current based on conditions, circumstances, and experience.

Identifying Risk. The first step of the risk management model involves identifying what could go wrong. To make this identification it is useful to compile a list of all emergency and nonemergency operations in which the department participates. The intent is to plan for the worst but hope for the best. There are many sources to assist with this identification process. The first, and possibly the most effective, is the department's loss prevention data. Seek input and ideas from department personnel, other health and safety officers, jurisdiction risk managers, trade journals, professional associations, and other service providers. When using ideas or information from other fire departments or organizations, simply consider local circumstances when formulating the list.

Evaluating Risk. Once the risks are identified, they can be evaluated from both a frequency and severity standpoint. Frequency addresses the likelihood of occurrence. Typically, if a particular type of incident (e.g., back injuries) has occurred repeatedly, these incidents will continue to occur until effective control measures are implemented.

Severity addresses the degree of seriousness of the incident and can be measured in a variety of ways, such as time away from work, cost of damage, cost of and time for repair or replacement, disruption of service, or legal costs. Using the information gathered in the identification step, the risks can be classified based on severity.

Establishing Priorities. Taken in combination, the results of the frequency and severity determinations will help to establish priorities for determining action. Any risk that has a low probability of occurrence (frequency) but has serious consequences (high risk or severity) deserves immediate action and would be considered a high-priority item (Figure 12.7.3). Nonserious incidents with a low likelihood of occurrence are a lower priority and can be placed near the bottom of the "action required" list.

Establishing Risk Control Techniques. At this point in the process, risks have been identified and evaluated, so it is time to find solutions. There are several approaches to take, including risk avoidance, implementation of control measures, and risk transfer.

In any situation, the best choice is *risk avoidance,* which simply means to avoid the activity that creates the risk. In an emergency services organization, risk avoidance frequently is impractical. Lifting a stretcher presents a serious back injury risk, but you cannot avoid this risk and still provide effective service.

An example of a situation in which avoidance has been very practical is the widespread, hopefully universal, use of sharps containers. The risks associated with recapping needles are well documented; therefore, recapping is no longer an ac-

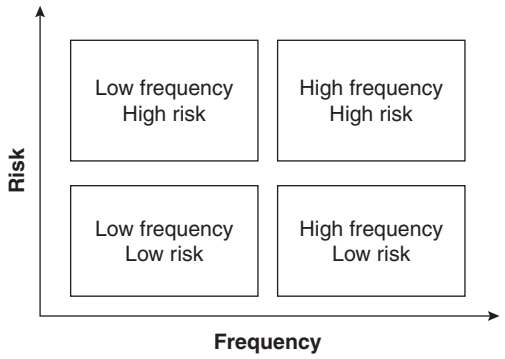

FIGURE 12.7.3 Risk Management Graph

cepted practice. This risky behavior can be avoided through the proper use of a sharps container.

The most common method utilized for the management of risk is the adoption of *effective control measures.* Although control measures will not eliminate the risk, they can reduce the likelihood of occurrence or mitigate the severity. Safety programs, ongoing training and education programs, and well-defined standard operating procedures (SOPs) are all effective control measures.

Some typical control measures instituted to control fireground injuries include accountability, use of full protective clothing, a mandatory respiratory protection program, training and education, and competent standard operating procedures. These control measures coupled together make an effective program that ensures safe fireground operations.

Risk transfer can be accomplished in two primary ways: physically transferring the risk to somebody else or through the purchase of insurance. For a fire or EMS organization, the transfer of risk may be difficult if not impossible. However, an example of risk transfer would be contracting out the operation and maintenance of helicopters for use by responders. The risks associated with those activities have been transferred to a private contractor.

The purchase of insurance transfers financial risk only and does nothing to affect the likelihood of occurrence. Buying fire insurance on a fire station, although highly recommended for protecting the assets of the department, does nothing to prevent the station from burning down. Therefore, insurance is no substitute for effective control measures.

Monitoring. The last step in the process is risk management monitoring. Once control measures have been implemented, they need to be evaluated to measure their effectiveness. Any problems that occur in the process have to be revised or modified. This final step ensures that the system is dynamic and will facilitate periodic reviews of the entire program.

The intent of the risk management plan is to develop a strategy for reducing the inherent risks associated with fire department operations. Regardless of the size or type of fire department, every organization should operate within the parameters of a risk management plan. This is a dynamic and aggressive process that must be monitored and revised annually by the health and safety officer.

Operational Risk Management

In order to address operational risk management and reduce level of risk during emergency operations, several components need to be incorporated into this process. Many components have a positive impact of reducing risk during fireground operations or any other type of emergency including as discussed in the section that follows.

INCIDENT COMMAND SYSTEM (ICS)

In the early 1970s, southern California experienced several devastating wildland fires. The overall cost and loss associated with these fires totaled $18 million per day. This multijurisdictional disaster was the impetus for the development of an improved interagency incident management system known as the incident command system (ICS). The incident command system is one of the beneficial results of a federally funded project called FIRESCOPE that was convened after these fires and whose charter was to examine various aspects of interagency response to incidents.

FIRESCOPE

The Fire Resources of California Organized for Potential Emergencies (FIRESCOPE) incident command system is primarily a command and control system delineating job responsibilities and organizational structure for the purpose of managing day-to-day fire and rescue operations. It also is flexible enough to manage catastrophic incidents involving thousands of emergency response and management personnel.

National Interagency Incident Management System (NIIMS)

This incident command system was developed by the wildland community in order to provide a common system for wildland fire protection agencies at the local, state, and federal levels. The NIIMS organization includes the Bureau of Land Management, the Bureau of Indian Affairs, the U.S. Fish and Wildlife Service, the U.S. Forest Service, representatives of State Foresters, and the National Park Service. NIIMS consists of the following five major subsystems that collectively provide a total systems approach to risk management:

1. The incident command system, which includes operating requirements, eight interactive components, and procedures for organizing and operating an on-scene management structure
2. Training that is standardized and supports the effective operations of the National Interagency Incident Management System
3. A qualification and certification system that provides personnel across the nation with standard training, experience, and physical requirements to fill specific positions in the incident command system
4. Publications management that includes development, publication, and distribution of NIIMS materials
5. Supporting technologies such as orthophoto mapping, infrared photography, and a multiagency coordination system that supports NIIMS operations

FIRESCOPE Model Incident Command System

Since the development of the incident command system, the fire service has experienced several challenges in understanding its application. As a result, inconsistencies in the system began to develop; other hybrid systems came into existence, further distancing a common approach to incident command. A single incident management system is critical for effective command and control of major incidents. At these incidents, a single department may interface with other agencies on the local, state, and federal levels. In order to reduce the inherent confusion that

may be associated with larger-scale incidents, a common command system must be used.

Need for a Single Approach

Recognizing the challenges that were occurring in the fire service in applying a common approach to incident command, the National Fire Service Incident Management System Consortium was created. Developed in 1990, its purpose is to evaluate an approach to developing a single command system. The consortium consists of many individual fire service leaders, representatives of most major fire service organizations, and representatives of federal agencies including FIRESCOPE. One of the significant outcomes of the work done by the consortium was the identification of the need to develop operational protocols within the incident command system, so that fire and rescue personnel would be able to apply the incident command system as one common system. In 1993, as a result of this, the IMS consortium completed its first document: *Model Procedures Guide for Structural Firefighting.*

FIRESCOPE adopted this in principle as an application to the Model FIRESCOPE Incident Command System. The basic premise is that the organizational structure found in the FIRESCOPE Incident Command System now is enhanced with operational protocols that allow the nation's fire and rescue personnel to apply the incident command system effectively, regardless of the area in the country to which they are assigned. The National Fire Academy (NFA), having adopted the FIRESCOPE Incident Command System in 1980, has incorporated this material in its training curriculum and will continue to reach the thousands of fire service personnel with one common incident command and control system.

It is important to note that the FIRESCOPE Model Incident Command System has had other applications or modules similar to the structural fire-fighting applications that have been in place for some time. These create a framework for other activities to operate in and further enhance the use of the incident command system. Examples are the multicasualty, hazardous materials, and the urban search and rescue applications.

The Federal Emergency Management Agency (FEMA) formally adopted the FIRESCOPE Incident Command System as the incident management system for any federal response required by the agency. Since then, several other federal agencies have adopted the FIRESCOPE Incident Command System.

Evolution of the Incident Command System

The concept of the incident command system (ICS) was developed more than 30 years ago in the aftermath of a devastating wildfire in California. During 13 days in 1970, 16 lives were lost, 700 structures were destroyed, and over 1.5 million acres burned. The overall cost and loss associated with these fires totaled $18 million per day. Although all of the responding agencies cooperated to the best of their ability, numerous problems with communication and coordination hampered their effectiveness. As a result, Congress mandated that the United States Forest Service design a system that would "make a quantum jump in the capabilities of Southern California wildland fire protection agencies to effectively coordinate interagency action and to allocate suppression resources in dynamic, multiple-fire situations."

The California Department of Forestry and Fire Protection; the Governor's Office of Emergency Services; the Los Angeles, Ventura, and Santa Barbara County Fire Departments; and the Los Angeles City Fire Department joined with the United States Forest Service to develop the system. This system became known as FIRESCOPE .

In 1973, the first FIRESCOPE Technical Team was established to guide the research and development design. Two major components came out of this work, the incident command system (ICS) and the Multi-Agency Coordination System (MACS). The FIRESCOPE ICS is primarily a command-and-control system delineating job responsibilities and organizational structure for the purpose of managing day-to-day operations for all types of emergency incidents. By the mid-seventies, FIRESCOPE agencies had formally agreed on ICS common terminology and procedures and conducted limited ICS field-testing. By 1980, parts of ICS had been used successfully on several major wildland and urban fire incidents. It was formally adopted by the Los Angeles Fire Department, the California Department of Forestry and Fire Protection (CDF), and the Governor's Office of Emergency Services (OES) as well as endorsed by the State Board of Fire Services.

Also during the 1970s, the National Wildfire Coordinating Group (NWCG) was chartered to coordinate fire management programs of the various participating federal and state agencies. By 1980, FIRESCOPE ICS training was under development. Recognizing that FIRESCOPE training could also satisfy the needs of other state and federal agencies in addition to the local users for which it was designed, the NWCG conducted an analysis of FIRESCOPE ICS for possible national application.

Widening the Application of ICS

By 1981, the incident command system was widely used throughout southern California by the major fire agencies. In addition, the use of the incident command system in response to nonfire incidents was increasing. Although FIRESCOPE ICS was originally developed to assist in the response to wildland fires, it was quickly recognized as a system that could help public safety responders provide effective and coordinated incident management for a wide range of situations, including floods, hazardous materials accidents, earthquakes, and aircraft crashes. It was flexible enough to manage catastrophic incidents involving thousands of emergency response and management personnel. By introducing relatively minor terminology, organizational, and procedural modifications to FIRESCOPE ICS, the NIIMS ICS became adaptable to an all-hazards environment.

Although tactically each type of incident may be handled somewhat differently, the overall incident management approach still utilizes the major functions of the incident command system. The FIRESCOPE board of directors and the NWCG recommended national application of ICS. In 1982, all FIRESCOPE ICS documentation was revised and adopted as the National Interagency Incident Management System (NIIMS). In the years since FIRESCOPE and the NIIMS were blended, the

FIRESCOPE agencies and the NWCG have worked together to update and maintain the Incident Command System Operational System Description (ICS 120–1). This document would later serve as the basis for the NIMS ICS.

National Incident Management System (NIMS)

The way this nation prepares for and responds to domestic incidents is changing. It will not be an abrupt change; best practices that have been developed over the years are part of this new comprehensive national approach to incident management known as the National Incident Management System (NIMS). Developed by the Department of Homeland Security and issued in March 2004, the NIMS will enable responders at all jurisdictional levels and across all disciplines to work together more effectively and efficiently.

One of the most important best practices that has been incorporated into the NIMS is the incident command system (ICS), a standard, on-scene, all-hazards incident management system already in use by fire fighters, hazardous materials teams, rescuers, and emergency medical teams. The ICS has been established by the NIMS as the standardized incident organizational structure for the management of all incidents.

In Homeland Security Presidential Directive-5 (HSPD-5), President Bush called on the Secretary of Homeland Security to develop a national incident management system to provide a consistent nationwide approach for federal, state, tribal, and local governments to work together to prepare for, prevent, respond to, and recover from domestic incidents, regardless of cause, size, or complexity.

On March 1, 2004, after close collaboration with state and local government officials and representatives from a wide range of public safety organizations, Homeland Security issued the NIMS. This system incorporates many existing best practices into a comprehensive national approach to domestic incident management, applicable at all jurisdictional levels and across all functional disciplines.

The NIMS represents a core set of doctrine, principles, terminology, and organizational processes to enable effective, efficient, and collaborative incident management at all levels. To provide the framework for interoperability and compatibility, the NIMS is based on a balance between flexibility and standardization. The recommendations of the National Commission on Terrorist Attacks upon the United States (the "9/11 Commission") further highlight the importance of ICS. The commission's report recommends national adoption of the ICS to enhance command, control, and communications capabilities.

BLENDING INCIDENT COMMAND SYSTEMS

There were several efforts to "blend" the various incident command systems. One early effort was in 1987 when NFPA undertook the development of NFPA 1561, then called *Standard on Fire Department Incident Management System.* The NFPA committee quickly recognized that the majority of the incident command systems in existence at the time were similar. The differences among the systems were mainly due to variations in terminology for similar components. That NFPA standard, later revised to its present title, *Standard on Emergency Services Incident Management Systems,* provides for organizations to adopt or modify existing systems to suit local requirements or preferences as long as they meet specific performance measurements.

National Fire Service Incident Management System (IMS) Consortium

Recognizing the continuing challenges occurring in the fire service in applying a common approach to incident command, the National Fire Service Incident Management System (IMS) Consortium was created in 1990. Its purpose was to evaluate an approach to developing a single command system. The consortium consisted of many individual fire service leaders, representatives of most major fire service organizations, and representatives of federal, state, and local agencies, including FIRESCOPE and the Phoenix Fire Department. One of the significant outcomes of the consortium's work was an agreement on the need to develop operational protocols within ICS, so that fire and rescue personnel would be able to apply the ICS as one common system.

In 1993, the IMS consortium completed its first document: *Model Procedures Guide for Structural Firefighting.* As a result, FIRESCOPE incorporated the model procedures, thereby enhancing its organizational structure with operational protocols. These changes enabled the nation's fire and rescue personnel to apply the ICS effectively regardless of what region of the country they were assigned to.

The NIMS provides a consistent, flexible, and adjustable national framework within which government and private entities at all levels can work together to manage domestic incidents, regardless of their cause, size, location, or complexity. This flexibility applies across all phases of incident management: prevention, preparedness, response, recovery, and mitigation. The NIMS provides a set of standardized organizational structures—including the ICS, Multi-Agency Coordination Systems, and public information systems—as well as requirements for processes, procedures, and systems to improve interoperability among jurisdictions and disciplines in various areas.

Department of Homeland Security

The Department of Homeland Security recognizes that the overwhelming majority of emergency incidents are handled on a daily basis by a single jurisdiction at the local level. However, the challenges we face as a nation are far greater than the capabilities of any one community or state but no greater than the sum of all of us working together. There will be instances in which successful domestic incident management operations depend on the involvement of emergency responders from multiple jurisdictions, as well as personnel and equipment from other states and the federal government. These instances require effective and efficient coordination across a broad spectrum of organizations and activities. The success of the operations will

depend on the ability to mobilize and effectively utilize multiple outside resources. These resources must come together in an organizational framework that is understood by everyone and must utilize a common plan, as specified through a process of incident action planning. This will be possible only if we unite, plan, exercise, and respond using a common NIMS.

When Homeland Security released the NIMS on March 1, 2004, Secretary Tom Ridge and Under Secretary Brown specifically highlighted compliance with the ICS as being possible fairly quickly. They recognized that in some cities, the fire and police departments have worked together using ICS for years. In other places, only the fire department has used ICS. Although law enforcement, public works, and public health were aware of the concept, they regarded ICS as a fire service system.

The NIMS ends this discrepancy because HSPD-5 requires state and local adoption of NIMS as a condition for receiving federal preparedness funding. Although ICS was first pioneered by the fire service, it is, at its core, a management system designed to integrate resources to effectively attack a common problem. This system is not exclusive to one discipline or one set of circumstances; its hallmark is its flexibility to accommodate all circumstances. Some purists may claim that a particular application of ICS is not consistent with the NIMS. Yet we need not approach ICS with the same mathematical precision used by an engineer. We are changing the culture of organizations and first responders at all levels of government. As long as implementation of ICS is consistent with the basic principles expressed in the NIMS, we will have made significant progress. Further refinements can be achieved over time based on experience with its use.

COMMUNICATION ISSUES

Emergency incidents involving fire fighter fatalities demonstrate that, despite technological advances in two-way radio communications, important information is not always adequately communicated on the fireground or emergency incident scene. Communication is integral to incident scene operations; it is the key to fire fighter safety and survival (Figure 12.7.4).

Fatalities and Injuries

Inadequate fireground communication is repeatedly cited as a contributing factor in many of the incidents through the United States Fire Administration Fire Fighter Fatality and Major Fires Investigation. Communication problems are continually cited as one of the four contributing factors in fires and emergency incidents in which fire fighters are killed or injured. Despite the obvious importance of effective communication on the emergency scene, only a limited amount of published research exists.

There are several United States Fire Administration investigation reports that cite communications-related issues as part of the "lessons learned" component. These investigatation reports include the following:

- *Wood Truss Roof Collapse Claims Two Fire Fighters, Memphis, TN*
  Two fire fighters operating an interior attack line were killed at this fire after a church roof collapsed.
- *Indianapolis Athletic Club Fire, Indianapolis, IN*
  Two fire fighters were killed on the third floor of a nine-story mixed-use building during a fire.

FIGURE 12.7.4 Communication as an Integral Part of Accountability (Photo courtesy of Martin Grube, Virginia Beach Fire Department)

- *Four Fire Fighters Die in Seattle Warehouse Fire, Seattle, WA*
  Four fire fighters were killed in a collapse at an arson fire in a warehouse.
- *Two Fire Fighters Die in Auto Parts Store Fire, Chesapeake, VA*
  Two fire fighters were killed after a roof collapse in a retail auto parts store.

Table 12.7.2 describes several key factors that create problems during emergency operations for fire fighters and continually surface during fire fighter fatality and injury investigation reports.

Standards for Radio Communications

NFPA 1561, *Standard on Emergency Services Incident Management System,* requires the fire department to develop standard operating procedures for radio communications, which address use of protocol and terminology at all types of incidents. There are definitive procedures in NFPA 1561 regarding radio communications, the incident management system, and emergency operations.

These procedures include the following:

- Clear text should be used.
- A radio channel should be provided for dispatch, and a separate tactical channel provided to be used initially during the incident.
- When a division or group is implemented, the fire department should provide a dispatch channel, a command channel, and a tactical channel.
- The fire department should provide the necessary number of radio channels relating to incidents with multiple tactical channels and the complexity of these incidents.
- Standard terminology will be established for transmitting information, strategic modes of operation, situation reports, and emergency notification of imminent hazards.
- The fire department should have procedures for the announcement of emergency conditions, which is termed "emergency traffic," as a designation to clear radio traffic.
- "Emergency traffic" should be declared by the incident commander, tactical level management component, or member who is in trouble or subjected to an emergency condition.
- Standard operating procedures should exist for telecommunicators (dispatchers) to provide support to emergency incident operations.
- Telecommunicators should be trained to function effectively within the incident command system and should

TABLE 12.7.2 Communications Issues

Key Issues	*Comments*
Unsuitable equipment	The chief communication problem reported by fire fighters and company officers is the difficulty with communicating from inside a fire when using full personal protective equipment, including SCBA. The majority of portable radios currently used by fire departments are not suited for the task.
Portable radios needed for all fire fighters	Despite some technical limitations, portable radios are a proven lifesaver during fires and emergency incidents. Portable radios should be considered a critical item of personal protective equipment similar to SCBA. *Ideally, every fire fighter working in an IDLH atmosphere should have a portable radio with an emergency distress feature.*
Little attention paid to human factors	There is available literature pertaining to the impact of human factors on effective fireground communication. Furthermore, while fire departments devote substantial time to manipulative skill training, relatively little training is provided to help fire fighters develop stress-tempered communications skills.
Importance of active listening	All fire fighters on an emergency incident should actively monitor their radios for important information at all times, not just when specifically queried. Communications should be emphasized as an essential part of fire fighters functioning as a tactical team, not just operating as individual entities.
Standard message formats and language	Fire departments can enhance fireground communications by creating standard message formats and using keywords consistently. Plain English is usually preferred over codes, especially when transmitting a complex message.
Tiered message priority	Keywords to prompt immediate action can be tiered based on their priority; for example, "Mayday" signals a life-or-death situation, whereas "Urgent" may be used to signify a potentially serious problem. Such message headers prompt the crew's listening priorities and radio discipline.
Attention to cultural factors	If necessary, fire fighters are not usually reluctant to circumvent the chain of command to report critical safety issues. There may be greater hesitation to communicate problems in completing an assigned task. However, this is usually due to a lack of situational awareness and not a fear of reprisal from other members. Studies on fire fighter communications show that sometimes the culture of bravery in the fire service is reflected in a reluctance to communicate quickly enough when help is needed. Repeated situations of this nature must be investigated by the department.

meet the requirements of NFPA 1061, *Standard for Professional Qualifications for Public Safety Telecommunicator.*
- The incident commander should be provided with elapsed time-on-scene information at emergency incidents in 10-minute intervals from the communications center.

INCIDENT SCENE REHABILITATION

The fire department should develop standard operating procedures that outline a systematic approach for the rehabilitation of members operating at incidents. Provisions addressed in these procedures should include medical evaluation and treatment, food and fluid replenishment, crew rotation, and relief from extreme climatic conditions. This program should outline an ongoing rehabilitation for simple or short-duration incidents as well as a process to transition into the rehabilitation needs of a large or long-duration incident.

Emergency Medical Service

Medical evaluation and treatment in the on-scene rehabilitation area should be conducted according to emergency medical service (EMS) protocols developed by the fire department in consultation with the fire department physician and the EMS medical director. If advanced life support (ALS) personnel are available, this level of EMS care is preferred.

The incident commander should consider the circumstances of each incident and initiate rest and rehabilitation of members in accordance with the fire department's standard operating procedures and with NFPA 1584 and Chapter 8 of NFPA 1500.

The incident scene rehabilitation group or division should include emergency medical care. The minimum level of emergency medical care available should be at least basic life support care. The assignment of an ambulance or other support crew to the rehabilitation function is essential during long-duration or heavy-exertion incident operations. This crew can assist with rehabilitation functions as well as be available to provide immediate basic life support needs for members. However, the advanced life support (paramedic) level of evaluation and treatment must be available quickly to ensure the proper level of care.

Analysis of Weather Conditions

Weather factors during emergency incidents can have a severe impact on the safety and health of the members. When these factors combine with long-duration incidents or situations that require heavy exertion, the risks to members increase rapidly. The fire department should develop procedures, in consultation with the fire department physician, to provide relief from adverse climatic conditions. Typical rehabilitation considerations for operations during hot weather extremes include the following:

- Moving fatigued or unassigned members away from the hazardous area of the incident
- Removing members' personal protective equipment
- Ensuring that personnel are out of direct sunlight
- Ensuring that there is adequate air movement over personnel, either naturally or mechanically
- Providing members with fluid replenishment, especially water
- Providing medical evaluation for personnel showing signs or symptoms of heat exhaustion or heat stroke

Typical rehabilitation considerations for operations during cold weather extremes should include the following:

- Moving fatigued or unassigned members away from the hazardous area of the incident
- Providing shelter from wind and temperature extremes
- Providing members with fluid replenishment, especially water
- Providing medical evaluation for members showing signs or symptoms of frostbite, hypothermia, or other cold-related injury

The incident safety officer should ensure that the incident commander establishes an incident scene rehabilitation tactical-level management unit during emergency operations as required by NFPA 1521, *Standard for Fire Department Safety Officer.*

Rehabilitation Division or Group

This component should be established in a safe environment away from the hazardous area of the incident. The resources needed at the rehabilitation tactical level management unit should include an environment to limit temperature stress, medical equipment, and adequate medical staff. Items that can assist in limiting temperature stress in cold environments include heat, blankets, and protection from the wind. For hot weather, items should include adequate shade, fans, air conditioning, and misting systems. Food and hydration needs include water and oral fluids, food, broth, and fruit. Also, for hydration, a 50/50 mixture of water and an electrolyte replacement drink can be provided. Medical equipment should include blood pressure cuffs, stethoscopes, oxygen, cardiac monitors, thermometers, and intravenous fluid and supplies.

SUMMARY

Fire fighting and the delivery of other emergency services continue to be a hazardous occupation. Significant improvements and advancements have been made in terms of fire fighter safety and health. The process starts with the development of a written risk management program. The risk management plan serves as documentation that risks have been identified, evaluated, and prioritized and that a reasonable control plan has been implemented and monitored. Other critical components that are needed to ensure the safety and health of our members include training and education, protective clothing and equipment, safe vehicle operations, use of an incident management system, an aggressive health maintenance program, and facility safety.

A considerable effort needs to be focused on the issues of fire fighter fatalities, debilitating fire fighter injuries, and occupational illnesses. Moreover, specific emphasis needs to address improvements with incident scene communications, personnel accountability of fire fighters, operation of fire department vehicles responding to an incident, and medical conditions of fire fighters.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on safety, medical, and health issues and programs discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents*
NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents*
NFPA 1001, *Standard for Fire Fighter Professional Qualifications*
NFPA 1002, *Standard for Fire Apparatus Driver/Operator Professional Qualifications*
NFPA 1003, *Standard for Airport Fire Fighter Professional Qualifications*
NFPA 1006, *Standard for Rescue Technician Professional Qualifications*
NFPA 1021, *Standard for Fire Officer Professional Qualifications*
NFPA 1041, *Standard for Fire Service Instructor Professional Qualifications*
NFPA 1061, *Standard for Professional Qualifications for Public Safety Telecommunicator*
NFPA 1071, *Standard for Emergency Vehicle Technician Professional Qualifications*
NFPA 1201, *Standard for Providing Emergency Services to the Public*
NFPA 1250, *Recommended Practice in Emergency Service Organization Risk Management*
NFPA 1403, *Standard on Live Fire Training Evolutions*
NFPA 1404, *Standard for Fire Service Respiratory Protection Training*
NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*
NFPA 1521, *Standard for Fire Department Safety Officer*
NFPA 1561, *Standard on Emergency Services Incident Management System*
NFPA 1581, *Standard on Fire Department Infection Control Program*
NFPA 1582, *Standard on Comprehensive Occupational Medical Program for Fire Departments*
NFPA 1583, *Standard on Health-Related Fitness Programs for Fire Fighters*
NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs*
NFPA 1851, *Standard on Selection, Care, and Maintenance of Structural Fire Fighting Protective Ensembles*
NFPA 1852, *Standard on Selection, Care, and Maintenance of Open-Circuit Self-Contained Breathing Apparatus (SCBA)*
NFPA 1901, *Standard for Automotive Fire Apparatus*
NFPA 1906, *Standard for Wildland Fire Apparatus*
NFPA 1911, *Standard for Service Tests of Fire Pump Systems on Fire Apparatus*
NFPA 1931, *Standard for Manufacturer's Design of Fire Department Ground Ladders*
NFPA 1932, *Standard on Use, Maintenance, and Service Testing of In-Service Fire Department Ground Ladders*
NFPA 1961, *Standard on Fire Hose*
NFPA 1962, *Standard for the Inspection, Care, and Use of Fire Hose, Couplings, and Nozzles and the Service Testing of Fire Hose*
NFPA 1964, *Standard for Spray Nozzles*
NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*
NFPA 1977, *Standard on Protective Clothing and Equipment for Wildland Fire Fighting*
NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Fire and Emergency Services*
NFPA 1982, *Standard on Personal Alert Safety Systems (PASS)*
NFPA 1983, *Standard on Life Safety Rope and Equipment for Emergency Services*
NFPA 1991, *Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies*
NFPA 1992, *Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies*
NFPA 1994, *Standard on Protective Ensembles for First Responders to CBRN Terrorism Incidents*
NFPA 1999, *Standard on Protective Clothing for Emergency Medical Operations*

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Chapter 8

Effect of Building Construction and Fire Protection Systems on Fire Fighter Safety

Revised by
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Chapter Contents

General Concerns
Simplified Principles of Building Construction
Building Codes and Building Construction Classification
Specific Concerns

Key Terms

building code, building collapse, building construction (types of), compartmentation, concrete, fire fighter safety, fire resistance, noncombustible construction, ordinary construction, timber

Fire department personnel have a very strong interest in building construction. They must fight fires in buildings, from those under construction to those built hundreds of years ago. Some building methods encountered are long forgotten, but the hazards still exist. For example, a reference to tile arch floors would be difficult to find in modern architectural texts, yet there are thousands of them still in existence and they do present a specific hazard.

This chapter looks at the fire department's involvement in and concerns about various aspects of building construction. For the safety of those they serve as well for their own safety, fire fighters must understand simplified principles of construction, be familiar with the building codes and building construction classification, and be actively involved in pre-incident planning. These activities will make fire fighters aware of issues regarding structural integrity, water supply, and so on when they arrive at the fire scene.

A number of sections and chapters in this handbook deal with aspects of building construction. Relevant chapters include all the other chapters in Section 12 as well as Section 1, Chapter 1, "Challenges to Safety in the Built Environment"; Section 1, Chapter 2, "Fundamentals of Structurally Safe Building Design"; Section 11, Chapter 4, "Fire Hazards of Construction, Alteration, and Demolition of Buildings"; Section 19, Chapter 1, "Types of Building Construction"; Section 19, Chapter 2, "Structural Integrity During Fire"; and Section 19, Chapter 3, "Structural Fire Safety in One- and Two-Family Dwellings."

GENERAL CONCERNS

Fire department functions related to building construction include the following:

- Reviewing and approving plans for fire protection features in new construction in cooperation with the building department. In some cases, the fire department has absorbed the building department.
- Making regular inspections that, among other functions, check on the reliability of code-specified fire protection features—both passive features, such as fire walls and the fire doors that protect openings in the fire walls, and active features, such as fire suppression systems. A most

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important function is ensuring that code-required life safety features, such as exit facilities, are fully usable as intended.

- Making pre-incident planning surveys to assemble and record information vital to the incident commander at a fire scene. It is most important that the information be retrievable instantly at the fire scene. A foremost purpose of pre-incident planning is to identify situations that are or can become hazardous to fire fighters. Some hazards may be sufficiently serious as to call for defensive fire-fighting tactics (i.e., exterior attack with no entry into the building). Examples would include fires involving dilapidated or abandoned buildings, posttensioned concrete in buildings under construction, and unprotected load-bearing steel.
- Acquiring knowledge of building construction. This is important in investigations of the origin, cause, and extent of serious fires.

The geodesic dome of the U.S. exhibit at Expo '67 in Montreal is pictured in Figure 12.8.1. Some architectural writers, unaware of the entire story, still praise this dome. It accommodated a huge number of visitors. After it was turned over to the city of Montreal, a workman accidentally touched a torch to the plastic covering. It totally burned in 10 minutes. The framework stands today as a monument to a tragedy that, by great good fortune, did not happen.

The planked ceiling conference room shown in Figure 12.8.2 is another example of a type of construction that should be avoided. This room is decorated with a virtual lumberyard of planks overhead. It is possible that the planks are treated to be flame resistant. In any case, fire involving the desks and chairs might cause failure of the hangers, usually set in lead anchors, allowing the planks to fall.

SIMPLIFIED PRINCIPLES OF BUILDING CONSTRUCTION

The fire officer should have knowledge of the principles of construction and the proper terms for various building elements.

FIGURE 12.8.1 Geodesic Dome at Expo '67 in Montreal (Source: Photo by D. Lion)

FIGURE 12.8.2 Heavy Fire Load in Conference Room of Fire-Resistive Building

Errors in principles or terminology can adversely affect the credibility of sound fire protection recommendations. Further, court testimony may be fatally discredited on cross-examination.

Some of the more important principles of construction include the following:

- Construction is primarily designed to resist the force of gravity and other stresses such as wind and snow loads under normal conditions.
- The supporting system of a building is composed of many elements designed to transfer the building load to the ground.
- Exposure to fire is not a normal condition and design provisions are made in some types of construction to protect the gravity-resisting (structural) elements from failing when exposed to fire. Unprotected structural elements can result in early and unexpected failure leading to partial or full collapse.
- Contents, not construction elements, typically drive the growth, intensity, and spread of fire; however, combustible construction elements can both contribute to the fire and lead to collapse.

Gravity and Building Collapse

If fire fighters are in, on, or adjacent to a structure when it fails, injury or death can result. Difficult and dangerous rescue efforts might be required. Only seconds may elapse between the time it is recognized that fire fighters should evacuate a structure and the failure of the structure.

In evaluating the hazards of building construction under fire conditions, the entire path of the load to ground must be considered. The parts of the system that can be the quickest to fail, such as connections or unprotected supporting elements, need to be considered. For example, laminated heavy timber beams may have substantial fire resistance but be supported by unprotected steel columns or cables that can result in failure. Lightweight timber trusses that can support the loads of roofs and floors generally have their parts held together with nail plates (sometimes called gusset plates). Exposure of nail plates

to fire can char the wood into which they are nailed, releasing the plates and resulting in collapse.

When the incident commander on the scene of a building fire determines that the *structure* is involved in or affected by the fire (e.g., unprotected steel), the announcement should be made that all fire fighters be alert for and report any evidence of potential failure. Fire departments should have an easily recognized signal that means immediate evacuation of a structure. Multiple short air horn blasts and a distinctive Mayday radio signal broadcast on all radio channels should be used. All units should acknowledge the radio announcement.

Evacuation drills should be carried out during routine training activities to overcome any reluctance of fire fighters to abandon their equipment except those tools that might be needed to get out and withdraw. The proudest ships in the navy conduct regular "abandon ship" drills.

Failure on the part of command officers to understand the principles of construction and their repercussions can cause fire fighter injuries and deaths. For example, a cantilever beam can be compared to a seesaw. It is supported in position by connections in the interior of a building. If these connections fail because of fire, the extended portion of the beam, and whatever it supports, will fall. In lieu of a cantilever, a suspended beam may be used. To the building designer, there is little difference in whether the reaction goes downward through a column or upward through a tension member, such as a cable to the wall. However, if the connection fails, the suspended beam becomes an unsupported cantilever and can fall on fire fighters.

In Figure 12.8.3, for example, tendons providing lateral support for the structure will be posttensioned in several increments as the building grows taller. They remain exposed until the building is finished. They will fail at 800°F (427°C) and thus collapse the structure, possibly causing fire fighter deaths. Wooden falsework and other combustibles provide sufficient fuel.

In another example (Figure 12.8.4), the cold drawn steel cable that supports the tram car loses its tensile strength at 800°F (427°C). Many of the stations are made of wood, which could provide sufficient fuel for a destructive fire.

FIGURE 12.8.3 Tendons Providing Lateral Structural Support

FIGURE 12.8.4 Steel Cable at Ski Station

Building Reaction to Fire

All structures have some resistance to fire-caused collapse. This can informally be described as *inherent* fire resistance, as distinguished from *legal* or code-specified resistance. The inherent fire resistance of one structure may be absent in another similar structure. Direct experience with this fire resistance, whether personal or organizational, is not transferable from one structure to another. Simply put, "What you know may not be so."

Through experience the fire service has developed some understanding of and criteria for inherent fire resistance. However, estimates of "safe time" in buildings on fire are invalid because the time elapsed since the start of the fire is rarely known. In particular, fire fighters must understand that a fire resistance rating of 2 hours, for example, does not guarantee 2 hours of safety. A structural element or wall with a fire resistance of 2 hours might not last 2 hours in actual fire conditions. It can fail sooner or last longer. In addition, failure of a single key element may cause a massive collapse. Many times fire fighters risk life and limb without knowing the degree of risk involved. Generally accepted indications of imminent collapse—softening, water flowing between bricks, smoke pushing from mortar joints, strange noises—are grossly inadequate, even for older buildings. If they are relied on solely to protect fire fighters from collapse in today's different, lighter buildings, disasters can certainly result.

Contents

The problems of structure fires cannot be isolated from the structure's contents. Most building fires originate in contents. Fires involving building contents can destroy noncombustible structures and damage fire-resistant structures. The hazard of today's fast-burning, high heat release rate contents is a major problem.

Occupancy classifications found in building codes in some cases provide a general indication of the combustibility of contents (e.g., factory occupancy, moderate hazard storage occupancy, etc.) but must not be relied on for fire-fighting operations. Materials with high rates of heat release and/or rapid flame spread can be found in many occupancy types.

As long ago as 1975, the Society of Fire Protection Engineers (SFPE) warned that "A high rate of fire development can create a condition that may tax or overpower traditional fire defenses. Defenses of the past, both passive and active (evacuation, alarm, ventilation, and manual fire control), have not been designed by engineer or code to anticipate this hazard. This is primarily a furnishings problem. Many occupancies (residences, office buildings, theaters, hospitals) are being affected."[1]

Other Hazards

A building involved in fire presents other serious hazards to fire fighters. Fire can spread in void spaces with little or no external evidence and burst out unexpectedly and increase in intensity when a nearby breach admits oxygen. Buildings of otherwise noncombustible or fire-resistive construction may have combustible interior finish on floors, walls, and ceilings that can contribute to rapid fire spread.

When live fire training is conducted in most typical training school structures, the hazards of collapse, hidden fire, and highly combustible interior finish are absent. There have been serious accidents during live fire training in abandoned buildings when these hazards were present. It is important to have adequate classroom instruction on these issues, followed by preincident planning exercises for the hazards of individual major buildings and general building construction.

BUILDING CODES AND BUILDING CONSTRUCTION CLASSIFICATION

Types of Building Construction

Building codes classify buildings according to the type of construction and the fire resistance of the various load-bearing and non-load-bearing elements, such as exterior and interior walls, columns, beams and girders, and floor and roof construction. NFPA 220, *Standard on Types of Building Construction,* describes five types of construction. The fire resistance requirements as determined by NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials,* will vary depending on the building element being considered. The details can be found in Section 19, Chapter 1, "Types of Building Construction." The types of building construction include the following.

Type I. Structural members of approved noncombustible or limited combustible materials with specified fire resistance ratings (exterior bearing walls 4 or 3 hours, etc.).

Type II. Structural members are the same as Type I but with lower or no fire resistance rating.

Type III. Exterior walls and structural members that are part of exterior walls are of approved noncombustible or limited combustible materials; and interior structural members, including walls, columns, and so on, are entirely or partially made of wood; no fire resistance rating greater than 2 hours.

Type IV. Exterior and interior walls and structural members that are portions of such walls are of approved noncombustible or limited combustible materials. Other interior structural members, including walls, columns, floors, and roofs, should be of solid or laminated wood without concealed spaces; no fire resistance rating greater than 2 hours. Note that wood timbers used in Type IV construction are assumed to have "inherent" fire resistance due to their mass and do not have a fire rating.

Type V. Exterior walls, bearing walls, columns, beams, floors, roofs, and so on are entirely or partially made of wood or other approved combustible materials; structural members may have a 1 hour rating or be nonrated.

Bearing in mind that the current classification has varying fire resistance requirements within a given type, the traditional or common terms associated with the NFPA 220 and *NFPA 5000®, Building Construction and Safety Code®*, "construction types" include the following:

Type I: Fire resistive
Type II: Noncombustible
Type III: Ordinary
Type IV: Heavy timber
Type V: Wood frame

These traditional classifications are very general and may not fully describe the fire resistance characteristics of any specific building. In addition, some buildings include several types of construction, particularly when additions have been made to older buildings. Some typical variations include the following:

- The construction of wood frame buildings has changed over the years. Prior to 1940, many multistory buildings were built with vertical framing members that created continuous void channels extending from the foundation to the attic space. This type of construction was referred to as "balloon construction" and allowed fire to spread upward rapidly through the exterior walls, sometimes without being detected by fire fighters. Balloon construction practice was replaced with construction in which each floor comprised a platform extending to the building perimeter. Platform construction cut off the vertical spread of fire. Although wood frame buildings with truss floors may be structurally considered as platform frame construction, the presence of horizontal floor voids interconnected vertically by plumbing voids can result in concealed fire spread similar to balloon frame construction.
- Brick buildings may be partially load-bearing brick or brick/block masonry on some walls and brick veneer over wood bearing walls on others. In some cases, the lower floor(s) are of masonry and the upper floors are brick veneer. Brick veneer may be applied over steel or concrete.
- Heavy timber buildings may have potentially dangerous departures from the ideal "mill construction," which is designed in all aspects to resist collapse from fire.
- Noncombustible buildings may have many combustible features, such as roofs, balconies, overhangs, and combustible materials in metal deck roof systems. Noncombustibility does not necessarily mean resistance to collapse.

• Fire-resistive buildings can have deficiencies that compromise the concept of compartmentation. For instance, large-area concrete floors require expansion joints. In a fire at a U.S. Postal Service Parcel Post Facility in New York City, there were large open areas that were pierced with many unprotected vertical openings; these openings consisted of conveyor belt systems, spiral mail chutes, duct systems, and flush floor openings.[2] In another example, melting aluminum expansion joints in the McCormick Place fire in Chicago dropped to the floor below, igniting combustible materials.[3] Ducts and wiring penetrations can provide paths for the spread of fire and smoke. It is not uncommon for fire barriers to be compromised after buildings are occupied. Inspection of compartmentation in new construction and after modifications and maintenance is important to achieve reliable compartmentation.

Fire-rated elements may vary greatly in materials. The test used, NFPA 251/ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials,* may give equal time rating to a wall of steel studs and plaster and a wall of wood and gypsum. However, S. H. Ingberg, who developed the concept of applying NFPA 251/ASTM E119 to wood structures and is considered the father of the fire resistance testing methods of the National Bureau of Standards (now the National Institute for Standards and Technology), issued the following warning:

> We must particularly distinguish between the fire resistance of a combustible and a noncombustible structure. While they may be equivalent in time, there is a world of difference in the protection afforded as it concerns the individual building, the hazard to nearby structures, and the hazard to life.[4]

Wood Frame Structures

The most prevalent construction material in the United States and Canada is wood. Wood can carry structural loads such as columns and beams. In older buildings, there are huge quantities of nonstructural wood used as lath to support plaster. Wood is also used for decoration and interior trim. A wooden interior in a restaurant in a high-rise building provided such a fierce fire that the fire department was unable to reach three trapped civilians, who finally jumped to their deaths.

For over 150 years, attempts have been made to render wood fireproof or noncombustible with no success. Wood can be surface treated to render it ignition resistant or reduce its surface flame spread. One method is to paint wood with an intumescent coating, which swells up like a marshmallow when heated, retarding ignition and the spread of flame. One problem in using this method to reduce the hazard of installed wood paneling is its untreated reverse side.

Wood can be rendered fire retardant by drawing out the sap and moisture and replacing it with chemicals. Fire-retardant-treated (FRT) wood is just that—fire retardant. It is still combustible.

In recent years, the dimensions of wooden structural members have been reduced and specialized wood structural members have been introduced. The removed wood had provided some inherent fire resistance due to its additional mass. Using sawn or laminated two-by-four lumber or flakeboard in wooden I-beams has reduced the mass of these wooden beams. These lighter beams can be expected to fail earlier in a fire,[5] because as soon as the web starts to burn, the strength of the beam is degraded.

In the construction of wood-frame row-type dwellings, no fire protection provision is resisted more than parapeting fire walls to separate the units. Parapeted fire walls present a special problem to the builder because they require skilled craftsmen to flash the wall properly to prevent leaks. It is much easier to place shingles on a flat, unbroken roof.

Plywood. Some years ago the practice of laying a 4 ft (1.2 m) sheet of ignition-resistant plywood on each side of a fire wall that did not penetrate the roof was adopted in lieu of parapeting. The treated plywood is supported on untreated, lightweight wood trusses, which are subject to early failure. Plywood, laid over the top of masonry fire walls, can delaminate and/or raise up and pass fire over the top of the wall. Furthermore, plywood over a rough-cut, concrete-block fire wall can be difficult to seal against the passage of fire, smoke, and hot gases.

In an attempt to prevent this extension, some codes specified a 4 ft (1.2 m) roof section of fire-retardant-treated plywood to be laid lengthwise along each side of the fire wall. Some of the chemicals used in the treatment reacted to heat and humidity and destroyed the plywood. Thousands of roofs required replacement.[6,7] In at least one jurisdiction, the underside of the replaced roofs is covered with a 4-ft (1.2-m) wide layer of gypsum board along the fire wall line. In the nineteenth century, plastering was used in an attempt to provide fire resistance to wood columns. Rot occurred under the plaster.

Wood Framing with Gypsum Board. Another method of protecting wood from fire is found in floor and ceiling assemblies and wall sections that combine wood framing with gypsum board membranes. A number of such floor and ceiling assemblies have received fire resistance ratings of 1 hour or more after being subjected to the NFPA 251/ASTM E119 test. One problem is that this fire resistance test was developed for floors of homogeneous, noncombustible materials, which were essentially the same from top down and bottom up. The one-way test in which the fire is applied from the bottom of a floor/ceiling assembly may not adequately determine fire resistance in a fully developed fire where the development of flashover can create severe temperatures developed at floor level, sometimes quite early in the fire.

As illustrated in Figure 12.8.5, in the NFPA 251/ASTM E119 test, the floor is exposed to fire only from below. Real fires, however, are different in that a fully developed compartment will involve a floor from the top down. Real fires may also start within the floor assembly itself, and in the case of wood trusses, may easily spread horizontally and vertically throughout a building's void spaces.

Trusses. The difficulty with fire fighters accepting the 1 hour resistance rating as indicating a degree of safety is even more serious in the case of lightweight gusset-plate trusses. When solid wood floor joists are used, each joist can act as a firestop, thus slowing the progress of the fire through the floor construction. In the case of a truss, the entire floor void, along with its

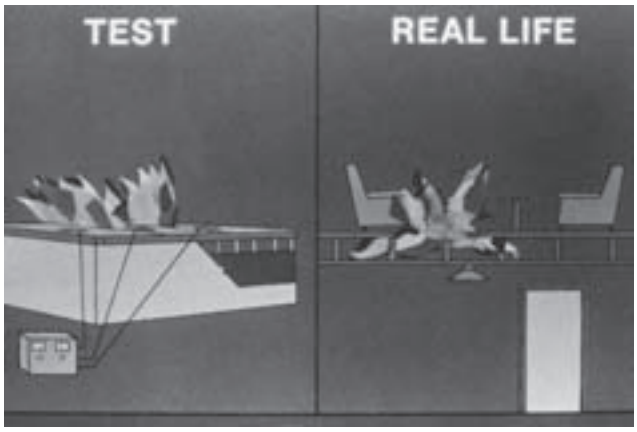

FIGURE 12.8.5 Spread of Test Fire Versus Real Fire

air supply, is available to the fire as soon as fire enters the void. The lightweight members of the truss are of small kindling-like dimensions. The voids can extend over sizable areas.

There are no fire-rated designs for firestopping (preventing vertical fire spread) or draftstopping (preventing horizontal fire spread) in the truss voids of frame buildings. The accepted practice of employing gypsum board is subject to improper installation and inspection, often due to a lack of appreciation of the purpose of draftstopping. Draftstopping is difficult to install and may be ineffective in preventing the extension of fire to adjacent truss voids, particularly when postconstruction penetrations are present. For example, firestopping is at the mercy of any worker with a pipe or cable to run (Figure 12.8.6).

Early collapse of a structure in which fire has penetrated into the truss voids is highly likely. A three-story, trussed-floor apartment house in San Antonio, Texas, collapsed moments after fire fighters evacuated the building. The fire started when a flammable liquid accidentally spilled on a floor, leaked down into the truss void, and ignited.[8]

A dangerous situation can result when trusses are permitted to extend from the floor voids on either side of a stairway to support the platform of a stairway that may serve as the single exit for the occupants and access for fire fighters. Incomplete firestopping can lead to fire spread and subsequent collapse.[9]

FIGURE 12.8.6 Firestopping Affected by Postconstruction Penetration

In another design the extended trusses may support a balcony that can be an area of refuge for occupants or provide entry for the fire department. A piece of gypsum board, plywood, or flakeboard may be used as firestopping to separate the floor void from the balcony void. There are no data indicating that such firestopping is adequate, particularly when it is penetrated for utilities. Casualties could result as fire units attempt to rescue occupants over ground ladders while the fire burns unchecked in inaccessible floor voids.

In one type of truss, the gusset plates and diagonal tension members were stamped from one piece of steel. If a fire causes a floor to collapse, the floor can fall on the floor below, causing it to collapse also because the tension members buckle out of the wood. Another new type of truss uses only finger joints and glue to hold the truss together.

Fire burning down into the floor void can come up on the other side of a rated wall, thus making dubious the concept that compartmentation is provided when a "rated wall" meets a "rated floor."[10] A ceiling light fixture can cause a fire that starts in the truss void. The fire can extend unnoticed from the truss void into the void between the plywood sheathing and the brick veneer and then back into the floor voids above. A collapse can result. In addition to collapse and fire spread, the truss floor provides a void in which carbon monoxide can accumulate.

Heavy Timber

The features of heavy timber construction that contribute to fire fighter safety are heavy masonry and brick walls; heavy dimensional timber used for columns and beams; heavy, thick wooden floors, which collapse only after many hours of fire fighting; and the lack of concealed spaces. However, it is dangerously inaccurate to consider building code–defined heavy timber construction as the equivalent of true mill construction.[11] Heavy timbers are slower to reach sustained burning than lighter wood members. This has lead to the term *slow burning* being applied to buildings of masonry exterior walls and timber interiors. Such a building is expected to retain its structural stability for a long time when subjected to a fire. Unfortunately, the slow-burning characteristic sometimes becomes long burning, so there is no merit to slow burning once the fire department can no longer remain in the building and must operate defensively.

The original concept of heavy timber construction, or mill construction, employed timber columns. Where the column intersected the floor girder, it should have been replaced by a solid cast-iron pintle, which passes through a hole in the girder. (A girder is any beam that supports other beams.) The small cross section of the pintle would cause it to be protected by the mass of wood girder. However, this procedure was ignored in many buildings. Some heavy timber buildings have cast-iron columns that may fail early in a fire. Where these columns pass through the floor girder, there is no reduction in size of the column. As a result, two "half moons" of the timber rest on a shelf protruding from the column. Failure of the shelf, or the loss of a

small amount of wood around this column, will cause the floor to fall.

Rehabilitated buildings may be fitted with unprotected steel columns, which can fail early in a fire. Sometimes Lally columns (steel columns filled with concrete) are used. In the nineteenth century, Lally columns were often cast iron and were drilled to release the steam from the concrete. Current columns may not be drilled and could explode when heated because of the steam generated when the concrete core is heated and releases water.

Heavy timber, slow-burning, or mill construction buildings should be carefully examined for these potentially disastrous weaknesses, which make invalid the assumption that the building will retain its stability for any appreciable time. Six Worcester, Massachusetts, fire fighters died in a heavy timber building that had been a cold storage warehouse. A complicated layout and smoke from cork and plastic insulation caused fire fighters to become lost. The building had not been pre-incident planned, and the stability of heavy timber buildings was immaterial to the outcome.

Plank and beam construction is sometimes called *western framing*. The typical 16 in. (406 mm) spacing of floor beams may be considered too boxlike and unattractive. Except in the roughest construction, a ceiling is installed to hide floor or roof beams. A take-off from heavy timber construction provides residences, churches (Figure 12.8.7), and other public buildings with an aesthetically pleasing interior by eliminating the ceiling and exposing the wood structure. Many churches are of plank on laminated wood beam or arch construction, often a fast flame spread potential. Heavy beams, widely spaced, are spanned with heavy tongue-and-groove planks instead of floorboards. The wood surface is planed smooth. Often a clear lacquer is used as a finish. This has the excellent advantage of eliminating void spaces. However, fire may still spread rapidly over these wood surfaces.

Long heavy timbers may be in short supply or are not available. It is common practice to splice timbers to attain the proper length. Laminated arches are commonly shipped in sections to be field spliced. A properly designed spliced timber will carry its load adequately in normal use but may fail disastrously in a fire. The arches of a Florida jai alai fronton were of spliced laminated timbers. Although the timbers were burned only moderately, the arches fell apart because the heated metal of the splice connections simply burned away the wood to which they were attached.[12]

Many old buildings are being adapted to other uses. Dropped ceilings provide huge voids through which hidden fire can travel (Figure 12.8.8). Nailing up "fire-rated" gypsum board does not solve the fire extension problem. As shown in Figure 12.8.9, a peaked truss roof is being erected to change the roofline of a flat-roofed building. The old combustible built-up roof covering was left in place. The exhaust duct was not extended through the new roof. Ventilating the new roof would be hazardous and useless. For additional information on timber construction, see Section 19, Chapter 2, "Structural Integrity During Fire."

Ordinary Construction

Ordinary construction is the term applied to buildings of usually combustible interior with load-bearing masonry exterior walls.

FIGURE 12.8.8 Dropped Ceiling Being Added

FIGURE 12.8.7 Church with Plank on Laminated Wood Beam Construction

FIGURE 12.8.9 Peaked Truss Roof Being Added (Source: David Harlow)

Originally, such buildings had brick or stone exterior walls and wood floors. The brick or stone walls were often required by law to limit fire spread from building to building in cities. In most building codes, the area of the city required to have construction that limits fire spread is defined by the "fire limits." In more recent times, in addition to brick and stone construction, exterior masonry construction may use brick and clay tile composite, brick and block composite, cast-in-place concrete, concrete block, hollow clay tile, and adobe.

Brick. Brick is attractive but expensive. Many buildings that appear to be of brick construction are actually a single layer of brick veneer on the face of a wood building. Brick veneer can be applied to any surface. Brick or stone veneer may be used to rehabilitate an old building. Imitation stone veneer is made of concrete cast in molds.

Brick veneer is totally dependent on the basic structure of the building for stability. If the supporting structure is damaged, the veneer may fall down. A veneer building is not a masonry building. It should be described by its basic construction type, for example, wood frame, steel, or concrete.

In the past it was possible to easily see the difference between brick masonry and veneer, because in solid masonry some brick courses were turned to show the ends (headers), whereas the others were laid lengthwise (stretchers). The development of the masonry wire truss has made it possible to lay all the bricks as stretchers, so the difference between masonry and veneer is no longer obvious.

The following are some causes of masonry wall collapse:

- Many brick walls are not totally brick. It was common practice to insert wood lintels over windows and doors. In many buildings, wood beams were laid in the wall to provide a level surface for floor beams and to tie the wall together lengthwise. When this wood burns out, a collapse is certain. This can be determined only by thorough pre-incident analysis.
- Water-soluble sand-lime mortar was universally used until 1880, was partially used thereafter for many years, and is still used today in the rehabilitation of older brickwork. This type of mortar can be washed out by weather or by hose streams. The loss of mortar to water leaks can cause some collapses when there is no fire.
- Although lightweight steel bar joists can fail early in a fire, first they will elongate. Elongating steel can push down masonry walls.
- Collapse of wood floors was early recognized as a hazard to the masonry in which the floor beams were imbedded. Collapse of floors can precipitate wall collapses. The beams may act as a lever pulling down the brick wall. In some areas builders corbelled out a ledge. The beams were set on the ledge, so that when they fell, the wall was undisturbed. In other cases, a "fire cut" (Figure 12.8.10) was required at the ends of wooden beams. In these beams, a 45 degree cut was made on the end, so that the top was shorter than the bottom. Thus, the beam could fall out of the wall without acting like a lever and disturbing the brickwork. Since wood is removed, the fire-cut beam may collapse earlier than would a beam solidly set into the wall. In some building renovations, fire-cut wooden beams that had sagged over time were simply turned over to provide an upward camber; thus, a minimal amount of wood was bearing on the wall. Another method uses beam boxes, which are cast-iron boxes laid in the brick wall to accommodate a girder. When the girder fails, the box remains in place and the wall is not affected.
- The impact load of debris from a wall collapse can cause the collapse of adjacent buildings with possible loss of fire fighters' lives.
- Unreinforced masonry buildings are liable to collapse in earthquakes, which is a concern to fire fighters who respond to earthquakes.
- Old masonry buildings have been renovated for other uses. Many have included the conversion of old downtown residences into commercial buildings. In many cases, the floor loads from files, safes, and merchandise can be much greater than that which previously existed. These heavier loads can place additional stress on the floor construction as well as the supporting wall construction. Commercial buildings may also represent higher fire loads than did the original residences.
- Some older masonry buildings were built with interior walls of balloon frame construction. Fire in such a wall spreads freely from floor to floor and into the floor voids. The wall is structural, and its damage can precipitate an interior collapse.
- More substantial buildings were built with interior masonry structural walls. Since the practical span of wooden beams was only about 25 ft (7.6 m), there were many small interior rooms. In many cases, walls have been removed to enlarge the interior space. The heavy masonry above was supported on a steel beam that, in turn, was supported by cast-iron columns, usually unconnected to the beam. The connection is vulnerable to any lateral thrust. Such an arrangement provided the larger space needed for a coffee shop in the century-old Vendome Hotel in Boston. Nine fire fighters died in 1972 when the beam-column arrangement failed.[13]

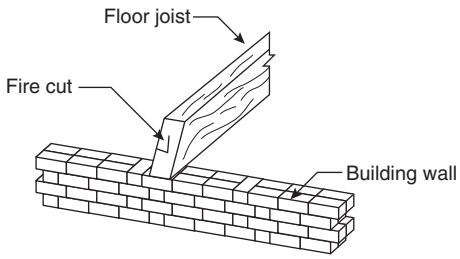

FIGURE 12.8.10 Cutaway Diagram of a Fire Cut on the End of a Wood Floor Joist

Beliefs About Construction. Beyond these indications, there are other dangers associated with building construction that the fire service needs to be concerned with. Some widely accepted beliefs regarding construction-related issues are open to question. Some of these beliefs may prove fatal to fire fighters or others at the fire scene.

One rule of thumb attempts to specify how far out from the building a wall would fall depending on its height. In other

words, to be safe from collapsing walls, fire fighters must be as far away from the wall as the wall is tall. This informal guideline is of doubtful validity: even if true for most of the wall, some bricks and timbers may land much farther out than anticipated.

Collapse of masonry walls is sometimes attributed to contraction caused by cold water hitting hot bricks. This theory is unproved. The greatest amount of water thrown in a defensive attack is directed through windows, not onto a wall. Considering the low heat transmission rate of brickwork, it is likely that the brick is at best only slightly cooled by the water.

Many older buildings have an outer layer of finished brick, which may be a veneer. A hose stream hitting such a wall can get behind the finished brick, tear the bricks off the surface, and endanger persons below.

The interior of ordinary construction buildings is almost completely of combustible construction. Where steel is used it may be left unprotected or enclosed in combustible voids that provide no protection from heat. The fire department may be completely unaware of the hazard of the hidden steel. Another major hazard of the voids that has been noted is the potential for hidden fires.

Alterations of the interior may leave hazardous floor conditions. For example, when a stairway is relocated, the former opening is rarely restored to a strength equal to that of the original floor. This presents a weak floor through which fire fighters can fall. In another example, the roof of the precast tilt slab concrete building shown in Figure 12.8.11 was fire damaged. Because the roof is vital to the stability of the building, the contractor's first move was to replace the tormentors, which braced the walls before the roof was in place. For more detailed discussions, see Dunn.[14]

Noncombustible Construction

Noncombustible construction is a building code term that unfortunately may not be literally true. Fire departments should be aware of what the local code permits under this heading. It is possible that substantial combustible components, such as a wooden balcony or roof or a combustible metal deck roof, are included in a noncombustible building. The fact that a material is noncombustible is not necessarily significant in reducing the fire loss or in reducing hazards to fire fighters. The two common materials of noncombustible construction are steel and concrete.

Steel. Steel is an extremely strong material. Heavy loads can be carried on light structural steel elements. Because of the small mass of the steel, all but very heavy members elongate as they are heated. Steel beams will elongate 9 in. (229 mm) in 100 ft (31 m) at about 1000°F (538°C).[15] This can be sufficient to push out wall panels and cause toppling. Elongating steel has pushed down many walls in this fashion. At slightly higher temperatures, steel reaches its collapse range. Collapse of steel roofs supporting the sprinkler piping can cause sprinkler system failures, resulting in massive destruction in several warehouse fires.

As steel trusses (like those shown in Figure 12.8.12) are heated, connecting ties can transmit undesigned torsional load to other trusses. This may result in failure of trusses away from the fire area. Four fire fighters died in Pennsylvania in the collapse of a "concrete" building in which the floor was supported by unprotected steel columns.[16] These unprotected steel struts could be loaded to twice the limit for permanent structural steel, thus lowering the failure temperature. A fire in combustible materials, often present in excavations, could cause the steel to fail. The adjacent structures could then collapse into the excavation.

Extreme caution should be the rule at any fire where unprotected steel is being heated. The potential consequences are not always evident. Pre-incident planning should be thorough, and limits should be set on fire-fighting procedures to ensure safety of personnel.

Concrete. Concrete is strong in compression but weak in tension. Plain concrete, usually found in the form of concrete

FIGURE 12.8.11 Fire-Damaged Roof

FIGURE 12.8.12 Unprotected Steel Struts

blocks, is used for compressive loads. Reinforced concrete is a composite material. Steel is incorporated into the concrete to provide the tensile strength. By definition, a composite material is one in which both elements must act together to carry the load. A failure of the bond between the steel and concrete destroys the composite nature and strength of the structural element.

Unlike steel, which needs to be protected from fire by an insulating covering, concrete can be inherently fire resistive. The resistance to fire is accomplished by the nature and thickness of the concrete itself. However, it is impossible to distinguish fire-resistive concrete from that which is merely noncombustible by simply looking at the concrete member.

Non-fire-resistive concrete has no specific fire resistance requirement and can fail early in a fire, even when exposed to only modest heat. No valid assumptions can be made as to when fire-exposed, non-fire-resistive concrete will fail. If the building is of monolithic construction, however, the load may be redistributed throughout the building, and a general collapse is unlikely. However, local collapse may cause injuries from falling concrete or from fire fighters falling through holes.

Precast concrete tilt slab buildings are now commonly used for warehouses and factories. Many of them are the equivalent of several stories high to accommodate high-rack storage. The integrity of the roof is vital to the tilt slab building. Failure of the roof can result in collapse of the tilt slab walls.

The roof may be carried on several types of beams. Most common are wood, steel bar joists, and concrete pretensioned tee beams.

Concrete tee beams would not generally be rated fire resistive unless the building was required to be fire resistive. If the concrete below the bottom tendon spalls off, the cold drawn tendon, which typically fails at 800°F (427°C), is exposed to the fire, and the beam is subject to failure.

A Metropolitan Dade County, Florida, fire lieutenant lost his life when prestressed tendons in tee beams in a carpet warehouse roof were heated to failure and the beam(s) collapsed. Massive reinforced concrete, fire-resistive multistory buildings have a good fire record. However, there have been cases of serious destruction, usually during long-duration, high-intensity fires. A recent fire in a concrete building loaded with tires caused heavy damage. A long-burning fire in the top floor of the Military Records Center near St. Louis, Missouri,[17] caused considerable elongation of the roof, which resulted in columns being torn off either the roof or the floor. After the fire, the top floor was removed.

Massive concrete is a substantial heat sink. The heat that is stored in the concrete is not available to extend the fire. However, the retained heat in the concrete may cause serious health hazards to fire fighters during operations and overhauling.

In posttensioned concrete buildings, the load is carried on the tendons (Figure 12.8.13). As a result, a failure of a tendon in a fire can lead to the failure of the building. Finished posttensioned concrete buildings cannot be distinguished by appearance from conventional reinforced concrete buildings. They are very different, however, with respect to fire operations. Spalled concrete can expose the tendons, resulting in failure. It is not safe to drill through a posttensioned floor to attack a stubborn fire on a floor below because the drill might cut a tendon and cause collapse. A hole alongside a tendon might permit the tendon to heat to failure. To cut large holes with jackhammers would be extremely hazardous in a posttensioned building.

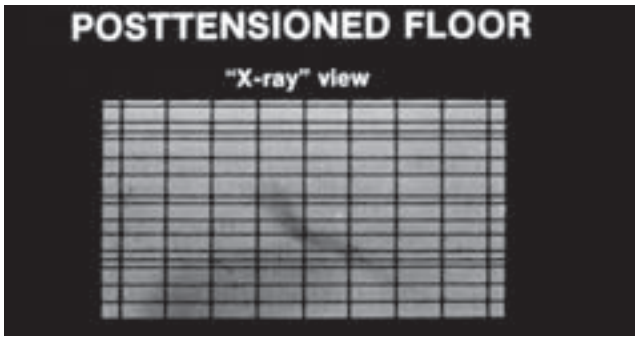

FIGURE 12.8.13 Location of Tendons in Posttensioned Concrete

Concrete Buildings Under Construction. The extraordinary rescue and body recovery operations required at the Oklahoma City, Oklahoma, bombing in 1995[18] could be repeated at a fire in a concrete building under construction if conventional fire-fighting tactics are followed.

When concrete buildings are under construction, the loads of freshly poured floors and structural elements are supported on temporary forms that are either combustible or, if made of steel or aluminum, subject to fire-caused failure. A massive failure of forms dropping one floor on another is almost certain to cause progressive collapse of several floors, possibly all the way to the ground.

In such cases, the command decision process should be the opposite of the traditional method. Traditionally, fire fighters rush into the structure and withdraw only when it is determined that the structure is unsafe. In the case of fire in concrete forms, which support thousands of pounds (kilograms) of concrete, it may be advisable to stay out until a decision can be made as to whether it is safe to enter the structure or even be near it.

On October 30, 2004, the top five stories of a 10 story parking garage collapsed in Atlantic City, New Jersey. Composed of both precast and sitecast concrete structural members, a column at or underneath the tenth floor (that was being poured) failed, trapping 24 construction workers. Three of them were killed.[19]

The situation in the case of posttensioned concrete construction is even more serious than it is for conventional reinforced concrete. Until the tendons are tensioned and the cables are stretched, the entire weight of the concrete, even hardened and dry to the touch, is supported on the concrete forms. If the forms burn, the entire floor or floors dependent on them will fall, possibly precipitating a total collapse. In 1974 a 14 story, posttensioned concrete structure under construction in Cleveland, Ohio, totally collapsed when fire attacked the forms. The fire chief, aware of the hazard, had kept the fire fighters out of the collapse area.

In 2000, a three-section, posttensioned, residential high rise was under construction in Key Biscayne, Florida.[20] Fire in exterior construction material spread to construction material in the interior. The fire department, cognizant of the posttensioned concrete hazard, adopted a defensive mode; that is, a no-entry mode. Many tendons were exposed to the fire, and three units were so damaged that they were demolished. It took several days for the explosive demolition contractor to prepare a safe plan for placing the explosives.

Fire fighters need to be aware that moisture remains in the concrete used to fill steel columns (Figure 12.8.14). In the nineteenth century, Lally columns were drilled to vent the steel. In a fire, the trapped moisture can heat until it becomes steam under sufficient pressure to cause the columns to explode. The explosion is not only dangerous itself but also can weaken the structure.

Fire-Resistive Construction

The major components of fire-resistive buildings are required to be similar to building components that have been subjected to the NFPA 251/ASTM E119 test. Test results are stated in the time to the last full hour (or half hour) the assembly withstood the assault of the test fire. Thus, a column might be rated as having "1-hour fire resistance" or a floor-ceiling assembly as having "2-hour fire resistance."

There may be no specific relationship between the time given in the rating and the time to failure of the structure in a real fire, however. There are many variables that affect the time a structural element can withstand fire exposure. The limit of confidence that one can have is that a 4-hour fire-resistive building is more fire resistive than a 2-hour fire-resistive building or that a 1-hour fire-resistive building is less fire resistive than a 2-hour fire-resistive building.

Fire-resistive buildings generally fall into the following three classes, corresponding roughly to the time they were built:

1. During the period 1880 to 1920, emphasis was on the building itself. Floors were of tile arch with or without protection of the steel beams. Vertical opening protection was not even considered. Fire resistance consisted of whatever the architect thought proper, because there were few requirements for fire resistance in the building codes. There are many such buildings still in use.

2. From 1920 to 1945, many building components were rated fire resistive in accordance with the ASTM E119 test. Steel frames were fireproofed with concrete. Floors were cast-in-place concrete. Stairways and elevators were generally enclosed. Fire and occupant loads were low because of limited floor areas due to the need for natural light and air. Many exit stairs were designed to provide an atmospheric break between the floor and the stairway, thus providing exit stairs that did not become contaminated with smoke. Sprinklers were generally not provided except for such buildings as the headquarters of the National Board of Fire Underwriters and high-rise factory buildings in New York City as a result of laws passed in the wake of the Triangle Shirtwaist fire. Only a few cities had high-rise buildings of this type. The Empire State Building represents the zenith of this type of fire-resistive construction.

3. From 1945 to present, many changes have occurred in building construction techniques. Air conditioning and fluorescent lighting have made extensive floor areas possible. Compartmentation in the form of full height partitions (found in older high-rise buildings and beneficial for slowing fire spread) have been replaced by short cubicle partitions. The increase in height and floor area has permitted a huge increase in occupants. Timely evacuation is difficult. Air conditioning may require nonoperable windows. Building height can generate strong stack effects, which can become a serious factor in smoke movement.

FIGURE 12.8.14 Concrete-Filled Steel Tube Columns

Combustible Metal Deck Roofs (CMDRs)

The so-called built-up roof of tar and layers of roofing material generally covered in stone is capable of self-sustained combustion when installed on metal decking, irrespective of contents. Such a roof is called a combustible metal deck roof (CMDR). If it is looked at it from below, the tar, which turns to gas when heated, is not visible, and the bar joist and corrugated steel void appear to be noncombustible. Frank Brannigan discovered the problem in 1946 at a fire in the Marine Corps Depot of Supplies in Norfolk, Virginia, and developed a tactical solution whereby heavy caliber streams were directed to the steel decking from a safe location to chill the steel and thus solidify the gas-generating tar. This technique was applied successfully at another fire in 1948. Until the total destruction of the General Motors Transmission Plant in Livonia, Michigan, in 1953, with a loss of $70,000,000, the problem of CMDRs remained largely unapprised.[21] Tests at Factory Mutual showed that 800°F for 5 minutes on the underside of the metal deck produces a self-sustaining fire.[22]

The U.S. Atomic Energy Commission had two roof deck fires in buildings with only minor combustible contents and developed the fixed protection solution, that is, automatic sprinklers to cover the underside of the roof, irrespective of the contents. The U.S. Air Force suffered a $170,000,000 loss at Tinker Field,[23] and the General Services Administration

suffered a severe loss in Fort Worth, Texas,[24] both caused by contractors cutting through the CMDR to install skylights. It is unsafe and useless for fire fighters to try to ventilate a combustible metal deck roof manually. Tests at Factory Mutual showed that a 56 ft^2 (5.2 m^2) vent was required to vent a small structure with no contents.[25]

Six Dallas fire fighters, planning to ventilate the roof of a store with a CMDR, fell into the fire when elongating steel bar joists pushed down a concrete block wall. Fortunately, they were near the edge and were recovered.[26] Twenty St. Paul, Minnesota, fire fighters were evacuated from a store with a CMDR 60 seconds before it collapsed. Two Memphis fire fighters were not so lucky when a CMDR in a retail store collapsed on them in 2003. An alternative to CMDRs is to install a Factory Mutual Type I roof or a UL "classified roof," which will not sustain independent combustion.

If there is a significant fire load, the height of the steel above the floor is no guarantee of stability during a fire. After the devastating 1967 McCormick Place Exhibition Hall Fire in Chicago, tests at Underwriters Laboratories Inc. showed that failure temperatures were reached in steel 30 ft (9.2 m) above the floor a few minutes after the fire started.[27]

Hose streams can cool steel being heated by the fire if a safe operating position is available. If the steel is elongating, it will retract to its original length when cooled. If it has started to fail, it will solidify in the shape it had reached. Contrary to a once-prevalent myth, the water does not cause the distortion of the steel. For a full explanation of the origin of the "don't put water on hot steel" myth, see Brannigan.[28]

SPECIFIC CONCERNS

The following areas of concern for the fire service relate, directly or indirectly, to fire fighter and public safety. There are no "minor" deficiencies in buildings being attacked by fire. Any single deficiency may contribute to loss of life or the destruction of the building.

Alarms and Staff Training

Building staff should be properly trained. A potential and, at times, fatal error is for a security guard or maintenance personnel to go to the floor from which the fire alarm has been received—thus walking right into the fire. The lone fatality in the spectacular 1988 First Interstate Bank fire in Los Angeles was the maintenance person who went to the fire floor to investigate.[29] Further, a guard went to the alarm floor of the One Meridian Plaza fire in Philadelphia, Pennsylvania, and barely escaped death.[30]

Sometimes personnel are temporary employees who have not had adequate instruction in their duties and responsibilities. Fire department personnel should inspect buildings during the night shift and question employees as to the actions they would take in the event of a fire alarm or for reported smoke.

Building staff has reset alarms to prevent the alarms from being transmitted to the fire department. This was a factor in a 12 fatality fire in the Westchase Hilton Hotel in Houston, Texas, in 1982.[31]

Delayed alarms can be due to a mistaken management perception that the arrival of the fire department is bad publicity. A policy of charging for false alarms should be carefully monitored to determine if it results in nontransmission of alarms.

Pre-Incident Planning

A thorough study of a target building should be made before the action pre-incident plan is developed. The fire department's pre-incident plan should examine each building as an individual problem. Problems and/or deficiencies in areas noted below may be present in buildings. Most were factors in serious fires.

The World Trade Center had been regarded as a significant advance in reducing weight and cost of high-rise buildings. There are serious questions as to the effectiveness of the "fireproofing" (insulation would be a better word) methods used as well as concerns about lack of compartmentation and "robustness" of shaft enclosures. Fire departments should review the final report of the National Institute of Standards and Technology's National Construction Safety Team investigation of the World Trade Center disaster.[32]

Automatic Sprinklers

Full automatic sprinkler protection, properly maintained, is a proven fire protection measure that can provide reasonable assurance of occupant and building fire safety. However, sprinklers can be inoperable. The fire department should carefully monitor the maintenance and shutdown of sprinkler systems. Special precautions and watch service should be required during periods of sprinkler impairment.

In many cases, building codes permit exceptions from or reductions in code provisions if sprinklers are installed. If the sprinklers are turned off when the building is occupied, it may be in violation of the code provisions.

Water Supply

The water supply system should be carefully checked for possible failures. Examples of water supply problems include water supply pumping system disconnection. At the time of the First Interstate fire, this was the case. Also, falling glass may cut lines supplying standpipes. Improperly marked standpipe connections have also been a major factor at fires.

Compartmentation and Structural Integrity

A fire-resistive building is generally designed to provide for compartmentation and structural integrity in a fire. Unfortunately, the design may be flawed or the construction faulty. Changes after the building was occupied may compromise the value of the compartmentation or structural integrity.

Compartmentation. Early fire-resistive design did not include compartmentation. It was believed to be sufficient that the building was "fireproof." Several disastrous fires in fire-resistive buildings proved the concept of "fireproof" to be faulty, and compartmentation became required. The following are points of failure in compartmentation:

- Many early fire-resistive buildings are still undivided and allow the passage of smoke and toxic gases throughout the structure.
- Floors are penetrated for wiring and other services. The openings are not always properly protected to restrict the passage of heat and smoke. Due to unprotected openings in floors, fire-resistive buildings can resemble a sieve to smoke and gases. The handful of fiberglass stuffed into the opening will not stop smoke and gases. Figure 12.8.15 illustrates penetrations to a floor.
- The reliability of horizontal compartmentation separating floors into fire areas or smoke compartments can be questioned. The wall may remain intact, but there may be utility openings through the walls that are not properly sealed.
- Fire barrier doors into stairways and between fire areas are required to have door closers and latches. These may be removed or doors found blocked open for convenience. This problem occurred at a high-rise apartment house that had both interior stairway doors propped open. A fast-spreading fire erupted, filling the stairs with heat and smoke. Four occupants died. It took almost 200 fire fighters to subdue the fire and to evacuate the tenants.[33]
- Automatic door closers are often made ineffective, generally for the sake of convenience. For example, it can be tempting to remove closers in a high-rise residence for seniors to allow residents to visit neighbors "for a moment." It is possible that the occupant of the apartment in which the fire occurs exits, leaving the door standing open. In such cases the hallway can fill with fire, and fire fighters could find it dangerous and sometimes impossible to advance the hose lines, particularly if the wind is blowing into the apartment. Few people have any concept of the heavy fire load and high rate of fire growth of today's furniture.

The best solution for the conflict between inconvenience and a potential hazard not understood by occupants is to have such doors equipped with magnetic latches. When the door is opened the electromagnet holds it open. Any fire alarm cuts the current to the electromagnet and the door closes. For smoke barrier doors in hallways, a detector is provided on both sides of the door. Some door closers have a smoke detector incorporated in the closer. Closers that incorporate only a fusible link are not effective for life safety since deadly quantities of gases can pass before heat operates the fusible link.

FIGURE 12.8.15 Unprotected Floor Penetrations

Structural Integrity. The structural integrity of a building may depend on how the fire resistance was achieved. The following are issues in structural integrity:

- Buildings with tile arch floors may not provide protection for the steel beams. In later buildings, skewback tiles were provided to protect the steel.
- Steel floor and ceiling assemblies using suspended ceilings are common. Unfortunately, ceiling tiles are easily removed and integrity is hard to maintain. The ceiling voids can allow smoke and fire to pass.
- Permitting steel columns to be unprotected in the plenum space is particularly dangerous. Failure of the ceiling membrane would subject the column to fire temperatures. The heating of only a short length of a column to failure temperature could have costly, or even catastrophic, effects on the building.

Spray-on fireproofing used asbestos fibers for many years. The health hazard of asbestos fibers now requires its removal. A most important question is what, if anything, is done to fire-protect the steel when the asbestos fireproofing is removed.

Flame Spread

Fire departments should be aware of the presence of combustible interior finish, such as plywood and combustible acoustical tile, in buildings. Older acoustical tile was made of compressed wood fibers and will burn furiously. It is usually installed on wood stringers, which enables burning on both sides of the tile. If it is applied with glue, the adhesive can add significantly to the rate of burning. This was discovered in the investigation of the Hartford Hospital Fire in 1961, in which 16 people died.[34] The combustible tile was glued to a suspended gypsum board ceiling that was surface-treated with a flame retardant. When the tile was tested, the adhesive caused a very rapid flame spread. When new tile is installed, it will probably need to meet flame spread requirements. However, there may be no requirement that the old tile be removed (Figure 12.8.16).[35] A very serious potential hazard is created if old combustible tile is left in place when a new "code-approved" suspended ceiling is installed below it.

Similarly, flame spread was a significant factor in the February 2003 Station nightclub fire in West Warwick, Rhode Island, which killed 100 people. Polyurethane foam soundproofing, installed around a platform used by musical performers, was ignited by indoor pyrotechnics. The entire room flashed over in 90 seconds.[36]

Other Areas of Concern

Construction in Occupied Buildings. Buildings can be partially occupied before construction is finished. Many major remodeling projects are carried on in occupied buildings. The fire department should be aware of any such construction. Special permits should be required for any construction after the certificate of occupancy is issued. A typical construction fire in

FIGURE 12.8.16 Old Combustible Tile Retained Above a New Suspended Ceiling

such a building can be a serious threat to the safety of all the occupants.

Lightweight Construction. The almost complete change from sawn lumber to gusset plate wood trusses and wood I-beams has profoundly changed the fire suppression environment. Tactics learned and experience gained on sawn joist and rafter buildings are not transferable to truss buildings. The truss floor introduces a new hazard, which creates a floor void in which carbon monoxide (CO) gas can accumulate.

Vacant Buildings. Large commercial and manufacturing buildings may be vacant due to remodeling for "adaptive use," lack of a tenant, upcoming demolition, or even abandonment by the owner. Sprinklers can have been shut off or removed. Open construction shafts can make vacant buildings one huge fire compartment. As demonstrated by a 1999 fire in a warehouse in Worcester, Massachusetts, which claimed the lives of six fire fighters, searching for homeless people and fighting fires in vacant buildings can be extremely dangerous.[37]

Added Roofs. New roofs can be constructed over the original roof to control leaks (rain roof) or for aesthetic reasons. These present serious problems in fire fighting. Harlow[38] provides detailed information.

Stadiums. Stadium fires in Texas and Georgia focused attention on the severe difficulties faced in fighting fires in the luxury "sky boxes." The potential for flaming plastic windows falling onto occupied combustible seats in the arena below is a serious risk. Fire departments should perform realistic risk assessments and, where indicated, require fire protection improvements.[39]

SUMMARY

This chapter presents the highlights of the problems that the effects of building construction present to fire suppression forces. Further detailed information can be found in *Building Construction for the Fire Service* and in the references cited. Knowledge and experience with building construction methods and materials can help improve fire department safety and efficiency.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the effect of building construction and fire protection systems on fire fighter safety discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 220, *Standard on Types of Building Construction*
NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations*
NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 252, *Standard Methods of Fire Tests of Door Assemblies*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 5000®, Building Construction and Safety Code®

Chapter 9

Fire and Emergency Services Protective Clothing and Protective Equipment

Bruce W. Teele

Protecting fire fighters, law enforcement officers, hazardous materials technicians, emergency medical personnel, technical rescue personnel, and other emergency responder personnel from the expected exposures and hostile operating environments that emergency operations pose is a complex issue. The following are key facets in minimizing emergency responder injuries and deaths:

- Thorough training of officers, supervisors, and response personnel
- Considerable medical and physical requirements and health maintenance
- A detailed and well-functioning incident management system
- Adequate staffing
- Closely supervised operating teams or crews
- Company/team/crew cohesiveness
- Clear and concise standard emergency operational procedures
- State-of-the-art personal protective equipment (PPE), including protective ensembles, clothing, and equipment that are consistently and properly used

Much has changed in these areas during the past several decades, and more must be done in the future. Emergency responder organizations should stay well informed of developments in all of these areas and provide the information and training to their personnel to keep them as current and informed as possible. Emergency responder personnel need to realize their human limitations and the dangers they face during operations in hostile environments. They must also understand that the inherent safety of participating as a member of a team in a well-planned operation under a safety-driven incident management system does far more for their safety than just relying on the PPE they use.

For related topics, see "Section 12, Chapter 7, "Safety, Medical, and Health Issues and Programs"; Section 12, Chapter 8, "Effect of Building Construction and Fire Protection Systems on Fire Fighter Safety"; and Section 12, Chapter 16, "Fire Department Apparatus and Equipment."

NFPA INVOLVEMENT

Historical Background

In the early 1970s, the National Fire Protection Association (NFPA) became directly involved with fire service safety issues through its technical committees and new standards. The effort began with the Technical Committee on Fire Department Equipment. This committee established a Sectional

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Key Terms

certification, emergency medical services, fire fighter safety, hazardous material, heat stress, industrial fire brigade, life safety rope, occupational safety and health, personal alert safety system (PASS), personal protective equipment (PPE), protective ensemble, safety officer, self-contained breathing apparatus (SCBA), technical rescue

Committee on Protective Equipment for Fire Fighters to specifically address these issues. Their documents were directed toward equipment standards.

The sectional committee developed a new document on respiratory protective equipment, and the association membership adopted NFPA 19B, *Standard on Respiratory Protective Equipment for Fire Fighters,* on May 17, 1971. This new standard prohibited the use of filter-type canister masks for protection of fire fighters from the products of combustion and allowed only self-contained breathing apparatus (SCBA) for fire fighter respiratory protection. This action was the direct result of fire fighters dying while wearing filter-type masks during fire-fighting operations. At least one court decision found that filter-type canister masks and other respirators that only filtered the atmosphere and did not provide a source of noncontaminated breathing air were inappropriate for use by fire fighters, as they did not provide protection from the known and expected respiratory hazards that fire fighters encounter during fire-fighting operations.

The second document from the sectional committee, NFPA 19A-T, was a tentative document (a preliminary document that is no longer a part of NFPA's codes and standards development process) that was the first to address protective clothing for structural fire fighting. Although NFPA 19A-T never became a standard, it was the basis for a future document on the same subject, NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting.*

In 1974, NFPA restructured the sectional committee as a separate and full technical committee for PPE. This new committee, the Technical Committee on Protective Equipment for Fire Fighters, was no longer under the direction of the Technical Committee on Fire Department Equipment. It assumed the responsibility for NFPA 19B and developed a new document, NFPA 1971, which was adopted on November 18, 1975. This document has been followed by a series of documents on PPE for structural fire fighting, proximity fire fighting, wildland fire fighting, hazardous materials emergencies, emergency medical operations, and special operations. The committee was renamed in 1988 as the Technical Committee on Fire Service Protective Clothing and Equipment.

Because of the continuing increase of the types of PPE being addressed by the committee and the areas other than fire fighting in which the committee was involved, NFPA created a Project on Fire and Emergency Services Protective Clothing and Equipment in late 1994. It is structured with a technical correlating committee managing the project and seven technical committees now responsible for electronic safety equipment; respiratory protection equipment; and for protective ensembles, clothing, and equipment for emergency medical services; hazardous materials; special operations; chemical, biological, radiological, nuclear (CBRN) terrorism incidents; proximity fire fighting; structural fire fighting; and wildland fire fighting; and for the selection, care, and maintenance of the PPE. Within this project, there are currently 15 active documents and more under development or in the planning stages.

In 1973, NFPA established the Technical Committee on Fire Service Occupational Safety and Health. This was the first NFPA committee to focus on the issues of the safety and health of fire fighters instead of just the PPE. In its early years, the committee considered many issues and then wrote a document, NFPA 1501, *Standard for Fire Department Safety Officer,* that was adopted on May 18, 1977.

NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*

The committee produced NFPA 1500, which became effective on August 7, 1987. NFPA 1500 was developed as an umbrella document, encompassing an entire fire department safety and health program. NFPA 1500 became the first nationally recognized consensus standard to address fire service occupational safety and health. It was the first national document on safety and health to be written by the fire service and fire service interest groups for the fire service. Prior to NFPA 1500, any safety and health measures had to be based on general industry standards and regulations that either did not adequately address fire service problems or were difficult to impose on a nonindustry agency.

The fifth edition of NFPA 1500 became effective in August 2006. NFPA 1500 is the fire services organizations' requirements, as it has the criteria for fire departments and fire fighters, rather than the product requirements that manufacturers must meet. NFPA 1500 is the document that makes it happen, as it requires fire departments to have, and fire fighters to use, protective clothing and equipment.

NFPA 1500 requires the provision and use of protective ensembles, clothing, and equipment that are certified as compliant with the appropriate NFPA PPE standard(s) for the intended application. The basis of the requirements is to provide for the protection of fire fighters who are responsible for various fire-fighting and other emergency operations. The fire department is required to provide the appropriate protective clothing and protective equipment for the task and operation.

The fire department is also required to ensure that the PPE is properly utilized and maintained. Accordingly, each fire fighter is to be provided training in the use and limitations of protective clothing and equipment.

OSHA INVOLVEMENT

In addition to NFPA 1500, in the United States there are federal and state regulations, generally under the federal Occupational Safety and Health Administration (OSHA) or the state equivalent, that include protective clothing and equipment as well as other safety and health issues.

OSHA first addressed fire service occupational safety and health in 1980 when it issued regulation 29 CFR 1910.156, the "fire brigades regulations." Although the federal OSHA regulations did not apply to state and local government employees, states that have federally approved state OSHA plans were, and still are, required to cover state and local government employees.

However, when OSHA issued regulation 29 CFR 1910.120 on hazardous materials emergency response, the U.S. Congress directed the Environmental Protection Agency (EPA) to issue identical regulations that would apply to state and local govern-

ment employees as well as volunteers in all 50 states. This EPA regulation is 40 CFR 311, which was issued June 23, 1989. Both 29 CFR 1910.120 and 40 CFR 311 include a mandatory reference requiring fire departments to be compliant with 29 CFR 1910.156. Therefore, wherever fire departments also respond to any type of hazardous materials incidents, the OSHA/EPA regulations apply to all operations for all fire departments in the United States whether career, career/volunteer combination, or all volunteer.

NFPA PPE STANDARDS

Two different types of PPE standards produced in the NFPA codes and standards development system are product standards and user standards.

Product Standards

Product standards specify the requirements to which manufacturers produce their PPE, and certification organizations inspect, evaluate, and test the product to determine compliance. All product standards are written to the extent possible in terms of performance requirements with pass/fail criteria and specific testing methods to evaluate each performance. These standards also have a chapter on design requirements covering those items that cannot be defined in performance criteria but must be inspected and evaluated by the certification organization in order to determine product compliance.

All product standards require manufacturers to have their product "certified as compliant" with the applicable NFPA PPE standard in order to claim the product meets the standard. Certification is a very important part of the PPE product standards as it gives a reasonable degree of confidence to end users and purchasers that the product they are purchasing or using has been found to meet the requirements of the standard and has been certified as such. The certification program includes an independent third-party certification organization that is accredited to certify PPE; evaluates and tests the product in accordance with the applicable NFPA PPE standard; applies labeling, listing, and follow-up programs for the product; and administers periodic product recertification and quality assurance programs for the manufacturer. The certification program is addressed in further detail later in this section.

User Standards

User standards specify requirements for the emergency responder organizations and personnel who purchase and use the PPE. These standards are written to assure the correct and safe use of the PPE and the proper selection, care, and maintenance of PPE. NFPA 1500 specifies which types of PPE are to be used for various emergency operations and that the PPE must be certified as compliant with the appropriate product standard. A new type of user standard now specifies the process of selection, care, and maintenance for different types of PPE. The first two standards in this series are NFPA 1851, *Standard on Selection, Care, and Maintenance of Protective Ensembles for Structural and Proximity Fire Fighting,* and NFPA 1852, *Standard on Selection, Care, and Maintenance of Open-Circuit Self-Contained Breathing Apparatus (SCBA).*

These selection, care, and maintenance (SCAM) standards specify requirements for segments of the organization's overall PPE program as required by NFPA 1500 by reference to the SCAM standards. The SCAM standards also specify the procedures for selecting PPE both prior to purchase and, in some cases in which different types of PPE could be used, prior to use, as well as the proper care, cleaning, maintenance, repair, storage, and removal from service or retirement of PPE. These SCAM standards are intended to provide enhanced safety for users by assuring that the PPE remains in optimum condition for user protection.

THIRD-PARTY CERTIFICATION PROGRAM

All NFPA PPE standards for emergency responder personnel require that the PPE be certified in accordance with the certification program specified in each standard. The certification program is an essential means of ensuring the quality of emergency responder PPE.

Certification includes an accredited, independent third-party certification organization that evaluates and tests the product in accordance with the applicable NFPA PPE standard and, on determining that the product does meet the requirements, permits the manufacturer to affix the certification organization's label, symbol, or other identifying mark to the product, indicating compliance. This is called the *labeling* portion of certification. The certification organization must also provide a listing service in which the organization publishes lists of products by specific type or model that have been evaluated, tested, and labeled as compliant products. This is called the *listing* portion of certification. In the *follow-up* portion of certification, the certification organization makes random periodic reviews of the manufacturing process and evaluates and tests the continuing production process to assure that the product remains compliant.

In addition, the certification organization reviews and monitors the manufacturer's quality assurance program. Manufacturers are required to be registered in accordance with the ISO 9001 quality control standard. Some may claim that following the ISO quality control requirements only means the manufacturer documents everything whether good or bad, that it is just a paper project. But when the manufacturer has certified a product as being compliant with an NFPA PPE standard, quality control is evaluated against the PPE standard so that the manufacturer and the certification organization, which monitors the quality assurance program, can always know the status of the product and can quickly identify any problems that could affect product certification. The certification organization also provides annual recertification of the product in which key tests are conducted to assure that the product remains compliant.

All items of emergency responder protective clothing and equipment that are claimed to be compliant with the appropriate NFPA standard *must* carry the label, symbol, or other identifying mark of the certification organization. Any PPE item that does not bear the label or mark of a third-party certification organization is *not* compliant with the appropriate NFPA

standard, regardless of the claims or statements that are made by the manufacturer, distributor, advertisement, or the garment or product label.

Requests for bids and purchase specifications should require the manufacturer to submit appropriate evidence of certification of the specific product and model that the manufacturer is bidding on. When releasing purchase specifications to solicit bids, purchasers should obtain copies of listings of certified PPE from certification organizations to assist in their review of bids received. These listings are the certification organizations' documents identifying which products have been tested and found to be in compliance with various standards. In all cases, purchasers should verify directly with the certification organization that the specific product and model certification are still valid *before* the purchase contract is signed or the purchase is made. After purchase, questions regarding the certification of any PPE item should be addressed to the indicated certification organization. Details of the certification and the labeling of PPE can be found in each NFPA product standard on protective ensembles, clothing, and equipment.

CLEANING AND MAINTAINING PPE

In all cases, the manufacturer's instructions for cleaning and maintaining its PPE must be followed. The manufacturer is required to provide specific printed or video cleaning and maintenance instructions with each item of PPE sold in order to be certified as compliant with the NFPA PPE standard. These instructions must be consulted and followed because failure to do so may reduce the protective qualities of the PPE or negate warranties. When the manufacturer's instructions for cleaning and maintenance that were provided with each new PPE item cannot be found, the product manufacturer should be contacted directly to obtain a new set of instructions.

The PPE selection, care, and maintenance (SCAM) standards mentioned earlier further specify the system for the organization's PPE program and how frequently inspections, cleaning, and maintenance must be performed. Recommendations (nonmandatory) for cleaning procedures are given if the manufacturer is no longer available to provide these instructions. Each SCAM standard states that whenever a difference occurs between the manufacturer's instructions and the SCAM standard, the manufacturer's instructions shall be followed.

Clean PPE reduces safety and health risks. It is recommended that PPE be cleaned frequently to reduce the level of, and bodily contact with, contaminants. Cleaning should prolong the life of the protective garments and help maintain the performance. Decontamination may not be possible when protective garments are contaminated with chemical, radiological, or biological agents. When decontamination is not possible, garments should be discarded in accordance with local, state, and federal regulations.

PPE is composed of a combination of materials. Each of these materials has unique characteristics, capabilities, and weaknesses. Even fabrics inherently flame resistant can have this characteristic negated by improper care and use.

Chlorine bleach must *not* be utilized for any PPE cleaning, decontamination, or disinfecting. Some components of PPE lose their physical integrity on exposure to chlorine bleach. Other components will actually lose their flame-resistant properties and thermal insulation capability on exposure to chlorine bleach. In any case, the protection provided by the PPE will be compromised.

Storage of PPE in direct sunlight, even for short periods of time, will substantially reduce protective qualities; the effects of such a reduction might not be visually apparent. Ultraviolet (UV) degradation will destroy or reduce the useful life of the PPE item. Color fading or color change often indicates that the garment has experienced UV degradation.

STANDARDS ON PPE FOR FIRE-FIGHTING OPERATIONS

Protective ensembles, protective clothing, and protective equipment for fire fighting are currently covered by two standards: one for structural fire-fighting protective ensembles and for proximity fire-fighting protective ensembles, and one for wildland fire-fighting protective clothing and protective equipment. These standards provide protection from physical hazards as well as thermal and environmental hazards and are designed to protect fire fighters against exposure to the hazards associated with each type of fire-fighting operation. The performance requirements are not intended to establish the limitations of the fire fighter's working environment but are intended to establish material performance requirements based on empirical field data and laboratory testing.

Proper sizing is an important part of the protection provided by PPE garments. PPE garments that fit properly allow air retention in the composite and the air adds insulation. Garments that are too tightly fitting squeeze air out and reduce the insulative qualities. Garments that are too loose or too tight can prevent the fire fighter from being able to reach, pull, climb, crawl, straddle, or jump and will contribute to fatigue. Improperly fitting garments are safety hazards as they do not permit the wearer to function with as little interference as possible. Sizing must also take into consideration the minimum overlap of two-piece ensembles (coat and trousers instead of a one-piece coverall style) to assure that there is no gap in the protection where the two elements meet. This overlap of protection must be provided in all working positions, including standing straight, crouching, crawling, reaching overhead, and stretching front, back, and side to side.

The preferred method of sizing is to measure persons individually for their PPE garments or ensemble. This assures a proper and safe fit for chest, shoulders, arms, waist, thighs, legs, and garment overlap areas of the fire fighter who will be wearing the garments. Another method used with standard stock garments is numerical sizes that are based on increments of chest and waist measurements, such as 32, 34, 36, 38, and so on. It can give individuals who conform to standard sizing measurements an effective fit in many situations; however, the garment overlap areas must be carefully considered. Yet another sizing method uses general sizing indicators such as S/M/L/XL/XXL. This sizing method is very general and the least accurate, combines a larger increment of chest and waist measurements in each size range, and is not recommended.

Some of the testing that the materials, components, composites, and ensemble elements for fire-fighting PPE are subjected to include the following: flame resistance, thermal stability, thermal insulation, convective heat resistance, radiant heat resistance, total heat loss capability (breathability), durability, dexterity, grip, electrical insulation, corrosion, abrasion, compression, cut, puncture, penetration, impact, energy absorption, retention, water penetration, viral penetration, and common liquids resistance.

Excessive Protection

One point of view about fire-fighting protective clothing is that it allows fire fighters to overextend themselves, thus getting into positions that are more likely to cause injury—positions that they would not be able to get into if they were not wearing such "sophisticated" clothing. Some think that the advanced protective clothing does not allow fire fighters to "feel the heat" and better judge their environment.

Fire fighters who overextend are not operating under close or adequate supervision or in an incident command system that controls the position, function, and safety of all operating teams. The advanced protective clothing can allow fire fighters, who are operating safely within the incident command system, to be able to perform more effectively.

Some advocate different levels of protection for various parts of the same protective ensemble. This is alleged to allow the fire fighters to "feel the heat" in areas of the body that are sensitive to heat but are believed to be not as severely exposed to the fire environment.

All parts of the fire fighter's body are sensitive to heat and equally exposed during most active operations and especially when conditions unexpectedly change. The philosophy of NFPA PPE standards has been to provide protection from the expected environment during proper, supervised operations and, if conditions deteriorate rapidly, to provide a margin of time for fire fighters to escape uninjured or with survivable injuries. The fire fighter must be afforded equal protection throughout the ensemble to reduce the possibility of injury or limit the severity of the injury.

Regardless of the level of protection afforded by any protective clothing, anything *except bare skin* can allow fire fighters to overextend, further enforcing the position that all operations must be managed by the incident command system and that fire fighters operate only under direct supervision within that system. Individual fire fighters who operate alone and not as a member of a company or a team, who operate without direct supervision, or who operate outside of the incident command system (a situation frequently called "freelancing" in the United States) cannot be permitted if safety is to be achieved.

The ability to judge heat buildup can differ depending on what fabrics the fire fighter is wearing. The level or intensity of heat that can be sensed in one garment may feel entirely different in another garment that was manufactured using different fabrics or component layers. There is not a single "measure of heat buildup" that can be applied to all protective garments. Likewise, it is impractical to rely on exposed human body parts to indicate heat exposure, as skin begins to burn at relatively low temperatures (about 135°F [57°C]) after a short exposure. It is actually a cultural issue and a training issue for the fire fighter to become familiar with how a particular ensemble transmits heat.

Heat Stress

Another viewpoint is that the thermal insulation of the protective clothing causes more injuries, due to heat stress, than lighter weight but less protective garments. Some positions state that these injuries are the result of the protective clothing.

Heat stress cannot be addressed by only the garment materials but must be approached from several factors that equally affect it. Simply put, the problem is protecting fire fighters from a very hostile environment in which thermal insulation is required and attempting to reduce heat stress to as low a level as possible.

In mild and moderate environments and at low and moderate work levels, differences in PPE garment materials are likely to have an appreciable effect on heat stress. In the most stressful situations of high-temperature environment or high work rates, PPE garment materials are unlikely to make any significant improvements in tolerance time. In addition to the total heat loss testing and material specifications, heat stress must also be addressed through other means.

Fire fighters spend considerable time in other than high heat environments and at other than high work levels. Relief can be provided from heat buildup inside protective clothing in mild and moderate environments and at low and moderate work levels, and NFPA PPE standards are addressing some of the garment and fabric issues of heat stress with a total heat loss test that measures the breathability of garments. This requirement is currently being met by use of breathable membranes in the PPE garment composite that do not compromise the other required protection.

For garments to be protective from the hostile thermal environment, thermal insulation is needed. Garments alone cannot keep a fire fighter both cool and comfortable and provide adequate thermal insulation necessary for fire-fighting operations in hostile thermal environments. All of the factors affecting stress and heat stress must be evaluated, including fire fighters' age, physical condition, and individual metabolism as well as how fire fighters are managed during incident operations.

Fire fighters who are operating in high-temperature areas or at high work rates must be cared for. These crews must be periodically rotated to allow rest, cooling, rehydration, monitoring of physiological conditions, and other measures as necessary. Simply reducing the insulation or weight of the protective garments will not benefit fire fighters and will not have any meaningful effect on heat stress. The entire spectrum of heat stress and stress-related problems must be fully addressed by the fire department.

Structural Fire-Fighting PPE

Thermal Environment. The PPE for structural fire fighting has been developed over the years after careful consideration of the expected thermal environment. The types of fire involvement and the general range of conditions and maximum exposure durations that might occur are shown in Table 12.9.1.

TABLE 12.9.1 Thermal Classification—Structural Fires

	Occurrence	*Height and Duration of Temperature and Thermal Radiation*
Class I	In a room or enclosed area that has been involved after the fire has been knocked down	Environmental temperatures up to 104°F (40°C) and thermal radiation up to 0.05 W/cm^2 for up to 30 min
Class II	When a small fire is burning in a room or enclosed area	Environmental temperatures from 105 to 203°F (41 to 95°C) and thermal radiation from 0.050 to 0.100 W/cm^2 for up to 15 min
Class III	When a fire in a room or enclosed area more completely involves the contents	Environmental temperatures from 204 to 482°F (96 to 250°C) and thermal radiation from 0.100 to 0.175 W/cm^2 for up to 5 min
Class IV	During ignition of fire gases, a backdraft, or flashover in a room or enclosed area	Environmental temperatures from 483 to 1500°F (251 to 815°C) and thermal radiation from 0.175 to 4.200 W/cm^2 for about 10 sec

Source: Adapted from http://www.cdc.gov/niosh/npptl/pdfs/ProjectHEROES.pdf.

Although achieving these exposure durations could be possible, most situations have other factors that can dramatically affect the durations. Two of many factors are preheating of the PPE at lower-class conditions prior to the higher-class exposure and effects (both positive and negative) on the thermal environment caused by fire-fighting operations. In any case, structural fire fighting is not designed to give full protection for the exposure durations sequentially through each class environment.

Because the thermal environment can change extremely rapidly during structural fire-fighting operations, the wearing of full ensembles is required for all operations when the fire is not under control and for many "under control" operations.

Protective Ensembles Used by the Fire Department of New York. In February 1995, the New York City Fire Department (FDNY), the largest fire department in the United States, required all of its 11,228 fire fighters to be equipped with and to wear both protective coats and protective trousers, rather than just protective coats with boots, for all fire-fighting operations. In 1996, FDNY required protective hoods also be worn with full protective clothing. FDNY's statistics for 1993 through 2005 show a significant reduction in burn injuries (Table 12.9.2) and time lost due to burn injuries (Table 12.9.3).

Over the years, other fire departments have also reported reductions in burn injuries when the change was made to full PPE from only protective coats worn with boots.

Protection for Structural and Proximity Fire Fighting Operations. The product standard for structural proximity fire fighting PPE is NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting* (formerly NFPA 1971, *Standard on Protective Ensemble for Structural Fire Fighting* and NFPA 1976, *Standard on Protective Ensemble for Proximity Fire Fighting*). This structural fire-fighting protective ensemble consists of the following elements: garments (coat and trousers), hoods, helmets, gloves, and footwear. Figure 12.9.1 from NFPA 1971 shows helmet test areas and landmarks for sample helmets that are conditioned through exposing the area to be impacted/penetrated to a radiant heat source.

TABLE 12.9.2 Reduction in Burn Injuries

	Burn Injuries		
	1993	*2005*	*Change*
Ears	185	43	–76.76%
Face	176	98	–44.32%
Hand	189	64	–66.14%
Head	76	25	–67.11%
Knee	355	43	–87.89%
Arm	283	52	–81.63%
Leg	162	45	–72.22%
Neck	406	72	–82.27%
Torso	64	19	–70.31%
Totals	1832	442	–75.87%

Source: Courtesy of FDNY.

TABLE 12.9.3 Reduction in Time Lost from Burn Injuries

	1993	*2005*	*Change*
Time Lost—Severe	10	0	–100.00%
Time Lost	1144	272	–76.22%
No Time Lost	60	13	–78.33%
Minor	184	27	–85.33%
Totals	1398	312	–77.68%

Source: Courtesy of FDNY.

The 2007 edition of NFPA 1971, the seventh edition, introduced *optional requirements* for protection from chemical, biological, radiological, and nuclear (CBRN) terrorism agents (chemicals, biological agents, and radiological particulate) that could be released as a result of a terrorism attack. These optional requirements can be selected by fire departments that are concerned about first response of their personnel to terrorism

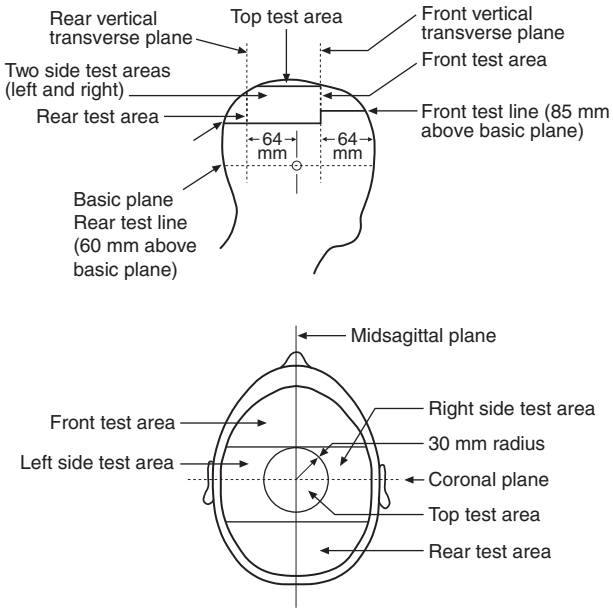

FIGURE 12.9.1 Helmet Test Areas and Landmarks (Source: NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting,* Figure 8.1.6.1, 2007, p. 1971-42)

incidents where "normal" fire-fighting protective ensembles offer little or no protection from CBRN terrorism agents. These optional requirements can also be selected where supplementary protective ensembles that are certified as compliant with NFPA 1994, *Standard on Protective Ensembles for First Responders to CBRN Terrorism Incidents,* for protection from CBRN terrorism agents are unlikely to be provided to the vast majority of fire-fighting first responders.

The CBRN optional protection can only be applied to an entire ensemble, including the specified CBRN SCBA for that ensemble, and cannot be applied to individual ensemble elements. The design and performance of the entire ensemble including the CBRN SCBA provide the CBRN protection for the wearer and depend on the proper use of the entire ensemble to accomplish this. No combination of individual ensemble elements short of the entire assembled ensemble will give CBRN protection.

These optional CBRN requirements apply to both structural fire-fighting protective ensembles and proximity fire-fighting protective ensembles and are built into the construction of the "basic" fire-fighting protective ensemble elements, so that nothing has to be added to or subtracted from the basic fire-fighting protective clothing in order to achieve the protection from CBRN terrorism agents. The optional CBRN requirements do not decrease any of the protection for the fire-fighting environments in which these ensembles are used.

Protective Clothing and Equipment (PPE). The use of "full structural fire-fighting protective clothing and equipment" (PPE), certified as compliant with the NFPA 1971, is required by NFPA 1500 for all structural fire-fighting operations. Full PPE includes the previously mentioned ensemble elements, as well as SCBA certified as compliant with NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services,* and PASS (personal alert safety system) certified as compliant with NFPA 1982, *Standard on Personal Alert Safety Systems (PASS).*

The user standard for structural fire-fighting PPE is NFPA 1851. This standard embraces the selection process for purchasing new PPE and the inspection, cleaning, care, repair, and removal from service of "in-service" PPE.

Specialized Fire-Fighting PPE

Approach Fire-Fighting Operations. There are other fire-fighting operations in which personnel can be exposed to very high levels of radiant heat and in which proximity PPE is not suitable. Approach operations are generally limited to incidents at fixed facilities that produce high levels of radiant heat and also produce conductive, convective heat but also include operations conducted at greater distances from the fire so that the principle thermal hazard is the radiant heat. Such operations usually consist of personnel "approaching" the fire area in order to position and set up unstaffed delivery points for exposure protection or application of cooling or extinguishing agents onto the fire area, such as master streams, and then withdrawing from the area affected by the radiant heat.

Radiant heat protection is necessary for personnel involved in such operations, but protection from convective and conducted heat is generally not necessary because personnel are not exposed to significant thermal hazard due to the distance from the fire at which they perform the operations. Lighter weight and more flexible approach protection can permit the personnel to expeditiously complete their functions and withdraw with less stress.

Entry Fire-Fighting Operations. Entry fire-fighting operations are extraordinarily specialized operations at fires that produce extreme levels of conductive, convective, and radiant heat. Entry fire fighting should not be confused with structural fire fighting. In structural fire fighting, fire fighters enter into a structure in which there is a fire in order to search for and rescue victims and to confine and extinguish the fire in the smallest possible area. They do *not,* however, *enter into the flames.*

In entry fire-fighting operations, in contrast, personnel actually *enter into the flames.* These operations are generally limited to incidents at fixed facilities where the need is known beforehand and tasks have been pre-incident planned. Frequently employees of the facility who have been specially trained and equipped perform the operations. Entry is made in order to perform critical tasks. These tasks might include opening or closing valves or operating other controls that will likely result in control of the fire with no other way possible to control the fire without performing these tasks. Because of the scope of these operations, highly specialized thermal protection from exposure to extreme levels of conductive, convective, and radiant heat is necessary for persons involved in such extraordinarily specialized operations. Such entry PPE is specifically designed for the particular situation in which it will be used and for the known

and expected hazards. There are no standards for entry PPE due to the unique individuality of each set of PPE.

Proximity Fire-Fighting Operations

Proximity fire-fighting operations are specialized operations that can include the activities of rescue, fire suppression, and property conservation at incidents involving fires producing very high levels of radiant heat, as well as conductive and convective heat. Proximity fire-fighting operations include fires involving bulk flammable liquids, bulk flammable gas, bulk flammable metals, commercial or military aircraft, and similar situations that release high levels of radiant heat.

Specialized thermal protection from exposure to high levels of radiant heat, as well as thermal protection from conductive and convective heat, is necessary for persons involved in such operations. Although fire fighters do not make direct entry into flame, they need such protection because of the scope of these operations and because of their closeness to the fire when conducting these operations. These operations are usually exterior operations but might be combined with interior operations. Proximity fire fighting is not structural fire fighting but might be combined with structural fire-fighting operations. Proximity fire fighting is not entry fire fighting.

The product standard for proximity fire-fighting PPE is NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting* (formerly NFPA 1976, *Standard on Protective Ensemble for Proximity Fire Fighting*). This protective ensemble standard consists of the following elements: garments (coat and trousers), helmets, shrouds, gloves, and footwear.

The use of full proximity fire-fighting protective clothing and equipment certified as compliant with NFPA 1971 is required by NFPA 1500 for all proximity fire-fighting operations. Full PPE includes the previously mentioned ensemble elements, as well as SCBA certified as compliant with NFPA 1981, and PASS certified as compliant with NFPA 1982.

Wildland Fire-Fighting PPE

Wildland fire-fighting operations are exterior operations incidents involving fires in natural ground cover, woods, trees, and other such vegetation. Such operations expose fire fighters to radiant heat, to some conductive and convective heat, and to many physical hazards.

Wildland fire-fighting PPE includes garments for upper and lower torso protection, overgarments, helmets, gloves, footwear, and fire shelters. The PPE is not presented as a total ensemble but as individual items that the incident commander can pick from in order to select the best combination for the particular incident conditions. The minimum necessary to meet the requirements of NFPA 1500 includes a fire shelter and protection for head, torso, hands, and feet.

Wildland fire fighting is the one fire-fighting operation in which respiratory protection is not required. At this time, some wildland fire-fighting organizations do use respiratory protection devices, usually of the air purifying respirator (APR) type or the powered air purifying respirator (PAPR) type. (See a more detailed discussion of wildland fire-fighting respiratory protection in the following respiratory protection section.)

The product standard for wildland fire-fighting PPE is NFPA 1977, *Standard on Protective Clothing and Equipment for Wildland Fire Fighting.* The use of PPE certified as compliant with NFPA 1977 is required by NFPA 1500 for all wildland fire-fighting operations. The PPE includes, as a minimum, the protective shirt, pants, helmet, gloves, and footwear (Figure 12.9.2). In addition, PASS certified as compliant with NFPA 1982 is also required.

STANDARDS ON PPE FOR RESPIRATORY PROTECTION

Self-Contained Breathing Apparatus (SCBA)

Self-contained breathing apparatus (SCBA) are required for all fire-fighting operations except wildland fire-fighting operations, as well as for any emergency incident operations where IDLH (immediately dangerous to life and health) atmospheres or oxygen-deficient atmospheres exist or are anticipated, including CBRN terrorism incidents, confined space rescue, hazardous materials emergencies, and certain technical rescue operations.

Both SCBA and supplied-air respirators (SAR, also called "airline respirators") are of the "atmosphere supplying respirator" family in which the respirator supplies the user with breathing air from a source independent of the ambient atmosphere.

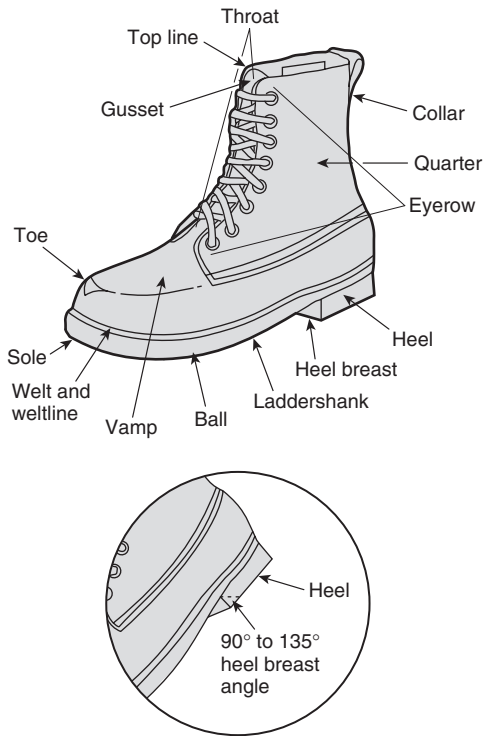

FIGURE 12.9.2 Footwear Terms (Source: NFPA 1977, *Standard on Protective Clothing and Equipment for Wildland Fire Fighting,* Figure 6.4.3, 2005, p. 1977-27)

SARs provide breathing air from a source that is *not* designed to be carried by the respirator user, while SCBA provide breathing air from a source that *is* designed to be carried by the respirator user. Where SARs incorporate a continuous air-line breathing air supply, and the SAR component is an integrated part of an SCBA that has a rated service time of at least 30 minutes, such SCBA/SAR can be used by emergency responders for extended duration operations, or for an increased exit time from the hazardous atmosphere.

There are two types of SCBA: open-circuit and closed-circuit. Open-circuit SCBA are respirators from which exhaled breath is vented to the atmosphere and is not rebreathed; closed-circuit SCBA are respirators in which exhaled air is rebreathed by the wearer.

Positive-Pressure and Demand SCBA

Positive-Pressure SCBA. All SCBA are classified as either positive pressure (also called pressure demand) or demand. OSHA regulations and NFPA standards require use of only positive-pressure SCBA for any IDLH or potentially IDLH atmospheres including structural fire-fighting operations. The use of demand SCBA for such operations is prohibited. The use of only positive-pressure SCBA became mandatory in the United States on July 1, 1983.

During normal use of positive-pressure SCBA, a positive pressure during inhalation and exhalation is maintained inside the facepiece in relation to the ambient atmospheric pressure. This positive pressure reduces the inward leakage of a contaminated atmosphere around the perimeter of the facepiece, but the positive-pressure feature cannot be construed to take the place of proper facepiece fitting and fit testing for each user. The positive-pressure feature cannot and will not compensate for any interference with the facepiece-to-face seal, such as from beards or other facial hair or from facial deformities, from eyeglass temple bows or straps, or from any other condition that passes through the area where the facepiece seals with the face, thereby preventing a proper facepiece-to-face fit.

Demand SCBA. Because demand SCBA operates on the principle of requiring negative pressure (inhalation) to initiate and maintain breathing airflow, OSHA regulations and NFPA standards do not permit use of demand SCBA for fire-fighting or other IDLH operations. The danger of the atmosphere surrounding the facepiece (the contaminated atmosphere) being drawn into the SCBA facepiece is significant.

Open-Circuit SCBA. Of the two types of SCBA, open-circuit is the SCBA where the exhaled breath is vented to the atmosphere and is not rebreathed. Open-circuit SCBA use an expendable source of breathing air that is stored under pressure in a cylinder. The breathing air is made available to the user through a regulator that automatically functions to reduce high air-storage pressures to lower usable pressures and to supply this breathing air to the user.

Open-circuit SCBA use compressed breathing air cylinders and are available in pressure systems from 2216 psi (15,279 kPa), 3500 psi (28,132 kPa), to 4500 psi (31,027 kPa). Regardless of the system pressure, all SCBA should be equipped with carbon filament or composite breathing air cylinders that are rated with a 30-minute or greater service life. The advantage of the carbon or composite breathing air cylinders is a significant lower weight achieved by the cylinder design. High-pressure systems have smaller cylinders that have less bulk and provide a smaller profile than a conventional pressure cylinder. Whereas the 2216 psi (15,279 kPa) cylinders can provide a rated service time of 30 minutes, the 3500 psi (28,132 kPa) cylinders can provide a rated service time of 45 minutes, and the 4500 psi (31,027 kPa) cylinders can provide a rated service time of 60 minutes.

Closed-Circuit SCBA. The second type of SCBA, closed-circuit, is the SCBA in which the exhaled air is rebreathed by the wearer. These SCBA recirculate the user's exhaled gas. The exhaled breath passes through an exhalation hose and through a carbon dioxide absorber, where the carbon dioxide is removed. Then it enters a breathing chamber, where it is mixed with additional oxygen from an oxygen source that is stored under pressure in a cylinder, and it is then available for inhalation. Closed-circuit SCBA can have a rated service life from 30 minutes to 4 hours.

OSHA and National Institute of Occupational Safety and Health (NIOSH) Regulations

Respiratory protection standards in the United States have recognized that unknown types and quantities of toxic elements of the products of combustion encountered during fire fighting do not allow the selection of different respiratory protective equipment for different exposures, as is often the case in the industrial environment. These atmospheres are classified as IDLH and require SCBA for respiratory protection.

OSHA has utilized National Institute of Occupational Safety and Health (NIOSH) and other OSHA regulations to establish minimum requirements for fire fighter respiratory protection. The OSHA *Fire Brigade Regulations,* 29 CFR 1910.156, requires the use of only positive-pressure SCBA that are certified by NIOSH under 42 CFR 84 and have a minimum rated service life of at least 30 minutes. OSHA requires that only positive-pressure SCBA be used during all structural fire-fighting operations; at all hazardous materials incidents; in oxygen-deficient atmospheres; in areas such as sewers, confined spaces, and silos; and wherever a hazardous or oxygen-deficient atmosphere may exist.

Nothing can be allowed to be in or pass through the area where the facepiece-to-face seal is made. Therefore, beards, drooping mustaches, long or wide sideburns, or other facial hair at any point where the face seal with the respirator facepiece is to occur or the wearing of eyeglasses with temple bows or straps are prohibited for persons who are required to use SCBA. OSHA has ruled (February 15, 1990) that ". . . these conditions have been shown to prevent a good facepiece-to-face seal, so that use of an SCBA by a person with any of the noted conditions (i.e., beards, drooping mustaches, long or wide sideburns, and other facial hair, temple bows/straps) is in violation of OSHA regulation 29 CFR 1910.134 (e)(5)(i), *regardless of what fit test measurement can be obtained.*" In addition, persons with conditions

such as severe skin pitting, loss of teeth, facial deformities, skull caps or head gear, or any other conditions or devices that prevent a proper facepiece fit are prohibited from using SCBA. SCBA manufacturers offer special prescription lens/frame assemblies that can be affixed inside the facepiece and do not affect the facepiece-to-face seal.

Breathing Air Cylinder U.S. Department of Transportation (DOT) Regulations

Compressed gas cylinders for breathing air are regulated in the United States by the Department of Transportation (DOT). U.S. federal regulations for the construction, testing, and maintenance of compressed gas containers are contained in 49 CFR 178, Subpart C. These DOT specifications apply to steel SCBA and large storage cylinders only. Cylinders constructed of manganese/steel and conforming to the preceding DOT specifications are designated by a DOT3A marking on the cylinder. Steel cylinders constructed of chrome alloy steel and meeting DOT specifications are designated by a DOT3AA marking on the cylinder, followed by the marked cylinder service pressure.

There are no specifications outlined in 49 CFR for composite cylinders. Therefore, the DOT developed special certifications known as "exemptions." DOT authorized composite cylinders to have a maximum service life indicated in the exemption. Most exemptions specify that composite cylinders have a maximum life of 15 years, but newer composite cylinders can have a longer designated service life. Composite cylinders that have a maximum life of 15 years are prohibited from being refilled after 15 years from the original hydrostatic test date. All U.S. retest facilities performing requalifications on composite cylinders are required by DOT to have a current copy of the cylinder's exemption available and must follow its instructions and conditions. DOT, which is the regulatory authority in the United States, specifies the cylinder requalification frequency of every 3 years for composite cylinders and the cylinder requalification frequency of every 5 years for all-metal cylinders. The organization/cylinder owner and retest facility are required by DOT to know how often to have the requalification performed. At this writing, DOT is considering changes to the requalification schedule for all cylinders, so changes to the previously noted cylinder requalification frequencies may be announced.

NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services*

SCBA Design. The product standard for respiratory PPE is NFPA 1981. The basic design and function of the SCBA must be certified by NIOSH in accordance with 42 CFR 84 as being positive pressure, having a rated service life of at least 30 minutes, and weighing no more than 35 lb (16 kg). Labeling of the SCBA must include the NIOSH certification plate and a certification organization's label denoting compliance with NFPA 1981.

SCBA Testing. Airflow performance testing measures the airflow that the SCBA can supply (Figure 12.9.3). Airflow must be provided to the wearer at 100 L/min volume without the facepiece pressure going negative during both inhalation and exhalation. The 100 L/min airflow exceeds the NIOSH certification requirement of 40 L/min volume.

Thermal cycle testing evaluates the proper function of the SCBA when exposed to various temperature extremes and tem-

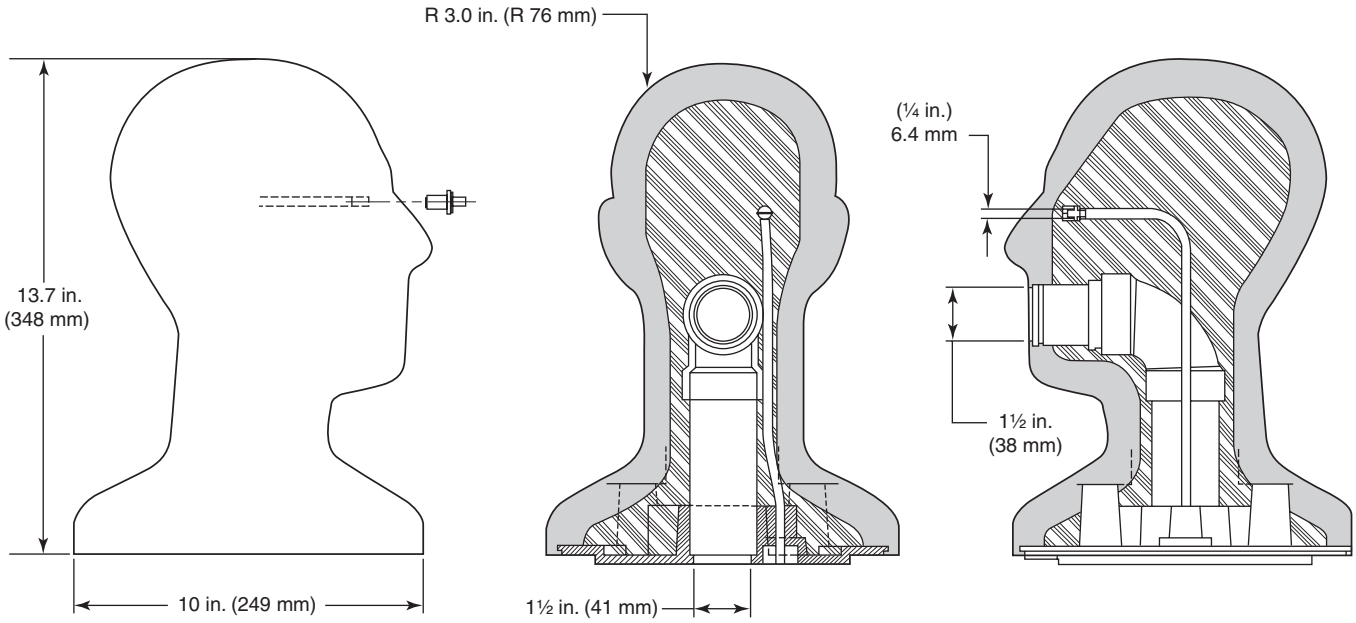

FIGURE 12.9.3 Test Headform (Source: NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services,* Figure 8.1.4.1, 2007, p.1981-23)

perature cycles through a series of four tests (cold-cold, hot-hot, cold-hot, and hot-cold).

Total heat and flame testing is tested for the entire SCBA. The SCBA, while mounted on a mannequin and attached to a breathing machine operating at 40 L/min, is conditioned for 15 minutes in a 203°F (95°C) oven. Immediately following the conditioning, the SCBA breathing rate is increased to 100 L/min and then exposed to a direct-flame contact that engulfs the entire SCBA for 10 seconds at temperatures between 1500°F to 2102°F (816°C to 1150°C), with an average mean of peak temperature at 1742°F (950°C). After this exposure, the SCBA is subjected to a drop test. Through the entire testing, the SCBA must operate as required by the standard, must not show any afterflame of the SCBA and all components beyond 2.2 seconds, must not shift from the proper mounting on the mannequin, and the facepiece lens must not obscure vision greater than 20/100.

SCBA are required to be equipped with a second independent End of Service Time Indicator, a heads-up display (HUD) that provides alerts and warnings on remaining breathing air supply, and a voice communications system in addition to the speaking diaphragm. Other performance requirements test for vibration and shock resistance, corrosion resistance, particulate resistance, fabric flame resistance, fabric heat resistance, and facepiece lens abrasion.

SCBA Certification. The 2007 edition of NFPA 1981, the sixth edition, introduced the major change of requiring all emergency services SCBA to also be NIOSH certified as CBRN SCBA in accordance with the NIOSH *Statement of Standard for NIOSH CBRN SCBA Testing.* This requirement will provide respiratory protection for CBRN terrorism agents (specified chemicals, biological agents, and radiological particulate) that could be released as a result of a terrorism attack.

Although major metropolitan areas may be more likely targets of a terrorist event, emergency responders from smaller communities away from urban areas could be called on to respond to urban areas where the emergency services have become overwhelmed by a terrorist incident and require assistance. Terrorists themselves may reside in small communities while they await their opportunity to strike. They may have the chemical, biological, or nuclear material in their possession, making the possibility of exposure greater for small rural areas. Terrorist attacks aside, CBRN-certified SCBA offers greater protection for the emergency services for a very minimal cost.

Protection from CBRN. CBRN protection offers verification of enhanced protection for emergency responders that is not otherwise available. Without CBRN protection evaluation, no SCBA components are tested for permeation, penetration, corrosion resistance, or other detrimental effects from exposure to toxic industrial chemicals during hazardous materials incidents and hazardous chemical warfare atmospheres. *NIOSH benchmark testing of non-CBRN hardened SCBA against CBRN agents demonstrated that chemical warefare agents (CWA) could cause catastrophic failures within minutes of exposure.*

The selection of the test challenge agents by NIOSH for CBRN protection was based on a comprehensive review of available technical data and consultations with other government agencies (e.g., Departments of Defense, Justice, Energy, etc.). Various chemical data lists were analyzed, including lists from EPA, ATSDR, NFPA 1994, U.S. Army Center for Health Promotion and Preventative Medicine (USACHPPM) Technical Guide 244, and classified sources. This review established a total of 151 toxic industrial chemicals and chemical warfare agents as potential candidates for challenge agents. The candidate agents were evaluated for permeation (molecularly diffusing through material) and penetration (seeping through interfacing components) characteristics as part of a review of their physical properties. This evaluation concluded that sarin (GB) and sulfur mustard (HD) could be selected as the two representative agents for the penetration/permeation test for the complete listing of 151 CWA and toxic industrial chemicals (TICs) due to their physical properties and molecular structure. NIOSH is unaware of any data that indicate the CBRN-certified SCBA provide less protection against TICs than their industrial counterparts.

The evaluation for CBRN protection provides verification and assurance that the component and material combinations in the approved SCBA configurations provide high resistance to permeation and penetration of hazardous atmospheres of toxic industrial chemicals and materials into the breathing air. This assurance is of importance to all responders who are subject to exposures of any hazardous industrial chemicals and materials.

Additional Safety Requirements. In addition to the CBRN requirement, new requirements were added to increase the safety to the users of emergency services SCBA and to better assure the proper functioning of the SCBA including the following:

- New breathing air cylinder retention requirement within the mounted position
- Mechanical voice diaphragm performance requirement increased to 80 percent minimum score at 5 ft (153 cm) distance
- New voice communications system with at least an 85 percent score at 10 ft (305 cm) distance
- New independent pressure gauge that would not be affected by failure of the HUD
- New water immersion requirements for electronic devices that are part of the SCBA that must function properly and remain watertight after exposures to 350°F (177°C) for 15 minutes and water submersion to 5 ft (1.5 m)
- New low power capacity requirements for electronic devices to assure that such devices will continue to function properly for at least 2 hours following activation of the lower power signal

The product standard for breathing air is NFPA 1989, *Standard on Breathing Air Quality for Fire and Emergency Services Respiratory Protection.* This standard provides requirements for breathing air quality of the overall respiratory protection program required by NFPA 1500. It covers testing frequency; qualifications for laboratories performing breathing air quality verification testing; breathing air quality levels for oxygen, carbon monoxide, carbon dioxide, condensed oil, and particulate content; hydrocarbon content; water concentration; and determination of odors.

The user standard for SCBA is NFPA 1852. This standard embraces the organizations' program for respiratory protection, the selection process for purchasing new SCBA, and the inspection, cleaning, care, repair, and removal from service of "in-service" SCBA.

Wildland Fire-Fighting Respiratory Protection Considerations

Wildland fire fighting is the only fire-fighting operation in which respiratory protection is not yet required. Concerns exist regarding the actual dangers of short- and long-term exposure to the products of combustion from wildland fires. Studies of air samples collected on wildland fire fighters and workers indicate potential for hazardous exposure (e.g., respirable particulate, carbon monoxide, formaldehyde, and acrolein). The health implications of short-term exposures and the potential health effects of long-term exposures are being studied.

It is current practice to consider wildfire smoke not IDLH, even though human health hazards have not been quantified. As a prudent practice, wildfire smoke exposure should be reduced. Fire fighters and crew supervisors should consider the level of smoke exposure of the tasks to be performed before committing personnel to action. Mitigation efforts could include short work periods, removal of crews from areas of heavy smoke concentration, rest periods with smoke-free air, or use of respiratory protection. Although SCBA offers the most complete respiratory protection, SCBA is not practical for use by wildland fire fighters who work for extended periods in remote locations. The weight of an SCBA, its limited use time, and breathing air cylinder recharging logistics make it impractical for use by wildland fire fighters.

A high-efficiency particulate air (HEPA) filter-equipped, air-purifying respirator could be considered an option for the filtration of respirable particles from the air to be breathed. The addition of sorbents to remove selected gases and vapors (e.g., P100 high-efficiency particulate filter plus organic vapor [OV] and acid gas [AG]) could also be an option when greater exposure is anticipated, as in a direct attack on a fire. Particulate respirators remove the irritation and make breathing seem easier, but they do nothing to protect from carbon monoxide (CO).

Any respirator being considered for use by wildland fire fighters must be NIOSH certified. Care should be exercised in the use of NIOSH-certified respirators because they have not been tested for heat resistance and flammability of the filter medium and have not been evaluated for their ability to provide protection from the products of combustion of wildfires.

STANDARD ON PPE FOR PERSONAL ALERT SAFETY SYSTEMS (PASS)

Personal alert safety systems (PASS) encompass devices that are known by several names, including personal distress alarm devices, personal distress locators, personal alarm locators, personal alarm monitors, and personal alarm devices. The concept of PASS involves several distinct features. The alarm signal must be able to be activated manually by the user. The PASS must also contain a sensor that senses movement or the lack of movement. The alarm signal must be capable of being activated automatically through interaction with the sensor under a specified series of events. PASS must also have a prealarm signal to prevent false alarms by alerting the user that the sensor has not sensed motion of the user and has activated the automatic alarm signal sequence.

Despite popular belief that PASS are a required part of "fire fighters' SCBA," PASS are not required to be (but can be) integrated with SCBA. PASS can also be a stand-alone device worn on part of the emergency services person's protective clothing. PASS can also be integrated with several items of protective clothing or equipment to enhance the sensing abilities over a wider area of the body, locate the sounders where the users can better differentiate between signals from their PASS and from other PASS, and disperse the weight and power sources over a greater area.

Automatic Notification

Emergency response personnel can become incapacitated during operations and might not be noticed by other members of the crew. These personnel may be aware that they need assistance and may be able to manually activate the alarm. If they are suddenly stricken, however, the automatic alarm must activate and call for assistance. Fire fighters, especially, can become trapped or disoriented in fire-fighting situations and can lose contact with others in their crews. They frequently behave in a disoriented manner as they attempt to escape. This scenario is particularly associated with fire fighter deaths caused by smoke inhalation. Even with the use of SCBA, fire fighters face similar dangers if they operate beyond the time limits of their breathing air supply.

Emergency services personnel need the capability to contact other workers at the emergency scene when they are in need of assistance. Equipping each member assigned to an emergency operation with a portable two-way radio is one approach, but automatic notification that could summon help if the member became incapacitated would still not be provided by today's portable radios.

Applicability of PASS

Although PASS are generally associated with fire fighters for use during emergency operations, PASS protection applies to all emergency services personnel who operate in hazardous environments where they could become entrapped or incapacitated and need assistance. Hazardous materials, emergency medical, technical rescue, skilled trades, and even, for certain operations, law enforcement personnel should use PASS where their safety and well-being can be easily compromised. Confined space, structural collapse, extrication, limited access, complicated area or building layouts and floor plans, and atmospheres that could become IDLH are some of the many emergency operations working environments where PASS should be used.

NFPA 1982, *Standard on Personal Alert Safety Systems (PASS)*

The product standard for PASS is NFPA 1982. PASS performance requirements test for intrinsic safety, corrosion resis-

tance, case integrity, temperature cycling resistance, temperature shock resistance, dust and particulate resistance, immersion and leakage, radiant heat resistance, flame resistance, impact resistance, retention system durability, and water drainage.

National Institute for Occupational Safety and Health (NIOSH)

During the work on the fifth edition of NFPA 1982, the committee addressed reports from the National Institute for Occupational Safety and Health (NIOSH), Division of Safety Research, regarding its investigations of fire fighter fatalities where there was evidence that the PASS alarm signal failed to function or was not heard by other personnel in the area and in some instances that there was water ingress to the electronic components that would diminish or cancel the alarm signal. The National Institute for Standards and Technology (NIST), Building and Fire Research Laboratory, partnered with NIOSH to characterize the performance of PASS devices in the fire-fighting environment. NIST determined that exposure to high-temperature environments caused the loudness of the alarm signal to be reduced. This reduction in loudness may cause the alarm signal to become indistinguishable from background noise of the emergency scene. Initial laboratory testing by NIST highlighted that this sound reduction may begin to occur at temperatures as low as 300°F (150°C). All PASS devices that were evaluated experienced significant alarm signal degradation at temperatures between 300°F and 500°F (150°C to 260°C). As the PASS cooled, the alarm signal on most of the units returned to preexposure sound levels.

NIOSH and others also noted that water ingress did occur or could have occurred in several cases, causing the alarm signal to cease to function with any effectiveness, but that after the PASS electronics dried, the alarm signal might again function.

These issues and others caused significant changes to the requirements, including the following:

1. Water immersion requirements and testing where PASS are exposed to 350°F for 15 minutes and then to water submersion in 4.9 ft (1.5 m) and also for 15 minutes for each of six cycles. It is then tested to determine that all PASS signals and electronic data logging function properly. Following this, PASS are reimmersed in the test water with the power source compartment(s) open for 5 minutes, and the electronics compartment is opened and examined to determine no water ingress.

2. High-temperature resistance and functionality requirements and testing procedures where PASS are exposed to 500°F (260°C) for 5 minutes. The PASS alarm signal must function at or above the required 95 dBA sound level for the required signal duration, electronic data logging must operate properly, and no part of the PASS can show evidence of melting, dripping, or igniting.

3. Tumble-vibration requirements and testing in which PASS are tumbled in a rotating drum for 3 hours and the PASS alarm signal must function at the required 95 dBA sound level and electronic data logging must operate properly

4. Requirements to prevent muffling of the alarm signal where PASS are evaluated in five positions (face down with arms extended, supine left, supine right, fetal right with knees drawn to chest, and fetal left with knees drawn to chest), and the alarm signal must function at or above the required 95 dBA sound level in each of the positions

Limitations of PASS

Users of PASS, whether or not the PASS were certified as compliant to editions of NFPA 1982 prior to the 2007 edition, are cautioned that PASS can fail to sound the alarm signal at the 95 dBA sound level, sound the alarm signal at an insufficient volume to make it audible from background noise on the emergency scene, or not sound the alarm signal at all. PASS could also have alarm signal muffling, water ingress, and vibration issues, all of which can negatively affect the ability of PASS to function properly and signal for help.

Despite PASS, there have been too many fire fighter fatality incidents in which fire fighters became entrapped, lost, or disoriented while performing interior structural fire-fighting activities. In these incidents, many of the fire fighters were wearing PASS devices but had failed to turn them on. The current edition of NFPA 1982 requires automatic activation of PASS, including remote activation, tethering, and integrating PASS with SCBA so that the PASS will be automatically activated when the air supply is turned on.

PASS cannot substitute for an individual's common sense, just as it cannot substitute for an active incident management system, close supervision of operating crews, communications, and a functional and adequate personnel accountability system to ensure that the assignment and location of each fire and emergency services personnel are known at all times. Although the addition of a PASS device does not guarantee safety, it is an important component to the fire fighter's personal protective ensemble.

STANDARDS ON PPE FOR EMERGENCY MEDICAL SERVICES

When emergency services personnel perform emergency medical services (EMS) or otherwise might be exposed to blood or other body fluids, these personnel must be provided with EMS PPE. OSHA regulation 29 CFR 1910.1030, issued March 6, 1992, sets the requirements for all emergency responders, health care workers, and others for appropriate actions to prevent contact with blood-borne pathogens.

Appropriate Clothing and Equipment

The U.S. Centers for Disease Control and Prevention (CDC) *Guidelines for Public Safety Workers* discusses the selection and use of appropriate clothing and equipment during medical emergencies. CDC recommends that disposable gloves be worn by all personnel prior to initiating any emergency patient care tasks involving exposure to blood or body fluids. Extra pairs of gloves should always be available. For multiple victims, gloves should be changed between patient contacts.

Gloves contaminated with blood or other body fluids to which universal precautions apply should be removed as soon

as possible, taking care to avoid skin contact with the exterior surface. The use of gloves does not eliminate the need to wash hands after emergency medical incidents. Hand washing is one of the most important elements of infection control.

Masks, eyewear, and gowns should be present on all emergency vehicles that respond or that might respond to medical emergencies or victim rescues. These items should be donned by all personnel prior to any situation in which splashes of blood or other body fluids to which universal precautions apply is likely to occur. Finally, contaminated gloves should be placed and transported in bags that prevent leakage and disposed of properly. In the case of reusable gloves, they should be cleaned, disinfected, and stored properly.

Because of the risk of salivary transmission of other communicable viruses and bacteria (e.g., herpes simplex and Neisseria meningitides, respectively) and the risk of HIV and hepatitis B and C transmission during artificial ventilation of victims, the use of mechanical respiratory-assist devices, such as bag-valve masks and oxygen-demand valve resuscitators, or pocket mouth-to-mouth resuscitation masks (i.e., double lumen systems), designed to isolate emergency response personnel from victims' blood and blood-contaminated saliva, respiratory secretions, and vomitus, is strongly recommended.

NFPA 1999, *Standard on Protective Clothing for Emergency Medical Operations*

The product standard for EMS PPE is NFPA 1999, which is the only standard, both from within and outside the emergency responder community that includes performance tests to ensure that each type of PPE has a barrier against penetration of blood-borne pathogens. The standard requires penetration resistance to body fluids and blood-borne pathogens that personnel can be exposed to during EMS functions. The EMS PPE barrier materials, including seams, are exposed to a bacteriophage suspension of a liquid inoculated with *E. coli* C bacteria for 1 hour. Materials are tested in both directions and cannot allow any penetration of the bacteriophage. EMS PPE items must also meet performance requirements for liquidtight integrity, material strength, physical hazard resistance, seam strength, and closure strength.

NFPA 1999 covers EMS PPE items, including garments, both full and partial, upper and lower torso protection; three types of gloves, examination gloves for patient care, work gloves for situations that pose higher physical hazards such as extrication, and cleaning gloves for handling and cleaning contaminated EMS equipment; footwear; and face protection. EMS PPE must provide the barrier protection to whatever parts of the body they cover. Although no partial protection is allowed for the EMS PPE item, the items might be configured to cover only part of the upper or lower torso, such as arms with sleeve protectors, torso front with apron-styled garments, face with faceshields, and so on.

EMS PPE face protection must meet requirements for liquidtight integrity in those areas of the facewear that are designed to provide biological protection.

For mass casualty incidents where civilian victims could self-present at medical care facilities without having been decontaminated by emergency services personnel at the incident scene, medical first receivers should have PPE protection so they can function and give care without themselves becoming victims. All of the PPE covered by NFPA 1999 will provide blood-borne pathogen protection for these personnel as well.

NFPA 1581, *Standard on Fire Department Infection Control Program*

The existing user document is NFPA 1581. (There is no PPE SCAM document at this time.) This standard is a comprehensive document on infection control and requires that the organization provide EMS PPE for each of its members for use while performing EMS operations. EMS PPE includes single-use gloves, fluid-resistant clothing, pocket masks, splash-resistant eyewear, respiratory-assist devices, approved sharps containers, and leakproof bags. It also establishes standard operating procedures for the selection and use of the appropriate EMS PPE for the specific hazards of each incident.

STANDARDS ON PPE FOR HAZARDOUS MATERIALS OPERATIONS

Anyone involved in a hazardous materials incident must be protected against potential hazards. The purpose of PPE is to shield or isolate individuals from the chemical and physical hazards that may be encountered during hazardous materials responses. Structural fire-fighting protective clothing and equipment, even when certified to the NFPA standard, provide little or no protection against hazardous materials and should not be used for hazardous materials incidents.

EPA Levels of Protection

The EPA has outlined four levels of hazardous materials protective clothing and respiratory protection: A, B, C, and D. The EPA defined these levels of protection primarily for workers at hazardous waste sites, where emergency conditions do not usually exist. These levels are commonly, and often inappropriately, utilized by emergency responders.

Although EPA levels of protection might be used as the starting point for ensemble selection, each ensemble must be appropriate for the specific situation. Ensemble design or configuration alone is not sufficient to ensure adequate protection. In other words, just having the right components to form an ensemble is not enough. The EPA levels of protection do not define what performance the selected clothing or equipment must offer.

Degree of Coverage

For emergency response, the only acceptable types of protective clothing are fully encapsulating suits, or totally encapsulating suits, and nonencapsulating or "splash" suits combined with accessory clothing items, such as chemically resistant gloves and boots. These descriptions apply to how the clothing is designed and do not apply to performance.

Hazardous materials protective ensembles should completely cover both the wearer and the wearer's respiratory pro-

tection. Wearing SCBA or other respiratory equipment outside the ensemble exposes it to the contaminated environment. SCBA used in hazardous materials emergency response is generally the same as that for fire fighting. In general, respiratory protective equipment is not designed to resist chemical contamination and should be protected from these environments.

NFPA Standards

The two product standards for hazardous materials emergencies PPE are NFPA 1991, *Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies,* and NFPA 1992, *Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies.*

NFPA 1991 requires that SCBA be worn on the inside of vapor-protective suits. NFPA 1992 allows liquid splash-protective suits to be configured either with the SCBA on the inside or the outside. However, it is strongly recommended that respiratory equipment be worn inside the ensemble to prevent its failure and to reduce decontamination problems.

The chemical resistance data provided by the manufacturer of the ensemble should be studied. Technical data packages are required to be provided by the manufacturers of protective ensembles that are certified to NFPA 1991 or NFPA 1992. Manufacturers of vapor-protective ensembles provide permeation-resistance data for their products, and manufacturers of liquid splash-protective garments provide penetration-resistance data for their products. Data should be provided for every primary material in the ensemble, including the suit or garment, hood, visor, gloves, and boots.

Permeation data should include the chemical name, breakthrough time (how soon the chemical permeates), permeation rate (the rate that the chemical comes through), and system sensitivity (comparison of test results from different laboratories).

Ensemble or ensemble element materials that show no breakthrough or no penetration to a large number of chemicals are likely to have a broad range of chemical resistance. If there are specific chemicals within the response jurisdiction that have not been tested, the manufacturer should be asked to supply test data on these chemicals.

The manufacturer's technical data package should document all the features of the ensemble and describe what materials are used in its construction. It should cite specific limitations for the suit and what restrictions apply to its use. Procedures and instructions should be supplied for at least donning and doffing, inspection, maintenance, storage, decontamination, and use.

Vapor-Protective Ensembles

NFPA 1991 covers vapor-protective ensembles that are designed to provide "gastight" and "liquidtight" integrity and are intended for response situations where no chemical contact is permissible or where the exposure is unknown. These ensembles now provide the mandatory requirements for CBRN protection at terrorism incidents where no chemical contact is permissible or where the exposure is unknown. Formerly, this was covered in the 2001 edition of NFPA 1994, *Standard on Protective Ensembles for Chemical/Biological Terrorism Incidents,* Class 1 ensemble requirements.

Performance testing includes permeation resistance to a specific battery of chemicals and gases selected as representative of the classes of chemicals encountered during hazardous materials emergencies. Vapor-protective ensembles must resist permeation by the hazardous materials present during a response. Permeation occurs when chemical molecules diffuse through the material, often without any evidence of chemical attack. Permeation resistance is measured in terms of breakthrough time of at least 1 hour or more. Chemical permeation resistance must be met for each chemical specified in ASTM F1001, *Standard Guide for Selection of Chemicals to Evaluate Protective Clothing Materials.* Any additional chemicals or specific chemical mixtures for which the manufacturer is certifying the ensemble must meet the same permeation performance requirements. Additional performance testing includes gastight integrity, liquidtight integrity, overall suit function and integrity, suit ventilation rate, and physical durability.

Liquid-Splash Protective Ensembles and Protective Clothing

NFPA 1992 covers liquid splash-protective ensembles that are designed to protect emergency responders against liquid chemicals in the form of splashes but not against continuous liquid contact or chemical vapors and gases. Liquid splash-protective ensembles and clothing can be used for protection with liquid chemicals that do not present vapor hazards. Materials that prevent liquid penetration can still allow chemical permeation since this PPE does not offer gastight performance, even if duct tape is used to seal clothing interfaces.

NFPA 1992 specifies a battery of liquid chemicals that are representative of the classes of liquid chemicals likely to be encountered during hazardous materials emergencies. Liquid splash-protective ensembles are for use only for protection from liquids with low vapor pressures and with no known skin absorption toxicity. Liquid splash-protective suits cannot be used for known or suspected carcinogens.

Performance testing includes penetration resistance to a specific battery of liquid chemicals selected as representative of the classes of chemicals that are encountered during hazardous materials emergencies. Penetration resistance is measured in terms of penetration resistance time. A chemical penetration resistance time of at least 1 hour or more must be met for each of the specified chemicals. Any additional chemicals or specific chemical mixtures for which the manufacturer is certifying the ensemble or clothing must meet the same penetration performance requirements. Additional performance testing includes liquidtight integrity, overall suit function and integrity, and physical durability.

Chemical, Biological, Radiological, Nuclear (CBRN) Incident PPE

Called weapons of mass destruction (WMD) by the military community, these or similar CBRN agents are expected to be used in attacks against civilian populations by terrorists. On the civilian side, these agents may take a different form and different concentration than WMD agents in battlefield conditions and are called CBRN terrorism agents.

First Responders. Civilian emergency response personnel will most likely be the first responders to see and be exposed to these terrorism agents. Support from federal government agencies, including the military, will be delayed due to several reasons, the least of which are not assembly and deployment time, transportation time to the incident site, or being committed to similar simultaneous attacks on military installations. Local fire departments, police and other law enforcement agencies, hazardous materials response teams, and emergency medical services providers will be the civilian response.

It is incorrect to view these local government agencies as the "first responders" if that is understood to mean they are involved in only the initial stages. Even though they will be the first to respond, they will remain the responders throughout the duration of the incident. Although, in the United States, state and federal agencies may respond, they will be present to assist and support the local jurisdiction and not to assume command and take over the operation and all the problems.

Because CBRN terrorism agents are intended to injure, incapacitate, or kill large numbers of persons, it is obvious the responders must rapidly identify such situations and protect themselves so that they may help others. PPE does exist for civilian responders to these incidents, and more PPE will be available as the technology progresses. Little of the current military WMD PPE can "transfer" to civilian responders as it is designed for military scenarios where it is used under significantly different environments, operations style, supervision, and deployment conditions.

Limitations to Protection. Civilian emergency response organizations must instruct their personnel that although existing PPE for fire fighting, EMS, or hazardous materials operations might provide some low level of dermal protection for a very short exposure, there is no evaluation or procedure to determine how much protection would be offered by each "in-service" PPE. The fact is that "in-service" (i.e., "used") PPE that is not certified as providing CBRN protection most likely will not provide any protection at all, or might provide only a few seconds of limited protection before the wearer could face severe or lethal exposures. The same problem exists for law enforcement agencies whose normal everyday PPE is not capable of protection from CBRN exposures.

NFPA 1994, *Standard on Protective Ensembles for First Responders to CBRN Terrorism Incidents.* NFPA 1994 is the product standard for CBRN terrorism incident PPE. Although this standard still covers the requirements for three classes of ensembles, the former NFPA 1994 Class 1 ensemble is now covered in the requirements of NFPA 1991.* NFPA 1994 now covers Class 2, Class 3, and Class 4 protective ensembles for CBRN terrorism incidents.

The 2007 edition is the second edition of NFPA 1994. As noted, NFPA 1994 no longer specifies a Class 1 ensemble, but has left the designation "Class 1" vacant. A new Class 4 ensemble was added to provide particulate protection for emergency responders to incidents where no chemical or biological agent is identified but where a particulate threat is present (including "white powder" incidents).

The CBRN protection requirements of NFPA 1994 apply to all emergency first responders at CBRN incidents. Individual agencies (law enforcement, emergency medical, medical first receivers, fire, hazardous materials, and skilled trades) need to define the operations for which their personnel are trained and develop detailed purchase specifications to assure the ensembles are designed to best support their operational needs while providing the CBRN protection.

All Class 2, Class 3, and Class 4 CBRN protective ensembles are required to be certified with a specific respirator certified by NIOSH as a CBRN SCBA, a CBRN APR, or a CBRN PAPR, or multiple CBRN respirators.

NFPA 1994 ensembles are intended to be pristine ensembles maintained in their own package until needed for use. They are intended to be single-exposure PPE and then discarded. These protective ensembles are intended for protection of fire, law enforcement, emergency medical, skilled trades, and other emergency services personnel responding to CBRN terrorism incidents or for emergency services personnel exposed to victims, materials, or the general incident environment during assessment, extrication, rescue, decontamination, triage, and treatment operations.

Ensemble Classes. The three classes of ensembles were developed for use in environments that can be generally described by considering the following:

- Exposure and delivery method
- Potential for skin contact
- Contaminant identification and concentration level
- Persistency (longevity) of the contaminant
- Threat of contamination and cross-contamination

Selection of the appropriate class ensemble must be based on a thorough risk assessment of the incident.

Class 2 and 3 ensembles are designed and tested for permeation resistance to chemical warfare agents and liquid industrial chemicals but at lower exposure rates commensurate with the intended protection level for the respective class. Class 4 ensembles are designed and tested for particulate inward leakage.

All ensembles are tested at exposure rates commensurate with the intended protection level for the respective class, inward leakage of exhaust valves, overall ensemble function and integrity, and for burst strength, puncture propagation, seam strength, closure assembly strength, visual acuity of facepiece or visor, maximum suit airflow, and cold weather performance.

NFPA 1991 (as discussed earlier) also specifies chemical and biological protection requirements for vapor-protective ensembles.

*Class 1 ensembles, the highest level of protection from vapor and liquid IDLH hazards, are intended for use at known or suspected CBRN incidents where the identity or concentration of the vapor or liquid is unknown, where most victims appear dead or unconscious and not ambulatory, or where liquid contact is expected, and no direct skin contact or inhalation can be permitted. These ensembles are now covered exclusively by NFPA 1991 vapor-protective ensembles. This high level of protection would be selected at incidents where exposure of personnel at these levels will result in the substantial possibility of immediate death, or immediate serious injury or illness, or the severe impairment of the ability to escape.

STANDARDS ON PPE FOR SPECIAL OPERATIONS

Technical Rescue Operations

PPE for technical rescue operations, including urban search and rescue (USAR), provides protection from physical, environmental, thermal, electrical, chemical flash fire, chemical splash, and blood-borne hazards. Technical rescue operations are commonly performed at incidents involving building/structural collapse, machinery or vehicle accidents, confined space entry, trench/cave-in rescue, and rope rescue. These operations include the functions of victim search, extrication, rescue, body recovery, and site stabilization.

Technical rescue PPE includes garments, helmets, gloves, footwear, and eye and face protection. The clothing portion of these ensembles might also be part of other PPE elements, such as a layer(s) or portion(s) of certain fire-fighting PPE, EMS PPE, and station/work uniforms.

The product standard for USAR and other technical rescue PPE is NFPA 1951, *Standard on Protective Ensembles for Technical Rescue Incidents.* The 2007 edition is the second edition of NFPA 1951. The document's title has been changed to *Standard on Protective Ensembles for Technical Rescue Incidents* to clarify that the standard applies to all emergency services organizations that perform technical rescue incident operations and not just to urban search and rescue (USAR) teams of state or federal governments. It embraces the broader audience of emergency responders for which these types of protective ensembles are developed to provide protection from the expected hazards common to these operations.

This edition specifies requirements for the following three different types of technical rescue ensembles:

1. A *utility* ensemble that provides protection from physical hazards and provides a basic flame resistance for the ensemble and the elements of the ensemble and provides a high level of "breathability" for the ensemble to aid in reducing heat stress for the wearers
2. A *rescue and recovery* ensemble that provides all the physical protection of the *utility* ensemble and in addition a blood-borne pathogen barrier to afford protection from infection from injured or deceased victims
3. A *CBRN* ensemble that, in addition to all the protections of the *utility* and *rescue and recovery* ensembles, also provides limited protection from chemicals, biological agents, and radiological particulates during terrorism incidents where chemical warfare agents or weapons of mass destruction could be used

It remains the choice of emergency services organizations to select the appropriate ensembles for the protection of their emergency responders based on the expected and anticipated technical rescue incidents to which their respective organizations will or could respond.

These ensembles do not apply to PPE for any fire-fighting operations or hazardous materials operations outside of CBRN incidents, due to the severity of those specific exposures. The standard also does not apply to PPE for wilderness search and rescue, water and swiftwater rescue, contaminated water diving, or cave rescue operations.

NFPA 1951 provides performance testing, depending on which ensemble is being evaluated, for total heat loss of garments, tear strength, fabric breaking strength, seam strength, and resistance to abrasion, corrosion, liquid penetration, flame, blood-borne pathogen, limited flash fire, and CBRN agents.

Life Safety Rope Operations

The life safety rope and system components covered by the NFPA PPE standard addresses a type of rope and system that are used to support the weight of emergency responder personnel and civilians during rescue, fire fighting, and other emergency operations, as well as during training for such operations.

Life safety rope is not a utility rope used to secure, raise, lower, or support equipment or machinery. Life safety rope and the system components are not intended for industrial fall situations or for recreational uses and are also not intended for lead climbing, mountain rescue, or cave rescue operations.

Life safety rope is not a dynamic rope; it is a static, low-stretch rope intended for use where the fall factor will not be greater than 0.25. The types of rope covered in the NFPA PPE standard are life safety rope, escape rope, and throwlines. Life safety rope is classified as light use or general use, depending on the minimum breaking strength.

Escape rope is a single-purpose, one-time use, emergency self-rescue (or self-escape) rope and not considered a life safety rope. A throwline is a one-person rope intended to be thrown to a person during water rescue or to tether rescuers entering the water.

The types of system components covered are auxiliary equipment including ascending devices, buckles, carabiners, descent control devices, load-bearing connectors, rapid links, rope grab devices, and snap-links; belts including escape belts and ladder belts; hardware including portable anchors, pulleys, and rings; Classes 1, 2, and 3 life safety harness; and software including anchor straps, pick-off straps, rigging slings, and webbing.

The product standard for life safety rope PPE is NFPA 1983, *Standard on Life Safety Rope and Equipment for Emergency Services.* NFPA 1983 provides performance testing of life safety rope, escape rope, throwlines, life safety harness, belts, auxiliary equipment, hardware, and softwear and includes breaking strength, minimum and maximum elongation, dynamic drop, static load, tensile, corrosion resistance, diameter, melting resistance, and colorfastness.

SUMMARY

Personal protective clothing and equipment play an essential role in the safeguarding of emergency personnel against the hazards of fire fighting. All NFPA product and user standards, including manufacture, cleaning, maintenance, and fit, must be adhered to in order to ensure effectiveness of protection. Fire fighters must be trained in the proper use of PPC and PPE and must also be informed of their limitations. PPC and PPE alone cannot ensure safety from hazardous exposure and must be considered only

one factor in a defense system that includes physical fitness, well-planned emergency procedures, and teamwork.

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Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire and emergency service protective clothing and protective equipment discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*
NFPA 1581, *Standard on Fire Department Infection Control Program*
NFPA 1851, *Standard on Selection, Care, and Maintenance of Protective Ensembles for Structural and Proximity Fire Fighting*
NFPA 1852, *Standard on Selection, Care, and Maintenance of Open-Circuit Self-Contained Breathing Apparatus (SCBA)*
NFPA 1951, *Standard on Protective Ensembles for Technical Rescue Incidents*
NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*
NFPA 1975, *Standard on Station/Work Uniforms for Fire and Emergency Services*
NFPA 1977, *Standard on Protective Clothing and Equipment for Wildland Fire Fighting*
NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services*
NFPA 1982, *Standard on Personal Alert Safety Systems (PASS)*
NFPA 1983, *Standard on Life Safety Rope and Equipment for Emergency Services*
NFPA 1989, *Standard on Breathing Air Quality for Fire and Emergency Services Respiratory Protection*
NFPA 1991, *Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies*
NFPA 1992, *Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies*
NFPA 1994, *Standard on Protective Ensembles for First Responders to CBRN Terrorism Incidents*
NFPA 1999, *Standard on Protective Clothing for Emergency Medical Operations*

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Chapter 10

Training Programs for Fire and Emergency Service Personnel

Jerry W. Laughlin

Chapter Contents

Need for Training
Organization of Training Delivery
Ensuring Quality Instruction
Internal Training Programs
External Training Sources
Training Safety
Training Records

Key Terms

blood-borne pathogen, distance learning, education, fire fighter safety, fire service instructor, Hazardous Waste Operations and Emergency Response (HAZWOPER) Standard, job performance requirement (JPR), learning, live fire training, National Fire Academy training

This chapter is an overview of the broad challenge of providing training for fire and emergency service personnel. The challenge includes a continuous need for training throughout an individual's career. Changes in technology constantly affect the lives of fire fighters in many ways. New hazards evolve and create risks to the public and fire fighters, but technology also provides new ways to deal with the risks. Training helps sort out the differences.

Acquiring and maintaining a high level of training in fire and emergency service personnel is more than a matter of efficiency; it can at any moment become a matter of personal survival. When a fire fighter responds to an emergency incident, a situation is already out of control. With a shortened time to think things through, rapid emergency response makes effective training more important.

In a world of highly specialized medical, legal, and other types of professionals, fire fighters must also remain generalists ready to respond to a bewildering variety of emergency incidents. The next emergency response could be for a residence fire or a high-rise fire, a hazardous materials spill or an explosion, a vehicle rescue or a swiftwater rescue. The response could require checking on a smell of smoke, fighting a raging fire that threatens a structure's stability, or handling a terrorist incident with mass casualties. The call could be for a rescue in an underground confined space or high on the side of a cliff. Training for each response is complex, and the skills needed must already be learned before the current emergency.

For related topics, see Section 4, Chapter 1, "Human Behavior and Fire"; Section 12, Chapter 2, "Organizational Benchmarking and Performance Evaluation"; and Section 12, Chapter 14, "Fire Rescue Stations and Fire Service Training Centers."

NEED FOR TRAINING

Personal Training

Health Education. The difficulty of maintaining a public service for 24 hours every day and the potential need to respond to unlimited types of service requests every day should be ample motivation for fire and emergency service personnel to expect and deliver a high level of training. Even as the number of reported fires has decreased in the last 25 years,[1] the number of medical calls has increased. And even as the number of civilian deaths and injuries has decreased, the number of fire fighters who die or are injured on duty has remained at a level that is too high. Analysis of fire fighter deaths and injuries reveals a long list of training needs that should be addressed, and all of them should be revisited periodically.

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Between emergency alarms, there is a need for wellness training to increase the physical fitness of emergency responders. Almost half of all fire fighter deaths on duty are from sudden cardiac incidents.[2] There is ample medical evidence that known risk factors contribute to this high number of deaths.[3] Some risk factors cannot be changed, such as male gender and increasing age. However, most heart attacks suffered by fire service personnel are preventable. Wellness training that addresses modifiable risk factors is not difficult or expensive. Risk factors that can be influenced by training, diet, and exercise between emergency responses include smoking, high blood cholesterol, high blood pressure, physical inactivity, being overweight or obese, and diabetes.

Transportation Safety. Responding to emergency calls has the inherent risks of transporting personnel and equipment in heavy vehicles moving through other traffic. Training is clearly needed to improve awareness of these risks and to improve the skills needed to operate emergency vehicles. NFPA statistics show that "firefighters are more likely to die traveling to or from a fire than fighting one, and motor vehicles pose a greater hazard than flames."[4] Almost all of these vehicle deaths can be prevented by training personnel to operate emergency vehicles safely.

Although the fireground is as dangerous as it ever was, incident by incident, the decreasing total number of fires has been associated with a lower number of fatalities on the fireground over the last 25 years. Now less than a third of fire fighter deaths occur on the fireground.[5] However, it is again clear that the number of fire fighter deaths and injuries on the fireground could be reduced further through training.

Skill Sets. A single "routine" fire emergency incident calls for a complex set of fire fighter skills, and all fireground activities must be completed in rapid succession under stressful and physically demanding conditions. Without retraining, skills deteriorate. Continuing training is necessary to keep these important skills ready for instant use. A fire in the upstairs bedroom of a two-story house provides many examples of the complexity of needed fire fighter skills. Personnel must be trained and equipped to conduct a search for residents who may have been incapacitated by the fire or smoke. If a victim is found, training in emergency medical response is critical. Other personnel must be trained to rapidly provide water to quench the fire, using knowledge of water locations and skills for operating fire department pumps, hose, and nozzles. Other personnel must be trained to assess the buildup of heat and harmful smoke inside the structure and know how to make the right decision about ventilating the heat and smoke through a hole cut in the roof above the fire. All of these complex tasks must be coordinated by an incident commander trained in each of the different tasks, in the responsibilities of command, and in the details of overseeing all of the tasks underway at the same time.

It is clear that the tasks are not only numerous and complex but also highly specialized. Pump operators must have the experience needed to anticipate water needs at the fire. Every fire can have different hydraulic requirements, and the operator must be trained to adjust to every variable. The chemistry of fire and the nature of building construction must be considered by the person intending to ventilate a roof. Individuals must be well trained to use these numerous and specialized skills almost automatically. The success of every task on the fireground can be affected by how quickly the tasks can be completed. The speed of completing the tasks is affected by the level of training.

NFPA Requirements. National standards of competency further specify a personal need for training. NFPA 1500*, Standard on Fire Department Occupational Safety and Health Program,* requires training in many areas. An entire chapter of NFPA 1500 addresses training and education requirements as a department responsibility and as a personal responsibility. Paragraph 5.1.9 states: "As a duty function, members shall be responsible to maintain proficiency in their skills and knowledge, and to avail themselves of the professional development provided to the members through department training and education programs."[6]

Training as an Obligation to the Community

Communities choose to provide emergency response services for protection of the entire community. Communities then have expectations that the services will be available and effective when they are needed. In turn, fire and emergency service personnel have an obligation to develop and maintain appropriate skills. When a citizen's life, family, or property is threatened, fire fighters who perform well under these difficult conditions will earn the highest respect and admiration for the fire department, and community support of the department will be strengthened. But when fire fighters are not trained well enough to perform as expected, community respect and support can disappear. Many times the difference is in the training that the responders have received.

Training is not a one-time event. Knowledge and skill levels must be repeated in order to be maintained. Given the variety of incidents that a fire department may face, many types of fires are not frequently encountered. It is the same with hazardous materials that may be released. Each incident can be significantly different, and considerable time can elapse between similar incidents. Experience alone, therefore, is not enough to keep skills well practiced and ready for instant use. Continuing training is required to prevent degradation of skills.

In addition, new challenges can emerge as manufacturers invent ways to combine chemicals to develop useful new products. During the transportation and storage of chemicals that occur before they are combined, the chemicals can burn, explode, or escape their containers and thereby endanger the populace. If a leak or explosion occurs, fire fighters and hazardous materials response teams must respond. The evolving use of chemicals is yet another situation that forces emergency responders to stay well trained. In addition, fire departments must also be ready to respond to terrorist incidents, which requires even more training.

Federal Requirements

Training increases fire fighter safety, helps fire fighters meet the community's expectation for effective emergency response, and prepares fire fighters for the evolving world around them

that presents frequent new challenges. Training is also mandated by federal requirements. These rules are the result of demonstrated problems that have adversely affected the public or the emergency responders. Three important requirements relate to hazardous materials, respiratory protection, and communicable disease.

Hazardous Materials. The Occupational Safety and Health Administration (OSHA) developed hazardous materials regulations to increase safety in hazardous waste operations and related emergency response. Called HAZWOPER and officially designated as 29 CFR 1910.120, this federal regulation details the requirements of employers and responders to plan for and safely respond to emergency incidents. Training is specified for anyone who might respond: "Training for emergency response employees shall be completed before they are called upon to perform in real emergencies. Such training shall include the elements of the emergency response plan, standard operating procedures the employer has established for the job, the personal protective equipment to be worn and procedures for handling emergency incidents."[7] Refresher training is also specified: Employees trained under these requirements "shall receive annual refresher training of sufficient content and duration to maintain their competencies. . . ."[8]

Respiratory Protection. Fire fighter respiratory protection is required in federal regulation 29 CFR 1910.134. The regulation stipulates that employers, including fire departments, must provide breathing protection and training "when such equipment is necessary to protect the health of the employee. The employer shall provide the respirators which are applicable and suitable for the purpose intended."[9] The employer must also create a written respiratory protection program that includes "training of employees in the respiratory hazards to which they are potentially exposed during routine and emergency situations."[10]

Communicable Disease. The blood-borne pathogen federal regulation is intended to protect fire fighters and other employees from infections that could result from contact with another person's blood. This is Code of Federal Regulations number 29 CFR 1910.1030. For anyone who could have occupational exposure to blood-borne pathogens, the employer must provide precautions. Again, training is required: "Employers shall ensure that all employees with occupational exposure participate in a training program which must be provided at no cost to the employee and during working hours."[11] The training must be provided annually. Paragraph (g)(2) lists the training requirements.

State Requirements

Although every state might be expected to offer or encourage training for emergency responders, some states have specific requirements. Washington State, through the Department of Labor and Industries and the Washington Industrial Safety and Health Act, places clear responsibility for training on the employer fire department as follows: "The employer shall provide training and education for all members commensurate with those duties and functions that members are expected to perform. Such training and education shall be provided to members before they perform emergency activities. Fire service leaders and training instructors shall be provided with training and education which is more comprehensive than that provided to the general membership of the fire department."[12]

A further Washington State example addresses training frequency: "The employer shall assure that training and education is conducted frequently enough to assure that each member is able to perform the member's assigned duties and functions satisfactorily and in a safe manner so as not to endanger members or other employees. All members shall be provided with training at least annually. In addition, members who are expected to perform interior structural fire fighting shall be provided with an education session or training at least quarterly."[13] Live fire training in Washington is required to conform to NFPA 1403, *Standard on Live Fire Training Evolutions.*[14]

Other states also mandate that NFPA 1403 requirements for live fire training be followed. For example, Florida enacted such a law after suffering fire fighter fatalities during two live fire training incidents.[15] (See the section in this chapter entitled "Training Safety.") Through its Firefighters Occupational Safety and Health Act, Florida has long required fire fighter employers to "provide training and education for all fire fighters and supervisory personnel commensurate with those duties and functions that such fire fighters and supervisory personnel are expected to perform. Such training and education shall be provided to fire fighters and supervisory personnel before they perform any emergency activities or other activities requiring such training."[16] In other words, before a fire fighter can respond to any emergency, training must already have been provided. The law also states that the fire fighter must be able to perform any activity in a satisfactory and safe manner.

ORGANIZATION OF TRAINING DELIVERY

It might be argued that training for career and volunteer fire departments should be identical because fire behaves in the same way regardless of the kind of fire department that responds. There is merit in this argument, but real-world economics often results in different funding levels for a large-city career department and a rural volunteer department. Different funding levels, when they are present, affect the availability of instructor training, equipment purchases, and time devoted to training. Of course, there can be exceptions in which a volunteer department has greater funding and more commitment for training than a nearby career department. But the complexity of a large city always creates the necessity, if not the funding, for a more varied training program.

Career Departments

A career fire department has the ability to offer and mandate training in ways that a volunteer fire department might not. Larger departments are more likely to have the funding resources to maintain a complete fire training bureau with multiple instructors, ample technical and audiovisual equipment, and realistic training simulators. Smaller departments usually

have at least one individual dedicated to training activities for the department.

Career departments in large cities have the added challenge of a more variable fire and emergency risk. Transportation hubs can have a very high exposure from the large volumes of hazardous materials being stored or shipped into, out of, and through them. Most waterfront developments add more specialized risks while at the same time limiting access. In large cities, public assembly events are more likely to occur. Training must be made available to address these and other normal hazards of cities. With the usual higher funding for training in career departments, any failure to provide ample training would invite embarrassing press questions and public resentment concerning the funding that was invested but not used effectively.

Volunteer Departments

Volunteer fire training has its own unique challenges. Volunteer members have the added burden of a full-time job that often interferes with sufficient time for training. Volunteer departments protecting rural communities may have a very low level of response activity, which is fortunate for the community but allows fire-fighting skills to degrade from lack of frequent activity or practice. This in turn makes training extremely important.

Volunteer fire fighters often have fewer average years of experience in fire fighting compared to career fire fighters. The volunteer nature of their service and the demands of other primary jobs and families on limited free time make it harder for volunteers to sustain their service over many years. Training in the basics of fire fighting is a constant need in many volunteer departments, which can interfere with another vital need for specialized training in a variety of hazards that may be present even in a small rural community. Because the needs for training are so great and funding can be low, volunteer fire departments must be innovative to find ways to fund and offer continuous basic training. There is no excuse for any fire department lacking trained members to protect the public.

Comprehensive Training

A fire department's training program can be full service and comprehensive, minimal, or nonexistent, depending on available funds and the training orientation of the fire chief. A minimal or nonexistent training program should not be acceptable. Reports from the National Institute for Occupational Safety and Health (NIOSH),[17] describing the lessons learned from fire fighter fatalities in the United States, repeatedly list prevention warnings that indicate insufficient training. Each warning that follows is from a NIOSH report and describes actions that should have occurred but did not and contributed to a fire fighter fatality. Each of the following represents a training failure:

- "Instruct and train firefighters on initiating emergency traffic (Mayday—Mayday) when they become lost, disoriented, or trapped."
- "Ensure firefighters are trained to recognize the danger of operating above a fire."
- "Train on the SOPs, the incident command system, and lost firefighter procedures with mutual aid departments to establish interagency knowledge of equipment, procedures, and capabilities."
- "Ensure that firefighters from the ventilation crew and the attack crew coordinate their efforts."
- "Develop, implement, and enforce standard operating procedures (SOPs) on the safe operation of emergency vehicles which include the use of seat belts."
- "Ensure that all drivers of fire department vehicles receive driver training at least twice a year."
- "Ensure that the Incident Commander conducts a risk-versus-gain analysis prior to committing firefighters to the interior and continually assesses risk versus gain throughout the operations."
- "Ensure that firefighters train with thermal imaging cameras (TIC) and they are aware of their proper use and limitations."

These lessons from actual incidents demonstrate that any department needs a full-service comprehensive training program to best prepare its members for the dangerous conditions that they face. A fire department that cannot train its members to stay safe also cannot live up to the expectations of the community that depends on an effective response by the fire department.

Many fire departments have some training needs that are similar, such as the basic operation of water delivery, forcible entry, ventilation, use of personal protective equipment, and obvious others. Department needs can also be diverse according to the characteristics of the community protected. An urban department will have different training needs compared to a rural department. A community with heavy industrial risks requires different training than a community with mostly residential structures.

ENSURING QUALITY INSTRUCTION

Instructor Attributes

When a fire department commits to a full-service comprehensive training program to best protect its members and citizens, it will be necessary to consider the qualities of an instructor in order to adequately plan the training program and implement individual training classes. When the NFPA national standard on fire instructor professional qualifications, NFPA 1041*, Standard for Fire Service Instructor Professional Qualifications,* was first developed, it reflected on one message of the influential Wingspread fire service meeting in 1966: "Professionalism begins with education." The NFPA 1041 technical committee concurred and stated that "the quality of any educational program is only as good as its instructional staff."

The professional levels of competence of fire service instructors are the subject of NFPA 1041, which presents the following three levels of progression:

- A Level I instructor "has demonstrated the knowledge and ability to deliver instruction effectively from a prepared lesson plan, including instructional aids and evaluation instruments; adapt lesson plans to the unique requirements of the students and authority having jurisdiction; organize the learning environment so that learning is maximized; and

meet the record-keeping requirements of authority having jurisdiction."

- A Level II instructor is someone who, in addition to meeting Instructor I qualifications, "has demonstrated the knowledge and ability to develop individual lesson plans for a specific topic including learning objectives, instructional aids, and evaluation instruments; schedule training sessions based on overall training plan of authority having jurisdiction; and supervise and coordinate the activities of other instructors."
- A Level III instructor is someone who, in addition to meeting Instructor II qualifications, "has demonstrated the knowledge and ability to develop comprehensive training curriculum and programs for use by single or multiple organizations; conduct organization needs analysis; and develop training goals and implementation strategies."

A comprehensive full-service training program should have instructors who meet the requirements of this national standard to at least Level I. That means they have received training on the nature of instruction and have passed the standardized exam to demonstrate competence according to the national standard.

A certified fire service instructor has been exposed to learning opportunities related to communication skills, components of a lesson plan and how to use one, how to prepare and maintain training records, the laws of adult learning, learning styles, methods of instruction, organizing the learning environment, operation and maintenance of instructional equipment, test administration, skills checklists, the need for feedback, and the requirements of educational confidentiality.

It is possible for an experienced fire service instructor to be competent without the formal process of certification, but certification ensures that an individual's competence has been evaluated by more than one person. The best combination is experience and certification of competence to the established national standard of performance.

Nature of Learning

A proper training session is much more than someone standing up and talking about a fire service subject. Even being an expert in a fire service subject does not mean that the expert understands or is automatically good at instruction. Effective training instruction does depend in part on the instructor's subject matter knowledge and skills, but effective instruction also must consider the general principles of learning and the particular needs of adult learners. This statement sums up a body of educational research: "There is increasing evidence that the effectiveness of learning can be determined by the methods used to teach. In other words, the way material is presented has an effect on how well you understand and remember it."[18] Certainly the material must be understood and remembered so that it can be used when it is really needed during an emergency on the fireground.

Individuals in a group of seemingly similar fire fighters from a single department can differ significantly in how they learn best. This does not mean that instruction must be tailored for every variation in individual learning style. However, awareness of these learning style differences can increase the chances that the instruction can be tailored so that is actually useful to the greatest number of individuals who need to learn something new. Therefore, the subject matter expert does need to be aware of learning styles.

So-called laws of learning also can help the instructor to appreciate different impacts on learning. Many laws of learning were studied by Edward Thorndike in the 1920s and 1930s and have been further developed and confirmed through educational research in various other settings. Although they may have differing names,[19] these laws can be applied generally to the fire service.

Law of Exercise. The law of exercise is already frequently applied to the fire service. It states that a person learns best and retains information longer when there is a chance for meaningful practice and repetition during the learning. People learn by doing. Instructors use repetition, but they also make sure that the right skills are being practiced and that the practice is followed by positive feedback.

Law of Effect. When the instructor gives positive feedback following a student's demonstration of correct skills, the law of effect is being used. It states that learning is better when it results in satisfying consequences. This can include praise or any other type of reward that the student values. A positive effect is also present when the adult learner can immediately see the benefits from training. To a lesser extent, this law can have an undesirable result: If the attempt at learning is associated with negative feedback and frustration, learning can be weakened and less likely to persist. This can also be called the law of reinforcement.

Law of Relevance. Other researchers realized that learning is more effective when shown to be highly relevant to the learner's life and work. Fire service training generally follows this approach. Realistic training has higher relevance, which makes it tempting to provide for live fire training, but the overriding safety requirements should not be forgotten.

Law of Response Level. Students may sometimes grumble about their workload, but this law provides that students do only as much as is required of them. It states "learners master skills and knowledge at the level at which they are required to respond during the learning process." This should motivate instructors to maintain high standards and not let any training activity be performed casually, since people will tend to operate at the same level used in training.

Law of Emotional Learning. This law works well in the fire service training environment. It states that when learning events are accompanied by intense emotions, the learning will tend to be longer lasting. This law fits with highly realistic and even stressful training conditions. A variation is the law of intensity, which states that using an intensely vivid or realistic stimulus in learning will more likely result in a change of behavior. There is a limit to the application of this law. When the training scenario becomes too intense, it can become dangerous and interfere with learning.

Law of Expectations. This law states that learner attitudes affect what and how much they actually learn. They are more likely to learn when they expect the learning to be positive. This expectation can be influenced by personal history, course format, attitudes of fellow students, and instructor attitudes. Situations where students and instructors do not want to participate in the training usually result in low levels of learning.

Law of Recency. This law reminds us that recent learning is stronger than earlier learning. Memory deteriorates, which is why frequent retraining is necessary. Information and skills that are not being repeated are being replaced by whatever has been happening more recently.

This sample of the laws of learning makes the point that instructors can be more effective when they understand the fundamental conditions of the learning process. Fire service training may be mandatory, but the good instructor will not make it seem that way. Results are what count. As more schools are being held accountable for the learning of their students, they have started to change their emphasis from just teaching a subject to ensuring that actual learning takes place. This approach is also appropriate for training fire and emergency service personnel. Since the training often involves critical safety messages for fire fighters, it is clear that the instructors should not be satisfied with merely teaching a class; they must use various forms of assessment to ensure that the members are learning.

Evaluation of Learning

A weakness of much in-service fire training is that too often no effort is made to ensure that some learning has occurred and that some behavioral change will take place. In-service training is rarely accompanied by any testing to measure what was learned. The best evidence of learning comes from testing the subject knowledge or skill before starting the instruction and then retesting after the instruction. Comparison of the two results is a measurement of what was actually learned during the class.

Criterion-referenced testing is intended to measure what a person has learned compared to a specific body of knowledge (criteria). The learning can be measured by multiple-choice questions, fill-in-the-blank questions, demonstration, or performance of the skill that has been taught to ensure that it can be accomplished correctly. This kind of testing is included in certification courses for instructors, which again shows the value of formal instruction for instructors. It is unfortunate and potentially fatal for fire fighters to discover during an emergency incident that they did not actually learn some important material in a previous lecture.

Proper evaluation of learning does take extra time, but undiscovered substandard learning can be much more costly. Another aspect of evaluation is that care must be taken to make sure that the evaluation is accurate and valid. The importance of accurate evaluation of learning applies especially to certification courses where there can be serious consequences for failing the criterion-referenced test. State fire training agencies have the means to statistically check the accuracy of the tests they use. Taking the time and effort to properly evaluate learning is an obligation for any instructor or training program.

Education Versus Training

The terms *education* and *training* have different meanings, although they are often used interchangeably. The differences are more important as fire agencies become more complex and need more analytical management skills to build on the technical skills of manual fire fighting.

Fire and emergency training is designed to increase proficiency in a particular skill. Training can also be applied to increasing knowledge in a particular area. It starts with a performance objective that can be described specifically. It ends with the trainee being able to demonstrate an ability to perform according to the stated objective or, if the performance objective is not met, the instructional activity can continue. This can be described as a training loop, in which the instructor provides information input, the student is tested to demonstrate learning, and the instruction is revised as necessary to provide the proper input. A fire fighter certification class is an example of training.

Education is learning that provides the student with a foundation of general knowledge that helps in problem solving and effective thinking. Education involves learning to think and reason. Pursuing a college degree, with core courses in English, math, history, and psychology, is education, even when study in the major subject area results in increasing specific knowledge and skills. The overall process is education when it contributes to efficient analysis techniques.

Although they are different, education and training can be combined. Training by itself, when measured and successful, transfers established facts and skills. Then a behavior, such as ventilating a fire scene, is predictable within a generally defined range. Training by itself can be described as reflexive. The mental functions required to put training techniques into practice could be considered relatively passive when compared to educational analysis. Education provides ways for the student to further analyze and understand why and what kind of ventilation is appropriate for varying conditions. Fire scenes are not always confined to the defined range covered in the ventilation training. There could be, for example, unique reasons why ventilation is not the correct solution in a particular situation. With broader education combined with training, the fire fighter or fire officer can better observe and apply critical thinking and reach informed conclusions.

Education and critical thinking become increasingly important as an individual advances in rank within a fire department. College attendance is not the only way to acquire education, but it is the most efficient way. Improved critical thinking can be the result of long years of experience, but not everyone grows at the same rate from the same experiences.

National Fire Academy Superintendent Dr. Denis Onieal believes that the educational component is most important in considering the fire service as a profession. "Many feel that the distinguishing characteristics of a profession," he writes, "are years of formal education, approval of an accrediting board, and continuing education requirements."[20] Onieal calls for combining our localized systems of training and education into a national one in order to demonstrate a more convincing professionalism. He would integrate the following four existing parts:

1. Training systems now available through local and state agencies and the National Fire Academy (NFA)
2. Standardization of the education systems now available through 2-year and 4-year colleges and universities and through NFA
3. Independent assessment of skills now available through the Pro Board and IFSAC
4. Broader reciprocity among systems of training and education

INTERNAL TRAINING PROGRAMS

Recruit Training

Recruit training is the basic staple of fire service training. Although some fire fighters transfer in from other departments, the typical candidate is completely new to the fire service. Training for this individual must start at the beginning. Although it has been noted that different types of departments in different communities will have different overall training needs, the basic recruit training of any fire fighter should be the same. A fire in one room of a one-story home requires the same response skills whether the department is career or volunteer, suburban or rural.

The recognized standard of fire fighter performance when the duties are primarily related to structural fires is NFPA 1001, *Standard for Fire Fighter Professional Qualifications.* Most state fire training agencies and progressive fire departments use this standard for developing a recruit training course. The standard describes the minimum job performance requirements for fire fighters in the duty areas of communications; fireground operations; rescue operations; and prevention, preparedness, and maintenance. For the recruit fire fighter, there are 19 listed job performance requirements in the duty area of fireground operations, each with related requisite knowledge and skills.

NFPA 1001 also includes an annex with information on how to use the job performance requirements (JPRs) in curriculum development and training design and evaluation. According to Annex B: "The statements contained in this document that refer to job performance were designed and written as JPRs. Although a resemblance to instructional objectives might be present, these statements should not be used in a teaching situation until after they have been modified for instructional use. JPRs state the behaviors required to perform specific skill(s) on the job, as opposed to a learning situation. These statements should be converted into instructional objectives with behaviors, conditions, and standards that can be measured within the teaching/learning environment. A JPR that requires a fire fighter to 'ventilate a pitched roof' should be converted into a measurable instructional objective for use when teaching the skill."

In-Service Training

In-service training sessions are conducted during the normal departmental work shift. Depending on the equipment available as instructional aids, any type of fire service training can be done on an in-service basis. The understanding is that any emergency call or any administrative assignment coming from higher authority will take precedence, and the training will be interrupted until the emergency or the other assignment is completed. When interruptions occur, training effectiveness can be reduced. The in-service instructor is usually from within the department or may be an officer or other member of the crew receiving training. This arrangement has the advantage of being economical, since no additional costs are incurred by instructors who are already on the payroll. A disadvantage is that the training session can suffer from distractions that interfere with learning. Members of the public may enter the station during the training with questions for the officer or some member of the crew. The station phone may ring. After returning from an emergency call, the training may be cut short due to meals or previously scheduled assignments. Some good training can occur in an in-service setting, but it is not the ideal arrangement.

Specialized Courses

The nature of specialized training often involves more detailed planning, special equipment not available at each station, or multiple crews receiving the same training at the same time. Specialized courses are often conducted at a central location such as a training bureau. Rather than a shift supervisor conducting the training, as during in-service training, specialized courses may require specialist instructors. Examples of specialized courses are new training procedures that must be extended to all personnel in a short time frame (such as the adoption of the National Incident Management System), training for new equipment being brought into the department (such as an aerial device or a thermal imaging camera), and highly technical courses (such as surface water rescue or hazardous materials response).

Training for each of these examples should also include a method of assessment to confirm that the intended learning actually occurred and that the training was worthwhile. Also important for specialized courses is to add documentation of this specialized training to the permanent training record of every individual participating in the session (see the section in this chapter entitled "Training Records").

Special Operations Training

Numerous public events remind us of ever-present dangers that call for special operations training for incidents that are outside the realm of routine fire and emergency service duties. Examples can be seen in such diverse incidents as terrorist attacks, major transportation accidents involving hazardous materials spills and explosions, and natural episodes such as hurricanes and multiple tornadoes. Although such incidents occur infrequently, when they break, the demands on fire and emergency services can be the most challenging and expensive situations where the highest level of training is required.

The events of September 11, 2001, provide grim reminders of the threat of overwhelming terrorist incidents using weapons of mass destruction. The Oklahoma City bombing is evidence that the threats can be internal to a country as well as external. In any event the training preparation is the same. Federal funding has provided extended training opportunities, but it remains to be seen if permanent lessons have been learned about training and preparedness. The 9/11 Commission report expresses

concern that "We learned that the institutions charged with protecting our borders, civil aviation, and national security did not understand how grave this threat could be, and did not adjust their policies, plans, and practices to deter or defeat it." Will the fire service be better trained and better prepared next time?

Transportation of hazardous materials across the United States is routine but still results periodically in multiple fatalities. In 2004 and 2005, there were train derailments in South Carolina and Texas that resulted in the spillage of the same dangerous chemical, chlorine. Fire departments protecting communities along these railways did not have comprehensive response training complying to the requirements of NFPA 472*, Standard for Professional Competence of Responders to Hazardous Materials Incidents.* Transportation of chemicals may be normal, but emergency service response to spills of any dangerous chemical is not yet normalized. Much work is still to be done to train these responders.

Successive hurricanes force home the importance of special operations training for responding to major natural disasters. At the same time the range of needed training has greatly expanded. From hurricanes like Katrina, responders learned of the importance of backup systems for communications, basic supplies such as batteries, and personnel accountability. A hurricane is an example of the need for multiagency training, since the response will involve multiple overlapping jurisdictions.

Training Classrooms, Buildings, Grounds, and Equipment

It has been mentioned that during training, learning is reduced when there are distractions during the instruction. Distractions can include the occurrence of unrelated physical and noisy activities in the vicinity of the instruction that draw the attention of the student away from the instruction. Ringing phones, fire department radios, and normal fire station activity are examples. For many reasons, classroom training sessions need a proper classroom environment. Trying to conduct classroom-type instruction in an open fire station engine room is difficult. A separate classroom is preferred, with desks or tables for writing, audiovisual equipment, adequate lighting and ventilation, and access to the tools that might be part of the instruction.

NFPA 1402*, Guide to Building Fire Service Training Centers,* provides valuable information for functional and safe training environments. This document addresses facility components and planning considerations, classroom needs, drill tower construction and use, special structures for live fire and smoke training, and space and equipment for outside training activities. Mobile training units are also discussed.

Classrooms and Libraries. For classrooms, NFPA 1402 states that "classroom size is dictated by the number of students and the type of training to be conducted." The guide serves to remind users of some important considerations for training facilities without being overly restrictive. Most hands-on skills training requires more space than instruction that is lecture only. Audiovisual equipment to supplement instruction is important. A good instructional facility will have functional seating and writing surfaces, with a common example being tables and stacking chairs for greater flexibility. Lighting and ventilation need to be adjustable to maintain a comfortable learning environment.

A library of fire-related books and magazines is an essential part of fire service training. The library should include references for departmental regulations, procedures, and history. Copies of national standards should be included. Computers and Internet access are becoming common to all libraries.

Realistic Training Simulations. Drill towers, smoke rooms, and live fire training structures are expensive to build properly, but they are important for training in basic fire fighting. Training towers and smoke and burn rooms allow realistic training simulations that help build confidence in fire fighters. The height of the tower should be typical of the buildings found in the locale, according to NFPA 1402. The value of realistic training simulation also introduces an extra responsibility to consider safety during this training (see the section later in this chapter entitled "Training Safety"). NFPA 1402, paragraph 8.18, recommends that "consideration should be given to the need for an observation/control tower in order to monitor various training functions from one location."

To reduce the frequency of disruption of training due to department emergency response, equipment used for training should be exclusively for training. Otherwise, the training of out-of-service personnel would be interrupted if in-service equipment is taken out of the classroom to respond to an emergency. This is a waste of time that is more costly than the purchase of equipment dedicated for training purposes.

High-Tech Training Center. Most training centers have been in existence for many years. They may be intended to serve a single department's needs, or several departments in a county or region may cooperate to maintain a training center. Most state-level training centers have also been in existence for many years. One of the newest and most comprehensive training centers has been built for the Tarrant County College Fire Service Training Center in Fort Worth, Texas. This 23-acre, $18 million complex with a realistic, all-hazard cityscape provides an impressive number of scenarios for realistic training. This training center calls itself a "high-tech theme park for firefighters."[21] Figure 12.10.1 shows fire fighters engaged in realistic training exercises.

The cityscape at the college is indeed a small city with built-in associated hazards designed to allow challenging training while maintaining safety controls. There are residential, commercial, warehouse, and high-rise structures that add realism to training for size-up, exposure protection, and apparatus placement. A train derailment and 18-wheeler truck fire scenarios can be used, and there are sites for trench and confined space rescue. The center may have the only controlled swiftwater rescue site anywhere available for fire service training.

One of the main motivations for the training center design was to provide a live fire training environment without the safety risks of acquired structures. As a result, the Tarrant County College Fire Service Training Center is one of the largest computer-controlled, gas-fired facilities in the world, according to the school. It features six separate live fire buildings.

FIGURE 12.10.1 Realistic Training Exercises (Courtesy of Tarrant County College)

In addition to the real-world props across the property, there is a 48,000 ft^2 (4460 m^2) classroom and administration building. A high-tech command and control center occupies the third floor, where operators can program, initiate, and monitor all training activities. Control has been emphasized throughout the complex. At the swiftwater site, the "river" flow can change from 80,000 gallons per minute (302,400 L/min) to a trickle with the turn of a switch.

The price tag of the Tarrant County College Fire Service Training Center means that the fire service cannot expect to see these facilities popping up everywhere, but it does represent what is possible in realistic training.

EXTERNAL TRAINING SOURCES

State Fire Training Agencies

Many states have designated an official agency to provide training for fire and emergency personnel throughout the state. In most cases there is a similar legislative authority, but there are significant differences in how state fire training agencies are funded. Fire fighter training is mandated in some states and is voluntary in others. With more funding, state fire agencies typically are able to offer more services.

The earliest state training programs focused almost exclusively on the basic skills of using hose and ladders and operating fire pumpers. Since fire departments in larger cities usually had staff to operate their own training sections, state fire training was often aimed at smaller departments that did not have the resources for a separate training staff. Individual state instructors, many of them retired fire fighters from larger cities, commonly traveled around a state and offered skills training to rural fire departments. The training was informal and the quality varied, depending on the experiences and abilities of the instructor.

Concerns about the adequacy and inconsistency of fire department training activities began to be expressed more forcefully by fire service leaders in the late 1960s. These concerns led to more calls for a set of performance standards to be used for acceptable levels of training and professionalism. Today, the core of most state fire training agencies involves more formal courses based on national standards rather than state or individual preferences.

Starting in the 1980s, state agencies began increasing use of NFPA's national professional qualifications standards to guide training. The use of a national standard was an idea that state political leaders could understand and support and has been accompanied by a rise in the funding for and importance of state certification authority and national accreditation. The organization of state training directors is the North American Fire Training Directors (http://www.nftd.org).

Certification. Certification in state training programs implies valuable benefits for students and for the departments sending the students for training. Certification is a written assurance to the student, the sponsoring fire chief, and the home community that the student conforms to specified requirements. Students should understand the different meanings of certification so that they can assure themselves that they are getting the training that they and their departments need.

The basic meaning of certification may be represented by a certificate of attendance, which usually indicates only an assurance that the student was present when a course of instruction was presented. With a certificate of attendance there is no automatic assurance as to the specific content of the course. There is no measurement of actual learning, such as an exam. One may infer the course content from the title, and there may be a course outline, but there is no accountability for skills learned. A student's experience in class could be passive with limited learning, but the student might still qualify for a certificate of attendance. To be more informative, this certification should specify the length of attendance in the course.

When a course has more requirements than simple attendance and it includes an examination of some kind to measure learning, the result for successful students who demonstrate minimum learning may be a certificate of completion. A person evaluating such a certification would need to know how course completion was defined. A fire training course might include requirements for demonstrating both knowledge and

skills, so someone evaluating a certificate of completion needs a way to clarify exactly what was completed. Another factor for evaluating a certificate of completion is the authority of the individual or agency issuing the certification. Someone's mother could physically issue a printed certificate, but her authority and credibility would be evaluated as weak. On the other hand, when an authorized state agency issues a certification of completion, the credibility of the course content can be judged as higher.

Certification to national standards has additional advantages and credibility. Ideally, this certification provides written assurance that a recognized national standard of performance has been met. This assurance should be the result of successful completion of a test based on the national standard. The highest credibility for a certification to national standards is when the certification is accredited.

Accreditation. Accreditation in the fire service is a system of evaluating the certifiers. The award of accreditation to a state fire training agency is a written seal of approval according the definition of accreditation. Creation of an accreditation system in the fire service was an important quality assurance step in making fire service training more valid and reliable. By observing other professions, fire service leaders in the 1960s who wanted to eliminate the unevenness of many training courses based on personal preferences proposed the National Professional Qualifications System, which was created in 1972.[22] Professional qualifications standards for specific fire-fighting job categories were the next step. Under their own authority, states could certify that individuals had been trained and were known to meet the requirements of the national standard.

The best assurance that the state program indeed meets the national standard is demonstrated when the state actions are evaluated by an independent third-party organization to ensure quality and eliminate politics or favoritism. The first national accrediting organization, set up by the Joint Council of National Fire Service Organizations, was the National Board on Fire Service Professional Qualifications (Pro Board, http://www.theproboard.org). A later accrediting organization, the International Fire Service Accreditation Congress (IFSAC, http://www.ifsac.org), grew out of Oklahoma State University. Both evaluate state fire training courses based on the same national standards from NFPA.

As a result, the accredited certification has the highest credibility and provides full disclosure to students about the definition of their certification. For example, a student awarded fire investigator certification from an accredited state fire training agency has assurance that he or she has demonstrated successful completion of tests measuring the knowledge and skills as specified in the national standard, NFPA 1033*, Standard for Professional Qualifications for Fire Investigator,* and that the state certifier has been checked by the independent third-party Pro Board and IFSAC and confirmed as having properly assessed the student's competency.

The Pro Board and IFSAC accrediting organizations use the national professional qualifications standards to accredit certification for the following subjects and levels (new subjects and levels may be added according to demonstrated need):

NFPA 472: Hazardous Materials Response for Awareness, Operational, Technician, Incident Commander
NFPA 1001: Fire Fighter I, II
NFPA 1002: Fire Apparatus Driver/Operator for Pumper, Aerial, Tiller, Wildland, Airport Rescue and Firefighting, and Mobile Water Supply Apparatus
NFPA 1003: Airport Fire Fighter
NFPA 1006: Technician Level for Rope Rescue, Surface Water Rescue, Vehicle and Machinery Rescue, Confined Space, Structural Collapse Rescue, Trench Rescue, Subterranean Rescue, Dive Rescue, and Wilderness Rescue
NFPA 1021: Fire Officer I, II, III, IV
NFPA 1031: Fire Inspector I, II, III; Plan Examiner I, II
NFPA 1033: Fire Investigator
NFPA 1035: Fire and Life Safety Educator I, II, III; Public Information Officer; Juvenile Firesetter Intervention Specialist I, II
NFPA 1041: Fire Service Instructor I, II, III
NFPA 1051: Wildland Fire Fighter I, II; Wildland Fire Officer I, II; Wildland/Urban Interface Protection Specialist, Coordinator
NFPA 1061: Public Safety Telecommunicator I, II
NFPA 1071: Emergency Vehicle Technician I, II, III
NFPA 1081: Fire Brigade Member for Incipient Industrial, Advanced Exterior Industrial, Interior Structural Industrial, Industrial Fire Brigade Leader
NFPA 1521: Health and Safety Officer, Incident Safety Officer

Federal Training Sources

National Fire Academy. The *America Burning*[23] report in 1973 documented the serious nature of the nation's fire problem and concluded that fire prevention and control should remain primarily local responsibilities. However, the commission appointed to study the federal fire problem at that time also recommended a new federal government agency "where the Nation's fire problem is viewed in its entirety, and which encourages attention to aspects of the problem that have been neglected" (p. x). Also recommended was the establishment of a "National Fire Academy for the advanced education of fire service officers and for assistance to state and local training program" (p. xi).

The National Fire Academy (NFA) has completed more than 30 years of operation and has won the respect of the fire service. Its educational courses are offered at the resident facility in Emmitsburg, Maryland, and throughout the nation in cooperation with state and local fire training organizations. Some courses are offered in distance learning formats. Leaving basic training to local fire departments and state fire training agencies, NFA resident courses deliver "specialized training courses and advanced management programs of national impact"[24] in an intensive learning environment.

Emergency Management Institute. Training to minimize the impact of natural and technological disasters on the American

public is the emphasis of the Emergency Management Institute (EMI). Its intended audience includes the fire service, but it serves the broader world of emergency management personnel in federal, state, and local governments and also volunteer organizations and other public and private sector representatives. EMI shares the campus of the National Fire Academy in Emmitsburg, Maryland. Courses are taught in residence at EMI and also in the states. Nonresident courses taught in the states are through cooperative agreements with state emergency management agencies.

Office of Domestic Preparedness. The United States Department of Homeland Security Office of Domestic Preparedness (ODP) "provides tailored training to enhance the capacity of states and local jurisdictions to prevent, deter, and respond safely and effectively to incidents of terrorism involving weapons of mass destruction."[25] ODP training is aimed at the full range of first responders, not just fire and emergency medical services.

ODP began in 1998 as a part of the Justice Department, but it was transferred to the Department of Homeland Security in 2002. Other federal training activities were transferred within Homeland Security with the title of Office of State and Local Government Coordination and Preparedness (SLGCP). This office administers the Assistance to Firefighters Grant Program. Grant funds can be used for a variety of fire service needs, including training.

Where the National Fire Academy specifically works with state fire training agencies and local fire departments to extend the outreach of NFA courses, OPD and SLGCP have a narrow coalition of training partners for the development and delivery of its training programs. A recent trend has begun to place more emphasis on partnering with more state and local fire agencies to meet the needs of first responder training.

Colleges and Universities

Individuals in fire and emergency services, as with individuals in any technical and managerial field, are increasingly valuing opportunities for higher education in fire protection and emergency medicine. Colleges and universities have been increasing these opportunities through a wider choice of college-credit courses and through additional degree and certificate programs at all levels.

Associate Degree. Community colleges have long been a source for associate degree programs in fire science technology and fire program administration. An associate degree is becoming more common as a requirement for fire department promotion to higher levels of advancement. When not tied to promotion consideration, some fire departments give value to higher education at the associate degree level by offering salary increases when the degrees are work related. A fire science technology degree also prepares an individual for a career in other areas of fire protection. A fire administration associate degree is especially helpful for someone seeking promotion, or it can be used to qualify for positions in fire safety organizations.

Associate degree fire science programs in community colleges combine study in general education subjects such as English, math, and chemistry with specialty fire protection courses such as fire hydraulics, hazardous waste operations, and building construction as related to fire suppression. Associate degree administration programs include the same general education programs and combine them with more management courses. Some programs may allow limited credit for fire department experiences. More formal programs often allow credit for previous state fire training accredited certifications. Some fire service management programs include teaching such certification courses as Fire Officer III and Fire Officer IV as part of the degree curriculum.

Bachelor's Degree. Universities in all parts of the United States now offer bachelor's degrees related to fire protection. Many are created to allow easy transferability of fire protection associate degrees from community colleges. Bachelor programs may also have several types of specialization, some with application in fire departments and some with application in other areas of fire protection. One state university bachelor's degree in fire protection has options for fire protection administration, fire protection engineering technology, fire and explosion investigation, industrial safety and risk management, and safety and industrial relations. There are also many opportunities for master's and even doctoral degree programs in fire protection that did not exist even 10 years ago.

Distance Learning Opportunities

Distance learning via the Internet has greatly expanded options for fire and emergency training. The fact that virtually every community college and university offers some classes online demonstrates how mainstream this relatively new format has become. The widespread success of online learning suggests that colleges and universities have found it to be successful. This is backed up by educational research showing that measurable student learning and student satisfaction with online courses can be equal to the learning and satisfaction in regular classroom courses.

Online learning can be especially important to adult learners. The typical advantages of online learning often fit closely with adult situations. A training course taught online means that the work of learning can be accomplished at home and on the weekends, so that the adult with a full-time job and family responsibilities does not have to juggle scheduled classes that may require an inconvenient commute. Online learning requires the same effort as classroom learning, but the schedule flexibility may be a critical consideration.

Not all fire and emergency service training can be provided in an online learning format. A fire fighter training course featuring many skill development requirements may not ever be feasible online, but an accredited certification course for Fire Officer I has already been conducted online by a state fire training agency.[26]

Not all online learning courses are created equal. Much variety exists in the educational value of courses labeled as online learning. Some nonrecommended online learning formats allow a single student to work alone without any deadlines for assignments, and the course content may be nothing

more than a textbook placed online for student reading. The learning is expected to occur simply from the student flipping the pages and reading the material online. Student satisfaction and completion rates in these courses are not as high as in other formats.

College and university online courses often follow a common format that has many of the successful features of a classroom course. About 80 percent of college and university online courses use similar course management software interfaces, named Blackboard and WebCT, to present online information to students. The course is presented in a normal semester or quarter time frame, and students participate in the class together, although at a distance. Research on this format shows good educational results. One particular benefit comes from student interaction, although again from a distance and in writing. Research shows that important learning, whether in a classroom or online, comes from student interaction during group discussion about the course content.

Training Companies

For-profit training companies have increased their offerings of training opportunities for fire and emergency personnel, even to the level of college courses. For-profit companies competing with colleges to provide technical training are usually big operations with a regional or national reach. In the fire service, the company may be just one or a few instructors with prior fire department experience or specialty experience. For-profit training can be seen with specialty areas in technical rescue, water rescue, and hazardous materials response.

The quality of for-profit training companies depends on the technical and instructional experience of the trainer. When such courses do not usually claim to fully address any national standard and the training company lacks independent third-party accreditation endorsement, anyone contracting for training must make an extra effort to be sure of what training is needed and what quality can be delivered.

Fire Service Organizations

In the United States and other countries, the following not-for-profit associations provide a valuable service to the fire service community in terms of training and other resources:

- The International Association of Fire Chiefs (IAFC, http://www.iafc.org) is an international trade association of fire chiefs. Membership is restricted to upper-level officers in fire departments. IAFC provides a large annual conference and trade show along with an advisory service and publications for its members. This organization also operates the Chief Fire Officer Certification project.
- The International Association of Fire Fighters (IAFF, http://www.iaff.org) is a national labor union representing career fire fighters throughout North America. Extensive advisory and training services are offered to its members with a focus on fire fighter health and safety.
- The International Fire Service Training Association (IFSTA, http://www.ifsta.org) is an advisory group to Fire Protection Publications, a division of Oklahoma State University. Membership is by invitation only. The group reviews and revises the extensive fire service training materials issued by Fire Protection Publications.
- The International Society of Fire Service Instructors (ISFSI, http://www.isfsi.org) is a trade association of individuals engaged in or interested in fire service training. The society provides conferences, seminars, and some training materials for its members and others.
- The National Fire Protection Association (NFPA, http://www.nfpa.org) is a public advocacy association that primarily develops voluntary consensus standards. Many of those standards apply to the fire service and provide valuable technical guidance. In addition, NFPA provides training materials and staff resources in support of fire and emergency service training.
- The National Volunteer Fire Council (NVFC, http://www.nvfc.org) is an organization whose membership is made up of delegates from state volunteer fire service organizations. It also has individual fire departments and fire fighter memberships. The organization is primarily engaged in lobbying for volunteer fire service issues but does provide some valuable training programs and resources.

There are typically several fire service organizations in each state and province that mirror the work of associations at the national level. State and local fire fighters, fire chiefs, fire instructors, and other associations vary in their commitment to training, but nearly all have some resources to offer.

TRAINING SAFETY

Injuries and Fatalities

Fire fighter injuries and fatalities during training in the last 25 years suggest that instructors can forget that a realistic training scenario can have disastrous results when safety is not a paramount consideration. Guidance for realistic but safe training can be found in NFPA 1403*, Standard on Live Fire Training Evolutions.* Development of this document started after numerous training deaths occurred across the United States, especially the tragic deaths of two fire fighters in 1982 during live fire training in Boulder, Colorado, using an abandoned wood-frame building. Rapid fire spread across a combustible low-density fiberboard ceiling, an inadequate water supply, inadequate exits, and a general lack of planning for the potential dangers contributed to these fatalities. The first edition of this standard was in 1986, with revisions following as more experience was gained in subsequent years.

Unfortunately, the availability of this safety guidance sometimes has been overlooked or ignored, with continued disastrous results. Three more fire fighters died in a live fire training exercise in 1987 in Milford, Michigan. Multiple fires had been set in an old frame house in an attempt to create a realistic fire scenario for training. The scenario, with a lack of planning, insufficient paths of escape, inadequate water supply, and large amounts of accelerants, was not in compliance with NFPA 1403. Four area fire departments took part in this exercise, but safety was not a sufficient priority to prevent the unanticipated flashover that occurred with fire fighters still inside.

Failure to follow the requirements of this important standard continues. The following newspaper and magazine headlines remind us of the consequences:

- "Instructor Suspended over Death of Trainee"[27] (Maryland)
- "Apparent Flashover at Controlled Burning Traps, Kills Delaware Asst. Chief"[28]
- "Iowa Firefighter Brothers Burned During Training"[29]
- "Career Lieutenant and Fire Fighter Die in a Flashover During a Live-Fire Training Evolution"[30] (Florida)
- "Volunteer Fire Fighter Dies and Two Others Are Injured During Live-Burn Training"[31] (New York)

The foregoing Florida headline incident from 2002 occurred in a vacant concrete-block dwelling. A fire in the structure was started to accompany search and rescue training. As a result, the two fire fighters in the training exercise did not have a ready water supply. As in the Boulder and Milford fatalities, there were insufficient paths of escape. This incident had designated safety officers and a rapid intervention team, but the fuel load contributed to a flashover only 3 minutes later. Four instructors positioned inside the structure to serve as interior safety officers were able to exit successfully, but the fire lieutenant and fire fighter in the training exercise died from smoke inhalation and thermal injuries. Now state law in Florida requires that training fires be in compliance with NFPA 1403.

The foregoing New York headline incident from 2001 forced a wider fire service audience to become aware of NFPA 1403 when the fire department officer supervising the training exercise was charged with felony counts of manslaughter and assault. The fire fighter trainee who died was 19 years old. The training officer was later convicted of criminally negligent homicide. During sentencing the judge said, "This was not an accident. This was a series of bad decisions, decisions that should never, ever have been made." Now the state offers two programs to prevent a reccurrence of this type of incident: "Live Fire Training Safety" and "Conducting Live Fire Training Evolutions." Both reference NFPA 1403.

Maintaining Controlled Training

NFPA 1403 explains its purpose with this statement: "The ongoing training of fire fighters is the cornerstone of good fire protection in today's world. However, the benefits derived from live fire training can be negated by the injuries and deaths suffered by fire fighters under unsafe and poorly supervised training conditions." Separate chapters address ways to maintain controlled training in acquired structures and in gas-fired and non-gas-fired training center buildings, using exterior props, and using exterior Class B fires.

The chapter on acquired structures for live fire training is especially important because the most preventable injuries and fatalities occur in acquired structures. It calls for students to have prior training to help them understand safety issues and recognize normal and abnormal fire behavior. The structure itself must undergo special preparations to minimize factors that contribute to uncontrolled burning. Fuel loads are limited. Prior to beginning any training fire, participants in a live fire exercise must become familiar with the building, the exit arrangements, and the plan for the training. Adequate water supplies must be available, and training instructors must be available in sufficient numbers to supervise the burn. Flammable or combustible liquids are not allowed to fuel the fire in these exercises.

TRAINING RECORDS

Training activities must be recorded and updated for easy retrieval. They provide a source of information for effective management decisions for planning and budgeting. Records document and guide professional development for all fire and emergency service personnel. Such records show who has had and who needs training for certification and recertification, internally and externally obtained education, and general compliance with personnel performance standards.

Fire training records are also important to meet various legal and statutory requirements, such as those from the Occupational Safety and Health Administration (OSHA). Fire department records are generally public documents, and citizens or members of the press may have the right to access these public records. But some records, such as test questions and employee personal training records, are not freely available to the public. However, these records are subject to disclosure through a court order or, in some cases, through written permission of the employee. The fire department or emergency agency must have clear-cut guidelines to spell out public access and to prevent the unnecessary and illegal disclosure of confidential information. Other NFPA standards also specify accurate and complete training records, including NFPA 1403 and NFPA 1500.

Guidance for record keeping is available in NFPA 1401, *Recommended Practice for Fire Service Training Reports and Records.* Separate chapters address elements and types of training documents, legal aspects of record keeping, and evaluating the effectiveness of the training records system.

Training elements generally include information about the who-what-when-where-why of training for each individual member of the organization. Every type of training that a department offers should be documented by records. Records may be used to identify, investigate, evaluate, or solve various problems. A resulting report should follow five steps as outlined in NFPA 1401 and summarized here as follows:

1. State the purpose and scope of the report.
2. Outline the method or procedure followed.
3. Present the essential facts.
4. Analyze and categorize the facts.
5. State the conclusions and recommendations from the analysis.

Besides the individual records of all training, NFPA 1401 presents five types of training reports that are often compiled. These include an inventory of training apparatus and equipment, plans and costs for needed training improvements, a periodic report on the evaluation of all probationary fire fighters, a monthly summary of all training division activities, and an annual report of activities with projected plans for the upcoming year.

SUMMARY

Training for fire and emergency service personnel should be varied and continuous. It is not only required by numerous federal and state regulations, but it is also the expectation of the people who finance public fire protection. Beyond these considerations, every fire department should make training a moral priority to protect the health and safety of its members. Finally, every fire fighter should demand an ongoing and comprehensive full-service training program to ensure that fire fighters can protect themselves and be ready to provide assistance to anyone else.

There are many sources for necessary training, including federal, state, and local agencies. When the training is provided by the local fire department, its leaders should ensure that the instruction offered concentrates on the right kind of learning and verifies learning through measured assessment. If a fire department, career or volunteer, is not using established national standards as the basis for its training, fire fighters or citizens should demand an explanation.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on training programs for fire and emergency service personnel discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents*
NFPA 1001, *Standard for Fire Fighter Professional Qualifications*
NFPA 1002, *Standard for Fire Apparatus Driver/Operator Professional Qualifications*
NFPA 1003, *Standard for Airport Fire Fighter Professional Qualifications*
NFPA 1006, *Standard for Rescue Technician Professional Qualifications*
NFPA 1021, *Standard for Fire Officer Professional Qualifications*
NFPA 1031, *Standard for Professional Qualifications for Fire Inspector and Plan Examiner*
NFPA 1033, *Standard for Professional Qualifications for Fire Investigator*
NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*
NFPA 1041, *Standard for Fire Service Instructor Professional Qualifications*
NFPA 1051, *Standard for Wildland Fire Fighter Professional Qualifications*
NFPA 1061, *Standard for Professional Qualifications for Public Safety Telecommunicator*
NFPA 1071, *Standard for Emergency Vehicle Technician Professional Qualifications*
NFPA 1081, *Standard for Industrial Fire Brigade Member Professional Qualifications*
NFPA 1401, *Recommended Practice for Fire Service Training Reports and Records*
NFPA 1402, *Guide to Building Fire Service Training Centers*
NFPA 1403, *Standard on Live Fire Training Evolutions*
NFPA 1451, *Standard for a Fire Service Vehicle Operations Training Program*
NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*
NFPA 1670, *Standard on Operations and Training for Technical Search and Rescue Incidents*

Chapter 11

Industrial Fire Loss Prevention

Revised by
Michael Snyder

Chapter Contents

Fire Risk Management
Fire Prevention and Control Program Management
Loss Prevention Program Motivation and Development
Management Loss Prevention and Control Program Framework
Quality Grading of Management Loss Control Programs
Emergency Organizations and Industrial Fire Brigades

Key Terms

emergency management, fire prevention, fire risk management, hazard identification, hot work, industrial fire brigade, industrial loss prevention, insurance, local emergency planning committee (LEPC), pre-incident planning, process safety, risk assessment, risk management

Fire and explosion loss consequences, which can involve property damage, business interruption, life safety hazards, environmental issues, damage to corporate image, and reduced future profitability, present a major threat to corporate goals and survival. Recognition of these consequences has prompted the development of fire and explosion loss prevention programs and emergency response organizations in many commercial and industrial organizations.

For related topics, see Section 3, Chapter 7, "Fire Hazard Analysis Techniques"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 9, Chapter 6, "Welding, Cutting, and Other Hot Work"; Section 11, Chapter 4, "Fire Hazards of Construction, Alteration, and Demolition of Buildings"; Section 12, Chapter 9, "Fire and Emergency Services Protective Clothing and Protective Equipment"; Section 17, Chapter 8, "Explosion Prevention and Protection"; and Section 20, Chapter 18, "Industrial Occupancies."

FIRE RISK MANAGEMENT

Fire risk management can be defined as the systematic application of management policies, procedures, and practices to the tasks of analyzing, assessing, and controlling fire risk in order to protect employees, the public, the environment, and company assets while avoiding business interruption (Figure 12.11.1). The typical priorities in fire risk management involve the following:

- Identifying and evaluating fire and explosion hazards/risks
- Developing programs and assigning management responsibilities to manage the identified risks
- Establishing emergency organizations to control fire and explosion incidents that do occur

Hazard Identification

A fire or explosion hazard can be defined as a characteristic of a system, plant, or process that represents a potential for an unplanned event leading to undesirable losses. The key words in this definition are "undesirable losses." Hazard identification is the process of recognizing hazards that can pose significant undesirable losses. Hazard identification should be a continuous activity in the evaluation of new materials, plant additions, and production modifications, as well as the continuing inspection and evaluation of existing facilities.

Resources, including various chapters within this handbook, many NFPA standards, and Internet websites such as those maintained by the United States Chemical Safety and Hazard Investigation Board, and the United Kingdom's Health and Safety Executive describe fire hazards in major industries and special process hazards based on current technology and past loss experience.

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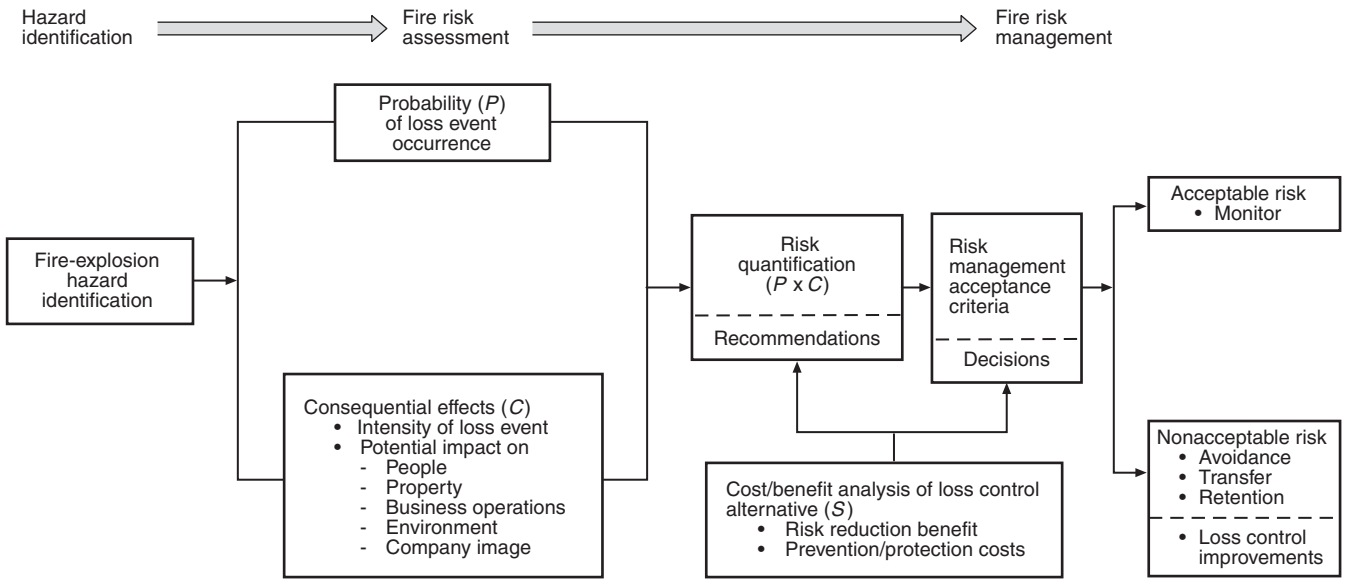

FIGURE 12.11.1 General Framework for Industrial Fire Risk Management

Risk Assessment

The risk assessment process consists of both identifying risks and estimating the probability and magnitude of potential fire and explosion losses. In recent years, there has been an increase in the use of formalized risk assessment methods to support decisions on fire safety issues. Predictive methods that integrate statistical data, deterministic models, and expert opinion increasingly are being used. The primary steps in fire risk assessment include the following:

1. Identification of the fire events that could lead to significant loss
2. Quantification of the fire risk—that is, probability of fire or explosion event occurrences and loss consequences—for the generated fire loss scenarios
3. Development and evaluation of alternative fire prevention and/or fire protection strategies (recommendations) to reduce the fire and explosion risk
4. Measurement of the estimated change in fire and explosion risk (difference in probability and/or consequences) associated with the alternatives

Addressing Probabilities. One of the most difficult tasks in the risk assessment process is addressing probabilities. Fire risk reflects both the probability of fire occurrence and the loss consequences of the fire. In both factors there is an element of uncertainty that must be recognized. Approaches for determining the probabilities of values for fire event occurrences are detailed later. If valid data on fire loss event frequencies are available and applicable, then probabilities can be extracted from this source. Often objective data sources are scarce. To evaluate the application of historical data, it is necessary to look at the following, both for the source of the data and for the situation under consideration:

- Design standards and quality
- Inspection methods and quality
- Maintenance philosophy and quality
- Operational philosophy and quality
- Safety standards and enforcement

If historical data sources are not available for the loss event(s) of interest, probabilities can be evaluated using inferential judgment based on available loss-trending information, such as equipment failures, human error, ignition sources, loss control elements, and damageability factors. Good sources of information include the NFPA Fire Analysis and Research Division and United Kingdom's Health and Safety Executive website.

Subjective estimation processes should be documented and should involve the best judgment a fire protection expert can make based on knowledge of contributing factors from past fire losses, site-specific evidence of loss control deficiencies, and exposed values. A very good reference on equipment failure data sources and application precautions is the AIChE's Center for Chemical Process Safety (CCPS) book entitled *Guidelines for Process Equipment Reliability Data, with Data Tables*[1] as well as the publicly available Process Equipment Reliability Database maintained on the CCPS website.

Quantifying Fire Loss. The physical intensity of fire-explosion consequences can be quantified in terms of the expected energy released (heat exposure, smoke and/or corrosive gas contamination, explosion blast overpressures, etc.), the area involved, and the duration of the fire. Probabilistic engineering assessment—and, in some situations, deterministic fire-explosion modeling tools—are utilized to aid the evaluation process. The *SFPE Handbook of Fire Protection Engineering*[2] provides information on various analytical techniques that can be used in this evaluation.

Once the intensity and duration of the potential fires have been quantified, the impact on both direct and indirect loss potential must be assessed. Direct losses include damage to buildings, equipment, and contents. Indirect losses include business interruption, liability for injury or death, environmental contamination, and damage to company image. For most quantification studies, loss potential is expressed in equivalent monetary terms.

Assessing Risks. The type of risk assessment conducted depends on the significance of the decision, the complexity of the problem, and the time and cost limitations. Routine code-compliance problems can often be handled by simple choices. Complex problems involving new technologies or high-hazard operations require application of more detailed risk assessment and decision analysis methods. Whatever method is used for the risk assessment, it is critical that the assessment is well documented and maintained in an easily accessible format to ensure that complete information is available for routine reviews of the assessment and to be readily available in the event that details of the assessment are questioned by either management or a regulatory authority.

Risk Management

Risk management addresses the value judgments involved in establishing acceptable levels of risk and methods of handling identified risks. The acceptable risk decision-making process is based on specific organizational goals and generally includes (in any order) the following:

- Profit (competitive market position)
- Protection of company assets (major loss exposures)
- Continued company operation (business interruption)
- Continued growth (expansion)
- Humanitarian concerns (employee and public safety)
- Community goodwill (potential embarrassment)
- Legal requirements (liability, building codes, etc.)
- Insurance company requirements
- Environmental concerns

If the risk is acceptable, no immediate action may be necessary, but monitoring for changes that could increase the risk must be done. If the risk is unacceptable, then decisions must be made about how to deal with the risk.

General options available to the risk management decision maker for handling fire and explosion risk exposure include the following:

1. Avoiding the risk by nonparticipation in risky operations
2. Reducing the risk through improved design or use of alternative manufacturing processes
3. Transferring the risk by purchasing insurance to cover potential losses
4. Financing alternative risk transfer arrangements such as captive or corporate funded reserves (self-insurance)
5. Providing loss control improvements
6. Developing a risk management program that includes a combination of the foregoing options

The sixth option generally provides a cost-effective approach for reducing fire loss potential and reducing the risk funding requirements for options 3 and 4. *Risk-Informed, Performance-Based Fire Protection* by T. F. Barry provides a detailed discussion with examples on the subject of risk and industrial fire protection.[3]

An important part of fire risk reduction is the development, implementation, and monitoring of comprehensive loss prevention and control programs. Written documentation should be provided for programs and updated periodically based on the major opportunities for risk reduction.

Recognition of Fire Risk Reduction Opportunities

Figure 12.11.2 illustrates a fire sequence event tree. It depicts primary areas of opportunity for reducing fire risk through implementation of fire loss prevention programs and emergency response organizations.

Initiating Fire. The likelihood of initiating fire events is reduced when fire hazards are adequately identified and evaluated and when quality fire prevention programs are developed, implemented, and audited. Equipment failure rate minimization via good mechanical integrity programs, human error reduction through effective procedures and training practices, and ignition

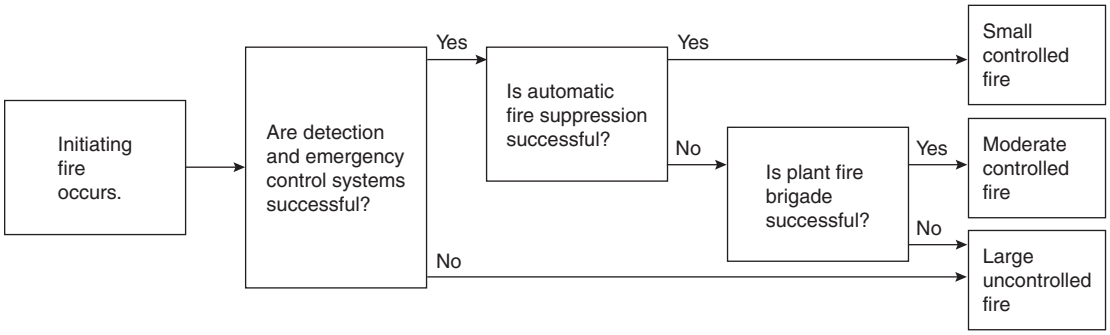

FIGURE 12.11.2 Fire Sequence Event Tree

control procedures such as hot work permits and safe practices all contribute to the overall reduction of initiating fires.

Detection and Emergency Control Success. Rapid detection of fires is the key to reducing the incident magnitude, duration, and the resulting physical damage as well as losses from business recovery time. Prompt detection and intervention through process control systems and successful automatic fire suppression may quickly control incipient fires and prevent them from progressing to large fires that create significant damage.

Process controls can also be used to prevent flammable chemical releases from igniting by quickly isolating flammable releases, thereby stopping the flow of fuel to the atmosphere. Activation of fixed water spray systems can disperse vapors or, with foam water spray, cover and suppress vapors to prevent ignition or control small fires. The prompt response of a well-trained and well-equipped industrial fire brigade can assist the process controls and fixed systems to control the release and limit the size of an emergency fire incident.

Computerized process controls, with extensive emergency shutdown features, are prevalent in large facilities such as refineries, petrochemical plants, and power generation facilities. Process control systems are also prevalent in smaller facilities such as compressed gas cylinder filling, paint spraying, and plywood manufacturing.

Automatic Fire Suppression. Programs related to the inspection, testing, and maintenance of fire protection systems such as sprinkler systems, fire pumps, foam water protection systems, and special extinguishing systems, such as gaseous agents and dry chemicals, improve the reliability of the fire suppression system. Properly designed, effective, and reliable automatic fire suppression systems can quickly control an incipient fire and reduce life safety and property damage exposures.

To ensure that automatic fire suppression systems remain fully functional, it is essential to establish and maintain a fire protection system impairment program that contains the following three aspects:

- Identification and notification of the impaired system
- Minimization of the impairment
- Provision of contingencies (i.e., shutdown of operations, fire watch, use of portable equipment)

The historical collection of large loss fires contains too many examples of situations in which a fire starts in a facility that had an improperly managed fire protection system impairment, which allowed a minor fire to grow, uncontrolled, into a fire resulting in catastrophic loss.

Industrial Fire Brigade Response Success. Industrial fire brigades provide a number of functions at industrial facilities. In addition to providing manual fire suppression support and backup to automatic fire systems, fire brigades assist in the development of prefire planning with responding public fire departments, employee emergency evacuations, and salvage operations following fire incidents. Other duties can include plant fire safety inspections, fire extinguisher training, fire equipment maintenance, and overall emergency coordination. Fire brigade organization and training are discussed later in this chapter.

FIRE PREVENTION AND CONTROL PROGRAM MANAGEMENT

Today few companies, in the face of severe global competition and the high cost of capital, could survive a major loss. Over the years, it has become apparent that people can substantially aid in the minimization of losses. It has been statistically demonstrated by major property insurance companies that the factor with the largest effect on the size of a loss by fire or explosion is what people do or fail to do.

Due to the numerous interfaces between the various engineering disciplines, as well as maintenance and operational programs, it is essential to place the responsibility for the fire protection program with a single individual or small group with direct access to top management. This individual must have sufficient authority to delegate responsibilities affecting plant fire protection across engineering discipline and departmental lines and even across separate divisions, such as engineering, plant services, utilities, safety and loss control, and emergency response. The implementation and enforcement of an effective fire loss control program are dependent on management involvement and support and effective use of property insurance services.

Management Roles

Management can be divided into three echelons, each of which makes important contributions to loss prevention and control: (1) executive management—the board of directors and company officers; (2) middle management—facility managers, department heads, and related staff managers; and (3) line management—the supervisors and team leaders who direct each phase of the operation.

In a relatively small organization, the owner may perform the functions of all three management levels. Although the owner's loss control problems may be fewer, or less complex, than those of the management group in a larger organization, some of the same judgments must be exercised. The owner who tries to be loss control manager may be at a disadvantage, however, because of the lack of specialized training in loss control and the absence of managers with whom to share expertise and creative ideas regarding a sound loss control program. This disadvantage need not pose a major obstacle. Expertise is available from professional loss control consultants, insurance companies, and fire departments.

In today's business environment, facility employees who manage property conservation and or loss prevention may also manage a number of other similar related functions such as safety and health, and security and risk management. To be effective they will need to partner with others within an organization to jointly share goals and objectives while complying with codes and internal programs.

Executive Management. Members of executive management establish company policy, make major financial decisions, de-

termine the product or service to be provided, and establish production levels. Executive management's primary goal is to guide the organization to produce a profit.

Regardless of insurance coverage, losses to plant property by fire, explosion, or other causes can disrupt profitability. On the surface, assets diverted to property protection would appear to be a nonproductive expenditure. However, after a serious loss, the need for an effective loss prevention/control program becomes apparent. For loss control programs to be effective, they must have complete support from executive management. In addition, once a program has been developed and accepted, executive management must insist on regular updates to monitor progress.

Middle Management. Middle management is responsible for the development, implementation, and monitoring of cost-effective loss control programs. The person with primary responsibility for loss control generally has the title of loss control manager. Depending on the organization, titles assigned to individuals vary, and in some cases, the individual may have several other titles when loss control is not a full-time function. To be effective, the assigned individual must have access to decision makers at the executive management level. Direct access would involve reporting to the officer level (e.g., vice presidents of engineering, finance, production, etc.). Indirect access would involve reporting to the director of risk management or other managers with direct access to executive management.

Major responsibilities of the loss control manager include the following:

Overall supervision. Defining loss control program functions, clarifying responsibilities, and ensuring that all procedures are properly carried out

Planning. Anticipating hazards and formulating plans and procedures for fire prevention and overall plant safety

Education and training. Providing employee training in fire prevention; making sure that all production processes and operations are carried out safely, and that contractors follow safe procedures according to company regulations (Figure 12.11.3)

Assignment. Delegating specific maintenance and emergency duties to employees, including guards, caretakers, patrol officers, and night workers

Coordination. Maintaining liaison with the following corporate departments and outside organizations:

- Production and engineering on new processes or materials that can introduce additional fire hazards within the facility
- Plant engineering and maintenance for fire protection installations, impaired protection, maintenance of fire protection equipment, and housekeeping
- The public fire department and insurance company on plant layout, location and type of hazardous processes, coordination of forces, location and type of fire protection equipment, fire doors, fire walls, defense plans, and main defense lines

Review and audit. Periodically checking the efficiency of the entire loss control program; reviewing details of the plan with line management; conducting drills and classes to maintain employee preparedness; auditing

FIGURE 12.11.3 Portable Fire Extinguisher Training—An Important Function for Many Loss Control Departments

and inspecting various facilities for compliance to organization loss prevention policies and plans

In smaller organizations, the facility manager or an appointee must assume these responsibilities.

Line Management. Implementation of a loss control program extends beyond the middle-management level. Unless the members of line management adequately perform their function, the program cannot produce satisfactory results.

Line managers, those with daily personnel contact, should aid in the information collection that middle managers incorporate into loss control programs. Once programs are implemented, line managers are responsible for regular enforcement of company policy.

With regard to employees and work areas under the line manager's supervision, it is the line manager who is responsible for the following:

- Training personnel to carry out individual duties in a loss control program
- Working with the loss control manager and staff in selecting employees for the private fire brigade or other program assignments
- Working with the loss control manager to establish priorities for inspection, testing, and maintenance of fire protection equipment
- Inspiring employees to develop a fire-conscious attitude and respect for the loss control program
- Insisting that access to all protection equipment, as well as all means of egress, be kept open
- Working closely with the loss control manager and staff to ensure that new equipment or processes are adequately protected before startup
- Reporting all occupancy changes that may affect loss control
- Working with the loss control manager and staff to ensure that fire exit drills are held regularly
- Accounting for each employee following facility evacuation
- Supervising emergency action when a fire or other property-related incident occurs in the absence of members of an established emergency organization

Insurance Company Roles

Many property insurance companies focus on recommending management programs that assist facilities to prevent and minimize property damage and business interruption losses. These services are provided to both large industrial sites and small retail operations. When considering the development of a program, management needs to take into consideration the size of the operation, reporting structure within the company, hazards involved, and how the program will be managed and/or directed.

Each insurance program needs to be tailored to address the risk elements that have been identified. Primary management program elements that are typically offered include the following:

- Impairments to fire protection systems
- Smoking regulations
- Maintenance
- Employee training
- New construction
- Preemergency planning
- Hazardous materials evaluation
- Cutting, welding, and other hot work
- Loss prevention inspection
- Handling insurance company recommendations
- Fire protection and security surveillance
- Fire protection equipment inspection
- Hazard identification and evaluation
- Proper housekeeping
- Handling and responding to losses or claims
- Handling inspections from enforcement agencies

Insurance Company Service Options

Today many insurance companies have reduced or eliminated service functions as part of their standard insurance program. In some cases the insurance companies have retained the services but operate with reduced staff and focus on loss prevention activities that support only the insurance underwriting placement. In other cases some property insurance companies have staffed up to sell or offer these services as part of the entire portfolio of insurance products. Some loss prevention services are considered as part of the insurance program but the service has a cost factor attached. The loss control program manager needs to understand what he or she is getting from the insurance companies and clearly understand the scope of the services, cost, and deliverables.

Most insurance policy contracts and loss prevention insurance inspection reports contain a disclaimer that outlines the limitations of the inspection survey or site risk reviews. Before a client spends money on insurance company recommendations compliance, the client needs to determine if the proposed corrective action will impact the insurance program and if the identified recommendation has other more cost-effective options.

Services provided by insurance companies are sometime labeled as "bundled." That is, the insurance policy and loss prevention or risk control services are provided at a fixed cost by one company. Remember that with this approach the loss prevention people work directly for the insurance companies, and the focus of service may be driven from internal insurance company standards or guidelines. In many cases, particularly for small facilities, this approach can serve to fulfill the needs of the risk control client. In other situations, such as a company with many large sites and operations, the client may wish to direct the loss control services to minimize the interruptions to operations in performing the inspections.

With continuing changes in the insurance industry, many more consulting companies now offer high-quality loss prevention and risk control type services, which they call an "unbundled" approach. This approach breaks apart the service elements from the insurance contract. In this method the client purchases the services directly and often separately from insurance coverage.

The following are items that should be included in a service contract with an insurance company:

- Term of agreement
- Duties of both parties—compliance with health, safety, and OSHA standards
- Confidentiality of data security
- Right to work product
- Warranty—limitation of liability
- Indemnity and insurance
- Compensation—upfront payment or schedule
- Termination of contract or agreement
- Miscellaneous rights
- Compliance with jurisdictional codes

These items can also apply to bundled loss prevention service from an insurance company.

Program Monitoring. Based on the approach, unbundled or bundled services, companies need to establish performance requirements in the contracts established for service. It is recommended that the service provider submit a quarterly stewardship report outlining all the activities, cost, and a scorecard measuring the key performance elements of the contract or service agreement.

Facility or company management must routinely audit the insurance services program, thereby providing a means to measure performance of the services delivered. Auditing also provides an effective tool for feedback on the program's strengths and pinpoints deficiencies.

LOSS PREVENTION PROGRAM MOTIVATION AND DEVELOPMENT

Human element factors play a significant role in most fire and explosions. Various statistical studies of loss incidents in a variety of industries have indicated the following general breakdown:

- Human factors (70–85%) (e.g., management program deficiencies, human operator errors)
- Equipment failures (10–20%) (e.g., design or maintenance deficiencies)
- External factors (10–20%) (e.g., earthquake, floods)

It should be noted that some products and equipment are less vulnerable to human error than others, so product or equipment performance can be a factor even though human error is also a factor. It is a mistake to treat the two as mutually exclusive.

To reduce human error leading to fire incidents, many companies are establishing and expanding policies and practices that prioritize the implementation and auditing of loss prevention programs. Integrated into many of these programs are insurance company guidelines, industry recommended practices, regulatory requirements, and NFPA standards.

Insurance Company Guidelines

Traditionally, industrial property insurance companies have focused on recommending management programs that assist in the prevention and minimization of property damage and business interruption losses.

Some of the primary management programs include the following:

- Impairments to fire protection systems
- Smoking regulations
- Maintenance
- Employee training
- New construction
- Pre-emergency planning
- Hazardous materials evaluation
- Cutting, welding, and other hot work
- Loss prevention inspection
- Fire protection and security surveillance
- Fire protection equipment inspection
- Hazard identification and evaluation
- Proper housekeeping

Each major industrial insurance company typically has guidance documents that can be used in conjunction with NFPA standards to implement effective loss management programs.

Modern commercial and industrial programs also include technical reviews of manufacturing equipment and processing hazards and can assist in the risk assessment of many specific manufacturing operations.

U.S. Federal Regulations

The Occupational Safety and Health Administration (OSHA) regulates many aspects of fire prevention and control within commercial and industrial occupancies. Specific regulations include the following:

Part 1910 Subpart E—Exit Routes, Emergency Action Plans, and Fire Prevention Plans
Part 1910 Subpart H—Hazardous Materials
1910.106—Flammable and combustible liquids
1910.107—Spray finishing using flammable and combustible materials
1910.108—Dip tanks containing flammable or combustible liquids
1910.110—Storage and handling of liquefied petroleum gases
1910.119—Process safety management of highly hazardous chemicals
1910.120—Hazardous waste operations and emergency response
Part 1910 Subpart L—Fire Protection
Part 1910 Subpart Q—Welding, Cutting, and Brazing
1910.252—General Requirements

Many of the foregoing OSHA regulations are derived from older versions of NFPA standards and have constituted leading industrial loss control practices for many years. Work is underway to update the references to more current versions of the NFPA standards. Several letters of interpretation issued by OSHA accept the use of more modern versions of the NFPA standards with some limitations.

Many states and local jurisdictions have adopted versions of NFPA standards to serve as the basis for regulatory requirements. The most commonly adopted standards include NFPA 30, *Flammable and Combustible Liquids Code,* to regulate the safety of flammable and combustible liquids, and NFPA 58, *Liquefied Petroleum Gas Code,* to regulate the safety of liquefied petroleum gas operations.

OSHA 1910.119, *Process Safety Management of Highly Hazardous Chemicals,* was introduced in 1992 and focuses on the application of performance-based management programs rather than specific engineering guidelines for the prevention of toxic releases, fires, and explosions on plant sites that use or store hazardous materials that exceed specific volume thresholds. Many of the regulatory requirements arising from this standard represented practices used by leading manufacturing companies for many years.

The following are the major program segments in CFR 1910.119:

- Employee participation
- Process safety information
- Process hazard analysis
- Operating procedures
- Training
- Contractors
- Pre-start-up safety reviews
- Mechanical integrity
- Hot work permits
- Management of change
- Incident investigations
- Emergency planning and response
- Compliance safety audits

In the mid-1990s the Environmental Protection Agency (EPA) promulgated 40 CFR Part 68, *Risk Management Program for Chemical Accident Prevention,* which focuses on the exposure of toxic chemical releases and fire and explosions to the public.

EPA's risk management program (RMP) elements include the following:

- Hazard assessments
- Prevention program
- Emergency response program, including procedures for informing the public and response agencies should an accident occur

EPA's RMP regulation requires development and implementation of management programs at facilities that manufacture, process, use, store, or transport regulated hazardous chemicals in quantities that exceed specified threshold limits as listed in the regulation. EPA's regulation rule adopts the OSHA CFR 1910.119 PSM regulation as the RMP's prevention program segment.

MANAGEMENT LOSS PREVENTION AND CONTROL PROGRAM FRAMEWORK

The details and complexity of program elements for loss prevention and control will vary depending on the type of plant facilities, nature of hazardous operations, complexities of processes, and exposures to plant employees and the public.

Primary management program elements can be categorized as follows:

Process Technology

- Process safety information
- Process hazard analysis
- Pre-start-up safety reviews

Mechanical Integrity Programs

- Process equipment
- Emergency safety devices
- Protection systems

Operating Procedures

- Written operating procedures
- Hot work permits
- Fire system impairments
- Flammable liquid handling and ignition control

Management

- Employee training
- Contractors
- Management of change
- New construction

Incident Management and Investigation

- Disaster/emergency management and pre-incident planning
- Incident investigations

Process Safety Information

For process, storage, and transportation operations involving flammable and hazardous materials, it is important to develop, document, and update process safety information, including information pertaining to the following:

- Hazards of the chemicals
- Process technology
- Equipment

Material hazards documentation provides pertinent hazard data for each chemical involved in a process or operation, including physical and chemical properties such as flammability and thermal stability data, reaction data, and any other property relevant to a particular hazard. Toxicity data are an important part of the package. In many cases, material safety data sheets (MSDSs) will satisfy this requirement, provided they contain the necessary details.

Chemical and flammability data can be extracted from numerous sources including the NFPA *Fire Protection Handbook.* Much of the data available in these publications are at atmospheric temperature and pressure. Experimental data appropriate to process conditions will sometimes be needed. Dust explosion data for explosion-venting calculations are presented in NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* which includes additional references. A considerable amount of dust explosion data can be obtained from various U.S. Bureau of Mines and NFPA publications.

Process Hazard Analysis

Hazard evaluation activities can be accomplished by trained plant personnel working with outside specialists when required. It is the hazard evaluation team's responsibility to study the process operation thoroughly, identify all the potential fire and explosion hazards, and recommend changes or further reviews to eliminate or control the identified hazards. A written report of the evaluation must be developed and should include the following:

- List of participants
- Methodology(s) applied
- List of documents, such as part and identification (P&ID) numbers and issue
- Summary of the findings
- Recommendations

All hazard evaluation reports, recommendation status reports, and follow-up documentation should become part of the process documentation file.

An organized approach is essential to conducting effective and efficient hazard evaluations. Hazard evaluation techniques include the following:

- Safety review
- Checklist analysis
- Relative ranking indexes
- Preliminary hazard analysis
- What-if analysis
- What-if/checklist analysis
- Hazard and operability (HAZOP) analysis
- Failure modes and effects analysis (FMEA)
  - Fault-tree analysis
  - Event-tree analysis
  - Cause-consequence analysis
  - Human reliability analysis

Each technique has specific application benefits, limitations, resource needs (staff, time, budget), and documentation requirements. It would be impossible in this chapter to describe each technique. An excellent reference that addresses those techniques in detail and provides illustrative examples is the Center for Chemical Process Safety's (CCPS) *Guidelines for Hazard Evaluation Procedures with Examples.*[4]

Pre-Start-Up Safety Reviews

A pre-start-up safety review should be performed for new facilities and for modified facilities when there may be changes in process safety information. The pre-start-up safety review should confirm the following:

- Construction is in accordance with design specifications.
- Safety, operating, maintenance, and emergency procedures are in place and adequate.
- Recommendations from insurance reviews and any process hazard analysis are adequately resolved.
- Operating procedures are in place and employees are trained.
- Fire prevention and protection systems are in service.

Mechanical Integrity Programs. A primary fire prevention objective is to prevent the release of flammable and hazardous materials from containment. A quality mechanical integrity program (MIP) is a key element in meeting this objective.

The purpose of an MIP is to ensure the safe operation of process and safety equipment through design, inspection, testing, preventive maintenance, and quality assurance monitoring.

The MIP policies and practices at facilities handling flammable and hazardous materials will have a major influence on the level of failures and accidents experienced. Establishing comprehensive programs is a key ingredient in successful loss prevention and control management and should include the following:

- Identification of all critical equipment requiring inspection, testing, and preventive maintenance
- Procedures and schedules for inspecting process vessels, piping, and associated process equipment and safety and protection systems
- Procedures and schedules for testing critical protective devices, such as pressure-relief valves, detection and alarm interlocks, emergency generators, and fire protection systems
- Quality assurance procedures to ensure corrective maintenance functions, employee qualifications, replacement part specifications, and so on

Systems that protect facilities and personnel from hazardous situations (e.g., toxic releases, fire, explosion) must operate effectively and reliably. Emergency safety devices and protection systems generally remain static for long periods of time and, therefore, need scheduled inspection, maintenance, and testing to ensure that these systems function correctly during an emergency. Testing and maintenance of emergency safety and protection devices are very important and must be covered by a formal system with full documentation. Some examples of equipment and systems include the following:

- Pressure-relief systems, vent systems, and devices
- Process monitoring devices and sensors
- Explosion vents
- Electrical grounding and bonding systems
- Dikes and drainage systems
- Gas and flame detectors
- Emergency alarm and communication systems
- Emergency shutdown devices and system interlocks
- Emergency generators
- Sprinkler and water spray systems
- Fire pumps
- Special suppression systems (e.g., dry chemical, foam)

Testing and inspection policies and procedures should follow applicable codes and standards, such as those published by the American Society of Mechanical Engineers (ASME), the American Petroleum Institute (API), the American Institute of Chemical Engineers (AIChE), the American National Standards Institute (ANSI), the American Society for Testing and Materials (ASTM), and the National Fire Protection Association (NFPA), where they exist, or recognized and generally accepted engineering practices.

Fire Protection Systems. An important mechanical integrity program component is the testing and preventive maintenance of fire protection equipment. Facility management must routinely assess the quality of fire protection equipment testing and maintenance programs. Procedures used to conduct this assessment include code compliance reviews, corrective maintenance tracking, maintenance team qualifications, program monitoring and updating, equipment replacement programs, and compliance with appropriate standards. Examples include the following:

- *Code compliance.* Are documented procedures in place that meet current NFPA standards for the maintenance and testing of fire protection systems? Are procedures being properly applied at the required intervals, and are documented/signed-off testing and maintenance logs being maintained and readily available for review?
- *Corrective maintenance tracking.* Are documented corrective maintenance and testing procedures in place, and is a tracking method showing completion-date status with sign-offs to verify completion readily available for review?
- *Maintenance team qualifications.* Are the people doing testing, maintenance checks, and corrective actions properly qualified and continually trained in conducting proper and efficient maintenance and in recognizing and correcting problem areas?
- *Program monitoring and updating.* Do procedures comply with the manufacturer's suggested maintenance for unique and specific equipment functions, and are procedures updated based on the manufacturer's experience, plant-specific experience, and/or equipment modifications?
- *Equipment replacement program.* Are equipment age, operating environment, and availability of spare parts considered in the updating and modification of maintenance and testing efforts, frequencies, and replacement of systems and system components?
- *Compliance with applicable NFPA standards:*

  NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
  NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
  NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
  NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
  NFPA 69, *Standard on Explosion Prevention Systems*
  NFPA 70B, *Recommended Practice for Electrical Equipment Maintenance*
  NFPA 72®, National Fire Alarm Code®
  NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
  NFPA 110, *Standard for Emergency and Standby Power Systems*
  NFPA 780, *Standard for the Installation of Lightning Protection Systems*

NFPA 25 addresses the inspection, testing, and maintenance activities for much of the standard fire protection equipment installed within most facilities, including the following:

- Sprinkler systems
- Standpipe and hose systems
- Private fire service mains
- Fire pumps
- Water storage tanks
- Water-spray fixed systems
- Foam-water systems
- Fire protection valves

Operating Procedures

Written Operating Procedures. It is important to develop and implement written operating procedures that provide clear instructions for safely conducting activities for each process that represents potential hazardous releases, fire, or explosion potential. The written operating procedures should address the following:

Steps for Each Operating Phase

- Initial start-up
- Normal operation
- Temporary operations, as needs arise
- Emergency operations (including shutdown)
- Normal shutdown
- Start-ups following outages

Operating Limits

- Consequences of deviations
- Steps to correct or avoid deviations
- Safety systems and their functions

Safety and Health Considerations

- Properties and hazards of process chemicals
- Exposure precautions, including controls (e.g., engineering, administrative, emergency response)
- Safety procedures for operating equipment
- Control measures in event of exposure
- Any special or unique hazards

Operating procedures should be readily accessible to employees at all times and must be maintained to reflect current requirements.

Flammable Liquid Handling and Ignition Control. The accidental release of flammable liquids or gases from containment and potential ignition present a major loss exposure. An effective management program should address personnel training in the handling of flammable liquids and control of ignition sources. NFPA 30 provides information on this subject. The following highlights some of the management issues, adapted from NFPA's publication, *Understanding Fire Protection for Flammable Liquids:*[5]

- Training of personnel should include the following:
  1. Thorough indoctrination of all employees, including supervisors, in the hazards associated with the storage, transfer, and use of flammable and combustible liquids
  2. Indoctrination of employees in the importance of keeping flammable liquids and vapors confined to closed equipment and containers

3. Indoctrination of employees in the importance of limiting the quantities of liquids in the work area to that amount needed for efficient operations
4. Training of employees in the need for constant attendance during all flammable liquid transfer operations
5. Training of employees in the proper procedure for control and cleanup of leaks and spills

- Control of ignition sources should include the following:
  1. Ensuring electrical equipment and wiring in the area are suitable for the hazard. NFPA 30 and NFPA 70, *National Electrical Code*®, specify the requirements for electrical equipment in hazardous areas.
  2. Not locating any equipment having open flames, hot surfaces, or radiant heat sources in areas where flammable or combustible liquids are used, handled, or stored
  3. Prohibiting the use of friction- and spark-producing equipment in areas where flammable liquids are used
  4. Providing adequate grounding and bonding of all equipment that handles or uses flammable liquids to minimize the accumulation of hazardous static charges. NFPA 77, *Recommended Practice on Static Electricity,* provides the guidelines for grounding and bonding of equipment.
  5. Prohibiting smoking, open-flame torches, and hot work in hazardous areas
  6. Establishing a program to ensure that all vessels, tanks, piping, and process equipment are properly drained and purged of flammable and combustible liquids *prior* to performing maintenance operations

Hot Work Permits. Hot work—that is, work involving burning, welding, or similar operations capable of initiating a fire or explosion—is common in the industrial workplace and is also one of the key element programs covered by OSHA Process Safety standard, 29 CFR 1910.119. Hot work continues to be one of the largest causes of fires in industry.

Hot work is defined in NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work,* as any work involving burning, welding, or similar operation that is capable of initiating fires or explosions. Examples of hot work activities include heat treating, grinding, thawing pipe, using powder-driven fasteners, hot riveting, and welding and allied processes (e.g., open-flame soldering, brazing, thermal spraying, oxygen cutting, and arc cutting). Other similar applications, such as grinding, chipping, or abrasive blasting, that produce a spark, a flame, or heat could also be included as hot work. These operations are potentially dangerous, depending on the type of work being performed and the environment in which it is performed. Details regarding the management of a hot work program may be found in Section 9, Chapter 6, "Welding, Cutting, and Other Hot Work."

The centerpiece of an effective hot work program is the hot work permitting process. The three steps to consider for hot work permits are recognition, evaluation, and control. Once the hazard is recognized (in part through the use of the facility-specific checklist on the permit), the extent of the hazard can be evaluated. Based on the severity of the hazard, a control can be developed to minimize or eliminate the hazard, which is then recorded on the permit. The control can include moving the hot work or combustibles, isolating the combustibles, and assigning a fire watch. The hot work permit, which is the start of any good hot work program, is a tool that assists the permit authorizing individual (PAI) to perform all three of these steps in coordination with the person performing the hot work (operator) and the fire watch (see Figure 12.11.4).

FIGURE 12.11.4 Fire Watch Monitoring a Hot Work Area

Precautions for hot work are as follows:

- Hot work should be prohibited in areas where sprinklers are out of service.
- Hot work should not be done in a flammable liquids room unless all liquids are removed.
- Sparks or molten metal should not be permitted to pass through doorways or cracks or holes in walls and floors.
- All exposed combustibles should be moved a minimum of 35 ft (10.7 m) from hot work operations. Noncombustible curtains must be used between the operation and combustible materials when adequate separation cannot be maintained.
- Floors should be swept clean. Wood floors should be wet down or covered with a protective shield, preferably sheet metal.
- Fire extinguishers must always be available at all hot work operations. Any extinguishers that are used should be replaced promptly.
- The immediate area and areas on floors above and below should be inspected for a minimum of 30 minutes after completion of a hot work operation for any sign of smoldering or damage caused by hot slag.
- When oxyacetylene equipment is not in use, the gas should be turned off at the cylinder valve.

Hot work done by an outside contractor should be closely supervised to ensure compliance with the hot work permit system. Approximately one of every three hot work fires reported occurs while outside contractors are engaged in hot work operations.

Fire System Impairment Procedures. Many large fire losses have been directly attributed to impaired fire protection systems or equipment. Major property insurance companies, during routine facility inspections, continue to find fire protection systems of all types out of service. The need for an effective impairment notification program is evident to eliminate the possibility of undetected shutdown of fire protection systems.

A protection system may become impaired for a number of reasons (e.g., maintenance, renovation, construction, equipment failure, or failure to reactivate the system or device). Facility managers and loss control managers should be notified *immediately* of any impairments during normal working hours. During off-hours, depending on the seriousness of the impairment, these same individuals may still want to be notified. This procedure should be addressed in detail in the company policy.

Any impairment program should require the following:

1. Assigning responsibility and authority to control the impairment to one individual. This is normally a plant engineer or fire protection safety supervisor. In an emergency, a shift supervisor or fire brigade chief may have the authority to impair a system, but the overall responsibility for the impairment remains with the loss control manager.
2. Educating plant personnel in basic precautions to be taken when a protection system or equipment is impaired. Precautions include the following:
   - Limiting the number, scope, and duration of impairment
   - Supplementing manual fire protection with extra extinguishers
   - Avoiding hot work operations
   - Shutting down any hazardous processes
   - Completing impairment work in a timely manner
   - Restoring protection system on completion of all work
   - Verifying, by testing, that the protection system is operational

The three forms of impairment are (1) concealed, (2) emergency, and (3) planned.

A concealed impairment is an unknown impairment. It occurs when a fire protection system is left out of service or removed from service by an unauthorized person. Concealed impairments should be discovered during activities conducted as part of a facility's fire protection maintenance and inspection program.

Emergency impairments are caused by unexpected events impairing the normal function of the protection system (e.g., a section of sprinkler piping freezing and bursting). Emergency situations are normally associated with confusion and a sense of urgency. To eliminate much of the confusion, a written procedure should be in a location available to all personnel.

When handling emergency impairments, the following steps need to be performed:

1. Isolate the area where the situation, or condition, is causing the impairment. If possible, the remaining protection system should be kept in service. Doing so may require temporary connections or bypasses.
2. Notify the shift supervisor and fire brigade chief that an impairment has occurred. Institute frequent patrols of the impaired area for fire safety issues.
3. Secure any hazardous production operation in the area where the protection system is impaired.
4. Properly tag out the impaired system or equipment.
5. Start repairs on the impaired system once the area is secured. Work on the impairment should continue until it has been restored to service. Hot work required for the repair should be performed in a protected area.
6. Place additional portable extinguishers and/or charged fire hoses in the impaired area at accessible locations.
7. Notify the public fire department that emergency impairment has occurred and the extent to which the protection system is out of service.
8. Notify the alarm company of the impairment, indicating whether any alarms have been affected.

A planned impairment is a scheduled impairment, typically involving improvement or modification to the present system. Such impairment might involve adding a new section of sprinkler piping or changing old sprinkler heads. When work has been completed, it is important to ensure that fire protection is properly restored. Each of the several steps required should be verified by the individual who authorized the impairment. These steps include the following:

1. Opening all valves that were secured during the impairment and conducting a drain test (Note: If during the test the pressure drops below normal, the system may have a restricted or partially closed valve.)
2. Placing all alarms and/or detection devices back in service

3. Restoring any fire protection equipment to "automatic" that was either secured or placed in "manual"
4. Verifying that portable extinguishers are in place and fully charged and hose lines are returned to racks or reels
5. Notifying plant supervisors (shift supervisors and fire brigade chief) that the fire protection system has been restored
6. Notifying the alarm service or central stations that the fire protection has been restored and that alarms will be verified
7. Notifying the public fire department that the fire protection system has been restored to service and all alarms activated

Self-Inspection. The effectiveness of operating procedures relies heavily on human actions, management oversight, and compliance to established procedures. It is essential that these procedures are audited on a routine basis to evaluate how well they are working and to identify any needs to improvement.

Management must take a positive approach in establishing a program for the periodic auditing of all operating procedures and systems. These audits should be conducted by individuals knowledgeable in the procedures and systems and include a procedure for documenting all findings and reporting them to appropriate levels of management. For those deficiencies that are severe and could be of imminent danger, the facility manager should be notified immediately and should take immediate corrective action. Key areas for self inspections and audits include the following:

Written Operating Procedures

- Check that written procedures are current.
- Ensure that employees are familiar with the content of written procedures.
- Check that the procedures are specific in detailing what should be done during abnormal and emergency situations.

Hot Work Permits

- Decide whether permits are required for all hot work activities.
- Review any facility standards or written procedures governing hot work control.
- View a sample of recently issued work permits for completeness and accuracy.
- Determine whether permit authorized individuals (PAIs) and fire watch personnel are trained.
- Check whether there have been any recent hot work–related fires and whether they were investigated. Determine whether recommendations from the investigation have been implemented.

Fire System Inspections and Impairments

- Review fire equipment inspection records for completeness and timeliness.
- Conduct field inspection of fire systems to ensure conditions match the inspection records.
- Conduct field inspections of fire water control valves and fire water supplies looking for any signs of system impairment.
- Request that facility personnel who are assigned to conduct fire system inspections demonstrate the methods used for their inspections and tests.

Flammable Liquid Handling and Ignition Control

- Check whether employees have a basic knowledge of flammable liquid terminology and hazards.
- Determine if storage of flammable liquid containers is in accordance with NFPA 30.
- Determine whether appropriate safeguards have been taken with open handling of flammable liquids.
- Check that gravity dispensing of flammable liquids uses flame arrestors and self-closing valves.

General Facility Loss Control Conditions

- Check whether poor housekeeping, waste, and combustible materials accumulations exist.
- Determine if careless smoking occurs.
- Check for the presence of oily rag storage in noncombustible containers with lids.
- Determine whether electrical switch gear is blocked and if there is storage of combustible material in electrical rooms.
- Check for improper maintenance of electrical conduits and junction boxes.
- Determine whether there are abnormal amounts of combustible in-process or finished products in areas where fire protection systems have not been adequately designed for this overload.

To simplify facility self-inspections, many property insurance companies and trade associations offer forms with items specific to many different types of occupancies and equipment. Forms should be specific enough to be usable and comprehensive enough so that no element of prevention or protection is overlooked.

Management

Employee Training. Employees should be educated in the hazards involved in the job and in the functions of emergency safety control and fire protection equipment. Employee training should be well documented. This includes initial, refresher, and supplemental training and certification. Initial training requires that all workers involved in a process, as well as newly assigned workers, be trained in the basics of the process, operating procedures, and associated hazards. Refresher and supplemental training should be given at least annually. After training, the employer should certify that workers have received and successfully completed the specified training.

Contractors. Prior to the commencement of work, contractors working at a facility or plant should be informed of the potential hazards of fire, explosion, or toxic releases. Contractors must be trained in the plant's safe work practices, and hot work procedures and be instructed in the provisions of the plant's emergency response plan.

Management of Change. Making design or operational changes that may affect the process hazard level without formal

review and authorization can lead to serious fire or explosion incidents. To reduce this potential, a management of change (MOC) program should be implemented. This program should establish written procedures to manage and document any changes to facilities or to process chemicals, technologies, or equipment, including fire protection equipment. Procedures should address the following:

1. Change of elements
   - Technical basis for the change
   - Impact on safety and health
   - Modifications to operating procedures
   - Necessary time period for the change
   - Authorization requirements for the change
2. Employee training prior to implementation
3. Revision of process safety analysis information
4. Revision of operating procedures

New Construction. Loss control managers should be directly involved in new construction project planning. Responsibilities should include the following:

1. *New construction site evaluation.* The loss control manager should determine if the following conditions exist at the site under consideration:
   - Adequate water supply to meet fire protection requirements
   - Exposure to flood
   - Exposure conditions involving adjacent facilities
   - Acceptable support forces, such as public fire departments, disaster relief, and medical teams
   - Impediments to quick response by support forces (e.g., lift bridges, railroad crossings, or heavily traveled highways)
2. *Facility and protection systems planning.* The following are loss control factors to be considered during the planning stage:
   - Using fire-resistant materials
   - Limiting the size of fire areas by the use of fire walls, fire doors, and so on
   - Segregating unusual concentrations of values (e.g., sensitive equipment and highly hazardous operations)
   - Ensuring emergency exits are adequate in number, size, and location
   - Providing physical protection (e.g., automatic sprinklers, hydrants, and standpipes)
   - Providing access for fire protection vehicles
   - Considering design for earthquake, wind, and heavy snow or rain
3. *Production operations involving new equipment or modifications.* Loss control management should participate in process planning, which may require the following:
   - Segregation to limit exposure from other operations
   - Special protection/suppression systems
   - Limited access or improved security
   - Special exit facilities
4. *Fire protection during facility construction.* Loss control management personnel should participate in the following duties:
   - Advising contractor personnel of loss control management policies (facility personnel must have authority to enforce compliance)
   - Acceptance testing of all fire protection equipment
   - Monitoring construction for compliance with specifications

Incident Management and Investigations

Emergency Planning. NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs,* and NFPA 1620, *Recommended Practice for Pre-Incident Planning,* provide a very good framework for developing, implementing, and maintaining a facility program to mitigate, prepare for, respond to, and recover from disasters and emergencies.

Key elements of an emergency plan include the following:

- Identification of hazards, the likelihood of their occurrence, and the vulnerability of people, property, and the environment to those hazards. Typical hazards considered include fires, explosions, earthquakes, floods, windstorm (tornado and/or hurricane), water/liquid damage, and flammable/combustible liquid spills.
- Preplanned response scenarios for identified hazards posing high risk
- An emergency organization within the facility capable of directing, controlling, and coordinating response and recovery operations
- Defined relationships and operational procedures between the facility emergency organization and municipal emergency service organizations
- Preferred methods of reporting fires and other emergencies
- Emergency escape procedures and emergency escape route assignments
- Procedures for employees who remain to operate critical plant operations before they evacuate
- Procedures to account for all employees after emergency evacuation has been completed
- Rescue and medical duties for those employees who are to perform them
- Procedures to ensure that critical fire protection systems remain operational, if at all possible
- Plans for business continuity in the event of a major emergency, including consideration for salvage, cleanup, and the use of alternative locations for conducting business
- Frequency and scope of training for employees based on their emergency responsibilities
- Plans for routine exercises and evaluations of the emergency plan

Prefire incident plans should be developed for each building and be organized in a format that is useful to the facility fire brigade and municipal fire service organizations. It should contain, at a minimum, the following information:

- A review of the facility layout and best access and evacuation routes for each area
- A discussion of facility construction features and their probable reaction during a fire incident
- An overview of facility operations, equipment, and associated fire hazards

- A review of available water supplies, fire pumps, sprinkler control valves, fire department connections, detection, alarms, and special suppression equipment
- Expected areas for spill and firewater drainage and runoff, and anticipated exposures created by them
- A description of available communications and preestablished plans with the responding public fire department
- The requirements for manual fire-fighting efforts, including the most appropriate tactics, equipment, and approach to be used by the brigade
- Information on ventilation systems that may cause the spread of smoke or may be utilized to prevent smoke spread
- An evaluation of chemical hazards and methods to handle spills
- The location of flammable liquid and gas system isolation valves and electrical power disconnects

FM Global provides several interactive tools, at no cost, to the Public/Volunteer Fire Service that aid in the development of prefire incident plans for sprinklered commercial and industrial properties.[6]

Incident Investigations. It is important to investigate every incident that results in, or could have reasonably resulted in, a major release, fire, or explosion accident. Most current investigation methods focus on determining the root cause of the incident and basing corrective actions on the root cause. Incident investigation program factors include the following:

- Incident investigations should be initiated promptly. Several U.S. government regulations require investigation of large incidents begin within 48 hours.
- Investigation teams should have plant and process knowledge as well as other specialties, such as fire loss investigation and root cause investigation skills.
- Incident reports should include the following:
  - Date of incident and date the investigation begins
  - Appropriate collection of relevant evidence from the investigation
  - Description of incident, root cause, contributing factors, and resulting recommendations
- Reports should be reviewed with appropriate personnel within the facility and retained in loss incident files.
- Recommendations should be addressed and resolved in a timely manner.
- Management should routinely review the status of open investigation reports and recommendations.

QUALITY GRADING OF MANAGEMENT LOSS CONTROL PROGRAMS

Example Grading System

It is beneficial to develop a quality rating system for loss prevention and control programs to provide a framework for budgeting and monitoring program investments versus program quality. Table 12.11.1 provides an example format for grading some primary loss prevention and control programs. This general framework can be expanded and customized as needed.

Many property insurance companies use other rating systems to evaluate the quality of a risk. Although the methods used are proprietary, each company assesses the intrinsic hazards of a facility to fire, natural disaster, and the specific hazards of the occupancy. Additional adjustments are made to the assessment based on the quality of the fire protection systems, capability of the fire water supply, the quality of other loss control programs, and status of previous recommendations at a given facility. It is important to understand the specific methods used by a facility's insurance company for rating risk, and this understanding should be part of an annual discussion with insurance company representatives.

The example quality scoring in Table 12.11.1 is based on the following four fundamental quality elements:

1. Planning (+40 maximum points)
   - Explicit goals and objectives (+5)
   - Well-defined scope (+5)
   - Clear-cut desired outputs (+5)
   - Consideration of alternative achievement mechanisms (+5)
   - Well-defined inputs and resource requirements (+10)
   - Identification of needed tools and training (+10)
2. Accountability (+40 maximum points)
   - Strong sponsorship (+5)
   - Clear lines of authority (+5)
   - Explicit assignments of roles and responsibilities
   - Formal procedures (+10)
   - Internal coordination and communication (+10)
3. Implementation (at the facility level) (+40 maximum points)
   - Detailed work plans (+10)
   - Specific milestones for accomplishments (+10)
   - Initiating mechanisms (+10)
   - Execution (+10)
4. Monitoring (program effectiveness) (+40 maximum points)
   - Performance standards (+5)
   - Performance measurement and reporting (+5)
   - Internal reviews (+10)
   - Audit mechanisms (+10)
   - Corrective action mechanisms (+10)

The following quality grading score ranges indicate the program level:

Example Program Quality Grading

- 140–160 Excellent-quality program score (i.e., exceeds minimum requirements)
- 120–140 Good-quality program score (i.e., meets expected program requirements)
- 100–120 Fair-quality program score (i.e., marginal, minor improvements needed)
- Less than 100 Poor-quality program score (i.e., major improvements needed)

A description and discussion of the following program factors are presented in *Plant Guidelines for Technical Management of Chemical Process Safety.*[7]

TABLE 12.11.1 Example of Management Loss Prevention and Control Program Quality Grading

PMS Program Safety	*Planning (S1)*	*Accountability (S2)*	*Implementation (S3)*	*Monitoring (S4)*	*Program Score S1 + S2 + S3 + S4*
1. Process safety information	20	20	30	35	105
2. Process hazard analysis					
3. Pre-start-up safety					
4. MIP—process equipment					
5. MIP—emergency safety systems					
6. MIP—protection systems					
7. Operating procedures					
8. Hot work permits					
9. Fire system impairments					
10. Facility self-inspection					
11. Flammable liquid handling and ignition control					
12. Employee training					
13. Contractors					
14. Management of change					
15. New construction					
16. Incident investigation					
17. Emergency planning					

MIP = Mechanical integrity programs. Points are allocated for example only.

Program Monitoring

Two important aspects of program monitoring are (1) auditing and (2) recommendation tracking.

Auditing provides a means to measure the performance of loss prevention and control programs. Audits document program progress and success and also demonstrate the interest of plant management in maintaining a high program performance quality. Effective auditing provides valuable feedback on the program's strength and pinpoints deficiencies in program areas that may need improvement.

A system for tracking recommended corrective actions resulting from the audit should be established. The system should assign responsibilities and provide a follow-up reporting mechanism that tracks progress and completion of action items.

EMERGENCY ORGANIZATIONS AND INDUSTRIAL FIRE BRIGADES

Fire-Fighting Capability Options

One of the most important aspects of emergency organizations is the creation, equipping, and training of private fire brigades, usually referred to as industrial fire brigades. The potential benefits versus the costs of a fire brigade program must be evaluated. Typical questions asked during this evaluation include the following:

- How much is a brigade program going to cost?
- How much time will employees need to spend in training?
- Who will conduct the training and where will it take place?
- How will time be scheduled for training all members on all shifts?
- Will personnel become more aware of fire and its causes and contributing factors, making preventing fires more likely?
- Will fires that are fought by trained industrial fire brigade personnel be fought more safely?
- Will property loss likely be minimized through prompt action by a trained brigade?

OSHA Subpart L and NFPA 600, *Standard on Industrial Fire Brigades,* provide many options to facility management when the level of facility fire-fighting capabilities are determined.

Option 1. *No employee will fight a fire.* This means that on notification of a fire, all employees will evacuate the facility. If

this option is selected, management must provide the means for protecting its assets and production as well as the integrity of the company. This can be provided through fixed fire protection systems and/or by relying on the local fire department. *Note:* Options 2 through 4 deal with incipient fires. An incipient fire is one that is in the initial or beginning stage and can be controlled or extinguished safely with portable fire extinguishers, Class II standpipes, or small hose systems without the need for protective clothing or breathing apparatus.

Option 2. *All employees will be trained (on an annual basis, at minimum) to use fire extinguishers to fight incipient fires.*

Option 3. *Designated employees will fight incipient fires.* This is the same level of training as required in Option 2. However, only specific employees throughout the plant are trained and are expected to respond to incipient fires.

Option 4. *An organized industrial fire brigade will fight incipient fires.* At this level, the management of the plant has written a specific organizational statement regarding the development of a fire brigade. This statement includes a specific leadership structure, procedures, training, and equipment necessary to perform incipient-level tasks. The organizational statement should be part of the site emergency plan. The brigade leaders must have training exceeding that of the regular brigade member. In addition, special hazards should be addressed in training and procedures for all brigade members. Hands-on training is required on an annual basis.

Option 5. *An organized industrial fire brigade will fight fires beyond the incipient stage.* This option incorporates the more sophisticated organization of Option 4 but adds more requirements. These include assessment of physical fitness, use of protective clothing and positive-pressure self-contained breathing apparatus (SCBA), quarterly training with hands-on training required annually, and higher levels of overall training and education. Fire brigades organized to fight fires beyond the incipient stage must meet the applicable requirements of advanced exterior fire fighting and/or interior structural fire fighting contained in NFPA 600. Option 5 is a significantly larger step than Option 4 in terms of training, organization, and equipment.

Based on the needs assessment of a facility (extent of hazard potential, existing fire prevention and automatic fire protection systems in place, and availability and adequacy of public fire department response), management should evaluate its hazards and select the appropriate option. The considerations for Options 1, 2, and 3 involve appropriate documentation in the facility emergency plan, basic training, and availability of basic fire-fighting equipment including fire extinguishers. Due to the complex considerations involved in Options 4 and 5, the remainder of this chapter will be devoted to them.

Often the type of facility that could benefit from an organized industrial fire brigade does not need a brigade organized to fight fires beyond the incipient stage (Option 5) and would probably find it financially difficult to support one. A team of well-trained individuals equipped to attack incipient fires (Option 4) is relatively easy to develop and maintain. In addition, the incipient fire brigade, due to its proximity to potential fires, its vested interest in the property it is protecting, and its level of training, is an excellent loss control resource. However, many large facilities will need a fire brigade organized to fight fires beyond the incipient stage to meet their loss control objectives.

Fire Brigade Organization

Based on the size and needs of the brigade, it is important that adequate organization and leadership be established. Specific roles and skill competencies for each position within a typical fire brigade are provided in NFPA 1081, *Standard for Industrial Fire Brigade Member Professional Qualifications.* Specific titles such as *chief* and *captain* are not important but are useful for discussing roles and responsibilities.

The *fire brigade chief* has overall responsibility for brigade operations. These include training, equipment, procedures, and maintenance of systems and equipment. The fire brigade chief may report to the *plant emergency coordinator* or may have the dual responsibility of chief and coordinator, depending on the size and needs of the plant. The fire brigade chief should possess qualifications commensurate with the responsibilities of the position.

Assistant chiefs of the fire brigade are the senior fire officers on each shift who report to the fire brigade chief. In this capacity, they are the primary brigade leaders or incident commanders for the typical brigade response on any shift. Personnel in this position generally have other full-time responsibilities. Under the direction of the assistant chief, the *captain* directs a fire brigade crew that is performing tasks such as rescue, fire suppression, salvage, and overhaul. In a small brigade, a *leader* may combine the duties of several leadership positions.

Command and control of fire brigade operations is provided by use of an incident management system compliant with NFPA 1561, *Standard on Emergency Services Incident Management System.* As part of the U.S. Department of Homeland Security's National Response Plan, the incident management system has been expanded to become the National Incident Management System (NIMS). A variety of training courses on the newly introduced National Incident Management System (NIMS) are available through the U.S. Department of Homeland Secuity.

Plant personnel who are selected to participate in the fire brigade must have proper physical, mental, and emotional qualifications, in addition to response availability (which is affected by each person's full-time job assignment). The tasks *brigade members* are expected to perform include regular training, fighting fires, rescue, and any other tasks outlined in the plant's brigade organizational statement.

Based on the occupancy and staffing levels of a particular facility, it may be necessary to include fire brigade support personnel who are not directly involved in fire fighting. For example, an *electrician* is responsible for isolation of electrical circuits in an area or control of specific equipment that the incident commander has directed should be shut down. The electrician should also ensure that the electrical service to fire protection systems is not inadvertently shut down.

A *pipe fitter* is an excellent resource for cycling fire protection system valves or operating process control valves that the

incident commander has determined should be closed to isolate specific piping. Maintenance personnel might respond as *fire pump operators* to ensure that the fire pumps have started or to take any manual actions necessary to ensure their operation. In addition, an operator stands by the pumps to monitor their condition or to take actions as directed to shut down the pumps or return them to regular service (standby or automatic start mode).

Staffing

To determine the number of fire brigade members required, it is necessary to define and document what duties the brigade will perform in the brigade's organizational statement. The brigade's primary responsibilities may include controlling and extinguishing the fire, evacuating threatened personnel, minimizing exposures to other areas, and coordinating the efforts of the public fire department.

In order to ensure the safety of brigade members, all fire fighting must be conducted in teams. Since it takes two fire fighters to operate a mobile 1½ in. (38 mm) hose stream of 75 to 100 gpm (300 to 400 L/min), the need for a team concept is further reinforced. A minimum of a five-member brigade fully clothed in their personal protective equipment would be required to provide one 1½ in. (38 mm) hose line: two firefighters to actively fight the fire; two on standby for rescue in the event something happens to the two fighting the fire; and one to act as the incident commander to coordinate the activities and provide communication. Personnel may also be needed to provide additional equipment, operate fire apparatus, set up smoke fans, initiate search and rescue efforts, and so on. In all facilities, minimum staffing levels must also take into consideration vacation schedules, employee absences, and shift schedules. A roster of two to three times the minimum number of responders is usually required to ensure adequate emergency staffing.

Concurrent with the fire-fighting operation, efforts should be made to reduce the damage caused by the fire and the fire-fighting efforts. This is accomplished through salvage and overhaul operations. Obviously, the more responsibilities expected of the brigade through the organizational statement, the greater the number of members that will be required.

Training

No single item is more important to the effectiveness of a fire brigade than a well-organized and well-documented training program. It is too late to develop skills at the time of an emergency. No brigade member should be allowed or expected to perform a duty at an emergency for which he or she has not been fully trained.

NFPA 600 requires that training sessions be held periodically, commensurate with the type of fire fighting expected by the brigade. The actual training frequency for a specific plant will vary depending on the fixed systems provided, the availability and quality of outside fire-fighting help, the frequency of actual fires, the number and experience of brigade personnel involved, the type and level of training provided, and so on. NFPA 1081 specifies a core set of job performance requirements, as well as site-specific requirements for personnel who perform as members of an organized fire brigade.

Training the brigade can be simplified by using contract agencies and groups such as the local fire department, state or county fire academies, colleges with fire programs, and private interests such as training consultants, the National Fire Protection Association, the International Society of Fire Service Instructors, and the International Fire Service Training Association. Public fire department training grounds are often available in the general area of a plant. These are especially helpful since they are usually arranged to emphasize hands-on training with actual fires. To ensure the safety of all training activities involving live fire hands-on training, make sure that the operation is compliant with NFPA 1403, *Standard on Live Fire Training Evolutions.*

As new personnel are added to the brigade, they should receive an orientation that addresses their responsibilities. This orientation should include classroom training that discusses the theory of fire, plant fire hazards, fixed fire detection systems, fixed fire suppression systems, personal protective equipment with special emphasis on self-contained breathing apparatus (for the structural brigade), and manual fire-fighting equipment available to the brigade. Finally, they should receive sufficient practice in actual fire fighting so that some skill is developed. Plant tours are generally needed to show the locations of fire hazards and fire protection equipment.

Fire-fighting training should be made as realistic as possible and should simulate the actual fire conditions expected. Too many brigades rely on stereotyped training that consists only of outside oil-pit fires or scrap-wood fires. This approach seldom prepares the brigade for the typical interior fires that will be encountered. For brigades that will fight fires beyond the incipient stage, practice with SCBA is especially important, since many plant areas have limited capability for ventilation.

An important part of training is conducting fire drills. Unannounced fire drills should be conducted to check the effectiveness of the brigade response and to identify whether the plant prefire plans are viable. It is during these drills that areas that are beyond the reach of hose lines or that are inaccessible because of equipment locations, locked doors, or other obstructions will be identified. The prefire plans should be revised as needed based on the drill critiques. All drill critiques should be documented. Drills should be conducted in a realistic manner using charged hose lines where possible. Brigades responsible for fire fighting beyond the incipient stage should use protective equipment and SCBA during all drills. Appropriate drills will make responses more automatic under the stress of an actual fire emergency.

The use of computer fire models might be considered as an aid in planning drills. These models can be used to predict likely fire-growth and smoke-spread scenarios. With this information, a more realistic assessment of fire conditions can be made and incorporated into drill scenarios. This same information could be adapted for use in prefire plans.

Fire brigade leadership training must be provided to all persons who may direct fire-fighting operations. Their leadership abilities will often determine the success or failure of the fire-fighting effort. This training should emphasize leadership and fire tactics. The brigade leader should possess a working knowl-

edge of the facility layout, fire hazards, existing protection, and plant operations. All brigade members, but especially brigade leaders, should be trained in the use of an incident management system (IMS). NFPA 1561 contains the minimum requirements for an incident management system, and various training courses on the newly introduced National Incident Management System (NIMS) are available through the U.S. Department of Homeland Secuity.

Pre-Incident Plans

NFPA 1620 provides a good framework for evaluating the protection, construction, and operational features of specific occupancies to develop a pre-incident plan that should be used by responding personnel to manage fires and other emergencies in such occupancies using available resources.

Pre-incident plans should be developed for each building and be organized in a format that is useful to the facility fire brigade and municipal fire service organizations. It should contain, at a minimum, the following information:

- A review of the facility layout and best access and evacuation routes for each area
- A discussion of facility construction features and their probable reaction during a fire incident
- An overview of facility operations, equipment, and associated fire hazards
- A review of available water supplies, fire pumps, sprinkler control valves, fire department connections, detection, alarms, and special suppression equipment
- Expected areas for spill and firewater drainage and runoff, and anticipated exposures created by them
- A description of available communications and preestablished plans with the responding public fire department
- The requirements for manual fire-fighting efforts, including the most appropriate tactics, equipment, and approach to be used by the brigade
- Information on ventilation systems that may cause the spread of smoke or may be utilized to prevent smoke spread
- An evaluation of chemical hazards and methods to handle spills
- The location of flammable liquid and gas system isolation valves and electrical power disconnects

FM Global provides several interactive tools, at no cost, to the public/volunteer fire service that aid in the development of pre-fire incident plans for sprinklered commercial and industrial properties.[6]

Fire-Fighting Equipment

The need for fire-fighting equipment varies widely. Equipment should be provided that is commensurate with the duties of the fire brigade and the hazards that it will encounter. When fire-fighting equipment is mentioned, a fire truck is often initially visualized because it is essential to the operation of public fire departments. Many industries, however, have large quantities of water available at a fairly high water pressure for fire-fighting purposes. Since a fire department pumper is used to transport fire fighters and fire equipment and to boost the water pressure, the pumper is seldom needed by the fire brigade. What is needed is a reasonable distribution of yard hydrants and hose houses, even in remote portions of the yard. NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances,* lists equipment required for hose houses.

Inside facility buildings, a well-designed interior standpipe system, installed according to NFPA 14, *Standard for the Installation of Standpipe and Hose Systems,* distributes hose stations throughout large industrial buildings. However, if the fire blocks access to one hose station, others usually will not reach the hazard. In addition, safety dictates that a backup hose line be established for the protection of the primary fire attack team(s). For these reasons, some means of easily transporting fire hose should always be provided within the plant. A vehicle or cart may be useful to carry additional equipment, especially to remote areas of the plant site.

Fire-fighting and supplementary equipment should be distributed throughout the plant with concentrations at convenient brigade access points. Each brigade member who fights fires beyond the incipient stage must be provided with protective equipment, commonly referred to as "turnout" gear, including helmet, coat, boots, trousers, and gloves, as required by NFPA 600.

NFPA 600 also requires the use of protective hoods to protect the head. Fire brigade members' hands receive a high percentage of injuries, indicating the need for gloves specifically designed for use in fire fighting. Foot and eye injuries are also prevalent. Steel-insole fire boots and fire helmets with eye/face shields will reduce these injuries. In addition, goggles and safety glasses have been shown to be effective in reducing eye injuries where SCBA is not needed. NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting;* NFPA 1975*, Standard on Station/Work Uniforms for Fire and Emergency Services;* NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus for Fire and Emergency Services;* and NFPA 1982, *Standard on Personal Alert Safety Systems (PASS),* cover protective equipment.

Only those familiar with fighting fires inside buildings can appreciate the amount of smoke, heat, and toxic gases generated during a fire. These fire products necessitate the use of positive-pressure SCBA if the fire has developed beyond the incipient stage. The use of protective clothing and SCBA allows fire brigade members to advance safely into a fire area much farther than otherwise would be possible. Because of the limited duration of the air supplied by SCBA during stressful conditions, spare air bottles are necessary.

Specialized equipment may be helpful in conducting fire-fighting operations. Items such as fire-fighting foam concentrate, foam nozzles and eductors, high-expansion foam generators, and handheld infrared heat detectors may be necessary. The need for such special equipment should be identified as a part of the plant fire hazards analysis. Portable communications equipment must be provided if an efficient and safe fire-fighting operation is to be conducted. The brigade leader must have a two-way radio to keep the plant operators and management informed of the situation, to request additional assistance or equipment, and to coordinate the efforts of incoming fire departments. Each fire-fighting team should also be provided with two-way radios to

facilitate communications with the brigade leader. Salvage and overhaul equipment will be needed to minimize water, smoke, and fire damage during and after a fire. Salvage equipment should include such items as ventilation fans (fans will require explosion-proof motors in many manufacturing facilities) and flexible ducts for smoke removal, floor squeegees, water vacuums, and tarps.

All fire-fighting, salvage, and personal protective equipment should be inspected regularly to ensure that it is both available and in good condition. Brigade members should conduct these inspections as part of their routine training program.

Municipal Fire Department Assistance

Regardless of the abilities and resources available to the facility fire brigade, it is a good practice to include the public fire department in pre-incident emergency planning. These personnel may be needed only in the case of a failure of the fixed fire suppression systems or in other unique circumstances, but good emergency planning includes providing for such possibilities. The facility emergency organization should realistically evaluate the local fire department to determine the level of assistance available.

If outside fire departments are to be used, it will be necessary to determine the minimum support they can supply and the response times involved. The number of personnel and response time may vary a great deal in many volunteer departments, depending on the time of day. The number and type of equipment available to respond should also be defined so that pre-incident plans can be developed accordingly.

Another reason for involving the local fire department might be the need for special equipment or capabilities that the facility itself cannot economically provide. These may include the ability to draft water from a static source, such as a pond or river. Departments have this basic capability with their pumpers. However, either the plant or the fire department must provide hard suction hose that may not be needed under normal conditions. The pumper must also be provided with adequate access to the water source. Other equipment, such as ladders, foam generators, and fire hose, should be considered. Compatibility of equipment, such as radio frequencies, SCBA cylinders, and hose threads, should be verified.

Management should not assume that the fire fighters from the local fire department have adequate experience and training in industrial fire fighting. In many cases, local fire department personnel may be most familiar with fighting structure fires with very limited water supplies. Such experience would certainly not provide the average fire fighter with an adequate background for attacking a flammable liquid fire inside a structure. It must be determined what the local fire department is familiar with and the levels of training that are provided for its personnel. The plant may even need to supplement the public fire department's training in the fighting of more typical industrial fires, such as those involving flammable liquids.

It is important to identify the legal relationships involved if the plant is located outside the formal fire department jurisdiction and to develop appropriate mutual assistance agreements. It is equally important to ensure that the incident management systems used by the brigade and municipal fire department are able to be effectively integrated, and determination is made on who will have overall command of an emergency incident (see Figure 12.11.5).

All public fire department personnel should be given periodic familiarization tours of the plant and should be involved in

FIGURE 12.11.5 Fire Brigade Leader Meeting with Municipal Fire Department Representative

pre-incident planning. Pre-incident plans made in conjunction with the public fire department should identify personnel assembly points, general fire attack approaches, equipment needs, and personnel requirements. The pre-incident plan should clearly define who will direct the combined fire-fighting efforts of the industrial fire brigade and the public fire department during an emergency. Plans should include a requirement that outside fire department personnel be escorted by facility personnel, whenever possible, for their safety. Regardless of the amount of time expended by the fire department, they cannot be expected to gain sufficient familiarity with the plant so as to operate safely during an emergency that may generate as much confusion as smoke. Combined drills should be conducted regularly so that the brigade and the fire department can learn to function as a team.

Fire Brigade and Hazardous Materials Response

Since the mid-1980s, there has been a substantial amount of legislation in the United States regarding the handling of hazardous materials and the response to emergencies involving hazardous materials. The most prevalent of these new U.S. federal laws are 29 CFR 1910.120, Hazardous Waste Operations and Emergency Response, and the Emergency Planning and Community Right-to- Know Act, which is Title III of the Superfund Amendments and Reauthorization Act of 1986 (commonly known as SARA Title III).

Under SARA Title III, local emergency planning committees (LEPC) were formed to develop pre-emergency plans. The LEPCs are composed of officials from fire departments, emergency medical services (EMS), law enforcement agencies, community groups, and emergency management organizations, as well as facility representatives from every plant that falls under the hazardous materials reporting requirements of the law.

Each community LEPC should have a comprehensive pre-emergency plan completed for each facility covered under the regulation. These plans should indicate what agencies will handle the response to any facility for which the plans were developed. In some cases, fire brigades may have the responsibility for response to hazardous materials incidents. If this is the case, the brigade must meet the requirements for a hazardous materials (hazmat) response team.

The requirements for a hazmat team include mandatory training, medical surveillance, procurement of necessary equipment, development of standard operating procedures, the use of an incident management system, and others, as required by OSHA 1910.120. Also, specific personnel decontamination procedures must be in place to ensure hazmat team members can safely leave a contaminated area.

The complexity of any plant fire brigade's involvement in hazmat activities will vary according to the chemical hazards encountered, the equipment and training necessary to control expected incidents, and the availability of resources from the community. It will also depend on the level of response expected by the response plans developed by the LEPC and the development of a facility emergency plan compliant with NFPA 1600. This may mean that the industrial fire brigade is not involved at all, is involved only as a first responder agency (which is responsible for recognizing that a hazard exists, calling for trained personnel, and securing the area), or is involved as a hazmat team.

Due to the extensive training time and the cost of equipment, a facility may be financially prohibited from having the fire brigade act as a hazmat team. Management must thoroughly understand and consider the costs and organizational commitment required to maintain a competent hazardous materials response team.

If a fire brigade must function as a hazmat team, management may consider developing a full-time emergency response organization because of the disruption that the additional extensive training and drill time would cause to work schedules. One type of facility where management might consider this decision is a high-hazard facility where outside assistance might be delayed.

Beyond the legislation, NFPA has issued two consensus documents regarding response to hazardous materials emergencies and qualifications for the responders. These are NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents,* and NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents.* These documents provide excellent support in developing hazmat response programs that will aid in complying with OSHA 1910.120 and SARA Title III.

SUMMARY

Industrial fire risk management responsibilities include identifying and evaluating fire and explosion hazards and risks, developing programs and assigning management responsibilities to manage the identified risks, and establishing emergency organizations to control fire and explosion incidents that do occur.

Fire loss prevention programs, which include written operating procedures, hot work permits, fire system impairment procedures, and self-inspections, are a good investment toward minimizing large fire loss potentials. The loss prevention and control program quality grading example provided in this chapter is a good starting point for assessing the quality of existing programs and areas of improvement. Once good programs are established, continuous monitoring and auditing are essential.

A fire brigade can make many contributions to plant risk management and loss control. Assurance that detection and suppression systems are functional and ready for use is a major contribution that is often overlooked. Quick response by a well-trained and well-organized brigade can minimize loss. The time spent developing the fire brigade and the overall emergency organization will raise the consciousness of the general employee toward fire safety. Moreover, it gives employees the message that management is concerned about fire protection and employee safety and, thus, improves employee morale and the efficiency of facility operations.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on industrial fire loss prevention discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™*
NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13E, *Recommended Practice for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems*
NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
NFPA 17A, Standard for Wet Chemical Extinguishing Systems
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 22, *Standard for Water Tanks for Private Fire Protection*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*
NFPA 34, *Standard for Dipping and Coating Processes Using Flammable or Combustible Liquids*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 58, Liquefied Petroleum Gas Code
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 70B, *Recommended Practice for Electrical Equipment Maintenance*
NFPA 72®, National Fire Alarm Code®
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA *101®, Life Safety Code®*
NFPA 110, *Standard for Emergency and Standby Power Systems*
NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents*
NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 601, *Standard for Security Services in Fire Loss Prevention*
NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*
NFPA 780, *Standard for the Installation of Lightning Protection Systems*
NFPA 1081, *Standard for Industrial Fire Brigade Member Professional Qualifications*
NFPA 1403, *Standard on Live Fire Training Evolutions*
NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*
NFPA 1561, *Standard on Emergency Services Incident Management System*
NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs*
NFPA 1620, *Recommended Practice for Pre-Incident Planning*
NFPA 1901, *Standard for Automotive Fire Apparatus*
NFPA 1962, *Standard for the Inspection, Care, and Use of Fire Hose, Couplings, and Nozzles and the Service Testing of Fire Hose*
NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*
NFPA 1975, *Standard on Station/Work Uniforms for Fire and Emergency Services*
NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus for Fire and Emergency Services*
NFPA 1982, *Standard on Personal Alert Safety Systems (PASS)*
NFPA 2112, *Standard on Flame-Resistant Garments for Protection of Industrial Personnel Against Flash Fire*

Chapter 12

Disaster Planning and Response Services

William Van Helden ❑ Terry Stewart

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Key Terms

continuity of government (COG), continuity of operations plan (COOP), disaster planning, emergency operations center (EOC), emergency planning, evacuation, hazard vulnerability analysis, incident command system, incident management system, infrastructure, mitigation, mutual aid, preparedness, recovery, response

Disasters are nothing new. They were a fact of human existence long before recorded history. Humans have lived with them and suffered through them. Many disasters have driven changes in how we live and how society has evolved. The 1666 Great Fire of London, for example, essentially resulted in the destruction of the city but also drove the creation of some of the very first building codes aimed at fostering fire safety. Christopher Wren was charged with rebuilding London and his plans required the use of brick and stone and forbade the use of thatched roofs. Improved sanitation was also a by-product that contributed to a healthier populace.

Natural and man-made disasters over the past four to five years have driven home to many the value of the planning required to handle these catastrophic events. Contributing to an awareness perhaps not seen in recent history were events such as the terrorist attacks of September 11, 2001, and the fear and tension that gripped the nation afterwards. Included in this as well were the anthrax contaminations and other scares, such as hurricanes Katrina, Charlie, Ivan, Francis, Wilma, and Jeanne, and the tsunami in Southeast Asia.

One might imagine that such heightened awareness would mean that almost every entity responsible for disaster operations would have well-thought-out, effective, and proven plans for handling these events. Sadly, that is not yet the case. Consider this: With the publication of this twentieth edition of the *Fire Protection Handbook,* this chapter is the very first devoted solely in this reference book to the subject of disaster preparedness.

For related topics, see Section 1, Chapter 7, "Protecting Against Extreme Events"; Section 1, Chapter 8, "Emergency Management and Business Continuity"; Section 4, Chapter 5, "Strategies for Occupant Evacuation During Emergencies"; Section 5, Chapter 3, "Disaster Preparedness Education"; Section 12, Chapter 17, "Pre-Incident Planning for Industrial and Municipal Emergency Response"; Section 12, Chapter 18, "Pre-Incident Planning for Emergency Response"; and Section 12, Chapter 19, "Community Risk Reduction."

NIMS/ICS APPROACH TO EMERGENCY PREPAREDNESS

National Incident Management System (NIMS) Defined

Pursuant to the U.S. Department of Homeland Security and presidential directives, federal, state and local governments have now been instructed to develop guidelines, standards, and protocols to implement a national incident management system (NIMS). In addition, all state and local governments are strongly encouraged to adopt NIMS as their single approach in order to prevent, prepare for, respond to, and recover from terrorist attacks, major disasters, and other emergencies.

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There have been several approaches to managing large incidents and disasters over the past two decades. Many of those had components similar to those of NIMS, but there was never one unified approach designated by the federal government to be the single all-hazards approach to managing disasters and other related incidents. Typically, the use of NIMS or other forms of incident command models began primarily with the fire service and then began to trickle into other branches of government. NIMS is now the single tool that will be used by all branches of federal, state, and local government, including fire, police, public works, and all other aspects in managing critical incidents.

As NIMS relates to planning, it is essential that every government entity identify who will fill the key roles in the system. Information on NIMS and the specific roles that are incorporated into the system can be found on the U.S. Department of Homeland Security website. On this website is a plethora of information to help local governments plan, including grant opportunities, online training, training via the National Fire Academy and Emergency Management Institute, and other key elements for successful implementation of NIMS. The NIMS incident command structure is based on the following three systems:

1. Incident command system (ICS) (Figure 12.12.1)
2. Multiagency coordination system
3. Public information systems

Core Values and Training

Some of the core values in the use of the NIMS have to do with span of control, unity of command, accountability, resource tracking, and operation of incident action plans. In response to the new NIMS compliance standards, most communities that are striving to be NIMS compliant are facing great challenges in the training aspects. One of the most important things to plan for over the next decade is the initial and recurrent training for all entities that will operate in a disaster setting. The level of training is defined in the NIMS documents from the Department of Homeland Security.

PHASES OF EMERGENCY PREPAREDNESS

Emergency Management Cycle

The four phases in the emergency management cycle are mitigation, preparedness, response, and recovery. As described in the following definitions, these four phases of the cycle make a loop and continually build on one another, with some phases perhaps occurring simultaneously:

1. *Mitigation.* Mitigation involves taking actions to reduce or eliminate risk to people and/or property from future hazards and effects.
2. *Preparedness.* Preparedness may be defined as a balance between the public sector, private sector, and the general populace. Plans are developed with all three of these elements in mind to prepare for, respond to, mitigate, and recover from all hazards.
3. *Response.* The organization responds to the actual emergency event with the goals of saving lives and protecting property by responding with the appropriate resources to care for the public and to begin to restore essential services.
4. *Recovery.* The community and organization begin to implement plans and procedures to attempt to bring normalcy back to that community or organization, while taking into consideration ways to mitigate future events.

These four phases are consistent with NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs,* which was endorsed by the 9/11 Commission for its relevance to the public and private sectors.

Mitigation

Mitigation can be defined as actions that should be taken or accomplished before an event to prevent it from causing disastrous effects or to reduce its impact, including the protection of life and property and ensuring continuity of operations and continuity of government. Considerations in mitigation should be current code compliance, all applicable standards and laws, and the fiscal impact.

Securing funds from the federal government in a post-disaster scenario for mitigation will often be strongly contingent on relationships and agreements between local governments. Therefore, it is essential that all local governments develop a strategic plan to identify those mitigation efforts based on an all-hazards approach. Many communities refer to this concept as a "local mitigation strategy," whereby the strategy helps communities identify areas that continually suffer damage from hazards, identifies means by which to correct the problems, and develops priority rankings for funding these projects.

An all-hazards approach to a mitigation plan must include all threats via a threat assessment and potential impact to a community. All hazards include natural threats, technological threats, and man-made threats. Public officials must be careful not to develop plans that are so rigid that they lack flexibility and diversity because of what might be considered a single major threat, such as a Gulf Coast storm. The public may spend a lot of time planning for hurricanes at the expense of less probable threats such as domestic security–related issues or health-related concerns such as a pandemic flu.

Preparedness

Preparedness may be defined as those plans, procedures, and tasks that are identified by agencies or local governments to allow them to successfully prepare for disasters in both the response and recovery phases. The preparedness phase is the time in which government and businesses have the most flexibility to assign roles and responsibilities to all facets of both the public and private sectors, in addition to educating the public about the critical elements for a successful response and subsequent recovery from a disaster.

Preparedness can consist of almost any action to ensure and improve the safety and effectiveness of a disaster response. Some of the key elements of preparation should be ensuring homeland security, prevention of and response to terrorist events, protecting and restoring critical infrastructure in accordance with the related disaster, preparation for law enforcement activities related

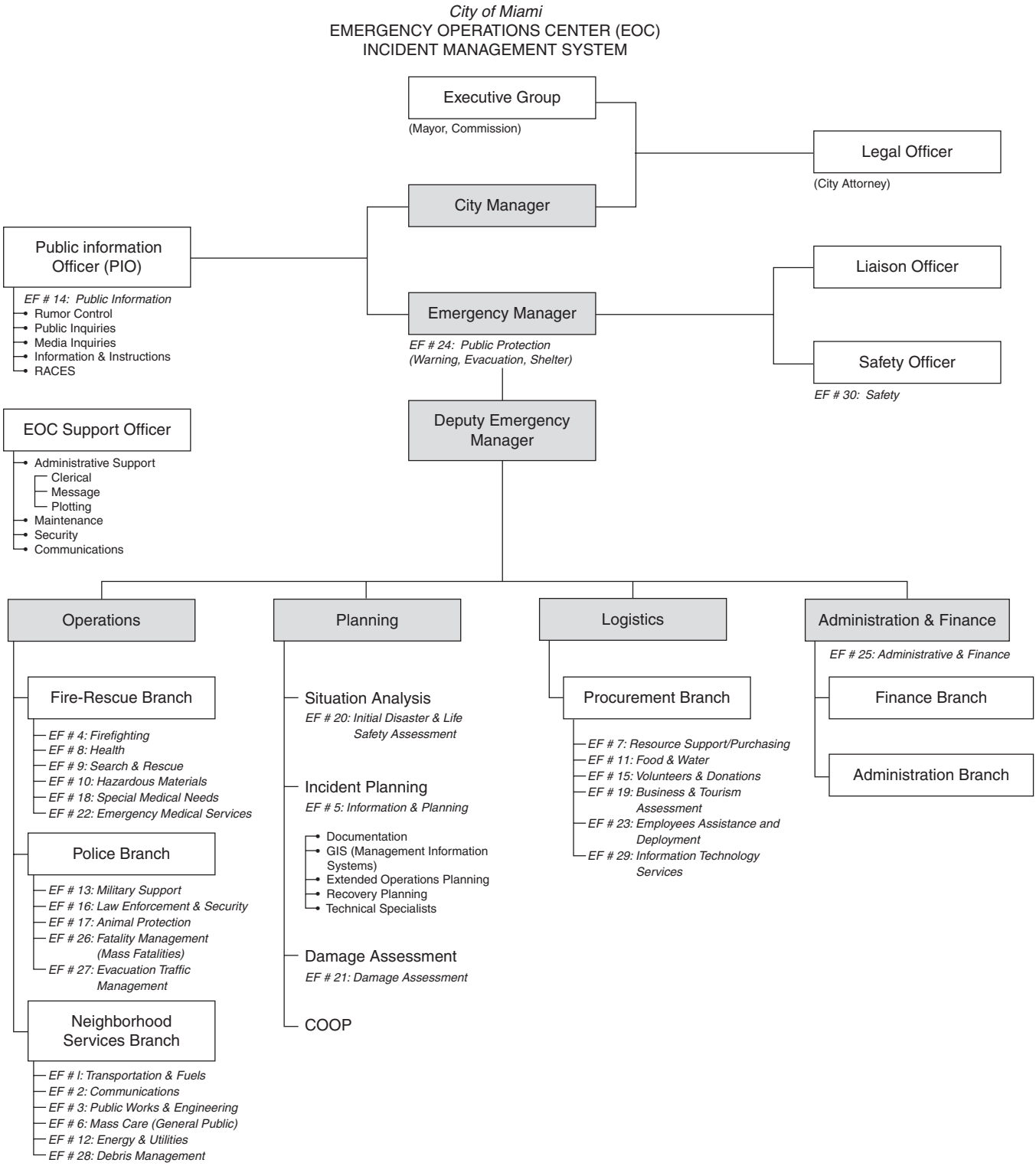

FIGURE 12.12.1 Incident Management System Operations (Courtesy City of Miami Fire Department, Division of Emergency Management)

to an all-hazards approach, and preparedness tasks that will help tie into mitigation efforts and all related recovery issues as noted elsewhere in this chapter. Unfortunately, many preparedness plans designed to be compliant with state and federal guidelines become so comprehensive that they are not practical during a real-time emergency. Therefore, it is strongly recommended that local governments put together a smaller field-operating guide (FOG) or other types of abbreviated versions of their planning

efforts when developing comprehensive emergency management plans (CEMPs).

Emergency plans that define actions to be taken in the field or other areas of government might be further enhanced by plans that present well-defined roles in the emergency operations center setting. The individual organization should clearly define and list roles pertinent to the disaster for which it has planned. Then it should identify potential positions or members of that organization to fill those areas of responsibility, as well as any other associated duties, requirements, and equipment that may be required for that role. All these should be tied into the national incident management system. Plans may be divided into several levels, which would include state plans, regional plans, local plans, and those divided into a specific department or agency. It is essential that all the plans work in concert and build on one another, especially as it relates to the request for additional resources via mutual aid and other agreements. See Section 5.7, Planning, and Section 5.10, Operations and Procedures, in the 2004 edition of NFPA 1600 for additional information about emergency management plans and procedures.

This planning effort should ensure a timely response and a maximum benefit-for-cost recovery in the aftermath of a disaster. As with any plan, if it is never exercised, it will be difficult to determine its potential effectiveness. All plans should have prescribed training exercises to draw those strengths or areas for improvement within the different plans. It is critical that training opportunities include all parties potentially involved and could range from a tabletop exercise to a statewide disaster drill for hazards such as hurricanes, earthquakes, or weapons of mass destruction.

Response

Response may be defined as the use of any and all resources to address the immediate, short-term, and long-term effects of a disaster. The goal of emergency response is to minimize and reduce suffering, loss of life, and property damage and to begin the restoration of essential services to that community. The response phase may be diverse in nature, depending on a variety of different factors, including the hazard itself, available resources, available mutual aid resources, public perception, and support from state and federal governments. Support from state and federal entities is not automatic and may often be contingent on that community's ability to fully and accurately portray the impact. During the response phase, communities must perform an impact assessment.

Impact Assessment. The impact assessment should describe the impact to the community, including the location and number of injuries and deaths, type and extent of damage, and immediate victim needs. The impact assessment should also describe the ability of that community to continue to provide essential services, including medical care, law enforcement, fire rescue, and emergency medical services. Impact to local hospitals and impact to local government infrastructure such as public works and utilities must also be detailed.

During the response phase, the request for mutual aid will be contingent on a community's available resources and needs. The importance of doing early reconnaissance of the community's needs during response cannot be stressed enough. Government officials often underestimate the impact to their local community, thereby delaying the response from state and federal officials. It is of critical importance that first responders and local agencies do not become so focused on the immediate situation that they forget to complete a rapid impact assessment of their community. In a nutshell, information to be reported should consist of the following:

- What has happened
- What is being done about it
- What is needed (specifically)
- What the gap analysis is for the needs of that community

All-Hazards Approach. An all-hazards approach to response may have to include a wide variety of initial first responders. In the event of a natural disaster, such as a hurricane or earthquake, management of debris removal on emergency thoroughfares will be essential to clear roadways for emergency vehicle access. Restoration of essential services such as water, ice, food, and power will also be of critical importance during the response and initial recovery phases (Figure 12.12.2).

An example of an all-hazards approach to hurricane preparedness occurred in many communities in Florida during the 2004 hurricane season, where local emergency responders found many people overcome by carbon monoxide poisoning during the aftermath of various hurricanes. Although emergency responders may be responding to the aftermath of a hurricane (natural hazard), all-hazards planning should include considerations such as carbon monoxide from generators, fuel leaks from overturned vessels in waterways, and other potential hazardous materials incidents that resulted from the hurricane.

However, if the disaster itself takes a different turn, as would be the case from the release of a weapon of mass de-

FIGURE 12.12.2 Distribution of Water and Ice at a Cape Coral, Florida, Point of Distribution (POD) Following Hurricane Wilma, October 2005

struction material, such as smallpox or a pandemic flu outbreak, then the response efforts may be drastically different. Local and state health departments will take key leadership roles in these events. Police and fire fighters may find themselves playing more of a supportive role in the response phase. The key to any response plan and successful operation is flexibility. If communities exercise their plans seriously, they will develop the relationships necessary to carry out a successful response to any disaster. However, if local, state, and federal governments fail to plan, train, and exercise accordingly, local governments' ability to respond to a critical event may be severely hampered.

State of Local Emergency. During either the preparedness phase or the response phase, it is common for local governments to declare a state of local emergency. In the interest of public safety, a state of local emergency is essential for city and county officials to enable them to carry out timely decisions. It is critical to have these states of local emergency and other critical ordinances or laws available and drafted by the local attorney's office in order to enact them in a timely manner.

Critical ordinances should include a state of local emergency, provisions for curfew, price gouging, lines of succession (continuity of government), emergency pay procedures that may already be outlined in a human resources manual, and the activation of local mutual aid agreements.

Recovery

Goals. The purpose of recovery planning is to anticipate what will be needed to restore a community to its full functioning capability. Successful recovery from any disaster is contingent on everyone within that community and the local, state, and federal governments understanding their roles and responsibilities. Recovery from a disaster can last anywhere from days to years, as was witnessed in the aftermath of Hurricane Andrew, which struck southern Florida in 1992.

The overall goals are to maintain leadership and continuity of government, maximize the use of local and regional resources, provide for the coordination of state and federal resources to assist a community in recovery, maintain communication to its citizens before, during, and after an event, provide the maximum support for disaster victims, make maximum use of damage assessment tools for the purpose of recovery planning, promote economic recovery, and bring the community back to some sense of normalcy.

Recovery can be broken down into short-term and long-term phases. Goals of short-term recovery would include restoration of essential services such as utilities; delivery of immediate social, medical, and mental health services; restoration of local government operations; reestablishment of transportation routes; debris management and cleanup; and disaster assistance to the local community, including assistance from both private and public sector organizations such as the Red Cross, FEMA, Small Business Administration, and so on.

The goal of long-term recovery is to restore the community to its predisaster state or an improved condition. Some of the major objectives to long-term recovery would include coordinated delivery of long-term health and social services, long-term housing, improved land use planning, restoration of the economy to predisaster levels, recovery of those dollars expended during the disaster through both public and private sector avenues, and the implementation of any mitigation strategies identified before, during, or after the disaster event.

Recovery Functions. The following is a list of recovery functions that may be utilized during a disaster event; the size and scope of the functions listed are completely dependent on the impact to the community from the disaster:

- Impact assessment (disaster assessment)
- Continuity of government
- Public information
- Human services
- Individual assistance
- Volunteers and donations
- Unmet needs
- Debris management
- Reentry and security
- Health
- Safety
- Repair and restoration of public infrastructure and services
- Building inspections and permits
- Rebuilding construction repairs and restoration
- Housing
- Redevelopment (planning and community development)
- Economic restoration and development
- Environmental concerns
- Mitigation
- Recovery administration and finance
- Mutual aid

Some communities have explored the use of a recovery task force. This task force will consist of key personnel from the public and, potentially, the private sectors who would meet before and after a disaster event to help guide and offer options to local government officials and help expedite recovery from a disaster. Although many communities can survive a minor or major disaster, few are prepared for a catastrophic event. Some of the recovery functions will become critical to the survivability of a community and the timeliness by which it is able to recover from an emergency.

Recovery from minor and major disasters is contingent on local and state response with some federal assistance. However, there must be a well-coordinated effort by federal, state, and local entities for a catastrophic event. How a community plans to recover from a catastrophic event is different from its recovery plans from a minor or major disaster. The initial basic considerations are still the same but the long-term reconstruction, rebuilding, and redevelopment issues can be overwhelming. Nothing will take the place of good planning and exercises that reflect those planning efforts. Finally, excellent relationships must exist between all levels of government in order to be successful in meeting a community's needs immediately after a disaster.

EVACUATION

Evacuations for disasters and catastrophic events can be broken down into two basic categories: pre-event and postevent. Unfortunately, many plans only account for evacuations in the predisaster phase and fail to give equal consideration to the repopulation of a community and/or critical facilities, such as nursing homes and hospitals.

Pre-Event Evacuation

Much consideration has been given in some states for people with special needs and transportation issues. They are two distinct categories. Many people with special needs are those who have a medical encumbrance that requires them to have some medical oversight in their home on a regular basis but does not require the definitive care that hospitalization would provide. Planning for the care of special needs people can be broken down into two categories: those that will require hospitalization due to type of equipment and care they need and those whose care can be satisfied at a special needs shelter (if available) where minimal medical care is rendered. Many communities have worked out interlocal agreements between public safety agencies and local health department officials for providing medical care with some additional support from private sector nursing and paramedics when available.

Some of the population of local communities will require special attention in the area of transportation. This can be one of the greatest challenges for communities with large populations of indigent, low income, and elderly. Communities such as Atlantic City, New Jersey, that are used to moving large volumes of people via mass transit and private busing are used to the concept of timely transportation of people to and from a specific area. This is the exception and not the rule. Many communities do not have enough infrastructure in the form of public transportation to facilitate a timely evacuation of the aforementioned populace.

It is important to have developed procedures and secured contracts with local school board resources, private sector bus companies, and even rail and taxi services. The successful use of this multifaceted approach to obtaining resources for evacuation requires extensive planning and written contracts with an associated cost for securing those services from private industry.

On rare occasions, such as the evacuation of New Orleans in 2005 and the evacuation of critical medical facilities in the Florida Keys, the Department of Defense or the National Guard may be used to supplement the local resources. Although in the past federal resources were typically not deployed until a substantial event occurred, there is a growing consensus that federal involvement must occur earlier and with a much stronger presence than in the past. When addressing such a large need for evacuation, the use of a staging officer is essential for coordination and deployment of resources, fleet maintenance, portable restrooms, and fuel, which are essential to the success of the evacuation.

Most communities lack the transportation infrastructure to handle the evacuation of a significant portion of their visitors and residents from a potential threat. Consideration such as contra flow (one-way traffic) must be put in place prior to the time an evacuation order is given in order to prevent gridlock. Unfortunately, studies have shown that many people make their decisions about evacuation based on local media more than direction from public officials. Therefore, the community should make it essential to pay attention to what the local media is stating about the event and should strive to have the best relationship possible with the local television, radio, and print media.

Postevent

The same consideration that is given to the evacuation of the population before the landfall of a hurricane or the arrival of any threat or potential disaster must be given to the repopulation of those evacuated portions of the communities. Critical to those planning efforts would be the coordination of when essential services are restored to the affected areas and the elimination of the threat and subsequent results from the disaster event.

HAZARD VULNERABILITY ANALYSIS

Information Gathering

A hazard vulnerability analysis is one of the initial steps in implementing a preparedness or mitigation program for a local community. Information gathered in a hazard vulnerability analysis will include FEMA documents, state and local government documents, and firsthand information that can be obtained either from local newspaper archives or interviews from people in the community who were present or participated in previous events. Hazards can be categorized typically either into natural, technological, or man-made events. Hazards can be indigenous to a specific community and they may change from location to location based on geography, population, and other specific elements such as critical or high-profile portions of an area or local government.

Probability Versus Impact

Although there are several models for performing a hazard vulnerability analysis, they all boil down to assessing "probability versus impact." Series of matrixes could be designed that would address the hazard and then the probability, whether it be high, moderate, or low, versus the impact, whether it be high, moderate, or low. From those indices communities can then determine the priority for planning and mitigation efforts for those specific hazards.

Hazards

Different elements or hazards to be considered may include agricultural freezes, air transportation accidents, civil disorder, droughts, floods, hazardous materials incidents, hurricanes, earthquakes, nuclear attacks, power failures, radiological incidents, terrorism, tornados, wildfires, tsunamis, cyber-terrorism, landslides, and heavy snow conditions. Criteria for evaluating the potential vulnerability and associated hazards to a community may be somewhat subjective, but all

communities will have to perform some sort of benefit/cost ratio. Although the threat of terrorism is widespread throughout many nations and large cities, it may be cost prohibitive to invest a large amount of taxpayer dollars into preparing for terrorism in a small rural community. However, that same rural community, depending on its location and hazards, may need to have substantial planning and investment into plans for tornados, earthquakes, hurricanes, or other threats indigenous to that community.

As each organization performs its own hazard vulnerability analysis, it will become readily apparent what the priorities are and where the critical funding should be allocated. A tiered plan or a master plan that would extend planning for those events for 5 or 10 years may be appropriate in order to prioritize the highest threats and eventually address all that could affect that community. See NFPA 730, *Guide for Premises Security,* for additional information on security planning.

IDENTIFICATION OF CRITICAL FACILITIES AND INFRASTRUCTURE

Purpose

The purpose of identifying critical facilities and infrastructure is to prioritize and identify those critical facilities, lifelines, or resources within the community that are essential to protect and ensure limited interruption in services. Usually it is not feasible to identify and perform an analysis on every critical facility in the community, so planners must identify those that are critical for providing essential services to that community and also those that are essential for response and recovery.

Categorization of Critical Facilities

Critical facilities are typically categorized into, but not limited to, the following areas: fire rescue, police, communications, transportation, utilities, government, hospitals, shelters, nursing homes, pump stations, and evacuation routes. When a critical facilities inventory is taken, certain elements of information to be ascertained are very important, and they may include the following: facility type, population and its nature, facility name, owner/operator, location, contact information, address, function, and importance to the community. It is also advisable when identifying these facilities that, in addition to street addresses, the latitude and longitude of the property are determined and maintained in a safe place.

A good example of a critical facility assessment can be found at the National Oceanic and Atmospheric Administration (NOAA) website at http://www.csc.noaa.gov/rvat/criticalEDD.html. Once the critical facilities assessment is completed, it can be used in many of the planning functions described in this chapter. Some of these functions may be given a higher priority depending on the threat. The vulnerability may also rise depending on the threat assessment to that critical facility through both the public and private sector avenues and the implementation of any mitigation strategies identified before, during, or after the disaster event.

RESOURCE TYPING

Purpose

One of the key elements for any successful disaster response is the successful integration of both public and private sector resources into any type of emergency or disaster. Within the national incident management system (NIMS), resource typing is already defined and broken down into different categories such as law enforcement, public works, fire fighting, and the like. Those resources are further defined into kind and type but the overall approach is to make sure all agencies are using one unified approach to categorizing and classifying those resources available in times of an emergency. Some pitfalls experienced by communities in the past have been requesting something as simple as a generator but not specifying the type, the size, or fuel type or not making sure that the generator had the appropriate electrical hookup. Using the principle of resource typing can assure that when a municipality requests a generator to support a specific mission, both the county and the state will understand what the community is asking and can respond in a timely manner.

Mutual Aid Agreements

It should be noted that resource typing is a work in progress and the federal government will continue to further define resource groups and the respective definitive data sets. However, the core elements for resource typing are in place. The specific terms and definitions are listed in the National Mutual Aid Glossary of Terms and Definitions at http://www.fema.gov/preparedness/mutual_aid.shtm#1.

As stated elsewhere in this chapter, all communities should have the appropriate mutual aid agreements in place in addition to contracts with the private sector for the purpose of acquiring resources that a community may not be able to readily provide through its specific governmental entity. Finally, all government entities are encouraged to participate in the Emergency Management Assistance Compact (EMAC), which will allow the timely redistribution of resources across state lines.

CONTINUITY OF GOVERNMENT (COG)

Government infrastructure and the people that work for governments are not immune from the effects of a disaster. Whether it is a disaster that affects a region, such as a hurricane, or one that is more localized, such as a terrorist bombing, infrastructure, personnel, or both will be affected. Since there is no way to predict the level of impact, plans should be made for the most major circumstance.

Although it is often poorly protected or poorly engineered (witness the levee system around New Orleans during Hurricane Katrina in 2005), infrastructure has received the most attention in disaster preparedness. During hurricanes, for example, most communities manage to get buildings boarded up and to bring in supplies in preparation. What is sorely lacking is the preparation needed to ensure continuity of government.

Continuity of Government Defined

Continuity of government is the survival of a constitutional form of government and the continuity of essential functions. Continuity of government is a legal consideration for continuity of leadership in a government organization, whereas continuity of operations is the administrative support for the continuity of government. (See the next section, "Continuity of Operations Plan (COOP)," for more information about continuity of operations.) In general, those functions are viewed as police, fire, and EMS response and also include provisions for public works functions. The broader and more effective the government services available for dealing with recovery, the less devastating will be the disaster.

Emergency Operation Centers (EOCs)

One of the first areas in which continuity planning began to be used was in the development and construction of emergency operations centers (EOCs). A properly designed and constructed EOC provides adequate room and resources to house the logistics and command elements of emergency services. It also ensures a safe location for these elements leading up to, during, and after the impact phase. EOCs have helped to make a significant difference in emergency services' ability to survive intact and continue operations. If the command and logistics structure of emergency services is crippled or destroyed, emergency personnel and their equipment, even if available and ready to serve, would likely not be very effective.

Fire service incident command systems have been a natural fit for dealing with disasters. They demonstrated the value of bringing together and integrating a variety of resources needed to manage an incident. Likewise, operations in EOCs during disasters now include personnel from utilities, transportation, finance, building departments, and so on. Most elements of the governmental structure are now involved and a part of the team, but something is still missing. Assuming that the EOC survives and functions as intended, preserving the command and logistics elements and enabling effective operations into the recovery phase, we could ask ourselves the following questions to help bring into focus why continuity of operations is so vital:

- How long will personnel be able to continue working if computer and data systems are destroyed or inoperable, meaning, among other things, that employees cannot be paid?
- Local governments often find during the recovery phase that certain important decisions must be made. How is that to be accomplished if the elected officials who should make those decisions are not available due to injury, death, or migration?

Continuity Plan Regarding Elected Officials

To ensure continuity of government, the continuity plan regarding elected officials should include the following actions:

- Prepare a plan for the relocation of some or, if necessary, all of the community's elected officials. Determine beforehand who will stay in the community, who will go, and under what circumstances.
- Be sure to enact enabling legislation, especially if the decision process or number of persons required for decisions is different from what it is normally.
- Craft the logistic mechanisms needed to support the distant interaction of the officials, such as telephone, computer, or videoconferencing.
- If the policy calls for elected officials to temporarily leave the community due to a disaster, be sure to preplan for locations in various geographic sites.
- Select alternative locations for your government's public meetings just in case the normal location is damaged, destroyed, or otherwise unavailable. Choose more than one, as an alternative site may be rendered unavailable as well. Citizens want to see that their government is functioning and want to be able to participate as well.
- Be aware that not every community has clear legislation or policy for the ordered succession of power or authority covering its elected officials. Check local legislation and speak with legal counsel to seek guidance on the matter. Do not rely on everyone to "do the right thing" just because a disaster has struck. Egos, alliances, distrust, dislike, and political maneuvering can quickly derail the government's opportunities for successfully handling a disaster. Being in the middle of a disaster and trying to reach resolution on this subject is not an enviable position. Deal with it well ahead of time. Keep in mind that in many communities this is a subject that may require the approval of the voters.

Continuity Plan Regarding Financial Issues

To ensure continuity of government, the continuity plan regarding financial issues should include the following actions:

- In advance, ensure that emergency purchasing mechanisms are established and authorized or enacted.
- Because disasters often severely tax a community's resources, make sure that the chief financial officer works with the CEO (or city manager, mayor, administrator, etc.) to ensure healthy financial reserves, including those specifically designated for major emergencies. Such reserves may serve to offset the cost of less severe emergencies and help to support the overall costs of major emergencies. Remember that federal and state reimbursing agencies do not compensate 100 percent and may refuse to reimburse for certain costs. Adequate reserves will help to bridge any such gap. In addition, those reserves may provide immediate funding availability until commercial paper loans or other bridge-type financing can be accessed.
- Establish and maintain a line of credit such as commercial paper that can function much like a bridge loan. Cleanup after a disaster can cost millions of dollars, money that a community may not otherwise have readily available. Private providers will not do the work for free, and their willingness to continue working in one community versus another community may hinge on the community's ability to pay. The federal government through FEMA and other agencies may provide reimbursement for a good portion of the costs, but be aware of the fact that reimbursement takes time and is not always guaranteed.

- Ensure that the CFO and his or her department have an excellent working knowledge and familiarity with the record-keeping requirements of FEMA and other federal or state reimbursing agencies. Equally as important is the need to properly train and manage the work of personnel who will be doing the record-keeping work in the field. Failure to properly prepare for and manage this function may well mean failure to receive reimbursement. For most communities, that is not an option that will bode well for its future financial health. Any training that is made available by the agencies is an absolute prerequisite.
- Be aware that in the run-up to and immediately after the impact phase of a disaster, it is possible that certain resources may be acquired only with cash. For this reason, it is wise for the CFO to ensure the creation of policies that will allow an adequate amount of cash to be obtained, safely stored, and legitimately accessed. In this case, "safely stored" means the cash is to be kept safe from the effects of the disaster as well as secure from theft or unauthorized access.

CONTINUITY OF OPERATIONS PLAN (COOP)

Objectives of Continuity of Operations Plan

The objective of a continuity of operations plan (COOP) is to ensure that a viable capability exists to continue essential functions across a wide range of potential emergencies, specifically when the primary operating facility is either threatened or inaccessible. The objectives of COOP planning include the following:

- To ensure the continuous performance of essential functions and operations during an emergency
- To protect essential facilities, equipment, records, and other assets
- To reduce or mitigate disruptions to operations
- To reduce loss of life and minimize damage and losses
- To identify and designate principals and support staff to be relocated
- To facilitate decision making for execution of the plan and the subsequent conduct of operations
- To achieve a timely and orderly recovery from the emergency and resumption of full service to all customers

The following are some other considerations that a COOP plan should include:

- Ability to implement the plan with or without warning
- When activated, ability to implement the plan within a 12 hour period
- Capability of maintaining operations for a period of at least 30 days
- Provision for the establishment of alternative facilities
- Provision for alternative means of operating, including telecommunicating (i.e., allowing employees to conduct business from their home or other remote locations via computer)
- Sharing of facilities with other organizations

All COOPs should be tied to continuity of government plans. Other key elements include payroll, accounts payable, and accounts receivable; in order to foster loyalty, employees who are serving the public in the immediate aftermath of a disaster must be taken care of. COOP planning will provide for specifics as to how those employees will be paid in the event that the normal processes in place to pay staff members are no longer possible.

COOP Steps

Steps in conducting a COOP include the following:

1. Identifying the essential functions to that specific organization
2. Identifying which of those functions must continue regardless of the circumstance
3. Prioritizing those functions
4. Establishing staffing and resource requirements in order to carry out those critical functions. Included in this process are succession planning and delegation of authority at least three levels deep for each individual department.
5. Identifying specific systems and/or facilities that must be provided to carry out those functions
6. Identifying any interdependencies among other related functions from that organization and other organizations within the community to carry out those critical elements

Public Works Considerations

As part of COOP, the community should keep in mind public works considerations such as debris management programs, policies to identify participants, and agreements with suppliers.

Debris Management Program. The community should have contracts in place with private providers to accomplish the pickup and disposal of any debris created by the disaster well in advance of any catastrophe. Be sure that the contract provides for specialized handling of certain hazardous or otherwise dangerous materials if needed. It should also have an element that includes provisions for heavy lifting equipment. Such contracts are essential because few, if any, communities have the resources to handle the volume of work to be done. Many communities have what is called a debris management plan in place, which is an all-encompassing plan outlining the procedures for a community to effectively and efficiently manage debris in the aftermath of a large-scale disaster.

The goal of a debris management plan should be to provide a framework for the rapid removal of debris, thereby protecting public health and safety and the business base of a community; ensure that disaster debris is processed in accordance with environmental regulations; minimize the effect on the existing incinerator and landfills in a given area; and maximize federal reimbursement for response and recovery activities.

Even New York City, one of the largest cities in the world, with far greater resources than most communities can imagine, relied on private providers to assist in the cleanup after the 9/11 terrorist attacks. These contracts may enable a community to quickly clear the roadways and allow emergency response as

well as travel routes for other community services. Not the least important of which is that it will also enable a more timely return of the commerce needed to provide resources and support the community's economic health. For a community with rivers, lakes, canals, or ocean access, remember to include those waterways in the cleanup contracts as well, especially where those waterways are navigable.

Establishing Policies That Identify Participants. Establish policies that identify which employees must be available and on what basis. Police, fire, and EMS personnel are accustomed to duty during disasters, but most other employees are not. The changing face of preparedness now recognizes the need for the entire government system to be part of the response. Because these participants are new to this emergency response environment, they may not understand or be comfortable with the demands being placed on them. Inform them ahead of time, adequately train and counsel them, and where possible, provide the support mechanisms to encourage their buy-in. Public works employees are not the only ones who are called on in this response methodology; virtually every government employee will be asked to participate. Personnel involved throughout the process are an indispensable asset for ensuring continuity.

Creating Agreements with Suppliers. Create agreements with fuel suppliers that have resources outside the immediate area. Be sure to include priority clauses in the contracts. Remember to provide for locations and methods to dispense the fuel the community acquires, including power supplies to operate dispensing equipment.

Establish agreements with the local electric utility provider to ensure that the most important facilities receive priority in the return of and maintenance of power. Further explanation of this process can be found in an earlier section, "Identification of Critical Facilities and Infrastructure."

Within purchasing agreements for parts, supplies, materials, and equipment, create clauses to establish how suppliers are expected to interact with other entities during instances of disaster. For example, water and sewer systems often receive significant damage due to uprooted trees, flooding, or other misfortune. The ability to get the systems up and keep them running could hinge on availability of parts and supplies. Do the suppliers normally expect payments within 30 to 90 days? Rather than depending on a supplier's goodwill, it is better to get these matters in writing.

Establish a listing of local heavy equipment resources and persons with the skills to operate them. Various private enterprises may have a variety of such equipment. Knowing who owns the equipment, where it is located, whom to contact, and who can operate it could be most helpful.

Information Technology Systems Considerations

As part of COOP, the community should keep in mind and implement the following information technology systems considerations.

Location of Technology Systems Within EOC. The part of the technology system that directly supports police, fire, and EMS dispatching and record keeping should be located within the EOC. Because an EOC must be designed to withstand and survive extreme natural disasters, it is an ideal location for technology systems. Remember that certain disasters such as radiological incidents or terrorist attacks on the EOC itself will make redundancy essential. A government's technology professionals must plan for redundancy in the system to protect the organization from system failure. Failure of this nature is itself a disaster of sorts. The systems are necessary to keep employee time records and process payroll, to enable accounts payable to process payments for goods and services, and to provide for a myriad of support services and record keeping.

Planning for Redundancy. Establish priorities that determine which systems are to be included in the redundant solution. Decide which elements must remain functional regardless of the circumstances and establish a system hierarchy that will drive the timing of when other elements are to be brought back on line.

Redundancy can be accomplished by contracting with private providers that specialize in this service. It can be done remotely in a different region, or options are available through some providers to bring in systems in completely self-contained semitractor trailers. For small governments with severely limited resources that prevent the acquisition of these services, there is an alternative. It may be possible to identify a similar community in a different region and craft a mutual agreement to provide technology assistance to one another during disasters.

MUTUAL AID AGREEMENTS

Categories of Mutual Aid Agreements

Mutual aid agreements can be divided into three basic categories. The first is the emergency management assistance compact (EMAC). EMAC is an interstate mutual aid agreement that allows states to provide mutual aid to one another through all types of disasters and is managed by the National Emergency Management Association. The next model is the intrastate mutual aid legislation, which is relatively new. This legislation is from the National Emergency Management Association and allows for intrastate mutual aid across different political subdivisions and has been modeled successfully in several states across the country. The third category is a state and county mutual aid agreement. This agreement allows for the deployment of local emergency responders under the auspices of EMAC.

Private Agreements

Private agreements with both the public and private sectors are contracts that can be successfully negotiated prior to a disaster, utilizing the local procurement or purchasing department. Typically, these contracts may have some stipend involved along with a variety of listed performance objectives.

Some communities have taken an all-hazards approach with different private sector models to include debris management, response of emergency generator power, food, comfort stations, rent-a-fence, cell phones, covering structures with tarps, and a

wide range of disaster services. Regardless of where a community is located, the most important aspect is to start building and developing those agreements and relationships needed to be successful in a disaster or emergency scenario.

LEVELS OF DISASTER PREPARATION

As stated in Florida Statutes 252.31 to 252.60:

> *Emergency* means any occurrence, or threat thereof, whether natural, technological, or man-made, in war or in peace, which results or may result in substantial injury or harm to the population or substantial damage to or loss of property.
>
> *Disaster* means any natural, technological, or civil emergency that causes damage of sufficient severity and magnitude to result in a declaration of a state of emergency by a county, the Governor, or the President of the United States.

Levels of disaster can be divided into three basic categories. The first is minor disasters. Minor disasters will necessitate the response capabilities of local government with only minimal need for state or federal assistance. Major disasters are those that will require not only the response of local government but also will necessitate state and federal assistance. Finally, catastrophic disasters are those disasters that require substantial state and federal resources and more than likely will include some support from the military.

Minor Disasters

Minor disasters are those that require the extensive use of local and possibly regional resources to respond to and recover from the specific incident. Critical elements to be considered for minor disasters are local mutual aid agreements, partnerships with both private and public sectors on a local level, coordination with state resources if there are multiple events occurring in the state simultaneously, and creating levels of expectation with both the public and elected officials that response and recovery to this disaster should occur within normal time parameters. Examples of a minor disaster might be multiple wildland fires, a flood, a blizzard, or even a minimal category hurricane.

Major Disasters

Major disasters that exceed local and regional capabilities will necessitate the response from both state and federal agencies. Of course, the type of disaster itself will dictate the type of response from both state and federal officials. There are common considerations for an all-hazards approach to major disasters. They are relationships, relationships, relationships. If local governments have not established the appropriate relationships prior to a disaster event, the success of the response to the event is questionable. Examples of major disasters include hurricanes, major fires, earthquakes, and multiple events of similar magnitude that require the response of local, regional, and state assets.

Local governments must forge relationships with their state and federal counterparts through a variety of different mediums such as drills, meetings, and other affiliations in order to make sure that clear lines of responsibility and communications are defined ahead of time. With recent events in the last decade, it has become readily apparent that communities that lack those relationships are not as successful as those that have forged them in advance. Other key elements in responding to and recovering from a major disaster include interlocal/mutual aid agreements, regional agreements to include multiple states, and a clear understanding of the National Response Plan (NRP) and its capabilities and limitations (Figure 12.12.3).

Typically, one of the chief concerns in major disasters is restoration of infrastructure and essential services. Because of the potential for interruption of these services, it is critical that communities have preplanned for these types of events based on a threat analysis and that they have substantial planning components in place for both continuity of government and continuity of operations.

Catastrophic Disasters

Catastrophic disasters are events that will require substantial state and federal assistance with military involvement. More than likely, catastrophic events will affect a community in a way that will overwhelm both local and state resources at least for a short period. Of great concern in catastrophic events is the loss of infrastructure and local government. Catastrophic events may include major hurricanes, earthquakes, weapons of mass destruction, or even a pandemic incident.

Such considerations as succession planning and relocation of critical facilities are essential and accomplished through COG and COOP planning. From a practical standpoint, if there is time to prepare for a catastrophic event, communities may consider relocating a portion of their resources, both human and material, to other locations that might be out of harm's way. Although relocation would not be practical in a disaster such as an earthquake, it could be a consideration for hurricanes and other events that may lend themselves to time for preparation and planning.

Of great concern to any local government would be a catastrophic event such as a widespread pandemic flu. Such an event would necessitate local governments to plan to operate on their own without the help and assistance of entities such as the state and federal governments. This would require substantial planning for a considerable cutback in essential services to any community. The reason for this change in potential support from other agencies could occur if it was an event that affected the whole country.

It is imperative that in advance of a disaster local government officials communicate to the public clearly and responsibly the officials' ability or their lack thereof to respond in the immediate aftermath of a catastrophic event. The public's personal responsibility cannot be overemphasized in planning for a minor, major, or catastrophic event. The responsibility of government is to give the public as much readily available information as possible in order to allow people to make informed decisions about their own safety.

With each disaster there seems to be a continued reliance on government to perform in a manner that it is not prepared for

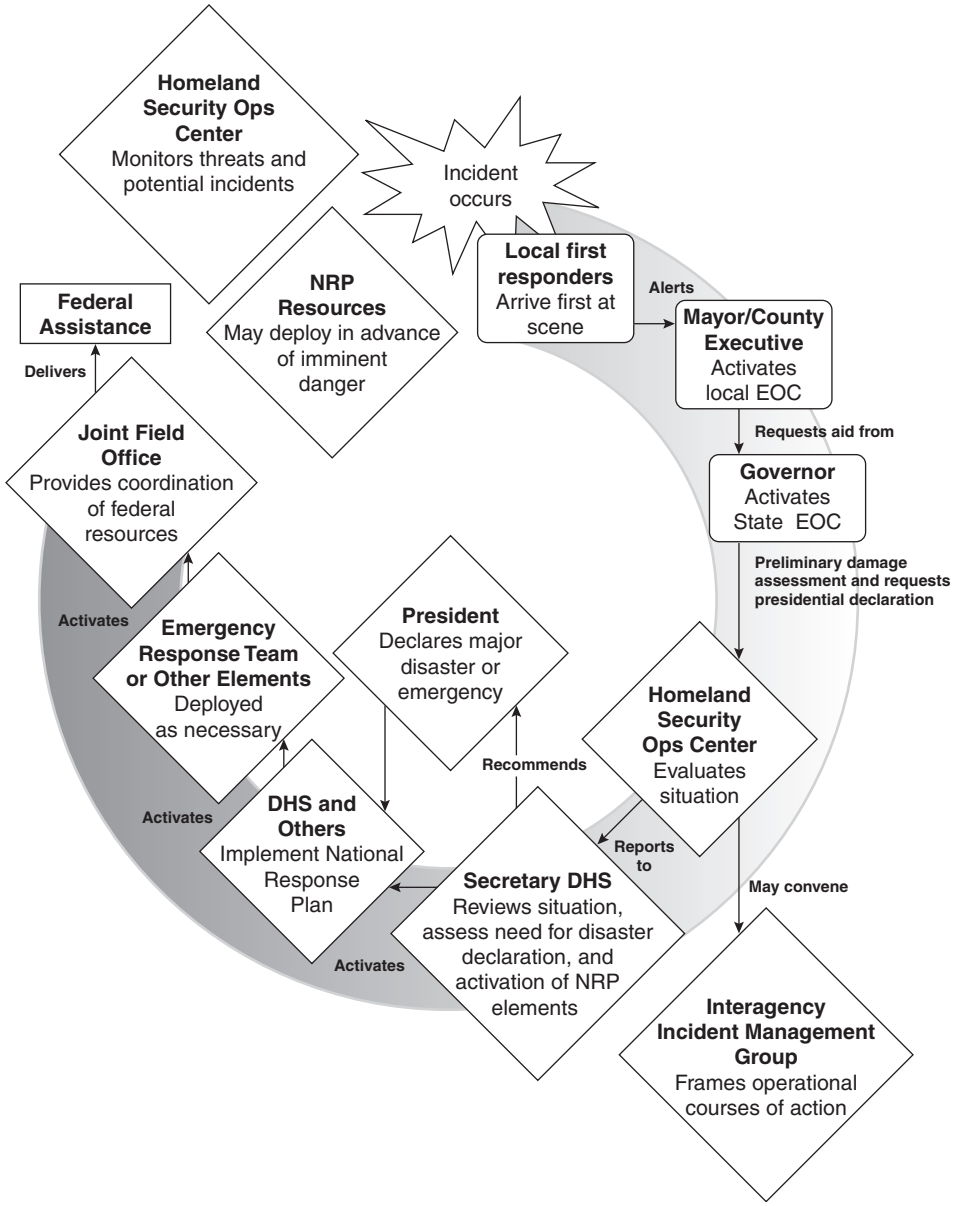

FIGURE 12.12.3 National Response Plan

or may not be equipped to do. In an effort to help mitigate some of these public expectations, it is critical to have a proactive public education program in which local officials are constantly communicating to the public.

GOVERNMENT VERSUS THE PUBLIC'S RESPONSIBILITY

Government organizations in general have become increasingly sophisticated and more efficient and effective in the quality of their responses to disasters. Part of this improvement is a result of constant assessment and refinement of response procedures, some is due to improved training and improved knowledge base of the responders and disaster managers, and another part comes from greater resources to get things done.

Disaster Responsibility in Pre-FEMA Times

In 1964 when the eye of Hurricane Cleo passed over Fort Lauderdale on Florida's east coast, the Federal Emergency Management Agency (FEMA) did not exist. Federal assistance did exist, but it was fractured and divided among many agencies. FEMA was created in 1979 under the administration of President Carter and was brought about by major disasters such as Hurricane Carla in 1962, Hurricane Betsy in 1965, Hurricane Camille in 1969, and Hurricane Agnes in 1972. The Alaskan Earthquake of 1964 and the San Fernando Earthquake in 1971 also tested

the foundations of disaster relief. Presidential disaster declarations were eventually established through the enactment of the Disaster Relief Act in 1974.

The individual citizen in pre-FEMA days did not have the level of resources to rely on that exists today. As a result, the average person understood that he or she had a critical responsibility to properly prepare for the disaster and its aftermath. In recent years, with the increased occurrence of natural and man-made disasters, the resources of local, state, and federal governments have been stretched beyond what officials could have ever anticipated. With so many advances in society today, citizens have grown increasingly accustomed to having their needs fulfilled in very short order.

Government's Responsibility in a Disaster

Although government will continue to strive to provide services at the best possible level, citizens must also remain mindful that their responsibility to take care of themselves and their families does not cease in a time of disaster; in fact, that is when it is more critical than ever that citizens have plans in place and ready to be enacted. An additional responsibility for government to aid in this process is the commitment to continually provide public education tools that will provide guidance to citizens in the development of their personal family emergency plans.

Government must continually shoulder a great responsibility in providing resources for disasters, but that does not relieve each person and each family from the responsibility to do their part in preparing for and surviving such events. Although there is no need to go back to the pre-FEMA days when federal assistance was more meager and fractured, there is clearly a need to regain the greater sense of self-reliance that once existed.

EMERGENCY SUPPORT FUNCTIONS, PUBLIC INFORMATION, AND RESOURCES

Emergency Support Functions (ESFs)

Emergency support functions (ESFs) are those functions that are carried out by federal, state, and local governments in response to a disaster. The initial emergency support function concept was developed by the federal government and contains 10 elements. States have taken the emergency support function concept and have expanded it, and local governments have expanded the concept even further.

The following is a list of the emergency support functions that might be found in a comprehensive emergency management plan (CEMP):

Comprehensive Emergency Management Plan Support Functions

- Transportation
- Communications
- Public works and engineering
- Fire fighting
- Information and planning
- Mass care
- Resource support
- Health
- Search and rescue
- Hazardous materials
- Food and water
- Energy and utilities
- Military support
- Public information
- Volunteers and donations
- Law enforcement and security
- Animal protection
- Special medical needs
- Business and tourism
- Damage assessment
- Public protection to include warning and evacuation
- Administration and finance
- Fatality management
- Debris management
- Safety
- Information technology

To some degree, many of these functions must be accomplished during the preparation, response, and recovery phases. For each function, it is critical that a lead person or organization be designated to carry out the identified tasks. Some functions may be more prominent in the response or recovery phase than others, depending on the threat and the aftermath.

Of significant importance is the ability for incident commanders to ensure that emergency support functions are integrated into a NIMS-compliant plan. There are several models that have successfully integrated these functions. Other communities have NIMS-compliant plans that are less transparent with regard to the emergency support functions. However, all the elements are still incorporated into their response and recovery procedures regardless of nomenclature. The elements described in this section are consistent with successful response and recovery plans.

Public Information

One of the most potentially confusing elements of a disaster occurs in the area of public information. If state and local governments fail to preplan, train, and develop protocol for coordination and communication, they may be creating a recipe for disaster regarding public response and opinion. Under the NIMS plan, a key element for coordination of public information is found in the joint information center (JIC). A JIC, which is an essential point for communication for all local entities involved in disaster response and recovery, is responsible for the overall coordination of public information. This can become essential when disasters cross jurisdictional and geographic boundaries.

Proactive approaches to public information include disaster seminars conducted on potential threats; publications such as an all-hazards brochure that would include all the hazards that may affect a community; and partnerships with local and national media services, which allow for developing and disseminating the multimedia projects a community may develop. Another approach is the use of technology to include interactive websites, DVDs, and other educational tools.

In 2005, for example, the city of Cape Coral, Florida, developed a 30 minute DVD solely dedicated to the process of hurricane planning and preparation as it relates to the unique features and needs of this waterfront community. The DVD has been well received and sought after by residents, businesses, and agencies and is distributed free of charge (Figure 12.12.4). It is also shown on the city's cable access television station regularly throughout hurricane season. Cape Coral's Emergency Management Bureau plans to develop annual updates to the DVD as a continued public education tool for the community.

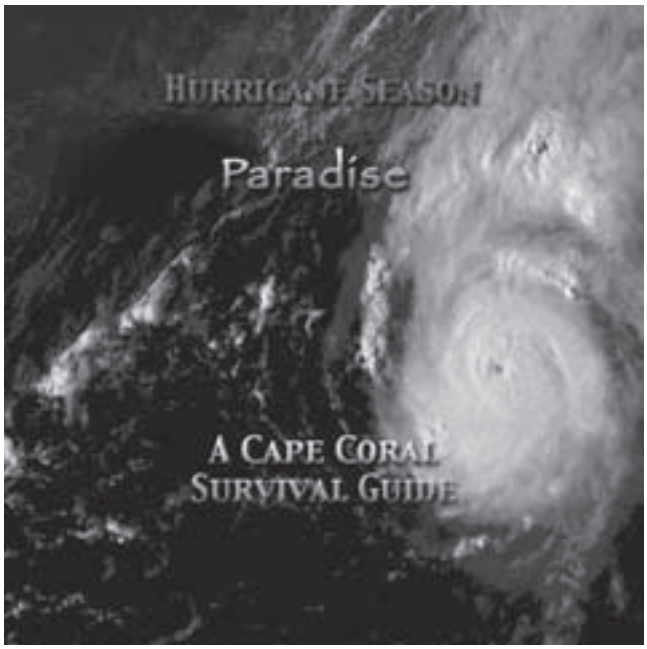

FIGURE 12.12.4 Cover of the Hurricane Preparedness DVD for the City of Cape Coral, Florida

Emergency Planning Resources

The following is a sample of additional resources to help define the context of this chapter and to provide thought processes for emergency planning:

- NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs*
- National Institute for Occupational Safety and Health (NIOSH), http://www.cdc.gov/niosh/homepage.html
- USFA Training and Education Learning Resource Center, http://www.usfa.dhs.gov/fireservice/training/lrc/
- State and local emergency agencies and plans
- International City/County Management Association (ICMA), http://www.icma.org/main/sc.asp
- Emergency management practices text (e.g., *Emergency Management: Principles and Practice for Local Government,* published by the International City Management Association [ICMA])
- National Incident Management System (NIMS), http://www.fema.gov/emergency/nims/index.shtm

RELATIONSHIPS BETWEEN LEVELS OF GOVERNMENTS AND PUBLIC AND PRIVATE SECTORS

Relationships Among Levels of Government

Depending on which arm of government the reader may represent, his or her perspective may differ regarding which one is of greatest importance. The reality is that each segment of government has its own vital role toward ensuring a successful response to a disaster.

Local Government. Local governments are most often in the trenches for the entire duration of disaster events, including during the preparation, response, and recovery phases. They are perhaps best positioned for the preparation and immediate response role. Who could possibly better understand the local area, its citizens' expectations, its needs, and the status of resources that are available?

Local governments, however, are ill positioned to handle catastrophic events without some form of assistance, whether that assistance is financial or otherwise. It is best for local governments to acknowledge this reality and work to better understand and facilitate their interactions with county, state, and federal agencies. Most local governments would find great benefit in developing solid relationships with their municipal or county emergency management agencies. These agencies serve as an invaluable source of support and information as well as a link to state and federal resources and training opportunities.

State Government. States serve their best role in bringing together resources and in managing regionally centered communications. They serve well in disseminating and controlling vital information and resources. Through the National Guard, states are also able to provide significant human resources and materials following catastrophic disaster events. Certain states such as Florida have stepped up the preparation element of their responsibilities by identifying strategic locations to prestage resources so they can be delivered with as little delay as possible.

Federal Government. When considering relationships on the federal level, a city that has not accessed opportunities to train and learn all it can about the offerings, rules, and regulations of FEMA is doing itself a disservice. For example, failure to properly complete the FEMA forms required for reimbursement could at the very least mean extended delays in recieving reimbursement for disaster-related expenditures. At worst, it could cause reimbursement to be denied. Understanding and working well with this federal agency is imperative. A wealth of information can be found on FEMA's website at http://www.fema.gov.

Relationships Between the Public and Private Sectors

Federal, state, and local disaster response organizations can bring together and effectively apply tremendous resources in the event of a disaster. All of those resources combined would still fall short without the addition of private sector resources. This is perhaps never truer than in the disaster recovery phase. When an earthquake, tornado, or hurricane strikes, millions of tons of debris must be removed and safely discarded. Few, if any, governmental entities have the resources to handle this work, yet the private sector does. Private providers can bring together resources from across the nation to accomplish this work and leave local resources available to handle the more routine daily functions required of a community.

Private sector organizations often feel a sense of obligation to their communities and are willing to contribute labor and resources toward recovery. It's important for the local government to have a close and cordial relationship with the private sector. Local government officials should not wait until after the event to begin building that much-needed rapport. If the stakeholders and the extent of their available resources are known, gaining access to those resources becomes much easier. Knowing who has heavy or specialized tools and equipment, who has expert skills, and who may have an inventory of materials needed to handle a major incident can make a huge difference in how rapidly or how well a community can respond.

Consider developing a list of what resources might be needed under various disaster scenarios, such as a tornado, hurricane, infectious disease pandemic, or terrorist attack. To do this exercise properly, include all elements of the response/recovery organization in the list, not just police and fire personnel. Then set about determining which persons or companies in the private sector might have those resources. Contact them and let them know what you are doing and that you may need to rely on them at some future date. You may be surprised at how eager they will be to assist.

Homeowners and neighborhood associations, fraternal organizations, and various clubs and professional groups are other types of resources that can help make a difference. Maintain a database, including names and contact information for the leadership of those organizations. Developing these relationships and contacts in advance may be more helpful than just accessing resources. Such contact information may help you in getting information out to the community in difficult times.

INTERNAL RELATIONSHIPS

Defined Leadership Roles

Disasters are a time of intense danger with little room for error. The circumstances are critical, the stakes are high, and the consequences of failure are dire. If the leadership roles have not been clearly defined or if the responsible persons fail to perform properly, things can go dreadfully wrong. Remember that leadership abhors a vacuum. Where leadership does not exist or where it does not appear to exist, it is likely that someone will attempt to fill the vacuum. Just imagine that scenario unfolding in the midst a major event.

"The way you practice is the way you play," according to a saying in the world of sports. In other words, the things that you routinely do are exactly those things that you will do when the pressure is on. It is equally true when dealing with disasters. If organizational leadership is weak or ineffective, it will not suddenly heal itself when a disaster arrives. If the organization is fractured and operates with only marginal departmental cooperation at best, then that is exactly what will exist during disaster operations. No matter how thorough the disaster plans, if the organization is not accustomed to operating as a team, then the chances for substantial error are significant.

There must be a role for every element of the organization. Those roles must be clearly defined, well documented, thoroughly trained, routinely practiced, and refined (Figure 12.12.5). They must also be respected by those assigned to every other area of responsibility. As vital as they are in certain phases of disaster operations, police, fire, and EMS are not the only important elements of the team. The importance level of any of those three will lessen when in the recovery phase of a hurricane; for example, when it becomes necessary to manage the removal and safe disposal of millions of tons of debris.

Role of the CEO and the Incident Commander

In local governments, a city or county manager or perhaps a strong mayor is the chief executive officer (CEO), that is, the top person in charge of the organization's day-to-day activities. Such is not always the case in disaster situations. Following the NIMS organizational structure, the event, if large enough, needs an incident commander. Depending on the nature of the event, the incident commander may be the police chief, the fire chief, the health department director, or someone else. Regardless of who it is, everyone must allow that person to do his or her job. Unfortunately, a CEO's need to control things can lead to conflicts and leadership confusion. The way for a CEO to avoid that and at the same time to reinforce the incident commander's role is to let him or her do the job and to visibly be there in support.

The flip side to this scenario is that the incident commander must be confident in his or her role to exercise strong leadership, perhaps in the physical presence of someone who is his or her superior in day-to-day operations. There is little question that this is a fine balance, which requires the incident commander and the CEO to carefully demonstrate through cooperation and support that they are a team. If the CEO is observed sending the right message, then it is simple for everyone else to accept and support the incident commander. The best way to avoid leadership conflict is through good communication, which starts with a clear understanding of the scope of each person's role, is reinforced with practice, and is further fortified through careful attention to the team concept.

FIGURE 12.12.5 Command Staff, Including the Mayor, City Manager, and Public Information Director at the Activation of the Cape Coral, Florida, EOC During Hurricane Wilma, October, 2005

SUMMARY

In the aftermath of events such as 9/11, tsunamis, earthquakes, floods, tornados, pandemics, and hurricanes that have affected the world in recent years, it is apparent that public and private organizations must plan for events that might impact their community. Such plans must be comprehensive yet easy to read and implement during a crisis. Planning must be pertinent, practical, and precise. Plans must include all the critical elements for response and recovery and do so in a systematic format to assure consistency and continuous improvement. Disaster planning is not an option in today's world. Public and private organizations must make every effort to be prepared for natural and man-made disasters, to move communities into a state of readiness, and to forge relationships with each other to respond to these disasters.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on disaster planning and response services discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1201, *Standard for Providing Emergency Services to the Public*

NFPA 1561, *Standard on Emergency Services Incident Management System*

NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs*

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National Institute for Occupational Safety and Health (NIOSH), http://www.cdc.gov/niosh/homepage.html

National Oceanic and Atmospheric Administration (NOAA), http://www.noaa.gov

National Response Plan (NRP), http://www.dhs.gov/xprepresp/committees/editorial_0566.shtm

USFA Training and Education Learning Resource Center, http://www.usfa.dhs.gov/fireservice/training/lrc

Chapter 13

GIS for Fire Station Locations and Response Protocols

Russ Johnson ❑ Mike Price

Chapter Contents

GIS Overview
GIS Analysis
Fire Station Location Planning
Response/Travel Time Standards
Determining Fire Station Locations
Fire Station Site Selection Factors
GIS Response Protocols

Key Terms

deployment, emergency management, emergency medical services, emergency response, fire station, geographic information system (GIS), reflex time, response time

The mission of the fire service is to protect life, property, and natural resources from fire and other emergencies. With increasing demands, the fire service must utilize the best tools, techniques, and training methods to meet public expectations. Risk management, preparedness, and mitigation have taken on new importance in light of the challenges facing fire departments today. One emerging tool that is helping the fire service optimize emergency services delivery is geographic information system (GIS) technology.

GIS supports planning, preparedness, mitigation, response, and incident management. GIS extends the capability of maps—intelligent, interactive maps—with access to all types of information, analysis, and data. When a fire occurs, any delay of responding fire companies can make the difference between the rescue of occupants versus serious injury or death. The critical time between fire containment and flashover can be measured in seconds. From the moment an emergency call is received, through the deployment of tactical resources, GIS helps reduce critical time and increases efficiency. GIS technology brings additional power to fire personnel for hazard evaluation, service demand analysis, and resource deployment. This chapter will examine how GIS technology is helping the fire service meet the needs of the community more efficiently than ever.

For related topics see Section 12, Chapter 14, "Fire Rescue Stations and Fire Service Training Centers"; Section 12, Chapter 15, "Public Emergency Services Alarm, Dispatch, and Communications Systems"; and Section 12, Chapter 16, "Fire Department Apparatus and Equipment."

GIS OVERVIEW

GIS Defined

GIS is a technology that integrates geographic features with tabular data to assess and better understand real-world problems. What is now GIS began around 1960 with the discovery that maps could be programmed using simple code and stored in a computer, allowing for future modification when necessary. This was a tremendous change from the era of cartography when maps had to be painstakingly created by hand; even small changes required the creation of a new map. The earliest version of a GIS was known as computer cartography and involved simple line work to represent land features.

GIS Map Layers

Unlike a flat paper map, a GIS-generated map can present many layers of different information that each provide a unique way of thinking about a geographic space. By linking maps to databases,

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Mike Price, a public safety GIS analyst at Entrada/San Juan, Inc., has a BS in geology/geophysics from Prescott College (AZ)/Western Washington University. He has over 30 years of experience in municipal fire protection, public safety, and emergency management and an extensive background in GIS mapping, spatial analysis, public safety modeling, and emergency management technology training.

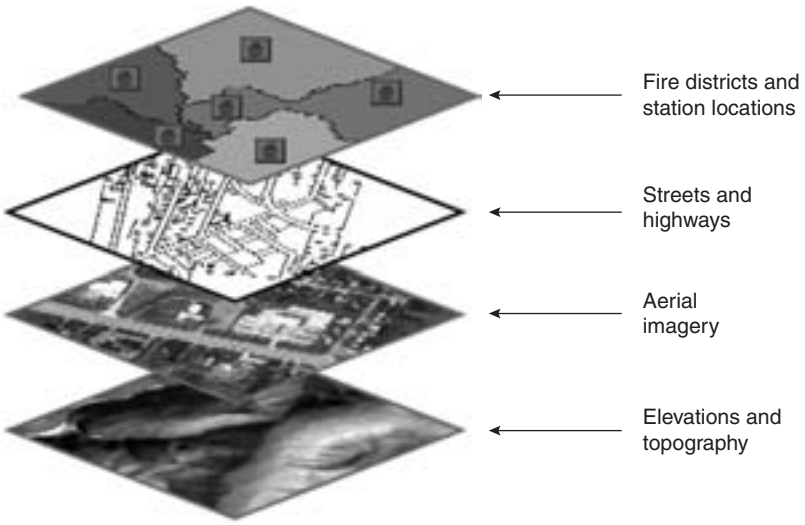

FIGURE 12.13.1 GIS Provision of Data and Information Through Map Layers

GIS enables users to visualize, manipulate, analyze, and display spatial data (Figure 12.13.1). Some GIS map layers that fire departments use include the following:

- Streets
- Parcels
- Fire hydrants
- Utility networks
- Topography
- Lakes and rivers
- Commercial and government buildings
- Fire station locations
- Police station locations
- Hospital locations
- School locations
- Satellite or aerial imagery
- Historical incident or emergency call locations
- Fire districts
- Public occupancies

Map layers can be selected and displayed (overlaid). These layers are linked to data tables that contain detailed information about the geographic features being displayed. The most powerful aspect of GIS is its comprehensive analysis capabilities. GIS analyzes and displays patterns, relationships, and trends through the geographic data layers to help users understand how the world works, make the best choice from among options, or develop plans through what-if scenarios.

GIS ANALYSIS

Incident Analysis

GIS can perform complex incident analysis to display trends, illustrate patterns, and identify areas of high call volume. A GIS display of historical incidents (represented by points or icons on the map where they occurred) includes attribute information for each incident. Attribute information (i.e., descriptive data about a map feature) contained in the underlying database can include the following:

- Incident type
- Incident cause
- Date of incident
- Time of incident report
- Units that responded
- Unit arrival times

Incidents can be queried based on incident type, cause, time, units assigned, or other variables contained in the attribute data (Figure 12.13.2). GIS searches the data tables, gathers data matching the spatial request, and displays the information on the map. Incident trend analysis can be done quickly, displayed

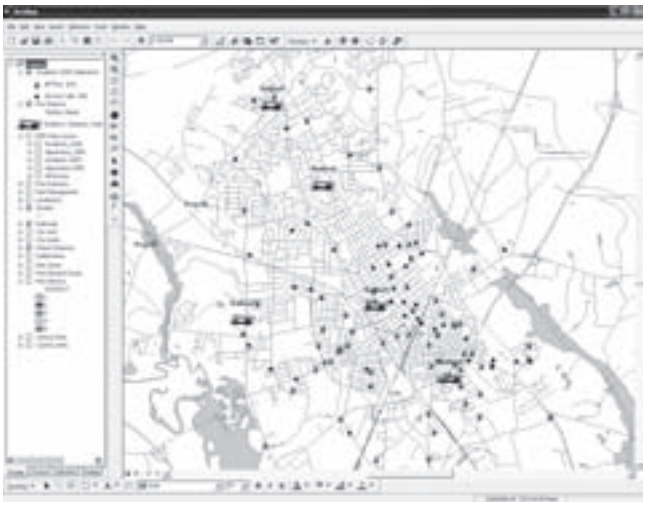

FIGURE 12.13.2 GIS Analysis and Display of Incidents Based on User-Defined Criteria (Time, Location, Cause, Geographic Area, etc.)

logically, and understood easily. For example, a GIS user could request to see arson fires that occurred between the hours of 1:00 a.m. and 5:00 a.m. on Saturdays in Fire Districts 1 and 2. GIS will interrogate the records database and place points on the map that match the request. Such analyses provide decision support for issues related to fire prevention, staffing requirements, and apparatus placement/deployment.

Travel Time Modeling

Using a fire station layer and a street layer, response time analysis can be performed (Figure 12.13.3). A street layer is often represented in GIS as a series of lines that intersect on the map, creating a GIS street network. Each street line segment between intersections contains attribute information such as road type, distance, and travel speeds (miles or kilometers per hour). This allows users to identify a station location, specify a travel time, and run a network analysis. The result will be displayed by an irregular polygon around the station that illustrates where the fire apparatus could travel in any direction for the specified time. This type of analysis can be performed on a single station or simultaneously on all stations to analyze gaps in coverage, establish run orders, and more.

FIRE STATION LOCATION PLANNING

The primary responsibility of a fire department is the delivery of fire and rescue services, normally originating from fire stations located throughout the area to be protected. To provide effective service, crews must respond in the minimum time possible after the incident has been reported and with sufficient resources to initiate fire, rescue, or emergency medical activities. Fire station location planning must take into account a number of variables, including the following:

- Importance of response time
- Flashover
- Fire department total reflex time sequence
- Emergency medical services

FIGURE 12.13.3 GIS Analysis and Display of Travel Times from a Station, Based on Information Contained in Street Centerline File

Importance of Response Time

Time is the critical element when an emergency is reported. Fire growth can expand at a rate of many times its volume per minute. Time is the critical factor for the rescue of occupants and the application of extinguishing agents to minimize loss.

The time segment between fire ignition and the start of fire suppression has a direct relationship to fire loss. The delivery of emergency medical services is also time critical. Survival rates for some types of medical emergencies depend on rapid intervention by trained emergency medical personnel. In most cases, the sooner trained fire or emergency medical rescue personnel arrive, the greater the chance for survival and conservation of property.

Flashover

Regardless of the speed of growth or length of burn time, all fires go through the same stages of growth. One particular stage, called *flashover,* is significant because it marks a critical change in conditions. Depending on room size, contents of the room, and available oxygen, flashover can occur in less than 2 or more than 10 minutes. Flashover occurs most frequently between 4 and 10 minutes. Measuring the time to flashover is a function of time and temperature. Fire growth occurs exponentially; that is, fire doubles itself for every second of free burn that is allowed. This can be plotted on what is known as the time and temperature curve (Figure 12.13.4).

A number of factors determine when flashover may occur. These include the type and arrangement of the fuels in the room, room size, and so on. Because these factors vary, the exact time to flashover cannot be predicted. Flashover can typically occur from less than 4 to beyond 10 minutes after free burning starts. A postflashover fire burns hotter and moves faster, compounding the search and rescue problems in the remainder of the structure at the same time that more fire fighters are needed for fire attack.

There are a number of critical time frames that the fire department can manage, as well as some it cannot, that affect success. The time from ignition to discovery to reporting of a fire is indirectly manageable. This time period can be managed through requirement of automatic detection and/or suppression systems and automatic reporting to the public safety answering point (PSAP). In a perfect world, all structures would be equipped with automatic detection and/or suppression systems. One factor that has helped to manage this segment of time is the increasing use of automatic smoke detectors in residential

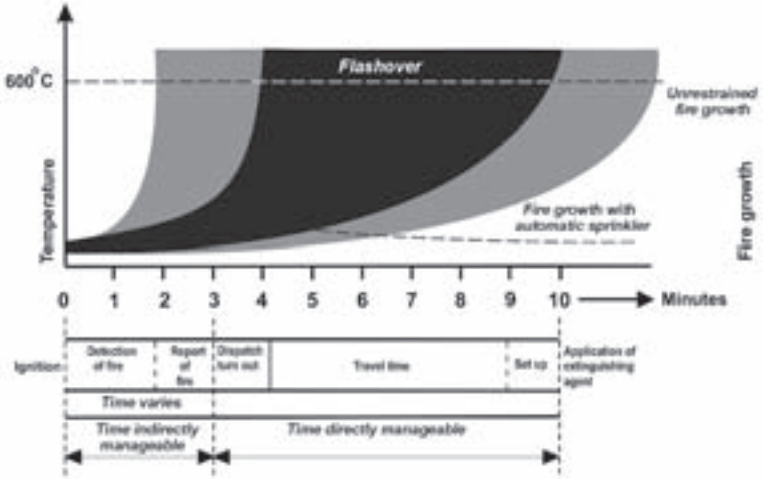

FIGURE 12.13.4 Fire Growth over Time and Sequence of Events That May Occur from Ignition to Suppression

occupancies. What is lacking, however, is automatic reporting to the public safety answering point.

Fire Department Total Reflex Time Sequence

The following are five steps in the fire department total reflex time sequence after receipt of an alarm:

1. Dispatch time
2. Turnout time
3. Response time
4. Access time
5. Setup time

Dispatch Time. Dispatch time is the amount of time that it takes to receive and process an emergency call. This includes the following:

1. Receiving the call
2. Determining the type of emergency
3. Verifying the location of the emergency
4. Determining the resources required to handle the call
5. Notifying the units that are to respond

Dispatch time is manageable by the way that alarms are received and the way that dispatch systems and activities are handled. Enhanced 9-1-1 (E9-1-1) and computer-aided dispatch (CAD) systems can minimize the time required to receive and process alarms.

Turnout Time. Turnout time is the period beginning when units acknowledge notification of the emergency to the initial point of response time. Turnout time may be managed to some degree by improving the method of communications between the dispatch center and the fire station to reduce the time processing the alarm information.

Response Time. Response time is the period beginning when units are en route to the emergency incident and ending when units arrive on the scene (wheel start to wheel stop). Response time is one of the most manageable segments of time in the entire sequence. Travel time can be managed by selecting strategic fire station locations based on the amount of time that it takes to travel from the fire station along the most efficient travel route to the incident scene.

Access Time. Access time is the time required for the crew to move from where the apparatus stops to the emergency. This can include moving to the interior or upper stories of a large building and dealing with any barriers along the way. Access time can be managed through a good prefire planning process that familiarizes the fire fighters with access points, automatic system controls, annunciator panel locations, and travel routes through the building. Key boxes can facilitate getting doors unlocked. Working with security forces at larger facilities to expedite access can also reduce access time.

Setup Time. Setup time is the time required for fire department units to set up, connect hose lines, position ladders, and otherwise prepare to extinguish the fire. Setup time includes disembarking the fire apparatus, pulling and placing hose lines, charging hose lines, donning self-contained breathing apparatus, making entry into the building, and beginning to apply water. The opportunity for saving time during setup is minimal, even for trained personnel.

Emergency Medical Services

The delivery of emergency medical services (EMS) by first responders is also time critical for many types of injuries and events. If a person has a heart attack and cardiopulmonary resuscitation (CPR) is started within four minutes, the victim's chances of leaving the hospital alive are almost four times greater than if the victim does not receive CPR until after four minutes. Figure 12.13.5 shows the survival rate for heart attack victims when CPR is available, and Figure 12.13.6 shows

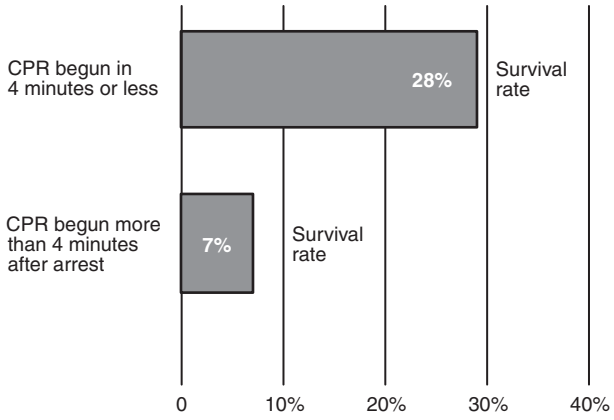

FIGURE 12.13. 5 Survival Rate of Heart Attack Victims When CPR Is Available (Source: Heartsaver Manual, American Heart Association)

the outcome for heart attack victims based on when CPR is provided

For both fire and medical emergencies, the basis for the placement of fire stations should be the amount of time that it takes to deliver adequate emergency resources to the point of demand from each fire station or combination of fire stations.

Reducing Response Times

The most effective way to improve outcomes for both fire and medical emergency response is to reduce response time. By understanding the objectives of each step in the response sequence, a fire department can measure its current performance against these objectives. That information provides the necessary framework for assessing the cost of reducing response time during any of these steps. The rest of this section will describe how GIS can be used to apply a rational decision-making process for reducing overall emergency response time.

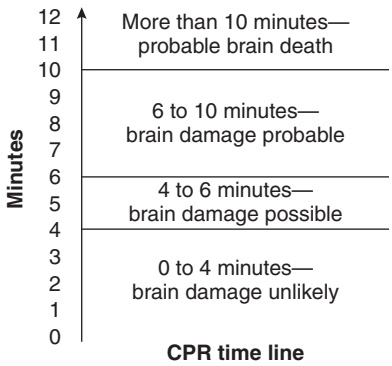

FIGURE 12.13.6 Outcome for Heart Attack Victims Based on When CPR Is Provided (Source: Data from http://www.firstaid.com)

Essentially, each community must decide its desired response and travel times. There are a number of factors that influence the selection of a specific response/travel time. All applicable factors must be considered when making a decision on a specific response/travel time for a community. Factors that should be considered include types of fire department services, reasonable travel time, size of area and type and amount of resources, and acceptable level of risk.

Types of Services. What types of services are delivered by the fire department? Does the department deliver both fire and emergency medical services or fire service only? The delivery of emergency medical services is an important factor in selecting a response/travel time because of the need to provide initial service as rapidly as possible.

Reasonable Travel Time. What is a reasonable travel time for the community? The selection of a response/travel time must be practical. A short response/travel time will enable a department to deliver services within a short period of time but will require more stations. Is there prescription for travel times based on the type of risk, hazard, or demand? Certain hazards or occupancy types may require a faster response time. Response time standards for the community may have to reflect a variation based on these types of considerations. The time or times selected must provide a balance between service expectations and the financial ability of the community to provide the necessary stations and resources.

Area Size and Resources. What is the size of the area being served and the type and amount of available resources? Large rural regions normally have longer response/travel times and fewer resources than urban or suburban areas. For example, a countywide fire response and emergency medical service operated by volunteer personnel will most likely have longer response/travel times than an urban or suburban area staffed by full-time career personnel. The demographics of the area being served and traffic patterns during peak periods, as well as past fire and EMS activity, must be considered.

Acceptable Risk Level. What level of risk is the community willing to accept? When a community selects a longer travel time, it must be willing to accept a larger level of risk. Accepting a larger level of risk may be based on past experience; for example, areas that take longer to reach may be known to have a significantly lower number of incidents.

The selection of a response/travel time for a community should be made after all factors are examined. In many cases, this decision should be made after the analysis has started and decision makers are able to review the results of the analysis.

There are several ways that a community can establish a response/travel time standard. Some of these are (1) the use of historical fire and EMS response data, (2) demand for service, (3) the level of care that the community wants to provide, and (4) the level of care that the community is able to afford. In some cases, the analysis will assist in establishing the standard after a number of scenarios are examined.

RESPONSE/TRAVEL TIME STANDARDS

National Standards

Three National Fire Protection Association (NFPA) standards contain time requirements that influence the delivery of fire and emergency medical services, as follows:

- NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*
- NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments*
- NFPA 1221, *Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems*

NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments.* NFPA 1710 contains time objectives that must be established by career fire departments as follows:

- Turnout time: One minute (60 seconds) for turnout time
- Fire response time: Four minutes (240 seconds) or less for the arrival of the first arriving engine company at a fire suppression incident and/or eight minutes (480 seconds) or less for the deployment of a full first alarm assignment at a fire suppression incident
- First responder or higher emergency medical response time: Four minutes (240 seconds) or less for the arrival of a unit with first responder or higher-level capability at an emergency medical incident
- Advanced life support response time: Eight minutes (480 seconds) or less for the arrival of an advanced life support unit at an emergency medical incident, for incidents in which the service is provided by the fire department

The standard states that the fire department must establish a performance objective of not less than 90 percent for the achievement of each response time objective. NFPA 1710 does contain a time objective for dispatch time in the following requirement: "All communications facilities, equipment, staffing, and operating procedures shall comply with NFPA 1221."

For the purposes of NFPA 1710, the following definitions apply:

> *Dispatch Time.* The point of receipt of the emergency alarm at the public safety answering point to the point where sufficient information is known to the dispatcher and applicable units are notified of the emergency
>
> *Turnout Time.* The time that begins when units acknowledge notification of the emergency to the beginning point of response time
>
> *Response Time.* The time that begins when units are en route to the emergency incident and ends when units arrive at the scene

NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments.* NFPA 1720 contains a time objective for dispatch time that requires "All communications facilities, equipment, staffing, and operating procedures shall comply with NFPA 1221." NFPA 1720 contains requirements for response times related to area population density.

NFPA 1221, *Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems.* NFPA 1221 requires that 95 percent of alarms must be answered within 15 seconds, 99 percent of alarms must be answered in 40 seconds, and the dispatch of the emergency response agency must be completed within 60 seconds at least 95 percent of the time. The time lines for dispatching shown in Figure 12.13.7 and Figure 12.13.8 are taken from NFPA 1221.

Standards of Response Coverage

Other guidelines for the deployment of emergency resources is the Commission on Fire Accreditation International's standards of response coverage. The standards of response coverage process has the following nine parts:

1. Existing deployment
2. Community outcome expectations
3. Community risk assessment
4. Distribution study
5. Concentration study
6. Historical reliability
7. Historical response effectiveness study
8. Prevention and mitigation
9. Overall evaluation

Existing Deployment. Existing deployment is an assessment of the department's current deployment configuration and capability. Included in the assessment is a review of the historical decision-making process of the agency. Is there a reason stations are in their present locations? What equipment has been purchased and why? Can these past decisions be changed?

Community Outcome Expectations. What are the current community expectations for fire protection and emergency service delivery? Included in this process is a review of response anticipated for the variety of fire risks in the community as well as man-made and natural disasters; it also includes EMS, heavy rescue, hazardous materials, aircraft and airport, and water and shipboard incidents.

Community Risk Assessment. What assets within the community are at risk? For example, structure fire risk might be assessed using fire and life safety factors such as fire flow and code compliance for life safety to determine a risk classification. Risk classes might include low, moderate, and maximum risk. Many communities may identify the majority of areas composed of dwelling units as moderate or typical risks. In addition, different responses may be provided to

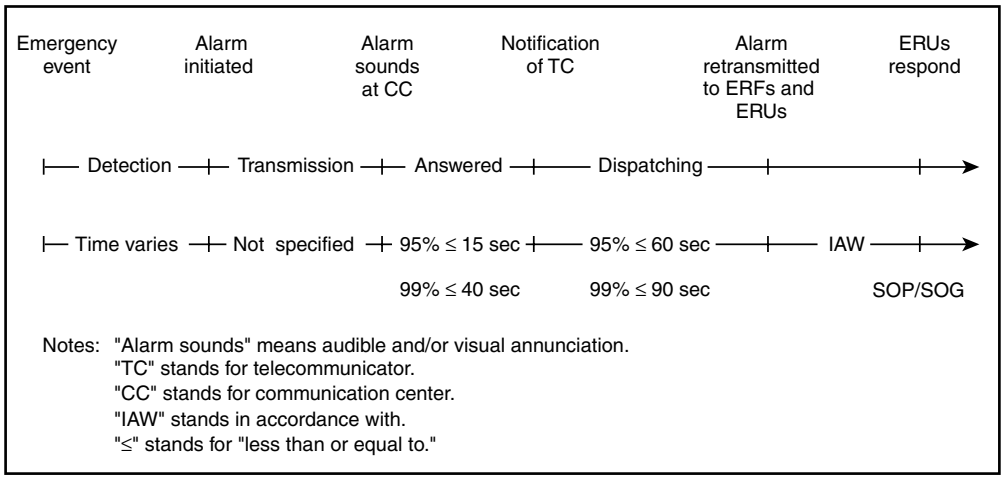

FIGURE 12.13.7 Alarm Time Line Where Primary PSAP Is Communications Center (Source: NFPA 1221, 2007 ed., Figure A.7.4.1[a])

urban, suburban, rural, or remote areas as defined using census terminology.

Distribution Study. Where are the locations of first-due resources?

Concentration Study. Where are incidents concentrated and what is the adequacy of the first alarm assignment or effective response force?

Historical Reliability. Is there a multiple-call frequency issue such as call stacking, or simultaneous calls within a specific area or areas?

Historical Response Effectiveness Studies. What percentage of compliance does the existing system deliver based on current performance goals?

Prevention and Mitigation. Are there tactics that can strategically affect the outcome of events that do occur? The United Kingdom released *The National Plan* in 2004, which replaced earlier standards of coverage documents. The new report found that without prevention and mitigation, the level of safety for responders and the public would reach a plateau. Using analysis of risk and looking at possible strategic actions may not only prevent the incident in some cases, but may also minimize the severity of an incident that does occur.

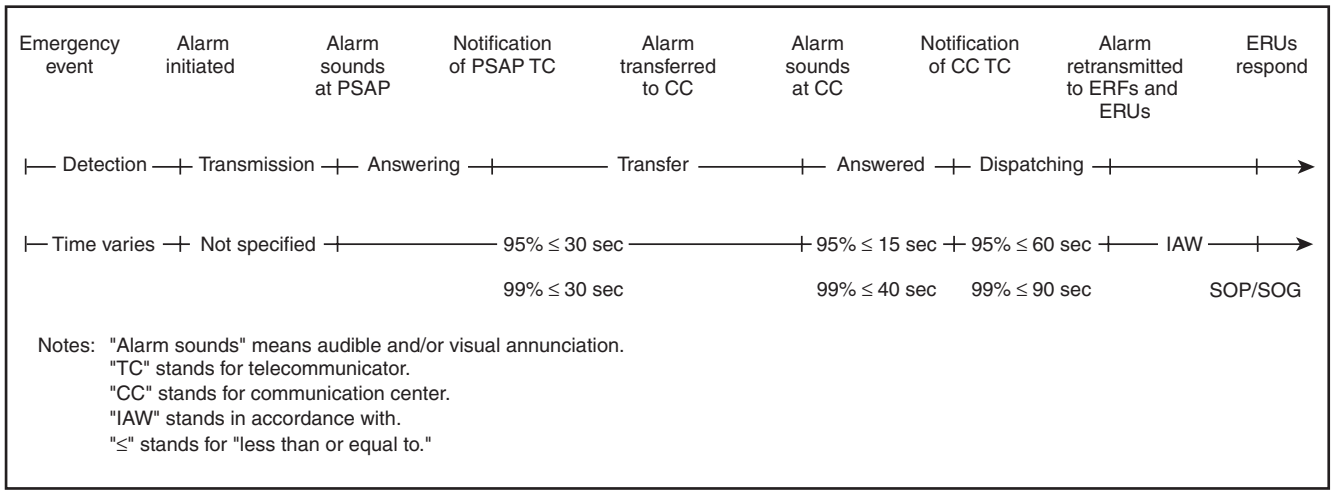

FIGURE 12.13.8 Alarm Time Line Where Primary PSAP Is Not the Communications Center (Source: NFPA 1221, 2007 ed., Figure A.7.4.1[b])

Overall Evaluation. Overall evaluation consists of proposing standards of response coverage statements by risk type, as in the following example:

> In 90 percent of all incidents, the first-due unit shall arrive within 4 minutes' travel or 6 minutes' total reflex time. The first-due unit shall be capable of advancing the first line for fire control or starting rescue or providing basic life support for medical incidents. In a moderate risk area, an initial effective response force shall arrive within 8 minutes' travel or 10 minutes' total reflex time, 90 percent of the time, and be able to provide 1,500 gallons per minute for fire fighting, or be able to handle a five-patient emergency medical incident.[1]

Risks Versus Response Time Standards

Some communities may elect to adopt several response time standards for various levels of risk in the community, or they may adopt one single response time standard for all risks. Here, a *risk* refers to a response location and the potential fire, occupant, and exposure problems that will be encountered. Providing several response/travel times based on the level of risk means that some areas will be reached in a shorter period of time than other areas. A single response time standard for the community or area served will provide approximately the same level of initial response to all areas of the community. Some of the risks that may be considered for various response/travel times follow:

- *Sprinklered versus nonsprinklered.* The fully sprinklered property is theoretically at less risk than the nonsprinklered property. The community may elect to place fire stations closer to the nonsprinklered property because of the ability of sprinklers to automatically put water on a fire.
- *Commercial versus residential.* The community must decide, in this case, where the greater risk is located. Is there a greater risk with the commercial property? At what time of day is the risk greater? Is the risk greater in residential occupancies at night?
- *Multifamily versus single-family residential.* Is the risk greater in multifamily residential areas than in single-family residential areas? Fire station location should be influenced by population factors.

The risk questions should address the following:

- High life hazard (i.e., loss potential) or high dollar value
- High incident rate areas versus low incident rate areas
- High rate of incidents that require a high level of resources versus low rate

The community that chooses to provide various levels of service to different areas, based on the level of risk, will require a much more complex fire station location study.

It should be noted that most of the information provided addresses career fire departments with stations staffed around the clock. For call and volunteer fire departments, turnout time typically will be greater. This is significant and must be considered in overall response time.

DETERMINING FIRE STATION LOCATIONS

Adopting a Response/Travel Time Standard

The first step in determining where a fire station should be located is the adoption of a response time standard or standards for the community based on the items discussed previously. Once the response time standard has been developed, it should be divided into specific time intervals for each of the components that make up total reflex time: dispatch time, turnout time, response time, access time, and setup time.

For most incidents, the dispatch time and turnout time can be established by using historical data. Setup time depends on the type and complexity of the incident. A single-family dwelling fire will generally require less time than a major fire in a high-rise building or an industrial complex. A thorough analysis will examine setup times and incident frequencies for several types of incidents. For larger incidents, the standard may be stated in terms of response time for the last of several units required for the total operation. Relevant times by type of incident can be established through training or historical experience.

Response time minus the cumulative time for dispatch, turnout, access, and setup yields the allotment for travel time. Once the response time standard has been established and a travel time standard selected, the process of determining or planning fire station locations can begin. Even though response time and travel time standards are selected prior to the beginning of the study, this does not mean that other times cannot be examined and used in the analysis. The final response/travel time may be selected after a number of scenarios are examined.

Using GIS for Fire Station Placement

Accuracy of Data. With the advent of modern software and computer technology, the selection of best fire station locations can be determined with a greater degree of accuracy using geography information system (GIS) technology. Unlike previous methods that employed grid and concentric circle analysis, GIS simulates the real road network of the area being analyzed. A high degree of accuracy is ensured by using actual travel distances, vehicle speeds, and time delays for roadway conditions (e.g., congestion, turning radius, weather, hills); accounting for one-way or unusable roadways; and implementing user-defined risk factors.

Additional data that may be used to ensure accuracy are historical response and travel times. This can be data taken from the computer-aided dispatch data or recorded manually. Data may include response/travel time, turnout time, time of day, and day of the week. All of this data can be analyzed to determine if there are specific traffic patterns that affect response times. If so, the base map can be adjusted to reflect alternate response routes or apparatus. In some instances, an alternate fire company may arrive more quickly due to heavy traffic at peak travel hours.

GIS Analysis Results. The results of GIS computer studies are a series of color maps of the street/roadway network that are easy to comprehend. These maps can show a variety of information, such as the street segments that can be reached from all stations for a specified target travel time, the overlap between stations,

the response area for each station, and other information, depending on the capability of the software program being used.

GIS analysis can effectively illustrate problem areas as well as proposed solutions. GIS can show various data for simulated responses to specific locations including apparatus and personnel on a time-arrival sequence, multiple alarms, and travel time to each street segment in the system. This will provide accurate information for critical decision making by an incident commander, including the ability to predict the time needed to assign resources for various emergency operations.

The response area for each fire station, based on the travel time specified, can be calculated and displayed. Each station's response area can be shown as different colors on the map. GIS analysis produces color maps that show the overlap between stations for a specified travel time. The color maps show the areas where there are two or more stations whose first-due response areas overlap, with the overlap colors different from the station response area colors. These maps can be used to determine multiple-company response to an area or to show where stations are placed ineffectively. Areas that receive no coverage or deficient coverage are also displayed.

Mutual-Aid Station Analysis. The response from mutual-aid stations can also be analyzed as part of the overall study, to show the arrival of additional resources. This is particularly useful to show the response of special apparatus and teams such as hazardous materials teams, advanced rescue teams, or other special teams. Given limited resources, a whole region can be analyzed using the entire resources of the region.

Examination of Alternative and Future Station Locations. Alternative and future station locations can be examined through the use of what-if scenarios, using various fire station locations and travel times. The information from these programs can be integrated with the data from local and regional planning groups to show where new stations and/or roadways may be needed to best serve existing and growing communities.

Comprehensive GIS Study. A comprehensive GIS-based fire station location study can be the central component of a master plan for fire station locations. This plan can show both the efficiencies and deficiencies of current fire station coverage for a specified travel time and provide a model for future fire station coverage using the specified or other travel time standards. Figures 12.13.9 through 12.13.17 illustrate maps from a GIS analysis that assess existing station locations as well as alternative station locations and additions.

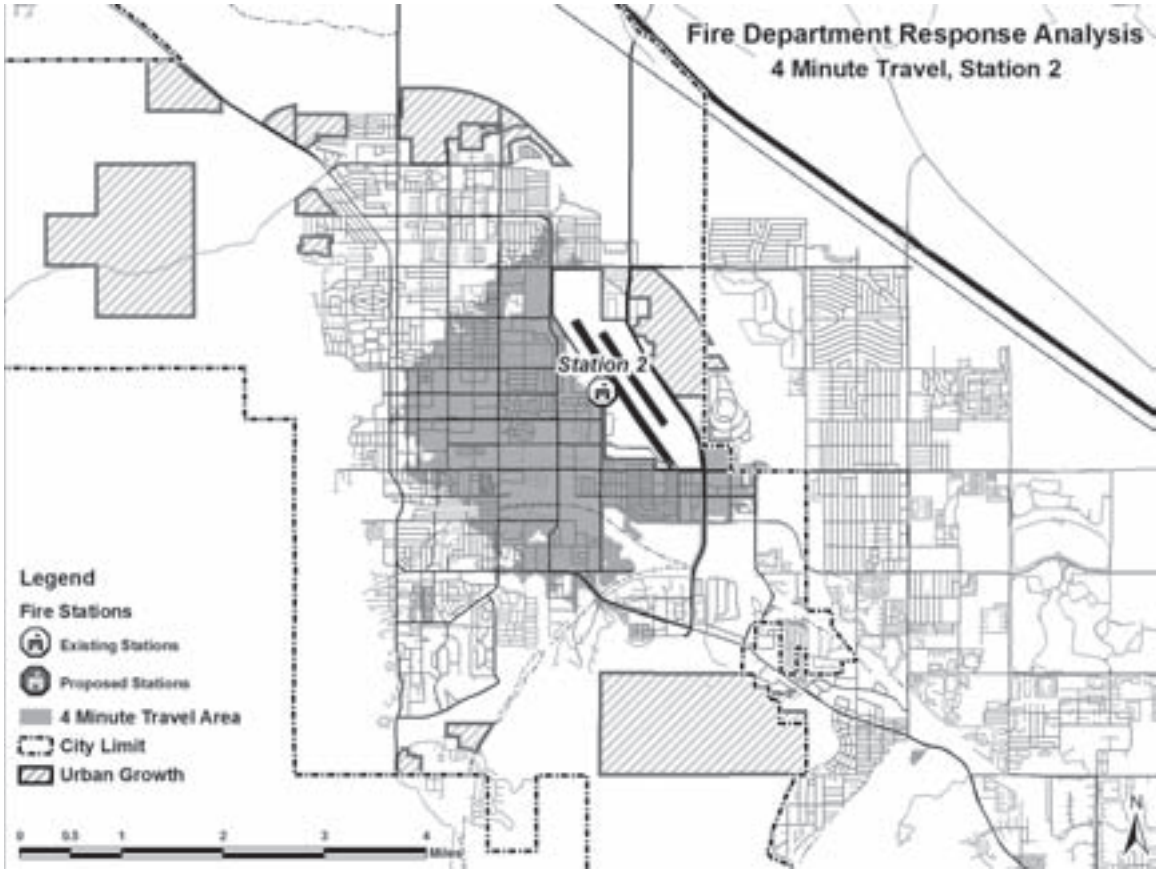

FIGURE 12.13.9 GIS-Generated Map Illustrating a Four-Minute Response Time Analysis from Station 2

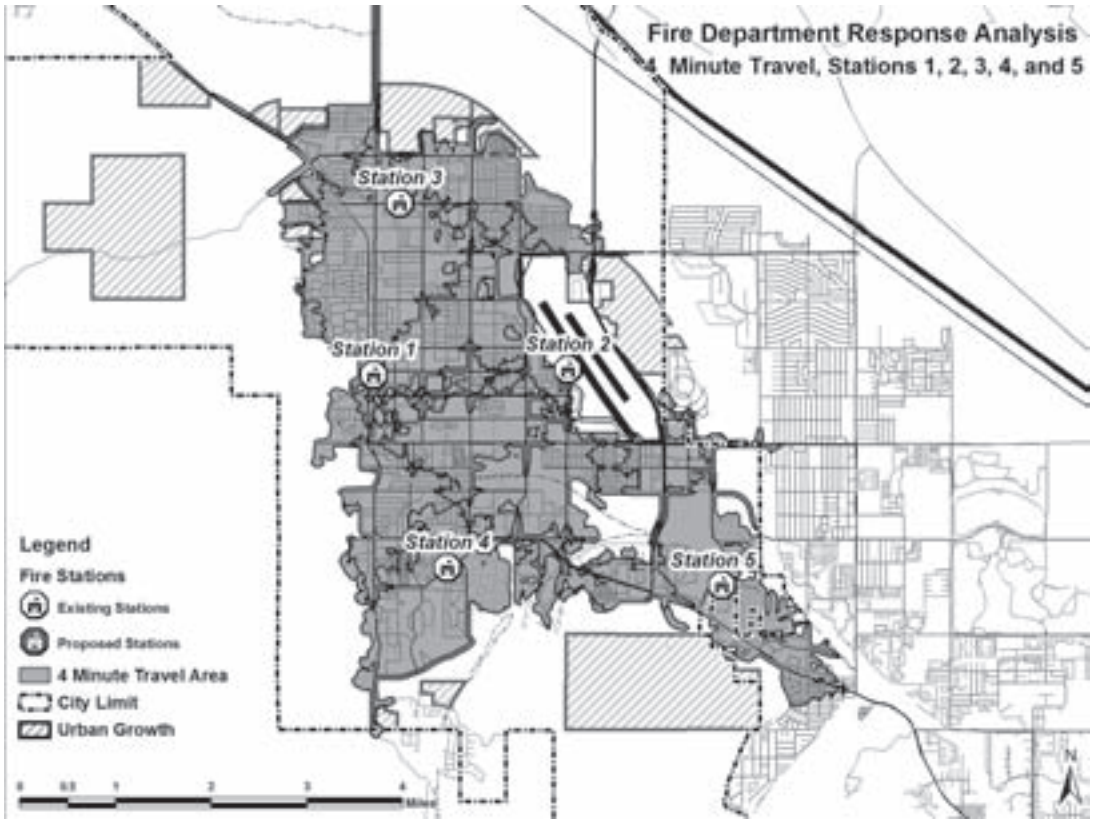

FIGURE 12.13.10 GIS-Generated Map Illustrating a Four-Minute Response Time Analysis from Stations 1, 2, 3, 4, and 5

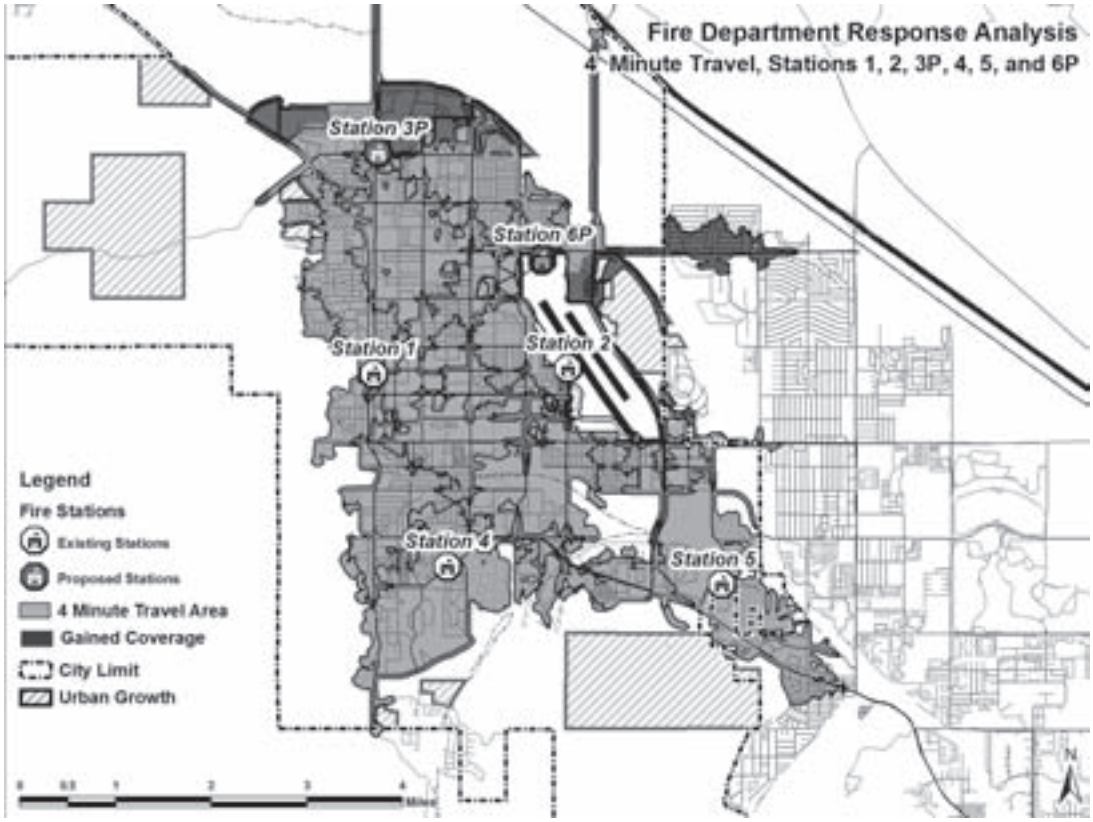

FIGURE 12.13.11 GIS-Generated Map Illustrating a Four-Minute Response Time Analysis from Stations 1, 2, 3P (Proposed Relocation), 4, 5, and 6P (Proposed New Station) and New Coverage Gained with Proposed New Station and Station Relocation

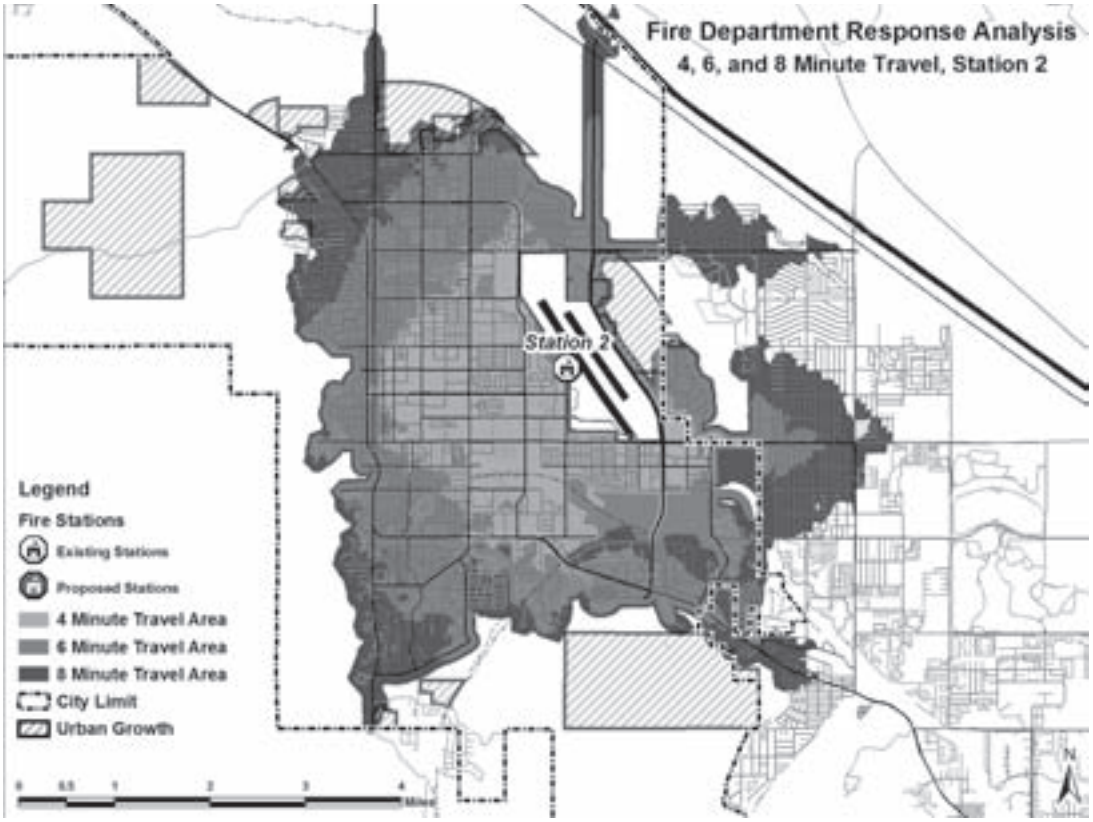

FIGURE 12.13.12 GIS-Generated Map Illustrating a Four-Minute, Six-Minute, and Eight-Minute Response Time Analysis from Station 2

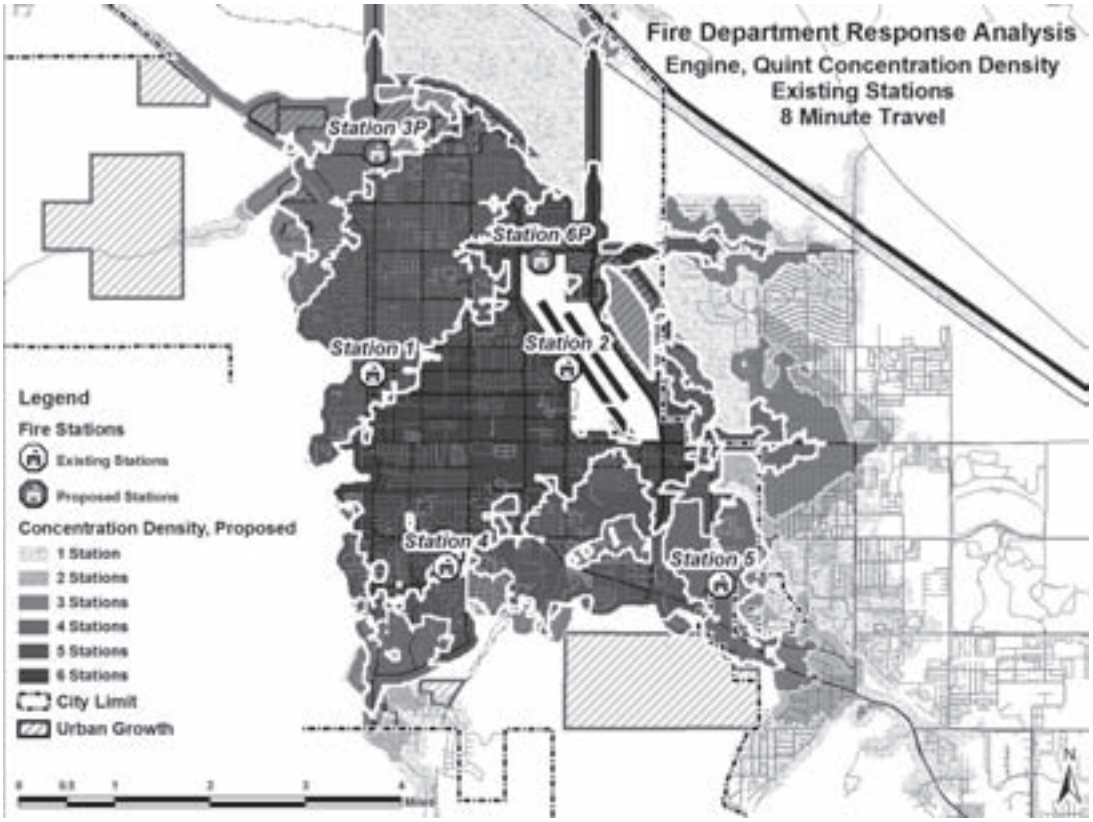

FIGURE 12.13.13 GIS-Generated Map Illustrating an Eight-Minute Response Time Analysis from Stations 1, 2, 3, 4, and 5. Shading indicates the number of apparatus that can be on scene in each area within eight minutes.

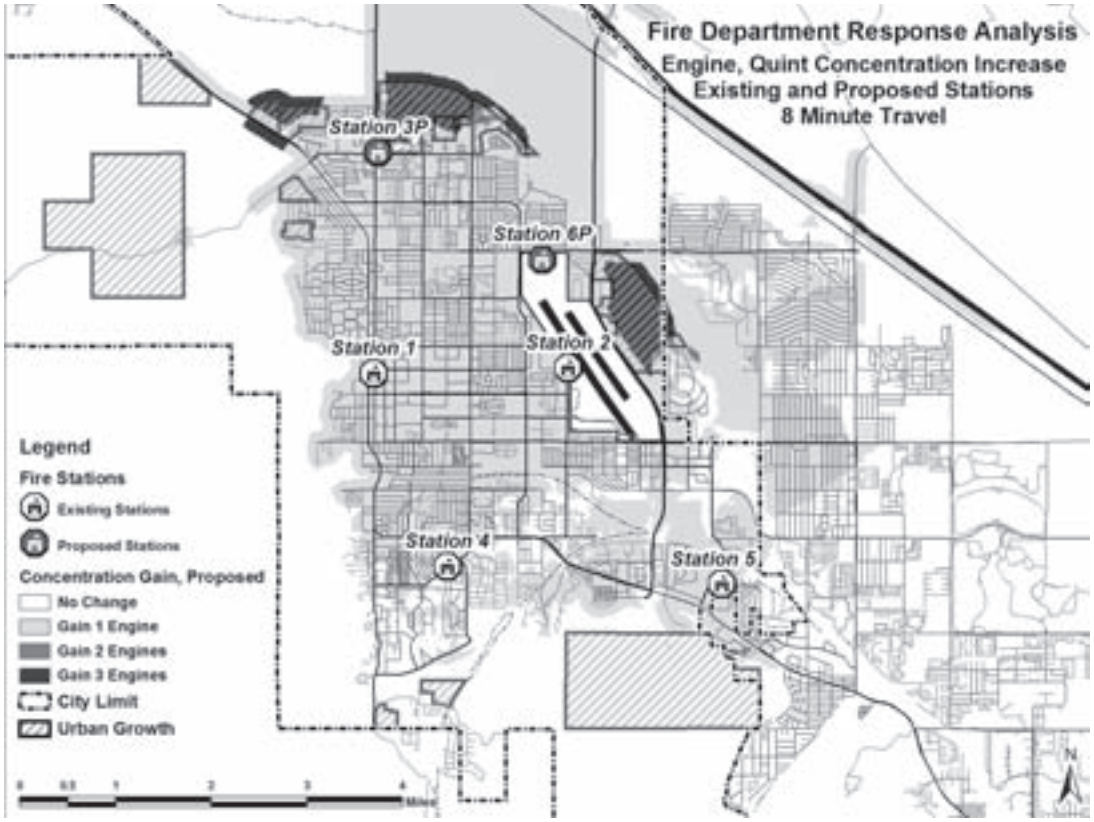

FIGURE 12.13.14 GIS-Generated Map Illustrating an Eight-Minute Response Time Analysis from Stations 1, 2, 3P (Station 3 Relocated), 4, 5, and Proposed New Station 6. Shading illustrates the number of additional apparatus that can be on scene in each area within eight minutes after proposed station changes.

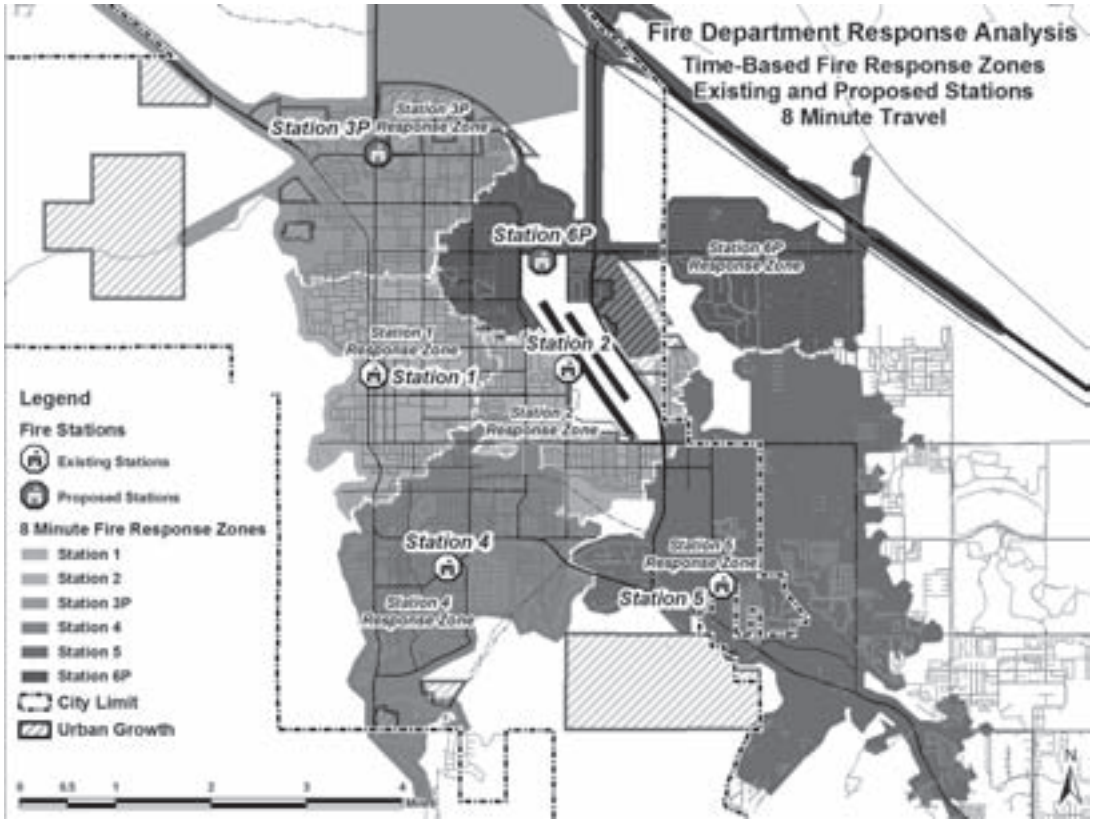

FIGURE 12.13.15 GIS-Generated Map Illustrating Fire Response Zones Based on an Eight-Minute Response Time Analysis from Proposed Stations

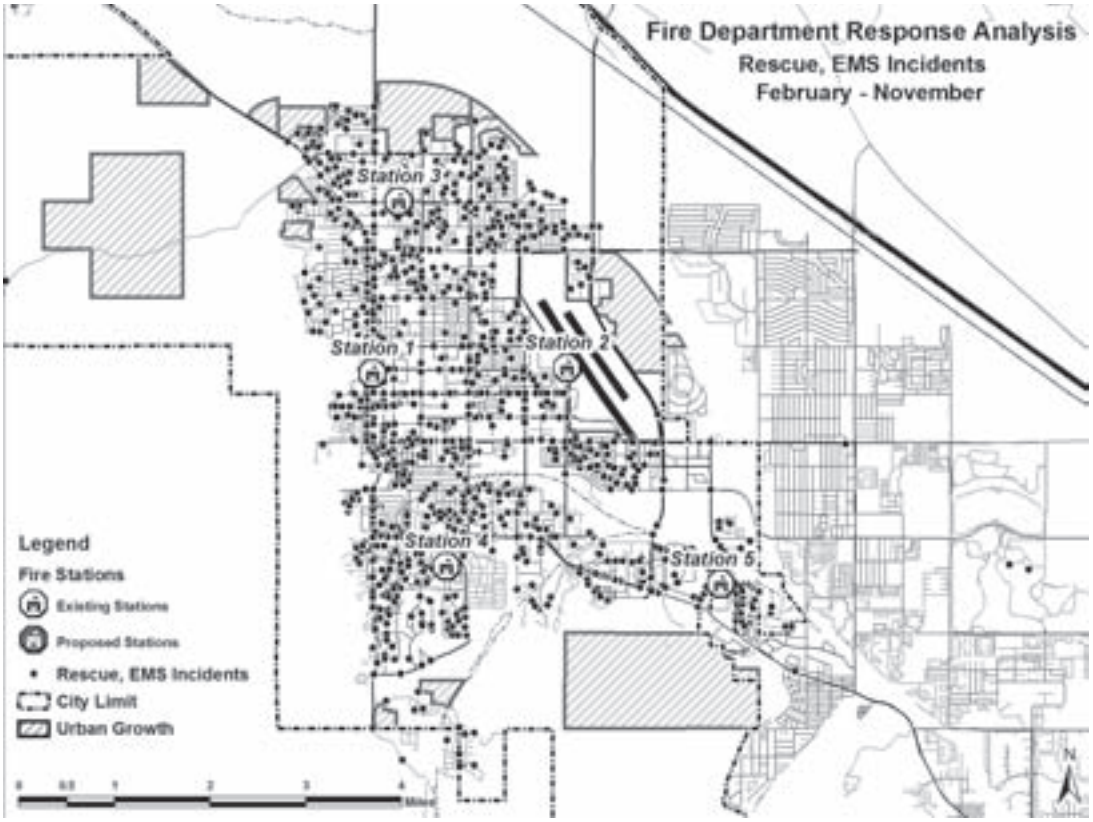

FIGURE 12.13.16 GIS-Generated Map Illustrating Fire, Rescue, and EMS Incidents Between February and November

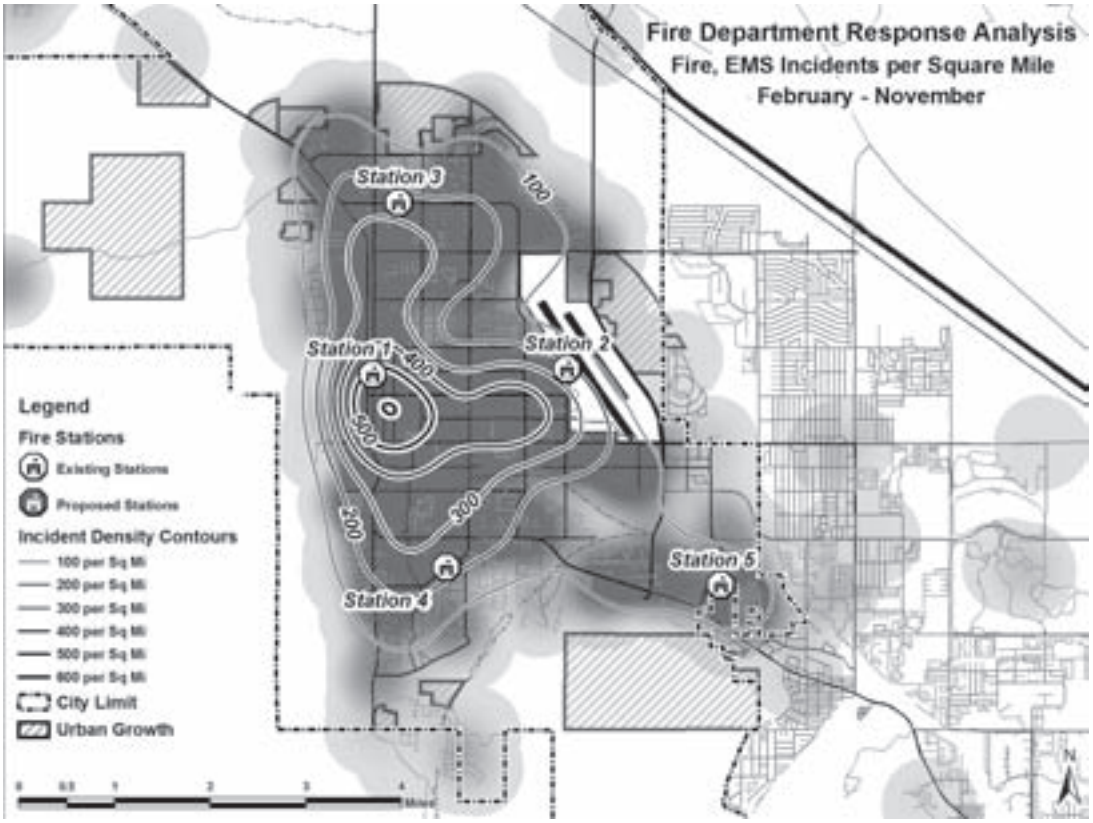

FIGURE 12.13.17 GIS-Generated Map Illustrating a Fire, Rescue, and EMS Incident Density Between February and November

Resource Allocation

Once the locations for fire stations have been selected, the program can be used to allocate resources to most efficiently cover the identified risks. A comprehensive GIS-based fire station location analysis provides the foundation for effective resource allocation that is critical to fire department and community master planning.

The colored maps and data are very useful when making presentations to citizens and elected officials. The computer programs take complex response scenarios, which may include many interrelated factors, and greatly simplifies them by producing color map images. Most of the maps and data are easily understood and provide factual data on the response of emergency equipment to specific locations.

All fire department planning that involves the allocation of resources requires a fire station location study. A proper study will show how the effective deployment of resources through proper station locations can improve emergency service to the community while minimizing both capital and recurring costs.

FIRE STATION SITE SELECTION FACTORS

Terrain

Once a location for a fire station has been determined, there may still be multiple choices for the precise site. One of the general items that should be considered when selecting a site should be the terrain and the susceptibility to flooding or other conditions due to weather. GIS can provide very detailed information regarding terrain features and optimum site location. GIS can analyze and display soil types, earthquake faults, elevations and slope, flood-prone locations, and other features important to station location placement. The size of the structure, the number of personnel assigned, and the provision of a training area will dictate the size of the site that is required.

Traffic Patterns

Another important consideration is the relationship to the adjacent streets and highways. An analysis of traffic patterns in the surrounding area will aid in determining whether the site is suitable for a fire station. The station must be located so that responding apparatus can enter streets and highways as safely as possible and return to the station without disrupting traffic and placing personnel at risk. It may be more desirable to locate a station on a side street rather than on a heavily traveled street.

Traffic pattern requirements for a specific site will differ for volunteer and career personnel. The major reason is that volunteers must respond to the station before responding to an emergency. Therefore, the site must allow easy access for volunteers responding to calls. There may be situations where apparatus is leaving the station and, at the same time, volunteers are still arriving. This is more complex than an all-career station, where all personnel are at the station and respond immediately to a call.

Response Time Standards

A primary responsibility of fire departments is to deliver fire and rescue services. Fire can grow at a rate many times its volume per minute; time, therefore, becomes a critical element when crews respond to an emergency. The timely delivery of services depends to a great extent on the location of the fire stations. Thus, when planning where fire stations should be located, the community needs to develop its response time standards. These standards are based on an analysis of the types of services to be delivered, what a reasonable travel time is, the size of the area to be serviced, the resources available, and the level of acceptable risk. Once the response time standards have been established, GIS can be used to determine fire station placement with a greater degree of accuracy.

GIS RESPONSE PROTOCOLS

GIS technology is being deployed in a number of other emergency response areas to increase efficiency, reduce response time, and provide higher-quality decision support information and data. This includes dispatch, mobile operations, and emergency management.

Computer-Aided Dispatch

Dispatchers have the important responsibility of processing emergency calls and sending the appropriate public safety resources to the emergency location based on the type and urgency of the incident. GIS is an important component of the dispatch system. Dispatch or CAD systems typically contain a file called the Master Street Address Guide (MSAG). This file contains street address information and service areas for the jurisdiction that the dispatch center services. As emergency calls are received, they may be accompanied with address information from the telephone company's emergency phone record database. This address is entered or electronically transferred to the CAD system, which compares it to MSAG. When the address is matched, the specific service area is also identified with the specific units that should be dispatched to the emergency. If the telephone company does not provide a digital address with the call, dispatchers must obtain it from the caller and type it into the system. Many computer-aided dispatch systems have begun to integrate GIS technology. GIS takes the address and automatically geocodes (places a point on the map) the incident and displays it on a map.

There are several benefits of having the incident displayed on a GIS map. New calls reporting the emergency may have different addresses but are reporting the same incident previously recorded. The GIS map display will illustrate that a different address making a call may be in close proximity to the original call location. Other benefits are shown in the following sections.

Global Positioning System (GPS). Many public safety agencies are equipping response units with global positioning system (GPS) devices, which provide the dispatcher (and perhaps other appropriate public safety managers) the ability to locate units through a GIS display and track them to the incident when dispatched. This is important during heavy call volume or for mobile vehicles such as police units and emergency medical units, because it provides dispatchers with a virtual, near real-time view of incident locations and emergency response units to activate an appropriate dispatch based on emergency unit availability.

Routing. GIS can quickly analyze and display a route from a station or GPS location to the emergency call. This route (depending on the sophistication of the street file) may be the shortest path (distance) or the quickest path (depending on time of day and traffic patterns). This information can be displayed to the dispatcher as well as on a mobile computer screen in the response vehicle. Vehicles equipped with mobile computers and GIS can also benefit by providing first responders with access to preplans, hazardous materials locations, photographs, and other location-based documents linked to actual specific locations through the GIS map display.

Move Up and Cover. During periods of high volume and simultaneous calls or a complex emergency, GIS can display areas of high risk that are left substantially uncovered. GIS can provide recommendations for reallocating available resources for better response coverage.

Emergency Wireless Calls. Wireless and cellular telephone technology have added to the necessity of GIS. Wireless phone–reported emergencies are not associated with an address, and the caller may not know his or her address or street location. GPS-enabled cell phones can provide latitude and longitude coordinates during an emergency call. Other technologies are available that triangulate the call location between cell towers or measure strength of signal to provide approximate location information. These coordinates are relatively meaningless to a dispatcher, but GIS can quickly process and display a latitude/longitude or other coordinate location. This enables the dispatcher to see the incident location or general area and the closest or quickest response units on the GIS display.

Records Management System. Dispatch systems often have a database to capture, store, and archive incidents. This database may be called a records management system or a CAD records system. The records stored in this database concerning emergency calls usually contain location information. GIS can link to and geocode (place a point on the map) the location that represents this event. These events can be analyzed and assessed by any field in the records database (time, incident type, etc.). GIS provides a powerful capability to see, understand, and assess a department's volume of business, developing trends, and response performance. The information within a records management system can be leveraged for additional purposes when geospatially enabled.

Mobile Operations

As wireless broadband networks expand, GIS support for tactical operations becomes more powerful. Mobile PCs, computer tablets, and handheld devices with GPS and wireless advances allow first responders to send and receive geographic information and incident updates. As shown in Figure 12.13.18, GIS mobile applications can provide the tactical map interface to information and data important to first responders. Information such as preplans, floor plans, and other documents are linked to building facility addresses and are easily displayed by clicking or touching the map. As fire and emergency medical services expand, the importance of GIS is becoming widely recognized. First responders must get to and size up the emergency and then deploy. The first responder's mission is to save lives and protect property and natural resources. GIS information support to the first responder mission can include the following:

- Incident location
- Quickest route
- Hydrant locations
- Preplans
- Photographs
- Floor plans
- Hazardous materials locations
- Utility control panels

The incident commander requires additional information to perform the command mission. Depending on the complexity and size of the incident, the information and data requirements may include information on the following:

- What exposures or other facilities are threatened by this incident
- Where incoming units should be positioned and assigned
- If a staging area or an incident command post is required, where parking lots, schools, churches, malls, or other suitable facilities are located
- If helicopter evacuation of victims is required, where suitable landing sites are located
- If medical triage or decontamination is required, where it can be implemented
- If hazardous materials are involved or a chemical plume is being generated, in what direction it is traveling, whom does it threaten, and what actions are required to protect and evacuate the public
- If an explosion is possible, who needs to be evacuated and where an immediate evacuation facility is located

All these decisions require maps and a variety of information from different sources. Having access to GIS data, imagery, school locations, parking lots, adjacent exposures, and hydrant locations provides an accurate picture of the event and supports critical command decisions.

Much of the information first responders require has already been collected but resides in a variety of formats and in numerous locations. GIS can integrate the information and provide it graphically to first responders through maps. GIS provides intelligent maps and allows the user to acquire other critical information. GIS can model explosions, plumes, and other potential emergencies. Instead of guessing or estimating evacuation requirements, transportation network problems, and other infrastructure threats, GIS will provide a more accurate prediction of the event and display potential consequences.

Emergency Management

During an emergency or crisis, maps play a critical role in response, search and rescue, mitigating further damage, and understanding the extent of the impacts. GIS is an appropriate platform for organizing the extensive amount of spatial data both generated and utilized during an emergency. A properly designed and implemented GIS will allow managers and

FIGURE 12.13.18 Sample GIS Mobile Application Providing Tactical Map Interface to Information and Data Important to First Responders (Courtesy of Chief Don Oliver, Wilson Fire Department, Wilson, North Carolina)

responders to access critical location data in a timely manner so that lives and property can be protected and restored.

Fire departments are the front line of defense for emergencies of all types. Large-scale emergencies range from natural disasters (e.g., earthquakes, floods, hurricanes, ice storms, etc.) to industrial or technological emergencies (e.g., train car derailments, petroleum fires, hazardous material spills, etc.) to terrorist attacks. Large-scale emergencies often involve multiple casualties, critical infrastructure damage, and evacuations; also, the emergency can last for several days or months.

Managing large-scale emergencies is complex and can involve search and rescue operations; displaced citizens; loss of utility services; and coordination among many departments, agencies, levels of government, and the private sector. One of the most complex challenges of emergency management is determining where damage is most extensive, where lives are most threatened, and where to assign limited emergency response personnel and equipment. During a major search operation for a lost or overdue hiker, GIS can accurately determine which sectors have been searched adequately and which sectors need to be revisited.

GIS provides a primary capability to organize, display, and analyze information for sound decision making. Integrating GIS data layers and imagery of the affected area or areas

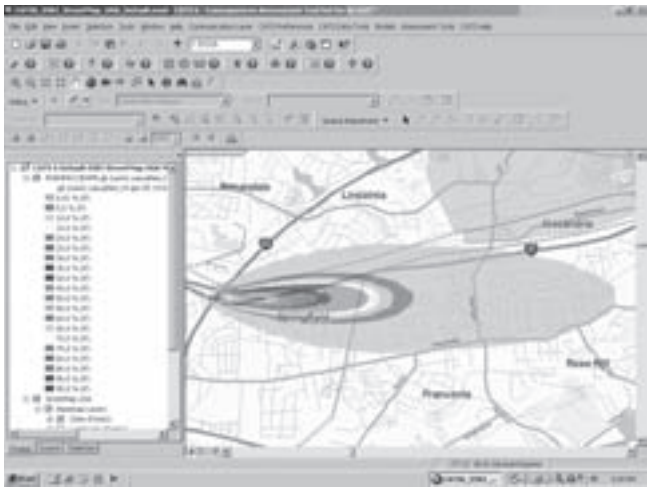

FIGURE 12.13.19 Sample GIS Model Illustrating How an Emergency Event (Plume, Explosion, etc.) May Impact the Area in Which It Occurs (Source: ESRI)

provides incident commanders with a comprehensive view of the emergency. GIS provides a primary capability to create a "common operating picture" for the incident. Emergencies are very dynamic and, as circumstances change, GIS can reflect these changes. GIS can incorporate temporal information (e.g., weather, hazardous materials locations, and emergency personnel locations) and model how an emergency might continue to evolve or what type of damage may be expected. These models could include the following:

- Chemical plume dispersion
- Blast models
- Hurricane tracks and effects
- Flood damage
- Earthquake damage
- Wildfire spread

GIS models illustrate how an emergency event (plume, explosion, etc.) may impact an area (Figure 12.13.19). In addition, GIS will analyze and display population effects, road closure requirements, best evacuation routes, potential shelters, and facilities out of the danger area that may support incident management.

Models provide incident commanders with a relative understanding of where evacuations may be necessary, potential damage to critical infrastructure, transportation network disruption, and so forth. Maps can be printed with the appropriate symbology to illustrate work assignments and incident facilities (e.g., incident command post helispots, staging areas, hot zones, etc.) and quickly dispersed to emergency personnel as part of the incident action plan. Areas with catastrophic damage are often confusing and disorienting to emergency personnel. GIS provides a view of the area before the damage occurred, including underground infrastructure, control points, potential hazardous materials locations, and other information to support emergency response actions.

SUMMARY

The fire service mission is to assist the public in the protection of life and property by minimizing the impact of fire, medical emergencies, and potential disasters or events that affect communities and the environment. Defending communities from natural or man-made emergencies through planning, preparedness, incident response, public education, and code enforcement is best accomplished through accurate information sharing. GIS is one of the most effective tools to analyze, define, clarify, and visualize community issues and problems to deliver emergency services to all.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on GIS for fire station locations and response protocols discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1221, *Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems*

NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*

NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments*

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Chapter 14

Fire Rescue Stations and Fire Service Training Centers

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Chapter Contents

Fire Rescue Station Design
Fire Service Training Center Design

Key Terms

fire rescue station, fire service training, live fire training, master plan

Fire stations and fire training centers can range from basic to complex. An adequate fire station could be a single bay with a desk at the back or it could be a multiple-company station that houses engines, ladders, ambulances, and a complete administrative function. Similarly, a training center could consist of just a small training tower or it could be a large campus that offers both classroom and practical education to hundreds of students at one time. Because there is no "one size fits all" solution, it is important to follow a planning and design process that creates the right facility for the community's protection and the department's training needs.

This chapter provides a general overview of the steps necessary to develop fire stations and fire training centers. The steps should be taken with the assistance of knowledgeable architects/engineers (A/Es) and should include the following:

1. Needs assessment
2. Planning
3. Design
4. Construction

This chapter provides ideas and insight for configurations, building options, and training props without providing an exhaustive list of possibilities. For related topics, see Section 12, Chapter 10, "Training Programs for Fire and Emergency Service Personnel"; Section, 12, Chapter 13, "GIS for Fire Station Locations and Response Protocols"; and Section 12, Chapter 16, "Fire Department Apparatus and Equipment."

FIRE RESCUE STATION DESIGN

Fire stations exist in virtually every city and town in the world, and there is a variety of functions that the fire stations have to serve. A fire station may be simply a garage to store a truck; others, in addition to housing trucks, provide housing for a complex hierarchy of offices for managing delivery of safety services. There are, however, many elements of fire stations that need to be present without regard to what is housed in the building. The design professional must be aware of these elements.

One of the most important elements of a fire station is whether or not it represents a safe and efficient place for people to use. A careful analysis of the proposed building and the functions it is

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expected to serve is required. There are obvious program elements consistent for all stations, such as security, fire protection, weatherproofing, and structural stability. The building where the fire equipment is to be housed must be designed to withstand the forces of man and nature. Other necessary design elements are lighting, heating or cooling, storage facilities, and emergency backup power.

It is very important when designing a fire station that a clear understanding between the design professional and the fire department be established in the conceptual design phase of the project. It is also necessary that the design professional have a clear understanding of the development costs of program elements to keep the total costs within the budget.

The fire station design must address the needs of its users. Even if it is a single-bay station without any other space required, consideration must still be given to the people who are going to use the station. If it is a complex that is planned for housing a mix of civilians and fire rescue personnel, the building must be functional for both the civilian and the fire rescue personnel. If the design professional is not familiar with the necessary elements of a fire station, then the project will be difficult to bring to a successful conclusion. The design professional cannot and should not depend on the fire chief to be aware of all of the elements necessary for a fire station, particularly architectural elements, that need to be considered in the design of the building.

Needs Assessment

Preparedness and planning are inherently important for the success of all public safety providers, particularly those in the fire and emergency services. Similarly in the design of a new station, the preparation and planning begin with a thorough needs assessment. This first step is critical and should be completed prior to any land acquisition. Ideally, determine the required station square footage and operational needs before beginning the assessment of potential sites. It is desirable to formalize this process with a design consultant and key staff. A common approach is to form a building committee to discuss the station issues and make decisions. Do not overlook comments and suggestions made by interested parties and end users, particularly members of the community who may have use of the building. If the future station will have shared or joint use, such as a police substation, be sure to include their representatives.

Another way to think of the needs assessment is comprehensive information gathering. The committee and design team want to know everything that will impact the design and operations of the planned station. This information will be generated from the following three-step assessment:

1. *Existing conditions.* Document existing spaces, room sizes (square footage), staff, equipment, apparatus, and so on.
2. *Current needs.* Determine what program spaces and sizes are currently required for the safe and efficient operation of the station. Consider what services and apparatus are required at this station.
3. *Future needs.* As best as possible, assess the future growth and development of the site's needs at least 20 years into the future. Many guidelines even suggest predicting 50 years out but may not be practical.

Room-by-Room Approach

The best way to approach the gathering of these data is with a room-by-room assessment. Consider who and how many persons will occupy the space and what functions will be supported. Provide the design team with a list of equipment and furniture for each space and note any special requirements such as additional phone/data outlets or storage needs.

Questions to anticipate during the needs assessment process include the following:

- How large will the staff be—current and future?
- What size and type of offices are required—private and shared?
- What type and size of apparatus will be used—current and future?
- Will the public have access to and use of this station?
- Will there be drive-through bays?
- What is the predicted future expansion of this station?
- Is there a current station prototype to follow?
- Where is protective gear cleaned and stored?
- How are hoses cleaned, dried, and stored?
- How will gender issues be addressed?
- What are the present and future storage needs?

Planning

Site Selection. The site for the building must be selected before the structural system can be determined. The site is usually determined by the analysis of many factors, including ISO evaluations and sometimes it is determined by a single factor. In any case, the selection of a building site is a task that requires some knowledge of fire department operations and goals. To properly site a fire station, an analysis of the department's response goals must be undertaken. If it is the goal of the department, for example, to respond to any incident within 4 minutes, the site location will be different than if the goal is a 9 minute response time. The analysis of response time must include a traffic study, addressing potential intersection delays, travel times, and access to travel routes. Response time for volunteers to the station should be part of the analysis, taking into consideration where they will be responding from.

Often a fire station is located in response to past growth; site selection, however, should be preemptive instead of reactive. Future growth projections, including the location and types of land uses, must be considered. The design team must project ahead 50 years to attempt to determine the growth patterns for the area and, thus, develop a site that serves the needs of the fire department.

Often fire stations are located on major travel routes based on the thinking that the response time is the most efficient. This approach has some validity, but it also removes what may be very expensive real estate from the tax base. An alternative approach is to locate the station on a secondary route, just off the major route, and utilize a signalized intersection to allow safe access to the major route. This plan improves emergency egress

and access to the station and reduces the risk for vehicular accidents and traffic stacking. With the recently developed technology to allow intersection signal control from fire apparatus, this method of secondary route location is becoming more popular, and the property on the secondary route is often not taxed at the same high rate as the property on the major route.

Once the site has been tentatively selected, it is necessary to consider improvements that must be made to construct the fire station. It is also necessary to consider such areas as parking for both fire fighters and apparatus, keeping in mind that the apparatus must have room to back in and sufficient turning radii, as well as visitor parking; drainage and runoff from storms; and security. A rule of thumb is two parking spaces for each member on a shift to allow for the shift change plus spaces for additional staff and a few spaces for the public.

Site Acquisition/Assessment. (See also sections on site selection and design for training centers.) Some rules of thumb for acquiring a desirable site include the following:

- Avoid congested thoroughfares, which increase the risk for accidents and traffic stacking, particularly during peak hours.
- Locate egress curb cut a minimum of 100 ft (30.4 m) from an intersection.
- Allow for a minimum 60 ft (18.2 m) apparatus apron measured from the street right-of-way to the apparatus bay doors.
- Avoid locating the station at the bottom of a hill.
- Avoid permanent barriers such as railroad tracks, one-way streets, or bridges prone to high-water risk.
- Avoid close proximity to schools or entertainment venues with heavy pedestrian and vehicular traffic.
- Allow 2 percent maximum slope of apparatus apron.
- Ensure minimum road width of 24 ft (7.315 m).
- Ensure good visibility and clear site lines for both approaching and exiting vehicles.

Site Due Diligence. A comprehensive site evaluation requires a thorough due diligence process and failure to do so may result in unexpected project costs or future complications. Potential building sites may have above- and below-ground issues that may create limitations or derail plans for that particular site all together. Some recommended due diligence steps include the following:

- *Environmental investigation.* A minimum Phase I is recommended; however, if the site had previous use for industrial, manufacturing, or filling station purposes, a Phase II investigation is recommended. Contaminated soil mitigation costs can be expensive.
- *Geotechnical investigation.* Many state building codes now define fire stations as essential facilities and require soil investigation as part of the permitting process. Poor soil-bearing capacity will impact the structural design, systems design, and pavement design of the station.
- *Archeological investigation.* For a nominal fee, an archeologist can access records for a Phase I archeological assessment of the site. This initial expense is minimal compared to the generally excessive financial and time constraints incurred when artifacts are discovered during construction.
- *Hazardous material investigation.* Prior to the demolition of any existing structures, certification that the station has been investigated for hazardous materials is required. Asbestos is generally the concern and abatement is normally expensive. The EPA will require certification of hazardous material abatement prior to demolition or construction.
- *Traffic studies.* If traffic is remotely a concern, consider a traffic study for current and future patterns. Peak hour congestion and projected rate increases will negatively impact response time and safety.
- *Future road improvements.* Check agencies with jurisdiction of thoroughfares bordering the potential site. Investigate future road widening or development plans.
- *Utilities.* Investigate existing and proposed utilities for the potential site. Relocation or connection costs and tap fees may be prohibitive. Because some station equipment may require three-phase service, check to see what service is available.
- *Storm water.* The Clean Water Act requires responsibility for the storm water generated from the station site. Consider how the storm water will be removed or detained on the property as it may require additional land or storm water utility upgrades.
- *Community concerns.* Try to gauge the potential negative impact of placing or removing a fire station in an existing neighborhood.

Establishing a Budget. Despite the best planning efforts, at the end of the day most decision makers naturally want to have some idea of the anticipated expenses. In some cases the budget alone will have the greatest impact on the station design and amenities. As such, it is wise to get a handle on the budget at the earliest possible convenience, so that educated decisions can be made before the design team has ventured far into the process. Additionally, the planning process may include determining what funding source or strategy is required and the potential for success. In establishing a budget a total project cost must be estimated. Total project cost is simply the sum of the *construction costs* (hard costs) and project *soft costs.*

Construction costs—often referred to as the bricks and mortar of a project—is the bid submitted by the contractors for material and labor and typically includes contractor overhead and profit, construction contingencies or allowances, and required construction inspections.

Soft costs are often overlooked in the budgeting and design process but are essential to the project. Though all the soft costs may not be known in the early planning phases, it is important to include some estimated amount. Experienced design consultants and vendors can provide valuable assistance. The following are a few of the anticipated soft costs to consider:

- Land acquisition expenses
- Site surveys
- Environmental assessments, studies, and abatement
- Hazardous material assessments and abatement
- Archeological assessment

- Geotechnical testing—soil borings
- Consultant fees
- Infrastructure and utility tap fees
- Permit fees
- FF&E—fixtures, furniture, and equipment
- Moving and storage costs
- Temporary facility costs
- Telephone/data/dispatch/cable
- Demolition expenses
- Audiovisual equipment
- Severe weather siren
- Building signage (beyond that required by code)
- Legal advertising—for consultants and contractors
- Ribbon cutting/grand opening ceremony expenses

Planning for Building Functions. The designer and the fire department personnel must work closely together on the development of the building plan and the relationship of the spaces to each other. The building must function properly for each type of use. If the building contains one or two bays for fire apparatus, it is not difficult to design the building efficiently. If the building will also function as an office, residence, and community center, then careful analysis of the relationship of the different spaces is necessary. One method of evaluating the spaces is to have the fire department personnel fill out a spreadsheet on each proposed room and its relevance to the other rooms in both importance and travel distance.

There are also other items to consider, such as the effect of the apparatus starting, leaving, and returning, on the other operations in the building. The noise and vibration caused by apparatus movement can be a distraction for other building uses. Fortunately, several methods of removing exhaust gases have been perfected and, with the proper installation of one of these systems, the effect of exhaust can be eliminated. However, the method selected for exhaust gas removal must be carefully considered. Some designers have simply opted to totally change the air in the apparatus bay when the apparatus is started or is returning. This method may not be desirable in areas where the air is conditioned either by heating or cooling and where a total change of air will result in the necessity of conditioning entirely new air in a relatively large space. The newer systems either filter the existing air or connect to the exhaust pipe of the vehicle and direct the exhaust completely outside the building.

The proximity of personnel to fire apparatus when a response is required must be considered when laying out a fire station. Because the key time for fire suppression and emergency medical operations is the time spent getting equipment out of the door, the building design should minimize the travel time of the personnel to the vehicles. Several spaces need to be in close proximity to the apparatus floor. They can include staff sleeping area, medical supply rooms, and equipment storage for fire trucks such as hose and spare self-contained breathing apparatus (SCBA) bottles. Locating these spaces next to the apparatus floor limits the travel necessary to replace supplies on the apparatus and increases efficiency.

Single Story Versus Two Story. It is design practice today to attempt to construct a single-story building within the allowable limits of the site. Because of concern over injuries, sliding poles in fire stations are a rapidly diminishing tradition but are still desired by some departments. It is far safer to design and construct a stairway for personnel to use. When a single-story building is not reasonable, care must be taken to properly design the building to limit the amount of travel from the first floor to other levels. One approach is to locate administrative functions on the second level and maintain, as much as possible, response functions, including sleeping accommodations, on the first floor. One-story stations are typically less expensive than two stories, primarily due to the fact that two-story stations will require an elevator and vertical circulation.

When the program for the building has been completed and a conceptual layout for the building has been created, it is necessary to begin to develop designs for structural stability, sewer, water, heating, cooling, ventilation, electrical, and fire protection. Each of these tasks is important to the functionality of the building. The structure of the building must be such that it supports all the operations of the building.

The structure must withstand the forces of nature, including snow, wind, rain, and earthquake. A fire station cannot withstand even the slightest failure of a structural component and, thus, must have a stronger frame than most buildings. The structural engineer must ensure that the building will not fail by using extra bracing and stronger components than normal for a comparable building size. All fire stations, regardless of size, should have a backup power supply in case of emergency. Adequate response time and sufficient power are critical (see FEMA 454 and 543).

Gender Separation. With both men and women in the fire and rescue service, many new issues have developed. Separate shower and bathroom facilities must be provided. Many of the existing fire stations were designed to accommodate only men. Therefore, they had one large "bunk room" where the entire company slept and one shower/bathroom facility. To avoid potential problems, men and women need separate showers and bathrooms. There are three ways to approach gender separation in fire station design, and each will impact the building's layout, construction cost, and departmental policies. The most common areas impacted by gender are sleeping quarters, locker, shower, and restroom facilities. The following are the three approaches:

1. *Separate but equal.* Separate but equally sized spaces and facilities for both male and female fire fighters
2. *Separate but unequal.* Separate but different sized spaces and facilities for both male and female fire fighters; typically larger facilities for male occupants
3. *Gender neutral.* Often referred to as unisex, spaces and facilities that can be equally shared by both. Individual bunk rooms fall into this category. Unisex shower rooms and toilet rooms are also common, and this option tends to be the most flexible and cost-effective.

ADA

The Americans with Disabilities Act (ADA) is a civil rights law that is enforced at the federal level by the United States Department of Justice. A citizen who believes there may be an

ADA violation may file a complaint with this agency. Contrary to some beliefs and actions, local government interpretations and waivers are not recognized in a court of law. As fire stations are public facilities (ADA category Type II), they will need to comply with these accessibility standards. Many states have adopted accessibility standards into their local building codes. Multistory stations are required to have elevators by this federal law. Familiarity and conformance with this law and guidelines in the station design process are required.

Sustainable Design

Sustainable design or green building design is a movement gaining acceptance at all levels of society. These principles stress responsibility for the impact of development and construction on the environment and resources through the promotion of energy conservation and alternative energy sources, sustainable site development, adaptive reuse, recycling, and so on. This entire process has been formalized into a certification process called the LEED (Leadership in Energy and Environmental Design) rating system, which provides standards and requirements for the different levels of certification. Additional information and resources on LEED and sustainable design can be obtained from the U.S. Green Building Council.

Typical Fire Station Space

For a majority of fire stations, the programmed spaces tend to fall into the following four categories:

1. Apparatus and vehicular storage
2. Administration
3. Residential and living areas
4. Operation and support

The following are some of the typical spaces that are programmed into fire stations. Not all of these spaces must be in every building, but this list is a guide to assist in the development of a program for a fire station.

Apparatus and Vehicular Storage. The fire trucks, rescue trucks, ambulances, and other support vehicles are housed in an *apparatus bay* (Figure 12.14.1). Design considerations must address the fact that heavily loaded trucks may sit day after day on the floor and that the trucks are loaded when they enter and leave the building. The trucks will be the full height and width allowed by law, and the station doors (recommended 14 ft × 14 ft [4.26 m × 4.26 m]) should be oversized to reflect this fact. Station bay width (minimum 16 ft [4.8 m] wide) for the trucks should be wider than in a normal garage because the trucks should and do receive some maintenance in place, and there needs to be space to open doors and tilt hoods without forcing the personnel to crawl over or under the trucks. Provide 5 ft (1.5 m) minimum clearance between the station bay doors and the front of the apparatus (see Figure 12.14.1). The bay should also have enough space to store minor repair items, perhaps on some shelves. The bay should be equipped with a system to vent exhaust gases from the trucks and be well lighted and heated. Most floor drains are installed under the trucks with sloping floors to collect drippings from the trucks. If floor drains are incorporated, then an oil/water separator must be used to limit pollution.

FIGURE 12.14.1 Large, Well-Thought-Out Apparatus Bay

Administration. Several types of *offices* are found in fire stations. Each subset of administration may require a different type of office. The minimum size of each office type does not vary much, but the equipment found in the offices is vastly different and will determine the required size. Shared office space for two or more individuals and open office areas with systems furniture can provide some economy of scale.

A chief's office is similar to that of the CEO of a corporation. The office requires space for the chief to work, as well as a space for meeting with other people. A fire prevention officer's office is essentially an engineering office and requires space for plans review as well as other office functions. The plans review space may be a drafting table or an oversized desk but should accommodate oversized plans sets. A secretarial office must contain space for the secretary to work and for a file cabinet, fax machine, copy machine, and other equipment often found in a modern office. A training office, which is basically a teacher's office, should be located next to a training space or seminar room so that training materials do not need to be carried great distances.

There are other types of tasks that may be required by fire administration such as receivables and payables, and these office types should be structured the same as any other business. In all cases, it is advisable to ascertain early on what personnel require private offices and what furniture and equipment are associated with each.

If the station serves an administrative function, then there should be space in the building for people to wait. This may be a small separate room or it may be a space near the offices, but it should not be a few chairs set up in a corridor. If conference rooms are desired, they are best designed large enough for multiple functions. Consider what activities will take place in each conference room and consider locations for white boards, audiovisual presentations, and storage. This room can serve as a place where administrative personnel can meet with individuals or small groups, for example, the fire prevention officer meeting

with a group of prospective developers or builders in a relatively private setting.

If a separate space for *training rooms* is desired, then it should be set up as a classroom (Figure 12.14.2). The room should be spacious, provide desks for the personnel to use, contain blackboards, allow space for slide and overhead projectors, provide adequate space for the display of training materials, and contain equipment for multimedia presentations and interactive training. The training room should also contain a lecture table for the instructor. The training room dimensions and proportions determine what type of audio can be used effectively.

The *watch room,* which has a variety of names (e.g., alarm room, station office), is essentially the office for the apparatus floor. This space can range from a minimum of 120 ft^2 (11 m^2), generally containing a desk, a chair or two, a phone, a map, and usually a radio, to a space for up to six or more people. The typical watch room serves as the place where paperwork for the apparatus, the log-in of calls, and station-to-apparatus communications are handled. The space is generally located adjacent to the apparatus floor to facilitate operations and has visual access to the bays and front apron. Often this is the place where visitors to the fire station first enter without going directly onto the apparatus floor.

A recent addition to fire station design is a small *exam room* near the front entrance of the station. The room can be set up similar to an exam room found at a physician's office. An increase in the number of walk-up emergency cases at fire stations has facilitated the need for this space to accommodate uninsured persons looking to the fire service for emergency care. These rooms serve as a location for blood pressure screening, and in areas prone to natural disasters they can become triage locations.

Residential and Living Areas. In fire stations where personnel are on duty at all times, *sleeping accommodations* commonly called the "bunk room" are provided for sleeping. Traditionally, bunk beds (two beds, one on top of another) were provided to save space. For a more "homelike" feel, many new sleeping areas are now being designed like dormitory rooms, which can vary from very simple (bed and lockers only) to more elaborate accommodations that include desk areas with computer and cable connections.

FIGURE 12.14.2 Training Room with Interactive Whiteboard

A growing trend in the volunteer fire and rescue service is to require or encourage volunteers to perform a "duty night" where they staff the stations at night. In many cases, this can reduce response time to emergencies by 4 minutes or more. To support these efforts, many amenities are being added for such volunteers.

Access from this area to the apparatus bays should be as direct as possible. The best case is to have this room on the same level of the station as the apparatus bays, because injuries have occurred when personnel traveled from the sleeping area to the bays using poles or stairs and because response time is faster. Although stairs are safer than poles, both have caused serious injuries and should be avoided. Some of these sleeping spaces have walls of soundproof materials of partial height, and some are full height.

In a large "bunk room" area, men and women can and do share sleeping facilities with few problems. This type of traditional arrangement helps to ensure that each member feels part of the company. Fire fighting is a team activity and every effort should be made to support the team concept. One problem that needs to be specifically dealt with is the clothing that is acceptable in these situations. Acceptable sleepwear could be an issued item from the fire department.

Some departments have provided separate sleeping facilities for women, which can have some negative consequences. Women may feel alienated by feeling that they are not part of the company. Also, from a practical point of view, it is not known how many men or women will be sleeping at the station on any given night. There may be a whole crew of women (as reported in one large West Coast fire department) or there may be none on duty. Designs that can double the amount of space and furniture needed for sleeping accommodations may result.

Having men and women sleeping in two-person, "dorm-type" rooms should not be allowed. A rule should be enforced that stipulates either all men or all women in each room. Also, using one-half or three-fourths height separation walls will provide privacy without sacrificing the company feeling that is so important to a well-functioning team of fire fighters.

Another trend occurred after fire departments started providing ambulance service. Separate sleeping rooms have been provided so that the EMS crew can be alerted for a call without disturbing other fire crews, which has many of the disadvantages noted in our previous discussion of women in the fire service. If this arrangement is a problem, some other type of alerting should be considered. Designating certain beds for the EMS crew and providing a separate telephone have been successful in some cases.

Adequate clothing storage should be provided for personnel to keep several sets of clean uniforms and other clothing. Many departments provide clothing storage areas for each person assigned to the station (Figure 12.14.3), which can mean up to three or four storage areas for each on-duty person. Volunteer departments that commit to having on-duty companies for immediate response may also need several clothing storage areas

FIGURE 12.14.3 Sleeping Room with Desk and Space for Clothing

for each person on duty. Several designs use a separate room for clothing storage with metal lockers and wooden benches similar to a dressing area of a sports facility.

For a staffed station, the *kitchen* quickly becomes an essential part of the building. The kitchen is where the fire fighters take their meals and their breaks. The eating area of the kitchen can also be used for training. The cooking area should be of commercial quality, due to the almost constant use of the kitchen (Figure 12.14.4). In a station with two or three full companies and a chief, the kitchen can be called on to serve upwards of 60 meals every day. If the kitchen is used in conjunction with a community room or other similar space that is, or may become, accessible to the public, then even more meals can be expected to be served in an emergency situation. Part of the kitchen must be reserved for storage of food, and each shift expected to use the station should have a separate space or pantry for food. The kitchen should also be equipped with at least one dishwasher but two are more desirable to ensure that, even if the station has a busy day, there will be clean, sanitized dishes for meals. The same is true of microwaves, which have an equal amount of heavy use. The kitchen should be designed to be similar in size to a commercial kitchen, and the dining area also should be designed based on the number of expected diners. The dining and kitchen areas need to be separated from the apparatus bay to prevent diesel contamination.

FIGURE 12.14.4 Kitchen Space in a Multiple-Company Station

Lounge or living room areas resemble the typical family room in many homes, except they are larger. A TV and videotape recorder will be found that can be used during training sessions or for relaxation between alarms. Several couches and chairs to accommodate the normal number of personnel in the station will be provided. Many departments prefer reclining chairs, which will require a larger space. The furniture is normally commercial grade to hold up under constant use. The area should provide a homelike environment for the comfort of the fire and rescue personnel.

Most fire departments have recognized the health and safety benefit derived from implementing a fitness or wellness program. If the program is not mandatory, *fitness/wellness rooms* are provided for the voluntary benefit of the staff. In designing this space, it is best to determine the type, sizes, and quantity of desired equipment first. The room size is a function of this information and the required clearances. Allow for a minimum 3 ft (0.914 m) corridor for quick access out of the room. The ceiling height should be established by the highest vertical equipment dimension and clearances. When laying out the room, consider such features as full length mirrors, wall-mounted fans or televisions, drinking fountains, and rubber flooring. Perimeter walls should be stabilized with plywood behind the finished gypsum wallboard and insulation for soundproofing.

Operations and Support. Regardless of whether or not the personnel are medical or hazardous materials responders, it is reasonable to assume that they will at some time encounter a contamination problem, either a biohazard or other type, that will require complete clothing removal. A *decontamination room or space* must be available where personnel can be decontaminated, beginning with the removal of the outer layer of clothes, and cleansing their skin without contaminating the rest of the station or its personnel. A room, or more likely rooms, with equipment to allow contaminated personnel to enter without touching anything, to remove and properly dispose of clothing, to clean themselves, and to don new noncontaminated clothing with some degree of dignity and privacy is required. The equipment involved includes foot-activated hampers, motion- or foot-operated wash basins and soap dispensers, automatic showers, automatic doors, and linen rooms for spare clothes and towels. Locating this room with a direct exterior entrance allows contaminated personnel to avoid spreading the contamination to other areas. Additionally, it is advisable to provide a toilet room adjacent to the decontamination room for similar reasons. As emergency medical services by the fire service become more common, the appropriate supplies for the service become more important. The supplies stored in an *emergency medical supply room* include narcotics, which require a large

degree of security. Other medical supplies have shelf lives that require frequent rotation. The diversity of the medical equipment needed to provide effective emergency medical services is increasing at a rapid rate. These items and the need to keep them clean and secure establish the need to have a room dedicated to the storage of medical supplies. This medical supply room should be located near the emergency medical vehicle(s) and must have a lock. It should be of such size that the equipment can be stored in a neat and orderly fashion. The room should be equipped with shelves and small cabinets, as well as a locked cabinet for narcotics and other regulated equipment. A double sink is also handy in this space. A room 10 ft by 12 ft (3.1 m by 3.7 m) generally will serve this purpose.

As with decontamination of personnel, protective clothing also needs to be cleaned. *Laundry rooms* are becoming a popular feature in fire stations. Turnout gear and other personnel clothing worn on the job need to be cleaned. It is not reasonable to expect personnel to take this equipment home to wash, and few commercial laundries will wash turnout gear. A commercial washer and dryer, as well as adequate venting, are necessary for this space. This space may best be incorporated into an area near where the fire personnel hang their protective gear during off-duty time (Figure 12.14.5). Separate and smaller residential-style laundries can be provided near the dormitory area for washing station laundry and sheets.

FIGURE 12.14.5 Lockers Providing Ventilation to Dry Equipment

A fire station layout must provide space for personnel to wash. Separate or unisex *bathing facilities and toilets* for men and women should include sinks, toilets, showers, and lockers, as well as closets for linen. These spaces should be of tile or some other type of construction to withstand constant use with very little care. The equipment in the space should be of such quality as to give an adequate time of use before renovation. The space allocated for these rooms can be based on the expected number of users. In addition to the space for personnel, space should be allocated in the building design for toilet facilities for other personnel or visitors to the station.

Construction

Construction materials, techniques, and types for fire stations are generally indigenous to the respective regions. Design professionals and engineers are normally well versed in the options and associated costs for construction and will have these discussions early in the planning and design phases. For each material specified and technique used, consider the following:

- Structural capacity
- Durability and degradation—how well the material will hold up to internal and external elements
- Maintenance requirements and costs
- Life cycle and replacement costs
- Energy efficiency

FIRE SERVICE TRAINING CENTER DESIGN

Fire training center design and construction are unique fields that require specialized expertise. Fire training centers can incorporate several types of building functions, such as the following:

- Classrooms
- Offices
- Apparatus bays
- Equipment storage and maintenance areas
- Auditoriums
- Break rooms (or cafeterias)
- Exercise facilities
- Working fire stations
- Emergency operations centers
- 9-1-1 call centers
- Television studios
- Living quarters

As complex as these combinations can be, it is the specialty, hands-on fire training props that make fire training center design especially challenging.

To succeed in designing and constructing a fire training center, the fire department needs to assign personnel who will be highly involved in all stages of the process, from planning through design and construction. This will provide the designers with needed expertise relating to fire training operations and current fire-fighting tactics that need to be taught. It will also ensure that the fire department's needs are heard and implemented.

The fire department should look ahead, beyond design and construction, to make sure that adequate funding and personnel will be in place to operate and maintain the training center once it is built. The basic process for planning, designing, and constructing a fire training center follows, along with types of features, buildings, and props that could be incorporated into the facility.

Needs Assessment

Many fire departments fall into the trap of trying to design the training center as the first step. Although it may be enjoyable to dream about different types of training props and to lay them out on a site plan, it is important to step back to the true starting point—assessing the need for the fire training center. Questions that need to be answered include the following:

- Why do you need a training center?
- Whom do you need to teach?
- What do you need to teach?
- What training resources do you already have?
- Do the existing resources provide effective training for a reasonable cost?
- At what rate is the community growing and will growth affect future training needs?

To answer these and related questions, a valuable resource is a working group representing the entities that might use the training center (see section headed "Identification of Potential Users" that follows). Tools available to the working group include meetings to exchange information plus written surveys to be filled out by potential users, either online or in paper format. It is important to gather data that help evaluate the need, such as the following:

- How many potential students exist?
- What is the geographical distribution of the potential students?
- What are the annual training requirements (curriculum and hours)?
- Where is training currently conducted and at what cost?
- What training requirements are not being met?
- If a new fire training center were built, who would use it?
- What classes and facilities at the new fire training center would be in highest demand?
- Would potential users be willing to pay fees to train at the training center?

These data, if properly gathered and interpreted, should provide enough information for the working group to know if the training center is really needed and, if so, what preliminary resources exist to help build, operate, and maintain it.

Architect/Engineer (A/E) Selection

Selecting an architect/engineer (A/E) should be one of the first steps. The A/E team typically includes an architect, civil engineer, electrical engineer, mechanical engineer, structural engineer, and a fire training center design consultant, if the A/E does not already have this expertise. It might be necessary to add a geotechnical (soils) engineer, environmental engineer, or other specialists to the team.

The role of the A/E is multifaceted. The A/E could participate in the needs assessment or should, at least, validate it. The A/E should perform all of the following:

- Determine training objectives (what skills need to be taught at the training center).
- Determine what buildings and training props are needed to facilitate the training objectives (prepare the program).
- Estimate how much land is required.
- Help find a suitable site.
- Estimate project budget.
- Assist with marketing the project to the city council, grant agencies, potential contributors, or the public at large.
- Prepare the master plan, which includes a site drawing that shows buildings, training props, roads, parking areas, utilities, and other features.
- Design the training center.
- Assist with bidding the project out to contractors who would construct the training center.
- Provide construction administration to help oversee and facilitate the project as it is being built.
- Provide postconstruction assistance with evaluations and maintenance.

While selecting the A/E, the fire department should look for the best combination of qualifications and those qualities that make the department believe it could work well with the A/E for the next several years. Most publicly funded projects require qualifications-based selection (QBS), as opposed to low-price selection, to ensure that the A/E is properly qualified to plan and design this specialized facility. A/Es with no fire training center experience should team with specialty consultants because designing K through 12 schools or fire stations does not provide the necessary expertise to design live fire training structures and other specialty training props (Figure 12.14.6). Vendors that sell training props, equipment, tools, or other items for fire training centers should not be hired as "consultants" for planning and design efforts because of potential conflicts of interest. Fire departments should seek independent advice about all of the options, not just those of one vendor. Be certain that companies that represent themselves as consultants do not also act as sales representatives for vendors.

Identification of Potential Users

Many fire training centers are intended for use only by the local fire department. Others are to be regional facilities used by career and volunteer fire departments from the extended region surrounding the facility.

If many departments and communities are involved, a regional consortium could be formed to pool resources (land, money, and personnel). There are several factors to be evaluated for a consortium. For example, which locality will provide the site? Which will operate and maintain the facility? How will the nonhosting consortium members support construction, operations, maintenance, and other costs? Will there be usage fees for rental and consumables? Will there be an annual contribution from each member of the consortium?

FIGURE 12.14.6 Live Fire Training Structure

Other agencies besides fire departments could be users of the training center. For example, law enforcement, EMS, emergency management, emergency operations center, 9-1-1 call center, and communications center departments are potential partners in a training center. If community resources are limited to the point that having separate facilities for these departments is not feasible, sharing certain facilities at one training center is an option. For example, classrooms, auditorium, physical fitness rooms, conference rooms, driver training course, and a training tower could be shared by the fire department and law enforcement agencies (police and sheriff) to maximize cost-effectiveness. Other critical training functions, however, could be kept separate, so that the fire department live fire training structure (burn building) and drafting pit are separate from the law enforcement shooting range and bomb disposal training area.

Identification of Operation and Maintenance Personnel

Before designing the training center, key personnel and budget decisions should be considered. Will there be full-time administrative staff, full-time instructional staff, and full-time maintenance staff? The answers to these questions will have a significant impact on the operations and maintenance budget once the training center is built.

Even though design has not begun, now is the time to start estimating operations and maintenance budgets. When requesting funding for construction, the department should also request operations and maintenance funds for the years immediately following construction to ensure that the proper budget is in place once the facility is built.

Identification of Funding Sources

Funding a new fire training center can be a tremendous challenge. Municipal capital outlay budgets and bond funds are the most common funding sources, but many departments need to supplement these funds. Other potential funding sources include the following:

- Construction grants
- Federal or state grants
- Local industry
- Donors
- Regional participants
- Other participating municipal or state agencies

Historically, federal grant funds could not be used for building construction, though federal grant rules should be explored for current opportunities before ruling out these funds for construction. Even if federal grants cannot be used for construction, they might be available for funding equipment, mobile training props, and training programs, allowing more of the local resources to be used for the construction of fixed buildings.

It is never too early to start marketing funding sources to gain support for the project. Some departments have needed years to obtain adequate financial support. Some departments have raised funds simultaneously with land acquisition and design phases, shortening the waiting period for construction to begin. Adequate funding ("seed money") for A/E fees for the initial programming, master planning, and perhaps land development submission will be necessary up front. This seed money will result in a well-developed master plan and budget, which could be used to help market funding sources for the full project cost.

Master Plan

Master planning initiates the design process. The key steps in creating the master plan include the following:

- Determine the training objectives.
- Write the program for training facilities needed to support the training objectives, including space requirements (space within buildings and space around training props). This program is the foundation for a successful project and should be established through significant interaction between the A/E and the fire department. Should it be necessary, the program could be adjusted during later stages of planning and design.
- Evaluate current and future needs.
- Create a conceptual site plan (Figure 12.14.7). This task should be coordinated with the "Site Selection and Design"

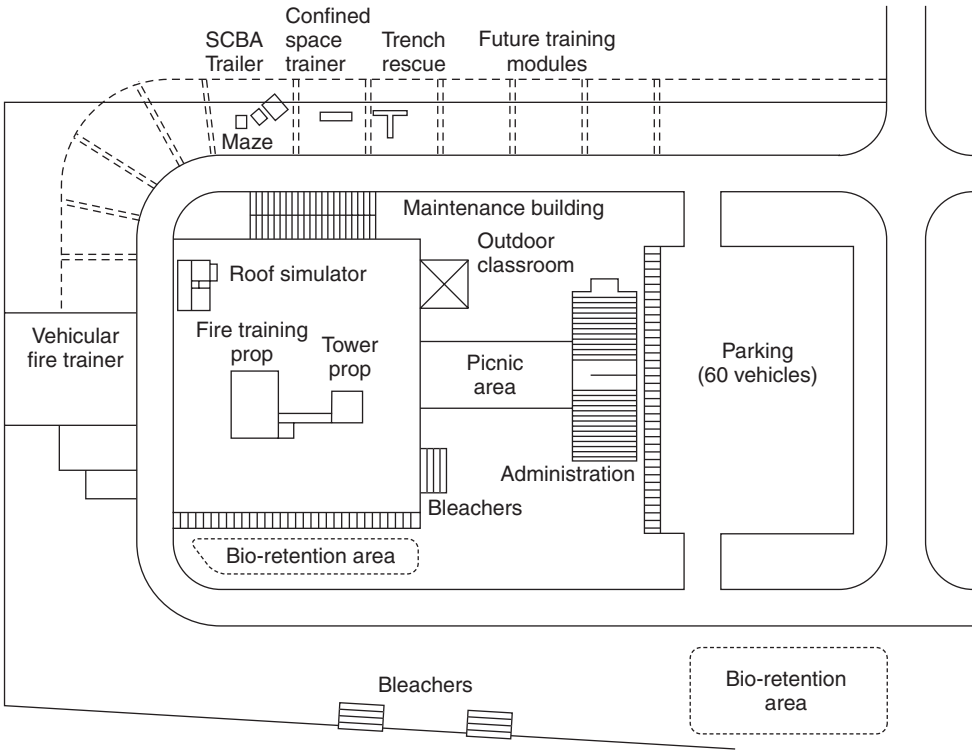

FIGURE 12.14.7 Sample Master Plan

tasks described later. The first draft of the conceptual site plan could be a simple "bubble diagram," showing approximate areas where buildings, props, and site features could be placed on the site. Eventually, the conceptual site plan will be more detailed, showing all features including their approximate shapes and sizes.

- Create conceptual plans of primary buildings and training props (Figure 12.14.8).

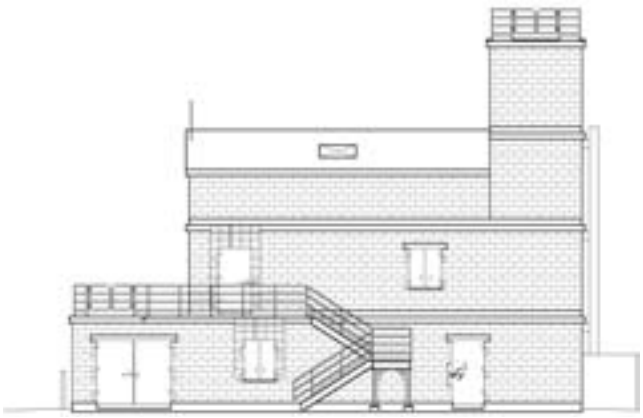

FIGURE 12.14.8 Conceptual Burn Building Elevation to Be Included in Master Plan

- Establish the budget for land acquisition, construction costs, furnishings, equipment, apparatus, and soft costs. Soft costs include fees (design, legal, and permitting), inflation, and contingency.

The site needs to be laid out to allow for future expansion. Training needs should be expected to change in the future, and the training center will need to adapt. Fifty years ago, training centers often did not need classroom spaces, and those classrooms were not designed for the technology demands of modern classrooms. After September 11, 2001, training for mass casualty incidents, building collapses, and multiagency concurrent training have been in higher demand. Many existing training centers do not have enough remaining space to accommodate these new needs. What new training will be needed 10 or 20 years from now? No one can predict, making future expansion capacity a critical component to the master plan. The master plan should consider the site issues listed next under "Site Selection and Design."

Site Selection and Design

Finding a suitable site can be difficult and requires perseverance. The process should coincide with preparation of the master plan because (a) the programming and space requirements of the master planning effort must be known in order to establish the selection criteria needed for the site search; and (b) on the other hand, the site must be selected before the master plan can be finalized.

Evaluating potential sites often involves filling out a criteria matrix that resembles a scorecard. There are many different features to evaluate for each site, as further described later. Scoring each of the needed features on a scale of 1 to 10 helps quantify which potential site is best suited. Some criteria can be weighted more heavily if they are more important. For example, a good score for environmental sensitivity might be more important than a good score for ease of obtaining a permit, especially if the latter could be overcome with a little extra time and effort on the part of the A/E. All potential sites should be scored, even if some appear at first glance to be unworthy of consideration, to validate the process and to confirm that the most suitable site is selected.

Resources for finding potential sites include local knowledge of the municipality and fire department, geographic information systems (GIS), local or state planners, tax maps, real estate companies, U.S. Geological Survey quad sheets, and other regional maps. The list of potential sites, and the evaluation of those potential sites, should look into the following criteria, at a minimum. These criteria will also impact the design.

Zoning. The area master plan, or similar document, should provide information about how potential sites are zoned. Industrial zoning or other suitable classifications are desirable, so that the training center is not located in a residential or commercial area.

Acreage. There seems to be no such thing as too much land at a training center. First, there needs to be adequate setback from neighboring properties, even if the neighbors are industrial in nature. Visible distractions (unsightly appearance of props, lights during night training, visible flames, and fire department activity), noise, and smoke have a negative impact on any neighbor. Creating adequate setback and visual buffering, through use of land berms, vegetation, fences, and buildings, has proven an effective method of minimizing complaints from neighbors.

Second, there needs to be ample space between the training props, so that crews working at the different props do not interfere with each other. If it becomes necessary to overlap working spaces around adjacent props in order to conserve land area, then those two props might not be usable simultaneously, requiring careful scheduling.

Third, there needs to be adequate distance between the training props and the conventional buildings (classrooms, offices, maintenance buildings, etc.). Smoke, noise, and lights interfere with the activities of these buildings and separating the props from the buildings is desirable.

Fourth, room for future expansion of the training center is desirable to be able to accommodate more students in the future plus different types of training that might not be known today but could be critical in the future.

There are many factors that can reduce the land that could be developed at a site. A 15 acre (6.1 hectare) site might have only 7 acres (2.8 hectares) that can be developed, once setbacks, wetlands, easements, or other restrictions are considered. Evaluate the developable acreage in addition to the overall acreage when selecting a site.

Location. On the one hand, it is desirable to have the training center close to the students to reduce travel time to the site. On the other hand, it is desirable to have the training center far from the population base to minimize its impact on the heavily developed portions of the community. A balance must be reached, including thoughts about potential community growth over the next 20 to 50 years. Many training centers that were built in remote, rural parts of a county found themselves surrounded by residential suburbs 10 to 15 years later.

Regardless of the site location, some students inevitably have a significant travel distance to the training center. In some cases, that is not a problem. In other cases, it affects cost (overtime requirements) and community protection (if a company that is training has to remain in service). Possible solutions for these issues include the following:

- Locate the site in a central location to balance the travel time of the students.
- Schedule other companies to backfill a station when that company is training.
- Provide sleeping facilities (dorms) at the training center, so that students attending weekend or longer programs do not have to travel long distances every day. Keep in mind that this solution is less common due to construction and operational costs.
- Provide satellite training centers, so that distant students can accomplish basic training closer to home and travel to the primary training center for specialized training.
- Provide mobile training props to take some of the basic training opportunities to the students rather than the other way around. This solution has been effective for training centers that serve large regions or entire states. Due to their size, it is difficult for mobile props to adequately simulate buildings, but several skills can be taught effectively with mobile props, including fire behavior demonstration, mask confidence (maze), aircraft fire fighting, and confined space skills.

Infrastructure. The site needs to have suitable infrastructure to support buildings, apparatus, and training operations. Site selection and design should consider the following:

- *Water supply.* Is potable water available? It will be required for drinking water, emergency eye washes and showers, restrooms, dining facilities, laundry operations, and similar functions. Potential sources include municipal water and wells. Water for training operations and irrigation could be potable or it could be supplied by tankers, ponds, or drafting pits. Recycling training water should be considered, and the A/E should look into methods for collecting training water and holding it for reuse. The recycling system could have a pumping station to charge hydrants around the site, or the system could include a series of dry hydrants. Water loss due to evaporation and conversion to steam should be considered when designing a recycling system, for the lost water will need to be replaced periodically by the fire department if precipitation is not adequate.
- *Sewer.* Is the site supported by municipal sewers or will a septic tank be required? Runoff from training operations usually does not need to go to sanitary or septic receptacles.

- *Storm water management.* Is a municipal storm sewer available to the site or will storm water be controlled on site through means of ponds, holding tanks, or other devices?
- *Power.* Is power readily available to the site? If not, the construction cost will increase.
- *Soils.* Are the soils suitable for supporting buildings, training structures, and roads used by apparatus? If there are loose fills, expansive clays, or rock on the site, there could be a significant cost impact.
- *Access roads.* Is the road network leading to the site suitable for supporting apparatus loads that will travel to and from the site?
- *Topography.* If the site is too hilly or too flat, the development costs could increase because soil might have to be added or removed. At some point in the site selection or site design process, a topographical survey will be required. This survey should also map the features of the existing site (buildings, areas of major vegetation, utilities, roads, and property lines).

Environmental and Other Restrictions. Due to the industrial nature of a fire training center, finding a site that meets environmental and other developmental restrictions is critical. Here is a sample list of items to evaluate for potential sites:

- Smoke plume and prevailing winds
- Water runoff that could include contaminants (soot, unburned Class A or Class B fuels, fire-fighting chemicals)
- Wetlands
- Endangered species habitats
- Protected vegetation
- Flood plain
- Landfill or hazardous materials
- Historical preservation
- Adjacency to airport or other facility that could impose restrictions on use and airspace above or around site

Public Access. Because there will be times when the public will need to access the site, it is best to design the site so that the public access areas, such as administration building, auditorium, and visitor parking, are near the road and main entrance. In most cases, this also puts the most attractive buildings near the road and main entrance, which is good for public relations.

Security. There are areas where public access should be denied, including training grounds and storage buildings. Fencing should be considered to separate the public access points, such as the visitor parking lot, from the rest of the site. Similarly, receptionists controlling locked doors could separate public areas in the administration building from offices, classrooms, and the rear doors that exit to the training grounds. Other security measures, such as cameras, manned gates at access points into the training grounds, and combination locks into storage rooms that contain harmful chemicals (or weapons if the facility is used by law enforcement), could be considered depending on the security needs.

Caution with Donated Land. Fire departments are sometimes offered land donations for the training center. The donation of an old landfill is a common example. Before accepting such a donation, the land should be evaluated for all of the environmental and other developmental restrictions that could make it expensive to develop, as listed earlier. It should also be evaluated for the infrastructure needs that are listed previously. In some cases, the department might not be able to afford the donation.

Design

Once the site is obtained, the master plan is in place, and the funding is available, it is time to design the facility. If hiring the A/E has been delayed until now, there is a good chance that the budget, land, and expectations could be off target. The A/E would need to validate all the work performed to date before commencing design efforts. Ideally, the A/E would have been retained during needs assessment to avoid potential delays.

The design process for a fire training center is similar to that of a fire station or any other conventional building. First, it is important to follow the applicable codes, standards, and guides. Some documents that relate to fire training center design include the following:

- State and local building codes, interpreted carefully for the training props
- NFPA 54, *National Fuel Gas Code*
- NFPA 58, *Liquefied Petroleum Gas Code*
- NFPA 86, *Standard for Ovens and Furnaces*
- NFPA 1001, *Standard for Fire Fighter Professional Qualifications*
- NFPA 1002, *Standard for Fire Apparatus Driver/Operator Professional Qualifications*
- NFPA 1402, *Guide to Building Fire Service Training Centers*
- NFPA 1403, *Standard on Live Fire Training Evolutions*
- IFSTA, *Essentials of Fire Fighting*
- U.S. Department of Homeland Security, Office for Domestic Preparedness, *WMD Training Program*
- State training guidelines, if any
- OSHA standards

The design process usually follows the standard steps of schematic design (15%), design development (35%), and construction documents (60%, 95%, and final).

The fire department should have constant opportunities to interact with the A/E, including chances to review the drawings at each stage and provide feedback. It is important to be vocal. A/Es require the fire department's input in order to provide a good design, starting with master planning through each step of design. If A/Es do not seem to listen, they should be confronted so that they can provide better service.

Four key design issues include (1) safety, (2) training effectiveness, (3) durability, and (4) ease of maintenance. Be sure the A/E explains at each stage how these issues are being met with the design.

Construction

Once the design is finished, the project will likely be bid to contractors (builders). The bidding process usually follows the

state and local procurement laws, especially if public funds are being used. For the most common form of bidding, the project is advertised, contractors give price bids based on information shown on the A/E's drawings and specifications, and the contract is awarded to the lowest responsible bidder.

The fire department should remain heavily involved during construction, including regular visits to the site and attendance at the construction progress meetings. Should anything look unexpected, the fire department should call the A/E. Occasionally, the fire department might want to make a design change during construction, which is feasible but usually requires paying a change order (extra charge) to the contractor, especially if the change alters something that has already been built. In most cases, it is better for design changes to be completed during the design phase.

During construction, the A/E's role includes the following:

- Run routine progress meetings.
- Make periodic site visits to observe construction.
- Review shop drawings.
- Answer questions from the field.
- Answer fire department's questions.
- Design modifications if the fire department requests design revisions or if unforeseen conditions require it.
- Process the payment applications.
- Communicate between the contractor(s) and fire department's representatives.

Postconstruction

When the dedication ceremony is over, there is a need for an operations and maintenance (O&M) budget, starting in the first year. Ideally, this funding would have been placed into the municipal budget during the planning phase. Budget items required for O&M include the following:

- Staff salaries and benefits
- Building maintenance (cleaning, lightbulbs, trash removal, and painting)
- Grounds maintenance (landscaping, roads, parking lots, and snow removal)
- Equipment maintenance (vehicles, gear, mannequins, and SCBAs)
- Utilities (water, electricity, gas, sewer, telephone, and Internet)
- Training fuel costs
- Noise, smoke, and runoff abatement costs, if any
- Training structure and training prop maintenance, including routine structural engineering evaluations of the live fire training structure (burn building), per NFPA 1403

Buildings at Fire Training Centers

The two most common buildings at fire training centers are classroom/administration buildings and support buildings. Other buildings could be included, such as fire stations, dormitories, and vehicle maintenance facilities, but the two primary building types are described next.

Classroom/Administration Building. The classroom/administration building could be a single portable classroom in a trailer or a large, multistory, multifunctional building (Figure 12.14.9).

Classrooms should accommodate the typical anticipated class size but have moveable partitions that could allow for larger or smaller classes within adjoining spaces. The classroom space should be multifunctional. One day it might be used for a classroom lecture, using the latest audiovisual and computer equipment. The next day it might be used to demonstrate SCBA equipment or to teach CPR on mannequins. As a result, it is beneficial to have tables and chairs that could be easily reconfigured or moved out of the way altogether. It is also beneficial to have durable finishes, for even if dirty gear will not be brought into the classrooms, the finishes will see ample wear and tear.

Classrooms could also be equipped to record sessions (video and audio), so that the sessions could be played again later at stations or other regional departments for distance learning opportunities.

Other functions to be considered in a classroom/administration building include the following:

- Dirty classrooms accessible from the outside drill area, so that students could enter in gear for classroom sessions relating to the hands-on training exercises being conducted; this function could also be out on the training grounds, in the form of outdoor classrooms
- Breakout rooms—small meeting rooms that allow for small group activities; a breakout room could also be used as a conference room or room for instructors to create curriculum and prepare for classes
- Offices for permanent staff
- Office for temporary staff and temporary instructors
- Formal conference room; could also serve as a breakout room for classroom sessions
- Work rooms, including printing, copying, and other functions
- Break room/kitchenette; for large fire training centers, there could also be a need for a full kitchen and cafeteria
- Library
- Auditorium for uses including large lectures and graduation ceremonies; tiered seating is problematic for comput-

FIGURE 12.14.9 Classroom/Administration Building

erized testing techniques, so a traditional auditorium might not be functional for examinations
- Audio/video functions, such as recording studio, editing rooms, and storage
- Physical fitness room; could be located in a support building instead
- Locker rooms and showers; not all training centers need these facilities. The training center could support the physical fitness room. If there is no physical fitness room, this function could be located in a support building closer to the training grounds. If this function remains in the classroom/administration building, it should have an exterior entrance from the training grounds, so that students in dirty gear do not pass through the clean portions of the building.
- Restrooms
- Heritage hall
- Storage areas for office supplies, training props, classroom equipment, training records, recordings of classroom sessions, cleaning supplies, break room supplies, and other equipment stored at the facility
- Parking, which should be sufficient to accommodate permanent staff, students, and visitors; if graduation ceremonies or other heavily attended public events are anticipated, the parking areas should be designed accordingly, or overflow parking areas should be identified on the site

Support Building. The support building serves the classroom/administration building as well as the training grounds (Figure 12.14.10). Functions in this building include the following:

- Vehicle storage and minor maintenance
- SCBA storage, refilling, and maintenance
- Locker rooms and showers; this function could be in the classroom/administration building instead
- Physical fitness room; this function could be in the classroom/administration building instead
- Restrooms
- First aid
- Storage for training props, equipment, and gear

FIGURE 12.14.10 Support Building

- CPAT course; a candidate physical ability test course could be set up in the apparatus bays, if the bays are large enough, in order to control the environment during the test

Training Structures and Props

The following is representative of training structures and props commonly found at fire training centers.

Live Fire Training Structure ("Burn Building"). A burn building is usually the first training structure provided at a training center. Its function is vital in teaching skills required by NFPA 1001, especially those requiring live fire training scenarios.

Burn buildings are exposed to harsh conditions and could deteriorate quickly if not designed correctly. There are three primary causes for damage. The first is heat, which could reach as high as 2000°F (1093°C) in areas of direct flame impingement, such as ceilings directly above training fires. The second is thermal shock, which is created when heated surfaces are sprayed with cold water. The third is abuse that is inherent in live fire training, such as impact from direct hose streams and impact from tools and gear carried by personnel.

No building materials are immune to damage from these conditions. Masonry cracks and gradually deteriorates. Steel warps and corrodes. Concrete cracks and spalls, a condition that occurs when pieces of concrete fall out of slabs or walls. Careful design and construction are required to eliminate the potential for damage to structural components.

When designing a burn building, the first step is to determine which type of fuel is required to meet the training objectives. The two primary options are Class A fuels and gas-fired props, which burn either LP or natural gas. The benefits of Class A fuels are the drawbacks of gas props, and vice versa. Some training centers have burn buildings that can accommodate both fuel options to achieve the benefits of both.

The structural elements of the burn building need to be protected with thermal linings. There are several options. For ceilings, the options tend to be proprietary ones. The options currently on the market are not equal products, in that different materials are installed in different ways from one vendor to the next. In choosing a thermal lining, the qualities to be evaluated include initial cost, long-term cost (including maintenance costs), verifiable evidence of durability and insulating capability, and references. Thermal linings for walls and floors could include the proprietary options but could also include more conventional options, such as fire bricks and masonry blocks. Steel is not an insulator, plus it tends to warp when exposed to heat. If steel is used as a thermal lining, it will need to be supplemented with additional insulation or ventilated air spaces, though these might not eliminate warping and the need for periodic steel replacement. Refractory concrete (calcium aluminate concrete) should not be used for structural components in burn buildings, given its track record of severe damage in burn buildings.

Two types of burn buildings are most often constructed. The first is a combination of concrete and masonry (Figures 12.14.11, 12.14.12, and 12.14.13). The second is preengineered steel. Each option has advantages and disadvantages and should

FIGURE 12.14.11 Two-Story Burn Building

FIGURE 12.14.12 Three-Story Burn Building with Attached Four-Story Tower

FIGURE 12.14.13 Five-Story Burn Building with Tower

be considered. Determining factors should include long-term cost, durability, and ability to provide realistic floor plans that simulate occupancies found in the community. The A/E should guide the discussions on options for building types, fuels, and thermal linings, as well as design the burn building and features.

Details should be designed for function as well as safety, durability, and ease of maintenance. For example, various roof pitches, roof ventilation cutout areas, durable doors and shutters that can expand and contract when exposed to heat while still blocking out light and keeping in smoke, and drainage scuppers should all be detailed by the A/E to ensure proper function and durability. Other potential features include forced entry doors, breach wall simulators, standpipes, temperature monitoring systems, rappelling anchors, and mock utility meters.

Around the exterior, it is best for the burn building to be accessible from all sides. Realistic challenges, such as curbs, street signs, and simulated overhead power lines (Figure 12.14.14), could be incorporated at one or more sides at low cost. Paving near the structure needs to be nonslip for ladders and durable for apparatus loads. Consider seasonal conditions as well, for asphalt could soften during hot summer days, making it susceptible to damage from apparatus loads and ladder bases.

In many cases, it is desirable for the burn building to be lockable at all accessible doors and windows, especially if the training grounds are not secured with a fence.

Training Tower. Training towers vary in floor plan and range in height from 3 to 10 stories, though 4 to 6 stories is the most common range (Figures 12.14.15 and 12.14.16). The construction of training towers is typically either wood or concrete, although steel towers have been used. Preengineered steel training towers are also available, usually combined with preengineered burn buildings. Other types of towers can be combined with burn buildings as well.

The following training functions are often performed at training towers and should be considered:

- Ground ladders to windows (could be various size windows), flat roof deck, pitched roof, or balconies
- Aerials; tower height should accommodate tallest aerial that is anticipated to be used in the community in the next 10 to 20 years
- Stair drills, both interior stairwells and exterior fire escapes
- Rappelling from roof, windows, and perhaps other locations unique to the community
- Standpipe connections and charging standpipe at fire department connection
- Search and rescue drills using artificial smoke or smoke from small Class A burns in a barrel, though soot from these fires could damage ropes
- Elevator shaft drills
- SCBA confidence maze (which could alternatively be in a shipping container on the site)
- Forced entry doors
- Technical rescue drills, including tripod over aligned manholes, high angle rescue, and building-to-building rescue

FIGURE 12.14.14 Simulated Power Lines and Other Obstacles Near Training Structure

FIGURE 12.14.15 Small Training Tower

Some towers have small floor areas and are used for basic ladder, stair, and rappelling drills. Other towers have larger floor areas in order to simulate various occupancies that exist in the community. Floor plan options should be considered in light of the search and rescue and other cold training opportunities already provided by the burn building.

In some cases, it is advantageous to combine the burn building and tower together, especially if site space is limited and if mid-rise evolutions need to be combined with live fire training. On the other hand, it could be more advantageous to separate the burn building from the tower, so that live fire training and tower drills could be conducted simultaneously by different classes. Furthermore, separating the two structures allows all four sides of the structures to be used for their intended purpose. If combined into one structure, the D side of the burn building and the B side of the tower, for example, would be eliminated from training possibilities.

Around the exterior, it is best for the training tower to be accessible from all sides, preferably with enough clearance for aerials to be utilized on all sides. Realistic challenges, such as curbs, street signs, and simulated overhead power lines, could be incorporated at one or more sides at low cost. Paving near the structure needs to be nonslip for ladders and durable for apparatus loads. Consider seasonal conditions as well, for asphalt

FIGURE 12.14.16 Large Training Tower

could soften during hot summer days, making it susceptible to damage from apparatus loads and ladder bases.

For hotter environments, consider a canopy roof over the roof, so that rappelling instructors and students can have shade during long training days. Like the burn building, it is often desirable for the training tower to be lockable at all accessible doors and windows.

Exterior Fire Training Props. Exterior fire training props are typically gas fired (LP in most cases because natural gas flames are difficult to see in daylight) and come in many configurations. Vendors offer props configured to simulate car fires, fuel spill fires, tank fires, dumpster fires, railcar fires, aircraft fires, shipboard fires, broken pipe/flange fires, outdoor grill fires, industrial fires, and other simulations. Many fire training centers have utilized the local gas company to design and build these training props as a lower-cost option to vendor-provided props. It is important to follow the gas code and all applicable NFPA documents, including the requirements of NFPA 1402 and 1403, when designing such props. Most A/Es do not have the expertise to design these props.

Mobile gas-fired props are being utilized more frequently, especially for statewide training and regional training. Rather than bringing students to a centralized fire training center, the mobile gas-fired props can be taken to the students. Mobile gas-fired props include trailers to simulate structure fires (though these props cannot provide the proportions of a burn building), car fires, aircraft fires, and tanker truck fires.

Exterior props could utilize Class A fuels instead of LP. For example, Class A materials could be burned in a junked car for training purposes. To conduct such burns, all closed containers, such as tanks, bumpers, pistons, shock absorbers, and some steering columns, must be removed from the car to prevent bursting. Any item that could have hazardous emissions, such as upholstery and plastics, should also be removed. In many cases, the car needs to be stripped to bare metal frame before being used for fire training.

Flammable liquid pits are becoming less common due to concerns about groundwater contamination and black smoke emissions. Should such a pit be utilized at a training center, the proper environmental containment is essential, as is setback from neighbors and other buildings/props at the training center for smoke dissipation.

Vehicle Extrication Training. Although some training centers have utilized gravel areas, most vehicle extrication training areas consist of a concrete pad that can accommodate several vehicles at one time for cutting and extrication exercises. Fluids should be removed from the vehicles before training but the concrete pad should be designed to ensure that any spilled fluids will be contained. Obstacles, such as precast concrete "Jersey barriers," could be added so that vehicles could be placed against the obstacles in order to make the training more challenging.

The vehicle extrication area could also be used for hazmat training by enlarging the pad to hold tanker trucks that could be used to simulate leaks and spills. The paved area provides space to practice containing hazmat spills.

Drafting and Pump Testing Area. When teaching the basics of pumping and drafting, it is necessary to have an area where the pumper can recirculate the water it flows rather than wasting resources and wetting down the training grounds. The two most common options are a pond, which could double as a storm water management device for the site, or a drafting pit, which is an underground concrete tank. For either case, there should be access to the water source for a suction hard sleeve and one or more dry hydrants, depending on the pump sizes. For the drafting pit, there should also be a horn-type steel tube or some other collection device to return the flow into the tank (Figure 12.14.17). The drafting pit should have a minimum capacity of 20,000 gallons (75,700 L). There should be a concrete pad, measuring approximately 50 ft × 25 ft (15.3 m × 7.7 m) adjacent to the pond or drafting pit for the pumper to be parked during operations.

Emergency Vehicle Operations Course (EVOC). An EVOC could include a large driver-training track that consumes more than 50 acres (20.2 hectares) of land, to simulate urban grids and highway interchanges. In most cases, however, a 1.5- to 2-acre (0.6- to 0.8-hectare) paved area is sufficient to teach the basic skills required by NFPA 1002. In many cases, the road network around the training structures and props can be utilized for driver training rather than building a dedicated driver training pad.

Outdoor Classrooms. Outdoor classrooms are typically open pavilion structures, with a wall on one side to hold a white board for use by an instructor. The pavilion offers students a place to sit on benches in the shade in dirty gear, to take in water and be cooled by fans (or warmed by heaters) while listening to instructors brief/debrief training evolutions. These structures also serve as shelters during sudden inclement weather. Outdoor classrooms could be equipped with restrooms, water fountains, emergency showers and eyewashes, first aid equipment, vending areas, and storage. It is good practice to provide several outdoor classrooms strategically located on the training grounds near clusters of training structures and props.

FIGURE 12.14.17 Drafting Pit

Other Training Props. There are numerous other training props that could be utilized, such as the following examples:

- Fire behavior lab, also known as a "flashover simulator," which consists of two shipping containers placed side by side and offset vertically, in order to demonstrate fire behavior
- Confined space prop, which could consist of any combination of connected vertical and horizontal pipes, manholes, tanks, and shipping containers with mazes inside. It is considered safe practice to keep as much of this prop above grade as possible, providing walkout access for all below-grade components.
- Trench rescue prop, which could consist of parallel concrete retaining walls holding back a hillside. Soil is placed between the walls, so that bracing is placed against the concrete walls during excavation. Should mistakes be made, the concrete retaining walls will ensure that a real trench collapse could not occur. The trench could be configured as a straight run, T-shape, or L-shape and should have a walkout condition for safety (Figure 12.14.18).
- Roof ventilation prop, consisting of a sloped, wood-framed structure built on the ground to allow roof ladder cutting exercises with no risk off falling of the roof of an actual building
- Rapid Intervention Team (RIT) prop, also known as FAST prop or RIC prop. This prop is a small, wood-framed structure that simulates conditions where fire fighters could get trapped, requiring rescue.
- Collapse rescue props, which could consist of basic concrete cutting props, basic balancing props, partially collapsed buildings with rubble on the floors, and rubble piles simulating fully collapsed buildings

SUMMARY

When developing a fire station or training center project, many issues must be considered. Because these factors will vary depending on the needs of the community, designers should adapt the application of the information presented in this chapter to suit local conditions and regulations.

The process of needs assessment, A/E selection, master planning, site selection, and design is consistent for both types of facilities, regardless of project scope and budget. Typical fire station spaces include an apparatus bay, sleeping accommodations, a watch room, a kitchen, a lounge or living room area, a decontamination room or space, and other functions. Fire training centers include a classroom/administration building, support building, burn building (live fire training structure), training tower, and various training props, such as drafting pits, exterior fire props, trench rescue props, confined space props, vehicle extrication areas, and others.

In all cases, the primary design issues are safety, functionality, durability, and ease of maintenance.

FIGURE 12.14.18 Trench Rescue Prop

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire rescue stations and training centers. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 54, *National Fuel Gas Code*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 1001, *Standard for Fire Fighter Professional Qualifications*
NFPA 1002, *Standard for Fire Apparatus Driver/Operator Professional Qualifications*
NFPA 1402, *Guide to Building Fire Service Training Centers*
NFPA 1403, *Standard on Live Fire Training Evolutions*

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Chapter 15

Public Emergency Services Alarm, Dispatch, and Communications Systems

Revised by
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Chapter Contents

Communication Centers
Radio Communications Systems
Personnel
Consolidation of Communication Centers
Reporting an Emergency
Processing Communications Within the Communication Center

Key Terms

alarm box, communication center, communications system, computer-aided dispatch, dispatch, emergency medical service, enhanced 9-1-1, Federal Communications Commission, fire alarm reporting system, hazardous material, joint powers authority (JPA), public safety telecommunicator, radio communication, radio frequency, repeater, transmitter

The goal of this chapter is to provide the *Fire Protection Handbook* user with an overview of public emergency services communication systems. It addresses issues related to the design, installation, operation, maintenance, and management of such systems and the facilities that house and support them.

In previous editions, this chapter addressed fire department communication systems. However, the widespread adoption of universal emergency number (9-1-1) service, coupled with requirements for formal training and certification of personnel and flexibility in resource allocation, has resulted in many jurisdictions combining central communication functions for all emergency services (fire, police, emergency medical services, etc.) into a single public safety answering point (PSAP) or communication center. Therefore, it has become increasingly difficult to address the emergency communication needs of the fire service without also addressing other emergency services.

NFPA recognized this trend when it changed the title and scope of NFPA 1221, *Standard for the Installation, Maintenance, and Use of Public Fire Service Communication Systems,* to NFPA 1221, *Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems,* commencing with the 1999 edition.

No two communities are exactly alike. Whether planning a new emergency communication system or evaluating an existing system, it is important to conduct an individualized needs assessment of the service area and then use it to analyze the emergency communication services provided and planned. In all cases, the requirements of NFPA 1221 should be followed.

For related topics, see the following: Section 12, Chapter 4, "Managing Fire-Rescue Departments"; Section 12, Chapter 13, "GIS for Fire Station Locations and Response Protocols"; Section 12, Chapter 16, "Fire Department Apparatus and Equipment"; Section 13, Chapter 9, "Emergency Medical Services and the Fire Department"; Section 14, Chapter 1, "Fire Alarm Systems"; and Section 14, Chapter 4, "Fire Alarm System Interconnections."

COMMUNICATION CENTERS

In creating any communication network, one must first establish a center point (communication center) through which all related process and control functions will be directed (Figure 12.15.1). A communication center may serve a single agency or area, multiple agencies under the control of a single political subdivision, several similar agencies from adjacent political subdivisions, an entire county, or any other large political jurisdiction. Combining fire, police, and emergency medical communications within a specific political jurisdiction (and for several adjacent jurisdictions) has

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FIGURE 12.15.1 Communication Center (Photo courtesy of Paul Ramirez, Phoenix Fire Department)

become an increasingly common management concept. If properly planned, such consolidations can provide positive results.

The communication center is where requests for emergency assistance are received and translated into an appropriate response. The communication center should be structured to provide logistical support to the responding units until the situation is under control. Accordingly, as an operating entity, the communication center must ensure that the equipment, personnel, and established procedures are adequate to satisfactorily perform in emergencies.

The communication center is a critical component of the jurisdiction's comprehensive emergency management plan. It is particularly important that communication center and emergency services communication systems be able to survive and continue to function during and after natural disasters such as floods, earthquakes, blizzards, hurricanes, and tornadoes. Such disasters may cause public utilities such as water, gas, and electricity to be unavailable to the communication center for extended periods of time. Lessons learned from past events and the probability of future events must be carefully considered and the communication center designed and equipped accordingly. One example is the resupply of fuel to emergency generators. A large-scale disaster could cut off normal sources of resupply, necessitating greater on-site storage than is required by code. There are resources that specifically address disaster management in the communications center. Resources to address these needs can be found at the National Emergency Number Association (NENA) website at http://www.nena.org or the Association of Public Safety Communication Officials (APCO) at http://www.apco911.org. In addition, the Commission on Accreditation of Law Enforcement Agencies (CALEA) at http://www.calea.org offers a Public Safety Communications Accreditation that specifically addresses disaster as well as all facets of communications. You do not need to be a police agency to use this resource. Finally, many statewide sheriff and chief of police associations offer free information on communication centers and disaster management for the communication center. Much of the free information offered applies to communications for the fire service as well.

Design Considerations

The following are some of the items that should be considered in the development of a communication center:

- Location
- Seismic stability
- Security (building layout and cameras)
- Emergency electrical power
- Wiring access (computer floor)
- Lighting (indirect lighting to prevent screen glare)
- Air conditioning (computers, dispatch, and personal environments)
- Air-conditioning backup
- Workstation layout (per Occupational Safety and Health Administration [OSHA] and Americans with Disabilities Act [ADA] regulations)
- Console arrangement (always consider ergonomics in your design for long-term employee health)
- Acoustics (background noise suppression)
- Restroom facilities
- Kitchen facilities
- Interior design
- Rest areas (lounges)
- Dormitories (sleeping quarters)
- Emergency rations
- Alternate locations
- Building storage areas
- Loading dock access or some type of access for future upgrades and deliveries
- Fire suppression systems

The communication center should be designed and constructed so the probability of interruption to operations due to fire or other causes will be minimized. Security concerns have changed significantly in the last few years. Today most communication centers have sophisticated security systems with features like key card access, security bollards, bullet-resistant or explosion-resistant glass, and much more. Simple things like restricted access to the communication center have become more critical today. When a separate building is not feasible and the communication center must be housed with other operations, such as city hall offices or in a fire station, the communication center should be properly separated from the remainder of the building by vertical and horizontal separations with a fire resistance rating of at least 2 hours and preferably with entrance only from the outside. Protection should be provided against fire exposures and unauthorized entry.

Alternate Communication Facility

An alternate communication facility that, when fully staffed, is capable of performing the emergency functions normally performed at the communication center should be provided. For example, a bomb threat or fire in the center requires both an alternate facility and a plan to evacuate the communication center. This alternate location should be totally removed from the primary location and should have all the necessary requirements for long-term usage. In the event of fire in the center, provi-

sions should be made to continue operations long enough to transfer operations to the alternate facility. In smaller facilities and jurisdictions that cannot afford an off-site backup, the communication center should make arrangements with neighboring jurisdictions for backup services. Many times reciprocal agreements of this nature can benefit both jurisdictions.

Communication Center Protection

Because of the types of activities conducted and the records maintained in any modern communication center, building and systems protection must be provided. Security begins at the entrance to the communication center and can be as simple as a dead-bolt lock or as complex as a computerized entry control system. Only authorized personnel should be allowed access to the center. The center should be protected against damage due to vandalism, sabotage, and civil disturbances. The lowest floor should be above the 100-year flood plain. Entrances into the center directly from the exterior, if provided, should be protected by a security vestibule. Windows, if provided, should be bullet resistant if they face an area accessible to the public. The communication center should be located in a fully sprinklered, fire-resistive, or noncombustible building. Alarms and supervisory signals from the building sprinkler system(s) should be monitored in the operations room. The center and the spaces adjoining the center should be provided with an automatic fire detection system that is monitored in the operations room. Evacuation signals should be designed to avoid interference with communications operations. Portable fire extinguishers should be provided throughout.

Heating, ventilating, and air-conditioning (HVAC) systems serving the center should be independent of the main building HVAC systems to avoid the possibility of smoke contamination from a fire elsewhere in the building. Fresh-air intakes should be located to minimize the possibility of drawing in smoke from a fire inside or outside the building. Consideration should be given to providing operator-controlled smoke-control modes for the center HVAC system. Interior finishes in the center should be noncombustible. Records must be properly safeguarded. Access to records should be limited to authorized personnel only. Off-premises storage of backup records, software, and so on is essential. This backup information should be updated on a regular basis. Cyber-security or computer security is becoming a critical component of communication center operations. It must be part of all plans for protecting the facilities.

Power

The communication center must be able to operate normally in the event of a power failure. Two sources of power need to be provided. Any loss of data can have a severe impact on the communication center, so an uninterruptible power supply (UPS) system is critical. In most cases, the primary source of power will be the commercial electrical distribution network with the secondary source being one or more on-site engine-driven generators. However, in some cases the primary power source may be one or more on-site engine-driven generators with the secondary source being other on-site engine-driven generators. Automatic transfer to standby power on failure of primary power should be provided. During this transfer process, the UPS system should automatically kick in to maintain adequate power while the generators start and come up to full power.

Engine-Driven Generators. Engine-driven generator installations should conform to NFPA 37, *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines,* and NFPA 110, *Standard for Emergency and Standby Power Systems.* The generators should be located in secured areas. Fuel should be stored on-site to permit a minimum of 24 hours of operation at full load without resupply, or in some cases a connection to a natural gas supply line should be established. Where the potential exists for longer interruption of primary power caused by natural disasters such as hurricanes and earthquakes, on-site fuel storage should be increased accordingly. Equipment essential to the operation of the generator, such as fuel transfer pumps and cooling systems, must be supplied with backup power from the generator. Generators should not depend on the public water supply (which might fail during a disaster) for engine cooling. Generators should be tested for at least 1 hour each week under load. This can be done by transferring the communication center's load to the generator or by loading the generator through other means such as an electric-resistant grid "load box."

In determining the capacity of the generator, essential loads in addition to those of the communication systems, such as HVAC systems, adequate lighting to permit personnel to perform their duties, fire protection and security systems, water supply and sanitary facilities operation, and so on need to be considered. In many cases your local utility company will provide an energy audit free of charge.

Uninterrupted Power Supplies and Battery Systems. Under worst-case scenarios, engine-driven generators can fail. Therefore, in addition to standby generators, communication centers should be equipped with stored emergency power supply systems (SEPSS) conforming to NFPA 111, *Standard on Stored Electrical Energy Emergency and Standby Power Systems,* to power essential electronic equipment. An SEPSS is defined by NFPA 111 as a system consisting of an uninterrupted power supply (UPS), a central battery system, or a motor-generator set powered by a stored electrical energy source, together with a transfer switch designed to monitor the preferred and alternate power sources and provide desired switching of the load, plus all necessary control equipment to make the system functional.

Electronic equipment, such as a computer-aided dispatch (CAD) system, is sensitive to momentary power interruptions during transfer from primary to standby power, as well as to voltage fluctuations normally associated with commercial power distribution systems. A momentary power outage or surge can cause systems to go off-line or damage sensitive circuits. Where such equipment is present and essential to operation of the communication center or network, it should be powered through a UPS conforming to NFPA 111. A UPS is a system consisting of a battery source, a converter, an inverter, and control equipment designed to provide clean, conditioned power for a finite period of time.

RADIO COMMUNICATIONS SYSTEMS

Radio System Selection

Considerable thought should be given to selecting the proper radio system, and professional personnel should be used to ensure the proper functioning of each system. For new systems, every entity should consider building an APCO Project 25 (P25) compliant radio system. A P25 radio system allows for multiple manufacturers' radios to work on the same system. Some older models are proprietary and can not work on other manufacturers' systems. For more information on P25 radio systems, you can go to the APCO website at http://www.apco911.org. Two other major considerations when upgrading or replacing your radio systems are FCC order 01-092 on narrow banding for UHF and VHF systems and FCC order 04-168 on rebanding for the 800-MHz spectrum. You can find further information on both of these critical subjects at http://www.fcc.gov.

An analysis of the service area and system configuration will help determine the number of base station transmitters, receivers, and repeaters needed and the number of radio channels (frequencies) required to support current usage and allow for future expansion. Small agencies may be able to operate with just a few frequencies. However, if a communication center serves multiple agencies, or if individual agencies consider the need for tactical on-scene frequencies, mutual-aid/interagency frequencies, disaster management, and the like, it is obvious why careful planning is necessary. Coverage overlays will need to be considered along with the topography of your area. Engineering will likely have to be done by the equipment manufacturer or an independent third party. The most important aspect will be the completion of a propagation study of the area. It is also critical that all aspects of the radio system meet recommended grounding standards as set forth by the radio's manufacturer.

Radio Frequency Selection

Several bands of radio frequencies are available to the public emergency services. These bands are VHF low band, VHF high band, UHF 450 MHz, and 700, 800 and 900 MHz. Each band of frequencies has its advantages and disadvantages, and the selection of a particular band will depend on factors such as frequency availability, area to be covered, type of terrain, number of radio units required, frequencies used by bordering fire districts, mutual-aid agreements, type of operation, and use of emergency medical radios.

Due to the finite number of available frequencies, it may be necessary for emergency response agencies to share radio frequencies. For small agencies, sharing radio channels with neighboring agencies having similar missions could be advantageous.

Type of Radio System Operation

The several types of radio systems available are as follows.

Simplex. This system utilizes a single radio frequency for both transmitting and receiving in all radios for each channel. With a simplex system, only one radio can transmit at any time and all others must receive.

Two-Frequency Half Duplex. This system utilizes separate frequencies for transmitting and receiving. As in the simplex system, half duplex allows only one radio to transmit at any one time.

Two-Frequency Full Duplex. The two-frequency, full-duplex system utilizes separate transmitting and receiving frequencies and permits simultaneous conversations in two directions.

Two-Frequency Repeater System. With this system, a high-powered base station repeater is centrally located at a favorable site overlooking the area to be covered, preferably on a mountaintop, a tall building, or a tower. The repeater receives a transmission from any radio in the system on one radio frequency and instantly retransmits or repeats the message on a second frequency that is received by all other radios in the system. A repeater system greatly increases the range of all of the radios in the system. It is especially useful in hilly or mountainous terrain where it might be impossible to talk directly from unit to unit. Repeater systems are two-frequency, half-duplex systems as described earlier.

Trunked Systems. The trunked system uses a group of radio frequencies. The system is controlled by a computer at the communication center or at the base station transmitter site. When a transmitter is keyed, it transmits its unique identity code to the computer. The computer instantaneously selects an available communications frequency and automatically directs the transmitting radio to use that frequency for the transmission. The advantage of this type of system is that it uses a group of available frequencies more efficiently by utilizing the capabilities of the computer to manage the radio traffic on each frequency. Thus, more radio traffic can be handled on the available frequencies without causing congestion and interference. The computer can prioritize traffic from competing transmitters based on their individual identity codes. For example, a request for a clear frequency transmitted by a fire department radio can receive a higher priority than a request from a nonemergency agency's radio. Provisions should be included to keep the system operational in the event of failure of the computer controlling the system.

In the interest of personnel safety, trunked radio system talk groups should not be used to fulfill the requirement for the provision of a simplex radio channel for on-scene tactical communications. A simplex radio channel is required because it enables emergency messages to be transmitted to and from on-scene command without reliance on communication equipment at another location.

Tone-Coded Squelch. In a tone-coded squelch system, each radio transmits a subaudible tone along with the voice signal. This audio tone is used to turn on the receiver so the conversation will be heard. Only the proper tone will activate the receiver, which eliminates the reception of radio interference.

Radio Paging Systems. Contacting emergency response personnel who do not normally monitor voice radio traffic can be easily accomplished with a radio paging system. A paging sys-

tem includes a paging encoder, which is located in the communication center, and individual pagers. Pagers that receive voice messages, alphanumeric text messages, or both are available. With voice messages, a signal from the communication center activates an alerting device (typically a beeping tone or vibrator) in the pager and turns on the receiver audio. The wearer can then hear the dispatch message. With alphanumeric text pagers, the wearer is alerted in a similar manner and the dispatch message is displayed on a text screen on the pager. In some cases with alphanumeric paging a two-way alphanumeric communication can be established aiding in the dispatch of calls. Systems typically have the capability of alerting an individual pager, a group of pagers, and all pagers associated with the system.

Commercial paging service is available in most areas. Although suitable for administrative paging, its use for emergency dispatching is not permitted by NFPA 1221, since the commercial system is not under the control of the authority having jurisdiction. The volume of traffic in a commercial system may significantly delay transmission of emergency messages. In addition, the authority having jurisdiction cannot ensure that commercial facilities not under its control comply with the requirements of the standard for communication centers and dispatching systems.

Use of Multiple Radio Channels

The size and complexity of each agency will determine the number of radio channels necessary for adequate communications. Very small agencies may require only one radio channel for their exclusive use, whereas agencies in large metropolitan areas will require many. A separate frequency exclusively for on-scene tactical communications is required for each agency (or multiple agencies sharing the same dispatch channel). In addition, all agencies having similar missions adjacent to one another should share a common mutual-aid radio channel. This is provided for by the Federal Communications Commission (FCC) and is usually managed on a statewide basis.

Transmitter and Repeater Locations

Care should be taken in selecting the main transmitter and repeater locations for the radio system. Each radio coverage area is unique and must be dealt with on an individual basis. A high, central location, such as a mountaintop or large hill overlooking the area to be covered, a tall building, or similar structure is generally the ideal site. (This depends on coverage requirements, frequency availability, and requirements for channel sharing.) Again it is critical that proper system engineering and propagation studies are done to provide for adequate coverage. Where none of the foregoing locations is present, a high antenna tower can be utilized. Towers are required, even on mountaintops, to ensure proper antenna system operation.

The availability of commercial power and telephone access is also desirable when locating a transmitter site. Standby power supplied by a generator and backup battery system or UPS must be provided to ensure the site remains "on the air" in the event of a commercial power outage.

In some locations, where commercial power is unavailable, solar power (solar panels), batteries, or generators may be used as the primary source of power for the site. If the base station or repeater location is remote and unattended, provisions should be made to secure the area against unauthorized entry and vandalism. Intrusion alarms should be monitored at the communication center. A chain-link fence should surround the area, and all radio equipment should be located inside a building, out of sight, and protected from the weather. Security, fire protection, standby power, and circuit protection considerations are similar to those of the communication center. Remote camera access from the communication center to monitor the radio sites is an excellent idea.

Alternate Transmitter

An alternate transmitter, preferably at a separate location, should be provided to maintain communications in the event of failure of the primary transmitter. The alternate transmitter should have the same operational capabilities as the primary transmitter. A high central location is also desirable for this site. Primary and backup power, circuit protection, security, and fire protection requirements are the same as those for the primary transmitter site.

The communication center should have the capability of selecting either the main or alternate transmitter. To ensure its readiness, the alternate transmitter should be used at least twice daily.

Radio Site Antenna Configuration

When more than one radio is installed at a single site, an antenna system may be required. It may be impractical for each radio to have its own separate antenna because considerable interference could be generated using separate antennas. When several compatible radios are used, it is customary to provide one or more transmitting antenna systems and a separate receiving antenna system. A base station repeater using a single antenna requires a duplexer in order to transmit and receive simultaneously. Several transmitters can be connected to a single antenna by use of an antenna combiner; several receivers can be connected to a single antenna through the use of a multicoupler. Keep in mind that some output degradation can occur when sharing antennas, so this method may not be the preferred method. Professional assistance should be utilized to design the antenna system for all radio sites.

The antenna design should provide maximum radio frequency (RF) isolation between transmitting and receiving antennas, which is usually accomplished by mounting them one above the other on the antenna structure. Coaxial cables should be used for connections between radios and antennas. These cables should be high quality and low loss, with length as short as practical. Good grounding of the antenna system is required to prevent damage due to lightning.

Access from Communication Center to Radio Site

If base station radio transmitters are located at the communication center, individual wires ("house cables") can be used to connect the operators' consoles to the proper base station. If the

base station radios are located remotely from the communication center, they can be connected by dedicated leased telephone lines, a microwave radio system, fiber-optics connectivity, or a point-to-point radio. Redundant links should be provided so that failure of a single link will not prevent operation of the remote transmitter site from the communication center. Adequate circuit protection should be provided at the communication center and at the remote site. Always meet or exceed the manufacturer's recommendations for circuit protection.

Mobile Radios

Mobile radios have high RF power output (typically 20–100 W) and, therefore, have considerable transmitting range. However, because they are vehicle mounted, they cannot provide on-scene communication once personnel leave the vehicle. Each emergency response vehicle should be equipped with a multichannel, two-way mobile radio that is capable of (1) communicating with the communication center over the assigned dispatch channel(s) and (2) communicating with other units on the assigned tactical channel(s). In addition, emergency vehicles that are assigned to respond to airfield emergencies should be equipped with mobile radios capable of operating on the aircraft ground control emergency channel(s). Each mobile radio should be equipped with a visual "transmit" indicator and a carrier control timer that disables the transmitter after a predetermined time as established by the authority having jurisdiction to prevent a malfunctioning radio from tying up a channel indefinitely. Mobile radios equipped with scanning receivers should have an automatic priority feature that causes the radio to revert to its priority channel automatically when that channel is being used. Consider P25 compliant radios. Spare radios should be kept on hand for exchange with malfunctioning radios. The minimum required by NFPA 1221 is one spare radio for each 20 radios or fraction thereof in service and not less than one unit for each (noninterchangeable) radio model in use.

Portable Radios

Each emergency response vehicle should carry at least one multichannel, two-way portable radio capable of operating on the assigned dispatch and tactical channels. Consider P25-compliant radios. Many agencies issue portable radios to each emergency responder on duty for both personnel safety and ease in dispatching. Radio discipline becomes crucial with that many portable units in use. Portable radios have the advantage that they can be carried (worn) by emergency response personnel. However, they have a much lower RF power output than mobile radios and, therefore, have a considerably shorter operating range.

Portable radios should be manufactured for the environment in which they will be used. For example, most portable radios need to withstand exposure to precipitation, rough handling, and ambient temperature fluctuations. Radios used in fire fighting must withstand repeated exposure to very rough handling, water, and high heat and humidity. Radios used where explosive vapors might be present also must be labeled as intrinsically safe. Portable radios should be designed to allow channels to be changed while the user is wearing gloves. Radios that are equipped with keypads should have a means for the user to disable the keypad to prevent inadvertent use. Each portable radio should be equipped with a "transmit" indicator and a carrier control timer that disables the transmitter after a predetermined time. Radios equipped with scanning receivers should have an automatic priority feature that causes the radio to revert to its priority channel automatically when that channel is being used. Battery chargers and stocks of charged spare batteries should be maintained on hand in quantities sufficient to provide for continuous use of portable radios during long-duration incidents. Spare radios (at least one spare for each 10 radios or fraction thereof in service) should be kept on hand for exchange with malfunctioning radios. For personnel who work in very noisy environments, provision of sound-attenuating headsets should be considered.

Diversity Receiver-Voter System. Because portable radios have a very low RF power output, this low power creates problems for communications over large areas. Portables can normally receive the high-power base station, but they do not always have sufficient power to transmit back to the main radio site. This problem can be eliminated by a diversity receiver-voter system in which radio receivers are installed in a uniform manner at various locations throughout the coverage area. This solution provides a receiver for each subarea in the system. In this manner, a portable radio should not be more than a mile or two from one of the receivers in its subarea.

The signal from each of these receivers is fed to the communication center. The voter is capable of switching from receiver to receiver in midsyllable so, as the RF signal rises and fades at each receiver, the dispatcher hears only the best signal received. A diversity receiver-voter system can also be incorporated into a repeater system to greatly exceed portable-to-portable communications. A block diagram of a simple diversity (subarea) receiver-voter system is shown in Figure 12.15.2.

Mobile Data Terminals. Mobile data terminals (MDTs) sometimes also called mobile computer terminals (MCTs) are small computer terminals that may be connected to a radio system, allowing that unit to access another mobile terminal, base station terminal, or computer. These units generally consist of a microcomputer that converts digital information into a signal

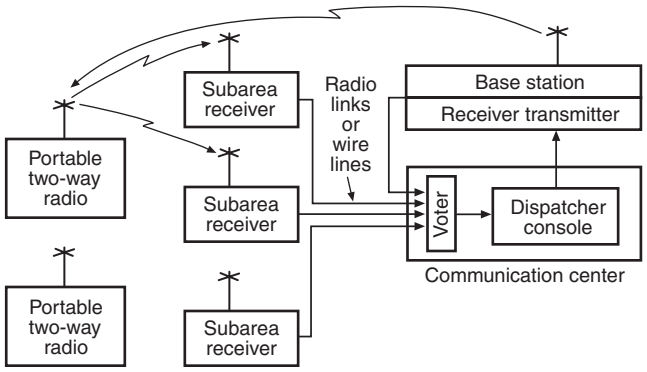

FIGURE 12.15.2 A Simple Diversity (Subarea) Receiver-Voter System

that a radio can transmit or receive. These units may have preprogrammed display capabilities where, by pressing one key, a canned message, such as unit status, condition, operator name, or even the time of day, can be sent. These units can be so reduced in size they can be handheld (including the radio).

Screen formats vary from simple light indicators to complex visual images including text and graphic characters. Some systems even have city maps or building drawings showing specific items relative to access, hydrant location, standpipes, and hazardous materials storage. Some today even have aerial photography for use by the field responders. One major consideration, however, is that these units may require dedicated, conventional radio channels. There are many options for having these computers be able to talk back to the communication center. It can be accomplished via an RF platform that is privately owned by the public safety entity. Some use cellular systems and still others use a hybrid system of RF and wireless hot spots. Consult with the manufacturer on the best system to serve your needs.

Emergency Response Facility Dispatch Notification. There are three items that should be included as part of a dispatch/alerting system: (1) a voice announcement or public address system to alert the company to an emergency response requirement, (2) a remote control for station lights annunciator, and (3) dedicated communication paths to ensure the reliable sending of the dispatch message. For agencies receiving more than 730 alarms per year, at least two means of alerting stations are required. Vehicles may even be included in this alerting process by the use of digital decoders or other suitable audible alarms. You can also consider having remote MDTs in each station connected to the CAD system, thus allowing for the computer event/incident to display in the station prior to response and allowing for a rip-and-tear function, so that the responding units can take the information with them for response. In addition some agencies now provide MDTs in their apparatus as well.

Emergency Medical Service Communications

In many communities, the communication center is involved in dispatching emergency medical services (EMS), both basic and advanced life support, to the citizens they serve (see Section 13, Chapter 9, "Emergency Medical Services and the Fire Department"). Each state has an EMS communications plan on file with the FCC, and these plans identify how the EMS communications system will be implemented in that state. The EMS system differs from the normal fire communications system in the approach the FCC has taken to frequency allocation. The FCC has set aside UHF frequency pairs for communications between field EMS personnel and base hospital personnel. These channels are shared and used in all 50 states. Therefore, to ensure quality, noninterfering communications on these channels during critical life-threatening incidents, it is imperative that local coordination prevail.

Hazardous Materials Team Communications

The development of hazardous materials (hazmat) response teams in the fire service has resulted in new communications requirements for safety. These new requirements are in two major areas: (1) hazardous materials information and (2) hazmat team communications from within encapsulating suits.

A major element in the successful outcome of hazardous materials incidents is the ability to rapidly obtain information about the material(s) involved. This generally involves contacting outside agencies for a variety of information. Mobile radio telephone patch(es) may be considered, but this usually ties up the only available radio channel. Cellular telephones should be carried on the hazardous materials team apparatus to facilitate obtaining needed information. This approach also allows a printer to be installed along with the telephone so that one of the hazardous materials computerized information services can be used for on-scene, rapidly printed information.

Cellular telephones also allow the hazardous materials team member's direct access to hazmat information services, reducing the potential for errors. The medical component of the hazmat team should be equipped with a medical radio for medical control and to obtain toxicological information from base hospitals.

Many hazardous materials team members must work inside encapsulating suits. They require special communications systems designed to meet their requirements for operational safety. Two-way wireless communications, preferably hands free, should be considered. A variety of radio systems that use bone, ear, or throat microphones for voice transmission are available to meet these needs. These radio systems come in simplex, half duplex, or full duplex. They use push-to-talk or voice-actuated circuits to transmit, and mobile repeaters may be integrated into them. An agency should thoroughly examine its needs and the experience of similar agencies in this area prior to purchase.

PERSONNEL

No matter how well designed, installed, and maintained, no system is better than the people who operate it. Communications systems should be supervised by responsible and competent people whose duties include directing, testing, and inspection programs. Public safety telecommunicators should be temperamentally suited to the position and be able to efficiently handle assigned duties. They should have the ability to remain calm, take decisive action during emergencies, remain alert during periods of inactivity and while carrying out normal repetitive operations, and work harmoniously with other people. They should also be familiar with operations.

Work schedules should be structured to provide for maximum efficiency. Stress and high activity lead to operator fatigue. Therefore, operators should be provided with a place to take work breaks in the communication center but outside the operations room.

Training

Communications personnel should not become isolated from the agencies they serve. Their structured training should be directed toward maintaining and improving their call-taking and dispatching skills, but it must also include a full understanding of all agency operations. Standard operating procedures should be provided in writing to ensure standard performance. Continual in-service training is a must to help maintain proficiency,

familiarize personnel with new equipment and new technologies, and to prepare employees for the next level.

The authority having jurisdiction should require call takers and dispatchers to be certified as meeting the requirements of NFPA 1061, *Standard for Professional Qualifications for Public Safety Telecommunicator.* Telecommunicators should be familiar with the geographic area they serve, including the locations of streets, landmarks, important and high-hazard structures, and locations of congested areas. Their training should include maintaining their call-taking and dispatching skills and understanding the needs and operating procedures of the agencies for which they take calls and for which they dispatch. It is important to note that many states have now set minimum training standards for telecommunicators. You should check with your state to see what training requirements apply.

Operating Procedures

Standard operating procedures for the telecommunicators should be provided in writing to ensure uniform performance in accordance with the requirements of the authority having jurisdiction in charge of the communication center. The authority having jurisdiction should develop standard operating procedures in conjunction with each emergency response agency served by the communication center to establish when a telecommunicator shall be assigned exclusively to an emergency incident in progress.

Staffing

The authority having jurisdiction should ensure that an adequate number of qualified telecommunicators are on duty at all times to promptly receive and process emergency calls (alarms). With very limited exception, at least one qualified telecommunicator should be on duty in the communication center at all times. Again, many states now require a minimum of two telecommunicators on duty. As the number of alarms increases, the staffing level should increase to ensure prompt receipt and processing of alarms, which may require varying staffing levels at different times based on anticipated call load established from historical data, weather forecasts, large public events, and so on. Where telecommunicators provide emergency medical instructions to callers prior to arrival of emergency response personnel, at least two telecommunicators should be on duty at all times, since giving emergency medical instructions can occupy one telecommunicator full time for several minutes. In addition to the telecommunicators, at least one supervisor should be on duty when more than two telecommunicators are on duty. The supervisor should be assigned to the operations room when more than three telecommunicators are on duty. Also keep in mind that with new federal requirements, the use of the National Incident Management System (NIMS) should be applied in any communications center. Keep in mind that an effective span of control under NIMS is five to seven people per supervisor in the communication center.

In jurisdictions receiving fewer than 730 alarms per year (average of 2 alarms per 24 hour day), a dedicated telecommunicator may not be required to be on duty at all times, where an alternate means approved by the authority having jurisdiction can effect the prompt receipt and processing of alarms as required by NFPA 1221. However, with the trend toward multiple jurisdictions and multiple agencies sharing communication center services, instances where this limited exception to NFPA 1221's requirement for full-time telecommunicators exists are becoming increasingly rare. For additional information on staffing requirements, consult the latest edition of NFPA 1221.

You may also want to consider that some states have now set minimum training and staffing standards for communication center employees. Review those requirements if there are any in your state. The two 9-1-1 organizations, the National Emergency Number Association (NENA) and the Association of Public Safety Communication Officials (APCO), both have recommended staffing standards as set forth by their advisory boards and staff. In some states the regulating authority has recommended adoption of either the NENA or APCO standard as the minimum staffing standard. Further information is available on their websites at http://www.nena.org and http://www.apco911.org.

CONSOLIDATION OF COMMUNICATION CENTERS

Consolidation of Functions

Many small-to-medium-sized jurisdictions have found that by consolidating communications functions with other jurisdictions, they can provide a higher level of service to their citizens at a lower overall cost. One of the major benefits of consolidation for these agencies is the ability to provide highly trained telecommunicators who are on duty 24 hours a day. A larger communication center will also have adequate backup to handle multiple, simultaneous incoming alarms, whereas the smaller center may not have the personnel to cope with them. The major benefit of consolidation is to provide an increased level of service at reduced costs.

Methods of consolidating communication centers vary, but the two most popular are forming (1) a joint powers authority (JPA) to provide this service as an independent agency or (2) one or more jurisdictions contracting with another jurisdiction to provide this service. Either system can work well and provide the same benefits to the participants.

Joint Powers Authority (JPA)

A joint powers authority (JPA) is an independent government entity established to provide specific services. There are several benefits of a JPA arrangement for combined communications versus other arrangements, but the major benefit is shared administration. With a JPA operating with an independent board of directors, no agency or jurisdiction that might set policy unacceptable to another agency or jurisdiction is in control. In this way, each participant has equal representation and equal responsibility to make the operation a success.

REPORTING AN EMERGENCY

Reports of fires and other emergencies originate from three principal sources: (1) the general public, (2) the business community (industrial, institutional, commercial, and mercantile), and (3) other public service/safety agencies. The reporting process may utilize any of the following means, individually or in combination: (1) telephones, (2) public alarm reporting systems, (3) two-way radio communications systems, and (4) intelligent transportation systems.

Telephones

The most common method is the conventional public switched telephone network (PSTN). Increasingly, however, communication agencies are seeing calls placed from wireless cellular customers and most recently from Voice over Internet protocol (VoIP) providers. Currently, almost all interface at some point to the public switched telephone network. However, there are a few VoIP providers that bypass the public switched telephone network and connect directly to the communication center.

Universal emergency number 9-1-1 service, where adopted, provides a universal, easily remembered telephone number for use by the public to summon emergency services. Enhanced 9-1-1 service provides both the calling number and the location of the related telephone instrument directly to the dispatcher. This indication is presented visually on a display screen at the call taker's workstation and can be automatically recorded if the communication center includes computer-aided dispatch (CAD) or computerized logging support systems.

With the relatively new nature of VoIP telephones, 9-1-1 access can be sporadic or nonexistent in some cases. Some VoIP providers are actually answering 9-1-1 type calls in private call centers not staffed by trained 9-1-1 professionals. Any automatic number or automatic location information for VoIP telephones should be considered suspect and possibly not correct. The good news is that many of the VoIP providers realize the critical nature of 9-1-1 and are working with 9-1-1 professionals to resolve these issues. To further complicate matters in many cases, if power goes out, VoIP telephones will have no 9-1-1 access of any kind. The Federal Communications Commission (FCC) has asked all VoIP providers to provide 9-1-1 access.

The increasing use of personal cellular telephones is both a blessing and a challenge to emergency response agencies. On the positive side, many lives have been saved by the ability of a victim or a bystander to dial 9-1-1 from nearly any location and swiftly summon help. However, high-visibility incidents, such as vehicle accidents on a major highway, can generate dozens or hundreds of calls for the same incident, overwhelming call takers and even the 9-1-1 system itself, thereby delaying receipt of calls for other emergencies. Also, use of a cellular phone negates the automatic location information features of the enhanced 9-1-1 system. If the caller is unable to accurately identify his or her location, the telecommunicator cannot determine where to send help. Over the last several years many wireless providers have installed technology to provide the callers cell site location and the latitude and longitude (x, y) coordinates of an actual cellular telephone. Many of the communication centers across the country have installed the technology to receive this information, but some have not. When taking incoming calls, it is necessary to be able to accept this technology and convert the coordinates into a street address. In urban areas, there may be hundreds of buildings and thousands of people within range of that cell site. There are still some issues with the technology, but its accuracy is improving daily. Actually, finding the victim may be much more difficult than if he or she were calling from a conventional, wired telephone.

Where 9-1-1 service is provided, telephone directory listings for emergency response agencies should indicate that 9-1-1 is the number to call for emergencies. Where 9-1-1 service is not provided, a specific telephone number should be assigned for emergency calls and should be publicized as such. Separate business numbers should be assigned for nonemergency use. Emergency telephone numbers should appear on the inside front cover or page facing the front cover of the telephone directory. They should also appear in the body of the directory under the name of the jurisdiction, under the headings "Police," "Fire," and "Ambulance."

Although there are some disadvantages to total dependency on a utility owned, operated, and maintained communications network, specifically with regard to emergency reporting during natural disasters, telephones are often the only means of communication available. Where present, outdoor pay phones increase the availability of telephones for emergency reporting. In general, the public telephone system, widely used for reporting fires and other emergencies, provides a very viable function.

Public Alarm Reporting Systems

From the perspective of the operator receiving an alarm, use of a public alarm reporting station (alarm box) eliminates the difficulty of determining the location from which the alarm is being transmitted. When actuated, an alarm box transmits a distinct code to the communication center, which enables the operator to pinpoint the exact location of the box.

Removal of public alarm reporting systems began to take place in many major metropolitan centers in the mid-1970s. This trend has since spread to smaller communities. System maintenance costs, vandalism, malicious false alarms, and the nearly universal availability of telephones for alarm reporting all contributed to the elimination of public alarm reporting systems in many communities.

Although not an alarm system, the expanding implementation of universal emergency number 9-1-1 service has further reduced the need for public alarm reporting systems. This is especially true where enhanced 9-1-1 service provides the alarm operator with the exact location of the caller.

Recently, however, some jurisdictions have shown an increased interest in the use of public emergency reporting systems. In poverty-stricken areas, many households may not have working telephones, and vandalism and other criminal activity have caused the removal of many public pay phones. Also, public emergency reporting systems have been shown to provide reliable alarm reporting during natural disasters, such as hurricanes, earthquakes, tornadoes, and blizzards, when the public switched telephone network becomes jammed with traffic or is physically damaged.

A typical public alarm reporting system consists of a mix of publicly accessible manual alarm boxes ("street boxes") and "master boxes" that can be actuated both manually and automatically by a connection from a protected premises alarm system. "Auxiliary boxes" that are activated by the protected premises alarm system but lack the ability for manual activation by the public are also sometimes used. In many cases, the operating jurisdictions reduce their legal liability by accepting auxiliarized connections from government buildings only and referring all others to private supervising station alarm companies. Requirements for installation, maintenance, and use of public fire alarm reporting systems are contained in Chapter 6 of *NFPA 72®*, *National Fire Alarm Code®*.

A public fire alarm reporting system may be used for the transmission of other emergency signals or calls, provided such transmission does not interfere with the proper handling of fire alarms. For example, systems employing voice communications between the street alarm box and communication center can be used to transmit alarms of nonfire emergency nature. Fire alarm boxes in a radio-type system can be provided with push buttons for calling the police department, the emergency medical service, or other emergency services, and signals can be transmitted directly to the service called. With parallel-type telephone systems (each box served by a separate circuit), the telecommunicator can cross connect to the proper emergency service, such as the police department, or systems can be arranged so authorized callers, such as law enforcement personnel, can be connected directly to their own agencies. For additional information on public fire alarm reporting systems, refer to Section 14, Chapter 1, "Fire Alarm Systems."

Another form of the public emergency reporting system is the motorist-aid call box system, installed on some limited-access highways. These systems typically take one of two forms. First, coded radio transmitters may be mounted on pedestals, similar to (or incorporated with) radio fire alarm transmitters, typically with multiple, publicly actuated messages such as requests for fire, police, emergency medical services, and motorist aid (towing) services. These may be battery powered, with solar panels providing battery charging during daylight hours, or user powered. Second, cellular-type telephones (in weatherproof enclosures) may be mounted on pedestals, which are arranged to dial only a preprogrammed telephone number when the handset is lifted or a button is pressed. These are typically battery powered with solar panels providing battery charging during daylight hours. In either case, when actuated, the call box sends a distinct identity code to the receiver so that the location of the actuated box can be readily determined.

Intelligent Transportation Systems

With increasing density in population centers and increased prosperity, vehicular traffic is increasing. This increase funneled into a fixed highway network in turn results in more incidents requiring emergency response. Increasingly, jurisdictions are using technology, including wayside and in-pavement sensors and video cameras, to enable them to monitor traffic on hundreds of miles of highways from a central control center. When an incident occurs, the operators at the central control center can take actions, such as notifying emergency response agencies, redirecting traffic using remote control of traffic signals and/or electronic message boards, and making public announcements via commercial radio and television stations. Mass transit systems and railroads have similar centralized control centers. How these control centers interface and exchange information with traditional emergency communication centers for police, fire, and EMS agencies is not currently addressed in detail in NFPA 1221. The standard may, however, be used voluntarily as a guide for construction and operation of such centers.

Vehicle manufacturers are equipping some of their models with emergency communication devices (based on land-based cellular telephone and/or earth-orbiting satellite systems), which enable the driver to initiate a distress call in an emergency. These messages are answered by telecommunicators at private communication centers, which may be hundreds or thousands of miles away from the incident site. The technology also exists to automatically send a distress message whenever a vehicle is involved in a crash. This message could include information such as the attitude of the vehicle (upright or otherwise), the number of occupants, the negative acceleration forces experienced, whether seat belts were in use, and whether the air bags deployed. These systems are in their commercial infancy, but their use can be expected to grow significantly. They are not currently addressed by an NFPA standard.

Public Alerting Systems

Public alerting systems can be used for the mass alerting of the public to both natural and man-made events (e.g., tornadoes, hurricanes, floods, hazardous materials release) that can be expected to result in the loss of life, health, or property. Public alerting systems utilizing outdoor audible devices such as sirens have been established on a limited basis, usually for specific target hazards (such as nuclear power plants and chemical plants), and their use is likely to grow. A logical control point for such a system is the jurisdiction's emergency communication center. Technology also exists to permit the deployment of personal/in-home alerting devices in conjunction with such systems. Public alerting systems, as such, are not addressed by an NFPA standard as of this writing; however, their inclusion in the 2007 edition of NFPA 1221 has been proposed.

Two-Way Radio Communications Systems

A commonly overlooked alarm/emergency notification source is the two-way radio networks of public safety agencies. Notification of incidents in watershed areas is typically reported by mobile patrols. Similarly, requests for supplemental dispatches to multiple-alarm fires usually originate from units in the field.

Communications between agencies in adjacent jurisdictions, as well as between agencies of a single jurisdiction, may often be expedited by using two-way radios.

PROCESSING COMMUNICATIONS WITHIN THE COMMUNICATION CENTER

Regardless of the method by which an alarm is received, the location of the emergency is the minimum information required

to respond to an emergency. The nature of the incident being reported is also obviously essential. However, bear in mind that thousands of responses to nonvoice notifications are made each year.

Data Collection Systems

To efficiently operate a communication center, reliable data must be available. To be useful, these data must be both accurate and readily available. The data may take a wide variety of forms, from card indexes to sophisticated computer files, and may include such categories as the status of vehicles, the availability of resources, geographic information, and personnel information. The following categories outline the various types and uses of data that can be collected and maintained by a communication center.

Incident-Related Data. It is important (and often a legal requirement) to keep accurate records of emergency incidents to which emergency response agencies respond. The types of data worth collecting include the following:

- Time of alarm
- Time of telecommunicator's initial response to alarm
- Time of dispatch
- Address
- Identifications and times of responding units
- Arrival times at the scene
- Departure times from the scene
- Radio traffic voice recordings
- Telephone voice recordings
- Times of significant events at the scene

Operational-Related Data. These data consist of information that must be rapidly available at all times to maintain efficient operation of the communication center. The data include the following:

- Geographic data
- Equipment data
- Response order data
- Occupancy/hazard information
- Additional resource data

Reports. Many types of reports are necessary for overall fire department management. Some of these reports will be required at regular intervals, whereas others will be required on demand to fill a specific departmental information need. A list of probable reports includes the following:

- Response time reports
- Emergency activity reports
- Occupancy activity reports
- Specific incident reports
- Reports for outside agencies
- Fire loss/injury reports
- Equipment-related reports

These reports can be used to project future needs of the agencies, such as location of new stations, hiring of additional personnel, and relocation of existing equipment.

Receipt of Alarms

Most alarms are received by telephone over the public switched telephone network. Automatic recording devices should be interconnected to all types of voice-reporting circuits, including radio systems.

Correct telephone numbers are the only means of positively identifying the location of an informant. Enhanced 9-1-1 service is designed to provide the call taker with an immediate reference to the number of the telephone in use and its specific location. The data are usually displayed on a CRT screen. The data input is formulated for electronic data processing (EDP) usage and can be fed concurrently to a departmental CAD system.

All public emergency reporting systems (e.g., municipal fire alarm systems) provide an individual code for each box installed, and the proper code is transmitted when the box is activated. All incoming coded signals are permanently recorded on printers integral to the specific systems and, in some cases, are also displayed on direct readout (LED, CRT, etc.) devices.

The translation of the numerically coded data into a usable address is performed with the aid of a running-card file or CAD system, which is necessary for processing of alarms.

Voice Recording and Reproducing Systems

The voice recording and reproducing system should consist of a multichannel recording device that provides a permanent, time-referable, unalterable, and court-admissible recording of all emergency-related telephonic/radio communications within the communication center.

The communication center supervisor(s) and at least one of the operators on duty should be totally familiar with the operation and maintenance of the multichannel recording device. Familiarizing other personnel is advisable, but responsibility should lie with no more than two individuals per watch or shift.

A multichannel recording system can provide the following:

- Verification of emergency messages
- A log of all emergency communications within the communication center
- Protection against false or exaggerated complaints
- Substantiation or negation of claims against the agency
- Added protection to the civilian population
- A training tool for telecommunicators
- Validation of response times

The importance of these various benefits will differ from agency to agency.

Running-Card Files

A running-card file contains a dispatch plan for every area of the jurisdiction served. The number of running cards in a given file depends on the size of the jurisdiction and the manner in which it has been indexed for responses. The most common method of indexing is to assign numeric designations to all intersections or to grids superimposed on a map of the jurisdiction. There is a specific running card to each intersection or grid. Public emergency reporting stations (alarm boxes) are normally assigned an

identity code corresponding to the intersection or grid closest to their physical location.

When an alarm is received, the telecommunicator utilizes the addresses and/or intersection data obtained from the informant to find the correct running card, which is referenced to determine the appropriate units to be dispatched.

Status-Keeping Systems

The ability to maintain an accurate record of the current status of all emergency units in the system is essential to a successful dispatch system and will aid in (1) minimizing response times, (2) ensuring appropriate response, and (3) collecting nonemergency unit activity information.

Status-keeping systems may involve the tracking of various pieces of information, such as the following:

- Availability of the unit for emergency response
- Service capabilities of the unit (e.g., paramedic service, extrication equipment, all-terrain capability)
- Location of the unit
- Means of contacting the unit (e.g., radio, phone)
- Miscellaneous items based on the particular agency's operating philosophy

The mechanism of a status-keeping system will vary, depending on the number of units on which status must be kept and the actual dispatch process utilized by a communication center. A small agency might utilize a manual system with a small manual status display board; a large agency may require a computer.

Dispatch Circuits and Equipment

A dispatch circuit is the means by which an alarm operator notifies units to respond to an alarm. In general, two separate dispatch circuits must be provided, but only one is required when fewer than 730 alarms per year are received.

The primary dispatch circuit should consist of one or a combination of the following:

- Dedicated wired circuit monitored for integrity
- Voice radio channel with duplicate base station transmitters, repeaters, microphones, encoders, control circuitry, and antennas (system must alert telecommunicator in the event of failure of signal transmission)
- Microwave carrier channel monitored for integrity
- Polling or self-interrogating digital data radio channel (if primary transmitter fails on operation, switchover to the second transmitter should be automatic, accompanied by alerting of the telecommunicator)
- Approved, dedicated telephone circuit that is monitored for integrity
- Fiber-optic connection that is monitored for integrity.

When they detect a circuit fault, systems for monitoring circuit integrity should provide both visual and audible notification to the telecommunicator.

The secondary dispatch circuit need not be monitored for integrity and should consist of one of the following:

- Dedicated wired circuit
- Voice radio channel (duplicate base station transmitters, antennas, etc. are not required for the secondary dispatch circuit)
- Approved dedicated telephone circuit or fiber-optic connection

A telephone connection through a public switched telephone network via regular dial-up mode or nondedicated telephone lines is not considered acceptable as an approved circuit. Where a telephone circuit is used as the primary dispatch circuit, a telephone circuit should *not* also be used as the secondary circuit. When radio channels are used for both the primary and secondary circuits, each circuit should consist of a separate radio system operating on a separate frequency with separate receivers at each emergency response facility.

Radio circuits can be used for voice and/or data transmission and are commonly used for dispatching. They have the advantage of transmitting alarms simultaneously to all units, regardless of whether they are in quarters or out in the field. Also, they are not dependent on wired circuits, unless the transmitter is connected by wired circuit to the communication center.

Wired circuits can be used for data and/or voice transmission. They are limited to transmission to fixed locations. Units in the field must still be contacted by radio.

A telegraph circuit is one example of a wired circuit. Once more commonly used, telegraph circuits are still in use in some jurisdictions. Telegraph systems transmit coded signals to emergency response facilities, where they are received on a variety of instruments, including gongs and punch or printing registers that register the coded signal with holes or marks on a paper tape. The location of the alarm is then decoded manually or electronically in a manner similar to that previously discussed. Other uses of wired circuits include voice, teletype, and computer data transmission.

Computer-Aided Dispatch (CAD)

Computer-aided dispatch (CAD) systems have become increasingly commonplace. NFPA 1221 categorizes CAD systems as Class 1, 2, or 3. The Class 1 system is the most sophisticated, utilizing computers to automatically track the status of all units and to select and recommend the appropriate available units for dispatch. On approval of the dispatch telecommunicator, signals and data are then transmitted by the CAD system to the appropriate emergency response facilities, personnel, or units. A Class 1 CAD system requires complete redundancy and, in the event of a computer failure, must automatically switch over to an online backup computer.

A Class 2 CAD system uses computers to support dispatching operations and transmit and receive data transmissions to and from emergency response facilities, personnel, or units. Redundancy is required; however, manual switchover to the backup computer is permitted.

A Class 3 CAD system uses desktop personal computer (PC) technology to support the dispatching telecommunicator. Typically, data (such as changes in unit status) are manually entered through keyboard operation by the telecommunicator. Class 3 CAD systems may be used to keep track of unit sta-

tus and to retrieve information regarding appropriate units to dispatch, occupancy hazards, pre-incident plans, and the like. Computer redundancy is not required by NFPA 1221 for Class 3 CAD systems.

Class 3 CAD systems typically utilize off-the-shelf hardware and software. Care must be used to select hardware that fully supports the software. Class 1 and 2 systems are more complex and are typically professionally designed or configured for a specific jurisdiction based on the user's requirements.

In all classes of CAD systems, a manual backup dispatching method must be maintained and available for use in the event of failure of the CAD system. Telecommunicators should periodically practice using the manual backup method so that they are familiar with its use. There should also be a hard-copy file of the information stored in the CAD system readily available on the premises to support manual dispatch should the CAD system fail.

CAD systems should be capable of exchanging data with the 9-1-1 system, other CAD systems, central stations (refer to Section 14 of this handbook), and intelligent transportation systems. CAD system computers should not be used for administrative applications; they should be kept free of time-consuming processes to allow rapid retrieval of dispatch information. It should be understood that CAD is a *method* of dispatching, not a dispatch *circuit.* Therefore, the presence or absence of a CAD system does not negate the requirement for two dispatch circuits.

Other Alerting Facilities

Radio alerting receivers in volunteer residences or places of business and radio pagers (i.e., portable receivers carried on the person) are frequently used for dispatching volunteer and off-duty personnel. Many agencies today also use some form of digital paging for administrative notifications and as a secondary means of notification in addition to voice systems. Many volunteer emergency response agencies have traditionally used outside sirens, air horns, whistles, or bells to alert volunteers when an alarm has been received. Although such devices remain in use in many areas, they do not comply with the requirements of NFPA 1221 as a method of dispatching and are considered supplemental to the required method(s).

Supervision and Testing Facilities

The communication center is where trouble signals from public emergency reporting systems are received and testing facilities are generally provided. In a leased telephone system, some test facilities are located in telephone buildings. In the event of trouble, both an audible and a visual signal should be provided. An audible signal may be silenced, but it should be designed to operate again in the event of trouble in any of the other circuits connected to the same supervisory device.

SUMMARY

Effective and reliable emergency communication systems play an essential part in the delivery of emergency services. In most cases, at least two independent communication paths or circuits should be provided for essential functions. These should be diversely arranged so that an event that damages one circuit is not likely to damage the other. Wire circuits (both metallic and fiber-optic) that are essential to the operation of a communication system should be monitored for integrity. Essential systems must be able to operate during power failures; therefore, backup power sources of adequate duration should be provided both at communication centers and at remote sites.

The communication center is the operational nerve center of the emergency service delivery system. It must be designed to prevent disruption of operations by fire, natural disaster, and criminal activity. An alternate communication center should be provided that, when fully staffed, is capable of performing the essential functions of the primary center. When a public safety answering point (the place where calls for help are first received) is not located within the communication center, it should meet the requirements for a communication center.

Whether serving one political jurisdiction or several, one response agency or many, the communication center needs to be adequately staffed around the clock to process emergency calls. Call takers and dispatchers, collectively called *telecommunicators,* provide human interface between a person calling for help and the emergency service delivery system. They need to be properly trained and familiar with the geographic area and agencies they serve. They need the ability to remain alert during periods of low call activity and calm during periods of high stress.

Two-way radio is an essential part of emergency services communication. Radio systems must be carefully designed to provide complete coverage of the service area. A sufficient number of frequencies should be provided to handle anticipated peak radio traffic. Separate tactical frequencies should be provided for uninterrupted on-scene communication. Where radio is the primary means of dispatching, duplicate radio base station transmitters should be provided. When used as a means of emergency dispatching, wireless paging systems should be under the direct control of the authority having jurisdiction.

Rapid technological and social changes, including proliferation of cellular telephones, increased emergency call volumes, increased demand for separate channels in a finite radio frequency spectrum, and expansion of intelligent transportation systems will continue to challenge the managers of emergency communication systems for many years to come.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on public emergency services alarm, dispatch, and communications systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 37, *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines*
NFPA 70, *National Electrical Code®*
NFPA 72®, *National Fire Alarm Code®*
NFPA 110, *Standard for Emergency and Standby Power Systems*

NFPA 1061, *Standard for Professional Qualifications for Public Safety Telecommunicator*
NFPA 1221, *Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems*

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9-1-1 Trade Organizations

Association of Public Safety Communication Officials (APCO), http://www.apco911.org.
Commission on Accreditation for Law Enforcement Agencies (CALEA), http://www.calea.org.
National Emergency Number Association (NENA), http://www.nena.org.

Chapter 16

Fire Department Apparatus and Equipment

Robert Tutterow

Chapter Contents

Apparatus
Roadability
Equipment Carried on Apparatus
Apparatus Procurement Policies
Inspection, Maintenance, Testing, and Retirement of Apparatus and Equipment
Ground Ladders
Hose, Couplings, and Nozzles

Key Terms

acceptance test, aerial ladder, aircraft rescue and fire-fighting vehicle, elevating platform, fire apparatus, fireboat, fire fighter safety, fire-fighting foam, fire hose, ground ladder, mobile water supply apparatus, nozzle (solid-stream), nozzle (spray), pumper, quad, quint, rescue vehicle, service test, squad vehicle, utility vehicle

Fire apparatus and the equipment they carry are essential to fire departments for providing fire suppression and emergency services. Without the proper tools and the knowledge of how to use those tools correctly, a fire department cannot do its job effectively. This chapter contains information on the standards used and procurement policies that should be followed in specifying and acquiring apparatus and equipment. In addition, there are many other items described that fire departments should consider in the design of their apparatus.

For related topics, see Section 12, Chapter 9, "Fire and Emergency Services Protective Clothing and Protective Equipment"; Section 15, Chapter 7, "Fire Pump Controllers and Power Supply Arrangements for Motor-Driven Fire Pumps"; and Section 16, Chapter 10, "Standpipe and Hose Systems."

APPARATUS

The basic fire apparatus in North America is a diesel or gasoline engine-driven vehicle that carries an extensive assortment of tools and equipment for fighting fires. Such equipment may include a pump, hose, water tank, aerial ladder or elevated platform, ground ladders, and various portable tools and appliances. The amount and capacities of the various fire-fighting components carried vary in accordance with the intended service of the particular vehicle.

For pumping operations and fire attack, the size of the pump and the amount of water, hose, and equipment carried will vary with the type of service the fire department provides and the nature of the community it protects, which can be predominantly urban, suburban, rural, or a combination of any of the three. The fire apparatus standards set 250 gpm (950 L/min) as the smallest fire pump, but pumps of 750, 1000, 1250, 1500, and 2000 gpm (2850, 3785, 4732, 5678, and 7570 L/min) capacities are popular for general municipal service. NFPA has promulgated two standards for the design of fire apparatus. They are NFPA 1901, *Standard for Automotive Fire Apparatus,* and NFPA 1906, *Standard for Wildland Fire Apparatus.* It is important to note that the Insurance Services Office (ISO) requires that pumpers meet the general criteria of NFPA 1901, that is, 750 gpm (2850 L/min).

Fire departments can supplement units equipped primarily for pumping and fire attack with other vehicles that provide a large variety of tools and equipment for support functions. These tools include ground ladders, forcible-entry tools, generators, lights, and rescue equipment. Such units are variously termed *rescue, squad,* or *utility vehicles.*

Equipment for Rescue Work

About one-third of the work at an average fire involves the use of tools and equipment in duties classed as rescue or ladder-company work. Apparatus suitably equipped for such service should be

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available at all structural fires and at major emergencies, such as significant highway accidents. Although pumping engines may carry considerable equipment, the larger aerial ladder and elevating-platform apparatus commonly transport additional equipment for forcible entry, cutting, and extrication. This type of apparatus provides effective elevated stream service and vehicle-supported, power-operated equipment for access to areas above the normal reach of ground ladders. Some fire departments go a step further and use aerial ladder *tenders* to carry support equipment. The tender does not have an aerial device, nor does it carry water or fire hose. Departmental procedures determine which apparatus respond to an incident.

In rural districts and in the outlying districts of cities where hydrant distribution is not complete, supplemental water-transport apparatus, defined as *mobile water-supply apparatus,* is common. Such apparatus has large water tanks with quick-fill and -dump connections. It may have a permanently installed pump. In most of the United States, they are referred to as "tankers."

A wide combination of fire-fighting equipment is often provided on a single fire apparatus. Besides combinations of water pump, hose, and water tank, commonly termed a *triple combination,* it is not uncommon to provide a booster pump and small-stream equipment on aerial ladder or elevating-platform apparatus or a water tower on a pumping engine. When fire apparatus is equipped with long ground ladders and other usual ladder-company equipment, in addition to the usual pumping engine equipment, the apparatus is referred to as a *quadruple combination,* or *quad.* If a power-operated aerial ladder or elevating platform is added, such apparatus is termed a *quint.*

The trend is toward apparatus designed to improve functional performance. Initial fire-attack capability for pumpers may include not only a variety of preconnected hose lines but also preconnected master stream capability or elevated-stream equipment. Pumpers are built with considerable compartment space for emergency medical service and rescue equipment. Combination fire-fighting rescue/pumpers can now be found in many fire departments.

NFPA 1901 deals with the design, performance, functions, and components of most fire apparatus. The current standard is broken down into chapters that address the requirements for different types of fire apparatus as well as requirements for many of the components installed on those apparatus.

Pumpers. Vehicles designed for sustained pumping operations during structural fire fighting and for supporting associated fire department operations are known as pumpers (Figure 12.16.1). NFPA 1901 requires a pump of at least 750 gpm (2850 L/min) capacity, a water tank of at least 300 gal (1135 L), storage for both supply hose and preconnected attack hose lines, and miscellaneous equipment.

Mini-Pumpers. Initial attack fire apparatus are defined as vehicles designed for making the initial fire suppression attack on structural, vehicular, or vegetation fires and for supporting associated fire department operations. Initial attack apparatus require a pump of at least 250 gpm (950 L/min) capacity, a water tank of at least 200 gal (757 L), and lesser requirements for hose and equipment than a pumper. Another term for initial attack apparatus is *mini-pumper.* This type of vehicle became popular in the early eighties, and then its popularity diminished. Today, mini-pumpers are slowly reemerging in municipal fire departments for use at parking garage fires. The mini-pumper is also now being used by a few departments as a first responder vehicle for emergency medical service.

FIGURE 12.16.1 Modern Pumper (Courtesy of Plano, Texas, Fire Department)

Mobile Water Supply Apparatus. Vehicles designed to transport water to the scene of an emergency where the water is applied by other apparatus or pumping equipment are defined as mobile water supply apparatus. NFPA 1901 requires these vehicles to have a water tank of at least 1000 gal (3785 L) with quick-fill and -dump capability, as well as limited hose and equipment to support the pickup and dumping of the water. Mobile water supply apparatus have a higher rate of rollovers per mile driven than any other type of apparatus. As a result, they also have a higher rate of fire fighter line-of-duty deaths from apparatus accidents than any other type of apparatus. In their design specifications, fire departments should pay particular attention to the center of gravity, braking capabilities, and handling characteristics of these types of vehicles.

Tank baffling is very important to the stability of mobile water supply apparatus. NFPA establishes tank baffling requirements. Fire departments should avoid used trucks with tanks that were used for non–fire service applications such as fuel or milk delivery. Typically, these trucks have little or no baffling.

Elevating-Platform Apparatus. Aerial ladder or elevating-platform fire apparatus are defined as vehicles designed to provide elevated fire-fighting and rescue capability. NFPA 1901 requires that these vehicles have a power-operated, self-supporting aerial device capable of attaining an elevation of at least 50 ft (15.3 m). Aerial ladders are required to support at least 250 lb (113.4 kg) at the tip in any position in which they can be placed. The elevated platform must be able to support at least

750 lb (340 kg) in any position in which it can be placed without water in the water delivery system. NFPA 1901 provides minimum requirements if a pump is installed. From 1997 to 1999, municipal fire departments reported 6300 aerial or ladder apparatus in use.[1]

Quints. Apparatus with a pump, water tank, hose storage area, an aerial or elevating platform with a waterway, ground ladders, and complement of equipment are known as quints. Quints have become popular in many fire departments. However, operating efficiency and capability tend to decrease if too many functions are to be performed by one piece of apparatus. The ability to position a quint on the fire ground for multiple purposes can occasionally be cumbersome. Fire departments must understand the staffing requirements of a multifunctional piece of apparatus. Moreover, if one feature of the apparatus requires repair, the entire apparatus must be taken out of service.

Special Service Vehicles. Apparatus that is multipurpose and that primarily provides support services at emergency scenes is known as a special service vehicle. These services could be rescue, command, hazardous material containment, air supply, electrical generation and floodlighting, or transportation of support equipment and personnel. The systems and components installed on these vehicles will vary with the support they are designed to provide and can range from no fixed systems to elaborate power generation or breathing-air compressor systems.

Mobile Foam Apparatus. Mobile foam fire apparatus is similar to a pumper except it may not carry any water but must have at least a 500 gal (1900 L) foam concentrate tank and foam proportioning capability. This apparatus is generally used in industrial environments for the control and extinguishment of flammable and combustible liquid fires in storage tanks and other flammable liquid spills. For information on foam systems used on other vehicles, see the section on foam and foam proportioning equipment later in this chapter.

Wildland Fire Fighting Apparatus. NFPA 1906 deals with the design, performance, functions, and components of wildland fire-fighting vehicles, defined as vehicles equipped with a pump, water tank, limited hose, and equipment. The vehicle must be capable of supporting pump-and-roll operations. Generally, these are smaller vehicles, frequently equipped with all-wheel drive; a small water tank; forestry hose; a small-volume, high-pressure pump; a number of portable water extinguishers; and various hand tools for fighting wildland fires. Larger vehicles may have up to a 500 gpm (1900 L/min) front-mounted or power takeoff (PTO) pump and a 500 gal (1900 L) or larger water tank to support wildland fire fighting as well as to provide exposure protection when structures or other properties are threatened.

Performance Requirements

NFPA 1906 includes requirements for auxiliary systems that are often installed on wildland fire apparatus. These may include a foam system or compressed air foam system, winches, and vehicle protection systems.

Both NFPA 1901 and NFPA 1906 define performance requirements for the apparatus and define tests to measure this performance. In the annex of each document, there are explanations of the requirements and details, as well as work sheets, to assist in the purchase of the apparatus. A separate annex in the standards provides a form that will guide purchasers through the process of determining and stating their needs in a fire apparatus, a valuable step in the specification process. Also, there is a separate annex outlining the criteria for retiring apparatus.

Persons buying the apparatus must specify the options that make it suitable for local needs. For example, requirements for fighting large brush fires in southern California are quite different from those for fighting fires in below-zero weather in northern Minnesota. Fire departments in the northern regions are well advised to specify snow and ice chain systems for their apparatus. Systems are available that engage the chains with the activation of a switch. NFPA 1901 and NFPA 1906 provide for standardization of many items for which uniform performance, measurable by tests, is desirable, but they allow the necessary flexibility to meet local needs that could not be supplied by one assembly-line production. Such differences include rated pump capacity, water-tank capacity, length of aerial ladders, height of elevating platforms, and many other important design features.

Besides the functional characteristics of a piece of fire apparatus, considerable thought should be given to personnel safety and operations. The design of the vehicle's driving compartment and riding spaces and the location of various components should be studied carefully. Only fully enclosed driving and crew compartments with sufficient seating for all fire fighters who are expected to ride on the apparatus should be specified. Fire fighters should never be allowed to ride standing up or in exposed positions on the rear or sides of the apparatus. The use of seat belts is mandatory in all cases. All of the equipment carried in the crew compartment area should be restrained in mechanical holding devices or placed in compartments. This minimizes the possibility of injury to fire fighters by flying objects in the event of a sudden stop or an accident.

The pump operator's panel may be positioned to the side, to the rear, or in a top amidships position. The position of valve controls and other control equipment will affect the overall efficient and safe operation of the apparatus. The better the operator's view, the more effective he or she can be.

ROADABILITY

Engines, Braking Systems, Weight, and Stability

Engines. Engines may be either diesel or gasoline types, but there are few gasoline engines capable of supplying sufficient power for modern apparatus. Consequently, diesel engines comprise almost all engines in apparatus manufactured. Fire departments must understand that the diesel exhaust is a carcinogen and provisions must be made to remove diesel exhaust from fire stations. This can be accomplished in one of three ways:

1. Source capture (hose connected to the exhaust pipe)

2. Air handling/filtration unit installed in the apparatus bay
3. On-board system contained within the apparatus

The engine size and horsepower must be chosen to correspond with the conditions of service and apparatus design. Apparatus must have enough power to move it over the road network on which it is expected to operate. Road tests are conducted with apparatus fully loaded with hose, water, ground ladders, the applicable personnel weight, and an equipment allowance weight. From a standing start, the vehicle must attain a true speed of 35 mph (56 km/h) within 25 seconds. The vehicle must maintain a minimum top speed of 50 mph (80 kph) on level ground. The vehicle must be able to maintain a speed of at least 20 mph (32 kph) on any grade up to 6 percent. This demonstrates that the vehicle has the necessary power to operate safely and efficiently in traffic. Although these tests demonstrate the power needed to negotiate the grades found in most communities, any special requirements that the apparatus climb very steep grades should be specified, and the finished apparatus should be tested to those requirements.

Braking Systems. A braking performance test is required. The vehicle must come to a complete stop within 35 ft (10.7 m) after attaining a speed of 20 mph (32 km/h). This test is required in NFPA 1901 and NFPA 1906 and Title 49, Code of Federal Regulations, Part 571, Subpart B, "Federal Motor Vehicle Safety Standards." This test is required to be performed only one time, not repeatedly, which is not realistic for emergency vehicles. Many agencies require secondary braking systems to be installed on their apparatus to enhance braking performance. NFPA 1901 requires that secondary braking systems be installed on vehicles weighing over 36,000 lb (16,330 kg) and recommends a system if the vehicle weighs over 31,000 lb (14,062 kg). There are four types of secondary braking systems:

1. Hydraulic retarder
2. Exhaust brake
3. Engine brake
4. Drive line

Agencies should match their driving conditions to the type of secondary brake desired. Secondary braking systems provide an extra margin of safety as well as extend the life of the primary braking system.

The set or parking brake provided is required to hold the vehicle on grades up to 20 percent. This may not be adequate for every fire department, so the agency needs to specify its particular requirements. Some states require parking brakes to hold on any grade.

Weight. Carrying capacity is one of the most important but least understood features of a vehicle. The gross axle weight rating (GAWR) and gross vehicle weight rating (GVWR) of the apparatus must be adequate to carry the weight of the fully equipped and staffed vehicle. This includes 200 lb (76 kg) per person personnel weight, a full water tank, the specified hose load, ground ladders, and a miscellaneous equipment allowance.

Extra care should be taken when determining the miscellaneous equipment allowance. Too many fire departments seriously overload apparatus by adding more equipment than the vehicle was designed to carry. NFPA 1901 specifies minimum equipment allowances of 2000 lb (907 kg) for pumpers and mobile foam fire apparatus, up to 2000 lb (907 kg) for initial attack vehicles depending on their size, 1000 lb (454 kg) for mobile water supply apparatus, and 2500 lb (1136 kg) for aerial ladder fire apparatus, elevating-platform fire apparatus, and quints. The equipment allowance for special service units varies by chassis gross vehicle weight rating from 2000 lb (907 kg) for smaller units to 3000 lb (1360 kg) for the largest units. NFPA 1906 specifies the equipment allowance for wildland fire apparatus, which also varies by chassis gross vehicle weight rating from a low of 300 lb (136 kg) to a high of 2000 lb (907 kg). Probably one of the most important things a fire department can do in developing specification for a fire apparatus is to realistically evaluate the weight of the equipment that the apparatus will carry and be sure the chassis will not be overloaded when that equipment is added to the vehicle.

One of the critical factors is the size of the water tank. Water weighs about 8⅓ lb per U.S. gal (1 kg/L). A value of 10 lb (4.54 kg) per gallon (to include the weight of the tank) is often used when estimating the weight of a full water tank, making a full 500 gal (1893 L) tank 2½ tons (2.27 metric tons). Larger tanks mean heavier vehicles, which may have limited mobility on rural roads and bridges. The efficiency of mobile water supply apparatus when transporting water to a fire depends on the vehicle's over-the-road mobility. Any apparatus that weighs too much for local operating conditions severely limits the capabilities of the fire department.

GAWR is the value specified by the vehicle manufacturer as the loaded weight on a single-axle system, and gross combination weight rating (GCWR) is the value specified by the manufacturer as the loaded weight of a combination vehicle, such as a tractor-trailer unit. GVWR is the value specified by the manufacturer as the loaded weight of a single vehicle, and it is the sum of the weights of the chassis, body, cab, equipment, water, fuel, crew, and all other loads. A number of components affect the GVWR, such as the springs or suspension system, the rated axle capacity, the rated tire loading, and the weight distribution between the front and rear axles. All chassis are designed with a "rated GVWR" or maximum total weight that should not be exceeded, whether by the manufacturer when building the apparatus or by the fire department after the vehicle has been placed in service.

Stability. The improper distribution of weight between the front and rear wheels can make a vehicle difficult to control and may require tires of different sizes to carry the load. Overloading of the vehicle not only affects the handling characteristics but also will result in increased maintenance problems with transmissions, clutches, drive train, and brakes, as well as suspension systems and tires. Many states exempt fire apparatus from meeting weight limitations; however, it is never a good practice to overload the vehicle. In the event the vehicle is involved in an accident, the overloading issue may be used against the department in litigation. Considerable attention is now being given to technology that enables vehicle stability. Most of the technology is electronics based and tied to the braking system. Sensors warn

the driver when the vehicle is in a potential rollover situation. Data from these systems can also be part of the information captured in a "black box." These systems are common in Europe and rapidly becoming available in the United States. Fire departments will be wise to learn about these systems and consider them in their design specifications.

Compliance with Government Standards

National governments promulgate motor vehicle safety standards that are applicable to all vehicles, including fire apparatus. In the United States, the Department of Transportation (DOT) enforces this legislation. It is unlawful to sell a vehicle that is not in compliance with the current federal standards. It is unlawful for manufacturers to build fire apparatus that do not conform to these standards. Because fire apparatus are complex and often require considerable lead time between the signing of a contract and delivery, the federal regulations provide that the standards in effect at the time the contract is signed must be those complied with, provided the apparatus is delivered within 2 years.

Additional requirements are placed on the apparatus and engine manufacturers in the United States by the Clean Air Act, which is enforced by the Environmental Protection Agency (EPA). Engines cannot be modified once approved by the EPA. These standards have caused some downgrading in engine performance, often resulting in the need to use larger engines than previously employed to obtain the same performance. Likewise, more frequent maintenance checks may be required due to mandated pollution-control devices.

Safety in Apparatus Design

Fire departments must consider safety as the primary concern when writing specifications and purchasing apparatus. Throughout history, fire fighters have been killed and seriously injured while driving, riding, and operating around fire apparatus (Figure 12.16.2). In a typical year, over one-quarter of all on-duty fire fighter deaths and thousands of on-duty fire fighter injuries have occurred during response or return.[2] In 2003, more fire fighters were killed responding or returning from incidents than killed at incident scenes.

FIGURE 12.16.2 Damaged Fire Apparatus (Courtesy of Charlotte, North Carolina, Fire Department)

The attention to apparatus safety was identified in the February 2004 National Fallen Firefighters Foundation's national summit on fire fighter safety. From this summit, 16 fire fighter life safety initiatives were identified. One of the initiatives was "Safety must be a primary consideration in the design of apparatus and equipment." In addition to apparatus design, there are two other areas of emphasis for safe apparatus that cannot be overlooked. These are driver training and apparatus maintenance. All three areas depend on each other. Failure to adhere to recognized safety standards jeopardizes the safety of fire fighters. Moreover, it puts the community at risk and creates a high risk of potential liability problems.

Fire departments must include an extensive apparatus driver/operator training program as part of their service delivery. Fire apparatus are big, heavy, complicated vehicles, and many drivers have never operated heavy vehicles prior to joining the fire department. It is imperative that no one operates a fire apparatus until he or she has been thoroughly trained. The fire department driver training program should be based on NFPA 1002, *Standard for Fire Apparatus Driver/Operator Professional Qualifications.*

Apparatus maintenance (discussed later in this chapter) has become more critical as apparatus have become more complicated. It is difficult to find qualified technicians to work on today's apparatus.

There are several areas of focus in apparatus design that impact fire fighter safety. These include audible and visible warning devices, steps and surfaces, mounting of equipment, cab ergonomics, and pump-panel layout.

Audible and Visible Warning Devices. The siren and air horn are the predominant audible warning devices for fire apparatus. These devices must be located as low and as forward of the cab as possible so the noise level will not cause hearing loss to fire fighters in the cab. NFPA 1901 states that the maximum noise level in cabs is 90 db while the vehicle is traveling at 45 mph (72 km/h). It must be understood that sirens are not as effective as they used to be, because any external sound is less audible to the occupants of today's road vehicles. Reasons include increased sound insulation in today's vehicles, use of high-volume sound systems, and use of cell phones. Visible warning devices, when specified to NFPA 1901 requirements, are the most effective warning devices.

Visible warning devices should be installed in a manner that portrays an outline of the vehicle. There are requirements for devices installed for the upper portion of the vehicle as well as the lower portion. Each portion must be divided into four warning zone quadrants (front, rear, and the two sides). The upper-portion devices are for warning traffic at a distance; the lower-portion devices are for warning traffic in close proximity to the vehicle. There should be two modes of operation for visible warning devices. One mode is for responding (calling for right-of-way) and the other mode is for blocking the right-of-way. The color of warning lights depends on local laws.

Amber, if permitted, has proven to be very effective at the rear of apparatus.

Fire departments should be careful not to use too many warning lights. Too many brilliant flashing lights can create serious risks, including blinding other motorists, attracting impaired motorists (whether through alcohol, drugs, or drowsiness) directly into the lights, and putting emphasis on the apparatus rather than personnel working at the incident. Purchasers must be aware of the electrical load requirements of audible and visible warning devices. In addition to electrical devices, all apparatus must have at least a 4 in. (100 mm) reflective stripe on at least 50 percent of the cab and body length and the rear and 25 percent on the front. The reflective striping adds an additional margin of safety to the warning lights and provides visibility to motorists in the event of warning light failure.

Steps and Surfaces. Fire departments must remember that many personnel operating on or around apparatus will be wearing personnel protective equipment (PPE), including self-contained breathing apparatus (SCBA), which is considerably more cumbersome than street clothes. In addition, they are often operating in a less than pristine environment, including wet, icy, oily, and nighttime conditions. It is important that all steps, standing surfaces, and walking surfaces be designed and constructed with fire fighter safety in mind. NFPA 1901 has many requirements addressing this issue. All steps must have at least a minimum surface area of 35 $in.^2$ (22,580 mm^2) and be able to support a minimum static load of 500 lb (227 kg). The first step leading onto an apparatus cannot be over 24 in. (610 mm) in height, and each succeeding step cannot be over 18 in. (457 mm) in height. All exterior surfaces that are designated by the purchaser as a step, a walking surface, or a standing surface must be slip resistant. NFPA 1901 provides an option of two tests that can be used to determine the coefficient of friction. Handrails must be placed at the entrance of cabs or anywhere else steps are located. The handrails must be slip resistant and between 1 in. (25 mm) and 1⅝ in. (41 mm) in diameter. Ground illumination is required anywhere fire fighters will climb on an apparatus, including beneath the cab.

Mounting of Equipment. Purchasers should review their need to mount equipment in the cab of apparatus and avoid doing so if at all possible. Loose equipment or equipment that can become loose in the case of an accident or sudden deceleration can be lethal. NFPA 1901 requires that, with exception of SCBA, all equipment carried in the cab must be enclosed in a latched compartment capable of withstanding a longitudinal 9-g force and a 3-g force in any other direction. SCBA must be stored in a bracket with a positive mechanical means of holding the SCBA in the event of a 9-g force in any direction.

Cab Ergonomics. Fire departments should consider the ergonomics of the cab from several aspects. The cab should be free of sharp edges and the doors should be free of any handles or latches that can snag clothing. All foot and hand controls should be within convenient reach of the driver. Frequently used controls should be placed so the driver can reach them without diverting attention from the road. Mirrors should be designed and placed so that adjustment is easy from the driver's seat, either through direct contact or remote control. This is also true for de-icing and defogging. The windshield should be large enough so that the driver has excellent visibility to the areas in close proximity to the vehicle. Seats should have a minimum width of 18 in. (457 mm), and headroom should be a minimum of 37 in. (940 mm). More headroom is recommended for apparatus with suspension seats. It is not recommended that helmets be worn inside cabs as they are not crash helmets; wearing them can actually be a contributing factor to an injury. Most importantly, the driver of the fire apparatus should never move the apparatus unless all occupants are seated and belted.

Pump Panel Layout. Fire departments should specify the layout of their pump operator's panel rather than leaving it up to the discretion of the manufacturer. The layout should be as simple and easy to understand as possible. Controls and indicators should be grouped according to their function. All pressure or flow-indicating devices must be located within 6 in. (150 mm) of the control. Ideally, there should be no intakes or discharges at the operator's panel because serious injuries and some deaths have occurred to pump operators as a result of hose rupture near the apparatus. NFPA 1901 prohibits any discharge larger than 2½ in. (65 mm) on the pump operator's panel. Pump and engine controls must be no higher than 72 in. (1829 mm). All controls and gauges must be properly labeled and illuminated.

Roadway Scene Safety. Increasingly, more emergency responders are being struck by motorists while working roadway incidents. In addition to roadway incident standard operating procedures (SOPs), fire departments should design and equip their apparatus to maximize fire fighter safety for such incidents. Consideration should be given to the following:

- Advance warning devices for motorists (such as directional signals and other signage)
- Traffic cones
- Safety vests
- Reflective and fluorescent striping

Chevron pattern reflective striping on the rear of the apparatus is proven to be an effective way to minimize the chances of an apparatus being struck from the rear. Particular attention should be given to the emergency warning lights. Excessive lights can have a detrimental impact, especially during darkness.

Black Boxes. Advances in vehicle electronics have led to the emergence of event date recorders or "black boxes" for fire apparatus. These recorders can capture information such as date, time, hard braking, speed, g-forces, and seat belt usage. They can also be linked to video and audio capturing equipment. Black boxes are very useful in helping with accident investigation. Also, by their nature, they aid in accident prevention as drivers know their actions may be reviewed.

Electrical Power for Apparatus

Electrical power needs for fire apparatus far exceed those of other commercial trucks. Sufficient electrical capacity for the

vehicle and its components is a major requirement for fire apparatus. Electricity is essential to start the apparatus reliably under all temperature and weather conditions. Emergency warning lights and sirens impose a heavy electrical demand with vehicle lighting and communication equipment as an added load. Electric rewind hose reels, pump controls, scene lighting, and electrically operated tools can all impose additional loads. Much of the equipment must perform when the apparatus is idling at a fire or other emergency, and the engine is not producing maximum output from the alternator. Electrical system performance tests are required for new apparatus by NFPA 1901.

Batteries, which are an integral part of the electrical system, must be a minimum of 1000 high-cycle, cold-cranking amps (CCA). However, the batteries should not be expected to carry the electrical load when the engine is idling; many of the electronic components on modern apparatus will not function properly if the voltage drops by 10 percent or more. It is also critical to provide a means for keeping the batteries charged while the apparatus is in the station. This can be done with an onboard battery conditioner or charger or with a polarized plug for connection to an external charger.

NFPA 1901 requires a load management system for the electrical components on the vehicle if the total connected electrical load exceeds the alternator output at idle. The load management system will shut off electrical loads if the alternator and batteries cannot keep up with the demand. The fire department should work with the manufacturer to determine which electrical components to shut down. These items should be ones that are less critical to the mission of the apparatus.

Documentation of a vehicle's electrical performance tests is required by NFPA 1901. A written electrical load analysis must include nameplate rating of the alternator, alternator rating at idle, minimum continuous load rating, total connected load, and individual intermittent load.

Fire departments should do considerable research to understand electrical systems before writing specifications and making a purchase. Special attention must be given to the maintenance of the electrical system after the apparatus is placed in service. A vehicle electrical system that needs frequent or major repairs is no asset and no bargain, whatever its purchase price and design capabilities may have been.

A department, when specifying apparatus, should require an electrical audit. The department or manufacturer could perform the audit. The audit determines the amperage required to power all electrical accessories so a determination can be made if the alternator supplied is large enough for the load. With more engine and transmission combinations becoming computer controlled, it is imperative that batteries be maintained properly.

Pumps for Fire Apparatus

A fire pump is defined as a pump of at least 250 gpm (950 L/min) at 150 psi (1035 kPa) net pump pressure. It must be capable of pumping 70 percent of its capacity at 200 psi (1380 kPa) net pump pressure and 50 percent of its capacity at 250 psi (1725 kPa) net pump pressure. The largest rated pump available is 3000 gpm (11,356 L/min). These large pumps are typically used in industrial settings such as refineries. Fire departments most commonly use pumps of 2000 gpm (7570 L/min) or less.

Certification. When new, fire pumps of 750 gpm (2850 L/min) or greater on fire apparatus are certified by tests witnessed by an independent third party. The certification test includes, among other things, a test at draft during which the pump must deliver its rated capacity for 2 hours at 150 psi (1035 kPa) net pump pressure, followed by two half-hour test periods during which 70 percent of rated capacity is delivered at 200 psi (1380 kPa) net pump pressure and 50 percent of rated capacity at 250 psi (1725 kPa) net pump pressure. The apparatus must also perform a 10-minute overload test, discharging rated pump capacity at 165 psi (1138 kPa) net pump pressure to demonstrate reserve engine power.

Pressure. The pump on initial attack fire apparatus is typically a pump of at least 250 gpm (950 L/min) but not more than 700 gpm (2650 L/min) at 150 psi (1035 kPa) net pump pressure. Like fire pumps, they must be capable of pumping 70 percent of their capacity at 200 psi (1380 kPa) net pump pressure, and 50 percent of their capacity is delivered at 250 psi (1725 kPa) net pump pressure. Pumps on initial attack fire apparatus may not be designed for long-duration pumping, although they must meet a 50-minute pump test and can be designed for longer operation.

The design requirements for fire pumps include the ability to develop 22 in. (55.88 cm) of mercury vacuum at 2000 ft (610 m) of elevation and the ability to deliver rated capacity while lifting water up to 10 ft (3.1 m) through 20 ft (6.1 m) of suction hose. Where a pump on a piece of apparatus is expected to perform at an altitude above 2000 ft (610 m), the purchaser must advise the apparatus manufacturer both of the altitude and whether a 10 ft (3.1 m) lift-suction capability is required, so that the proper engine and pump can be provided.

The pump and the attached piping and valves are designed for 500 psi (3448 kPa) hydrostatic pressure. Depending on the size of the pump, one or two large suction intakes and at least one auxiliary gated suction intake are required. This auxiliary intake is normally a 2½ in. (64 mm) intake and is provided so an additional water supply line can be taken into the pump without shutting down. It is also a means of connecting a supply line in mutual-aid operations if hose connections for the large intake are not compatible. As the large suction intake provides the least restriction, normal supply to the pump should be through that intake, whether directly or through a suction siamese.

Discharge Outlets. Discharge piping from the pump feeds a variety of outlets and, in some cases, may feed a master stream device directly. Fire pumps 750 gpm (2850 L/min) or larger are required to have two 2½ in. (64 mm) discharge outlets and enough additional outlets to allow the capacity of the pump to be discharged. If the apparatus is equipped with an aerial device with a prepiped waterway, the pump must be piped directly to the waterway.

To control the development of water hammer in the pump and hose lines, any 3 in. (76 mm) or larger valve should be designed to restrict changing the position of the flow-regulating

element from full close to full open, or vice versa, in less than 3 seconds. The pump should be further protected by a permanently installed intake pressure-relief system that is 2½ in. (64 mm) or larger and discharges directly to the atmosphere. The surplus-water-discharge location should be away from the pump operator's position and may terminate in a male fitting so hose can be attached to carry any water away from the apparatus.

The pressure on the discharge side of the pump must also be controlled, either through an automatic relief valve or a pressure control device that controls the excessive discharge pressure. The device is required to limit the pressure rise on activation to a maximum of 30 psi (207 kPa) and be capable of operating over a range of 90- to 300-psi (620- to 2070-kPa) discharge gauge pressure.

Midship Mounting. For the past few decades, the midship-mounted pump has been the standard configuration. It is powered by the vehicle engine through a pump transmission that redirects power from the rear wheels to the pump itself. Power is transferred with the vehicle in a stationary position and only after the parking brake has been set. An interlock should be provided to ensure that the engine speed cannot be advanced until the parking brake is set, the transfer is complete, and the chassis transmission is either in neutral or in the correct gear for pumping. Otherwise, the apparatus may move when the engine speed is advanced. New automatic transmission designs allow the use of a power takeoff (PTO) to transmit power to a large pump. They should be limited to no more than 1250 gpm (4732 L/min), due to horsepower requirements through the PTO. The PTO feature has led to a steady rise (20% per year) in rear-mounted pumps in the U.S. market. (Over 99% of the European market uses rear-mounted pumps.) There are many benefits of a rear-mounted pump, including increased compartment space, a cleaner pump panel, a better pump operator position (270 degree visibility), weight reduction of between 400 lb (181 kg) and 1000 lb (454 kg), and decreased service time. If a fire department chooses a rear-mounted pump, it should also consider a reinforced rear bumper to protect the pump during minor collisions.

On smaller pumps, the power is often transferred to the pump through a PTO device. In some designs, the pump is mounted at the front of the chassis where it is driven through a clutch arrangement from the front of the engine.

Auxiliary Capacity. Some fire apparatus will have auxiliary pumping capability as either a separate pump for small-volume/high-pressure operation or as a third stage in the main pump to develop higher pressures. Typically, auxiliary pumps have a capacity of 100 gpm (379 L/min) or less and may be capable of providing discharge pressures up to 600 psi (4137 kPa) or more. If an auxiliary pump is provided and is interconnected with a fire pump, suitable valving and controls should be provided to preclude the introduction of higher pressures into piping and fire hoses not designed for the pressure. Auxiliary pumps are often used to supply pressurized hose reels of small-diameter hose that can be used in extinguishing rubbish fires, grass fires, and other small fires.

Transfer Pump. Another type of pump, designated as a transfer pump, is used to assist in filling or dumping water tanks on fire apparatus. These pumps have a minimum rated capacity of 250 gpm (946 L/min) at 50 psi (345 kPa) and are typically used with mobile water supply apparatus to draft water from a static source to fill a water tank or to move water from the tank to a folding tank or other tank arrangement on the fire ground.

Wildland Pumps. There is a variety of pump products used on wildland fire apparatus. NFPA 1906 defines four ratings for wildland pumps. Low-pressure pumps are rated at 100 psi (690 kPa), medium-pressure pumps are rated at 150 psi (1035 kPa), high-pressure pumps are rated at 300 psi (2070 kPa), and extra-high-pressure pumps are rated at 400 psi (2760 kPa). All of these pumps are available in a variety of discharge capacities. NFPA 1906 also requires that the pumps be capable of pump-and-roll operation (i.e., pumping while the apparatus is in motion). This is accomplished by either driving the pump through a PTO arrangement or using a separate engine to drive the pump. The use of skid-mounted, self-contained fire-fighting packages, complete with pump and engine, water tank, hose, and equipment, are popular in the wildland fire-fighting arena.

Hose-Carrying Capability

The amount of hose carried should be sufficient to support the function of the apparatus. Operations involving pumpers typically need the most hose. NFPA 1901 requires a minimum of 800 ft (244 m) of 2½ in. (65 mm) or larger hose and 400 ft (122 m) of 1½ in. (38 mm), 1¾ in. (44 mm), or 2 in. (51 mm) hose. However, most fire department pumpers carry a minimum of 1200 ft (366 m) of 2½ in. (65 mm) or larger hose and 400 ft (122 m) of 1½ in. (38 mm), 1¾ in. (44 mm), or 2 in. (51 mm) hose. Some fire departments carry 2000 ft (610 m) or more of 2½ in. (65 mm) or larger hose, and 800 to 1000 ft (244 to 305 m) of 1½ in. (38 mm), 1¾ in. (44 mm), or 2 in. (51 mm) hose on their pumpers to permit more versatile use of the apparatus.

Predominantly, fire departments use hose diameters at least 2½ in. (65 mm) in size for supplying water from a hydrant or in a relay operation. Through comparative analysis, many fire departments have determined that 5 in. (125 mm) is the most efficient and economical size to supply pumpers.

NFPA 1901 requires a minimum of 30 ft^3 (0.85 m^3) of hose storage on a pumper although most pumpers have at least 55 ft^3 (1.56 m^3) of space. A larger hose storage area will likely be needed for large-diameter hose. Even if large-diameter hose is not used, a larger hose bed may be required to carry the hose necessary to flow the capacity of the pump. Often the hose bed space is designed to provide a split hose load. By splitting a hose load into two bed sections, either one long lay or a shorter double hose line can be made quickly, saving considerably on the time and personnel needed to establish flows approaching the capacity of the pumper. A convenient way to relate needed hose capacity to pumper discharge capability is based on the relative water-carrying capacity of various sizes of hose at normal operating pressures, as follows: 250 gpm (946 L/min) for 2½ in. (65 mm) hose; 350 gpm (1325 L/min) for 3 in. (76 mm) hose; 500 gpm (1893 L/min) for 3½ in. (89 mm) hose; 750 gpm

(2839 L/min) for 4 in. (100 mm) hose; and 1300 gpm (4921 L/min) for 5 in. (125 mm) hose. Thus, moving 500 gpm (1893 L/min) 1000 ft (305 m) requires 2000 ft (610 m) of 2½ in. (65 mm) hose or 1000 ft (305 m) of 3½ in. (89 mm) hose. In short lines, some increases in flow may be obtained by higher discharge pressures, but in longer hose lines, increased flow will be minimal.

Fire departments should pay close attention to the accessibility of hose storage areas in developing their specifications. Hose should be stored in a manner that fire fighters can easily deploy without having to climb on the apparatus. The same is also true when repacking hose. There are many places and many ways hose can be stored on an apparatus. It is very common (and advisable) for fire attack lines to be preconnected. Preconnected lines can be deployed from the rear, front, and sides of an apparatus. Some fire departments use slide-out hose trays to facilitate repacking of hose.

In 2005, NFPA issued a requirement that all hose be secured in a manner to prevent accidental deployment. The requirement was prompted by the death of a child who was struck by a hose being dragged by an apparatus. In addition, there were numerous incidents of accidental hose deployment causing property damage. The standard does not specify how hose must be secured. That is left up to the manufacturer and the fire department.

Water Tanks

The majority of fire apparatus equipped with pumps are also equipped with water tanks. The tank supplies water to the pump for initial hose streams before water from hydrants or suction sources is available. NFPA 1901 requires that initial attack vehicles must have a minimum 200 gal (757 L) water tank; pumpers and quints must have a minimum 300 gal (1136 L) water tank; and mobile water supply apparatus must have a minimum 1000 gal (3785 L) water tank. NFPA 1906 requires that wildland apparatus carry a minimum of 125 gal (473 L). Most pumpers in municipal settings have at least a 500 gal (1900 L) water tank; pumpers in rural settings often have 750 gal (2850 L) to 1000 gal (3785 L) water tanks.

All water tanks should be constructed of noncorrosive material or materials that are protected against corrosion and deterioration. Tanks being used today are typically constructed of plastic material. Almost all water tanks, regardless of material, carry a standard lifetime warranty. Water tanks should be equipped with a water-level indicator visible at the pump operator's position. One or more sumps with a 3 in. (76 mm) or larger removable pipe plug should be provided so that debris in the tank can be cleaned out.

All tanks must have baffles to minimize water movement when the vehicle is in motion. The dimension of any spaces in the tank, either transverse or longitudinal, should not exceed 48 in. (1220 mm) or be less than 23 in. (584 mm). The baffle arrangement should allow an adequate flow rate from the tank to the pump, which is typically tested to 80 percent of the tank capacity.

The tank fill opening should be at least 20 $in.^2$ (12,900 mm^2) and vents/overflows at least 12 $in.^2$ (7742 mm^2). The venting must be matched to the maximum fill and discharge rate so as not to overpressure the tank. The overflow outlet should direct any water behind the rear axle so as not to interfere with rear-tire traction.

NFPA 1901 requires that tanks on mobile water supply apparatus have a single outlet capable of allowing water to be dumped from the tank at an average rate of 1000 gpm (3785 L/min). Likewise, a single external fill connection is required that permits a minimum-filling rate of 1000 gpm (3785 L/min) from sources outside to the unit. Even if the apparatus is not designed specifically to be a mobile water supply apparatus, it is good practice to have this rapid-fill and -dump capability, if the water tank holds more than 1000 gal (3785 L).

Fire departments that use apparatus with water tanks in excess of 1000 gal (3785 L) should pay close attention to the center of gravity and overall stability of the vehicle in order to avoid rollover accidents. Furthermore, these types of apparatus are heavier and require that drivers receive additional training to become familiar with the handling characteristics.

Aerial Ladders

Aerial ladders have been used by fire departments for more than a century to gain access to the upper floors and roofs of buildings (Figure 12.16.3). Aerials can be laborsaving devices if they can be strategically positioned. One fire fighter can set an aerial device, whereas three fire fighters are required to raise a 35 ft (10.668 m) extension ladder. The first aerials were manually operated before spring-assist and air-assist hoists were introduced. Current aerial ladders are steel or aluminum truss construction with hydraulic hoists and ladder controls. All aerial ladders are mounted on a turntable that must be capable of rotating a full 360 degrees in either direction.

Mount and Stabilization. All aerial ladders must have stabilizers and outriggers to keep the units from tipping over during operation. There are many interlocks in an aerial ladder to keep one function from causing problems with another function and causing harm to fire fighters and the apparatus. Fire departments

FIGURE 12.16.3 Aerial Ladders (Courtesy of Charlotte, North Carolina, Fire Department)

must fully understand interlocks and thoroughly train personnel on their function.

Aerial ladders can be mounted on a straight chassis or a tractor-drawn chassis (tillers). The advantage of the tractor-drawn units, which are not as popular as they once were, is improved maneuverability in narrow streets. However, improved designs in straight chassis have provided fire departments the opportunity to purchase highly maneuverable units. In addition, many aerial units built today also have a pump, water tank, and hose bed. These features are not common on tractor-drawn units. Moreover, it takes two fire fighters to drive a tractor-drawn aerial.

Size and Capacity. Common sizes of aerial ladders range from 75 ft (22.8 m) to 135 ft (41.1m). The rated height of an aerial is measured by a plumb line from the top ladder rung to the ground with the ladder fully extended at its maximum elevation. A locking mechanism is required to hold an aerial in its desired extended position. A locking mechanism is also required to hold the aerial in the nested position. The rear-mount aerial ladder has become common. This arrangement places the turntable over the rear wheels, with the ladder extending forward when bedded, which results in shorter overall vehicle lengths. In some cases, a shorter aerial ladder mounted on a pumper chassis provides a useful combination of devices for fire attack. A mid-mount aerial generally provides fire departments a vehicle with lower overall height when the aerial is in the nested position. This is crucial for older fire stations with low door openings and in jurisdictions with low overpasses.

Aerial ladders must have a minimum rated capacity of 250 lb (114 kg). Many departments choose to use a heavier rated capacity. Aerial ladders rated above the minimum are rated in 250 lb (114 kg) increments.

Aerial ladders must have a minimum width of 18 in. (457 mm) at the narrowest point of the ladder. Rungs must be spaced 14 in. (356 mm) on center, and the top rails along the sides must be at least 12 in. (305 mm) high. The ladder must support 250 lb (114 kg) at the tip of the fly section with the ladder fully extended in a horizontal position without water in any permanently piped water system. It must support the same weight at the tip of the fly section with the ladder at 45 degrees with water flowing.

Fixed Waterway. Aerial ladders may be equipped with a fixed waterway to the tip of the fly section or some other section. Where such a waterway is provided, it should be capable of flowing 1000 gpm (3785 L/min) at 100 psi (690 kPa) nozzle pressure through a 45-degree, side-to-side range of motions and through an arc of 135 degrees from a line parallel to the ladder and downward. Often the monitor and nozzle on these systems are controlled remotely by electric wires or radio control. The friction loss in the water system between the base of the swivel and the monitor outlet should not exceed 100 psi (690 kPa) with 1000 gpm (3785 L/min) flowing and the water system at full extension.

When the aerial ladder is not equipped with a prepiped waterway, a detachable ladder pipe provides elevated fire-stream service. When supplied by 3 in. (76 mm) hose up the ladder, 600 gpm (2271 L/min) is the practical maximum that can be supplied in normal fireground operations. The ladder pipe is normally provided with 1¼-, 1⅜-, and 1½-in. (32-, 35-, and 38-mm) smooth bore tips and with a 500 gpm (1893 L/min) spray nozzle.

Stability. The aerial ladder must be stable when a load 1½ times the rated capacity is suspended from its tip while the aerial ladder is in its least stable position and the vehicle on which the ladder is mounted is on a firm, level surface with the stabilizers extended to a firm footing. The aerial ladder must also be stable when a load 1⅓ times the rated capacity is suspended from its tip when the vehicle on which it is mounted is placed on a firm surface that slopes downward at 5 degrees in the direction most likely to cause it to overturn. Again, the stabilizers are extended to a firm footing. The stability of the apparatus is checked during the certification tests, and the vehicle cannot show any signs of instability during these tests. Innovations in aerial devices have led to the development of several nontraditional aerial devices. Elevated piercing nozzles are being installed on airport crash-vehicle apparatus. One manufacturer has teamed with a construction equipment company to develop an elevated device for multiple purposes such as ventilation, breaching concrete walls, removing debris, and an elevated stream.

Elevating Platforms

Elevating platforms are of three principal designs. In the first, the platform is mounted on an articulated boom that travels in the arc desired by the operator. In the second, the platform is mounted on an extendable or telescopic boom, in much the same fashion as an aerial ladder. In the third design, the platform is mounted on booms that are both articulated and telescopic.

Protection Features. For fire fighter safety, an elevating platform is clearly the best choice for aerial devices. By description, the platform provides a more user-friendly work area for fire fighters when in an elevated position. It provides a level of protection not available on straight ladders if fire fighter(s) unexpectedly become enveloped in the products of combustion. It provides a safe working area during rescue operations for both fire fighting and technical rescue incidents. In addition, the platform provides space for tools, hose, and other needed equipment. Finally, the platform is uniquely functional during the rescue of persons with limited physical abilities. This is becoming more important for two emerging reasons: (1) baby boomers are becoming senior citizens and, therefore, the population of persons with limited mobility is rising at a faster rate; and (2) high-rise residential buildings are becoming more numerous in urban areas.

Fire departments are advised to consider the cycle time to raise and lower an elevating platform if there is no ladder from the turntable to the platform. Platforms on extendable ladders provide the best of both worlds when rescuing victims from elevated positions (Figure 12.16.4).

All elevating platforms must have a stabilizer system to keep the units from tipping over during operation. There are many interlocks in an elevating platform to keep one function

FIGURE 12.16.4 Elevating Platform

from causing problems with another function and causing harm to fire fighters and the apparatus. Fire departments must fully understand interlocks and thoroughly train personnel on their function.

Characteristics. Platforms are available with booms designed for elevations from approximately 75 ft to more than 200 ft (23 m to 61 m). The rated height of an elevating platform is measured by a plumb line from the top rail of the platform to the ground, with the platform raised to its maximum elevation. In selecting an elevating platform, it is important to know its reach and elevation capabilities under all operating conditions. The articulated-boom design provides its maximum horizontal reach at approximately half of its maximum elevation. The extendable telescopic boom of the same nominal length generally permits somewhat greater horizontal reach at higher and lower elevations. The telescopic boom often has an extending ladder attached to it, which provides access to and from the platform while it is elevated.

The platform itself must be a minimum of 14 ft^2 (1.3 m^2). There must be a continuous guardrail around the platform. The distance from the top of the guardrail to the floor of the platform must be between 42 in. (1069 mm) and 44 in. (1118 mm). There cannot be an opening below the top of the guardrail that is greater than 24 in. (610 mm) in any direction. A heat reflective shield must be included on the front, sides, and bottom of the platform to protect fire fighters. In addition, a water curtain spray assembly must be installed under the platform for additional protection. The water curtain must flow at least 75 gpm (284 L/min). The surface of the platform must be skid resistant and include holes to drain any water that might accumulate.

All designs provide stable platforms with controls located both on the platform and at ground level. The ground-level controls must be able to override the platform controls so an operator on the ground can move the platform away from danger if the platform operator is in trouble.

An elevating platform should be able to carry a load of at least 750 lb (340 kg) in all operating positions without the water system charged. Units of 110 ft (34 m) or less should be able to reach their maximum elevation and extension and to rotate 90 degrees within 150 seconds. An advantage of an elevating platform in operation is that the platform can be moved quickly from window to window for fire-fighting or rescue purposes.

Platforms are designed to provide elevated fire streams. The platform turret or turrets must be able to rotate through at least 45 degrees up, down, and to each side. The mobility of the platform permits the operator to change the turret location quickly, as desired. The apparatus must be designed so that, regardless of the position of the platform and the direction of the stream, the equipment can be operated safely while it discharges 1000 gpm (3785 L/min) at 100 psi (690 kPa) nozzle pressure. The friction loss in the water system between the base of the swivel and the monitor outlet should not exceed 100 psi (690 kPa) with 1000 gpm (3785 L/min) flowing and the water system at full extension.

The stability requirements described earlier for aerial ladders also apply to elevating platforms. In addition, there are requirements in NFPA 1901 for the hydraulic system, for the structure, and for quality control during manufacture that apply to both aerial ladders and elevating platforms.

Water Towers

The success of elevating platforms on the fireground during the 1960s was a prelude to the use of hydraulically operated water towers designed to apply large flows on a fire from effective heights and positions. Such water towers have proved very useful and have been widely accepted in both large and small communities as an important addition to the attack capabilities of a pumper.

Water towers are designed to discharge 1000 gpm (3785 L/min) or more at 100 psi (690 kPa) nozzle pressure in either a straight stream or a spray pattern and to move the boom and the nozzle both horizontally and vertically under the control of the operator for the best application of water on the fire.

Like elevating platforms, water towers may be of either articulated or telescopic boom design. Heights typically range from 50 to 75 ft (15.2 to 22.9 m). The tower is mounted on a turntable or pedestal to permit it to rotate 360 degrees in either direction and rotate with the nozzle operating at rated capacity. The telescopic type may be equipped with a ladder extending the full length of the boom. In such cases, the ladder should meet the same requirements as those of an aerial ladder.

Water towers are typically installed on pumpers with the controls grouped at the pump operator's position so the operator has full control of the pressure, volume, and stream pattern and position. The stability requirements described for aerial ladders apply for water towers as well. NFPA 1901 also provides requirements for the hydraulic system, the structure, and quality control during manufacture.

Foam-Proportioning Equipment

Where the potential for encountering serious flammable liquid fires is present, fire departments can provide, on the apparatus, various types of foam-making equipment or other agents that are more effective than plain water. NFPA 1901 specifies minimum requirements for foam systems. There are several methods of mixing foam concentrate with water to form the foam that

is delivered through a fire stream. Eductors that siphon foam concentrate through a pickup tube that is inserted in a foam concentrate container can be installed in the hose line at the pump discharge. The foam concentrate can also be premixed with water in a tank before it is pumped through a hose line. An around-the-pump proportioning system, consisting of an eductor mounted between the pump's discharge and intake, can be used. Balanced-pressure systems use water pressure between the bladder inside a pressure tank that contains foam concentrate and the walls of the tank to force foam concentrate into a water stream. Another method is to use a concentrate pump to directly inject foam into the pump's discharge. Regardless of the method used, all controls and indicating devices for foam systems must be located at the pump operator's panel.

Foams used for flammable liquid fires (Class B) typically form a film over the surface of the liquid that is on fire, thus removing the oxygen supply. Increasingly, fire departments are using foam for Class A fires such as wildland fires and structure fires. Class A fires typically reduce the surface tension of water, causing it to penetrate burning material and increase the cooling effect of the water. Special foams are also available for certain types of polar solvent/alcohol and unusual liquid fires.

Some departments also use compressed air mixed with water and Class A foam for suppression. This hardware is referred to as compressed air foam systems (CAFS) and was originally developed for wildland fire suppression application, although compressed air foam is now showing strong growth in urban and suburban fire departments for structural fire fighting. The rule of thumb for the ratio of water and air is 1 gallon of water per 1 cfm of air. CAFS systems provide the fire fighter with a lighter weight, charged hose line, and the capability to see exactly where the foam solution has been applied. The use of Class A foam and CAFS is currently gaining widespread acceptance by fire departments.

Portable Pumps

In selecting portable pumps, fire departments should be careful to choose models that will give the needed flow characteristics at a safe, continuous engine speed. Portable pumps for fire department service are usually centrifugal type. They are grouped in categories based on the pressure-volume characteristics that make them suitable for various classes of work. Low-volume streams at high pressure are intended mainly for grass and brush fire operations. Pumps delivering relatively large volumes at low pressures can be used to supply pumps on fire apparatus or to refill water tanks where a static water supply is beyond the reach of suction hose on fire apparatus. These pumps may also be used for dewatering operations. NFPA does not have a standard on portable pumps.

Communications Equipment

Effective communication is essential for any fire department operation. Every fire department vehicle should be equipped with a two-way radio that operates on all frequencies used for dispatch and fireground communication. Providing a radio speaker and microphone at the apparatus operator's position so messages can be heard above the usual noise on the fireground is highly desirable. In addition, each vehicle, including the chief officer's vehicle, should carry portable radios for effective fireground communications.

Vehicles may also be equipped to send and receive hard-copy messages or to receive visual displays of information, including maps and fire hazard data that may be transmitted from the communication center. These can be referred to as mobile data terminals (MDTs) or mobile status terminals (MSTs) depending on the type of data being transmitted. Also, laptop computers, usually in hardened cases, are becoming commonplace in many apparatus. Automatic vehicle locating (AVL) systems are now used in most larger jurisdictions. Cellular phones are also gaining popularity in fire apparatus and chiefs' vehicles. They can be used on the fireground or at hazardous materials incidents. They are especially beneficial in providing added value to the emphasis on customer service in today's fire and EMS service.

Fire departments must consider their communications equipment needs when they purchase the apparatus. The rapid growth of mobile information technology is as applicable to fire apparatus and equipment as to any other sector of society. Typically, communications equipment is installed after the purchaser receives the vehicle from the manufacturer. Considerations include mounting, grounding, visibility, wire chases, antenna, and shielding from outside wave interference.

Specialized Apparatus

There is a wide diversity of fire apparatus designed for special types of service. These units, which should be designed with the rigors of fire duty in mind, should conform to the general requirements outlined in NFPA 1901.

Many fire departments operate a vehicle to support rescue services, carrying equipment that deals with everything from emergency medical service to vehicle extrication to building collapse. The larger of these vehicles are typically equipped with a large 120/240 V electric generator, hydraulic rescue tools, and a wide variety of hand tools, power tools, and devices for jacking, shoring, cutting, and breaching. This emergency equipment typically supplements that carried on pumpers and ladder trucks. Many rescue vehicles have fully enclosed bodies to provide places for personnel to ride, to provide shelter for emergency medical treatment, and to provide an environment for incident scene rehabilitation during inclement weather.

Fire departments are equipping vehicles to support operations dealing with the spill or release of hazardous materials (Figure 12.16.5). The size and amount of equipment on these vehicles will vary with the role that the fire department sees for itself in such operations. Typically, these vehicles carry a library of materials to assist in identifying a hazardous material, tools and equipment for shutting valves or stopping leaks, materials for diking or absorbing spills, and special drums for recovering leaking drums. They also carry specialized clothing to protect the fire fighters while they are working in the contaminated area.

Fire departments can use a dedicated SCBA service unit to field-service SCBA and recharge depleted air cylinders on the fireground. These vehicles may carry numerous spare SCBA

FIGURE 12.16.5 Vehicle That Supports Operations Dealing with Hazardous Materials

cylinders for exchanging depleted cylinders, several large air cylinders arranged to allow for refilling of SCBA cylinders in the field, or both large cylinders and a high-pressure air compressor for filling SCBA cylinders in the field. Small fire departments may not need a separate vehicle, but every fire department should be able to provide full SCBA cylinders in the field.

Some fire departments find it advantageous to have separate vehicles with large generators to provide 120/240 V electricity. These units may have a generator of 15,000 W or larger. The generator may be driven by its own engine or hydraulically, with the hydraulic pump driven by the vehicle engine or directly from a PTO on the vehicle's transmission. These units typically carry floodlights, electrical cord and adapters, and various power tools.

Electrical wiring or equipment on an emergency vehicle must be properly installed and grounded. This equipment is typically used under conditions of extreme wetness, where failure to properly install and maintain the electrical integrity of the wiring and equipment will result in injury or death to persons using the equipment.

Larger departments also have units dedicated as "command" vehicles. These self-contained vehicles typically carry an array of communications equipment as well as provide an environmentally controlled area for command officers to plan and direct emergency operations. Since the September 11, 2001, attacks and several natural disasters, many fire departments have been active in planning and training for possible similar mass destruction events. Considerable federal and state grant monies have been made available to help departments purchase equipment for these types of incidents. Large recreational vehicles (RVs) have been modified into command-type vehicles. Heavy-duty step vans have also been outfitted as command vehicles.

There has been an increase of tractor-drawn units to transport the vast amounts of equipment necessary for large disasters. In addition, there has been a rapid increase in the number of trailers towed by pickup trucks or SUVs. Departments must fully understand the training and state licensing requirements to operate these vehicles.

Chief Officers' Vehicles

Fire departments often provide vehicles for use of staff and command officers. In larger fire departments, sizable fleets of vehicles are maintained. Vehicle transportation is necessary for chief officers, fire prevention officers and inspectors, training officers, communications officers, fire investigators, and others. Some fire departments pay a mileage allowance for the use of private cars. This may not be a good arrangement, especially where response to emergencies may be involved, as private vehicles are generally not properly equipped with warning lights and sirens or otherwise properly marked. They may also not be properly insured for that type of service.

All fire department vehicles that respond to fires and emergencies must be equipped with warning lights, sirens, and radio communication equipment that can operate not only on local emergency networks but also on the mutual-aid frequencies the department shares. The vehicles should be clearly identified as fire department vehicles. They should carry protective clothing and equipment for the officers and their staff aides, as well as portable fire extinguishers, first-aid equipment, and hand lights. If command officers are using the vehicle, it should also carry directories containing prefire plans on properties in the area served, water distribution plans, and reference books on hazardous materials.

Fire departments can provide their command officers with sports utility vehicles (SUVs) or other vehicles with large interiors in which the necessary equipment and materials are mounted or provided for ready access. The SUV has been the vehicle of choice for chief command officers. However, crew cab pickup trucks are proving to be a popular alternative to SUVs. The comfort and space of the cab are similar to that of SUVs, with the improved benefit of isolating stored equipment away from the cab area. This minimizes cab debris, offensive odors from used fire equipment such as personal protective equipment, as well as noise from equipment vibration. With the general public's increasing use of SUVs, vans, minivans, pickup trucks, and crossover vehicles, fire departments should consider the safety and visibility of the chief officer's vehicle. Sedans are usually very low profile and are difficult for other drivers to see. Moreover, chief officers are not able to see other drivers as well if they are in a sedan.

Fireboats

Fireboats are available in various sizes and types, in accordance with local needs, and vary from large tugs to fast, jet-propelled fire and rescue craft. Fire departments or port authorities may operate them. U.S. Navy and Coast Guard vessels are also equipped to provide fire-fighting services. As rescue has evolved into a fire service function, airboats, hover craft, "john" boats, inflatable rafts, and other waterborne craft are now found in many fire departments.

NFPA 1925, *Standard on Marine Fire-Fighting Vessels,* provides the minimum requirements for the construction of new fireboats or the conversion of existing boats to fireboats. The

standard designates three classifications based on length, pumping capacity, and other criteria.

Fireboats are principally used to protect vessels in a harbor; protect piers, pier sheds, and cargoes along the waterfront; protect yachts and houseboats in basins and marinas; assist in marine rescue from all types of water accidents; and serve as pumping stations to provide large flows at fires within reach of hose lines supplied by the boats. Fireboats may also provide a valuable emergency source of water for fire protection, should an earthquake or other accident interrupt the normal supply. Some fire departments operate hose trucks, or "fireboat tenders," that carry large-diameter hose to allow fireboat-pumping capacity to be used at shore fires along the waterfront.

The size, type, pumping capacity, and equipment carried by fireboats will depend on the type of service expected of the vessels. Fireboats must carry much of the same equipment as pumpers, ladder trucks, and rescue vehicles on land. They need foam-making equipment and may carry quantities of special extinguishing agents. Fireboats need radar as well as radio communication for safe operation under all weather conditions and, at times, in heavy smoke. SCBA is essential for fireboat crews.

Pumping capacity for individual fireboats varies from 500 gpm (1893 L/min) for very small craft to 10,000 gpm (37,854 L/min) or more for larger vessels. Pumping capacity is rated at 150 psi (1035 kPa) discharge pressure, as with pumpers. Some small jet-powered fireboats rely on their jet pumps to supply water for fire fighting. These pumps may develop substantial volumes at pressures adequate to supply turret nozzles attached to the pump, but it may be difficult to provide the necessary pressure to supply the hose streams to fight ship fires or fires ashore, unless additional pumps are provided to meet standard pressure requirements.

Large pumping capacity boats are not as popular as they used to be because they are slow and cumbersome. Smaller, faster, and more nimble boats capable of working in shallow water are becoming popular. Smaller fireboats are now designed to have a pumping capacity of 2000 gpm (7570 L/min). These boats can also be transported on trailers across land and placed in the water as needed.

Fire departments' decision making on fireboats should be based on the expected responses. If rescue is a function of the boat, then the boat should have a stable platform large enough to accommodate a victim. Sufficient lighting must be available for the work platforms. Another consideration is the ease with which rescue personnel can get a victim out of the water and onto the boat.

For the safety of personnel, fireboats should not be operated by only one person. They should be equipped with enough personal protective equipment for all persons on the boat.

Airport Crash Trucks

Specialized apparatus is required for aircraft rescue and fire-fighting service at airports. In many cities, such equipment is part of the municipal fire department. In others, it is maintained and operated by an airport authority. NFPA 414, *Standard for Aircraft Rescue and Fire-Fighting Vehicles,* covers the design and performance requirements for aircraft rescue and fire-fighting vehicles equipped for rescuing occupants and combating fires in aircraft at or near an airport. The size, number, and type of airport crash trucks needed are determined by Federal Aviation Administration (FAA) regulations. Airports are given an index number based on the number of flights and passengers. The index number determines the number and type of airport crash trucks required.

NFPA 414 covers three types of vehicles: (1) major fire-fighting vehicles, (2) rapid intervention vehicles (RIVs), and (3) combined-agent vehicles. RIVs are intended to reach the emergency site quickly so rescue operations can be started before the major vehicles arrive. Airport crash apparatus should include a small rescue vehicle, which can also serve as a command vehicle, and a "nurse" tanker carrying additional water and extinguishing agents where needed. Crash trucks can be modified to fight fires in hangars and other airport structures, but this use should not detract from the primary function of these vehicles.

Because of off-highway performance needs, the vehicle weight of crash trucks should be distributed equally over all wheels. These vehicles need greater axle and chassis clearances than standard fire apparatus, as well as high-acceleration characteristics. Positive drive to each wheel is required to negotiate soft ground, snow, and ice. The positive drive can be provided by torque proportioning, by no-spin differentials, or by other automatic devices that ensure that each wheel, rather than the axle, is driven independently.

EQUIPMENT CARRIED ON APPARATUS

Apparatus must be equipped with the tools necessary to accomplish fireground operations. The NFPA fire apparatus standards include listings of equipment and appliances needed with various types of fire apparatus. When developing specifications for fire apparatus, the fire department must evaluate its operation and determine how the apparatus will be used and what equipment will be necessary to support its operation.

Most fire apparatus carry hose. Pumpers typically carry the most hose, as the operational purpose of a pumper is to establish a continuous water supply and apply water to the fire. Use of larger-diameter supply hose (4 in. [100 mm] and 5 in. [125 mm]) for supplying water to pumping apparatus is common, with 5 in. (125 mm) providing the most efficiency. The length to be carried will depend on such things as hydrant spacing and distances to water supply points. Attack hose in 1½, 1¾, or 2 in. (38, 44, or 51 mm, respectively) diameters is common for hand-held hose lines for interior attack, and 2½-in. (65-mm) diameter hose lines are common when larger flows are required during exterior attack or to protect exposures. A variety of nozzles that will produce both spray and straight streams are carried for the various sizes of hose.

Besides hose, nozzles, and ground ladders, fire fighters need a wide variety of other equipment to perform their jobs. This includes SCBA, cutting tools for forcing entry and ventilating smoke from a building, positive-pressure fans and/or smoke ejectors for ventilation, salvage covers for protecting unburned contents, and a variety of fittings and adapters for use with hose lines, generators, portable lights, thermal imaging cameras, and electrical cord. The complement of equipment

carried will vary from department to department, based on the needs and operations of the companies. Career and combination departments typically must transport their structural personal protective clothing when responding to nonfire events, which historically is stored in the cab. However, consideration should be given to specifying a dedicated compartment for this use. This is particularly true for the driver/operator. In addition, fire departments that perform emergency medical and rescue operations must carry an array of equipment and supplies for delivery of that service.

Fire departments should list all of the equipment that will be carried on the apparatus and determine its weight and storage space requirements. It is critical that sufficient space and carrying weight be allotted for the equipment when the apparatus is designed so the equipment does not cause the apparatus to become overloaded. A well-designed apparatus will maximize the space available for equipment by including pull-out trays, drawers, and other means of organizing the storage. Equipment should be stowed in a manner that is secure and easily identifiable. A missing piece of equipment should leave a conspicuous void space. Heavy pieces of equipment should be stored as low to the ground as possible. In determining space and weight needs, fire departments should anticipate their future needs and understand that they will likely encounter unforeseen needs. The apparatus cab should not be a place to store equipment. Only equipment used during the response should be stored in the cab. The tendency to store equipment in cabs for convenience or quick action upon scene arrival should not override the hazards of having equipment come loose during an apparatus accident. For equipment used during the response that is carried in the cab, it must be positively secured to withstand the g-forces of an impact as described in NFPA 1901.

APPARATUS PROCUREMENT POLICIES

Procurement Process

The responsibility for procurement of fire apparatus and equipment should rest with the agency operating the fire department, whether a municipality, fire district, or private industry. In some cases, procurement is a cooperative measure in which a larger unit of government contributes to the cost of providing fire apparatus for fire departments serving its territory. In a few cases, state governments contribute to local fire apparatus costs. In some areas, several fire departments have banded together to generate standard apparatus specifications to buy apparatus in quantity and realize significant cost savings. Various fire department groups also cooperate in volume purchases of hose and other equipment.

When the fire department is an agency of municipal government, it is the responsibility of the latter to provide for all public fire-fighting equipment. Providing the necessary funds is the responsibility of the appropriate fiscal authorities, but the actual selection of the equipment should be the responsibility of the fire department management. The chief administrative officer of the fire department, aided by a staff of technical specialists, should keep the municipal administrator informed of the age and condition of department equipment and should prepare specifications consistent with applicable national standards for items that need to be replaced. The technical specialists should include at least the following: master mechanic, safety officer, driver/operator, training officer, and fire fighter. In autonomous volunteer fire departments, a purchasing committee may be appointed to procure apparatus. In municipalities, the city purchasing department usually purchases the apparatus. The purchasing department should not try to tell the fire department what type of fire apparatus it should use but should see that required procurement procedures, such as open competitive bidding, are followed.

The annexes of NFPA 1901 and NFPA 1906 contain helpful suggestions covering the purchase of fire apparatus, including developing specifications, reviewing proposals, dealing with manufacturers, and accepting completed apparatus.

In general, the purchase and replacement costs of fire apparatus should be a regular item of the fire department capital budget. In most cases, except for accidents, the requirements can be planned and funded on a long-range basis. Systematic apparatus replacement provides the fire department with reliable apparatus at all times. Improvements in fire apparatus design can be introduced, maintenance costs become more favorable, operating efficiency increases, and equipment remains reliable.

The apparatus procurement process, if performed properly, will take several months. The experience can be rewarding as well as frustrating. The process involves gathering information and learning as much about apparatus as possible. Information can come from several sources. Among the best sources are educational seminars, trade shows, and other fire departments. Once the information is gathered, specifications must be developed. Dividing the specifications into a format consisting of general requirements, construction specifications, and a bid evaluation sheet will facilitate the procurement. An alternative to construction specifications is performance specifications.

Another method of procurement that has gained in popularity in recent years is the request for proposals (RFP). This process allows bidders to be more competitive and it encourages innovation. In some cases, purchasers require bidders to submit their pricing separately. This allows for the evaluation of the technical merits of the bid without the bias of the cost factor. It is always a good idea to have a prebid conference with potential bidders to allow for all questions to be asked and answered in a consistent manner and provide for an equitable base of knowledge about the purchaser's expectations.

Once a bid is awarded, the fire department should have a preconstruction conference with the successful bidder, thus allowing the purchaser and apparatus builder to focus on the construction process. The purchaser should require drawings for approval and should have an understanding of how any change orders will be handled. Throughout the process, it must be clear to both the builder and purchaser how many factory inspection visits are needed and who will pay for them. Many fire departments require three factory visits: a preconstruction visit to understand how the manufacturer builds its apparatus, an intermediate visit to inspect basic components that are not readily visible after final assembly, and the final inspection. Factory visits allow for a quality control inspection by the purchaser as well as an opportunity to identify any unforeseen changes that

may be required. The visits assure that the purchaser is getting exactly what is being paid for. They should be conducted thoroughly and professionally.

An often overlooked part of the procurement process is the training and maintenance requirements for the apparatus. The complexity of fire apparatus requires that the user be trained. The purchaser must state up front what the training expectations are from the manufacturer.

Lease or Lease/Purchase

Lease or lease/purchase of fire apparatus can be an alternative to outright purchase. Income tax benefits and depreciation accrue to the actual, commercial owner of the apparatus; and the fire department, which is tax exempt, realizes savings in overall life-cycle cost. In addition, the department does not have to expend a large purchase price at one time but can spread the cost of apparatus over several years. Furthermore, there is no capital tied up in the event the department wishes to trade, exchange, or dispose of the apparatus. Closed and open-ended leases are available, and the finance department of the municipality should evaluate these alternatives carefully. In a smaller or volunteer department, a local banker can advise the purchasers of the advantages of a lease versus a purchase arrangement.

Any lease or lease/purchase contract should clearly spell out who is responsible for maintenance, repairs, and liability. Likewise, the contract should clearly state the conditions under which either party may terminate the arrangement.

As stated earlier in this chapter, there is an annex in both NFPA 1901 and 1906 that provides guidance on the retirement of apparatus. The annex explains how technological and safety advancements should be a primary consideration in the retirement of apparatus. This is especially applicable to apparatus that are not subjected to heavy use. Some departments have determined that rotating its fleet before the apparatus is worn out reduces maintenance costs and provides a much higher return on resale of the apparatus. This method provides for a modern fleet and a more equitable distribution of resources for both fire fighters and the public. A few larger departments have started to implement "total care" arrangements through lease agreements. The apparatus is leased, maintained, tested, and replaced by the supplier in accordance with the contract.

All fire departments should have a fleet replacement plan that averages the costs over several years for ease in budget development and justification. For larger departments, this can be as simple as a certain percentage of apparatus a year. For smaller departments, it could mean allocating and investing appropriate amounts of funds for capital improvements.

Acceptance Tests

Acceptance tests are designed to demonstrate that apparatus will perform as specified in the purchase contract. Tests should be performed within 10 days of delivery and before the apparatus is accepted. The tests should be conducted by the manufacturer's representative and in the presence of persons whom the purchaser may have designated in the delivery requirements. Normally, the fire chief or a designated representative is the acceptance authority. Third-party acceptance is gaining in popularity and should be considered by the agency. Costs for third-party testing are generally associated with the purchase price of the vehicle.

The acceptance-test requirements for fire apparatus and its various components should be detailed in the purchase specifications and should be based on the manufacturer's certification tests and any additional tests the fire department desires to ensure that the apparatus performs to specification. The acceptance tests should always be conducted in the community, so that any problems that developed during the delivery of the apparatus will be detected.

If the apparatus is equipped with a pump, a test plate is required at the pump operator's position that gives the rated discharge and pressures, together with engine speed determined by the manufacturer's certification test for the unit. The no-load governed speed of the engine, as stated on a certified brake horsepower curve, is also given. Tests are conducted to see that the water tank can flow the specified rate to the pump.

Documentation of electrical system performance tests must be supplied with the apparatus. These tests include reserve capacity test, alternator performance test at idle, alternator performance test at full load, and low-voltage alarm test.

Aerial devices are inspected and tested in accordance with the requirements in NFPA 1911, *Standard for Service Tests of Fire Pump Systems on Fire Apparatus,* as part of the certification tests. In addition, the stability of the aerial device is tested with the aerial device on a level surface and then on a firm surface sloping downward at 5 degrees in the direction most likely to cause it to overturn. The vehicle cannot show any signs of instability during these tests. These stability tests should not be conducted other than at the manufacturer's facility.

If the aerial device is equipped with a prepiped waterway, the system is flow tested to determine whether the water system can flow 1000 gpm (3785 L/min) at 100 psi (690 kPa) nozzle pressure with the aerial device fully elevated and extended. If there is a fire pump on the vehicle, the test is conducted using that fire pump, and the intake pressure to the fire pump cannot exceed 20 psi (138 kPa).

Other components and systems on the apparatus such as foam systems, line voltage electrical systems, and air systems should also be tested to be sure they have been installed properly and are working as designed.

INSPECTION, MAINTENANCE, TESTING, AND RETIREMENT OF APPARATUS AND EQUIPMENT

Program Setup

Equally important to the procurement of proper fire apparatus and equipment is their inspection, maintenance, testing, and retirement. Because apparatus are vital to life safety, they must be in top-notch condition. A regular inspection, maintenance, testing, and retirement program should be set up to ensure that all apparatus and equipment are serviced and tested in accordance with the manufacturer's recommendations and NFPA standards. The program should define the roles and responsibilities for the personnel and outside agencies involved. Fire apparatus are

becoming increasingly more complex, and attention to such a program cannot be neglected.

Based on concerns expressed by the National Transportation Safety Board (NTSB) in a 1991 report about the quality and type of maintenance on fire apparatus, the NFPA issued a preventive maintenance standard in 2000. In 2007, the NFPA issued a combined standard to include maintenance as well as testing. The new standard is NFPA 1911, *Standard for Service Tests of Fire Pump Systems on Fire Apparatus.* The old pump testing standard and aerial testing standards were merged into this document. NFPA 1911 should be the guiding document for fleet maintenance for all departments. It is a very user-friendly standard with several useful charts and checklists that any department can use. The standard defines the minimum requirements for fire departments to establish a preventive maintenance program. The standard is comprehensive and covers chassis, cab, body, low-voltage pumps, foam systems, aerials, CAFS, line voltage, air systems, winches, and breathing-air systems.

Apparatus safety should be the primary objective of a fire department's fleet management program. In fact, NFPA 1911 states that safety is the primary consideration in the decision to retire apparatus. The program should be in a written format and should include criteria for taking apparatus out of service. A thorough inspection program that covers the various systems of the apparatus should drive the program. Any preventive maintenance program should be conducted in accordance with the manufacturer's requirements.

Only qualified personnel should conduct the fire department's preventive maintenance program. NFPA 1071, *Standard for Emergency Vehicle Technician Professional Qualifications,* defines the minimum job performance requirements for an emergency vehicle technician. The standard prescribes two levels of competency. The EVT Certification Commission (EVTCC) offers a certification program for emergency vehicle technicians. The program recognizes mechanics as having demonstrated a working knowledge and skill required for emergency vehicles. Fire departments should insist that their mechanics become certified. Because of the complex systems associated with fire apparatus, an emergency vehicle technician must have knowledge and training that exceed that of typical automotive mechanics. The emergency vehicle mechanic must be able to inspect, diagnose, maintain, repair, and test the functions of the apparatus. It is the responsibility of the fire department to assure that its vehicles are maintained by qualified mechanics in accordance with their competencies. There are several state and regional fire mechanics associations that offer excellent training and networking opportunities for emergency vehicle technicians.

Retirement of Apparatus

The topic of when to retire a piece of apparatus has been debated for decades. Larger fire departments with high-volume responses typically replace their apparatus based on maintenance costs and general wear and tear. However, most fire departments do not have the call volume to justify maintenance costs or wear and tear as sufficient substantiation to replace apparatus.

NFPA has addressed this situation by calling attention to the technological advances in apparatus, particularly in regards to safety. Annex D of NFPA 1901 references previous editions of the NFPA 1901 as benchmarks for replacement. There are at least two dozen clearly identifiable safety features found on today's apparatus that were not required or available in the seventies or eighties. Safety and technological advances will definitely continue, as will the need to consider apparatus replacement on these criteria.

Service Tests of Pumps. All pumps should undergo service tests at least annually and after any major repairs. These tests demonstrate that the pump/engine combination is capable of meeting the performance requirements of the original certification or acceptance tests. Records of service tests are important evidence of proper apparatus maintenance.

NFPA 1911 outlines the procedures for the service test. The test should cover the following items:

- A test pumping from draft for 20 minutes at 100 percent of rated capacity at 150 psi (1039 kPa) net pump pressure; 10 minutes at 70 percent of rated capacity at 200 psi (1380 kPa) net pump pressure; and 10 minutes at 50 percent of rated capacity at 250 psi (1725 kPa) net pump pressure
- An engine speed test to determine if the engine is capable of reaching its no-load governed speed
- A vacuum test to ensure that the pump and the attached piping are still tight
- A pressure control test to ensure that the pressure control device can control the discharge within the specified limits
- A check of the accuracy of the gauges and flow meters

The purpose of the test is to ensure that the pump is generally in good condition, that the pump casing and various fittings are tight, and that the transfer valve is operating properly, if the pump is a series parallel type. If rated capacity cannot be obtained at 150 psi (1035 kPa) and the pump is not cavitating, or it appears that the pump, engine, pump accessories, or other parts of the power train and pumping equipment are not in good condition, the apparatus manufacturer, an authorized representative, or a competent mechanic should be contacted for advice so the condition can be corrected. Personnel conducting the pump service tests should take safety precautions, including working on a slip-resistant surface and putting guards around pressurized hose lines.

Service Tests of Aerial Devices. Aerial devices also need to be service tested periodically. These devices develop problems not only from use at fires but also from responding to and returning from alarms. NFPA 1911 requires a yearly inspection of the aerial device and of the prepiped water system, if so equipped, and a test of their operation. NFPA 1911 requires additional nondestructive tests, at intervals not exceeding 5 years, that check structural components for hardness, welds for cracks or discontinuities, and bolts and pins for wear or internal flaws. The full testing should be done any time the aerial device has had major repairs or if the department has reason to believe that it has exceeded the manufacturer's design criteria to ensure that it can be returned to service.

A qualified fire department mechanic can normally conduct the annual inspection and testing. The more complex,

nondestructive tests require expertise that may be beyond the abilities of fire department personnel. The qualifications of the inspection personnel and the test protocols used are outlined in NFPA 1911. Only personnel meeting those qualifications and having the proper equipment should do nondestructive testing.

Refurbishing Apparatus. Fire departments may wish to consider refurbishing an apparatus rather than purchasing a new one. NFPA 1912, *Standard for Fire Apparatus Refurbishing,* provides the minimum requirements for refurbishing an apparatus. The standard provides for two levels of refurbishment. In a Level I refurbishment, the vehicle receives at least a new chassis frame, cab, front axle, steering, and suspension components. The new items must comply with the latest revision of NFPA 1901. In a Level II refurbishment, the vehicle receives an upgrade of major components or systems but these upgraded components only need to comply with NFPA standards in effect at the time the apparatus was manufactured. The standard provides an excellent specification form in the appendix or annex for purchasers to use. All refurbishments must be performed in accordance with Title 49, Code of Federal Regulations, Part 571, Subpart B, "Federal Motor Vehicle Safety Standards." As with the purchase of new apparatus, a refurbishment process must make safety a primary concern.

The decision to refurbish must be evaluated very carefully. It must be noted that the number of apparatus being refurbished has steadily declined over the past 10 years. Though refurbishments are less expensive than new apparatus, they are still very expensive. A careful cost analysis will aid fire departments in this decision. The analysis should include the age of the vehicle (depreciation), the anticipated remaining life of the vehicle, resale value of the vehicle, proposed cost of refurbishment, and time out of service during refurbishment. The result needs to be related to the cost of a new vehicle. A refurbishment program should not be initiated for the sole purpose of improving the cosmetic appearance of the vehicle.

The refurbishing process is as detailed as purchasing a new apparatus. Detailed specifications should be written as part of an overall procurement process. It is critical that both the purchaser and the manufacturer understand each other's expectations and have them in writing. Refurbishments typically expose unforeseen areas that need to be upgraded or repaired. For this reason, fire departments should establish a contingency fund.

GROUND LADDERS

Ground Ladder Characteristics

Most apparatus carry ground ladders designed for rescuing persons and gaining access to buildings for fire-fighting purposes. Ladders may be constructed of wood, aluminum, fiberglass, or a combination of aluminum and fiberglass. Aluminum is by far the most common material used. All ground ladders used in the fire service should be designed and built to conform to NFPA 1931, *Standard for Manufacturer's Design of Fire Department Ground Ladders.* The NFPA 1901 standard allows fire departments flexibility in determining the appropriate ladder lengths for their needs. There are varying length requirements for pumpers, attack vehicles, quints, and aerial devices.

Loads that fire ladders are designed to support vary according to the type of ladder. Extension ladders, single ladders, and roof ladders built since 1984 are designed for 750 lb (340 kg) maximum load; folding and pompier ladders are designed for 300 lb (136 kg) maximum load. Load limitations are based on the use of the ladder supported at the top end against a building and set at a 75½ degree angle. This angle is measured from the horizontal with the ladder in the raised position. At smaller angles, the ladder may be unable to support the design load.

Although the NFPA apparatus standards list the minimum requirements for ground ladders on each type of vehicle, careful consideration should be given to the ladder needs of the area served. Manually raised extension ladders more than 40 ft (12 m) long are generally not required because aerial ladders and elevating platforms provide adequate emergency access to upper floors and roofs. If congested conditions prohibit the placement of aerial apparatus to provide effective aerial service, however, additional or longer ground ladders should be provided. It must be recognized that additional personnel are required to raise longer ladders and that the space available for ladders on some vehicles is limited.

Ground Ladder Service Testing

NFPA 1932, *Standard on Use, Maintenance, and Service Testing of In-Service Fire Department Ground Ladders,* calls for service testing all ladders at least annually and at any time the ladder is suspected of being unsafe. The tests are designed to show that the ladder is safe for continued use under the conditions for which it was originally designed. The service-test procedures must be carefully observed to ensure that the ladder is not damaged. Ladders also should be inspected visually, as outlined in NFPA 1932, to detect loose rungs, loose bolts and rivets, weld defects, cracks, splintering, breaks, discoloration, and other signs of possible weakness that might warrant testing to determine whether the ladder is safe to use or needs repair.

There is a misconception that the procedures used to test ground ladders are destructive. It is true that the load test may appear to be damaging, but a safe ground ladder will pass the annual load tests for many years.

HOSE, COUPLINGS, AND NOZZLES

Fire hose is the vital link between the water supply and the nozzles used to project streams on a fire. Fire hose failure can put fire fighters at great risk. Hose must be rugged, dependable, and capable of carrying water under substantial pressures, yet flexible and sufficiently easy to handle. Fire department management should be concerned with selecting the proper grades and types of hose and with maintenance to ensure maximum useful life. These two factors are covered in detail in NFPA 1961, *Standard on Fire Hose,* and NFPA 1962, *Standard for the Inspection, Care, and Use of Fire Hose, Couplings, and Nozzles and the Service Testing of Fire Hose.* Aside from unavoidable mechanical injury at fires, a hose's dependability and length of life rest on three factors: (1) the quality and suitability of the

hose purchased, (2) the care with which it is handled at fires, and (3) the maintenance and care the hose receives.

Types of Fire Hose

Fire hose is manufactured for at least four uses:

1. *Attack hose.* Fire attack by fire department personnel
2. *Large-diameter supply hose.* Relaying water through large-diameter hose from a source to the fire
3. *Occupant use hose.* Occupant use in buildings from standpipe systems
4. *Forestry hose.* Fire department use at wildland fires

Each of these types has minimum requirements for strength. Attack hose is designed for a minimum service-test pressure of 300 psi (2069 kPa) to meet a normal highest operating pressure of 275 psi (1896 kPa). If a higher working or operating pressure is needed, the purchaser needs to specify a higher service-test pressure. The most common size of interior attack hose is 1¾ in. (44.45 mm). For larger fires, 2½ in. (63.50 mm) is often used.

Large-diameter supply hose has a minimum size of 3½ in. (89 mm) and a minimum design service-test pressure of 200 psi (1380 kPa) to meet a 185-psi (1276-kPa) normal highest operating pressure. Large-diameter hose is typically used as supply hose or hose to supply ground placed master stream appliances. The most common size is 5 in. (127 mm).

Occupant use hose has a minimum size of 1½ in. (38 mm) and a minimum design service-test pressure of 150 psi (1035 kPa) to meet a 135-psi (931-kPa) normal highest operating pressure.

Forestry hose is only available in 1 in. (25 mm) and 1½ in. (38 mm) sizes and has a minimum design service-test pressure of 300 psi (2069 kPa) to meet a 250-psi (1725-kPa) normal highest operating pressure.

All hose must meet a proof-test pressure—formerly an acceptance-test pressure—of twice its service-test pressure, a burst-test pressure of three times its service-test pressure, and a kink-test pressure of one-and-a-half times the service-test pressure.

NFPA 1961 provides requirements for the hose jacket, the lining and the lining adhesion, any covering and its adhesion, the tensile strength of the hose, the ultimate elongation of the hose, and the cold resistance of the hose. Tests are outlined to verify these requirements. Another section in NFPA 1961 defines how the hose must be marked.

Care, Maintenance, and Testing of Fire Hose

Fire hose should be properly maintained to ensure its reliability. Burst hose at a fire may seriously injure fire fighters and other persons and may mean a loss of time in bringing a fire under control. NFPA 1962 and the manufacturer's instructions should form the basis of a hose care and maintenance program.

Hose carried on fire apparatus should be loaded to reduce edge wear and loaded so that air can circulate around it. The hose storage areas should be protected by waterproof covers to keep the hose dry and to protect it from ultraviolet rays and from debris.

Hose installed at yard hydrants at industrial plants should be kept in well-ventilated hose houses in such a way that air can circulate and excessive heat can be avoided.

To prevent damage and permanent set to the rubber tube, hose should be removed from the apparatus or hose house at least quarterly and reloaded so the folds are in a different position. If hose jackets are of cotton or synthetic construction, the hose should be cleaned and dried after use to remove possible abrasive or contaminating material and to protect the hose compartment of the apparatus against rust or water damage.

When used for fighting fires, fire hose is subject to severe strains, pressure surges, burning embers, and abrasion. Care should be taken to lay hose so that damage will not result from contact with sharp or rough objects. Vehicles should not be driven over hose lines. Where it is necessary for fire department vehicles to cross, hose bridges should be used if possible. When it is necessary to hoist hose lines, hose rollers can make the task easier and prevent mechanical injury. A hose extended up a ladder should be supported by a hose-rope tool to minimize the strain on hose couplings.

Pressure surges are a principal cause of damage to fire hose. Shutoff nozzles should be opened and closed slowly because sudden closure of nozzles can cause severe pressure surges, or water hammer, that can be extremely damaging to both hose and pumping apparatus. Pressure-relief devices on pumping engines should always be used to control unexpected, sudden increases in pressure.

In cold climates, care should be taken to prevent water from freezing in the fire hose. Once a hose line has been charged, a small amount of water should be left running through the hose because moving water does not freeze readily. Sharp bends should be avoided in any frozen hose. Care must be used in chopping hose free from ice after a fire so as not to cut the hose. The ice should then be allowed to melt off the hose, and any hose that has been frozen should be service tested before being placed back in service.

Care must also be taken to avoid burning the hose at forest and grass fires. As fire is knocked down and the nozzle is advanced, the hose may come in contact with hot spots or embers. When hose has been returned to the fire station, it should be laid out where it can be inspected, swept, and washed as needed to remove dirt and contaminants.

Good hose record keeping is necessary for accurate data on hose performance. Records for hose on racks, on reels, or in hose houses or similar enclosures may be kept at the hose location or at a central location on the premises where the hose is located. Fire department records should include a complete record of all hose. Upon delivery and acceptance, each length of hose should be given an identification number to be used throughout its service life. The ongoing record of the hose should include all testing and repairs and, ultimately, the reason it was condemned and removed from service.

All fire hose, except occupant use hose, should be tested at least annually and after repairs, or at any time it has had hard usage and its condition is suspect. NFPA 1962 includes required service-test procedures and a typical annual hose-test record form. The standard also specifies service-test pressures for hose manufactured before July 1987. Hose manufactured after that date has the service-test pressure stenciled on it.

Fire departments should avoid using the fire pump of an apparatus to test fire hose if at all possible. Apparatus fire pumps are not intended for hose-testing applications. Using smaller, low-volume, high-pressure pumps will minimize the unnecessary wear on a fire pump. Personnel conducting hose tests should take precautions against being in close proximity to charged hose lines.

Occupant use hose (normally stored on a rack or reel) should be examined carefully at least once a year. This annual physical inspection should consist of a visual examination to see that the hose has not been vandalized, that the couplings and nozzle are attached and free of debris, and that there is no evidence of mildew, rot, chemicals, vermin, or abrasion. Racked hose should be reracked with the folds in a different location. Five years after the date of purchase and every three years thereafter, the hose should be service tested, as it should be any time the condition of the hose is questionable.

Fire Hose Connections

The need for standard fire service connections is most apparent during mutual-aid operations. When hose couplings, nozzles, and other equipment do not conform to standards, it becomes necessary to use adapters, thus complicating fire-fighting operations.

NFPA 1963, *Standard for Fire Hose Connections,* applies to connections on fire-hose couplings, suction-hose couplings, relay supply-hose couplings, fire pump suction, discharge valves, fire hydrants, nozzles, adapters, reducers, caps, plugs, wyes, siamese connections, standpipe connections, sprinkler connections, and all other hose fittings, connections, and appliances that connect to fire pumps, hose, and hydrants.

The standard defines requirements and tests to verify the design and performance of couplings on fire hose. These include issues of minimum waterway size, internal strength, connect and disconnect capability, retention, and performance after rough usage, high-temperature conditions, and low-temperature conditions. There are also requirements for the gasket material used with the couplings.

For threaded connections in the 10 sizes from ¾ to 6 in. (19 to 152 mm) used in fire protection, the standard gives the dimensions for the American National Fire Hose Connection Screw Thread, abbreviated throughout as NH but also known as NST and NS. It also gives the dimensions for gauges, gaskets, and gasket seats associated with threaded connections. These threaded connections are defined by specifying, in sequence, the nominal size of the connection, the number of threads per inch, and the thread symbol. The 10 standard sizes of threaded connections are designated in Table 12.16.1.

To accommodate the increased use of nonthreaded connections on large-diameter hose, the machining dimensions for nonthreaded connections in 4 in. (100 mm) and 5 in. (125 mm) sizes are defined to ensure interchangeability as well as to prevent accidental disengagement of the couplings. Finally, the standard defines when the different thread sizes should be used on hose connections, nozzles and shutoffs, and both the initial connection and subsequent connections on large-stream devices.

TABLE 12.16.1 Standard Sizes of Threaded Connections

0.75–8 NH	3.5–6 NH
1–8 NH	4–4 NH
1.5–9 NH	4.5–4 NH
2.5–7.5 NH	5–4 NH
3–6 NH	6–4 NH

Nozzles

Nozzles used in the fire service are of either the spray or solid-stream design. A spray nozzle can produce a straight stream with similar characteristics as a stream from a solid-bore nozzle. Nozzles for 1, 1½, 1¾, and 2 in. (25, 38, 44, and 51 mm) hose are typically spray nozzles. Nozzles for 2½ in. (65 mm) hand lines and for master stream devices may be of the spray or solid-stream design. All hand line nozzles should be equipped with shutoff valves, either as an integral part of the nozzle or as an attached item.

Fire department nozzles for 1½ in. (38 mm) hose normally are designed to discharge approximately 95 to 125 gpm (360 to 473 L/min). Nozzles for 1¾ and 2 in. (44 and 51 mm) hose normally are designed to discharge approximately 125 to 200 gpm (473 to 757 L/min). Nozzles for 1 in. (25 mm) hose generally discharge in the 20 to 30 gpm (76 to 114 L/min) range. A standard hose stream from a 2½ in. (65 mm) hose with a 1⅛-in. (29-mm) smooth bore tip is 250 gpm (946 L/min) at 50 psi (345 kPa) nozzle pressure.

Solid-bore nozzles have a straight open tip that generally is attached to some type of stream shaper. These nozzles are designed to hold the solid stream together as water is thrown a considerable distance. The design of the nozzles provides a gentle taper from the diameter of the inside of the hose to the diameter of the tip to reduce the turbulence that causes a stream to break up.

Requirements for spray nozzles are covered in NFPA 1964, *Standard for Spray Nozzles.* There are three general types of spray nozzles: (1) the basic spray nozzle, (2) the constant-gallonage spray nozzle, and (3) the constant-pressure (automatic) spray nozzle.

The basic spray nozzle is an adjustable-pattern spray nozzle in which the rated flow is delivered at a designated nozzle pressure and nozzle setting. Due to its basic design, the flow (gpm [L/min]) will vary as the pattern is changed from a straight stream through a wide-spray pattern. This is caused by the orifice size changing to affect pattern adjustment.

The constant-gallonage spray nozzle is an adjustable-pattern spray nozzle in which the flow is delivered at a designated nozzle pressure. At the rated pressure, the nozzle will deliver a constant gallonage from straight-stream through a wide-spray pattern by maintaining a constant orifice size during flow-pattern adjustment. These nozzles are popular because the friction-loss characteristics in the hose and the nozzle pressures remain constant regardless of the selected orifice setting.

A constant-pressure (automatic) spray nozzle is an adjustable-pattern nozzle in which the pressure remains con-

stant through a range of flows. The constant pressure provides the velocity for an effective stream reach at various flow rates, which is accomplished by means of a pressure-activated, self-adjusting orifice baffle. These nozzles can produce streams whose discharge varies considerably but whose visual characteristics and stream reach remain the same. The user should not be misled by a good-looking stream that lacks the adequate flow for proper fire attack. However, these are very effective nozzles if the fire department understands the principles behind the automatic nozzle—namely, that the volume of water, not the pressure alone, extinguishes fire.

There are other nozzles available for special purposes. For decades, fire fighters have argued over the effectiveness of spray nozzles versus smooth bore tips. The argument usually is more emotional than logical. One key difference is that a spray nozzle can be placed in the "straight-stream" mode for basically the same effect as a smooth bore tip. However, a smooth bore tip cannot be converted to a spray pattern. These include nozzles used in the aspiration and delivery of foaming agents, very high-pressure spray nozzles that are designed to deliver small flows at pressures in the 400 to 800 psi (2756 to 5516 kPa) range, and spray nozzles used on standpipe hose for first-aid fire protection.

SUMMARY

The selection and purchase of fire department apparatus and equipment are obviously an important part of any fire department's business. For volunteer fire departments, the largest portion of their budget is dedicated to vehicles and equipment. In career and combination departments, it is usually second to salaries and benefits. Foremost, the selection and purchase process must be based on community needs. Careful research and planning are crucial to meeting these needs. Fire vehicles and equipment are very specialized and technical in their nature. They cannot be purchased at the local car dealership, corner hardware store, or megadiscount store.

Fire departments must be knowledgeable about all applicable standards and laws that impact the design, performance, use, and maintenance of the equipment. The selection and purchase of apparatus and equipment must take into account several factors. The foremost factor is the safety of the fire fighters and the public. As stated earlier in this chapter, one of the 16 Firefighter Life Safety Initiatives of the National Fallen Firefighters Foundation states: "Safety must be a primary consideration in the design of apparatus and equipment." Another factor is how the vehicle or equipment fits in with previous purchases. In addition, the fire department must provide training on the proper use of all the vehicles and equipment and must provide maintenance for the items purchased as described by the manufacturer.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information about fire department apparatus and equipment discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 414, *Standard for Aircraft Rescue and Fire-Fighting Vehicles*
NFPA 1002, *Standard for Fire Apparatus Driver/Operator Professional Qualifications*
NFPA 1071, *Standard for Emergency Vehicle Technician Professional Qualifications*
NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*
NFPA 1901, *Standard for Automotive Fire Apparatus*
NFPA 1906, *Standard for Wildland Fire Apparatus*
NFPA 1911, *Standard for the Inspection, Maintenance, Testing, and Retirement of In-Service Automotive Fire Apparatus*
NFPA 1912, *Standard for Fire Apparatus Refurbishing*
NFPA 1925, *Standard on Marine Fire-Fighting Vessels*
NFPA 1931, *Standard for Manufacturer's Design of Fire Department Ground Ladders*
NFPA 1932, *Standard on Use, Maintenance, and Service Testing of In-Service Fire Department Ground Ladders*
NFPA 1961, *Standard on Fire Hose*
NFPA 1962, *Standard for the Inspection, Care, and Use of Fire Hose, Couplings, and Nozzles and the Service Testing of Fire Hose*
NFPA 1963, *Standard for Fire Hose Connections*
NFPA 1964, *Standard for Spray Nozzles*

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Chapter 17

Pre-Incident Planning for Industrial and Municipal Emergency Response

Michael J. Serapiglia

Chapter Contents

Pre-Incident Planning Defined
Planning Process
Data Components

Key Terms

building construction, industrial fire brigade, occupancy classification, pre-incident planning, public fire department

A pre-incident plan is one of the most valuable tools available for aiding the fire department and the on-site fire brigade if available, in effectively controlling a fire or other emergency incident. The plan can be used by responding personnel to help them effectively manage emergencies with available resources. Planning for fires in industrial and commercial facilities increases the confidence and ability of fire service personnel to deal with most emergency situations. More importantly, it increases the potential for saving lives and property. This chapter will discuss the pre-incident planning process, who needs to be involved in this process, and the type of information industrial and commercial facilities need to gather.

For related topics, see the following chapters in Section 12: Chapter 1, "Planning for Public Fire-Rescue Protection"; Chapter 11, "Industrial Fire Loss Prevention"; and Chapter 18, "Pre-Incident Planning for Emergency Response."

PRE-INCIDENT PLANNING DEFINED

Pre-incident planning can be defined as a written document resulting from the gathering of general and detailed information/data to be used by public emergency response agencies and private industry for determining the response to reasonably anticipated emergency incidents at a specific facility.

In simple terms, pre-incident planning is ensuring that responding emergency personnel know as much as they can about a facility's construction, occupancy, and fire protection systems *before* an incident occurs. With this knowledge, the fire department can compare a potential incident at the facility with its available resources and plan the department's response accordingly. Pre-incident planning is not restricted to building components. It includes other factors and conditions that may be relevant to an emergency at a particular site.

Pre-incident planning is not easy. It takes considerable effort by the fire department to get a pre-incident planning program up and running. As growing demand for an expanding scope of services collides with limited budgets and other resources, fire departments are faced with much competition for staff time and money.

This means that pre-incident planning is more important than ever, not just for the traditional reasons of greater effectiveness and safety, but also for greater efficiency in resource utilization. No matter what effort it takes, fire departments today literally cannot afford *not* to pre-incident plan. The more information available, the better the opportunity for an incident commander to manage the incident successfully. Advance knowledge of the facility could mean the difference in managing the incident properly.

Proper training is also critical to pre-incident planning success. The individuals doing the pre-incident surveys and preparing the resulting documentation (Figure 12.17.1) must have the proper

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FIGURE 12.17.1 Pre-Incident Planning Session

level of training. Conducting the survey requires much more than walking through the building. It requires asking the right questions about construction features, storage arrangements, water supply adequacy, and sprinkler system components and design. This information must then be converted into a usable format for both fire department training and an actual incident.

The burden for successful pre-incident planning does not rest with the fire service alone. Pre-incident planning requires three-way open communication among facility management, the fire service, and the property insurance industry. Other agencies might also be able to provide valuable input during the development of the pre-incident plan. Such agencies include police, security, public utilities, environmental agencies, and contractors.

Facility management must take a coordinating role in pre-incident planning and be willing to host a joint meeting of all three entities. At this meeting, management must be willing to share information that its property insurance carrier has most likely already gathered about the hazards within the facility and the level of protection that is available. Most highly protected risk (HPR) insurance carriers are willing to provide this information, if they have the consent of facility management. The fire department must then take this information and incorporate it into its response plan for the facility.

When pre-incident planning is successful, everyone benefits. The fire department manages its response effectively, which results in a safer response and minimized property loss. A minimized property loss keeps the facility in business, which maintains the tax base for the fire department's budget. And the loss cost is kept low for the property insurance carrier.

Conducting pre-incident planning is not the same as inspecting for code violations. When pre-incident planning, the fire department representative takes the facility "as is" and develops a response strategy around existing conditions. Conducting pre-incident planning is not an attempt to improve fire prevention or identify code violations at the facility. Its sole purpose is to prepare for an incident at the facility under existing conditions. Pre-incident planning assumes an incident will occur. It makes no special effort to prevent a fire or eliminate a hazard, but rather it is preparation for an incident, regardless of the likelihood.

Assume for a moment that a facility in the community is known to have several automatic sprinkler system code deficiencies. Also assume that the facility's management has agreed to correct the situation within 90 days. What happens if a fire occurs the day after tomorrow? Just because the code violations have been documented does not mean a pre-incident plan is not needed. Code inspections and pre-incident planning are two distinct functions with two different purposes.

The fire department that is responsible for both code inspections and pre-incident planning needs to handle these types of situations with tact and diplomacy. When conducting code inspections, it is easy to stand behind the delegated authority of the position. But the fire department will never get the cooperation it needs for effective pre-incident planning if an authoritative approach is taken. The difference between each function must be understood by the fire department and communicated effectively to facility management.

Pre-incident planning is continuous. Many major fire incidents can be traced back to a change—often seemingly

minor—that took place at a facility. Perhaps the packaging of the products stored in the warehouse was changed from cardboard to plastic. Or maybe some renovations took place that left concealed spaces unprotected by automatic sprinklers. Maybe the on-site suction tank for the fire pump is going to be drained and repainted over the next several weeks and it is the only adequate water supply for the facility.

If a pre-incident plan is prepared once and never updated, these changes could go unnoticed until it is too late. Keeping up with changes in a facility requires a high level of commitment, communication, and cooperation among the pre-incident partners. For example, depending on total area and intended use, installation of modular office buildings at an existing property may not trigger code requirements for sprinkler protection, but egress issues may be impacted and should be thoroughly evaluated.

Determining the best frequency for updating pre-incident plans depends on the facility. Updating once per year may be fine at some locations but could be woefully inadequate at other locations.

Pre-incident planning requires a willingness by facility management to bring the fire department in and tell them what they need to know (e.g., "The sprinkler system in the warehouse is not currently adequate to protect what we're storing there"). It requires the fire department to know what questions to ask and to react positively when they get the truthful answers to those questions. And it requires the property insurer to act as an information link between the two.

PLANNING PROCESS

From the fire department perspective, once a facility has been selected, the owner/operator should be contacted. The needs and benefits of pre-incident planning might have to be explained in detail. The fire department should explain the nature of the information required, because the facility might have to arrange to have certain specialized employees available when the visit is made.

Situations may arise in which the selected property encompasses building areas in more than one municipality. In such cases, it is important that all fire service agencies involved be included in the planning process. The cooperation of multiple agencies in the planning phase will help assure smooth operations during the emergency incident phase.

When selecting a property, do not limit the choices to the largest facilities. Consider medium and small locations in which on-site emergency response resources and protection features may be limited. Locations such as commercial storage facilities for swimming pool supplies and municipal or private golf courses should not be overlooked. A number of challenging fires involving pool treatment chemicals have been documented over the past 10 years in large bulk retail stores. Although the quantities may be different, similar hazards are presented. When was pre-incident planning last conducted at your local golf course? Large clubhouses, battery charging and storage areas for electric carts, flammable or combustible liquid storage for maintenance vehicles, and significant quantities of pesticides and fertilizer are commonly found at such locations.

The pre-incident planning process can be shown as a flowchart (Figure 12.17.2). Obviously, much time and effort will be needed with the collection of data. This will involve consulting with the facility's staff and other individuals as necessary. The site will need to be visited to get an overview of the layout, construction, occupancy, and fire protection features.

Most major industrial and commercial facilities have developed an emergency operations or crisis plan in which the actions to be taken in the event of an emergency have been specified. A review of the emergency operations plan by the fire department can provide valuable insight into the actions to be coordinated by both facility personnel and the fire department. Incorporating the emergency operations plan into the fire department pre-incident plan is beneficial in case the facility personnel are assigned certain responsibilities but circumstances during the emergency prevent them from performing these duties.

A number of commercially available software programs may be utilized to assist in the recording of data. These programs are also useful in developing building drawings and a general layout of the facility.

Once the data are collected, decisions will need to be made about what data to keep and how the data should be stored, retrieved, and presented. The method of presentation is best left up to the discretion of each fire department, but it should be based on the fire department's incident management system.

Many fire departments keep certain parts of the plan in the dispatch center for reference. The dispatcher may transmit a facsimile of pertinent sections of the plan or the entire plan to a fire station prior to apparatus responding to an incident. This same information may also be sent directly from the dispatcher to the incident commander on scene. Others use computers in apparatus to store and retrieve information. Other departments may keep hard copies of the pre-incident plan in the individual fire stations or the apparatus itself. A sample pre-incident planning data form is shown in Figure 12.17.3.

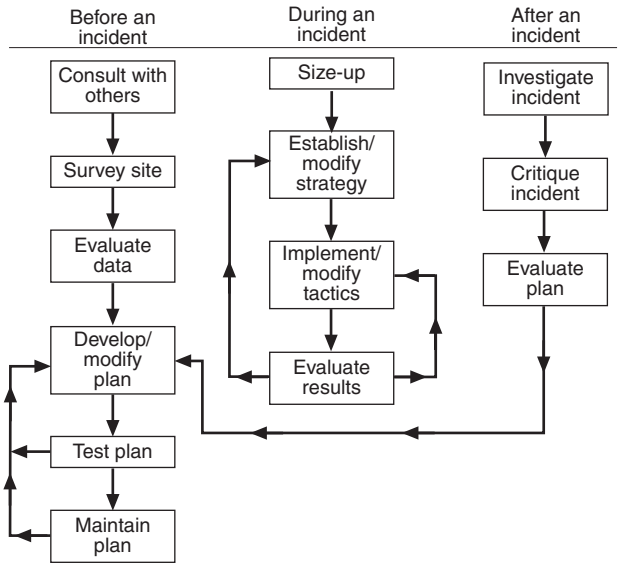

FIGURE 12.17.2 Pre-Incident Planning Process Flowchart

Pre-Incident Planning Data Gathering Form

Date: 7/24/93 Number of employees: 43

Location: 20511 Hicks Rd. Phone number: 708-634-3035

Sport Fashions

(Name of company and address)

Owner name/operator name: Fashion Apparel USA/Fred Jones Mfg.

Access to site: Streets— 1000-ft private drive with many large potholes to main west of Hicks Rd.

Lockbox: Outside of office door on left side

Annunciator panel—location:

Outside of office door on right side

Fire department connections—location:

1. Front of Guard House at Hicks Rd. entrance; 2. W. corner fenced yard, accessible from Ridge Rd.

Door locations/forcible entry notes:

1. Office-use lockbox key; 2. Dock office, center, E. side, 24-hr occy. ex. weekends;
3. Pump house—lockbox key at main office.

Storage configuration hazards:

Clothing warehouses; stock in cardboard boxes on back-to-back double row racks 23 ft high; 8-ft-wide aisles, ordinary wood pallets; no solid shelves

Construction: Width (side facing fronting street): 345 ft

No. stories: Depth: 200 ft

Height: 1 story = 27 ft

Wall construction: Insulated metal

Roof construction: Support structure — Steel joists on unprotected steel beams and columns

Roof covering — Built-up layers w/tar and gravel

Location of vertical and horizontal cutoffs (space separation—fire walls):

Type of fire doors: 12-in. HCB w/parapet at offices

Utilities:				
Gas	Unit heaters	Cutoff points	100 ft w/guard house
Electrical		Cutoff points	1. 200 ft
Oil pumps	None	Cutoff points	2. Ridge Rd. side
Propane tank	None	Cutoff points	

Critical exposures: Side 1: Open Side 2: Automatic sprinkler whse 90 ft

Side 3: Open Side 4: Open

Protection (on site): Public water: 1650 gpm

Residual pressure: 51 psi Normal static at site: 65 psi Test date: 6/14/2007

Sprinkler design: 1380 gpm 57 psi

FIGURE 12.17.3 Pre-Incident Planning Data Form

In-rack sprinklers provided: [x] Yes [ ] No

(#) Booster pump 1500 gpm 40 psi Driver type Elec.

(#) Fire pump 2000 gpm 75 psi Driver type Diesel

Hose stream supply: On site: Pond Public: 16-in. main—Hicks Rd.

Hose length to reach: Hydrant—200 ft; Pond—600 ft

Water demand: for AS: 1610 for hose streams: 500 gpm

Venting: Manual hatches: [ ] Yes [x] No

Automatic: _____ Powered: _____

Power switch locations: _____

_____

Special conditions:

Employee head count location: Guard house—Main Hicks Rd. entrance

Contact person: Days—Mgr. Fred Jones; Nights—Shift Foreman

Special units needed: 2nd ladder truck on 1st alarm from Ft. Mudge FD. Shift commander must request dispatch to TX.

Other: _____

Sketch details:

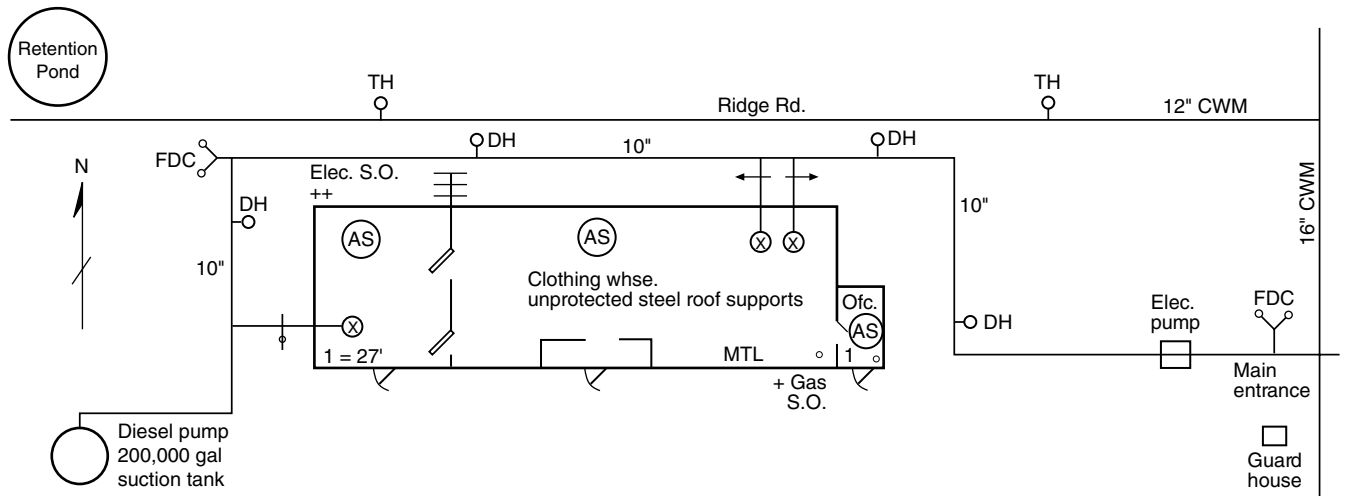

FIGURE 12.17.3 Continued

Testing and practicing the pre-incident plan will provide an opportunity to fine-tune the data and to revise and update the plan.

During the incident, the pre-incident plan should become the foundation for operations. It will provide important data that will assist the incident commander in developing appropriate strategy and tactics for managing the incident. Changes in conditions might dictate a revised strategy, including adjustments to responses and tactics. Throughout the incident, consulting the pre-incident plan will keep the incident commander informed about factors that might affect the success of any given strategic or tactical adjustment.

Each incident provides an opportunity for improvement. Assumptions, predictions, and accuracy of the pre-incident plan should be evaluated in light of the actual results during the incident. Modifications to the pre-incident plan should be made as necessary, and the plan should be retested, especially if the modifications are extensive.

DATA COMPONENTS

Building Construction

Construction features, such as structural framing systems, building materials, and the interior and exterior finishes, can be key factors in the rate and extent of fire spread within a building. The fire conditions in a building of fire resistive construction will be markedly different from those in a building constructed entirely of combustible materials. Fire development, intensity, and spread can be far better controlled in structures of fire-resistive construction. The size of the building, both vertical and horizontal, can also have a drastic effect on the decision process that takes place during an emergency. Awareness of these features by the fire department is important in estimating the potential fire problem and ultimately confining the fire to a limited area. Figure 12.17.4 shows a team reviewing the details of a building's specialized gas detection system.

Wall Construction. The pre-incident plan should include information regarding construction materials for exterior walls, such as metal panel, masonry, or wood frame. This information will be helpful in determining the potential for exposure protection, the potential loss of structural integrity, and the ability to access the building interior.

Roof Construction. Information on roof construction is also needed. This information includes the roof support, such as wood joist, steel joist, or steel beam; the roof deck, such as steel, metal panel, wood plank, or concrete; and the roof covering, such as built-up tar and gravel or insulated membrane system. The type of roof construction can have an impact on ventilation operations, can create exposure problems, and, most importantly, can increase the dangers to fire fighters. The pre-incident plan should also note how venting will be accomplished and the location of any manual or automatic vents. The decision to place fire fighters on a building roof during a fire should be based

FIGURE 12.17.4 Operational Overview of Flammable Gas Detection System

partly on advance knowledge of the particular roof construction. Roofs unprotected by automatic sprinklers, even those of fire-resistive construction, can collapse very early during a fire incident.

While conducting the survey, look for indicators of truss construction and consider marking facilities with an easily identified symbol. One such arrangement exists in the state of New Jersey. The New Jersey Uniform Fire Code requires identifying symbols be permanently affixed to the front of structures with truss construction. "F" signifies a floor with truss construction; "R" signifies a roof with truss construction; "F/R" signifies both a floor and roof with truss construction. Samples of truss identifying symbols are shown in Figures 12.17.5 (a) (b).

Ceilings and Attics. False ceilings and common attics can lead to fire spread within a building and impair the ability of fire fighters to control the fire. These construction features can create safety hazards by permitting fires to burn undetected in areas that are not readily visible. Awareness of these structural features allows fire fighters to prevent or reduce fire spread in these areas.

Floor Construction. Like roofs, similar information should be gathered about the building's floor construction, since the same collapse potential may exist. In addition, information should be obtained regarding the floor's capabilities for drainage, especially where flammable and combustible liquids are used or stored.

Means of Egress. The location of a building's entrances and exits, interior hallways, stairs, or other travel paths can be extremely valuable information in developing strategy or directing rescue, fire control, or other tactical operations. Familiarity with building access is often key to directing fire attack efforts that will confine the fire to the involved area, rather than driving it into uninvolved portions of the structure.

Vertical Openings. Vertical openings can exist in the form of open stairways, conveyor openings, utility shafts, elevator shafts, and so on. These openings can affect the travel of fire, heat, and smoke.

(a) (b)

FIGURE 12.17.5 Truss Symbols (Courtesy of John B. Smith, Fire Sub-code Official and Fire Marshal (Retired), Raritan Township, New Jersey)

Horizontal Openings. Barriers to horizontal smoke and heat movement can exist in the form of fire walls, fire doors, smoke barriers, and so on. Attention should be given to the protection provided for horizontal openings. The types of fire doors provided and their method of closure should be noted.

Occupancy

The type of occupancy is important in establishing incident priorities and tactical operations. An awareness of a facility's operations and contents increases the fire department's ability to fight a fire in that facility effectively and safely.

Life safety considerations should be the first priority for pre-incident planning. Many factors can influence the number and location of people in industrial and commercial facilities: hours of operation, day of the week, time of year, and the physical layout of the facility all have an impact on the type of life safety concerns the fire fighters may be faced with during an incident.

The operations within a facility can be classified into several general categories, such as office, retail, manufacturing, warehouse, and so on. However, each occupancy has its own unique characteristics that should be considered during pre-incident planning. Office buildings may have extensive computer rooms or laboratory areas, retail facilities may have large storage areas, and manufacturing occupancies have many different types of specialized equipment, hazardous materials, and hazardous processes.

Material safety data sheets (MSDS) should be reviewed for information on hazardous materials. Locations of MSDS files and related data, as well as the facility personnel responsible for this information, should be included in the pre-incident plan. Such information may be provided in a lockbox and should be noted on the facility drawing.

Due to extensive chemical inventories at some facilities, consideration should be given to obtaining electronic files. Chemical inventories, material safety data sheets, and related information can be stored on compact discs, portable drives, or on the hard drive of laptop computers. For the latter, some locations may have network connection capabilities and will allow uploading or viewing of site information during emergencies.

Warehouses have a wide range of occupancy considerations: commodity classifications, storage height and configuration, controlled environments, and limited access areas. Special attention should be paid to warehouses storing large quantities of hazardous or toxic materials, flammable or combustible liquids, aerosols, roll paper, rubber tires, and plastics. All of these types of commodities have proved to be substantial fire protection challenges over the years.

The pre-incident plan should detail salvage needs, as well. Often the largest part of a loss within an industrial or commercial occupancy is due to smoke damage outside of the immediate fire area.

With all occupancies, a critical component of pre-incident planning is keeping up with changes. If the occupancy of an area changes, the adequacy of the existing sprinkler system design and available water supply must be reviewed. This is especially

important in warehouse occupancies. Changes in product commodity classification and storage height and configuration can be subtle and occur over a period of time. If the sprinkler system design or the water supply are inadequate for the type and arrangement of storage, fire control in the area of ignition is unlikely.

Protection

Knowledge of the fire protection systems in a building, of how these systems operate, and of what actions are necessary to supplement these systems are essential to pre-incident planning.

Automatic Sprinkler Systems. Sprinklers play a vital role in the protection of industrial and commercial facilities. Pre-incident planning must determine not only whether or not the building is sprinklered but also whether or not the sprinkler system (and its available water supply) is adequate for the occupancy of the building. This determination may be beyond the capabilities of the fire department personnel assigned to do pre-incident planning. Resources outside of the fire department must be utilized, if necessary, to make this determination. This is where a team approach to pre-incident planning with the facility's property insurance carrier can be crucial. The facility itself may also have personnel either locally or at the corporate level that have this information. A fire protection engineer might need to be consulted if the information cannot be determined elsewhere. If the sprinkler system is not adequately designed to meet the protection requirements of the occupancy in the building, the building is essentially an "unsprinklered" building.

Pre-incident planning should include obtaining the minimum sprinkler system flow and pressure requirements for each major area of the facility. Most sprinkler systems installed today are hydraulically designed systems, which should have a placard posted on the riser indicating the specific flow and pressure design characteristics of the system. A key point: although the placard indicates what the system was designed for, that design may not be what is needed to protect the current occupancy.

An important part of pre-incident planning for protection features is to anticipate potential sources of sprinkler system failure. These potential problems can be summarized into three major categories:

1. *Design deficiency.* The water supply feeding the sprinkler system or the sprinkler system itself is not properly designed for the occupancy. The original system design might not have been adequate, or a change to a more hazardous commodity or storage array might have resulted in an inadequate system. Even seemingly minor changes in some occupancies, such as warehouses, can compromise existing sprinkler protection.

2. *Impairment to the sprinkler system before a fire.* This generally occurs when a sprinkler system is actually shut off during new construction or building renovations, or when an obstruction, such as a rock, works its way into sprinkler piping and blocks the flow of water.

3. *Impairment to the sprinkler system during a fire.* The system is impaired when any sprinkler control valve is shut prematurely during a fire. This obviously turns off the water to the sprinklers. Well-meaning facility employees or fire fighters may shut the valve in order to reduce smoke or to control water damage; however, this action only prevents sprinklers from gaining control of a fire in its critical development stage. Even if the valve is turned on again later, the fire might have grown beyond the point where sprinklers can control it.

The location of sprinkler control valves, and the building areas they protect, must be determined during pre-incident planning. Facility management should post signs that will help fire fighters locate these valves upon arrival. Knowing where control valves are located is essential because checking to make sure they are open is one of the first actions the fire department should take when it arrives on scene. This action, combined with establishing the water supply, is key to ensuring that the designed sprinkler system is doing the job it was intended to do, that is, protect the building structure and its occupants, including fire fighters entering the building to complete final extinguishment.

The location of the fire department (threaded or quarter-turn) connections should be determined. The connections should be identified as to whether they feed the entire site, individual buildings, individual systems, or standpipes. Threads should be physically checked for compatibility with the fire department thread.

Water Supplies. The most common source of water for the sprinkler system is a public water supply. In some cases, if the volume of the public supply is adequate but the available pressure is too low, a booster pump is connected to the public supply to boost the system's pressure to the necessary level. Current water supply results should be available or tests should be conducted to obtain current information.

A static water source would usually require a fire pump to provide the necessary water volume and pressure to the system. Tanks, wells, reservoirs, and rivers are examples of these suction sources.

Where either booster pumps or fire pumps are provided, it is important to note their size, pressure settings, starting arrangement, and power and fuel supply. Fire fighters responding to an incident should check to make sure that required fire pumps have started, particularly when the fire pumps are the only adequate source of water.

Regardless of the source, a sprinkler system's water supply should be capable of meeting not only the sprinkler demand but also the demand for hose streams. The water source chosen should be carefully selected so that the primary water supply for the sprinkler system will not be reduced. The location and capacity of hydrants, both public and private, should be determined. Where hydrant systems and water mains are not available, alternative resources must be determined to deliver sufficient water to the fire scene.

Special Protection Systems. Some facilities may have other types of protection systems, such as dry chemical, foam, carbon dioxide, or other gaseous extinguishing systems. The presence of these systems should be noted, as well as the areas they protect. In most cases, these systems will be considered supplementary to automatic sprinkler systems.

Standpipes. The pre-incident plan should note if available standpipe systems are of the wet or dry type and the size of the hose discharge outlet. If pressure-reducing or other regulating valves are provided at the outlets, information on adjusting or removing these devices should be understood. Small hose stations may be provided and supplied from the sprinkler system. The pre-incident plan should note if these stations will be impaired if the sprinkler system is shut off in a particular area.

Fire Alarm System. The type of alarm system should be determined as to the type of detection provided (smoke, heat, waterflow) and the method of transmittal to the fire department. The presence of an alarm system does not eliminate the need for a follow-up telephone call from the facility confirming the nature and exact location of the alarm. Figure 12.17.6 shows fire fighters engaged in the pre-incident planning task of studying a building's layout to confirm the location of alarm devices.

Procedures should be established for facility management to notify the fire department when sprinkler systems, fire pumps, special extinguishing systems, or alarm systems are taken out of service, regardless of the duration. If alarms are out of service, a temporary notification procedure should be instituted. When the fire department is notified of an impairment, the pre-incident plan should be referred to and contingency actions considered.

Site Considerations

Access. Familiarity with local streets and roads in the area can provide the best access route to the location. Pre-incident planning can also provide alternative ways to reach the area should normal routes become unusable due to bridges with weight restrictions, narrow streets, road construction, flooding, drifting snow, railroad grade crossings, and so on. Alternative approaches for responding units also allow for the placement of additional apparatus. It is important to determine which units will respond and from what direction they will come. This information can help in the safety of apparatus approaching the same intersection from different directions. Assignments for fire companies based on probable order of arrival, including any neighboring companies that may respond on an automatic mutual aid, can increase the effectiveness of the fireground operation.

Security. Data regarding security service at the site should be obtained. The number of security personnel on duty, where they are normally located, areas of "restricted" access, and the presence of guard dogs are among the items that should be reviewed. The location of any lockboxes and their contents should also be noted. An emergency call list of facility staff for off-hours should be obtained.

Exposures. Exposures to the site can be both structural and nonstructural elements, such as neighboring buildings, fuel storage tanks, standing or tidal waters, vegetation, wooded areas, yard storage, and airport flight paths.

Utilities. All utilities for the site should be reviewed. The type of fuel, storage location, and quantities should be noted, along with the locations of the emergency shutoffs.

FIGURE 12.17.6 Team Checking the Location of Alarm Initiating Devices

The location of the entrance for electric power should be noted. Also the location of the nearest disconnecting means within the facility as well as the nearest one outside the facility should be determined. If an electric-driven fire or booster pump is provided, it is important to determine the reliability of the power supply, noting if power lines run through the facility and if an independent feed has been provided so that the pump will remain running even if the facility has been shut down.

The location of emergency generators should be noted, as well as what equipment is powered when normal power is lost. Special consideration is needed if the emergency generator also supplies power to an electric-driven fire or booster pump.

Heating, ventilation, and air-conditioning (HVAC) systems can contribute to the spread of smoke throughout a facility. The ability to engage or disengage these systems as needed and the location of automatic and manual controls for this equipment should be documented. Facility services, such as domestic water, compressed air, and steam, should also be reviewed.

Environment. Runoff of fire-fighting water contaminated with hazardous waste must be considered. Data should be gathered on the location of water drainage collection points, potable water supply locations, and any other potential exposures. The anticipated exposure should be measured against the expected fire scenario, based on the facility's other construction, occupancy, and protection features.

Outside Assistance

During many incidents, fire service personnel are assisted by other agencies or other industrial facilities capable of providing the support functions necessary to control the fire. Interagency and outside assistance can be vital to the outcome of emergency incidents.

If automatic response agreements result in a mutual-aid fire department arriving first on the scene, this department should be involved in the pre-incident planning process and should receive copies of the finished documentation.

Other assistance may include traffic control by police; the use of specialized resources, such as fire-fighting foam stored at another industrial facility; utility service control for electric, gas, and water systems; and other items, such as sand, barricades, and heavy construction equipment.

Because the amount and type of interagency assistance will vary in different areas, pre-incident plans should identify what is available and how to effectively request a timely response when it is needed.

SUMMARY

Pre-incident planning is a valuable tool for emergency responders to effectively control a fire or other emergency incident. Preparing for emergency incidents by visiting specific target hazards and recording pertinent information is required to successfully manage the incident and minimize the potential for life and property loss.

The pre-incident planning process requires a team effort in collecting information, developing the plan, and implementing the plan. Facility management, the municipal fire service or other emergency response organization, and the property insurance company are all key players. Sharing of information through open and frequent communication is an effective means to address the many facets of developing a pre-incident plan. Very few, if any, fire departments have the resources by themselves to effectively develop pre-incident plans for all types of industrial and commercial facilities within their jurisdiction. The varying nature and complexity of processes found in the industrial sector necessitate a collective approach to plan development.

Pre-incident plans must be viewed as living documents and be periodically updated as conditions warrant. A continuous improvement process should be implemented to assure emergency responders have a tool that is complete and current. Collecting pertinent data must be accomplished by site visits to the targeted facility. However, a pre-incident plan is not a fire safety inspection. Pre-incident planning assumes an emergency incident will occur. Commercially available software programs may be used to record data and develop the plan. Regardless of how the plan is developed, it should be remembered that the plan is intended for use by emergency responders. Therefore, it is necessary for the information to be clearly written, concise, and representative of current conditions.

Although there are many aspects to effectively managing an emergency incident, pre-incident planning is a critical component. Assuming that an incident will occur and preparing for it with a written plan is a proven means to minimize the potential for life and property loss.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on pre-incident planning for industrial and municipal emergency response discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13E, *Recommended Practice for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA *101®*, *Life Safety Code®*
NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 1142, *Standard on Water Supplies for Suburban and Rural Fire Fighting*
NFPA 1201, *Standard for Providing Emergency Services to the Public*
NFPA 1250, *Recommended Practice in Emergency Service Organization Risk Management*
NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs*
NFPA 1620, *Recommended Practice for Pre-Incident Planning*

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Chapter 18

Pre-Incident Planning for Emergency Response

Revised by
John Norman

Chapter Contents

Overview of the Pre-Incident Planning Process
"COAL WAS WEALTH" Process
Information Retrieval and Dissemination

Key Terms

computer-aided dispatch, exposure hazard, height and area, pre-incident planning, site visit, size-up, standard operating procedure, water supply (fire protection)

Pre-incident planning is a vital tool for all fire departments, municipal or industrial, career or volunteer, large or small. Information gathered during a pre-incident planning visit is a key component of a fire officer's size-up during an actual incident. Size-up can be described as an evaluation of problems and conditions that affect the likely outcome of a fire. Size-up is an information-gathering process, akin to gathering intelligence in a military campaign. Pre-incident planning is done to allow fire-fighting personnel to view conditions within a structure or site, evaluate what these conditions are likely to develop into in the event of an emergency, and then develop strategies for dealing with the potential problems. The great advantage of pre-incident planning is that it is done pre-incident. Three o'clock in the morning, with high winds and heavy rain lashing your face, and fire extending in all directions as you watch, is not the best time for gathering critical information.

NFPA has recognized the necessity for pre-incident planning by issuing a series of consensus standards beginning in 1993. In 1998 the first comprehensive pre-incident standard (NFPA 1620, *Recommended Practice for Pre-Incident Planning*) was adopted and published, with an updated edition following in 2003. This standard and its accompanying appendices present a very detailed examination of the topic and process, including several examples of preplanning forms and documents. NFPA 1620 should be reviewed carefully by any department initiating a pre-incident planning program or updating an existing one. The examples presented in this chapter illustrate one particular approach and the experiences of a fire-rescue department that has engaged in pre-incident planning for many decades.

For topics related directly to this chapter, see the following chapters in Section 12: Chapter 1, "Planning for Public Fire-Rescue Protection"; Chapter 3, "Needs Assessment and Hazard Analysis"; Chapter 8, "Effect of Building Construction and Fire Protection Systems on Fire Fighter Safety"; and Chapter 12, "Disaster Planning and Response Services." For information on calculating water supply requirements, see Section 15, Chapter 3, "Hydraulics for Fire Protection."

OVERVIEW OF THE PRE-INCIDENT PLANNING PROCESS

Prior to implementing a pre-incident planning program, fire department leadership must establish the priorities that it wants to cover in the program. In an ideal world, every structure and site in a department's area of responsibility would be subject to pre-incident planning (PIP). This is a very attainable goal in some organizations, such as suburban towns consisting primarily of large segments of nearly identical tract housing, whereas it may be totally unrealistic in other areas that consist of great numbers of large complex and different buildings. In the case of the former, the PIP may have occurred in the form of past responses that have developed into standard

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operating procedures or guidelines (SOP/SOG). Departments facing the latter situation have a tendency to preplan only "target hazards" and let SOPs or SOGs take care of the remaining structures. That is fine, as long as the fire understands that and remains cooperative, fitting into the framework of "standard" incidents. Too often though, nonstandard situations develop, and that is where PIP pays dividends. I argue for developing pre-incident plans (Figure 12.18.1) for all locations in your response area.

The Size-Up

To be effective, pre-incident planning should address the information that fire-fighting personnel, particularly the incident commander, will need in order to develop their strategy for dealing with potential incidents. Most pre-incident planning focuses on aspects of the size-up that can be known beforehand and that are likely to remain static until an event occurs, such as building construction or occupancy loads. Pre-incident planning should also be flexible enough to take into consideration temporary situations that pose unusual risks or hazards, such as a disruption to the fire protection water supplies or introduction of a one-time flammable process.

A fire officer's size-up begins at the moment the alarm is received, and it continues until the emergency is under control. Pre-incident planning can give much-needed physical information, such as the size and construction of the building or site. Other parts of a fire officer's size-up however, such as weather conditions, location and extent of the fire, and time of day of the event, cannot be completed until the emergency begins. Pre-incident planning should focus on items that are likely to be difficult to obtain at the time of an incident, such as interconnections between buildings that are not visible from the street.

Pre-Incident Site Visits

Larger departments probably have greater resources than smaller departments, but every department has constraints on the amount of resources that can be devoted to PIP. This is one reason why many departments concentrate their PIP on the target hazards. The collection of data on buildings takes time. The fact is, though, that many buildings have been standing in our communities for 50 or 100 years, just waiting for us to come to preplan them. What valid excuse is there for not having done so if a serious mishap occurs that could have been detected by a pre-incident visit sometime during the previous 100 years?

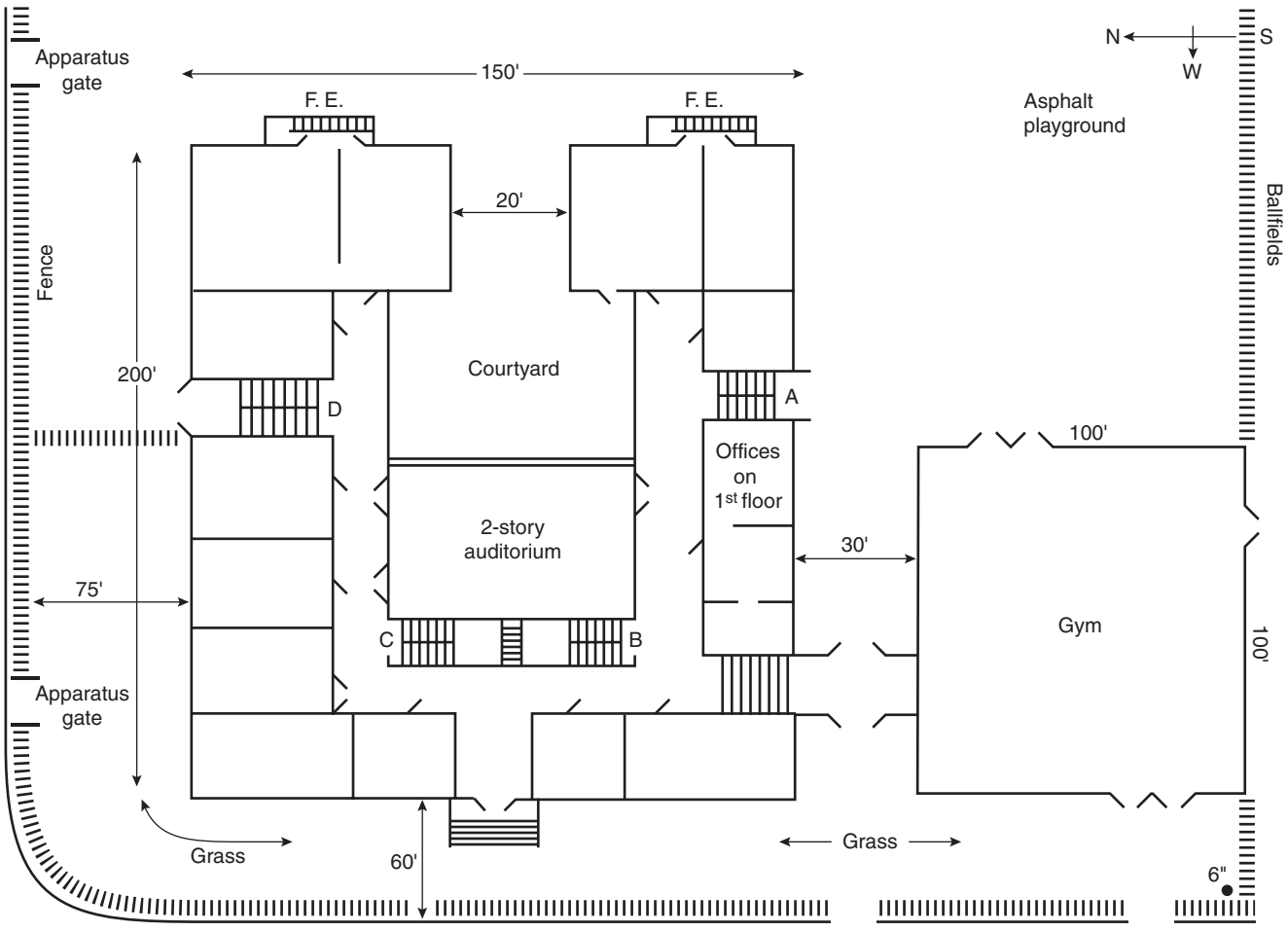

FIGURE 12.18.1 PIP Sketch of a Nonindustrial Facility

When sending fire fighters into a site for a pre-incident planning visit, tell them to approach the site as if they were going to be returning there for a serious fire 15 minutes after they conclude. They will want to examine the location for what could kill them and remember the hazards, so they can avoid them if they were to have a fire. Of course, not all fire fighters remember everything they saw in a building a year or two, or five years prior. That is the point of documenting conditions (Figure 12.18.2) and preparing a written plan or training program that can be reviewed periodically to refresh the memories of fire personnel and can also be used at the time of an actual incident to augment the incident commander's size-up as he develops his strategy and implements tactics.

Identifying Hazards and Obstacles

Pre-incident planning is not just for structural fire fighting. An all-hazards approach is as applicable to PIP as it is to other aspects of emergency services operations. Some nonfire PIP is actually mandated by federal law. For example, OSHA's standard on confined space operations requires that the rescue agency responsible for a premises be permitted access to representative spaces annually to practice rescue procedures. Clearly, this is intended to foster pre-incident familiarization with the space and develop procedures for dealing with potential incidents—that is pre-incident planning.[1]

Outlining and Analyzing Necessary Information

After establishing what types of hazards or occupancies are to be included in the program, the next step in the PIP process is to determine what information will be needed during the data collection phase. This may vary depending on the occupancy of a particular location, but should be geared to gathering the information the incident commander will need to know in order to handle a working structural fire or other emergency. Again, efforts should focus on those aspects that cannot be readily determined from the street upon arrival and create nonstandard situations for which an SOP is not suitable.

Developing a Standard Format. Once the outline of the desired information is determined, a standard format must be developed to capture the information and process it for future use. This can vary from a simple written preplan form to an electronic database that shows details such as floor plans, location of exits and/or hazards, and other details. One tool that has proven to be invaluable is a digital camera. A series of images documenting details about a structure (Figure 12.18.3) can save many miles of travel to and through a site and is extremely valuable for refresher training on a site. It would be helpful if the same person, or a small team of people, collected all the PIP data, since this would produce consistency in what is collected and how it is analyzed, but in larger jurisdictions this may be impractical. (In Phoenix, Arizona, a fire protection engineer attached to the special hazards unit is used in the data collection and formatting phase, leading to a high degree of consistency and expertise.)

Analyzing Information About a Site. Once the site has been visited and the basic data collected, a rational analysis of the site and the hazards present must be conducted, and a plan is created for dealing with the problems that have been detected. The solutions may take many different forms, from taking a

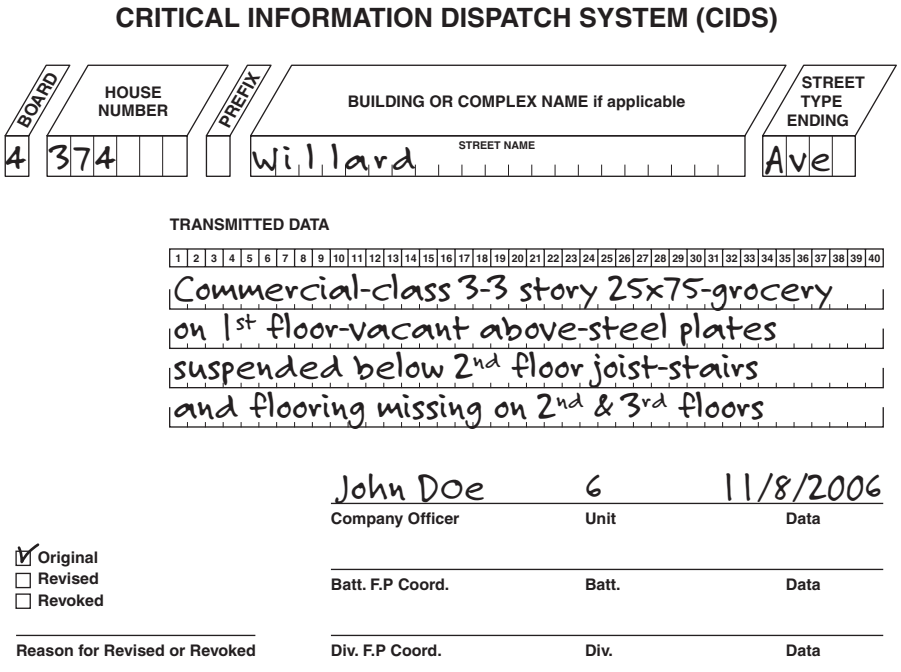

FIGURE 12.18.2 Critical Information Dispatch System Output for PIP

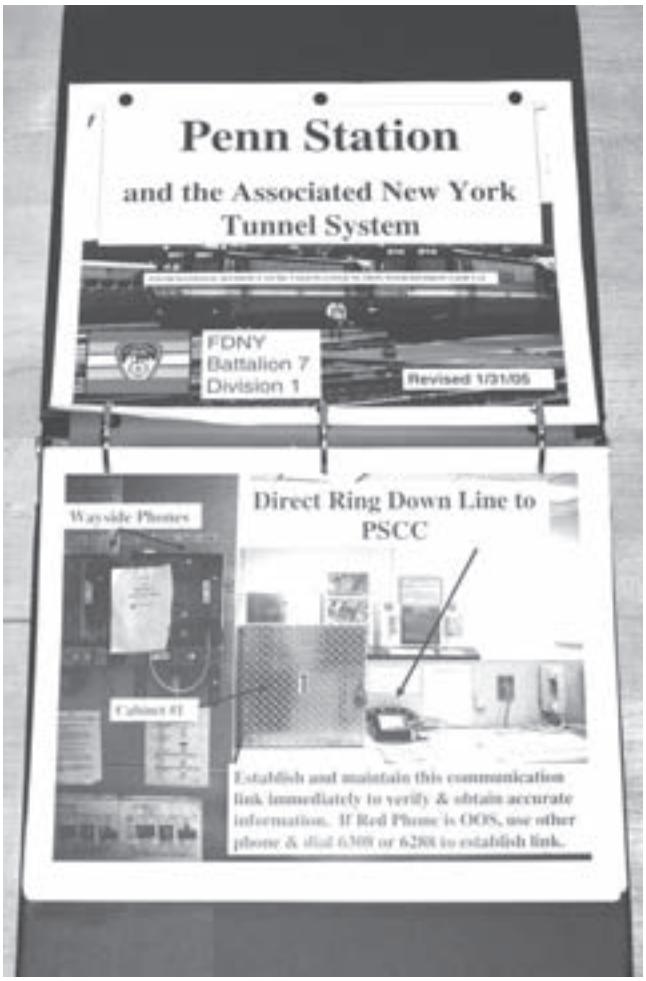

FIGURE 12.18.3 Digital Photos for Use in Pre-Incident Planning Sessions

strictly defensive posture in the event of serious fire exposing lightweight construction elements or some particularly hazardous chemical storage, to arranging for an immediate response of additional resources on the first report of an emergency, such as having an additional ladder company assigned for reports of a fire in a school with handicapped children as students. At some sites, much of the planning, such as determining critical openings in firewalls that will be reinforced with hose streams in the event of a fire, can take place during the site visit. Larger, complex sites may require several visits to complete. It may be necessary to do additional research on chemical hazards, for example. This type of research can better be performed in an office setting with suitable resources at hand. Then the fire fighters can return to the site once a basic plan is established to analyze it in place.

Selecting Personnel to Develop the Plan. The selection of personnel for developing the pre-incident plan is crucial. In many jurisdictions, an experienced chief officer is assigned this task. In some cases, departments have hired private consultants to do much of the basic information gathering. (An excellent example of the work done by one such group is the high-rise building data sheets developed by the Massey Disaster Planning Group. These multipage documents provide a written text-based summary of building features as well as visual illustrations of such elements as floor plans, elevator and stairwell arrangements, HVAC and standpipe riser diagrams, and other critical factors that are essential to the incident commander's size-up.

Avoid the temptation of assigning the task of developing the pre-incident plan to company level officers or members of the Bureau of Fire Prevention (or Special Hazards for that matter). Although they can be extremely helpful in collecting and interpreting the raw site data, the personnel who are actually responsible for fireground command should make all the strategic decisions when formulating the action plan, since they will be deciding what will actually be implemented. It is essential as well that, if a department operates as different shifts, the appropriate commanders of each shift reach a consensus on actions to be taken to avoid conflicting messages or actions.

Using the Plan

After the plan has been developed, it should not be set on the shelf as personnel move on to the next task. The job is not complete until all members who may play a role in the implementation have been thoroughly educated on it and given the opportunity to demonstrate their proficiency. That may require periodic visits to the site for drills or exercises and/or tabletop exercises using the photos and plans developed during prior site visits. These visits should occur at least annually on all affected shifts. Some structures may require more frequent visits due to changing conditions.

The general picture of pre-incident planning that was outlined in the preceding sections can be summarized as follows:

1. Determine priorities to address—that is, life hazards, firefighter traps, and critical infrastructure.
2. Decide what data is needed.
3. Develop a standardized information capture method, preplan form, and so forth.
4. Train collectors to gather information.
5. Perform visits and collect data.
6. Develop strategic and tactical plans.
7. Distribute copies to all potential users.
8. Train users on objectives.
9. Review the plan periodically (annually at minimum).
10. Revise as needed, redistribute, and retrain.

"COAL WAS WEALTH" PROCESS

When deciding what information to include in the plan, it is helpful to consider what will be required in the incident commander's size-up. New York City fire officers use a 13 point outline of factors when conducting their size-up or pre-incident planning. This process covers the majority of fireground considerations and is summarized in the acronym "COAL WAS WEALTH."[2]

The COAL WAS WEALTH process includes the following points:

C Construction
O Occupancy
A Apparatus and staffing
L Life hazard

W Water supply
A Auxiliary appliances
S Street conditions/special matters

W Weather
E Exposures
A Area and height
L Location and extent of fire
T Time
H Hazardous materials

The elements of the COAL WAS WEALTH process are often arranged in order of priority, broken down as shown in the following paragraphs.

Life Hazard

Life hazard is produced by a combination of several other size-up elements: time of day, the occupancy, location, and extent of fire all combine to endanger victims. Pre-incident planning can and should identify the occupancy, especially when there is more to the building than meets the eye. Commercial buildings that are partially occupied with residential areas are prime locations for preplanning, since responding fire units would normally not conduct an aggressive search for life at a late-night fire in what is perceived to be a commercial building. The preplan information gathered here could mean the difference between life and death for sleeping tenants in this situation. Many older cities have seen a renaissance of some of their older commercial neighborhoods as residential occupants moved into vacant manufacturing spaces in loft-type buildings. In New York City, this practice was originally begun by people in the artistic community, who valued the high ceilings and large floor spaces of the former commercial areas for artistic projects such as sculpting and painting. These urban pioneers were known as "artists in residence," and the commercial buildings that had some residential spaces were known as A.I.R. buildings. An extensive campaign was conducted by the fire department to identify these buildings, which then were required to be marked with a prescribed sign to alert responding fire fighters to the A.I.R. Later, when a computer-aided dispatch system came into use, an entry for A.I.R. buildings also served to alert fire fighters to the life hazard in the building they were responding to. Both systems represent pre-incident planning at work.

Occupancy

The occupancy of a structure has many impacts on the fire officers' strategy. One major impact, as just discussed, is the life hazard, which may vary with the time of day. Schools, for example, have a life hazard that varies greatly with the time of day. Hospitals and apartment houses, on the other hand, have a high life hazard around the clock, whereas storage warehouses and similar occupancies have a uniformly low life hazard regardless of time of day. The occupancy should serve to determine the level of risk to fire fighters that will be tolerated when developing the strategy. Where the occupancy poses great threats to fire-fighting personnel, and where the civilian life hazard is minimal, a defensive strategy should be developed.

The occupancy has a great effect on the fire load within the structure, which will dictate water supply requirements, and affect other aspects of the incident commander's strategy. Manufacturing and storage occupancies typically have large, open floor areas that may translate into fires that are beyond the scope of handline control. Large open floor spaces should alert fire fighters to look for truss construction, a collapse danger. Another aspect of occupancy is the presence of hazardous materials that may be a required part of the ongoing business conducted in a facility, such as cyanides in a plating plant. Hazards in other locations are not as obvious however, and fire fighters may have to look deeper for hazards, such as in a freight warehouse where manufacturing and use of dangerous goods does not occur (other than the use of propane for forklifts or similar items) but which can be locations for transshipping nearly any dangerous commodity produced elsewhere. The handling of hazardous materials should be noted on pre-incident planning forms, citing quantities stored, location of storage, and any special concerns such as incompatibility with water or other materials, or the need for special extinguishing agents.

Time

Pre-incident planning may not seem to have a great deal to do with time, since we cannot predict exactly when a fire will strike a given structure, but there are several time-related concerns that directly impact fire-fighting operations, including time of day, time of year, and perhaps most important, the elapsed time from when the fire began. The time of day may prompt the response of an additional ladder truck to a school with handicapped children, but only during school hours. PIP should account for seasonal changes that affect operations, such as winter plans that identify additional resources for snow removal or hydrant thawing or additional brush fire units to be staged during high fire danger periods.

Elapsed burn time is a crucial indicator of the likelihood of structural collapse. Structural collapse is very difficult to predict, due to the many variables that can be involved: the type of construction, fire loading, length of burn before the alarm is transmitted, alterations to the original structural design—either through routine structural alterations or deterioration from exposure to weather or industrial processes. It is important to remember that long before the alarm sounds, the structural engineer who designed the building set a time limit for the effectiveness of fire-fighter actions. A crucial element to understand is that the time frame starts when the fire reaches flashover and begins to attack the structural elements. The elapsed time from flashover is one of the primary indicators of an impending collapse. Knowing the class of construction is an important component of this evaluation, as it is an indicator of how long the building will resist structural failure. Pre-incident plans should make it a high priority to identify structures that will likely face collapse

dangers, especially those that are vulnerable to relatively short burn times.

Construction

A critical factor that must be included in any pre-incident plan is the building's construction. The first concern is the ability of a building to resist collapse when attacked by fire. It is not advisable to rely strictly on labels given to building assemblies such as a two-hour rated floor or wall. There are many factors that affect how long it will take a given structural element to fail, including the fire loading of the area that exposes the element, damage that has occurred to it from explosions, prior fires, weather damage, vandalism, and so on. It is good to recall that one of the "three-hour rated" World Trade Center towers collapsed in under one hour of fire exposure.[3]

Construction has other implications, including the amount of compartmentation present, which can either promote or thwart the spread of fire. Large, open floor spaces provide an opportunity for fire to spread readily throughout the exposed area and are indicators of the presence of truss construction.

A third factor is the degree to which the building itself adds to the fire load. With wood construction, the building itself may constitute a heavy fire load. Directly related to a building's combustible construction is the number of hidden voids that fire can travel in. Voids such as cocklofts, pipe chases, and channel-rail voids are responsible for the destruction by fire of more buildings than any other construction-related factor.

A comprehensive listing of all buildings in your area that are built using lightweight techniques is critical to fire-fighter survival, along with a clear department policy stating that a fire that has reached the flashover stage in one of these structures will only be fought from defensive positions until the fire has been knocked down and ventilation and lighting conditions permit a careful examination of the structural elements. This information should be recorded in a computer-aided dispatching system (CADS) message. The idea behind pre-incident planning is to allow rational decisions to be made based on the information that has been gathered during the pre-incident planning visit. Decide what you want your people to do, then write it down for them as policy, and let them know about it!

For a further discussion of the impact of building construction on fire personnel, see Section 12, Chapter 8, "Effect of Building Construction and Fire Protection Systems on Fire Fighter Safety."

Area and Height

The area and height of a given building are two obvious concerns during size-up, since they indicate the maximum potential fire area. Sometimes, however, the size of a structure is deceptive when viewed from the street. This may be because the building is built on a sloping grade, which may cause fire personnel on one side to view the structure as one-storied whereas personnel on another side see it as two-storied. A similar situation contributed to the deaths of four fire fighters at a fire in Seattle in 1995. Pre-incident planning could have established the actual size and facilitated communications during the event, as personnel on different sides of the structure refer to the same area.

The height of the building has obvious effects on the need for aerial devices. PIP can build into a department's protocols the need for calling such aerial devices, especially when they are not normally part of a routine response for that type of structure.

The area of a building is also an important item for PIP. Look for buildings that will require modifications to the standard attack, especially those buildings that exceed the reach of preconnected attack lines. It may be necessary to create a separate hose bed for larger structures, in order to provide a sufficient length attack line to cover all areas. For the most part, the frontage of a building (width and depth) visible from the street indicates the area of the structure, but the obvious is not always correct. The presence of interconnecting openings between what appears to be two separate and distinct buildings effectively combine the structures into one large potential fire area. Such an interconnection should be prominently displayed in the pre-incident plan that is developed for the structure, including a notation of the presence and condition of any opening protective devices, such as fire doors or deluge sprinkler systems.

Location and Extent of Fire

It might be impossible to determine the location and extent of the fire until after a fire starts, but PIP can often identify likely locations for a fire to begin and also give an idea of the likely extent of fire, based on an analysis of the hazards present. Certain process hazards, such as paint spraying, are notorious points of ignition, as are occupancies such as restaurant kitchens, especially those that typically deep-fry foods. Pre-incident planning should indicate the location of such hazardous areas within a facility, and also indicate the proximity to features such as fire barriers and stairwells that may be threatened.

The location of the fire will influence the tactics used to control it. The lower the fire is in a building, the more serious the hazard, since more of the building is exposed to rapid vertical fire spread. Pre-incident plans should focus on identifying any vertical arteries such as pipe and elevator shafts, as well as open stairwells that will require hose-line protection or physical examination.

Some potential fire locations create special fire-fighting problems, and as such, should warrant particular attention during PIP. The top floor of most Type III (ordinary brick and wood-joist) and Type V (frame) structures has some type of void space above the top floor. Known alternately as a cockloft or attic, this void space creates access problems for fire fighting and allows rapid fire spread over the entire top floor in many cases. Pre-incident plans should note the presence of such voids, as well as the location of any access points or fire divisions that may be present.

Exposures

Exposure hazards are another factor that is relatively easy to determine beforehand but which might be difficult to determine at the time of an emergency. The easiest way is often to view the surroundings from the roof of the structure being preplanned. Any structure that is separated from the building in question by

less than the height of the building being preplanned can be in immediate danger, due to the potential for collapse of the walls. Other factors to consider are the construction of the walls of both buildings and the number and size of openings (especially windows) in the opposing walls. Frame walls, especially those covered in combustible materials such as asphalt and vinyl siding, should be noted, and plans should be developed as part of the PIP for protecting these exposed walls with hose streams. For buildings that have exposure protection systems in place, such as exposure sprinklers (exterior, often open deluge heads, located at the eave line), those locations and controls should be noted and operating procedures developed. The examination of exposures should include all six sides of the fire area—front and rear, left and right, top and bottom. The risk to taller nearby structures is especially important to preplan for.

Apparatus and Staffing

The items discovered during PIP will assist in determining what resources are required. The pre-incident planning process should have pointed out the need for specific types of apparatus, such as an aerial device to reach areas above grade or to provide an elevated stream for fire attack or exposure protection. Other items that should be part of PIP are the length of supply lines required to reach a source of water supply that is adequate for the hazard. The pre-incident plan should indicate the number of engine companies that will be required to establish a relay if that is required, and many plans indicate items such as the location that each unit should take in order to speed the establishment of such an operation.

Pre-incident plans may have to be created to deal with contingencies that affect the staffing required at an incident. It is common practice in cold weather climates to make provisions for additional staffing during periods of peak snowfall. Similarly, agencies having large wildland areas or urban-wildland interface often place additional staffing on units or place additional units in service during peak wildfire danger periods.

Water Supply

Water supply is a key element of pre-incident planning. Water supply requirements depend on the fire load and the volume or area involved. There are several methods and formulas to determine how much water is required for a given fire area. In the case of larger facilities, in many areas, the insurance services office (ISO) may have already performed a detailed analysis of the needed fire flow. Contact the area ISO office for assistance. For PIP purposes, in most structures it is usually sufficient to utilize some variation of the Iowa State University fire flow formula to determine how much water is required. Briefly stated, the needed fire flow can be estimated by calculating the area of the structure and multiplying this figure by a factor that depends on the fire loading and construction involved. This factor ranges from 14 gpm/100 ft^2 (53.2 Lpm/9 m^2) for lightly loaded areas such as residential rooms and spaces in noncombustible buildings, to 30 gpm/100 ft^2 (114 Lpm/9 m^2) or more for locations with heavy fire loads, such as paint storage. More water is required if the building itself is of frame construction or if exposures may be threatened and require protection. As an example, a one-story, 100 ft by 100 ft (30.3 m by 30.3 m), ordinary construction furniture showroom should have at least 3000 gpm (11,400 Lpm) available to satisfy basic needed fire flow.

After determining the needed fire flow, PIP for water supply involves flow testing the water sources around the hazard, including such alternative supplies as drafting sites, relay operations, and tanker shuttles. Remember to include sources such as nearby private fire pumps taking suction from supplies separate from the municipal system.

The needed fire flow will help to determine apparatus and manpower requirements. Pre-incident planning for providing the needed fire flow involves how the water will be moved to the incident site. Arrange for sufficient numbers of pumpers, with the appropriate size and length of supply lines, to move the water from the source to the incident scene. Also consider the number and type of discharge appliances that will be required to apply the needed fire flow at the most efficient location(s). Often, a combination of handlines, fixed or portable master streams, and aerial streams will be required.

For further information on calculating water supply requirements, see Section 15, Chapter 3, "Hydraulics for Fire Protection."

Auxiliary Appliances

The presence and serviceability of auxiliary fire protection systems is an item that deserves high priority in any pre-incident plan. Sprinkler systems, standpipe systems, foam systems at bulk oil storage plants, halogenated agents, CO^2, and dry-chemical systems for special hazards such as restaurant grease ducts and spray paint booths, are all key components of a structure's fire defenses. Auxiliary appliances that are out-of-service require adjustments to the strategic plan and must be prominently displayed in any pre-incident plan. Such a condition, even if only temporary, might require further action, such as temporarily vacating the structure's occupancy, or placing fire guard personnel on duty to provide for prompt detection and suppression in lieu of the out-of-service systems. Such planned activities should be documented in the fire department's plan for the specific facility or in a standard procedure or guideline for such outages.

Pre-incident planning should identify what auxiliary appliances are present, what their operational status is, the location and method of operating controls, and what potential workarounds exist for partial service interruptions. For example, both standpipe systems and sprinkler systems are routinely supplied through a fire department siamese connection. In the event of an obstruction or failure of the siamese, is it possible to supply the system through another connection? Stretching a supply line to a first- or second-floor hose outlet of a standpipe system is one example of such a workaround. With a sprinkler system, a similar arrangement may be possible, with assistance of building engineering personnel. Document all such workarounds in detail in a section of the pre-incident plan dedicated to auxiliary appliances.

Weather

Weather conditions may not seem to be something that can be preplanned, but many specific policies can be pre-planned for common events. Large-scale, high-impact events, such as

hurricanes, blizzards, tornadoes, and so on, should each have in-depth plans for continuity of operations in communities that are subject to such events. These plans may require suspension of services during the peak of the storm, relocation of apparatus and personnel out of areas that are subject to dangerous conditions such as flooding, or added staffing prior to the arrival of the most severe conditions. The plan should be available to all personnel beforehand, so they can anticipate what may be asked of them and make arrangements to be available when called on. The fact is that these unexpected events sometimes occur when those who are most familiar with the plan are not available, and it falls on those less familiar with the planning for implementation. It helps to have seen the plan before being called on to deal with it.

Weather can have serious impacts on fire-fighting efforts. High temperature and high humidity rapidly fatigue fire fighters. Freezing temperatures hamper fire-fighting operations by causing ice accumulations and slipping hazards, and fire fighters must use caution to avoid injury. Severe cold can cause mechanical failures, frozen hydrants and freezing of other water supplies. High winds wreak havoc on fire attack, fanning flames into blowtorch-like proportions. All of these events should figure prominently into plans for dealing with their consequences and should be part of a fire department's library of contingency pre-incident plans.

Street Conditions/Special Matters

Street conditions are another item that at first glance appear to have little impact on pre-incident planning, but in fact, many factors that result from difficult street conditions can and should be dealt with in the PIP stage. Construction trenches for water, sewer, or gas mains may separate the apparatus from the fire building, preventing fire fighters from reaching the front of the building. In that situation, the aerial apparatus should enter the block, since it can reach over a trench. Meanwhile the engine company should position at the nearest intersection and hand-stretch a hose line along the sidewalk. This procedure is likely to differ drastically from most departments' normal SOP and might require modifications to apparatus hose loads, but it is a good opportunity to incorporate pre-incident planning into tactical operations.

Similarly, deep snow and ice can bury hydrants and block streets altogether. Pumpers should remain out on the cleared main artery and hand-stretch lines into the snow-clogged side streets. This is very time-consuming and may require additional personnel, an issue that should be addressed in the winter weather contingency preplan.

Another situation that requires pre-incident planning is a work stoppage of mass transit agencies. Bus and subway strikes add tremendous volumes of traffic to urban arteries and can result in emergency vehicles being gridlocked and therefore unable to reach the scene of an emergency. Planning with traffic management and law enforcement personnel should identify emergency routes that will be kept open for emergency vehicles. Again, it may be necessary to hand stretch hose greater distances than routinely envisioned. Be alert for such *temporary* situations and have a plan, and the necessary hosebed arrangements, to deal with them.

Hazardous Materials

The presence of hazardous materials is one of the most important factors to determine in any pre-incident plan. Hazardous materials pose problems for fire fighters, ranging from health hazards to accelerated fire extension. The presence of poisons or explosives could prompt the fire department to take a strictly defensive posture and not conduct any fire-fighting operations. Information about specific hazards should be researched with an emphasis on actions to be taken in the event that fire or other conditions threaten the material. Details of the name(s) and properties of the materials, quantities and locations of the hazardous materials, as well as recommended procedures for dealing with emergencies should be entered prominently into the pre-incident plan. Specialized extinguishing agents can be located and arrangements made for their use in the event of an emergency, including working out financial arrangements for paying for the agent if it is not normally part of the fire departments arsenal.

INFORMATION RETRIEVAL AND DISSEMINATION

Pre-incident planning is a multistep process that involves gathering information, analyzing that information, developing an action plan, and then making that plan available to those who need it during an emergency. This last step, information dissemination, can be as complicated as the other parts, and requires as much forethought to accomplish well.

Three-Ring Binders

The simplest pre-incident plan process involves written documents stored in three-ring binders kept on responding apparatus (Figure 12.18.4). These plans, as others, should be the subject of training sessions to ensure that all responding personnel have at least a basic awareness that such plans exists and knowledge of the more important elements of the specific plans. This training must be ongoing to be effective. One of the biggest drawbacks of the three-ring binder is the "crying wolf" syndrome that develops when it is necessary to manually check every address that you respond to. Another drawback of the three-ring binders is the size of the plans themselves. A typical high-rise building plan, for example, would require a data sheet with building personnel contact information; a site plan; riser diagrams for stairs, elevators, and standpipes; heating, ventilating and air-conditioning (HVAC) zone and riser diagrams; floor plans for typical floors; and a building profile (side view) showing any setbacks where the building changes dimensions. (A setback occurs where a building's floor plan is smaller than the floors below that point, creating a roof area outside the smaller floor. This roof area may be useful to allow fire fighters to work on the outside of the building.) Separate sheets should be provided for each hazardous material used or stored on site. Very quickly, a set of pre-incident plans for an urban response area can take up several large binders, complicating retrieval efforts in moving apparatus. Paper plans should either be laminated or stored in sealed plastic sheet protectors to protect them from the weather

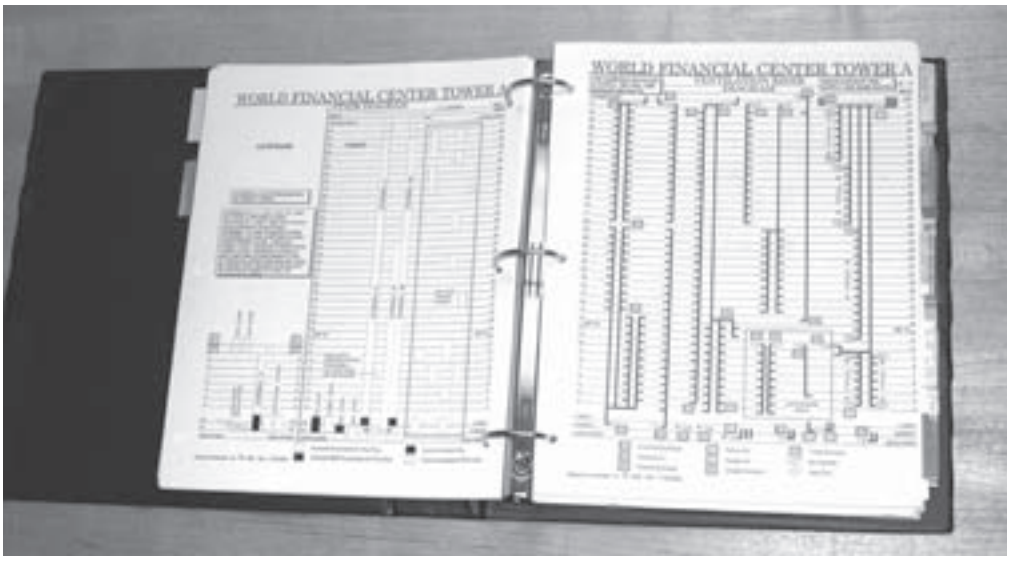

FIGURE 12.18.4 Three-Ring Binders Used to Present Pre-Incident Plan Information

and also allow use of a marker or grease pencil for writing or drawing on them.

In the past, some departments used microfiche cards to provide field commanders with a complete set of pre-incident plans for large numbers of buildings. This system was extremely cumbersome to use due to the need for multiple cards of information that had to be sorted through, as well as the need for a special microfiche reader. An additional drawback was the length of time needed to produce the microfiche cards and the expense of keeping them current.

CADS

When properly used, a computer-aided dispatching system (CADS) is by far the most effective tool for recalling PIP information. CADS surpasses the human memory and the three-ring binder as well in its ability to store and promptly retrieve information. Whereas fire personnel usually know about the most obvious and deadly hazards, other hazards may escape their initial attention. In these situations, a CADS-generated reminder could provide the crucial warning, averting what might otherwise become a fatal encounter.

Data Entry and Retrieval. PIP information should be recalled automatically whenever an alarm is transmitted from a building address that is on file. A CADS systems saves time and effort in its computer searches by only displaying hazard information when there is data on file for the address in question. Of course, any computer-generated information is only as good as the information that was entered. This means that field units must have some quick and simple method of reporting the conditions that they encounter. It also means that the information must be kept up-to-date. For this reason, any occupancy that is subject to CADS hazard display should be inspected at least annually and the information verified.

Responsibilities of Property Owners. Computers have the ability to store large quantities of complex information and display that information in detail. One difficulty is inputting all that information. In many cities, as the CADS systems have been developed or expanded, data entry issues have been resolved by requiring the property owners of certain "target hazards" such as high rise buildings, to provide the information in a standardized electronic format. Often this can be accomplished using a commonly available electronic program that architectural or engineering firms use. This reduces the amount of work required by the municipality and provides a rapid means of updating the system as new structures are erected or as major renovations occur.

Transmission of PIP Messages. Computer-generated PIP messages can be transmitted to field units by any of several means. A dispatcher can read a message to responding units as part of an alert message, highlighting the fact that there is critical information available, or the message can be displayed on a video display terminal, teletyped to each unit, or repeated over radio channels about 1 minute after the initial alarm. The recommended practice is to teletype the alert message (which gives the field unit a hard copy to refer to,) display the information on a mobile data terminal aboard the apparatus, and also broadcast the message over the radio after the units are on the road. These methods serve to present the information to anyone who may have overlooked it, as well as to verify the listing after the fire fighters have had a moment to consider it. The responders can then pull up the detailed plans for each structure and review the individual hazards they have highlighted in advance.

Data Storage. Advances in information storage and retrieval systems have made it feasible to store large amounts of data on laptop or notebook-size computers. In conjunction with wireless communications devices, access to mainframe databases is

FIGURE 12.18.5 Wireless Data Transmission for Field Access to Mainframe Capabilities

possible, placing extremely detailed pre-incident planning information at the incident commander's fingertips (Figure 12.18.5). In the near future, it will be possible for an incident commander to be in touch with multiple sites, providing real-time modeling of events such as a chemical release. Such information, in conjunction with information previously gathered and evaluated during the pre-incident planning stage, will increase the safety of all persons affected by an event. Security of such information must be considered in the age of potential terrorist threats, but this should not stop an emergency response organization from pursuing the gathering and use of as much vital information as is available.

SUMMARY

The pre-incident planning process is a critical component of an incident commander's size-up and decision making process. The failure to gather information about a hazard that could claim the life of a responder and is available beforehand borders on reckless behavior. Emergency responders owe it to themselves, their families, and their communities to avail themselves of as much information as possible about the situations they may face. The specifics of what type of information to gather for each type of structure or occupancy may vary. A military unit would never plan an operation without attempting to gain intelligence about the opposing force. Neither should our emergency responders.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on pre-incident planning processes discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following document.)*

NFPA 1620, *Recommended Practice for Pre-Incident Planning*

Chapter 19

Community Risk Reduction

Revised by
Edward Kirtley

Chapter Contents

Components and Fundamentals of a Community Risk Reduction Initiative
The Five "E"s
Role of Community Engagement
Role of Leadership in Community Risk Reduction

Key Terms

Learn Not to Burn®, mitigation strategy, NFPA Champion model, public fire and life safety education, risk reduction, *Risk Watch*®, stakeholder

The last decade has seen a significant change in the scope of mission for most fire departments in the United States and Canada, as well as many other nations around the world. It is difficult to find a fire department today that strictly deals with fire suppression. Rather, fire departments have expanded their mission to reflect the changes in society and historical events such as 9/11. Today most fire departments are involved in some level of prehospital medical care varying from first response to advanced life support transport. Some departments, such as the Phoenix Fire Department, are working with local public health providers to assist with preventive health care.

Other programs have grown significantly. Following the Oklahoma City bombing, the first attack on the World Trade Centers, and the 9/11 attacks, many departments have developed technical rescue programs to deal with events involving confined space rescue, whitewater rescue, and high-angle rescue. Also, many fire departments are becoming actively involved in disaster preparedness and response. Hurricane Katrina emphasized the need for the fire department to be an active participant in a community's preparedness for natural disasters.

These changes also extend into the area of prevention. Once a program dedicated to only preventing fires, prevention programs now address such issues as preventing childhood injuries, reducing the impact from disasters, and so on. This expansion of the prevention mission mirrors the growth of other fire department responsibilities. In short, fire departments are now active participants in reducing and mitigating many various risks in the community. This "all-risk" mission is having an impact on how fire departments do business in the new millennium. Specifically, the all-risk mission has resulted in departments utilizing a community-based comprehensive strategy to reduce the highest priority risks faced by the community.

This new all-risk approach to community risk reduction is taken from the approach successfully used by public health agencies for decades. This multifaceted approach builds on the traditional three "E"s of prevention—education, engineering, and enforcement—to include *emergency response* and *economic incentives.* The original three "E"s were first noted in President Harry Truman's 1947 Conference on Fire Prevention. The addition of the two latter "E"s specifically reflects the role of emergency response in risk reduction, something that was previously considered part of prevention. Collectively the five "E"s are known as *mitigation strategies.*

Another significant change in strategy is the active involvement of the community in identifying the risks and participating in the risk reduction process. Again, this strategy is frequently used by public health agencies, especially when working with target groups that are at high risk from illness and injury. With this change fire departments may no longer stay in the shadows and be the silent heroes. The local fire department must become actively engaged in the community, including high-risk groups and neighborhoods that are hard to reach and engage. It is important to look at each of these components of community risk reduction.

See also Section 1, Chapter 1, "Challenges to Safety in the Built Environment"; Section 5, Chapter 3, "Disaster Preparedness Education"; and Section 12, Chapter 12, "Disaster Planning and Response Services."

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COMPONENTS AND FUNDAMENTALS OF A COMMUNITY RISK REDUCTION INITIATIVE

Components

Two major components of a community risk reduction program are use of the five "E"s and engaging the community. The first component, using the five "E"s, is part of a comprehensive approach to reduce the chosen risks. It should be noted that there are numerous risk reduction planning processes that can be employed by a community to determine the leading risk(s) to be addressed. Many are variations of the traditional five-step planning process introduced by the U.S. Fire Administration 30 years ago. For this introduction to community risk reduction the planning process will not be discussed.

The second component of community risk reduction is engaging the community, especially the groups that are mostly likely to be negatively impacted by the risk(s). Engaging the community involves the fire department becoming active in community organizations, participating in community events, and so on. Community engagement taken one step further involves the emergency response crews and companies becoming involved in their specific neighborhoods. The goal of engaging the community is to gain the trust of those living the neighborhoods and community, and from that trust and credibility eventually gaining their support for risk reduction activities.

Both components are discussed in more detail later in this chapter.

Fundamentals

Three fundamentals of community risk reduction help to clarify how and when the five "E"s are applied to risk reduction. These fundamentals are use of a risk reduction planning process, use of the resources of multiple organizations, and use of multiple mitigation strategies.

Risk Reduction Planning. A risk reduction planning process is used to select the highest risk(s), identify the risk factors and contributing factors, and then select the mitigation strategy or strategies—that is, 5 "E"s—which have the highest probability of success with the resources available.

Resources of Multiple Organizations. The community risk reduction process must utilize the resources of multiple organizations to effectively implement the mitigation strategies. A single fire department will seldom—if ever—have adequate resources to implement the five "E"s to the level necessary to reduce risk. Rather, the department seeks out government and community partners who have resources and influence that can be consolidated into one communitywide risk reduction initiative.

Use of Multiple Mitigation Strategies. Any community risk reduction initiative is most effective when all five mitigation strategies are applied to the risk issue. Studies conducted by the United States Centers for Disease Control[1] are clear: the use of only one strategy is unlikely to result in any change in the community risk. Ideally, all five strategies will be applied. However, this is not always possible due to a lack of resources, specific risk factors, and so on. The point is that whenever possible during the planning process as many of the strategies as practical should be applied.

The importance of using several mitigation strategies is clearly demonstrated in the 2000 David and Lucile Packard Foundation report, *The Future of Children: Unintentional Injuries in Childhood.*[2] In its preface, editor Richard E. Behrman, M. D., calls on those in the field to go beyond education alone and to address preventable childhood injury through a multifaceted public health approach:

> . . . the most effective injury prevention efforts are often those that focus on public policy change, reinforced through legislation or regulations. Public policies—such as requirements that young children be restrained in car seats, that prescription medications have child-resistant caps, and that children's sleepwear be flame retardant—save the lives of thousands of children each year. Yet there are many more opportunities to reduce childhood injuries through policy change that have not been seized. Uniform statewide requirements that children and teen bicyclists wear helmets, fences that enclose swimming pools on all sides, and environmental changes that slow the speed and density of traffic in residential areas are just a few strategies that could further reduce childhood injuries if widely implemented.[2]

Dr. Behrman concludes his statement of purpose with an important caveat:

> These public policy strategies have a greater likelihood of being implemented and enforced if they are coupled with community-wide efforts to change social norms about the acceptability of safety behaviors, and adequate financial resources to ensure the availability of safety devices.

THE FIVE "E"S

The five "E"s are the mitigation strategies of education, enforcement, engineering, emergency response, and economic incentives (Figure 12.19.1). Each strategy is summarized below.

Engineering

The objective of engineering is to build safeguards into products and materials that, by their design, eliminate or reduce the risk. These engineering safeguards are built into the environments where we live and into the products we use. For example, the use of fire-resistant sheetrock in residential construction restricts and slows the spread of fire in the home. The resident does not have to take any action for the sheetrock to work. This passive nature of engineering safeguards is a key to their success. Although most fire departments do not specifically design engineering safeguards, fire prevention personnel routinely apply

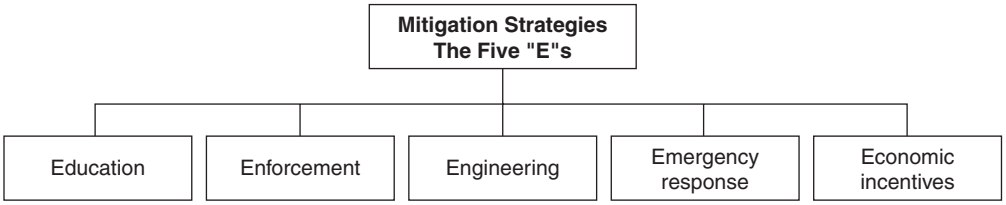

FIGURE 12.19.1 The Five "E"s as Mitigation Strategies for Community Risk Reduction

the safeguards through fire and building codes in both new and existing construction.

Education

Education is a widely used strategy by the fire service. The objective of an education strategy is to raise public awareness and understanding about fire, thereby changing high-risk personal behaviors. This change in behavior results in lowering the incidents of fire as well as reducing the injuries from fire. Public education programs such as the National Fire Protection Association's *Learn Not to Burn*®, *Risk Watch*®, and *Remembering When* have made a significant and measurable impact on reducing the fire problem. As of August 2006, NFPA had documented the following:

- 203 save incidents resulting in 558 lives saved from *Learn Not to Burn*
- 38 save incidents resulting in 71 lives saved from *Risk Watch*[3]

Because public education is so widespread and in some cases easy to implement, this strategy is perceived to be highly effective. Unfortunately, public education when used alone is the least effective of the five strategies.[4] Still, fire safety education remains a vital strategy in community risk reduction. This contribution has resulted, at least in part, in an impressive track record. Fire deaths in the United States and Canada have each fallen by roughly half in the past 25 years and fire deaths relative to population by even more. The role of education in this reduction, although believed to be important, has not been substantiated.

Education is also an important component in changes arising from engineering and enforcement mitigation strategies. North Americans made great strides in both safety technology and the safe use of technology. As of 2004, for example, 96 percent of homes in the United States had at least one smoke alarm, the highest rate of home smoke alarm usage in the world. Changes have been made in the United States and many other countries in the design of products ranging from upholstered furniture to mattresses to lighters to space heaters to manufactured homes. And the well-established systems by which model codes and standards are developed, adopted into law by reference, and enforced by national, state, and local authorities ensure that engineering achievements involving products, structures, vehicles, processes, and systems tend to move fairly rapidly into programmatic achievements at the grass-roots level.

However, much remains to be done. And with most fire departments now also responsible for providing emergency medical services to their communities, a fire department's role in prevention education has expanded to encompass a much broader range of issues.

Enforcement

The goal of the enforcement strategy is to reduce risk through the use of codes and standards. In this regard, enforcement utilizes many engineering innovations. For enforcement to be effective, the local department must have the ability to require compliance with the adopted codes and standards. This is accomplished through the use of code inspectors, building plan reviews, engine company inspections, and so on. As departments move into other risk areas compliance will require cooperation with other agencies that have similar authority.

Economic Incentives

The use of economic incentives is another strategy commonly employed along with other strategies. The goal of economic incentives is to influence personal or corporate behavior through financial incentives or disincentives. For example, when a department provides smoke alarms at no cost to home owners, economic incentive is being used. Similarly, when a developer chooses to install residential fire sprinklers in order to be able to build more houses in the same area under the building code, an economic incentive is being employed.

Emergency Response

Emergency response has always been a fire department function, but the types of emergencies to which fire fighters respond have increased. Consequently, the evolving scope of emergency response makes it the newest addition to the traditional three "E"s of engineering, education, and enforcement. Communities and risk reduction planners have realized that there are many risks that simply cannot be mitigated effectively through the other strategies. In these cases there must be an adequate emergency response capability to mitigate the problem when it occurs. For example, communities in Southern California have adopted codes and standards to minimize the risk of wildland fires. Well-designed public education programs have been delivered. Yet, wildland fires still occur and threaten hundreds of homes each season. Only a well-equipped and well-trained emergency response force can contain and control the fire to protect lives and

property. Although the other strategies contribute to mitigating the risk, ultimately fire fighters and fire apparatus are required.

ROLE OF COMMUNITY ENGAGEMENT

The second component of community risk reduction is engaging the community, especially the groups that are mostly likely to be negatively impacted by the risk(s). Engaging the community involves the fire department becoming active in community organizations, participating in community events, and so on. Community engagement taken one step further involves the emergency response crews and companies becoming involved in their specific neighborhoods. The goal of engaging the community is to gain the trust of those living in the neighborhoods and community, and from that trust and credibility eventually gaining their support for risk reduction activities.

For community engagement to have a positive impact on a community risk reduction initiative it must precede the risk reduction initiative. In addition, community engagement should be viewed by the fire department leadership and membership as an everyday approach to doing business in the community. This approach has proven to be very effective for local law enforcement agencies which use the term "community policing" to describe community engagement.

Principles of Community Engagement

The Centers for Disease Control have identified four principles of community engagement.[1] The principles should be built into any fire department effort of engaging the community. The four principles are as follows:

1. The goal of the engagement process must be clearly stated with each neighborhood or community group engaged. In other words, the public must be aware of the goal of the engagement activities. In this case the goal is to build a positive relationship and then get the groups involved in a community risk reduction process.

2. The decision makers and leaders in the fire department must be knowledgeable about the community and the groups living there. Most communities today are diverse and include groups from several ethnic and cultural backgrounds. The leaders must also understand current issues in the community such as the economy, political structures, and so forth.

3. A key foundation of community engagement is establishing a relationship of mutual trust and communication with each stakeholder group in the community. These relationships are built by both senior leaders *and* personnel at the company level who actually provide emergency and nonemergency services to the groups.

4. The senior leaders must understand, and appreciate, that each stakeholder group and neighborhood has the right to self-determination when it comes to the engagement and risk reduction processes. If a group does not want to participate in the risk reduction planning process, the group has that right. The groups also have the right to disagree or even challenge the fire department on risk reduction issues. This principle must be applied during times of conflict if a trusting relationship is to be built and maintained.

Relationships with Stakeholders from Other Cultures

Many of the groups who have a vested interest in the reduction of community risk, called stakeholder groups, will be from cultures that are different from the prevailing community culture. These groups are generally immigrants or members of a minority group. Building relationships with these groups may be the greatest challenge in engaging the community. The University of Kansas's Community Tool Box has developed the following nine recommendations for building relationships with other cultures:[5]

1. Make a conscious decision to establish friendships with people from the other cultures and stakeholder groups. This begins with a commitment by the fire chief to engage the stakeholder groups.
2. Put yourself in situations where you will meet people of other cultures. This is most easily achieved by response companies, code inspectors, and so forth, that is, those who regularly have the opportunity in the course of daily business to meet with the public.
3. Examine your biases about people from other cultures. This should begin when interactions begin.
4. Ask people questions about their cultures, customs, and views.
5. Read about other people's cultures and histories. This information is readily accessible through the Internet.
6. Listen to people tell their stories. This requires spending time with members of another culture.
7. Notice differences in communication style and values; don't assume that the majority's way is the right way.
8. Risk making mistakes. Most members of other cultures will understand and be patient.
9. Learn to be an ally. This is a key to building a trusting relationship.

NFPA Champion Model of School-Based Delivery

Another approach to engaging the community in a prevention or risk reduction initiative was developed by NFPA. Even though the model was designed specifically for a public education application, many of the principles will apply to a community risk reduction initiative. The NFPA Champion Model of School-Based Delivery has been taught as part of the NFPA Champion program since 1995. The NFPA identified several fundamental qualities that appear to correlate with long-term success in implementing public education programs. Together, they comprise the NFPA Champion Model of implementation.

The Champion Model relies on 10 components or "'C's to Success" and these qualities can be used as a checklist to assess a community's readiness to initiate, evaluate, and institutionalize a comprehensive public safety program in the school environment and the community at large. The 10 "C"s provide

a framework for success, proven to be effective in establishing and delivering messages and lessons that modify behavior, reduce injuries, and save lives. The 10 "C"s to Success are coalition, champion, careful planning, compelling case, credentials, collaboration, continuity, creativity, camaraderie, and commitment. The information described in each "C" references public education, but the same approach applies to a risk reduction initiative utilizing any or all of the 5 "E"s.

Coalition. For reasons discussed earlier, NFPA has concluded that the most effective way to reduce unintentional injuries is to work through a community coalition. That coalition should include (at a minimum) a representative from each of the following organizations: the fire department; the police department or local law enforcement agency; a health organization (hospital, health department, school nurse, or local SAFE KIDS representative); a school administrator (principal or curriculum director); and a classroom teacher from a school where the program will be implemented.

Champion. Every coalition needs to select a leader (or "Champion") who will be responsible for the coalition's efforts, from planning and implementation to evaluation and expansion of the public education project. Long-term success depends on the Champion's ability to think strategically, to motivate and coach others toward common goals, and to document and communicate program results to key decision makers, coalition members, teachers, other participants, and the public.

Careful Planning. Successful coalitions need to develop a written strategic plan outlining a clear set of written goals, measurements, and timeframes. Although each participating organization will have its own individual priorities, successful coalitions will be able to come to consensus on an achievable number of objectives toward which every member can make a contribution. The strategic plan will assign responsibility for each of the following areas: program development; training and implementation; support, promotion, and communication; strategic alliance building and fundraising; and research and evaluation. Progress needs to be documented. As the coalition develops, the plan must be updated and the leadership structure redefined.

Compelling Case. By analyzing the incidence of unintentional injuries in a community and focusing first on those neighborhoods or areas at highest risk, a Champion coalition can achieve dramatic results early in the program and use that momentum to gain support for further expansion. Start small, document the team's progress, and use concrete examples of the program's effectiveness to justify expansion. The extent to which a coalition can articulate an urgent need and define the tangible benefits of its program will largely determine the level of media attention, funding, and community involvement the program receives. To learn more about how to reach those at highest risk to fire, see Section 5, Chapter 5, "Reaching High-Risk Groups."

Credentials. A program's reputation will be determined by the quality of the materials used and the manner in which they are delivered. A coalition should select an established curriculum that has been thoroughly evaluated by independent researchers. Put professional educators in the lead role of teaching the core subject matter, since they have the necessary training and consistent access to guide student learning. Seek the participation of well-qualified, highly respected experts to serve on the coalition with the common goal of supporting the classroom teachers. Strive to enhance professional development and keep informed of new trends and innovations in the injury control field.

Collaboration. Successful public education initiatives are those that enjoy a high level of commitment from the community: the board of education, teachers, the fire department, the police department, and other agencies that have a specific mission to prevent childhood injuries. After teachers have introduced the core safety lessons to their students, local safety experts can then visit classrooms and reinforce lessons with their "real-world" perspective. NFPA suggests giving experts a copy of key lesson points to ensure consistency and accuracy of messages delivered by outside experts.

Continuity. Because people learn best through repetition and practice, the most effective way to teach injury prevention skills is through repeated, age-appropriate learning opportunities extended over a period of years. A successful program will target each age group in the program with messages they can understand. Injury risks to children change as they grow older; therefore, safety messages should become more comprehensive and complex as students mature. Also, growth brings the ability to understand and absorb more complex information and associated behaviors, and so safety messages should be tailored to a child's development, finding the right time to teach them all they will need to know throughout their lives.

Creativity. Communities are encouraged to supplement public education programs with elements (such as performance experiences) designed to address local needs. The creative use of safety trailers, clowns and puppets, coloring and comic books, and so on helps customize the program and provides an important sense of ownership. Creative reinforcement techniques can also enhance student knowledge gain and retention, so long as the information presented does not replace or conflict with the program's core messages. Educational programs delivered infrequently and with insufficient student preparation and reinforcement have not been shown to yield positive results.

Camaraderie. NFPA always makes time for fun during its public education training workshops. And the same concept can be applied in any community coalition. Sharing meals, attending planning retreats together, even playing an ice-breaker game before meetings can help build strong, trusting relationships and keep everyone on the team coming back for more.

Commitment. Successfully implementing a public education program is a major initiative for any community, regardless of its size or available resources. It requires hard work, the commitment of individuals and community organizations, and, most importantly, persistence. Although your initiative may be filled

with challenges, there will also be rewards, including knowing that fewer children are being injured and that your community is a safer place to live, work, and play.

Both engaging the community and building relationships with other cultures requires a strong commitment on the part of the department leadership to community risk reduction. Without this strong commitment from leadership most community risk reduction initiatives are doomed to failure.

ROLE OF LEADERSHIP IN COMMUNITY RISK REDUCTION

Society relies on a basic infrastructure that gives shape to the quality of life in a community. Transportation, utilities, code enforcement, school, and recreational systems are but a few examples of the diverse parts of this infrastructure that allow community residents to make individual choices in an interactive social context. Policy makers understand that weaknesses in these infrastructure systems can result in performance failures at a given point in time and everyone will get less of what they want. Plans that are developed today revolve around design and maintenance of "system" components rather than simply addressing programs and issues separately without considering the impact of decisions on overall system performance. In other words, every problem is considered in a broad systems context, and special care is taken to maintain the infrastructure components that allow systems solutions to work most effectively in a dynamic environment.

Any systems approach begins by laying out the infrastructure of organizations, technologies, incentives, laws, and internal arrangements that seek to give structure to those interactions, so that needless inefficiency and disruption is minimized. Fire departments and other fire service organizations should address community risk reduction more holistically in terms of community infrastructure and systems approaches, rather than as separate programs that may at times appear disconnected from each other.

Systems Management and Leadership Model

A community risk reduction system describes basic components required to protect life and property in a community. The components may be programs or groups or the infrastructure that allows them to work together effectively towards solutions. There is not one single program or intervention strategy that will address the many ways that people can be killed or injured and property destroyed as a result of fire, natural disasters, terrorist attacks, or other causes. Furthermore, every program strategy is affected by many groups, whether it is designed to include them or not.

A system describes the component parts of a whole and their interactions. Each piece depends on the others for overall system effectiveness. Within a fire service organization, its components of this community risk reduction system can be divided into line and staff responsibilities.

Line Services. Line services are mission-driven and include risk reduction involving public education programs, emergency response, and emergency management:

- *Prevention through consensus codes and built-in protection.* These codes for prevention and mitigation govern structures, hazardous facilities and contents, as well as built-in protection, such as automatic fire sprinklers, and so on. Code-related services also include fire investigation, inspection, and enforcement activities.
- *All-risk public education programs designed to teach people how to prevent harmful situations and to survive should a situation occur.*
- *Response to emergency incidents such as fires, medical emergencies, natural disasters, hazardous materials events, or technical rescues.* This would include nonemergency service requests answered by emergency responders and the area of emergency (disaster) management.

Staff Services. Staff services are in place to support the primary mission and are provided to *internal* customers. Too often, risk reduction has been considered a support program to the emergency response system. However, community risk reduction is a line service as its customers are *outside* the fire department. Like any service provided within the mission of the organization, community risk reduction requires adequate staff support to be successful:

- *Prepare members to perform their roles.* This includes training the people in the organization to perform in their assigned roles within all areas.
- *Management of finances and human resources.* Support for the members who actually provide the line and staff services externally and internally. This includes issues such as adequate compensation, policy direction, definitive planning, safety issues, humane treatment, and other areas related directly to making people as effective as possible.
- *Community partnerships, relationships, and politics.* This includes maintaining positive and productive relationships internally and externally, an appreciation for (and understanding of) the importance of developing effective strategic alliances, and functioning effectively in the political arena with policy makers. This is achieved through engaging the community and its stakeholder groups whenever and wherever possible by all members of the department.
- *Management of physical resources and technology.* This means building and maintaining the infrastructure and equipment necessary to be effective. This includes management of facilities, the fleet, dispatch and communications systems, and other nonhuman resources.

These represent the component parts of the community risk reduction infrastructure. The mission is delivered effectively to the extent that these are brought together and managed in a systems approach. Failure of any of the individual parts of the system can result in failure of the mission in a given situation.

Executive Level Commitment

It is almost impossible for any program to be successful without the support and commitment of the chief executive officer of the organization. Programs that function in spite of the chief struggle every day. Be it fire suppression, health and safety, labor

relations, fire prevention, media relations, fire and life safety education, EMS, training, or special operations—without the visible, active support of the chief, program results will usually be mediocre at best.

Community risk reduction programs that have full executive level support within the organization are effective, meaningful components of the service delivery system. This executive level support is demonstrated by actions such as the following:

- Representing the importance of community risk reduction inside and outside the organization
- Describing how community risk reduction integrates into the mission
- Identifying community risk reduction as a recognized program within the organizational structure
- Assigning responsibility and accountability for community risk reduction to a specific manager
- Ensuring a community risk reduction voice in decision making and planning processes
- Providing adequate personnel and other resources dedicated to community risk reduction programs
- Supporting the ongoing professional development of those involved in community risk reduction by allocating funds to attend regional and national meetings and trainings or conferences
- Including community risk reduction in strategic and operational plans, as well as budget packages
- "Opening doors" for community risk reduction staff inside the organization and within the community

Community risk reduction, like any other program, is successful in fire departments where the chief and other leaders want it to be successful and consistently act that out. It is treated and represented as a key organizational responsibility and a critical component of the community risk reduction infrastructure of a community.

SUMMARY

NFPA recommends a multifaceted, coordinated risk reduction process at the community level to address local risks. This requires engaging all segments of the community, identifying the highest priority risks, and then developing and implementing strategies designed to mitigate the risks.

Fire departments can serve a vital role in the concerted community risk reduction effort. The public safety needs of communities increasingly place fire department personnel in the role of emergency responders—first on the scene not only in a fire emergency, but in medical emergencies, natural disasters, and acts of terrorism as well. With a proven record in prevention and responding effectively to fire emergencies, fire safety advocates often have the credibility and expertise to organize their communities around broader safety and risk issues. Most fire department leaders are encouraging their members to get more involved in their communities to strengthen organizational credibility and influence. There are a variety of ways this can be accomplished, and community risk reduction is the program that provides perhaps the greatest opportunity.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on concepts of community risk reduction discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following document.)*

NFPA 1035, *Standard for Professional Qualifications for Public Fire and Life Safety Educator*

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SECTION 13

Organizing for Public Sector Emergency Response

Gary Tokle

13.1 Fireground Operations
13.2 Organizing Rescue Operations
13.3 Fire Streams
13.4 Alternate Water Supplies
13.5 Wildland Fire Management
13.6 Public Fire Protection and Hazmat Management
13.7 Aircraft Rescue and Fire Fighting (ARFF)
13.8 Managing the Response to Hazardous Material Incidents
13.9 Emergency Medical Services and the Fire Department

For the first time, the *Fire Protection Handbook*® includes one section that concentrates on non-emergency fire department functions (Section 12) and a second section on organizing for public sector emergency response. Section 13 on emergency response is composed of nine chapters, including new chapters on airport rescue fire fighting and on emergency medical services.

Chapter 1, "Fireground Operations," describes the role of standard operating procedures, the incident commander, the national incident management system, pre-incident planning and size-up, and offensive and defensive fire extinguishment, as well as ventilation and overhaul. Fire fighter safety and property conservation are addressed.

Chapter 2, "Organizing Rescue Operations," introduces a highly specialized fire service function. Discussion of community resource planning (CRP), confined space rescue, rescue operations, rope rescue, technical rescue, specialized technical rescue, the technical rescue team, and trench rescue are included.

Fire streams, the topic of Chapter 3, "Fire Streams," are an integral part of fire extinguishment operations. The chapter covers fire department pumpers, solid-stream and spray nozzles, hose line fire stream calculations for flow rate and friction loss, and aerial devices.

Expanded treatment of water shuttle operations is a feature of Chapter 4, "Alternate Water Supplies." The chapter presents information on determining minimum water requirements and estimating available water supply, structure and site surveys, and natural and developed sources of water. Agreements, permits, water supply vehicles, and drivers are also considered.

Chapter 5, "Wildland Fire Management," provides a brief summary of past wildland fires and establishes the characteristics of wildland fire, then discusses the ways to prevent fires in wildlands or the wildland/urban interface and mitigate their effects. "Firewise" communities, prescribed burning, and fire fighter safety are also discussed.

Chapter 6, "Public Fire Protection and Hazmat Management," defines hazardous materials and summarizes the variety of laws, regulations, and consensus standards that govern them.

Chapter 7, "Aircraft Rescue and Fire Fighting (ARFF)," is new to the *Fire Protection Handbook.* The chapter explains the tools, techniques, agents, and objectives of aircraft rescue and fire fighting. Also provided is a review of the regulations and industry standards that influence the levels of training, staffing, and equipment at airports, as well as information about typical aircraft emergencies and ARFF response procedures.

Chapter 8, "Managing the Response to Hazardous Materials Incidents," provides a focus on hazardous materials response by considering hazard classes and divisions, weapons of mass destruction (WMD), bulk packaging, damage assessment, decontamination, and elevated temperature material. Personal protective equipment for hazardous materials response is also covered.

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During the past fifty years, fire service–based delivery of emergency medical services (EMS) has grown to be the principal operational delivery program in the majority of fire departments. In recognition of the significant role of EMS in the fire service, the section closes with another new chapter, Chapter 9, "Emergency Medical Services and the Fire Department." This chapter identifies the various factors, standards, and performance measures that can be utilized by fire departments in their analysis and improvement of the emergency medical services program. A Process Performance Indicator Index is also introduced.

Chapter 1

Fireground Operations

Bernard J. Klaene ■ Russell Sanders

Chapter Contents

Standard Operating Procedures
Pre-Incident Planning
Size-Up
Incident Action Plan
Deployment and Organization
Life Safety
Extinguishment
Property Conservation

Key Terms

Beverly Hills Supper Club fire, defensive fire extinguishment, emergency action plan, fire fighter safety, incident commander (IC), national incident management system (NIMS), offensive fire extinguishment, overhaul, pre-incident planning, size-up, standard operating procedure, ventilation (fire fighting)

Combating structure fires is the reason fire departments were created, and structure fires remain one of the most formidable challenges facing modern fire departments. Structure fires are often labor-intensive, complex operations requiring a large number of people and equipment resources. Therefore, it is not surprising that the largest share of fire fighter injuries and deaths occurs on the fireground.

When fire prevention and public education efforts fail, or built-in fire protection equipment is unable to completely extinguish the fire, fire suppression by a fire department is the last line of defense for a building and its owner and occupants. In this respect, structural fire fighting today is much the same as it was 100 years ago. The primary tactic then, and now, is applying water directly to the burning fuel. However, over the past century, there have been numerous innovations to aid the modern fire fighter in conducting safe and effective fireground operations. These innovations include the following:

- Application of risk management principles to fireground operations
- Computerized pre-incident planning information
- National incident management system (NIMS)
- Improved fireground communications
- Fire fighter safety standards and regulations
- Improved and standardized personal protective clothing
- Widespread use of lightweight attack fire hose
- Large-diameter water-supply hose
- Thermal imaging devices

Successful fire departments prepare for potential fire operations prior to actual alarms. In pre-incident planning for fires within its jurisdiction, the fire department provides staffing, apparatus, and equipment based on a survey of the fire potential within the department's response area.

Training is also an important part of pre-incident preparation. Therefore, fire fighters receive extensive training on the proper use of apparatus, tools, and equipment, as well as on fireground tactics and strategy.

This chapter follows a logical methodology. It begins with a discussion of preparatory measures, followed by commentary on evaluating a specific fire situation and by the development of an incident action plan based on that evaluation or size-up. The chapter concludes with a review of the deployment and organization of fire department resources needed to safely and effectively limit the loss of life and property.

See also the following chapters in Section 12: Chapter 1, "Planning for Public Fire-Rescue Protection"; Chapter 7, "Safety, Medical, and Health Issues and Programs"; Chapter 8, "Effect of Building Construction and Fire Protection Systems on Fire Fighter Safety"; Chapter 12, "Disaster Planning and Response Services"; Chapter 17, "Pre-Incident Planning for Industrial and Municipal Emergency Response"; and Chapter 18, "Pre-Incident Planning for Emergency Response."

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STANDARD OPERATING PROCEDURES

Some departments prefer very specific procedures; others allow more flexibility. In either case, it is essential that fire fighters be given instructions regarding initial activities at the fire scene. These instructions take the form of standard operating procedures or standard operating guidelines. The term *standard operating procedures* is used here to refer to either standard operating guidelines or standard operating procedures.

Standard operating procedures (SOP) address any operation that can be handled using a standard approach. Some SOPs are the same from one community to the next; others are not. For example, the tactics necessary to extinguish an automobile fire in both a large metropolitan setting and a rural setting are much the same. However, the SOPs for combating a large structure fire in an urban setting with conveniently located fire hydrants versus the same structure fire in a rural setting with a limited water supply would be very different. Furthermore, a high-rise SOP would be useless to a small rural department that does not protect high-rise buildings either within its jurisdiction or within a mutual-aid response area.

As incident situations and resources vary, so should SOPs. However, all departments should have SOPs on some common items, including the following:

- Command
- Company operations
- Water supply
- Staging
- Accountability systems
- Rapid intervention crews
- Use of protective clothing
- Operations in buildings with built-in fire suppression equipment
- Special occupancy operations

When SOPs are being written, regional planning and cooperation are important. Incident management system, accountability system, and rapid intervention crew SOPs are especially important at the scenes of large incidents, because often these incidents require more resources than a single fire department can provide. When mutual-aid operations are likely, it is important for all responding departments to use the same procedures and conduct joint training operations to ensure safe and predictable on-scene operations.

PRE-INCIDENT PLANNING

The pre-incident plan provides information for a specific building or group of buildings. Pre-incident planning is essential to successful operations in large or complex structures and in buildings that are protected with built-in fire protection systems.

The first step in pre-incident planning is to prioritize the buildings that are to be planned. Pre-incident planning is a labor-intensive activity. Few departments have the resources needed to pre-incident plan all buildings within their jurisdiction. Furthermore, rarely would there be the need to develop pre-incident plans for all buildings in a fire department's response district.

Buildings that present an extraordinary hazard to fire fighters and those with a potential for a large loss of life or property top the list of buildings that must be pre-incident planned. In addition, large commercial and industrial facilities usually require a pre-incident plan, as do structures with confusing floor plans and buildings with built-in fire protection systems. (See NFPA 1620, *Recommended Practice for Pre-Incident Planning,* Section 12, Chapter 17, "Pre-Incident Planning for Industrial and Municipal Emergency Response," and Section 12, Chapter 18, "Pre-Incident Planning for Emergency Response.")

Once information is assembled on a specific property, the incident commander (IC) must be able to quickly and easily access the information at the incident scene. Three-ring binders may be an acceptable way to handle a limited number of pre-incident plans, but computerized pre-incident plans are more easily and more quickly searched and can place more information at the IC's fingertips. Pre-incident plan information should be formatted to be user friendly and be limited to information of value to the IC.

When facing a fire at a large or complex property, the IC is placed at a great disadvantage if he or she does not have advance knowledge of the building's contents or layout. Due to the stress and distractions associated with emergency conditions, the IC should be familiar with the pre-incident plan before arriving at the incident scene. Ideally, the IC would take an active role in developing the plan and conducting training sessions using the pre-incident plan.

There are several degrees of pre-incident planning, ranging from formal pre-incident plans to a simple notation regarding hazardous conditions at a specific building. Formal pre-incident plans usually include a narrative in outline form that briefly describes important features of the property. More important, formal pre-incident plans will typically include drawings depicting features important to the IC. Formal pre-incident plan drawings for an industrial complex with several buildings will show the location of various buildings within the complex as shown in Figure 13.1.1. There will also be drawings of each individual

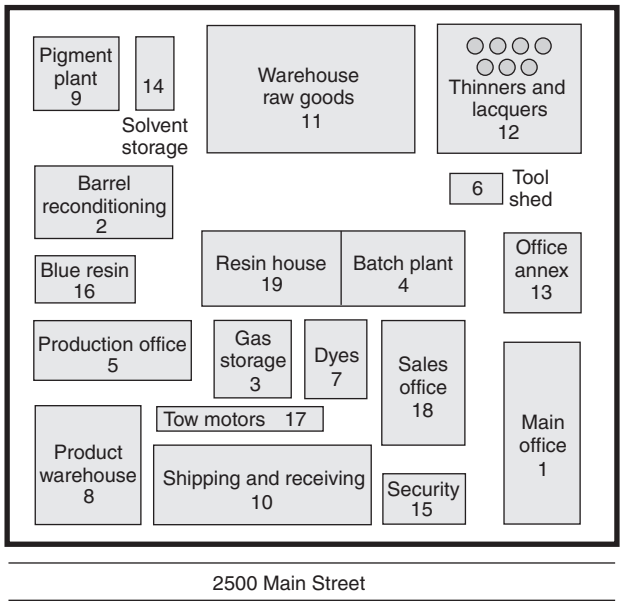


FIGURE 13.1.1 Complex Pre-Incident Plan Drawing

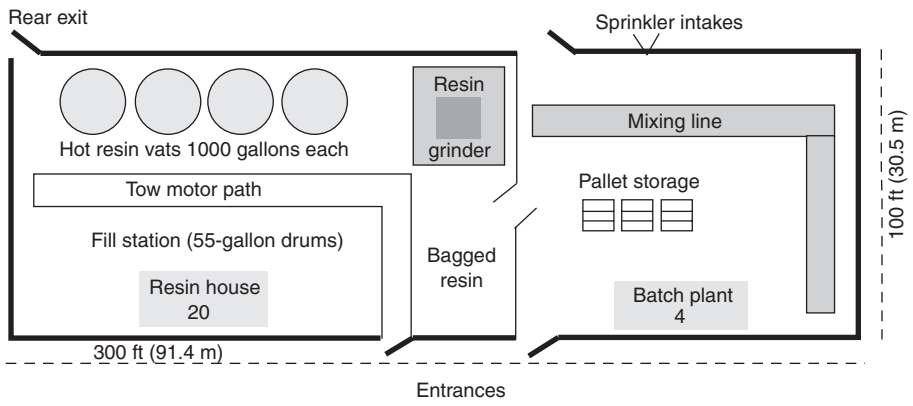


FIGURE 13.1.2 Formal Pre-Incident Plan Drawing

building as shown in Figure 13.1.2. Pre-incident plans for an apartment complex may show only the location of buildings within the property.

Fire officers should survey their response areas on a regular basis, noting hazards, such as deteriorated and vacant buildings, hazardous work locations (overhead cranes, chemicals, heavy machinery, etc.), and anything else that poses a significant safety hazard to responding fire fighters. One of the key reasons for conducting pre-incident planning surveys is to identify potentially dangerous structural conditions and related hazards. These hazardous conditions should immediately be reported and corrected, thereby eliminating hazards that could prove deadly during incident-scene operations. (See Section 12, Chapter 8, "Effect of Building Construction and Fire Protection Systems on Fire Fighter Safety.")

An analysis of the probability of extinguishment should be accomplished during pre-incident planning. Several rate-of-flow formulas are used by fire departments.[1] These formulas are useful in determining the probability of extinguishment, as well as the resources needed to extinguish a fire in large, undivided areas. Most of the rate-of-flow formulas use rudimentary mathematics, but they are very difficult to calculate at the incident scene when interior dimensions may not be known and the IC is busy developing an incident action plan and deploying and organizing fire companies. Therefore, the rate-of-flow formula for large, undivided areas (areas beyond the capability of two standard preconnected hose lines) should be calculated as part of the pre-incident plan.

Both pre-incident plans and standard operating procedures contain information that is critically important to the IC when making his or her incident-specific size-up. Therefore, the IC and all responding fire fighters should have a thorough understanding of these documents and routinely conduct training exercises to reinforce this information.

SIZE-UP

Size-up is the evaluation of factors as they exist at the time of an incident. Many of these factors can be known in advance through pre-incident planning, but some will not be known until the incident occurs.

The relative importance of size-up factors is subject to change. As an example, weather can be categorized as critically important when at the extreme or as unimportant under mild conditions. When occupants are known to be inside a burning building, life safety factors are pre-eminent. Time factors can be closely related to life safety. A high-rise office building may have thousands of occupants during normal business hours but only a few people at other times. Thus, time of day can be a critical size-up factor. Quite often structural conditions are the single most important factor in the size-up. Fire officers must understand the basic structural design elements, their weaknesses, and signs that the building is in danger of collapse. The NFPA publication *Building Construction for the Fire Service*[2] should be considered essential reading for anyone serving as an IC or safety officer at a structure fire.

The significance of size-up factors is directly related to the following operational priority list:

1. Life safety
2. Extinguishment
3. Property conservation

Additional considerations are environmental impact, heritage protection, and business/mission continuity. The size-up list in Figure 13.1.3 includes the major factors affecting size-up.

The size-up process continues throughout the incident as the IC continuously evaluates and reevaluates each critical incident factor. There is a direct correlation between the IC's size-up and the quantity and quality of information available. The more quality information that is available to the IC, the more accurate the size-up. The more accurate the size-up, the better the odds that the incident will be managed in a safe and efficient manner.

INCIDENT ACTION PLAN

The IC uses the information in the SOPs and the pre-incident plan, through the size-up process along with information gathered to develop a safe and effective incident action plan. The result should be a straightforward, easy-to-understand strategy emphasizing the IC's major tactical objectives.

Size-Up Checklist

LIFE SAFETY
- Structural stability
- Collapse zone
- Probability of extinguishment
- Building complexity and layout
- Adherence to SOPs (use of SCBA, etc.)
- Organization and coordination of the operation
- Primary and alternative egress routes
- Accountability and rapid intervention
- Smoke and fire conditions
- Occupancy type
- Evacuation status
- Estimated number of people in the building
- Occupant proximity to fire
- Mobility of occupants
- Awareness of occupants
- Occupants' familiarity with building
- Rescue options (stairs, ladders, others)
- Staffing needed to complete primary search and rescue
- Staffing needed to complete secondary search and rescue
- Medical status of occupants

EXTINGUISHMENT
- Offensive/defensive
- Automatic suppression equipment (sprinkler, deluge, other)
- Manual suppression equipment (standpipe)
- Water supply
- Pump capacity
- Rate of flow
- Fuel load of contents
- Fuel load of the structure (walls, ceilings, support members, etc.)
- Number and size of hose lines needed for extinguishment
- Additional hose lines needed
- Staffing needed for fire lines
- Internal exposures
- External exposures
- Ventilation status

PROPERTY CONSERVATION
- Salvageable property
- Location of salvageable property
- Property susceptability to water damage
- Probability of smoke damage
- Damage resulting from entry and ventilation
- Water pathways to salvageable property
- Salvage methods available
- Alternative water removal methods

STRUCTURE
- Signs of collapse
- Construction type
- Roof construction
- Previous damage
- Live and dead loads
- Water load
- Access/forcible entry
- Extension probability
- Age
- Height and area
- Location of large undivided areas
- Enclosures and fire separations
- Exit facilities

RESOURCES
- Staffing needed versus staffing available
- Additional staffing available (on call, on duty, or mutual aid)
- Staffing available in staging
- Apparatus needed versus apparatus on scene
- Additional apparatus available (department or mutual aid)
- Additional apparatus available in staging
- Water supply needed versus water supply available
- Special resource needs

TIME
- Time of day
- Day of week
- Time of year
- Special (e.g., holiday season)

WEATHER
- Temperature
- Humidity
- Precipitation
- Winds

FIGURE 13.1.3 Size-Up Checklist

Like size-up, the incident action plan is a dynamic process. The IC revises the incident action plan as information gathered through size-up reflects the changing conditions at the incident scene. In developing and revising the incident action plan, the IC compares the fire fighters' risk exposure to potential outcomes (risk-benefit analysis). In structural fire fighting the offensive-defensive decision is often the most critical factor in the risk-benefit analysis and is, therefore, the foundation on which the incident action plan is developed.

The offensive-defensive decision is subject to change based on the IC's ongoing size-up, specifically the risk-benefit analysis. Occupants or fire fighters exposed to extreme risk may warrant placing additional fire fighters at risk. However, once savable occupants and/or fire fighters are evacuated from the building, the benefit side of the risk-benefit analysis is reduced, as is the level of acceptable risk. NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program,* provides the basis of this risk-benefit analysis, stating:

- Activities that present a significant risk to the safety of members shall be limited to situations where there is a potential to save endangered lives.
- Activities that are routinely employed to protect property shall be recognized as inherent risks to the safety of members, and action shall be taken to reduce or avoid these risks.
- No risk to the safety of members shall be acceptable when there is no possibility to save lives or property.
- In situations where the risk to fire department members is excessive, activities shall be limited to defensive operations.

DEPLOYMENT AND ORGANIZATION

With the incident action plan in place, fire-fighting crews and support resources are deployed to accomplish the tactical objectives identified in the incident action plan. As needed, the IC assigns the necessary subordinate sections, branches, divisions, groups, strike teams, and task forces to reduce the span of control and create an effective incident management organization. The IC coordinates, organizes, and manages the overall operation, being careful to avoid dangerous tactics, such as combining offensive and defensive attacks.

Assigning company-level operations should be included in the fire department's SOPs. Fire-fighting task assignments are usually divided into two categories: (1) tasks typically performed by an engine company crew and (2) tasks typically performed by a truck company crew.

Simply put, engine company work involves extinguishing the fire. Members assigned to truck company duties assist engine companies in gaining entry, laddering the building, controlling the spread of fire through ventilation, and evacuating occupants. This assignment of tasks into two basic categories does not mean that an engine company crew could not be assigned to a truck company task, such as search and rescue, or that a truck company crew could not be assigned tasks directly related to extinguishment. However, dividing company-level operations into these two general roles simplifies the deployment of forces and contributes to safe and efficient incident-scene operations. Even departments that do not have an aerial apparatus should divide operating crew assignments into these general types of tasks.

As long as the apparatus carries the right tools and the fire fighters receive proper training, it doesn't matter what type of apparatus delivers the fire fighters and equipment to the scene. What does matter is that both the traditional truck and engine company duties are accomplished in a coordinated manner by properly equipped, well-trained fire fighters.

LIFE SAFETY

The fire fighter's life is valued as being as important as any other human life, and the fire fighter is the most valued resource of any fire department. Measures taken to reduce the risk posed to fire fighters are essential and critical components of the life safety priority. NFPA 1500 identifies many provisions to improve fire fighter safety at the incident scene. (See Section 12, Chapter 7, "Safety, Medical, and Health Issues and Programs.")

NFPA *101®*, *Life Safety Code®*, requires minimum egress facilities for occupants of a building. In many cases, the occupants of a building will use these egress facilities to evacuate on their own, once they realize there is a need to escape. When possible, using the building's normal egress facilities to evacuate is preferred. The design features of the building's egress system, with the exception of elevators, are typically the safest way to exit a burning building and sometimes provide places of safe refuge within the structure. If stairways have not been compromised, they offer the easiest and safest egress routes from the upper floors of a building. Other evacuation methods are available to the fire department, but these tend to be more staff intensive and hazardous.

Rescue and evacuation via interior stairs, fire escapes, aerial apparatus, and ground ladders are common rescue methods used by fire departments. Elevators, scaling ladders, ropes, helicopters, life nets, and air bags are atypical rescue methods and often expose the rescuer and the victim to extraordinary danger.

In terms of search and rescue operations, large, complex buildings present a greater challenge for the IC and increase the risk to fire fighters. Buildings with flexible floor plans or with multiple additions often result in a mazelike configuration that results in confusing paths to egress routes. The tragic fire at the Beverly Hills Supper Club is an example of this problem (Figure 13.1.4).

To protect occupants, the IC must have sufficient staffing to extinguish (or at least contain) the fire, assign adequate personnel to search and rescue operations, and treat and transport the injured while preventing re-entry. The staffing needed to meet the requirements of the life safety priority will depend on several factors, such as the following:

- Number of occupants at risk
- Rescue method(s) used (e.g., stairway, fire escape, aerial apparatus, portable ladder, life line/rope)
- Condition of the occupants at risk
- Fire size and intensity
- Smoke conditions
- Weather conditions
- Accessibility (need to force entry)

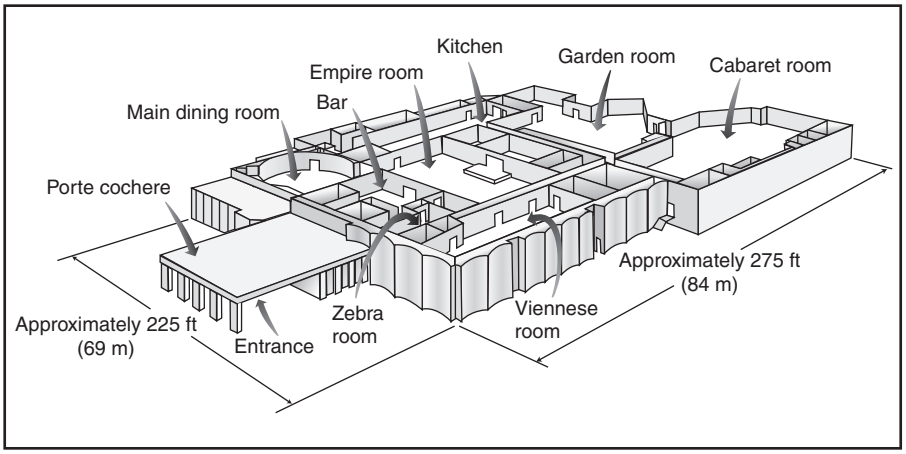
EXTINGUISHMENT

Offensive Fire Extinguishment

There are two general types of operations at a structure fire: offensive and defensive. During offensive operations fire fighters enter the burning building and conduct interior life safety, extinguishment, and property conservation duties. Offensive operations are preferred whenever they can be conducted safely and effectively. Even though extinguishment is the second incident priority, offensive extinguishment is often the most important life safety tactic.

Manually extinguishing a fire on the interior of a building is an arduous task. The objective of the offensive fire attack is to apply a sufficient quantity of water directly on the burning

(a)



(b)

FIGURE 13.1.4 (a) Mazelike Floor Plan of the Beverly Hills Supper Club, Southgate, Kentucky; (b) Beverly Hills Supper Club Fire, 1977

fuel to achieve extinguishment. Once fire fighters determine the location of the fire, the essential question to be answered is how many gallons per minute (gpm) (liters per minute [L/min]) are required to extinguish a given fire with properly placed hose lines. Calculating the rate of flow allows the IC to match the number and size of fire hose lines to the waterflow necessary to extinguish the fire.

Calculating Rate of Flow. Some ICs prefer to use trial-and-error methods in determining the rate of flow. Using a trial-and-error method, the IC continues to add hose lines until the fire is knocked down or extinguished. The problem with trial-and-error methods is that fire fighters generally start with the department's standard preconnected hose line and simply continue adding more hose lines of the same type and size, when larger-diameter hose is actually needed.

There are three basic calculation methods used to determine the rate of flow:

$$\text{Royer/Nelson: } \frac{\text{Volume in ft}^3}{100} = \text{gpm} \qquad \frac{\text{Volume in m}^3}{0.748} = \text{L/min}$$

$$\text{U.S. National Fire Academy: } \frac{\text{Area in ft}^2}{3} = \text{gpm} \qquad \frac{\text{Area in m}^2}{0.074} = \text{L/min}$$

Sprinkler calculations: Flow based on fire load

Most practitioners agree that there is a minimum flow requirement needed to extinguish a given fire, and that rate-of-

flow calculations are useful. However, there is disagreement as to which of the calculations is best. Each of these formulas are useful, but each also has limitations. Some rate-of-flow calculations are entirely empirical in nature; others are based on a considerable body of research and testing. Even the calculations based on research and testing are inaccurate under certain conditions because of the assumptions made and/or research conditions. Thus, rate-of-flow formulas are used to develop a rough approximation of the gpm (L/min) needed to extinguish a fire in a specific compartment.

The rate-of-flow calculations shown on page 13-8 are designed to calculate the required flow for offensive fire attacks within enclosed areas. When using rate-of-flow calculations, the IC's objective is to meet or exceed the calculated flow requirements by assigning the appropriate hose, nozzles, and water supply necessary to deliver, at a minimum, the total flow requirements. To properly calculate the rate of flow, the compartment size or fire area must be determined. Often this is extremely difficult at the incident scene. Therefore, as a practical matter, it is much better to determine the required flow during pre-incident planning and include this information in the pre-incident plan. Likewise, all department members should know the flow rates of the nozzles and hose combinations used by their department.

Protecting Properties with Fire Protection Systems. When fire protection systems protect the structure, the offensive attack takes on an entirely different character. A properly operating and maintained fire suppression system means that manual fire fighting will most likely be limited to supporting the building's suppression system and letting the system do the job it is intended to do. Efforts should be directed toward maintaining the system in a fully operational status and providing backup hose lines to complete extinguishment. Departments protecting properties with fire protection systems should have SOPs addressing operations in these buildings. Pre-incident planning is essential for any building protected by an automatic fire suppression system, as improper tactics could diminish the effectiveness of the building's built-in fire protection systems.

Protecting Properties with Standpipe Systems. Standpipe systems are not automatic fire suppression systems because they require human intervention. However, a standpipe system is an extremely valuable tool when conducting an offensive attack. In fact, in high-rise structures it may be impossible to conduct an effective interior operation on upper stories without a standpipe system. Fire departments should have standpipe SOPs in place and should have prepared pre-incident plans for these buildings. Departments protecting buildings with standpipe systems will normally have standpipe equipment available based on the needs identified within their response area.

An important part of the pre-incident planning process involves determining the flow capacity of fire pumps and the pressures available at various levels throughout the building. If the standpipe is a low-pressure system equipped with pressure-reducing valves or reducing adapters, provisions should be taken to either increase the pressure available at the standpipe outlet or provide hose and nozzles capable of providing an adequate flow at low pressures.

Defensive Fire Extinguishment

A defensive or nonattack strategy is used whenever the risk-benefit analysis reveals that the risk to fire fighters outweighs any possible benefit that might be achieved by conducting an offensive attack. Fighting a fire in a building that is unstable and where there are no lives to be saved is a clear example of the risk to fire fighters outweighing the possible benefits, thus justifying a defensive strategy. However, it is not always that clear-cut, as the IC will often have inadequate information or conflicting reports. The IC's training and experience are key factors in selecting the proper attack (or nonattack) mode.

Defensive attacks are almost always exterior operations and are generally conducted in the following situations:

- A risk-benefit analysis indicates that risk is too great in terms of what can be saved.
- Building's structural integrity or fire conditions prohibit entry.
- Resources needed for an offensive attack are greater than resource capabilities.

When a fire threatens the structural integrity of a building, fire fighters and apparatus should be moved outside the collapse zone. Given the uncertainties associated with how a building will collapse, the collapse zone should be equal to the height of the building plus an allowance for debris to scatter. The inability to apply water from a distance equal to the height of a building may lead to a nonattack decision for tall buildings in danger of collapse.

When evaluating an external exposure, operational priorities remain the same: (1) life safety, (2) extinguishment, and (3) property conservation. With these operational priorities in mind the IC must recognize a total loss when they are confronted with one. During a defensive attack, the building of origin is sometimes written off in favor of saving nearby property.

A question arises during a defensive attack as to whether it is better to apply water directly to the burning building or onto external exposures. Applying hose streams directly into the burning structure is an exposure protection tactic that has merit, but the intensity and depth of the fire may be such that it is impossible to significantly reduce the volume of fire in this manner. If a large volume of fire cannot be contained, and other structures are in close proximity to the fire building, it is best to apply water to the outside of the exposed buildings. Radiant heat will travel through transparent substances such as water. Therefore, directing a stream of water between the buildings is less effective than applying water directly to the exposed buildings. Furthermore, the distance between the exposed structures and the volume and location of the fire have much to do with prioritizing exposure protection. Wind direction and speed also play a role in this decision.

For the majority of defensive fire attack operations, master streams are the streams of choice. The IC should be aware that, if improperly placed, these very powerful streams could push the main body of fire toward areas that are not yet exposed, including into nearby buildings. Once master streams are in position, on-scene personnel must be controlled. Rarely are there too many fire fighters on the scene of an offensive operation.

However, when an unsuccessful offensive operation is discontinued and a defensive operation initiated, it is common to have more fire fighters than needed on the scene. Therefore, it is imperative for the IC to maintain strict control and accountability of on-scene personnel. Personnel inside the fire zone should be kept to a minimum, and offensive attack lines that are no longer needed should be disconnected. These and similar actions will reduce the temptation for fire fighters to freelance and attempt unsafe tactics.

PROPERTY CONSERVATION

Property conservation tactics can substantially reduce property loss. Property conservation is the last priority on the operational priority list; being the last priority should not be misconstrued, however, as being unimportant. Given the fact that fire departments are expected to save both lives and property, property conservation measures are an important part of the incident operation.

Life safety and extinguishment activities are assigned first, with property conservation being delayed until staffing is sufficient to address all life safety and extinguishment tasks. However, personnel should be assigned to specific property conservation duties, such as covering or removing exposed furniture as soon as possible. Also, it is important to remember that when life safety and extinguishment activities are performed properly, property damage is kept to a minimum. For instance, attacking the seat of the fire with the proper size and type of attack line—one that flows at or above the rate of flow—will quickly extinguish the fire and result in less water damage. Likewise, proper ventilation will direct smoke and heat away from the unexposed structure and contents. Once staffing permits, the IC should simultaneously attend to all three operational priorities during offensive fire attacks.

Overhaul

The purpose of overhaul is to ensure that the fire is completely extinguished. When sizing up the building prior to initiating overhaul operations, the IC must determine if the fire has severely damaged the building's structural components. If not, it should be safe to allow fire fighters to enter the building and complete overhaul duties. In some cases, where there is only minor damage to the structure and/or contents, it might be safe to allow the building's occupants to reenter.

To keep property damage to a minimum and to ensure that the fire is completely extinguished, overhaul must be accomplished in a well-planned, systematic manner. Walls, ceilings, and other structural components are checked and, if necessary, opened during overhaul. Opening concealed areas will release smoky, toxic, and smoldering materials into the work area. Ceilings, walls, and floors may contain asbestos or other harmful materials. Therefore, fire fighters and fire investigators operating inside a building during overhaul operations must be in full protective gear, including self-contained breathing apparatus (SCBA), until the building is completely free of smoke and airborne contaminants.

Ventilation

Ventilation is one of the IC's most important tactical considerations. In the past a tactic known as indirect application was popular. The indirect application method involves the application of a finely divided stream of water into an unventilated enclosure to gain maximum heat absorption from the water by converting it to steam. This tactic presents a hazard to occupants who have not escaped the building as it disrupts the heat balance making it much hotter at the floor level, and produces large quantities of steam within the enclosure.

Modern tactics call for a direct fire attack, coordinated with natural or mechanical ventilation. The direct attack involves applying water directly on the burning fuel. While the extinguishment crew applies water on the seat of the fire, a second crew ventilates the building to relieve the structure of heat and toxic products of combustion.

Proper ventilation can have a positive effect on all three operational priorities (life safety, extinguishment, and property conservation). Conversely, improper ventilation can adversely affect all three operational priorities and place both victims and rescuers in grave danger. The effects of proper and improper ventilation on the operational priorities are shown in Figure 13.1.5.

	Proper Ventilation	*Improper Ventilation*
Life Safety	• Pulls fire away from trapped occupants or their means of egress	• Draws fire toward victims or can extend fire through their exit path
Extinguishment	• Limits fire spread by channeling fire toward nearby openings and allows fire fighters to safely attack the fire	• Spreads the fire into previously undamaged areas • Can cause a backdraft or let the fire gain headway while lines are being advanced
Salvage	• Limits smoke, heat, and water damage by allowing an interior attack and removing the products of combustion, which are often the primary cause of damage	• Causes excessive and unnecessary damage • Does not relieve the damaging products of combustion but rather spreads them throughout the building

FIGURE 13.1.5 Effects of Proper and Improper Ventilation

SUMMARY

Pre-incident planning and standard operating procedures (SOPs) are essential elements of successful fireground operations. Pre-incident planning is particularly important in large and complex structures. Advance knowledge of some of the factors leading to strategic decisions before an incident occurs will reduce the information processing needs of the IC in the crucial early moments of an operation. Predesignating initial fireground operations using SOPs allows the IC to process information while a predictable course of action is taking place.

Next the IC develops an incident action plan based on an initial size-up and deploys forces to carry out the strategic objectives. The incident management system then provides the means to organize and manage the on-scene operation. The goal of this process is to fully utilize available resources in a safe, effective, and efficient manner.

This chapter is intended to provide a cursory overview of fireground operations. A complete discussion of this topic is beyond the scope and space limitations of this handbook. For a more detailed study of this and related topics, see the Bibliography.

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NFPA Codes, Standards and Recommended Practices

Reference to the following NFPA codes, standards and recommended practices will provide further information about fireground operations. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13E, *Recommended Practice for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA *101®*, *Life Safety Code®*
NFPA 170, *Standard for Fire Safety and Emergency Symbols*
NFPA 220, *Standard on Types of Building Construction*
NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*
NFPA 1142, *Standard on Water Supplies for Suburban and Rural Fire Fighting*
NFPA 1145, *Guide for the Use of Class A Foams in Manual Structural Fire Fighting*
NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*
NFPA 1521, *Standard for Fire Department Safety Officer*
NFPA 1561, *Standard on Emergency Services Incident Management System*
NFPA 1620, *Recommended Practice for Pre-Incident Planning*
NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*
NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments*

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Chapter 2

Organizing Rescue Operations

Richard Wright

Chapter Contents

Specialized Technical Rescue
Community Resource Planning (CRP)
Development of a CRP Database
CRP Agreements
Information Maintenance
Conceptualization and Planning Process
Technical Rescue Teams and Program Examples

Key Terms

community resource planning (CRP), confined space rescue, rescue operations, rope rescue, specialized technical rescue, technical rescue, technical rescue team, trench rescue

The term *rescue* literally means to remove from confinement or danger. Rescue operations constitute a significant part of the functions typically performed by emergency response organizations worldwide. Although some of the more "typical" rescue operations, such as rescuing someone from a burning building, are regarded by some as commonplace, emergency response agencies must be prepared for the more complex situations that require highly specialized training, techniques, and equipment. The complexity of rescue responses can vary greatly with the incident and may prove to be overwhelming to an unprepared response agency. Typically, the training and experience of these responding agencies will be the principal factors in a safe and successful outcome of a rescue operation.

See also Section 12, Chapter 1, "Planning for Public Fire-Rescue Protection"; and Section 13, Chapter 1, "Fireground Operations."

SPECIALIZED TECHNICAL RESCUE

Rescuer Safety

Whatever the circumstances surrounding an incident, perhaps the most important consideration is the preservation and safety of the rescue personnel. An appropriate motto for rescue personnel should be, "Don't become a victim." This advice is especially significant when we consider the number of well-intentioned rescuers who, while attempting to save someone else's life, have lost their own lives due to a total disregard for personal safety. Unfortunately, these heroic individual efforts will often thwart an otherwise effective team effort by adding yet another victim to an already difficult situation. Response organizations should establish a systems safety approach to all rescue operations in order to limit the risk to rescuers while maintaining a viable and effective response and operational capability. *Systems safety approach* may be defined as a definitive system within the scope of technical rescue operations, whereby all rescue equipment, procedures, and operating personnel are continually analyzed in accordance with an established set of safety guidelines to reduce the potential for system or operational failure. The analysis may include both visual and tactile checks of rescue systems and system components as well as confirmations of readiness for those responsible for operating them.

Typical Versus Specialized Technical Rescue

There are several forms of rescue in the world of emergency response. Some of those considered more "typical" may include interior search and rescue within the scope of fireground operations and extrication of entrapped occupants from automobiles involved in motor vehicle crashes. The term *typical* denotes an event that is common. Although each situation is slightly different, this

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regular occurrence allows the task to become somewhat routine. The emergency response organization generally finds it easier to maintain a desired level of competency with these types of rescue operations because they perform them so frequently.

Contrasted with the everyday rescue situations are those that require rescuers to have specialized training and techniques far above the norm in order to handle the emergency situations appropriately and without additional incident. These rescue operations may be seldom used but are vital when needed. Because of their infrequency of use, they may also pose the greatest risk to response agencies due to the potential for errors in judgment or inefficiencies in the level of skill associated with less familiar territory.

Until a few years ago, very little had been done to identify the most common of these situations and to determine the qualifications necessary for agencies performing these operations. However, the National Fire Protection Association (NFPA) has sought to address these concerns through the establishment and continuing development of two standards: NFPA 1670, *Standard on Operations and Training for Technical Search and Rescue Incidents,* and NFPA 1006, *Standard for Rescue Technician Professional Qualifications.*

NFPA 1670, *Standard on Operations and Training for Technical Search and Rescue Incidents*

NFPA 1670 focuses on *organizations* that wish to achieve a certain level of competency in one of several different technical rescue disciplines. This standard does not address the qualifications for individuals but rather establishes the level of operational capability needed for organizations wishing to perform technical rescue.

Forms of Technical Rescue. Although more disciplines may be added as the document evolves, there are currently seven different forms, or disciplines, of technical rescue identified within this standard, with plans to add additional disciplines in the next revision. The seven forms are as follows:

1. *Structural collapse rescue.* The location and removal of victims from collapsed buildings or other structures
2. *Rope rescue.* The use of rope and associated equipment to raise, lower, access, or otherwise move victims and rescuers in a specific environment; the methods used will vary based on the response area of the authority having jurisdiction
3. *Confined space rescue.* The removal of persons ill or injured within enclosed structures having specific characteristics, including all of the following:
   - Having limited access and egress
   - Able to be bodily entered (a person can get his or her entire body into the space)
   - Not intended for continuous human occupancy
   - Having one or more serious life or safety hazards or, in some cases, merely the potential to contain these hazards
4. *Vehicle and machinery rescue.* The extrication of persons entrapped in various transportation conveyances as well as fixed machinery
5. *Water rescue.* The rescue of persons in one or more of the following four water-related disciplines:
   - Dive
   - Ice
   - Surf
   - Swift water
6. *Wilderness search and rescue.* The location and removal of persons trapped or stranded within a wilderness environment
7. *Trench and excavation rescue.* The location and removal of persons from collapsed trenches or other excavations (Figure 13.2.1)

Note that most of the disciplines classify rescue operations within a specific environment; others (e.g., rope rescue) deal with techniques that are commonly used in almost every environment. Regardless of the discipline, each chapter identifies certain capabilities that must be developed by an organization in order to achieve one of three levels of technical ability: awareness level, operations level, or technician level. Through a hazard analysis and risk assessment, the authority having jurisdiction determines which of the technical rescue disciplines to acquire and the associated level of capability needed.

These requirements, along with those for incident response planning, operational and personal protective equipment, and safety, are all covered within the scope of the chapter on general requirements and are applicable to the responding organization regardless of the technical rescue discipline or disciplines and associated capability they decide to develop.

Levels of Capability. The following is a paraphrased synopsis of the general scope of each of the three levels of capability stated within NFPA 1670.

Awareness: Awareness-level organizations should be capable of recognizing and avoiding the hazard. Intervention is minimal, although allowed in certain circumstances (e.g., external retrieval of a person in a full-body harness that is attached to

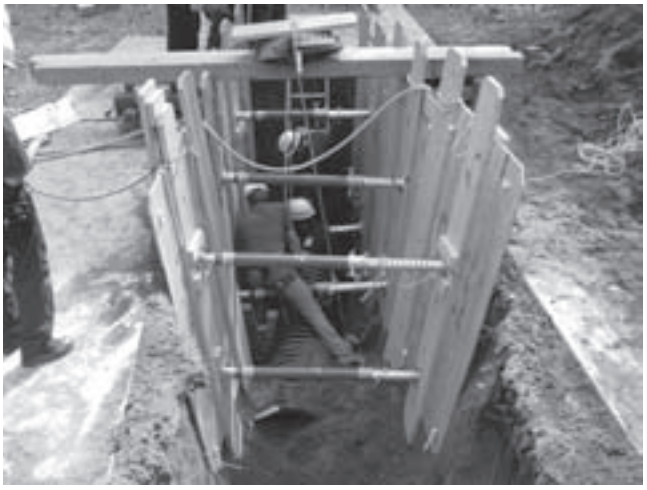

FIGURE 13.2.1 Trench Rescue (Photo courtesy of Wright Rescue Solutions, Inc.)

a mechanical winch device). One of the primary responsibilities of an awareness-level organization is to isolate the scene and call for appropriate qualified assistance to handle the situation.

Operations: Operations-level organizations are able to perform certain simpler rescues and are required to have all of the capabilities necessary for the awareness-level agency with additional skills and abilities as listed within that technical rescue discipline. The organization's ability to intervene is greatly enhanced, although the organization must still plan for the deployment and utilization of appropriate specialized assistance.

Technician: Technician-level organizations have determined that they will achieve the highest level of capability afforded by the standard in a particular technical rescue discipline. Although this is the highest level of capability, having this listed capability is not an assurance that the organization is able to handle every situation. There are obviously incidents so complex that even technician-level capabilities may not prepare the organization to mitigate the hazards without specialized assistance.

At each of the levels of capability, a successful technical rescue operation depends on assessing the need for, planning, and acquiring the necessary special equipment and services. Organizations should also note that many of the technical rescue disciplines cited in the standard require certain levels of compliance with other related disciplines. For instance, confined space rescue at the operations level requires both operations-level rope rescue and operations-level trench and excavation rescue, due to the close association of these three technical rescue disciplines.

NFPA 1006, *Standard for Rescue Technician Professional Qualifications*

In contrast to NFPA 1670, NFPA 1006 is directed toward assuring proficiency in *individual* rescue team members. Like NFPA 1670, this standard contains many of the same technical rescue disciplines, but there is currently only one level of capability—the technician level. Rescuers wishing to be compliant with this standard must complete a number of job performance requirements (JPRs) to achieve the status of "rescue technician." The standard utilizes a "core plus one" philosophy—that is, a person who wishes to become a specific type of rescue technician must complete a group of core JPRs that are common to all technical rescue disciplines plus the specific JPRs listed within the chapter for that particular technical rescue discipline. These core requirements are listed in Chapter 3 of the standard and involve four different areas:

1. *Site operations.* The activities to be undertaken at a specific site to manage the rescue incident
2. *Victim management.* The manner of treatment given to those requiring rescue assistance
3. *Maintenance, inspection, cleaning and repair of protective equipment, clothing, and tools*
4. *Ropes/rigging*

Although additional disciplines will be added to future editions, the rescue technician disciplines listed within the current version of NFPA 1006 are as follows:

- Structural collapse rescue
- Rope rescue
- Confined space rescue
- Vehicle and machinery rescue
- Surface water rescue
- Trench rescue

Although the core requirements are common to all of the specific rescue disciplines listed, a person cannot become a generic "rescue technician." Instead, he or she must become a technician specific to one or more rescue disciplines. Most of the technical rescue disciplines correspond to those listed in NFPA 1670. The greatest difference between the two standards is that NFPA 1006 applies to *individuals* and NFPA 1670 applies to *organizations.*

It is interesting to note that, at the time of this writing, the technical committee for NFPA 1006 is proposing significant changes to the structure of the document. In future editions, there may be sections for "Operations" and "Technician" levels for individuals within certain or all disciplines. To a degree, these individual qualifications would correspond with NFPA 1670's organizational requirements. If such changes are implemented, the name of the standard will be modified to a more appropriate title that will address professional qualifications for "technical rescuer" rather than "rescue technicians."

Technical Rescue Operations: The Bigger Picture

NFPA 1006 and 1670 deal with a variety of specific technical rescue disciplines, but many other types of specialized situations occur that require extraordinary expertise not commonly available in most communities. The following is a listing of some, but not all, specialized forms of rescue not addressed within NFPA 1670 and NFPA 1006:

- Urban search and rescue
- Hazardous materials (hazmat) rescue operations
- High-rise rescue
- Helicopter rescue
- Tunnel rescue
- Heavy rescue applicable to air, rail, and maritime
- Large-scale disaster response rescue (of both the natural and human variety)

The need for specialized rescue teams is typically based on a thorough analysis of community risk, which should typically include a review of both present conditions and past situations. Through this analysis, an acceptable level of risk may be determined. What is considered "acceptable" must be identified and balanced with the capabilities of the emergency response organization and the availability of additional specialized assistance. Armed with this information, the response community may take action to become better prepared for those rare but potentially devastating incidents.

The effectiveness of the preparation is based on the degree of awareness, knowledge, training, resources, and planning that has been achieved. Simply identifying the risk and actions necessary to address future incidents is not adequate preparation. Only through structured implementation of the action plan will the response organization be ready and capable of handling the specialized rescue operation.

The development of an effective technical rescue capability requires a thorough understanding of and commitment to every facet of need. The obvious necessities include appropriate training, personnel, and equipment required to safely mitigate the hazards and accomplish the rescue goals. In addition, a high degree of commitment (from all organizational levels, including both motivational and financial support for these programs), good logistical planning, and a thorough investigation into the legal ramifications are necessary to achieve a successful rescue operation. Based on the assessed risk, the cost of the support mechanism may be sizable in terms of money and time. It may very well add up to more than the average response organization can come up with by itself.

The development of specialized technical rescue teams will continue to be a major influencing factor in the national emergency service community. The need for the specialist versus the generalist approach toward operations will drive the development of this unique delivery system. The emergency service community must maintain both proficiency in the delivery of its services and the safety of the personnel who perform those various responsibilities. Identification of and planning for specialized rescue situations enhance incident response capability. The successful outcome of special rescue incidents relies on skills, training, planning, and deployment of adequately prepared and outfitted personnel and resources.

COMMUNITY RESOURCE PLANNING (CRP)

Common technical rescue incidents can often provide significant challenges that border on the overwhelming for smaller organizations. However, even the largest of emergency response agencies can be taxed by the demands of those rescues when associated with large-scale disasters. Despite the effective placement of an incident management system, the planning and logistical demands placed on incident managers, coupled with the requirements for meeting tactical deployment requests, can impede or impair the most efficient of organizations or departments. Because of the potential complexities associated with certain rescue situations and the variety of conditions and parameters that may be present at site-specific or large-scale disaster incidents, outside resources from other agencies and jurisdictions may have to be solicited, and then allocated and deployed when acquired, to enhance and support operational incident requirements.

The need for comprehensive community risk assessment has been well demonstrated and is considered a necessary first step in planning for the complexities of technical rescue. One component of community risk assessment planning focuses on the development of a database of outside resources that could be used to facilitate strategic and tactical objectives.

Through community resource planning (CRP) an agency or jurisdiction can identify internal deficiencies and provide a system for outside resource allocation so the agency's ability to respond to and operate at rescue incidents is augmented and so on-scene incident commanders will have the necessary resources. As with any incident response, the successful intervention, operation, and termination of the incident are directly related to the availability and deployment of resources, coupled with the effectiveness of the tactical assignment of these resources, the incident objectives, and the time management parameters.

A community resource plan delineates the resources needed for various anticipated rescue incidents and, thus, decreases the time required to identify, locate, and request the necessary resources. CRP is not a new concept within the fire and emergency service delivery system. Identifying and using mutual-aid agencies to augment daily fire, rescue, and emergency medical service (EMS) alarm assignments is commonplace in many jurisdictions. Supplementing local personnel and equipment with mutual-aid agency resources allows the receiving agency to deploy adequate resources at a given incident and increases its ability to mitigate the incident conditions.

The size, organizational structure, internal capabilities and resources, operating environment, and technical rescue capabilities of the department, along with the identified community risk hazards, will govern the development of the community resource plan. The magnitude, severity, and frequency of incidents will also dictate the methodology of the planning process.

The method used to identify and formulate the various resources and develop the community resource directory (CRD) is unique to each agency's community resource plan. The CRP and CRD augment the jurisdiction's capabilities during rescue operations and provide the framework and operating structure to build effective, safe, and timely rescue operations. The community resource plan establishes contacts; identifies procedures; and initiates agreements with local, jurisdictional, regional, and/or state and national entities for the procurement of identified resources. Through careful and thorough research and planning, a useful database can be developed that includes procurement procedures and memoranda of agreement.

DEVELOPMENT OF A CRP DATABASE

There are four basic functional areas that can be generally associated with the categories of resource planning for rescue response. These include but are not limited to (1) equipment, (2) supplies, (3) services, and (4) technical support.

Since the CRP and CRD are established and defined by the agency's or department's limitations or deficiencies, they are also directly related to the risk potential to which the community and jurisdiction are susceptible. The agency's current operational capabilities and its existing mutual-aid agreements and assignments are factored in with the community risk profile and analysis in order to determine the agency's limitations and deficiencies.

The resulting information forms the foundation for the research and development of an external resources database. The following lists provide an overview of items that could be included in the database. These lists are not all-inclusive.

Equipment

- Aerial lifts
- Air tools

- Backhoes
- Bulldozers
- Cellular phone companies
- Compressors
- Computer equipment supply and rental companies
- Concrete construction form suppliers
- Concrete cutting, breaking, and sawing firms
- Construction equipment
- Conveyors and material handlers
- Cranes, rigging/erectors
- Excavators
- Fire equipment and supply firms
- Flood lighting and searchlights
- Forklifts
- Generators
- Ham radio operators groups
- Hydraulic, pneumatic, and mechanical equipment
- Hydraulic tool distributors
- Light and heavy equipment firms
- Loaders, trenchers, skid-steer loaders
- Portable pumps
- Public works agencies
- Radio communications and equipment suppliers
- Sawing and cutting equipment
- Scaffolding
- Shoring
- Television and communications companies
- Tent suppliers and distributors
- Welding supply companies

Supplies

- Bag, burlap, and canvas manufacturers
- Battery distributors
- Building materials supply firms
- Chemical supply and distributor companies
- Compressed gases supply distributors
- Fire equipment and supply firms (local/regional)
- Fuel distributors
- Grocers and food suppliers
- Hardware supply firms
- Ice
- Lumberyards
- Medical supply companies
- Portable shelter and tent firms
- Power tool suppliers
- Rental service and supply companies
- Restaurants
- Utility companies

Services

- Aviation/helicopter services
- Awning and canopy manufacturers
- Baking companies
- Banquet and party supply companies
- Beverage suppliers and distributors
- Boat supply companies
- Bottled water distributors
- Buses: public, private, school district
- Catering companies
- Fencing companies
- Glass/windshield repair companies
- Ice distributors
- Motorcycle, all-terrain/ATV firms
- Portable restroom supply companies
- Rubbish/dumpster suppliers and haulers
- Tire distributors/repair firms
- Towing services
- Transportation services
- Tree- and debris-removal firms
- Trucking and leasing companies

Technical Support

- American Concrete Institute
- American Institute of Architects
- American Institute of Steel Construction
- American Public Works Association
- American Society of Consulting Engineers
- American Society of Safety Engineers
- Association of Building Contractors
- Association of Engineering Geologists
- Association of General Contractors
- Concrete Reinforcing Steel Institute
- Construction Specification Institute
- International Association of Bridge, Structural, and Ornamental Iron Workers
- Local and regional professional societies, associations, and trade groups
- National Society of Professional Engineers
- Physicians and surgeons professional associations

Contractors

- Demolition contractors
- Drilling and boring contractors
- Excavation contractors
- General contractors
- Heavy-equipment operators
- Steel erectors and fabricators
- Utility contractors

Consulting Engineers and Architects

- Architects
- Chemical engineers
- Civil engineers
- Construction engineers
- Environmental engineers
- Marine consultants
- Mechanical engineers
- Safety, health, and hygiene engineers
- Sanitary engineers
- Soil engineers
- Structural engineers
- Surveying engineers

Other

- Electric equipment and supply distributors
- Environmental and remedial contractors

- Hazardous waste abatement companies
- Highway and transportation agencies
- Industrial rescue teams
- Land surveyors
- Search-and-rescue dog handlers
- Wilderness search groups/associations

After the appropriate CRP database items are determined, the data collection process must identify local, regional, state, or other appropriate contacts, that is, companies, firms, agencies, or individuals that will ultimately provide the identified resources.

CRP AGREEMENTS

The next phase in the community resource plan requires the initiation, preparation, and adoption of appropriate types of agreements that clearly define the scope and conditions for the provision of services, equipment, and/or supplies established by the CRP. These agreements can take the following forms:

- Memoranda of agreement (MOA)
- Mutual-aid agreements (MAA)
- Service agreements (SA)
- Service retainer or contracts (SR/SC)

These agreements should be reviewed and approved by the legal council having jurisdiction within the department to ensure that the agreement and its parameters are equitable, concise, and that all liability issues have been addressed.

INFORMATION MAINTENANCE

The documents and data contained within the CRD "yellow pages" for complex incident management provide for the timely identification, call-out, and deployment of required resources, based on specific incident parameters. As with any other resource or reference document, the CRD and database should be updated and revalidated on an annual basis, so as to ensure that individual contact names, phone numbers, and conditions are valid and current. In addition, it is important to identify and document any changes in the resource listing that may affect its usefulness within the database. It is not uncommon for products, services, or materials to change or be withdrawn, especially when dealing with equipment, supply, or service companies, thereby compromising the dependability and/or function of the CRP.

Financial constraints, budget curtailments, staffing limitations and reductions, and limited resource acquisitions can prevent the initiation of programs or delay expansion of existing services. All proposals must be thoroughly assessed, properly planned, and adequately developed in order to effectively implement program goals. Technical rescue team development relies heavily on a thorough understanding of the issues surrounding the needs associated with such a team, coupled with an appropriate planning process that will ultimately lead an agency toward its established goal of enhanced rescue capabilities or deployment of specially trained and adequately outfitted personnel for technical rescue responses.

CONCEPTUALIZATION AND PLANNING PROCESS

The conceptualization and planning process is defined by the following 10 parameters. Each of the following must be thoroughly identified and addressed:

1. What type of specialized rescue team(s) is required?
2. What risk factors are present or potential within the jurisdiction?
3. What level of expertise currently exists within the organization?
4. How can system enhancement be best achieved?
   - Short term
   - Intermediate
   - Long term
5. What level or degree of technical capabilities can the plan achieve?
6. How can the services be best achieved?
   - Interdepartmental
   - Local
   - Regional
   - Countywide
   - Intercounty
   - Cooperative agreements with industrial or private teams
   - Outside agencies
7. What is the current projected level of interest of staff and personnel?
   - Interest
   - Motivation
   - Availability for staffing requirements
   - Previous levels of special/specific training
   - Employment/trade experience
   - Fire/rescue/EMS response experience
   - Educational background
   - Time commitment requirements
   - Personal risk factors
   - Dedication
8. What are the projected financial considerations and impacts?
   - Short term
   - Intermediate
   - Long term
9. What influencing regulations/standards must be complied with in the United States?
   - NFPA
   - OSHA
   - ANSI
   - NIOSH
   - DOT
   - DOL
   - API
   - NASAR
   - AAUS
   - Other
10. What is the time commitment for organization, development, and implementation of the program initiative?

Efforts must be made early in the conceptualization and planning process to ensure that the commitments and objectives being developed can be achieved within the organization. Initial interest may be high with any new program but may quickly wane as the demand of increased training and time commitments take their toll.

State/Federal Regulations

Regulatory impact of associated state/federal regulations, along with the influence of recognized national standards (such as those previously discussed of the NFPA), will also influence and help direct the planning, organization, and training process. These regulations and standards may assist the planning group or committee in identifying relevant issues that may impact the development of objectives, goals, and organizational scope for the subsequent team's deployment.

Research and Data Gathering

Efforts should be made by the relevant departments and agencies to research and obtain information from other departments and teams around the country in order to gain the wealth of information that can be analyzed and disseminated, with applicable information applied and augmented in order to meet with local conditions, factors, and team objectives. By eliminating redundancy in program planning and technical rescue team applications, this research and data-gathering network can save a tremendous amount of time and effort. Information gathered from departments that have developed technical response teams in the past added to information about operation methods and equipment and about changes to the methods and equipment as the result of field-proven experience can only help to provide a time-tested and time-proven foundation of data.

TECHNICAL RESCUE TEAMS AND PROGRAM EXAMPLES

Technical Rescue Teams

Departments and agencies that are considering developing specialized technical rescue teams must understand the long-term commitments and the level of dedication required to fulfill the operability and usefulness of team activation. A department or agency must identify the appropriate types and levels of technical service(s) necessary as the needs or risks within the jurisdiction or community change. In the 1980s, many jurisdictions hastily implemented hazardous materials teams as the wave of this concept and the need for a hazmat response swept through the emergency services only to find that the demands of time, financial support, and commitment levels necessitated a reevaluation of their level of commitment and degree of involvement.

Technical Rescue Program Examples

The following examples are typical technical rescue program elements that can facilitate the development of rescue operation capabilities for technical rescue specialties. Although the detailed skills are typical, the time frames for the initial delivery of such programs vary significantly from jurisdiction to jurisdiction. Unless regulated by standards, the time needed to run through the program should be determined by how long it takes to be thoroughly introduced to the necessary skills. This initial session must be followed with ongoing practice sessions and performance evaluations to ensure competency in the skills acquired. Initial training without ongoing practice will allow rescue personnel to forget the specialized techniques vital to the successful completion of a technical rescue operation.

The initial program delivery times represent those commonly seen within today's emergency response community. They should not be misconstrued to be a standard. An appropriate time frame for initial delivery and, more importantly, ongoing refresher training may vary significantly, depending on the learner's experience and level of routine emergency response activity. For instance, a fire fighter assigned to a busy rescue unit may require less formal continuing education time than does a volunteer industrial rescue team member who is normally assigned as an operator on a process unit. The fire fighter is more closely associated with the required skills on a routine basis, which may act as an on-the-job training session. This is not to imply that on-the-job trial and error is the most efficient way to train rescue team members but rather to illustrate that some people may require more formal training than others to achieve the same level of competency. Obviously, the time required to achieve competency will also vary based on the complexity of the subject matter presented.

These examples utilize NFPA 1670 as the basis for their content and outline all three levels of capability. NFPA 1670 provides a basic outline for course content in any one of the seven disciplines currently listed.

Rope Rescue. Rope techniques are a basic underlying skill for most other types of rescue. Most fire fighters will be familiar with basic rope techniques and knot tying as part of the basic fire fighter curriculum. An awareness of rope rescue operations can be taught to most rescuers in only a day (Figure 13.2.2).

FIGURE 13.2.2 Rope Rescue (Photo courtesy of Wright Rescue Solutions, Inc.)

The initial awareness-level training session should include basic size-up and recognition of the need for rope rescues, information on what resources are necessary for rope rescues and how to procure them, mechanisms and procedures for on-scene site management, recognition of general hazards associated with rope rescue and methods for mitigating them, and development and implementation of procedures for the identification and use of personal protective equipment.

An operations-level training session could cover rope rescue techniques such as knot tying, orientation to rope and rope-related equipment, rigging principles and edge protection, single- and multiple-point anchor systems, belay systems, lowering systems, rope/pulley mechanical advantage for raising, both ascending and descending a fixed rope, and using litter attendants (tenders) in rope rescue systems. With the prerequisite of awareness, it is likely to take three days (24 to 30 hours) to bring an average group to familiarity with operations-level systems and procedures. A combined awareness- and operations-level training session may be commonly presented in a five-day format.

With the awareness- and operations-level programs as prerequisites, the technician-level program can possibly be presented within approximately one week (40 hours). The technician-level program may cover more complex anchoring and rigging techniques, more advanced use of rope/pulley mechanical advantage, high-line rope systems, passing knots through components of the rescue system, and use of other, more specialized rope rescue techniques within the high angle environment. In NFPA 1670, the term *high angle* denotes those environments in which the load is supported predominantly by the rope rescue system. *Low angle* refers to a situation in which the load is supported mostly by itself and not by the rope rescue system.

All sessions, regardless of the time frame, should include a balanced regimen of both classroom and practical application. The rope techniques and systems must also be tailored to the environment in which they will be used. Although conceptually identical, system configurations and application may vary significantly based on the environment and their intended purpose (i.e., mountain rescues versus structural/urban rescues).

Unfortunately, response organizations often dismiss rope rescue technique training because of the absence of high-rise structures or mountainous terrain. A risk assessment may reveal an absence of elevated structures or terrain but it may still reveal the presence of a high degree of risk for incidents associated with removal of victims from depths such as pits, channels, or ravines. These situations may require the same, or greater, level of rope rescue capability as do emergency rescue situations within a community of high-rise structures.

Confined Space Rescue. NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program* and OSHA's 29 CFR 1910.146 define the term *confined space* similarly. Both standards say that a confined space must have all of the following characteristics:

- Be large enough and so configured that a person can enter and perform assigned work
- Have limited or restricted means for entry or exit
- Not be designed for continuous human occupancy
- Have a serious safety or health hazard or, in some cases, the mere potential for such

The hazards within confined spaces are no different from those experienced in other incidents on a regular basis. The real danger of rescue from confined spaces lies in the inability to readily escape those hazards. Because persons are forced to work within these sometimes cramped, poorly ventilated, and congested areas in close proximity to equipment and processes, the potential for incident is significant (Figure 13.2.3).

The OSHA regulation makes provision for those spaces in regulated industry that do not contain actual or potential hazards; the NFPA does not. Because the NFPA standards deal with response for rescue, they assume that any incident to which an emergency rescue team is called may have the potential for some sort of hazard within that space. This is the better-safe-than-sorry approach and constitutes sound reasoning. Another difference is that OSHA deals with worker safety and rescue occurring only within regulated facilities. The NFPA standards are intended for rescue operations regardless of their location, whether within a petrochemical facility or a backyard well. When comparing the two standards, we can see that they are similar in content but different in the scope of application. For this reason, terminology between the two standards may differ slightly even though the goals are similar.

An awareness of confined space rescue may usually be taught within a day. Content should include size-up of existing and potential conditions, initiation and establishment of contact with patients/victims, recognition and identification of hazards

FIGURE 13.2.3 Confined Space Rescue

associated with nonentry rescues, site control and scene management methods, recognition of confined spaces, and procedures for nonentry type rescues.

Organizational training at the operations level is associated with rescues from spaces whose configuration creates minimal potential for difficulty during entry-type rescues. For instance, spaces that have a clear line of sight with the patient/victim, contain no entanglement or other hazards, have an opening large enough to enter with a self-contained breathing apparatus (SCBA) worn in the manner intended by the manufacturer, and can accommodate two or more rescuers should present less difficulty for rescuers than a space that is greatly congested with an 18-in. (0.45-m) round entry portal and a patient/victim who is out of sight, 30 ft (9.1 m) from the entry point.

These training sessions should include certain basic rope systems required for safe entry and egress from less hazardous configurations, protective measures for rescue entrants, methods for assuring that the entrants can physically and psychologically handle working in tight spaces, understanding the duties of the various team functions within the scope of a confined space emergency, atmospheric monitoring procedures, use of appropriate packaging methods for these spaces, procedures for performing an entry-type rescue in these spaces, and some method of transferring patient/victim information to emergency medical services on delivery. Initial training sessions for the operations level are commonly taught within three to five days (24 to 40 hours).

Technician-level organizations should receive training to allow entry-type rescues into more complicated spaces. The initial training for technician-level organizations should include continuing size-up of changing conditions during rescue operations, information on medical surveillance programs for rescue team members, planning response for entry-type rescues into hazardous environments, and implementation of that planned response. Although program duration varies significantly, most technician-level programs are taught within two to five days (16 to 40 hours). Operations-level training should be considered a prerequisite for technician-level training.

SUMMARY

The daily demands imposed on fire and emergency service agencies can, at times, overwhelm the best-prepared and best-trained departments and their personnel. Support for specialized technical rescue operations is often neglected due to already overburdened response demands and budgetary constraints. Although it is true that these highly specialized techniques are not used as frequently as more routine basic rescue and fire suppression techniques, they have a no less vital role in saving human life within the realm of emergency response. Incidents of this type *will* occur. Rescue response organizations *must* have the skills and/or resources necessary for safe and effective deployment and subsequent operations. Departments and agencies should prepare appropriately to meet the challenges and demands associated with the risk potential and hazards present or projected for their jurisdiction and community.

The area of specialized technical rescue operations must be an integrated emergency system. Through proactive planning, community-based risk assessment and evaluation, preparedness training, resource development, and contingency planning, fire and emergency service agencies can effectively prepare and anticipate the manner in which they can handle incident responses, while maintaining the highest degree and consideration for the safety and well-being of their personnel and emergency responders. Technical rescue operations require a fine balance of training, knowledge, skills, risk management, and resources.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on rescue operations discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 220, *Standard on Types of Building Construction*
NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents*
NFPA 473, *Standard for Competencies for EMS Personnel Responding to Hazardous Materials Incidents*
NFPA 1001, *Standard for Fire Fighter Professional Qualifications*
NFPA 1006, *Standard for Rescue Technician Professional Qualifications*
NFPA 1201, *Standard for Providing Emergency Services to the Public*
NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*
NFPA 1521, *Standard for Fire Department Safety Officer*
NFPA 1561, *Standard on Emergency Services Incident Management System*
NFPA 1600, *Standard on Disaster/Emergency Management and Business Continuity Programs*
NFPA 1670, *Standard on Operations and Training for Technical Search and Rescue Incidents*
NFPA 1983, *Standard on Life Safety Rope and Equipment for Emergency Services*

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Chapter 3

Fire Streams

Michael A. Wieder

Chapter Contents

Fire Department Pumpers
Nozzles
Hose Line Fire Stream Calculations
Reaction Forces in Hose Lines, Nozzles, and Aerial Devices

Key Terms

aerial ladder, Bernoulli's equation, continuity equation, Darcy-Weisbach formula, elevating platform, fire department pumper, fire stream, flow rate, friction loss, hose line, hydraulics calculations, nozzle (solid stream), nozzle (spray), pump discharge pressure

Water has always been and remains the primary fire-extinguishing agent. Therefore, the movement of water from its source to the fire is a significant operation in most kinds of fire fighting. A typical fire department delivery system consists of the following:

- A water supply source
- One or more fire department pumpers
- Various types of fire hose to move the water from the source to the fire pump and from the pump onto the fire
- Nozzles for the final delivery

Fire apparatus driver/operators and fire officers must understand the basic principles of water movement through the aforementioned elements in order to establish effective fire suppression operations.

This chapter includes a description of the most important details of producing effective fire streams, including fire department pumpers, nozzles, hose line fire stream calculations, and reaction forces in hose lines and nozzles.

See also Section 13, Chapter 4, "Alternate Water Supplies"; and Section 15, Chapter 3, "Hydraulics for Fire Protection."

FIRE DEPARTMENT PUMPERS

Purpose and Components of Fire Department Pumpers

The primary purpose of fire department pumpers is to move water with adequate pressure from a source to the fire. Water supply sources can be divided into two basic groups: static and pressurized. Static sources include lakes, streams, ponds, rivers, and water shuttle dump tanks. Pressurized sources include fire hydrants, elevated storage tanks, or supply hoses from another fire department pumper. More information on water supply sources can be found in Section 15 of the *Fire Protection Handbook.*

In addition to pumping water for fire streams, fire department pumpers serve other functions, including transporting fire fighters; auxiliary extinguishing agents (foam, dry chemical agents, etc.); and other fire-fighting, emergency medical, and rescue equipment to an incident scene.

Fire pumps may also be installed on other types of fire apparatus, such as mobile water supply apparatus (tenders/tankers), aerial apparatus, aircraft rescue and fire-fighting (ARFF) vehicles, wildland apparatus, rescue vehicles, and fireboats. Design requirements for pumpers, aerial apparatus, water tender/tankers, and rescue vehicles are contained in NFPA 1901, *Standard for Automotive Fire Apparatus.* Design requirements for wildland fire apparatus are contained in NFPA 1906, *Standard for Wildland Fire Apparatus.* Design requirements for ARFF vehicles are contained in NFPA 414, *Standard for Aircraft Rescue and Fire-Fighting Vehicles.*

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Modern fire department pumpers, also called engines, wagons, and triples, are generally equipped with a centrifugal-type pump as their main fire pump. The centrifugal pump, a nonpositive displacement pump, consists essentially of one or more rotating discs called impellers. The impellers are mounted on a shaft that may turn from 2000 to 4000 rpm in order to transmit energy in the form of velocity to the water. A casing surrounds each impeller to collect the water and convert the velocity to pressure. A fire pump that has a single impeller on the shaft is called a *single-stage pump.* If the shaft has two impellers mounted on it, the pump is called a *two-stage pump.* Two-stage pumps have transfer valves that allow water to be discharged from one impeller to the next (called series operation; used for maximum discharge pressures) or through both impellers at the same time (called parallel operation; used for maximum discharge volumes). Centrifugal pumps also have the equipment necessary to provide pressure regulation and to prime the pump when using a static water supply source.

Piston, rotary gear, and rotary vane pumps are positive displacement-type pumps that provide a fixed amount of water with each movement of the pump. They are no longer used as the primary pumps on fire apparatus. They are, however, used for special purposes, such as high-pressure booster pumps and as priming pumps for centrifugal pumps.

Characteristics of Fire Pumps

Two important characteristics of fire pumps are (1) the discharge volume and (2) the discharge pressure. They make up the final output of the pump. The discharge volume is the amount of water pumped per unit of time, such as gallons per minute (gpm) or liters per minute (L/min). Apparatus may be equipped with flowmeters to measure the discharge volume being provided by the pump. The discharge pressure is the pressure at which the pump is discharging water. The discharge pressure is measured in pounds per square inch (psi) or kilopascals (kPa). It is also sometimes measured in bar with 1 bar equal to 100 kPa. The discharge pressure (as well as the intake pressure, if any) is measured by pressure gauges attached to the pump piping.

Pumps are rated according to their discharge volume at 150 psi (1035 kPa) when drafting through 20 ft (6 m) of intake hose at a lift of 10 ft (3 m). Apparatus fire pumps are also required to provide 70 percent of their rated capacity at 200 psi (1380 kPa) and 50 percent of their rated capacity at 250 psi (1725 kPa). These ratings are summarized in Table 13.3.1. Common capacities for pumps used on modern fire apparatus range from 500 gpm (2000 L/min) to 2500 gpm (10,000 L/min), although larger-capacity pumps are available.

Pumping operations start with water from either a pressurized source, such as a hydrant, or from a static water source, such as a pond. Drafting operations are required in the latter case. The factors that affect the height (lift) limitations to which water can be drafted and the flow rate are interrelated. These factors are as follows:

- Atmospheric pressure
- Water temperature
- Friction loss in the intake hose and strainer
- Velocity energy

TABLE 13.3.1 Standard Pumps

Rated Flow Rate		70% of Rated Flow Rate		50% of Rated Flow Rate	
gpm @ 150 psi	*L/min @ 1035 kPa*	*gpm @ 200 psi*	*L/min @ 1380 kPa*	*gpm @ 250 psi*	*L/min @ 1725 kPa*
500	2000	350	1400	250	1000
750	3000	525	2100	375	1500
1000	4000	700	2800	500	2000
1250	5000	875	3500	625	2500
1500	6000	1050	4200	750	3000
1750	7000	1225	4900	875	3500
2000	8000	1400	5600	1000	4000
2250	9000	1575	6300	1125	4500
2500	10,000	1750	7000	1250	5000

The lift at a given flow rate can be determined by

Lift = Atmospheric pressure minus water vapor pressure
minus strainer and intake hose friction loss
minus velocity energy

Atmospheric pressure varies from day to day according to the weather conditions and the elevation above sea level. Since drafting is essentially the creation of a partial vacuum in the pump and intake hose, the total energy available for moving the water from the source to the pump is the atmospheric pressure. The nominal atmospheric pressure, 14.696 psi (101.333 kPa) absolute at sea level, usually rounded to 14.7 psi (100 kPa) absolute, can theoretically provide a lift of almost 34 ft (10.5 m). However, remember atmospheric pressure drops about 0.5 psi (3.4 kPa) for each 1000 ft (305 m) above sea level.

As mentioned earlier, fire pumps receive their capacity ratings based on their drafting ability through 20 ft (6 m) of intake hose at a lift of 10 ft (3 m). As the amount of lift is increased, the discharge volume capacity of the pump will be decreased accordingly. Under actual conditions, a pump in excellent condition and able to pump its rated capacity at sea level should be able to draft and pump at least some water at lifts of up to 25 ft (7.6 m).

Often atmospheric pressure is given in inches of mercury. If this is the case, it must be converted to feet of water using:

$$h_w = 1.13 h'_{\text{Hg}}$$

where

h_w = Feet of water

h'_{Hg} = Inches of mercury

The vapor pressure reduces the amount of vacuum that is possible and, consequently, reduces the total lift. Vapor pressure depends on the water temperature and is measured in terms of feet (meters) of water. Table 13.3.2 lists common values of vapor pressure as a function of water temperature.

Another factor affecting the total lift is the friction loss in the suction hose and the strainer. The friction loss in the suction hose depends on the hose diameter, hose length, and the

TABLE 13.3.2 Vapor Pressure

Water Temperature		Vapor Pressure	
°F	°C	ft of water	kPa
60	16	0.59	1.8
80	27	1.20	3.6
100	38	2.20	6.6
120	49	3.90	11.7

TABLE 13.3.3 Suction Hose Friction Losses per 10 ft (3 m) Length

Suction Hose Diameter		Friction Loss			
in.	mm	psi	kPa	ft	m
4	100	$0.022q^{2a}$	$0.0109q^{2b}$	$0.0519q^2$	$0.00978q^2$
4½	115	$0.013q^2$	$0.0061q^2$	$0.0291q^2$	$0.00054q^2$
5	125	$0.007q^2$	$0.0034q^2$	$0.0162q^2$	$0.00033q^2$
6	150	$0.003q^2$	$0.0014q^2$	$0.0066q^2$	$0.00014q^2$

[a] q = gpm/100.
[b] q = L/min/100.

flow rate of the water. Equations for the friction loss in various sizes of suction hose are shown in Table 13.3.3. The friction loss through the strainer is a function of the flow rate and the strainer diameter. The friction equations for the various strainer sizes are shown in Table 13.3.4.

TABLE 13.3.4 Suction Strainer Friction Losses (Loss = Cq^2)

Suction Hose Diameter		Friction Loss			
in.	mm	psi	bar	ft	m
4	100	$0.0418q^{2a}$	$0.0202q^{2b}$	$0.0966q^2$	$0.00229q^2$
4½	115	$0.0367q^2$	$0.0178q^2$	$0.0848q^2$	$0.00142q^2$
5	125	$0.0224q^2$	$0.0108q^2$	$0.0517q^2$	$0.00093q^2$
6	150	$0.009q^2$	$0.0043q^2$	$0.0207q^2$	$0.00054q^2$

[a] q = gpm/100.
[b] q = L/min/100.

The velocity head also affects the total lift of the pump. The velocity head is given by $V^2/2g$, where V is the water velocity in feet per second (meters per second) and g is the acceleration due to gravity and is equal to 32.2 ft/sec^2 (9.81 m/sec^2). The velocity can be found by using the continuity equation, $Q = VA$ where Q is the flow rate in cubic feet per second (cubic meters per second) and A is the cross section of the suction hose in square feet (square meters). However, the flow rate is usually given in gallons (liters) per minute and the suction hose diameter is in inches (millimeters). Consequently, Table 13.3.5 can be used to determine the velocity head in the suction hose without tedious calculations.

To find the friction loss in parallel suction hoses (FL_P), divide the friction loss (FL_T) by the square of the number of lines, that is,

$$FL_P = \frac{FL_T}{\#\ \text{lines}^2}$$

TABLE 13.3.5 Velocity Head (V) for Suction Hose, ft (m) Water

Flow, Q		Suction Hose Diameter (D), in inches and millimeters											
		3.0 in.	76 mm	3.5 in.	88 mm	4.0 in.	100 mm	4.5 in.	114 mm	5.0 in.	125 mm	6.0 in.	150 mm
gpm	L/min	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m
100	378	0.32	0.09	0.17	0.05	0.10	0.03	0.06	0.02	0.04	0.01	0.02	0.0
200	757	1.28	0.39	0.69	0.21	0.40	0.12	0.25	0.05	0.17	0.05	0.08	0.0
300	1136	2.88	0.88	1.55	0.47	0.91	0.28	0.57	0.17	0.37	0.11	0.18	0.0
400	1514	5.11	1.56	2.76	0.84	1.62	0.49	1.01	0.31	0.66	0.20	0.32	0.0
500	1892	7.99	2.44	4.31	1.31	2.53	0.78	1.58	0.48	1.04	0.32	0.50	0.1
600	2271	11.51	3.51	6.21	1.90	3.64	1.11	2.57	0.78	1.49	0.45	0.72	0.2
700	2650			8.45	2.58	4.96	1.51	3.09	0.94	2.03	0.62	0.98	0.3
800	3028			11.04	3.36	6.47	1.97	4.04	1.23	2.65	0.81	1.28	0.3
900	3407					8.19	2.50	5.11	1.56	3.36	1.02	1.62	0.4
1000	3785					10.11	3.08	6.31	1.92	4.14	1.26	2.00	0.6
1100	4163					12.24	3.73	7.64	2.33	5.01	1.53	2.42	0.7
1200	4542							9.09	2.78	5.97	1.82	2.88	0.8
1300	4921							10.67	3.25	7.00	2.13	3.38	1.0
1400	5300							12.37	3.78	8.12	2.47	3.92	1.1
1500	5677									9.32	2.84	4.49	1.3

For example, with two parallel suction hose lines of the same size and length, divide the calculated suction hose friction loss by 4.

In solving the lift equation, all units must be compatible, that is, converted to the equivalent feet (meters) of water or kilopascals. Atmospheric pressure is usually given in terms of inches of mercury (or kilopascals). Table 13.3.6 can be used to convert the atmospheric pressure to the equivalent pressure in feet (meters) of water.

For SI units: 1 in. Hg = 3.385 kPa; 1 psi = 6.895 kPa; 1 ft = 0.305 m.

EXAMPLE: Find the lift in feet of water (or kilopascals, which can be converted to meters of water by multiplying by 9.84).

Atmospheric pressure = 27.00 in. of mercury (91 kPa)

Water temperature = 60°F (16°C)

Flow rate = 1100 gpm (4163 L/min)

TABLE 13.3.6 Inches of Mercury Vacuum Compared with Height of Water and Corresponding Pressure

Vacuum	Pressure		
in. Hg	*psig*	*psia*	*ft water*
0.00	0.000	14.696	0.000
1.00	–0.491	14.205	1.132
2.00	–0.982	13.714	2.263
3.00	–1.473	13.223	3.395
4.00	–1.965	12.731	4.527
5.00	–2.456	12.240	5.658
6.00	–2.947	11.749	6.790
7.00	–3.438	11.258	7.922
8.00	–3.929	10.767	9.054
9.00	–4.420	10.276	10.185
10.00	–4.912	9.784	11.317
11.00	–5.403	9.293	12.449
12.00	–5.894	8.802	13.580
13.00	–5.385	8.311	14.712
14.00	–6.876	7.820	15.844
15.00	–7.367	7.329	16.975
16.00	–7.858	6.838	18.107
17.00	–8.350	6.346	19.239
18.00	–8.841	5.855	20.370
19.00	–9.332	5.364	21.502
20.00	–9.823	4.873	22.634
21.00	–10.314	4.382	23.766
22.00	–10.805	3.891	24.897
23.00	–11.297	3.399	26.029
24.00	–11.788	2.908	27.161
25.00	–12.279	2.417	28.292
26.00	–12.770	1.926	29.424
27.00	–13.261	1.435	30.556
28.00	–13.752	0.944	31.687
29.00	–14.244	0.453	32.819
29.92	–14.696	0.000	32.862

Suction hose diameter (strainer diameter) = 5 in. (125 mm)

Suction hose = Two lengths, 10 ft (3 m) each

SOLUTION: U.S. customary units

From Table 13.3.6, atmospheric pressure of 27.00 in. of mercury equals 30.556 ft of water.

From Table 13.3.2, vapor pressure at 60°F equals 0.59 ft of water.

Using Table 13.3.3, the friction loss for 10 ft of 5 in. suction hose is $0.0162q^2$. Q = 1100 gpm. However, q is in 100s of gpm and $Q/100 = q$.

Therefore, q = 11.

Thus: Friction loss = $(0.0162)(11)^2$ = 1.96 ft for 10 ft
or (2)(1.96) = 3.92 ft for 20 ft

From the suction strainer equation listed in Table 13.3.4:

$$\text{Friction loss} = 0.0517q^2$$

Where q = 11 as in the suction hose equation

$$\text{Friction loss} = (0.0517)(11)^2 = 6.26 \text{ ft}$$

The velocity head (from Table 13.3.5) is 5 ft.

Therefore, lift = 30.56 – 0.59 – 4 – 6.26 – 5 = 14.71 ft.

SOLUTION: Metric units

Atmospheric pressure = 91 kPa

From Table 13.3.2, vapor pressure at 16°C equals 1.7 kPa.

Using Table 13.3.3, the friction loss for 3 m of 125 mm suction hose is $0.0034q^2$. Q = 4163 L/min. However, q is in 100s of L/min, and $Q/100 = q$.

Therefore, q = 41.63.

Thus: Friction loss = $(0.0034)(41.63)^2$ = 5.89 kPa for 3 m
or (2)(5.89) = 11.78 kPa for 6 m

From the suction strainer equation listed in Table 13.3.4:

$$\text{Friction loss} = 0.0108q^2$$

Where q = 41.63 as in the suction hose equation

$$\text{Friction loss} = (0.0108)(41.63)^2 = 18.71 \text{ kPa}$$

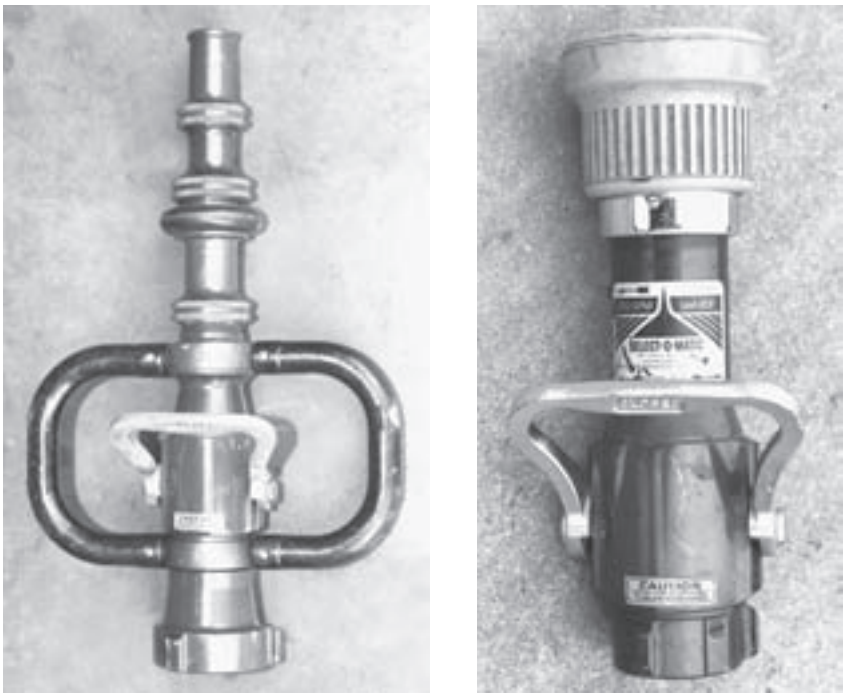
The velocity head (from Table 13.3.5) is 14.9 kPa.

Therefore, lift = 91 – 1.7 – 11.78 – 18.71 – 14.9 = 43.91 kPa
(converting to meters, 43.91/9.84 = 4.46 m)

NOZZLES

The purpose of a nozzle is to shape the stream and convert pressure energy to velocity (kinetic) energy. In this way, the water can be applied to the fire in the appropriate quantity and from an adequate distance. The two most common basic types of fire service nozzles are solid stream and spray (fog) nozzles (Figure 13.3.1).

The governing hydraulic characteristics of nozzles are flow rate, diameter, and nozzle pressure. Flow rate is the amount of water flowing out of the nozzle per unit time and is measured in gallons per minute or liters per minute. Nozzle pressure is most



(a) (b)

FIGURE 13.3.1 (a) Solid-Stream Nozzle; (b) Spray Nozzle

commonly measured at the tip of the nozzle in units of pounds per square inch (psi) or kilopascals (kPa).

Solid-Stream Nozzles

Solid-stream nozzles are classified according to the nozzle tip diameter. The diameters range from ¼ to 2½ in. (6 to 65 mm) or larger. The nozzle sizes are generally available in ⅛ in. (3 mm) graduations. Nozzles up to 1⅛ in. (29 mm) or perhaps 1¼ in. (32 mm) are generally considered to be for "handlines," that is, those held manually. As a rule of thumb, handline solid-stream nozzles are usually operated at a nozzle pressure of 50 psi (345 kPa).

Solid-stream nozzles larger than about 1¼ in. (32 mm) have such large reaction forces that they must be mechanically restrained. These are called master stream nozzles. They may be mounted to the apparatus, affixed to a portable base, or attached to an aerial device. As a rule of thumb, master stream solid-stream nozzles are operated at a nozzle pressure of 80 psi (552 kPa).

Solid streams are useful where extreme range is desired, where it is necessary to penetrate soft material, such as peat, or when thermal degradation of spray streams prevents proper penetration to the seat of the fire. Solid streams are also less affected by wind currents than are spray streams. Solid-stream nozzles are also the preferred nozzle for use with compressed air foam streams (CAFS).

Solid-stream nozzles are also useful in measuring waterflows, since both their diameter and discharge pressure can be easily measured. The discharge pressure is measured by holding a Pitot tube and gauge in the fire stream (Figure 13.3.2).

The Pitot tube is inserted in the stream at a point that is equal to one-half the diameter of the nozzle tip away from the tip. From this information, the flow rate can be computed. It is related to the diameter and nozzle pressure by the following equations:

$$Q = 29.7d^2\sqrt{NP}$$

FIGURE 13.3.2 A Typical Pitot Tube and Gauge

where

Q = Flow rate (gpm)

d = Nozzle diameter (inches)

NP = Nozzle pressure (psi)

For SI units, the flow equation is:

$$Q = 0.0666 d_m^2 \sqrt{NP_m}$$

where

Q = Flow rate (L/min)

d_m = Nozzle diameter (mm)

NP_m = Nozzle pressure (kPa)

Theoretical flows from various nozzles at different nozzle pressures can be found in Section 15, Chapter 3, "Hydraulics for Fire Protection."

Solid streams, with a lower surface-area-to-volume ratio, do not have as good heat-transfer characteristics as do spray nozzles and, consequently, are not as effective in absorbing heat. Another disadvantage of a solid stream is that it is a better conductor of electricity than a spray stream.

Spray (Fog) Nozzles

Spray nozzles, or fog nozzles as they are sometimes called, produce varying degrees of a water spray pattern. Most modern spray nozzles are adjustable from a straight stream to a very wide-angle spray pattern. The stream pattern angle is customarily measured at the angle between the outer limits of the pattern core and expressed in terms of degrees (e.g., a 30 degree pattern or a 60 degree pattern).

Spray nozzles are generally classified according to the size of their hose coupling and their flow rate in gallons per minute (liters per minute). The flow rate capacity of a spray nozzle will depend on the design of the particular nozzle. There are two basic designs for spray nozzles: (1) fixed gallonage nozzles and (2) automatic nozzles. Fixed gallonage nozzles are designed to flow a set number of gallons of water at a specified nozzle discharge pressure. Most of these nozzles have rated flow volumes when the nozzle pressure is at 100 psi (690 kPa). However, some newer nozzles are designed to operate at lower nozzle pressures. These are particularly useful when operating from a standpipe system in high-rise fire-fighting operations as the pressures may not be available to supply nozzles at 100 psi (690 kPa). Fixed gallonage nozzles may be designed to allow only one specified flow rate, or they may have an adjusting collar that allows the nozzle to be set for one of four or five predetermined flow settings.

Automatic nozzles are the most common type of spray nozzles in use today. Automatic nozzles, also referred to as constant pressure nozzles, are basically variable flow nozzles with pattern-change capabilities and the ability to maintain the same nozzle pressure. If the volume supplied to the nozzle changes, the automatic nozzle maintains approximately the same nozzle pressure and pattern. This feature is made possible by a baffle that moves automatically, varying the spacing between the baffle and the throat.

A stream from an automatic nozzle can "look good" but may not be supplying sufficient water for extinguishment or protection. It should be the goal of the driver/operator to provide an acceptable flow of water at the discharge pressure for which the nozzle is designed. As with fixed gallonage nozzles, most automatic nozzles are designed for a 100 psi (690 kPa) discharge pressure.

The discharge volume available from a spray nozzle will vary depending on the size of the nozzle and hose line and the pressure being supplied from the fire pump. Keep in mind, for example, that a 1½ in. (38 mm) automatic spray nozzle may be used on either a 1½, 1¾, or 2 in. hose line. Table 13.3.7 shows typical flow rates from automatic spray nozzles.

Flow rates are determined experimentally, either by a flowmeter or by flowing water into a tank and measuring the time for a given quantity. Flow rate information is obtained from the manufacturer and, as mentioned previously, is usually reported as the flow rate at 100 psi (690 kPa) nozzle pressure.

Flows for other pressures may be obtained by using the flow equation:

$$Q = 29.7 d^2 \sqrt{NP}$$

and finding the equivalent nozzle diameter d_e, using

$$d_e = \sqrt{Q / 29.7 \sqrt{NP}}$$

where

Q = Flow rate (gpm)

29.7 = A constant

d_e = Equivalent nozzle diameter (in.)

NP = Nozzle pressure (psi)

For SI units the flow formula is

$$Q = 0.0666 d_m^2 \sqrt{NP_m}$$

and finding the equivalent nozzle diameter d_e, using

$$d_e = \sqrt{Q / 0.0666 \sqrt{NP_m}}$$

where

Q = Flow rate (L/min)

0.0666 = A constant

TABLE 13.3.7 Flows from Typical Automatic Spray Nozzles

	Flow Rate	
Nozzle Type	*gpm*	*L/min*
¾ to 1 in. (19 to 25 mm) automatic nozzle	10–60	38–227
1½ in. (38 mm) automatic nozzle	30–250	114–946
2½ in. (64 mm) automatic nozzle	125–350	473–1,325
Master stream automatic nozzles	350–10,000	1,325–37,854

d_e = Equivalent nozzle diameter (mm)

NP_m = Nozzle pressure (kPa)

HOSE LINE FIRE STREAM CALCULATIONS

The end goal of most fire service hydraulics calculations is for the driver/operator to determine the necessary discharge pressure setting on the fire pump needed to supply the desired amount of water to the nozzle(s) or the next pumper in a relay pumping operation. This pressure setting is most commonly referred to as the *pump discharge pressure (PDP),* although in the past it was also known as the "engine pressure." The methods for mathematically calculating the pump discharge pressure are described here. However, algebraic manipulation of the equations can yield any variable, providing the other quantities are known.

Special techniques, known as "field hydraulics" or "rule of thumb," are used by driver/operators for approximate results. The methods shown here give more precise results, but they are generally too involved for field applications. Details on rule-of-thumb fire stream calculations can be found in the fire-fighting hydraulic texts listed in the bibliography.

The calculation of the pump discharge pressure depends on a number of variables, including the required nozzle pressure, friction loss in the hose layout, and pressure loss or gain due to elevation changes. As previously discussed, the required nozzle pressure will depend on the type of nozzle being used. Handline solid-stream nozzles are operated at 50 psi (345 kPa), master stream solid-stream nozzles are operated at 80 psi (552 kPa), and all standard spray nozzles are generally operated at 100 psi (690 kPa). There are some spray nozzles now available that are designed to operate at 75 psi (518 kPa). The hose friction loss is a function of the hose diameter, hose length, discharge volume, and any appliances, such as wyes or monitors, used in the hose layout.

Elevation pressure (*EP*) is the loss or gain of potential energy due to elevation changes between the pump and the nozzle. This is determined by the equations:

$$EP = 0.434h \text{ (SI units: } EP_m = 9.81h_m)$$

where

EP = Elevation pressure in psi (kPa)

h = Elevation change or head in ft (m) of water

For ease of calculation, in the fire service these equations are commonly rounded as follows:

$$EP = 0.5h \text{ (SI units: } EP_m = 10h_m)$$

The basis of these calculations revolves around three fundamental hydraulic principles: Bernoulli's equation, Darcy-Weibach equation, and continuity equation.

Bernoulli's Equation

This equation is a special form of conservation of energy. For a pumper hose line system this becomes:

$$PDP = NP + FL \pm EP$$

where

PDP = Pump discharge pressure in psi (kPa)

NP = Nozzle pressure in psi (kPa)

FL = Friction loss in psi (kPa)

EP = Elevation pressure in psi (kPa)

Darcy-Weisbach Equation

$$FL = (fV^2L)/(2gD)$$

where

g = Acceleration due to gravity, ft/sec^2 (m/sec^2)

f = Friction factor, a dimensionless number

L = Hose length in ft (m)

D = Hose diameter in in. (mm)

V = Velocity in ft/sec

Continuity Equation

This equation is a special form of conservation of mass.

$$Q = VA$$

where

Q = Flow rate, ft^3/sec (m^3/sec)

V = Velocity, ft/sec (m/sec)

A = Area, ft^2 (m^2)

These equations can be manipulated to result in friction loss equations and a modern version of the Underwriters equation.[1]

Friction loss is the loss of energy resulting from the internal friction between the moving particles of water and the friction between the water and the lining of the hose. The friction loss depends on water viscosity, flow rate, hose diameter, hose length, and the roughness characteristics of the hose lining. Although the viscosity is partly a function of the water temperature, the change is insignificant in the ranges of the temperature of water commonly used for fire fighting. The flow volume, hose diameter, and hose length are variables that are determined by the fire-fighting requirements. The roughness of the hose lining cannot be easily measured and is generally determined experimentally and reported as the friction factor. Consequently, all variables, except the flow volume, hose diameter, and hose length, are embodied in the friction factor, *f,* of the Darcy-Weibach equation and in the continuity equation. Putting all constants into one constant factor results in the modern fire service friction loss equation:

$$FL = cq^2l$$

where

FL = Friction loss in the total hose layout in psi or kPa

c = A coefficient based on the size and type of hose

q = Flow of water through the entire layout in hundreds of gallons per minute or hundreds of liters per minute ($q = Q/100$).

l = Length of hose in hundreds of feet or meters ($l = L/100$)

The suggested coefficients for various sizes and types of hose are shown in Table 13.3.8. These coefficients should be considered averages for the size and type of hose to which they are applied. The friction factor for modern fire hose varies from manufacturer to manufacturer. For more specific information on the exact coefficient for any particular brand of hose, contact the manufacturer of the hose.

The preceding equation replaces the old, less accurate, and more complex equation $FL = (2q^2 + q)l$. The old equation required all sizes of hose, other than 2½ in. (65 mm), to first be converted to equivalent lengths of 2½ inch (65 mm) hose before being plugged into the equation. However, the old equation was based on hose technology from the 1930s and 1940s. The results produced by this equation did not reflect the actual friction loss in modern (smoother) fire hose. Those interested in the old equation are referred to the bibliography.

The following are examples of calculating pump discharge pressure using the information described earlier:

EXAMPLE: Calculate the pump discharge pressure necessary to adequately supply 300 ft (90 m) of 2½ in. (65 mm) rubber-lined hose that is equipped with a solid-stream handline nozzle with a 1¼ in. (32 mm) tip. The position of the nozzle is 10 ft (3 m) above the level of the pump.

SOLUTION: U.S. customary units

$$Q = 29.7d^2\sqrt{NP}$$

$$Q = 29.7(1.25)^2\sqrt{50}$$

$$Q = 29.7(1.5625)(7.07)$$

$$Q = 328 \text{ gpm}$$

$$q = 328/100 = 3.28$$

$$FL = cq^2l$$

$$FL = (2)(3.28)^2(300/100)$$

$$FL = (2)(10.7584)(3)$$

$$FL = 64.55 \text{ or } 65 \text{ psi}$$

$$EP = 0.5h$$

$$EP = (0.5)(10) = 5 \text{ psi}$$

$$PDP = NP + FL \pm EP$$

$$PDP = 50 + 65 + 5$$

$$PDP = 120 \text{ psi}$$

TABLE 13.3.8 Recommended Friction Loss Coefficients for Single Hose Lines

Hose Diameter			Friction Loss Coefficient	
in.	*mm*	*Hose Type*	*psi*	*kPa*
¾	19	Booster	1100	1741
1	25	Booster	150	238
1¼	32	Booster	80	127
1¼	32	Linen	127	201
1½	38	Rubber lined	24	38
1½	38	Linen	51.2	81
1¾ with 1½ couplings	45 with 38 couplings	Rubber lined	15.5	24.6
2	50	Rubber lined	8	12.7
2	50	Linen	12.5	19.8
2½	65	Linen	4.26	6.75
2½		Rubber lined	2	3.17
2¾ with 3 couplings	70 with 77 couplings	Rubber lined	1.5	2.36
3 with 2½ couplings	77 with 65 couplings	Rubber lined	0.80	1.27
3 with 3 couplings	77 with 77 couplings	Rubber lined	0.677	1.06
3½	90	Rubber lined	0.34	0.53
4	100	Rubber lined	0.2	0.305
4½	115	Rubber lined	0.1	0.167
5	125	Rubber lined	0.08	0.138
6	150	Rubber lined	0.05	0.083

SOLUTION: Metric units

$$Q = 0.0666 d_m^2 \sqrt{NP_m}$$
$$Q = 0.0666(32)^2\sqrt{345}$$
$$Q = (0.0666)(1024)(18.5742)$$
$$Q = 1267 \text{ L/min}$$
$$q = 1267/100 = 12.67$$
$$FL = cq^2l$$
$$FL = (3.17)(12.67)^2(90/100)$$
$$FL = (3.17)(160.5289)(0.9)$$
$$FL = 457.99 \text{ or } 458 \text{ psi}$$
$$EP = 10h$$
$$EP = (10)(3) = 30 \text{ kPa}$$
$$PDP = NP + FL \pm EP$$
$$PDP = 345 + 458 + 30$$
$$PDP = 833 \text{ kPa}$$

When using the foregoing formulas to determine the pump discharge pressure for wyed hose lines of the same size and length, keep in mind the following considerations:

1. The friction loss for the total hose lay is the sum of the losses in the supply hose, *one* of the wyed lines, and the wye appliance (if applicable).
2. When determining the flow in the hose line that is supplying the wye, remember to add the flows from *all* of the wyed lines.
3. If the total flow through the wye appliance is less than 350 gpm (1325 L/min), do not consider the friction loss through wye to be important. If the flow exceeds this amount, add 10 psi (70 kPa) to the friction loss in the hose.

EXAMPLE: Calculate the pump discharge pressure necessary to adequately supply 400 ft (120 m) of 4 in. (100 mm) hose that is wyed off into two 150 ft (45 m), 2½ in. (65 mm) rubber-lined attack hose lines. Each attack line is equipped with a spray nozzle that is designed to flow 250 gpm (946 L/min) at 100 psi (690 kPa). There is no elevation change in the hose lay.

SOLUTION: U.S. customary units

$$FL = cq^2l$$
$$FL_{2½ \text{ inch}} = (2)(250/100)^2(150/100)$$
$$FL_{2½ \text{ inch}} = (2)(6.25)(1.5)$$
$$FL_{2½ \text{ inch}} = 18.75 \text{ or } 19 \text{ psi}$$
$$FL_{4 \text{ inch}} = (0.2)(500/100)^2(400/100)$$
$$FL_{4 \text{ inch}} = (0.2)(25)(4)$$
$$FL_{4 \text{ inch}} = 20 \text{ psi}$$
$$FL_{\text{Total}} = FL_{2½ \text{ inch}} + FL_{4 \text{ inch}} + \text{Appliance loss}$$
$$FL_{\text{Total}} = 19 + 20 + 10$$
$$FL_{\text{Total}} = 49 \text{ psi}$$
$$PDP = NP + FL_{\text{Total}} \pm EP$$
$$PDP = 100 + 49 + 0$$
$$PDP = 149 \text{ psi}$$

SOLUTION: Metric units

$$FL = cq^2l$$
$$FL_{65 \text{ mm}} = (3.17)(946/100)^2(45/100)$$
$$FL_{65 \text{ mm}} = (3.17)(89.49)(0.45)$$
$$FL_{65 \text{ mm}} = 127.66 \text{ or } 128 \text{ kPa}$$
$$FL_{100 \text{ mm}} = (0.305)(1892/100)^2(120/100)$$
$$FL_{100 \text{ mm}} = (0.305)(357.97)(1.2)$$
$$FL_{100 \text{ mm}} = 131 \text{ kPa}$$
$$FL_{\text{Total}} = FL_{65 \text{ mm}} + FL_{100 \text{ mm}} + \text{Appliance loss}$$
$$FL_{\text{Total}} = 149 + 131 + 70$$
$$FL_{\text{Total}} = 350 \text{ kPa}$$
$$PDP = NP + FL_{\text{Total}} \pm EP$$
$$PDP = 690 + 350 + 0$$
$$PDP = 1040 \text{ kPa}$$

If determining the friction loss in wyed lines that have differing flows, hose sizes, or hose lengths, calculate the friction loss in each of the wyed lines and use the highest result added to the supply line and appliance loss (if applicable) in determining the total friction loss for the hose layout and ultimately the required pump discharge pressure.

The friction loss formula described previously may also be used when determining the friction loss in siamesed lines of equal length. However, in this case a different set of coefficients is required. The coefficients for siamesed lines are contained in Table13.3.9. When determining the friction loss in siamesed lines using this formula, q should be determined by using the total flow through both lines.

EXAMPLE: Calculate the pump discharge pressure necessary to adequately supply a portable master stream device equipped with a 500 gpm (1892 L/min) spray nozzle operated at 100 psi (690 kPa) being supplied by two 3 in. (77 mm) with 3 in. (77 mm) couplings, each 600 ft (180 m) long. There is no elevation change in the hose lay, but assume that the master stream appliance creates a 10 psi (70 kPa) pressure loss.

SOLUTION: U.S. customary units

$$FL = cq^2l + \text{Appliance loss}$$
$$FL = (0.17)(500/100)^2(600/100) + 10$$
$$FL = (0.17)(25)(6) + 10$$
$$FL = 25.5 + 10$$

TABLE 13.3.9 Recommended Friction Loss Coefficients for Siamesed Lines of Equal Length

Number of Hose Lines and Their Diameters in in. (mm)	Friction Loss Coefficient *psi*	*kPa*
Two 2½ in. (65 mm)	0.50	0.789
Three 2½ in. (65 mm)	0.22	0.347
Two 3 in. (77 mm) with 2½ in. (65 mm) couplings	0.20	0.316
Two 3 in. (77 mm) with 3 in. (77 mm) couplings	0.17	0.268
One 3 in. (77 mm) with 2½ in. (65 mm) couplings, one 2½ in. (65 mm)	0.30	0.473
One 3 in. (77 mm) with 3 in. (77 mm) couplings, one 2½ in. (65 mm)	0.27	0.426
Two 2½ in. (65 mm), one 3 in. (77 mm) with 2½ in. (65 mm) couplings	0.16	0.253
Two 3 in. (77 mm) with 2½ in. (65 mm) couplings, one 2½ in. (65 mm)	0.12	0.189

FL = 35.5 or 36 psi

$PDP = NP + FL \pm EP$

PDP = 100 + 36 + 0

PDP = 136 psi

SOLUTION: Metric units

$FL = cq^2l$ + Appliance loss

$FL = (0.268)(1892/100)^2(180/100) + 70$

$FL = (0.268)(357.97)(1.8) + 70$

FL = 172.68 + 70

FL = 242.68 or 243 kPa

$PDP = NP + FL \pm EP$

PDP = 690 + 243 + 0

PDP = 933 kPa

Attempting to mathematically calculate the pressure loss or pump discharge pressure in siamesed lines of unequal length is an extremely complicated process that involves advanced mathematical techniques. Because these situations are so rare in real-life operations, a detailed description of these operations is omitted here. Consult the references listed in the bibliography of this section for more information on this matter.

REACTION FORCES IN HOSE LINES, NOZZLES, AND AERIAL DEVICES

When water is discharged from a hose line, there are two reaction forces acting on the line: (1) hose line reaction and (2) nozzle reaction. Both contribute in varying degrees to the total reaction that is present in any hose nozzle flow configuration. For purposes of simplicity, each is treated separately in this chapter.

Hose Line Reaction Forces

Reaction forces occur in hose lines when the direction of waterflow is changed by a bend in the hose. Between the hydrant and nozzle, the velocity is constrained in the hose and the acceleration is zero, as shown by the equation

$$Q = AV$$

where

Q = The flow rate

A = The cross-sectional area

V = The average velocity

Figure 13.3.3 illustrates a typical handline situation where enough push must be applied at the bend to resist the reaction force F_3. There is no problem where the hose bends off the ground.

Figures 13.3.4 and 13.3.5 are charts by which values of the reaction F_3, in pounds force, can be directly determined. To obtain reactions in other sizes of hose, Figure 13.3.4 includes a table of conversion factors to use in calculating reaction forces, expressed in pounds force, in hose of other diameters; and Fig-

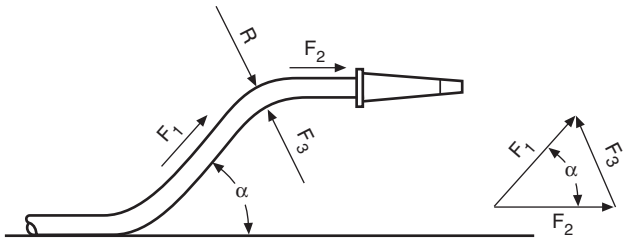


FIGURE 13.3.3 Reaction in a Hose Line

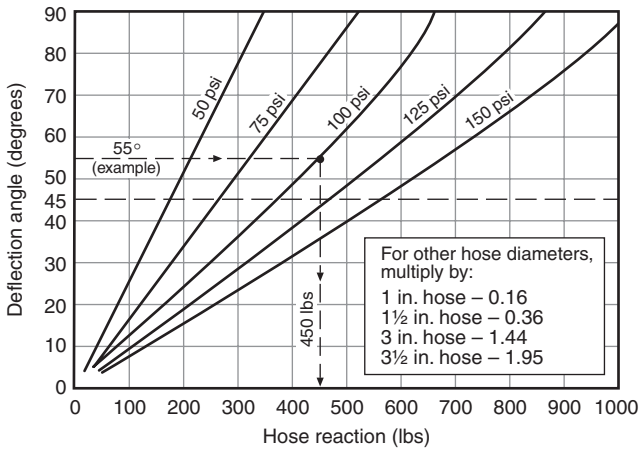


FIGURE 13.3.4 Reaction Forces in 2½ in. Hose

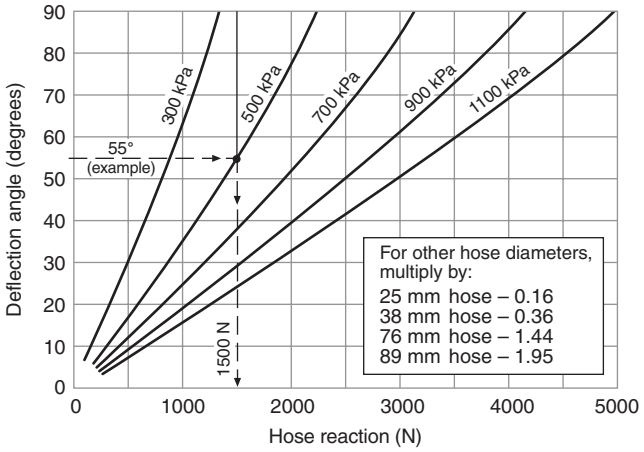


FIGURE 13.3.5 Reaction Forces in 65 mm Hose

ure 13.3.5 includes a table of conversion factors to use in calculating reaction forces, expressed in newtons (N), in hose of other diameters.

EXAMPLE: What is the reaction at a 55 degree bend in 1½ in. (38 mm) hose if the pressure is 100 psi (690 kPa)?

SOLUTION: On the deflection angle side, move horizontally from the 55 degree bend to intersection with the 100 psi (690 kPa) curve. From there go down vertically to the reaction scale and read 450 lb (204 kg). From Figures 13.3.4 and 13.3.5, note that the factor for 1½ in. (38 mm) hose is 0.36. Multiplying 450 (204 kg) by 0.36, the answer is 162 lb (73 kg).

Nozzle Reaction

Water discharging from a nozzle produces a reaction that is opposite the flow of water and known as nozzle reaction. As flow and pressure are increased, the nozzle reaction increases. Nozzle reaction of solid-stream nozzles may be calculated by means of the following formula:

$$NR = 1.5d^2NP$$

where

NR = Nozzle reaction (lb)

1.5 = A constant

d = Nozzle diameter (in.)

NP = Nozzle pressure (psi)

For SI units:

$$NR = 0.0015d_m^2NP_m$$

where

NR = nozzle reaction (N)

0.0015 = A constant

d_m = Nozzle diameter (mm)

NP_m = Nozzle pressure (kPa)

EXAMPLE: Determine the nozzle reaction created when a 1¼ in. (32 mm) solid-stream nozzle is being operated at a discharge pressure of 50 psi (345 kPa).

SOLUTION: U.S. customary units

$$NR = 1.5d^2NP$$

$$NR = (1.5)(1.25)^2(50)$$

$$NR = (1.5)(1.5625)(50)$$

$$NR = 117.19 \text{ lb}$$

SOLUTION: Metric units

$$NR = 0.0015d_m^2NP_m$$

$$NR = (0.0015)(32)^2(345)$$

$$NR = (0.0015)(1024)(345)$$

$$NR = 529.92 \text{ N}$$

Another formula that may be used for both solid-stream and spray nozzles is:

$$NR = 0.0505Q\sqrt{NP}$$

where

NR = Nozzle reaction (lb)

0.0505 = A constant

Q = Nozzle discharge (gpm)

NP = Nozzle pressure (psi)

For SI units:

$$NR = 0.0226Q_m\sqrt{NP_m}$$

where

NR = Nozzle reaction (N)

0.0226 = A constant

Q_m = Nozzle discharge (L/min)

NP_m = Nozzle pressure (kPa)

EXAMPLE: Find the nozzle reaction when a 250 gpm (946 L/min) spray nozzle is operating at 100 psi (690 kPa).

SOLUTION: U.S. customary units

$$NR = 0.0505Q\sqrt{NP}$$

$$NR = (0.0505)(250)(\sqrt{100})$$

$$NR = (0.0505)(250)(10)$$

$$NR = 126.25 \text{ lb}$$

SOLUTION: Metric units

$$NR = 0.0156Q_m\sqrt{NP_m}$$

$$NR = (0.0226)(946)(\sqrt{690})$$

$$NR = (0.0226)(946)(26.27)$$

$$NR = 561.64 \text{ N}$$

Reaction Forces in Aerial Ladder and Elevating Platform Streams

The reaction of master streams, either solid or spray, discharged from aerial ladders or elevating platforms creates a tremendous amount of stress on the aerial device. Some of these stresses, such as leverage effects and displacement of centers of gravity, are magnified as the aerial device is further extended. Thus, the stability of the whole structure could be threatened if the aerial device is extended, or if the elevated master stream is operated, beyond its design limitations. Likewise, a sudden loss of pressure when a hose line bursts or a pump stops may cause a whipping action that can result in damage to the aerial device. Because there are many variable forces acting on aerial ladders, elevating platforms, or water towers in service, it is quite impractical to devise tables of specific reactions.

Fire fighters must be particularly cautious with detachable ladder pipes and hose that are used in conjunction with light-duty aerial ladders. In this circumstance, the detachable ladder pipe should always be operated in line with the main beams or trusses of the aerial ladder. Light-duty aerial ladders have little resistance to torsional effects, so detachable ladder pipes should be incapable of horizontal travel exceeding 15 degrees. Rotation of the ladder turntable is the correct way to rotate the stream from these ladder pipes. When possible, these detachable ladder pipes should be operated from the turntable of the apparatus using sets of ropes to control the up-and-down motion of the nozzle. This eliminates the need to place a fire fighter in the precarious position of directing the stream from the tip of the ladder.

Care should be used also in elevating and lowering the stream, because this changes the direction of the thrust on the ladder mechanism. The fly ladder should not be raised or lowered while a ladder pipe is discharging, and under no circumstances should the vehicle be moved with the ladder pipe discharging. All such streams should be gated to permit movement of the ladder and vehicle without shutting down the pump.

Finally, consult the apparatus manufacturer's recommendation when choosing the size of hose to be used to supply the detachable ladder pipe. Most aerial ladders are designed for a single 3 or 3½ in. supply hose to be run up the ladder to the ladder pipe. Using a larger hose could result in overloading the ladder, thus risking a catastrophic failure of the device.

In general aerial ladders with piped waterways and elevating platforms are equipped with remote-controlled nozzles that are capable of a wider range of motion than are detachable ladder pipes. The remote controls for these devices will typically not allow the nozzle to operate a stream outside of the safe operating area. Driver/operators should be familiar with the recommended operating procedures and safe loading parameters for these devices.

SUMMARY

The effective supply of water through hose lines to nozzles is one of the most basic tenets of fire fighting and municipal fire protection. Fire apparatus driver/operators must be able to effectively calculate the required flows and pressures needed to adequately supply fire fighters operating attack lines. This calculation is important from both an operational and a safety standpoint. The information contained in this chapter allows fire-fighting professionals to realistically calculate waterflow pressure and quantity through hose lines and nozzles. It also allows for the calculation of the resultant reaction pressure that will be created at the nozzle. The application of this information will assist in providing useful pre-incident planning and fire scene tactical operations.

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Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire streams discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 414, *Standard for Aircraft Rescue and Fire-Fighting Vehicles*
NFPA 1901, *Standard for Automotive Fire Apparatus*
NFPA 1906, *Standard for Wildland Fire Apparatus*
NFPA 1911, *Standard for Service Tests of Fire Pump Systems on Fire Apparatus*
NFPA 1961, *Standard on Fire Hose*
NFPA 1962, *Standard for the Inspection, Care, and Use of Fire Hose, Couplings, and Nozzles and the Service Testing of Fire Hose*
NFPA 1964, *Standard for Spray Nozzles*

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Chapter 4

Alternate Water Supplies

Laurence J. Stewart

Chapter Contents

Sources of Alternate Water Supplies
Occupancy Hazard Classification
Structure and Site Survey
Natural Water Sources
Developed Sources of Water
Agreements/Permits
Estimating Available Water Supply Capacity
Water Supply Vehicles, Water Shuttle Operations, and Drivers

Key Terms

alternate water supply, cistern, construction (type of), dry hydrant, minimum water requirement, occupancy hazard classification, water shuttle operations, water source (developed), water source (natural), water supply (mobile)

This chapter provides information for the planning and utilization of a water supply or supplies that the fire department creates and uses for fire suppression. Fire suppression cannot be accomplished without water sources and the ability to move the water by some selected method. The water in the "supply" created by all types of alternative water supply methods should always be considered nonpotable water.

The development of alternative water supplies is a four-step planning process centering on answers to the following questions:

- How much water is required?
- Where is the water?
- How can dry hydrants help?
- How can water be moved to the fire?

This chapter does not cover (1) the providing of water to any government-operated or government-subsidized water system that is either out of water or has its supply drastically curtailed or (2) the providing of water to forest fire suppression units.

See also Section 15, Chapter 1, "Fixed Water Storage Supplies for Fire Protection"; and Section 15, Chapter 6, "Water Distribution."

SOURCES OF ALTERNATE WATER SUPPLIES

A fire department operating without a water system with hydrants or one with a very limited number of hydrants has two means of getting water: (1) from supplies on the fireground, which can be constructed or natural, or (2) from supplies transported to the scene. Alternative water supplies for fire department operations come from water obtained directly from either static water, flowing water, or water contained within some type of storage tank. Water from these sources is not part of a pressurized water system. Alternative water supply operations can also encompass the use of water from fire hydrants that are part of a pressurized water system. In such a case, the water from the hydrants is "loaded" into mobile water supply apparatus and shuttled to a distant fire scene, or it may be moved both within and beyond the "boundaries" of the pressurized water system through the use of hose. The distinctive feature of this type of water use is that the fire department provides the water by means of hose, varying types of pumping apparatus, and/or mobile water supply apparatus. (The latter will be referred to in this chapter as MWS apparatus.)

Proper planning in developing water supplies for fire fighting requires that built-up areas and water supply needs be identified within the response area. The fire service has always experienced fire control difficulties in isolated areas. One of the main problems is the lack of an adequate water supply. The availability of an adequate amount of water for control and extinguishment is an important consideration for fire chiefs and a factor that influences the majority of their fire-fighting decisions. A portion of the training of suburban and rural fire departments emphasizes the need for the conservation of the meager water supply available in many areas. A limited amount of water at a working fire challenges all phases of fire fighting. Once the areas with waterflow needs have been identified, a building/site survey should be conducted to determine the water supply needed for fire protection.

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Minimum water supplies are determined by the following criteria:

- Classification of occupancy hazard
- Classification of construction
- Structure dimensions
- Exposures, if any

In order to establish the necessary quantity of water available for fire suppression, various criteria must be converted into numerical equivalencies. Tables 13.4.1 and 13.4.2 provide the data for establishing the variables used in the water supply formula. The following occupancy hazard classes number and Table 13.4.2 classification number will be used in the formulas calculating minimum water requirements.

OCCUPANCY HAZARD CLASSIFICATION

Occupancies are divided into categories based on the risk and the development of fire spread. The occupancy hazard classification number is a mathematical factor to be used in calculating minimum water supplies. The lowest occupancy hazard classification number is 3; it is assigned to the highest hazard group. The highest occupancy hazard classification number is 7; it is assigned to the lowest hazard group. NFPA 1142, *Standard on Water Supplies for Suburban and Rural Fire Fighting,* provides the minimum water supply requirements, based on occupancy classification, construction classification, and total volume of the structure.

Occupancy Hazard Class 3

Occupancies in Class 3 are considered severe hazard occupancies, in which quantity and combustibility of contents are high. A fire in a Class 3 occupancy would tend to develop very rapidly and have high rates of heat release. Examples of this classification include occupancies having conditions similar to the following:

- Cereal or flour mills
- Combustible hydraulics facilities
- Cotton picker and opening operations (cotton gins)
- Die casting facilities
- Explosives and pyrotechnics manufacturing and storage facilities
- Feed and gristmills
- Flammable liquid spraying facilities
- Flow coating/dipping facilities
- Linseed oil mills
- Manufactured homes/modular building assembly facilities
- Metal extruding facilities
- Plastic processing facilities
- Plywood and particle board manufacturing facilities
- Printing plants using flammable inks
- Rubber reclaiming facilities
- Sawmills
- Solvent extracting facilities
- Facilities with straw or hay in bales
- Textile picking facilities
- Facilities upholstering with plastic foams

Occupancy Hazard Class 4

Occupancies in Class 4 are high hazard occupancies, in which quantity and combustibility of contents are high. Examples of this classification include occupancies having conditions similar to the following:

- Barns and stables (commercial)
- Building materials supply storage facilities
- Department stores
- Exhibition halls, auditoriums, and theaters
- Feed stores (without processing)
- Freight terminals
- Mercantile facilities
- Paper and pulp mills
- Paper processing plants
- Piers and wharves
- Repair garages
- Rubber products manufacturing and storage facilities
- Warehouses (e.g., those used for furniture, general storage, paint, paper, and woodworking industries)

Occupancy Hazard Class 5

Occupancies in Class 5 are considered moderate hazard occupancies, in which the quantity or combustibility of contents is

TABLE 13.4.1 SI Metric Unit Conversion Factors for Occupancy Classifications

Occupancy Classification Number	*SI Metric Unit Conversion Factor*
3	0.0224
4	0.0299
5	0.0373
6	0.0448
7	0.0523

TABLE 13.4.2 Construction Classification Numbers

0.5	*0.75*	*1.0*	*0.75*	*1.50*
Type I construction (fire resistive)	Type II construction (noncombustible)	Type III construction (ordinary)	Type IV construction (heavy timber)	Type V construction (wood frame)

expected to develop moderate rates of spread and heat release. Examples of this classification include occupancies having conditions similar to the following:

- Amusement centers
- Clothing manufacturing plants
- Cold storage warehouses
- Confectionery product warehouses
- Farm storage buildings (e.g., corn cribs, dairy barns, equipment sheds, hatcheries)
- Laundries
- Leather goods manufacturing plants
- Libraries (with large stockroom areas)
- Lithography shops
- Machine shops
- Metalworking shops
- Nurseries (plant)
- Pharmaceutical manufacturing plants
- Printing and publishing plants
- Restaurants
- Rope and twine manufacturing plants
- Sugar refineries
- Tanneries
- Textile manufacturing plants
- Tobacco barns
- Unoccupied buildings

Occupancy Hazard Class 6

Occupancies in Class 6 are considered low hazard occupancies, in which the quantity or combustibility of contents is expected to develop relatively low rates of spread and heat release. Examples of this classification include occupancies having conditions similar to the following:

- Armories
- Automobile parking garages
- Bakeries
- Barber or beauty shops
- Beverage manufacturing plants/breweries
- Boiler houses
- Brick, tile, and clay product manufacturing plants
- Canneries
- Cement plants
- Churches and similar religious structures
- Dairy products manufacturing and processing plants
- Doctors' offices
- Electronics plants
- Foundries
- Fur processing plants
- Gasoline service stations
- Glass and glass products manufacturing plants
- Horse stables
- Mortuaries
- Municipal buildings
- Post offices
- Slaughterhouses
- Telephone exchanges
- Tobacco manufacturing plants
- Watch and jewelry manufacturing plants
- Wineries

Occupancy Hazard Class 7

Occupancies in Class 7 are considered light hazard occupancies, in which the quantity or combustibility of contents is expected to develop a relatively light rate of spread and heat release. Examples of this classification include occupancies having conditions similar to the following:

- Apartments
- Colleges and universities
- Clubs
- Dormitories
- Dwellings
- Fire stations
- Fraternity or sorority houses
- Hospitals
- Hotels and motels
- Libraries (except large stockroom areas)
- Museums
- Nursing and convalescent homes
- Offices (including data processing)
- Police stations
- Prisons
- Schools
- Theaters without stages

STRUCTURE AND SITE SURVEY

Information needed to compute the minimum water supplies that should be collected during the structure/site survey (Figure 13.4.1) includes the following:

- Area of all floors, including attics, basements, and crawl spaces
- Height between floors or crawl spaces and in attics from floor to ridgepole
- Construction materials used in each structure, including walls, floors, roofs, ceilings, interior partitions, stairs, and so forth

FIGURE 13.4.1 On-Site Survey of Structure

- Occupancy (occupancies) of structures
- Occupancy (occupancies) of yard areas
- Exposures to structures and yard storage and distances between them
- Fire protection systems, such as automatic and manual protection systems, hydrants, yard mains, and other protection facilities
- On-site water supplies, including natural and constructed sources of water

Classification of Construction

There are five recognized types of construction, with the type of materials used in each type of construction listed and the type of construction assigned a numerical number. The assigned number becomes another mathematical factor to be used in the formula for calculating minimum water supplies. The slowest burning or lowest hazard type of construction (i.e., fire resistive) is construction classification number 0.5. The fastest burning or highest hazard type of construction (i.e., wood frame) is construction classification number 1.5. Where there is more than one type of construction in a structure, the higher classification number should be used for the entire structure.

Construction classifications listed in Table 13.4.2 have been simplified for quick use. If more complete definitions are needed, refer to NFPA 220, *Standard on Types of Building Construction.*

Calculating Minimum Water Requirements

Before determining such things as the type of pumpers and MWS apparatus to use and how to pump water from a source, the fire department should focus on the water requirements of the response area. This means determining how much water is required to extinguish a fire at each structure in the response area. To calculate this amount, three pieces of information are needed: the materials stored in the building, the building's construction, and the size (total volume) of the structure. This information can be gathered during the on-site surveys of the buildings in the response area outside of the pressurized water system. (The formulas were developed by an NFPA 1142 committee.)

Structures without Exposure Hazards: Minimum water supply

$$= \frac{\text{Total volume of structure}}{\text{Occupancy hazard classification number}} \times \text{Construction classification number}$$

Structures with Exposure Hazards: Minimum water supply

$$= \frac{\text{Total volume of structure}}{\text{Occupancy hazard classification number}} \times \text{Construction classification number} \times 1.5$$

NATURAL WATER SOURCES

Using natural water sources, such as streams, springs, lakes, ponds, and wells, provides a relatively inexpensive quantity of water. Reliability must also be considered when planning water supply distribution. Research may be necessary to determine that a source can supply the minimum water requirements in all seasons and during all variations in weather. Inspection of water sources is an ongoing process. Records should be updated with any seasonal fluctuations, flood or drought conditions, and freezing problems noted.

Streams

Streams, including rivers, bays, creeks, and irrigation canals, can represent a continuously flowing source of substantial capacity. When considering water from flowing streams as potential water sources, the fire department should take into account the following factors:

- *Flowing capacity.* The stream should deliver water in capacities compatible with the water requirements determined necessary for the hazard.
- *Climatic characteristics.* Streams that deliver water throughout the year and are not susceptible to drought are desirable for fire protection. However, if such streams are not available, a combination of supplies might be necessary. In many sections of the country, streams cannot be relied on during drought seasons. If the stream is subject to flooding or freezing, special measures might be necessary to make the stream usable under such conditions (Figure 13.4.2). Similar circumstances might exist during wet periods or when the ground is covered with snow.
- *Accessibility.* A water site should provide the necessary access to ensure availability to the site in all normally expected weather conditions encountered in the area 24 hours per day, 365 days per year. Distance and terrain from the all-weather road to the source should be such as to make the water readily available. In some cases, special equipment should be used to obtain the water, especially in areas where the water surface may become frozen. Where roadways to the water supply are provided, they should be constructed with a suitable approach for fire department access.

Ponds

Ponds tend to offer lower quantities of water but may be numerous in the area. Reliability issues are similar to those of streams. Ponds can include lakes or farm ponds used for watering livestock, irrigation, fish culture, recreation, or other purposes while serving a secondary function for fire protection. Valuable information concerning the design of ponds can be obtained from county agricultural agents, cooperative extension offices, county engineers, and so forth. Most of the factors listed relative to streams are pertinent to ponds, with the following items to be considered:

- The minimum annual level should be adequate to meet the water supply needs of the fire problem the pond serves.
- Silt and debris can accumulate in a pond or lake, reducing its actual capacity, while its surface area and level remain con-

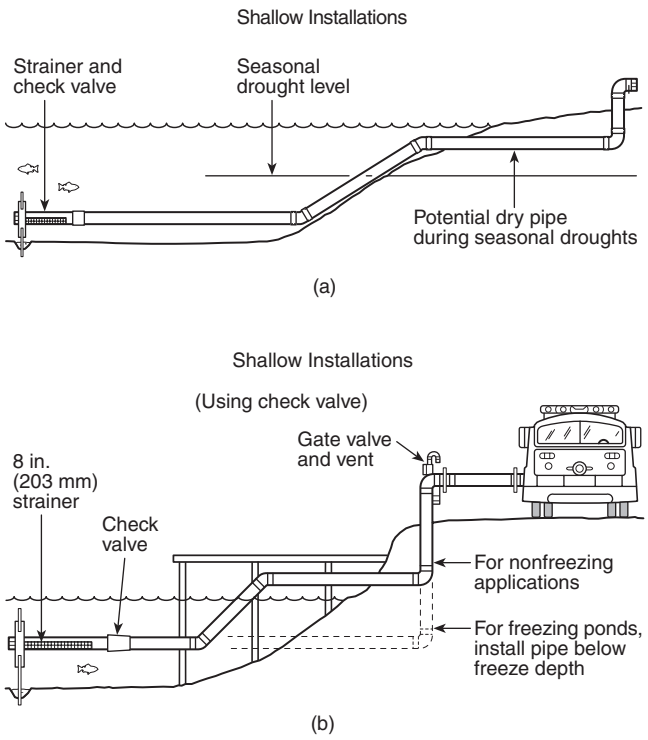

FIGURE 13.4.2 Dry Hydrant Installation (a) Shallow Stream Installation Based on Seasonal Drought (b) Shallow Stream Installation Based on Seasonal Drought and Freezing Conditions (Courtesy of Stan Merrett, ETT, L.L.C.)

stant. This can provide a deceptive impression of capacity and calls for at least seasonal inspections.

- Accessibility should always be considered. Many recreational lakes are provided with access by roads, driveways, and boat-launching ramps and are available for fire department use. Some large lakes, formed by a dam on a river, might have been constructed for purposes such as generating power, controlling floods, or regulating the flow of a river. During certain periods of the year, droughts, drawdowns, and so forth can cause such lakes to have very low water levels. The water under such conditions might not be accessible to the fire department for drafting by the fire department pumping unit, even where a paved road for boat launching has been provided and extended into the water at normal water levels for several feet or meters. Under such conditions, other provisions should be made to make the water supply fully accessible to the fire department.

Other Natural Water Sources

Other natural water sources might include springs and artesian wells. Individual springs and occasional artesian water supplies exist in some areas. These other natural water sources are generally of more limited capacity, but they can be useful for water supply, subject to reasonable application of the recommendations listed for ponds and streams. In many cases, it might be necessary to form a temporary natural pool or form a pond with a salvage cover, for example, to collect water for the use of the fire department when using a spring or an artesian well.

DEVELOPED SOURCES OF WATER

The developed sources of water supplies adapted for fire fighting are limited only by the innovation of the fire department. Developed sources include cisterns, swimming pools, quarries, mines, automatic sprinkler system supplies, stationary tanks, driven wells, and dry hydrants.

Cisterns

Cisterns, one of the oldest sources of emergency water supply, are important sources of water for fire fighting, domestic consumption, and drought storage in many rural and beach areas. Cisterns should have a minimum usable volume as determined by the authority having jurisdiction, using the methods described in NFPA 1142. There is no real limit to the maximum capacity. A cistern should be accessible to the fire apparatus or other pumping device, but it should also be located far enough from the hazard so that personnel and equipment are not endangered. The water level of a cistern can be maintained by rainfall, by water pumped from a well, by water hauled by a MWS apparatus, or by the seasonal high water of a stream or river. Because its surface is often relatively inaccessible and the water is stagnant, the cistern can present a freezing problem. One method for minimizing freezing is to use a dry hydrant protruding into the water at a point below the local frost line. Cisterns should be capped for safety, but they should have openings to allow inspections and use of suction hose where needed. There should also be some type of protective boundary for the area in which the cistern is located to prevent unauthorized entrance to the area.

If a dry hydrant is not installed in a cistern, then (depending on local conditions) a heavy pipe or a pike pole can be adequate to break an ice formation. In fact, the weight of the suction hose itself can be sufficient to break the ice, provided there is no danger of damaging the strainer, the hose, or the hose threads. Floating a log, a bale of hay, or a bale of straw or placing a partly filled, floating barrel on the surface of the water are some methods for providing an ice-free surface area in a cistern or other water source.

The construction of cisterns is governed by local conditions of soil and material availability. Practical information can be obtained from local governmental departments or agricultural agencies.

Some engineering considerations to be taken into account in designing cisterns include the following:

- The base, walls, and roof should be designed for the prevailing soil conditions and for the loads encountered where heavy vehicles are parked adjacent to each other.
- If groundwater conditions are high, the cistern should not float when empty.
- Suction piping should be designed to minimize whirlpooling.
- Vent piping should be of sufficient size (as shown in NFPA 1142).

Maintenance factors to be considered by the fire department include the problem of the evaporation of water or other low water conditions and the freezing problems previously discussed.

Swimming Pools

Swimming pools are an increasingly common source of water for fire protection. Even in some areas with normally adequate hydrant water supplies, swimming pools have been a factor in providing protection, such as in cases in which water demands have exceeded availability. Swimming pools provide an advantage in that they are sources of clean water, but they have major drawbacks due to the weight of fire department vehicles and poor accessibility for large apparatus.

Swimming pool distribution is better than hydrant distribution in some areas of the country. If the fire department intends to use a swimming pool as a water supply, it should develop these water sources by working with property owners through pre-incident planning.

If fire department accessibility is considered when designing the pool, a usable water supply should be available to the fire department for supplying direct hose lines or a source of water for MWS apparatus filling. Most swimming pools are built in areas requiring security fencing or walls, and these can complicate accessibility. Fences and walls can be designed for fire department use. However, should there be an incident in which fire department use of the pool has been permitted and there has been no other method provided for access through the protective area created by a fence, the fence can be lifted to allow the suction hose to be used (Figure 13.4.3).

A swimming pool located virtually under the eaves of a burning house can be a very poor location from which to pump if there are problems of fire exposure to the work area. Pumping from a neighboring pool, if it is close enough, or setting the water-hauling program in motion is frequently preferable to pumping from the pool of the burning house.

In most cases, a solution to the problems of accessibility can be achieved through pre-incident planning and might call for long lengths of suction hose, portable pumps, dry hydrants, siphon ejectors, or properly spaced gates. Portable (or floating) pumps, which are designed for large-volume delivery at limited pressures to deliver water to portable folding tanks or fire department pumpers, are frequently ideal for use where accessibility problems exist.

FIGURE 13.4.3 Fire Fighters Entering a Fenced-Off Swimming Pool Area

Fire fighters must take care to ensure that structural damage will not occur to a pool and the surrounding area if the water is used for fire fighting. Lightly built cement or poured concrete pools can be subject to structural damage, cracking, or collapse when drained. In addition, a pool in extremely wet soil will tend to float upward when drained; therefore, it might be necessary to refill the pool as soon as the fire is under control and MWS apparatus can be released from fire duties.

Some pools are holes of compacted earth covered by a plastic surfacing or light-gauge metal panels placed against such earth or a special fill. Such pools can collapse internally if emptied. It might be possible to use a limited portion of such water sources but not the entire available water supply. Therefore, not using these pools at all might be prudent.

Another consideration is whether the ground surrounding a pool will support the weight of a fire department vehicle without collapsing. The fire department should study and know the various pool limitations within the area served by consulting with the builders and installers of these pools.

Livestock Watering Ponds and Tanks

The local fire department representative responsible for planning water supplies should contact the owner of a farm, ranch, or similar type of area where livestock are kept and make him or her aware of the need for, and amount of, water required for that fire department to supply fire suppression to any/all buildings. Such tanks and ponds should be sized to be adequate in volume for both farm and fire department use and should be located to be readily available to the fire department. Tanks should be placed on the edge of the barnyard and on a side accessible to the fire department, with the pumper or pump taking suction through a connection on the tank or by suction hose. These watering tanks and ponds are often filled and maintained by a pump operated by a windmill or by an electric pump (Figure 13.4.4).

Wells and Well Systems

Wells and well systems are becoming increasingly popular as water supplies for fire-fighting purposes at industrial properties, shopping centers, subdivisions, and farmhouses located in rural areas beyond the reach of a municipal water distribution system.

In areas with suitable soil conditions—for instance, areas that have soils of a very sandy nature—driven wells or water-jetted wells might be used to obtain water for fire fighting. These wells are pipes that have been driven into the ground and that usually have perforations about the base to allow the entry of water. From the threaded pipe head (or a fitting attached to the body of the pipe), a pump connection can be made to draft water, much as from a well hydrant. A high water table is a prerequisite to using this method of obtaining water. Fire-fighting units in areas conducive to this technique should have the necessary equipment

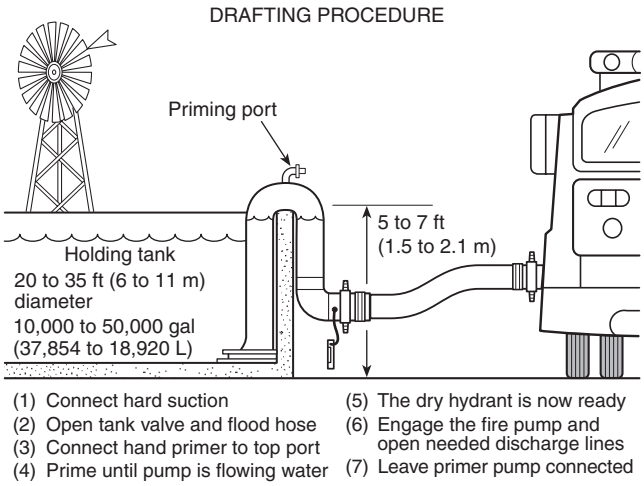

FIGURE 13.4.4 Drafting Procedure for Farm Holding Tanks (Courtesy of Stan Merrett, ETT, L.L.C.)

FIGURE 13.4.5 Dry Hydrant

for such installations. Some state and local governments have regulations or licensing requirements that govern well construction. Such restrictions will probably increase in the future.

Where water is supplied by one or more electricity-driven or engine-driven pumps used for irrigation or industrial use and where fuses and/or batteries are removed during periods when the water is not needed, the fire department should make provisions with the pump owner to ensure that power can be made available when needed for water supply.

Dry Hydrants

Per NFPA 1142, a dry hydrant is defined as "an arrangement of pipe permanently connected to a water source other than a piped, pressurized water supply system that provides a ready means of water supply for fire-fighting purposes and that utilizes the drafting (suction) capability of fire department pumpers" (Figure 13.4.5). Dry hydrants have the following features:

- Consist of a nonpressurized pipe system
- Use relatively inexpensive piping materials and other supplies
- Are permanently installed in existing lakes, ponds, streams, and cisterns
- Provide a means of access whenever needed, regardless of weather
- Allow years of simple operation with a minimum of maintenance

Dry hydrants should be installed at reliable water sources. The placement of dry hydrants at water sites should follow a process of planning, design criteria based on the site and water location, permit (i.e., land owner permission), and the construction and installation of the hydrant on site. A strategically placed dry hydrant system, with all-weather road access, significantly reduces water point setup and turnaround time to the fireground, improves the life safety of the fire fighter, and may reduce insurance costs.

Design Characteristics. Local topography, climatic conditions, and access to materials, among other factors, will determine the design characteristics of each installation (Figures 13.4.6 and 13.4.7). Distance to the water combined with the difference in elevation between the hydrant head and the water source and the desired gallon-per-minute (liter-per-minute) flow will affect the pipe size that needs to be used. All installations should use, as a minimum, 6 in. (152 mm) pipe. With longer lateral runs and higher volume flow, 8 in. (203 mm) or 10 in. (254 mm) pipe sizes can become necessary for the horizontal lengths.

Local preferences and experience, along with access to materials, will determine the type of pipe and fittings best suited for the job. In some parts of the country, brass and bronze caps and steamer connections, along with iron, steel, and bituminous cement pipe and fittings, are being used for hydrant materials.

In many parts of the country, however, Schedule 40—and in areas where there are freezing conditions expected as normal

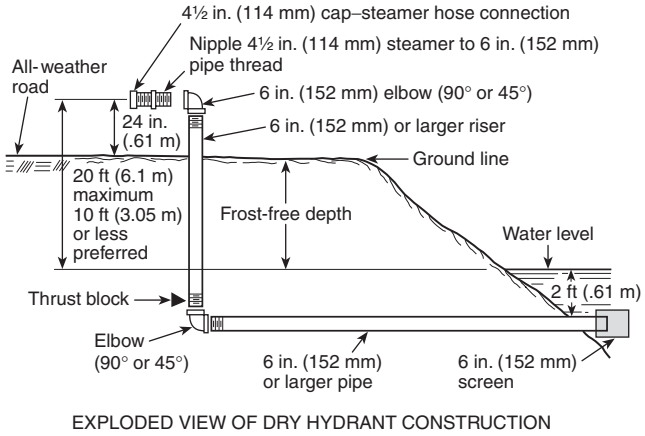

FIGURE 13.4.6 Dry Hydrant Construction Using Iron, Steel, or PVC Pipe

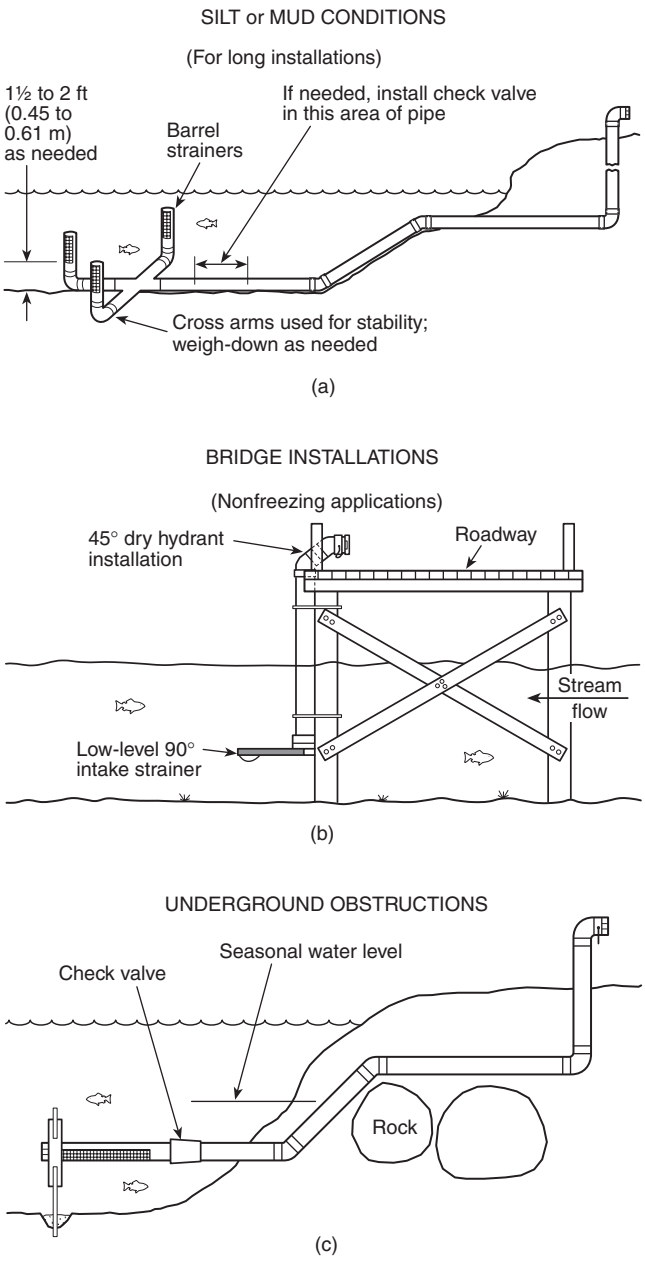

FIGURE 13.4.7 Dry Hydrant Installation (a) for Silt and Mud Conditions, (b) from a Bridge, and (c) Overcoming Underground Obstructions (Courtesy of Stan Merrett, ETT, L.L.C.)

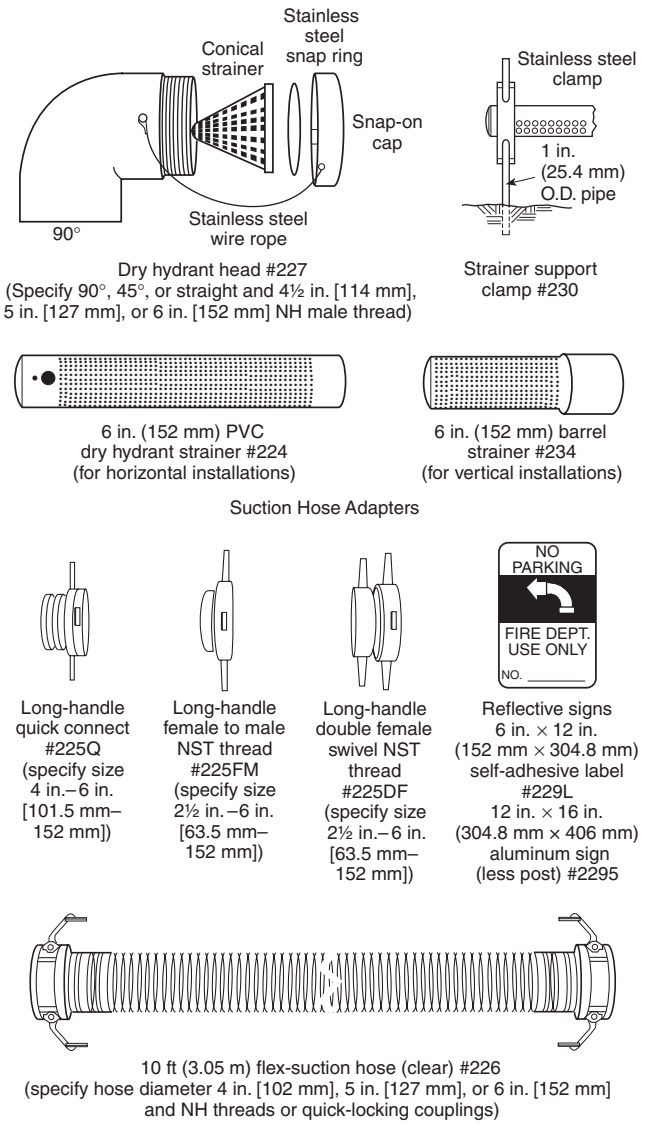

FIGURE 13.4.8 Commercially Available Dry Hydrant Components (Source: Wisconsin Department of Natural Resources)

weather criteria, Schedule 80—PVC pipe, fittings, and connections are used (Figure 13.4.8). Many fire service manufacturers are now offering premade and preassembled suction screens, hydrant heads, and supports that come ready to attach to the pipe. Steamer fittings should be compatible with the fire department's hard suction hose size and thread type.

The dry hydrant design has features that make its use accessible to many rural fire departments and property owners in terms of personnel and financial resources. The type and class of pipe for a particular dry hydrant installation should be determined through the consideration of the following conditions: soil, corrosion susceptibility, climate, and susceptibility of pipe to other external loads, including earth loads and traffic or vehicle loads. All exposed surfaces should be primed and painted to protect the pipe and prevent deterioration of the material.

Preferably no more than two 90 degree elbows should be used in the total dry hydrant system. Also desirable is the installation of long-sweep elbows at the bottom of the riser where the lateral run connects. Long-sweep elbows can be constructed with two 45 degree elbows and a 2 ft (0.6 m) length of pipe. If any portion of the dry hydrant above ground level becomes damaged in any manner that would make the hydrant unusable when connection is made to pump suction hose, the use of a long-sweep elbow could allow drafting to continue, although at a much reduced rate of flow.

NFPA 1142 contains numerous design criteria, such as a recommendation for a 6 in. (150 mm) minimum inside diameter of the pipe and limit of 10 to 12 ft (3 to 3.7 m) for static lift. See Figure 13.4.9 for a checklist of dry hydrant design features.

Dry Hydrant Design Features Checklist

Design factors are affected by:

- ☐ Desired flow from the hydrant in gpm
- ☐ Suitability of pipe materials
- ☐ Size and type of available fire aparatus pumper

The following design features are suggested for dry hydrants using PVC pipes:

- ☐ Use 6-in. (150-mm) diameter pipe as a minimum.
- ☐ Use Schedule 40 pipe as a minimum.
- ☐ Prime and paint all exposed pipe.
- ☐ Use a minimum number of elbows.
- ☐ Joint and cement all connections properly.
- ☐ Purchase or construct a suction screen with adequate hole openings.
- ☐ Ensure that total area of strainer holes exceeds four times the area of the diameter of the pipe.
- ☐ Ensure that installation depth is below the frost-free depth for the area. (Consult local university extension service or state Department of Natural Resources.)
- ☐ Ensure that installation depth is sufficiently below the average 50 year drought or appropriate state criteria for drought. (Consult engineer, soil conservationist, or hydrologist.)
- ☐ Place horizontal pipe level on minus grade of 1 to 2 in. (25.4 to 50.8 mm) per 100 ft (30.5 m), unless depth of cut is too great.
- ☐ Note that for streambed installation (with low flow depth less than 2 ft [0.6 m]) the strainer section may be buried below bed of stream and covered with gravel.
- ☐ Install dry hydrant as close as practical to the water source.
- ☐ Note that a flow of 600 to 1000 gpm (2271 to 3785 L/min) from the hydrant is desirable.
- ☐ Avoid designs with lifts in excess of 17 ft. (Above this height vapor pressure will begin to exceed atmospheric pressure and cavitation will occur, making pumping virtually impossible.)
- ☐ Consider friction loss at high lifts. (Calculate losses using Mannings formula or Hazen-Williams equations.)
- ☐ Position the pump intake at a higher elevation than the hydrant connection. (Doing so will eliminate air bubbles, which will limit flow and also prevent the operator from getting wet.)
- ☐ When rock is encountered, adjust installation to fit the rock profile. (Additional bends may be necessary.)

FIGURE 13.4.9 Dry Hydrant Design Features Checklist

Advantages of Dry Hydrants. Knowing the quantity of available water in area streams, ponds, and cisterns gives the fire department an advantage only if the water is readily accessible. Where a water site is located so that MWS apparatus will be the water transportation method, the amount of available water will be less than it would be if pumped directly onto a fire from the same water site. Whenever MWS apparatuses are used, critical factors become the supply of an uninterrupted flow, the supply of a predictable amount of water being transported, and the maintenance of the supply for the duration of the fire or until a lesser flow is required.

Improved Access. Installation of as many dry hydrants as possible where permits can be obtained and the sites made all-weather accessible will ease both the complexities and the lesser availability of water that will be incurred when comparing shuttle operations to water transported directly to the fire scene by hose from a water site. Additionally in those areas without water mains and domestic fire hydrants, dry hydrants can provide a simple, cost-effective solution to water sources without delay.

Time Saving. The time saving is considerable. Multiple lengths of hard suction hose extending to the water are not needed; usually one section to the dry hydrant is enough. The strainer is also permanently attached, saving more time. Fewer people are needed to make a hookup compared to the number needed to make a conventional direct drafting hookup. Planned placement of dry hydrants with the proper accessibility will allow fire departments to supply water for fire protection to all areas where coverage can effectively be provided.

Cost Saving. The saving can be financial, as well. Fire departments can save money by reducing fuel and equipment costs through shorter transportation distances and lower operational demands. Because dry hydrants use untreated water, communities can preserve more of their treated water supplies. Homeowners may also save on their insurance rates.

Planning Considerations. Planning for dry hydrants involves several considerations and should involve all affected agencies and private concerns so a coordinated effort can take place. Some factors to consider are:

- Current and future population and building trends
- Protection of property values
- Potential for loss
- Fire history of the area protected
- Current water supply systems
- Other potential water sources
- Cost of project
- Equipment and personnel of the local fire department
- Training needs of the fire department
- Other specific factors of local concern

Location of Dry Hydrants. The location of individual dry hydrants is also influenced by several factors. After conducting a water source survey of the area, the fire department should use a county road map to mark potentially good sites. These sites should be marked in a priority order, since most fire departments

will not have sufficient funding for all the dry hydrants that may be desired. The following features should be considered when considering dry hydrant sites.

Maximum Travel Distance Between Dry Hydrants. The travel distance between dry hydrants can vary for several reasons. For use in shuttle operations, it has been found that the amount of water transported by MWS apparatus to the fire scene, regardless of the size of the water tank on the MWS apparatus, will not be appreciably increased when water fill sites are further than 3 mi (4.8 k) from the fire site. This distance would produce a travel time of about 6 minutes between the water and the fire, assuming an average safe constant speed for a loaded truck of 35 mph (56 kph).

Water Depth at the Source. Careful note should be made about the useful depth of a lake or pond, which is from the minimum foreseeable low-water surface level to the top of the suction strainer (not the bottom of the lake). The low-water mark considers tides, drought, freezing, and other considerations, such as when the water level is lowered to generate power. The absolute lowest level must be not less than 2 ft (0.6 m) to prevent a vortex or whirlpool, which could allow air to enter the pump and cause loss of pump prime. Consideration for the height of the "low" water level above the strainer should be made for conditions such as ice and for floating leaves during the fall of the year. Plans for these or for any other conditions, even if seasonal, that could cause clogging of the strainer or cavitation of the pump should be made.

Composition of Bottom Material. For long-term useful hydrant operation, the best composition for the bottom of a lake, stream, or pond is sand, gravel, rock, or a combination of these. Decaying vegetative matter could clog the suction screen.

Ease of Digging. Surface area and condition in the vicinity of the dry hydrant site is a factor in the installation of a dry hydrant. A backhoe or whatever machinery is to be used to "trench the dry hydrant" will need to get close enough to the water's edge so as to be able to dig out below the surface of the water to the needed depth for the dry hydrant.

Protection of the Connection. A location that is conveniently accessible to fire apparatus may also be exposed to accidents from passing vehicles. An impact barrier constructed of partially buried posts may be needed to prevent a vehicle from damaging a dry hydrant in a heavily traveled area. Special markings, as deemed appropriate by the authority having jurisdiction, should be used to avoid damage from snowplows.

Cost. The cost of a dry hydrant installation depends on local practices and the length of pipe needed. This cost must be factored in when deciding where to locate dry hydrants.

Presence of Other Utilities. The presence of other utilities in the digging area must be considered. A careful check should be made for the presence of buried lines and pipes; utility companies should be notified before digging is started. The numbers to call in each state can often be found in the local telephone company phone book and are found with a title similar to "Call Before You Dig."

Ownership of the Land. The water supply officer or other authority should contact the legal property owner to secure written permission in conjunction with the attorney representing the government entity in whose legal area the land lies. If a possible dry hydrant site is along a road right-of-way, then town, county, or state approval may be required. In some cases Corps of Engineers or power company approval may also be needed. Obtaining written permission is an important requirement that may take some time.

AGREEMENTS/PERMITS

Regardless of the type of water source used and the water site from which it is obtained, a document granting permission by the owner for the use of the area as well as documents listing any other locally applicable considerations should be on file. A written explanation of what is needed and what the fire department will do to install the dry hydrant can be mailed or delivered personally. Conditions for the best use of the particular site should be set forth. This explanation will usually provide the prospective property owners with information that will make them more comfortable with the conversations and legal technicalities that will follow.

The attorney representing the local government whose fire department will be utilizing the site should formalize all legal issues. The local government attorney should consider all actions that can reasonably be assumed to be involved and to arise out of the use of water source site and should enumerate them in the legal paperwork. The agreement should be signed by the property owner, the head of the government entity (or his or her designated representative), the chief of the fire department, all other departments of the entity (or contractors if they are to be used) that will have a part in the development/improvement of the site, and the entity's attorney. At a minimum these people should be listed on the agreement since they will deal with the greatest number of actions involved in the completion of each site for fire department use and continued operations.

ESTIMATING AVAILABLE WATER SUPPLY CAPACITY

A simple method for estimating the flow of water in a creek is to measure the width and depth of the creek, drop a cork or any light, floating object into the water, and then determine the time it takes the cork to travel 10 ft (3.1 m). To obtain complete accuracy, the sides of the creek should be perpendicular, the bottom should be flat, and the floating object should not be affected by the wind. Where the sides and bottom of the stream are not uniform, the width and depth can be averaged. For example, consider a creek with a width of 4 ft (1.2 m) and a depth of 6 in. (15.2 cm) and where the flow of water is such that it takes 45 seconds for a cork to travel 10 ft (3.1 m). The following equation applies:

$$\text{Volume of water} = W \times D \times TD = \text{ft}^3\ (\text{m}^3)\ \text{of water}$$

$$\text{Flow rate} = (\text{Volume of water})/T$$

where

W = Width (ft [m])

D = Depth (ft [m])

TD = Travel distance (ft [m])

T = Time (sec)

$$4\ \text{ft} \times 0.5\ \text{ft} \times 10\ \text{ft} \times 20\ \text{ft}^3\ \text{of water}$$

or

$$1.2\ \text{m} \times 0.15\ \text{m} \times 3.1\ \text{m} \times 0.56\ \text{m}^3\ \text{of water}$$

Since the cork takes 45 seconds to travel a 10 ft (3.1 m) distance:

$$\text{Flow rate} = 20\ \text{ft}^3/45\ \text{sec} = 0.444\ \text{ft}^3\ \text{of water/sec}$$

or

$$\text{Flow rate} = 0.558\ \text{m}^3/45\ \text{sec} = 0.0124\ \text{m}^3\ \text{water/sec}$$

and

$$1\ \text{ft}^3 = 7.5\ \text{gal and } 60\ \text{sec} = 1\ \text{min}$$

Therefore,

$$(0.444\ \text{ft}^3/\text{sec}) = (0.444\ \text{ft}^3/\text{sec})(60\ \text{sec/min})(7.5\ \text{gal/ft}^3)$$
$$= (0.444/0.00223)\ \text{gpm} = 199\ \text{gpm}$$

Also

$$1\ \text{m}^3 = 1000\ \text{L and } 60\ \text{sec} = 1\ \text{min}$$

Therefore,

$$(0.014\ \text{m}^3/\text{sec}) = (0.0124\ \text{m}^3/\text{sec})(60\ \text{sec/min})(1000\ \text{L/m}^3)$$
$$= (0.0124/0.0000167)\ \text{L/min} = 744\ \text{L/min}$$

A short-form method of estimating pool capacity is as follows:

$$L \times W \times D \times 7.5\ \text{gal}\ (1000\ \text{L})$$
$$= \text{Estimated capacity in gallons (liters)}$$

where

L = Length (ft [m])

W = Width (ft [m])

D = Estimated average depth (ft [m]) from water line (ft [m])

These dimensions should be estimated or rounded off if the pool is of stylized construction.

$$1\ \text{ft}^3 = 7.5\ \text{gal}\ (1\ \text{m}^3 = 1000\ \text{L})$$

For a noncircular pond of irregular shape, sketch the pond outline to scale on grid paper. Circumscribe straight lines to average the irregular outline as much as possible around the shape. Calculate the area of a rectangle covering the entire pond. Subtract the scaled grid squares that fall outside the pond area. Use the final figure as $L \times W$ in the foregoing formula.

To make a rough estimate of the water volume in a pond when exact dimensions are not known, visualize the relative size of a football field, if you can, and use that area as a starting point. A football field is roughly an acre. Every foot (0.30 m) of average usable depth would provide about 325,000 gallons (1,230,000 L).

WATER SUPPLY VEHICLES, WATER SHUTTLE OPERATIONS, AND DRIVERS

Mobile Water Supply (MWS) Apparatus

The term *mobile water supply (MWS)* will be used here as referenced in NFPA 1901, *Standard for Automotive Fire Apparatus.* Incident management system (IMS) terminology and designation of what has always been termed a *tanker* is a "vehicle" (aircraft or helicopter) that delivers water from above. For ease of use throughout, we will refer to a wheeled ground apparatus (vehicle) as an MWS apparatus. We will consider the MWS apparatus as being mounted on a single- or tandem-axle chassis. Issues dealing with tractor-trailer water supply vehicles are not addressed in this chapter.

Rural fire departments are often fortunate to have usable water supplies in their jurisdictions, but that water is rarely in the immediate area of a fire where it is needed. MWS apparatus are necessary for any fire department that wants a method to provide a water supply to areas where there is no existing water supply system. MWS apparatus can also be used to supplement areas where the existing water supply system may not provide the desired flow of water. MWS apparatus are necessary for most rural fire departments and can be useful to suburban departments with weak municipal systems.

MWS apparatus may be found in a variety of configurations, with or without pumps on board. Fire apparatus may be generally classified as pumpers or MWS apparatus, or they may be manufactured to provide both functions. Some vehicles used previously for transporting other liquids have been used by fire departments, but safety considerations should be more important than economic ones. The fire department should ensure that any vehicle used to transport water passes a safety inspection; that it has reliable brakes, chassis, and transmission; and that it is designed to carry the weight of the water that it will transport. Above all, the weight of water should never allow the total vehicle weight to be greater than the rated maximum weight rating of the vehicle.

Over the years, departments utilizing hauled water have tended to use any means to carry water and have exercised a great deal of ingenuity in doing so. Recently, there has been a trend in fire departments in rural areas to use standard pumpers and MWS apparatus with tanks in the 1000 to 1500 gal (3785 to 5678 L) range. Significant progress has been made in such MWS apparatus techniques as loading and unloading and in maintaining a continuous fire stream, based on the fire flow study, during the entire fire-fighting operation.

Specially built and designed MWS apparatus are ideal, but many fire departments are forced to fight fires without

adequate standard equipment. Since the job of putting out fires will require, on occasion, water-carrying capacity greater than a fire department's capability, a sound mutual-aid or automatic-aid program is necessary and is far superior to makeshift, unsafe equipment that is not designed for emergency service.

In building and buying nonstandard apparatus, serious consideration should be given to the safety and serviceability of the equipment as well as the safety of the members of the department. A department that depends on an assortment of MWS apparatus designed primarily for other use might need expert assistance in checking the equipment for safety before putting it in service.

If satisfactory service is to be obtained from MWS apparatus, the size of chassis necessary to safely carry the load, the horsepower of the engine necessary to perform on the road and at the fire site, the completed vehicle's weight distribution, and the gear train combination best suited for the operation in that specific locale are factors that should be carefully considered in the purchase or construction of the apparatus. The apparatus components, such as the baffling of the tank and the center of gravity, are just as important as the engine, axles, and other driveline components and should not be overlooked. Some fire departments that have pumpers equipped with large booster tanks have retrofitted these pumps with a dump system.

Water Shuttle Operations

Obviously, sufficient water supply for fire suppression services is a very critical component to the overall fire suppression capabilities of a fire department. Typically, rural areas do not have the necessary infrastructure to support "urban type" water delivery systems. Where fire hydrants exist, they are typically on smaller water lines with relatively low flow capacity and are generally spaced quite some distance apart. As a result, fire departments with large rural areas within their protection areas must rely on alternate means of providing adequate fire flow during fire suppression activities.

It is important for companies to be able to obtain water from sources other than hydrants at the fireground and operate a MWS apparatus shuttle to provide adequate water supply for fire-fighting operations. This is not limited to rural applications and may be necessary to supplement hydranted areas where there is inadequate water supply.

Key components in MWS apparatus shuttle operations in rural water supply include the following:

- Selecting water sources
- Selecting MWS apparatus travel routes
- Developing MWS apparatus fill and dump station operations
- Calculating and meeting waterflow requirements

A critical part of establishing a water supply on a continuous basis is the capability to deliver water to the scene within 5 minutes of the initial arriving fire apparatus. Calculating the rate of water delivery to the scene is based on the total water supply required. The rate of water delivery is a separate calculation from the water application rate.

The following are two primary factors to be considered in the development of MWS apparatus operations:

1. The amount of water carried on initial responding units
2. The amount of water that can be continuously delivered after initial response

A number of fire departments have developed water-hauling operations to the point where they have a maximum continuous flow capability (a sustained fire flow) of 1000 to 2000 gpm (3785 to 7570 L/min) at the fire scene. Such continuous flow requires several MWS apparatus to haul such large quantities of water with a developed water source near the fire site. To improve the safety factor by reducing congestion on the highways, the departments often send the MWS apparatus to the water source by one road and use another route for the MWS apparatus to return to the fire scene. Therefore, the time for the department to travel from the fire to the water source (T_1) might be a different time than the travel time back to the fire (T_2). The reduction of congestion on the highway provides for a safer operation and can increase the actual amount of water hauled.

The maximum continuous flow capability at the fire scene is calculated as follows:

$$Q = [V/(A + T_1 + T_2 + B)] \times k$$

where

Q = Maximum continuous flow capability (gpm [L/min])

V = Mobile water supply capacity (gal [L])

A = Time (in minutes) for the MWS apparatus to drive 200 ft (61 m), dump water into a drop tank, and return 200 ft (61 m) to starting point

T_1 = Time (in minutes) for the MWS apparatus to travel from fire to water source

T_2 = Time (in minutes) for the same MWS apparatus to travel from water source back to fire

B = Time in minutes for the MWS apparatus to drive 200 ft (61 m), fill MWS apparatus at water source, and return 200 ft (61 m) to starting point

k = 1.0 for vacuum/pressure MWS apparatus; 0.9 for all other MWS apparatus due to spillage, underfilling, and incomplete unloading

The dumping time (A) and filling time (B) for the formula should be determined by drill and by close study of water sources. Equipment does not have to be operated under emergency conditions to obtain travel time (T), which is calculated using the following equation:

$$T = 0.65 + XD$$

where

T = Time (in minutes) of average one-way trip travel

X = Average safe constant speed factor

D = One-way distance (miles [kilometers])

The factor 0.65 represents an acceleration/deceleration constant based on miles per hour developed by the Rand Corporation.

Where an apparatus is equipped with an adequate engine, chassis, baffling, and brakes, a safe constant speed of 35 mph (56.3 km/hr) can generally be maintained on level terrain, in light traffic, and on an adequate roadway. Where conditions will not permit this speed, the average safe constant speed should be reduced.

Using an average safe constant speed of 35 mph (56.3 km/hr), the *X* factor is calculated as follows:

$$X = 60/\text{average safe speed} = 60/35 \text{ mph} = 1.7$$

The formulas make it possible to determine water availability at any point in an area. As an example of how to calculate the water available from a supply where the water has to be trucked to the fire scene, consider the following applications of the formula.

EXAMPLE: If tank capacity (V) is 1500 gal (5678 L), the time (B) to fill the MWS apparatus with water is 3.0 minutes, and the time (A) to dump the water into a portable tank is 4.0 minutes.

The distance (D_1) from the fire to the water source is 2.1 mi (3.38 km). As the MWS apparatus returns by a different road, the distance (D_2) from the water source is 1.8 mi (2.9 km).

SOLUTION: First, solve for T_1, the time for the MWS apparatus to travel from the fire to the water source, and then solve for T_2, the time for the MWS apparatus to travel from the water source back to the fire.

Due to good weather and road conditions, the constant MWS apparatus speed traveling from the fire to the water source is 35 mph (56.3 km/hr).

Use the travel time formula as follows:

$$T_1 = 0.65 + XD_1$$

where

$X = 1.7$

$D_1 = 2.1$

and where at a constant speed of 35 mph (56.3 km/hr)

$$T_1 = 0.65 + 1.7D_1$$

$$T_1 = 0.65 + 1.7 \times 2.1$$

$$T_1 = 0.65 + 3.57$$

$$T_1 = 4.22$$

At a constant speed of 35 mph (56.3 km/hr), a MWS apparatus traveling 2.1 mi (3.8 km) will take 4.22 minutes. Due to traffic lights, the average MWS apparatus speed between the fire and the water source is 30 mph (48.3 km/hr).

Use the time travel formula as follows:

$$T_2 = 0.65 + XD_2$$

where

$X = 2.0$

$D_2 = 1.8$

and where at a constant speed of 30 mph (48.3 km/hr)

$$T_2 = 0.65 + 2.0D_2$$

$$T_2 = 0.65 + 2.0 \times 1.8$$

$$T_2 = 0.65 + 3.6$$

$$T_2 = 4.25$$

Use the following formula for calculating the maximum continuous flow capability:

$$Q = [V/(A + T_1 + T_2 + B)] \times k$$

where

Q = Maximum continuous flow capability (gpm)

$V = 1500$

$A = 4.0$

$T_1 = 4.22$

$T_2 = 4.25$

$B = 3.0$

Therefore,

$$Q = [1500/(3.0 + 4.22 + 4.25 + 4.0)] \times 0.9$$

$$Q = (1500/15.47) \times 0.9$$

$$Q = 97 \times 0.9 = 87 \text{ gpm } (329.3 \text{ L/min})$$

The maximum continuous flow capacity available from this 1500 gal (5678 L) MWS apparatus is 87 gpm (329.3 L/min).

To increase the maximum continuous flow capability of the MWS apparatus, any of the following changes can be made:

- Increase the capacity of the MWS apparatus
- Reduce the fill time
- Develop and provide additional fill points, thus reducing travel time
- Reduce the dump time

With rural fire response distances normally being very long, the number and size of MWS apparatus available to the department are of paramount importance. This information will assist the department in calculating the probable mobile water supply volume that will be available at various fire locations. Equally important in increasing the maximum continuous flow capability of a mobile water supply is the reduction of the distance between the source and the building or fire. The distance can be reduced by increasing the number of water supplies, drafting points, or both.

The minimum water delivery rate to the fire scene is based on the total water supply needed. Table 13.4.3 provides the rate at which water should be available at the fire scene to meet the demands of the fireground operations.

Driver Training

Drivers of emergency vehicles, especially those carrying large quantities of water, face circumstances that make driver training especially important. Fire departments often overlook this reality. Included in this oversight are some of the following factors:

- Few fire department members have been previously trained, drive vehicles of this type in their professional life, or are

TABLE 13.4.3 Minimum Water Delivery Rate to Meet Water Supply Needs

Total Water Supply Required	*Rate Water Is Available at Incident*
Up to 2,499 gal (9,459 L)	250 gpm (950 L/min)
2,500 to 9,999 gal (9,460 to 37,849 L)	500 gpm (1,900 L/min)
10,000 to 19,999 gal (37,850 to 75,699 L)	750 gpm (2,850 L/min)
20,000 gal (75,700 L) or more	1,000 gpm (3,800 L/min)

aware of the action of liquids during transport. Only effective training can prepare them to handle this type of vehicle. Continuous testing should be planned to ensure personnel continue to meet qualifications.

- Because of the effect of the load on the vehicle's center of gravity, even a two- or three-axle vehicle used as an MWS apparatus will have driving characteristics unlike those of other vehicles or fire apparatus.
- The weight of the water can reduce handling characteristics and increase braking distances. Water weighs 8.3 pounds per gallon (1 kg/L); in a 1000 or 2000 gallon (3785 or 7570 L) tank, the extra weight can be a dangerous factor if it is not considered at all times.
- The occurrence of fires is usually infrequent, allowing specialized driving skills to deteriorate unless training is regular.
- Roadways in rural areas may not always be repaired as frequently as they are in urban areas. Potholes and washed-out areas can be extremely hazardous for a heavily loaded truck.
- Emergency situations produce dangerous distractions to apparatus drivers (and anyone else). There is a natural tendency that makes everyone want to perform each task faster so the fire can be stopped as quickly as possible. However, too much haste results in poor decisions, and numerous safety factors can be overlooked.

Vehicle Weight and Safety

The weight of any large fire apparatus, and especially the weight of water in an MWS apparatus, produces extra stress on the vehicle's chassis, transmission, and brakes. Drivers must be trained regularly on the special risks of driving emergency apparatus.

The fire department should check every bridge and culvert location in its response districts, both primary response and mutual aid, to ensure that all bridges and culvert locations are rated to safely carry the weight of every responding fire department vehicle/apparatus. The ability of fire department personnel to determine bridge ratings should not be the overwhelming task that it might initially appear to be. In view of the current use of computers by state highway departments to inventory their bridges, load limits should be readily available.

If there is any bridge or culvert that will not support the weight of a particular department unit, the driver of that unit should be made aware of this fact. The fire department should have other specific routes planned to ensure response to fires within the area involved or should take specific action to ensure that adequate water supply can be delivered by other means. Examples include using a pumper taking suction from the river to pump water across the bridge through large hose lines or servicing the area from another water supply site that has a safe bridge to the area or, ideally, that does not require the use of a bridge to respond.

Access to Water Supplies

The location of any water site and the water available from that source will be usable for fire department operations only if the site is accessible. Training at the site for fire department operations, including making personnel aware of any limitations of the site and/or of the waterflow, should be part of planned fire department operations.

Access Roadways. Often a suitable approach, which might call for a roadway, must be provided to allow the fire department to reach within 10 ft (3.1 m) of the water supply. However, at some sites and in some areas of the country, constructing a roadway may not be necessary due to soil conditions. Other sites might already have roadways provided or pavement installed with the construction of an entranceway or a gate to provide access to the water supply. Other sites may be reached on foot only and may require a path to be constructed and maintained so that portable pumps can be carried to the site. Each site should be evaluated by the fire department to determine the best way, within the fire department's means, for using the water supply.

Most artificial lakes are constructed with heavy earth-moving equipment. In order for the property owner to construct a roadway for fire department use, the fire department should make the property owner aware of the needs of the fire department while the heavy equipment is still on the job.

While the roadway to the water supply is being developed, consideration should be given to providing a 90-ft (27.4-m) diameter turnaround for the mobile water supply apparatus. Where conditions at the supply site do not make a turnaround feasible, adequate hose lengths from the pumping unit at the supply site will be needed to provide water for MWS apparatus to fill up at the location or locations where they will be stopped. Regardless of this fill-up location, adequate room must be provided for the MWS apparatus to maneuver during arrival at and departure from the parking/standing area. However, a turnaround or looped facility will still need to be provided at the fill point on the right-of-way.

In some states, a fire department cannot use a bridge to park a mobile water supply while it is being filled because it would block traffic on the road. However, the fire department might be able to use the water source by moving the fill point off the bridge and to the right-of-way. The fire department needs to check with the state department of transportation and abide by the appropriate laws governing the situation.

In some cases, such as in marsh or swamp areas, installing a dry hydrant with a suction line in lieu of an access road is desirable. The fire department will have access to the hydrant from the shoulder of the main road. So as not to block the road during pumper operations, a suitable parking area on the shoulder of the road should be provided. The basic recommendations in Table 13.4.4 can be useful in the design of such an area so that pumpers can be employed efficiently and safely.

Bridges. Bridges that were built years ago may have been built for farm-to-market use and were designed for much lighter vehicles than are in use today. Those bridges now carry not only greatly increased traffic loads but heavier vehicles as well. As a result of this situation, which exists in many suburban and rural areas and probably even in some urban areas in the United States, some bridge collapses have occurred. In addition, many states did not provide complete bridge inspection and maintenance programs. Because of these major factors, most states now subject bridges to certain types of inspections and mandate those inspections within specific time frames.

As a result of bridge failures, the U.S. Federal Highway Act of 1968 required, among other things, that all states, counties, and cities receiving federal highway funding implement a program to inspect each bridge in the federally funded system every two years. Additional bridge collapses prompted amendment of this law in 1976 to include all bridges on the public roads system.

During the last few years, a number of states have set up bridge inspection programs, and the current safe tonnage is now being posted. Throughout the entire country, a large number of bridges have been restricted to below the legal weight limit for which the road and bridge were originally designed. One state with over 15,000 bridges reported that 50 percent of all its bridges are now posted below the original maximum load limits, and 25 percent of these bridges are unsafe for use by a fully loaded school bus or fire department apparatus.

In some states, the state highway department has consulted fire officials, explained the situation, and required that the fire department list the unsafe bridges in order of their importance to the fire service. The highway departments then attempt to upgrade these bridges on the basis of fire department priority.

The long-range nature of the bridge problem makes it a matter for serious consideration when planning purchases of apparatus. MWS apparatus size must be restricted to volumes that will not cause overloading. State law determines whether a fire service is held financially responsible for damage to a bridge; however, a good policy for every fire department is to check the bridge load restrictions before purchasing a new piece of apparatus. The lighter the equipment, the more bridges the department can use. Although this may necessitate the purchase and use of smaller tank size MWS apparatus, prior planning will enable these units to be used just as effectively as MWS apparatus with larger tanks and should not be considered a limitation to fire service operations.

TABLE 13.4.4 Recommendations for Roads to Water Supplies

Road Feature	*Recommendation*
Width	Roadbed—12 ft (3.7 m) Tread—8 ft (2.4 m) Shoulders—2 ft (0.6 m)
Alignment	Radium centerline curvature—50 ft (15.2 m)
Gradient	Maximum sustained grade—8 percent
Side slopes	All cut-and-fill slopes to be stable for the soil involved
Drainage	Bridges, culverts, or grade dips at all drainageway crossings
	Roadside ditches deep enough to provide drainage
	Special drainage facilities (e.g., tile) at all seep areas and high water table areas
Surface	Treatment as required for year-round travel
Erosion control	Measures as needed to protect road ditches, cross drains, and cut-and-fill slopes
Turnaround	Designed to handle the equipment of the responding fire department with a minimum diameter of 90 ft (27.4 m)
Load-carrying load capacity	Adequate to carry maximum vehicle expected
Condition	Suitable for all-weather use

Source: NFPA 1142, *Standard on Water Supplies for Suburban and Rural Fire Fighting,* Table B-6.2, National Fire Protection Association, Quincy, MA, 1999.

SUMMARY

Providing water for fire suppression purposes by using alternate water supplies enables fire departments to have a continuing water supply where none existed previously or may provide additional water for emergency or backup use. The alternate water supply sources include natural water sources, such as streams, springs, lakes, and ponds, and developed sources of water, such as cisterns, swimming pools, stationary tanks, driven wells, and dry hydrants.

Once the community's water needs have been determined, the water sources pinpointed, and agreements made with property owners, a plan should be worked out for moving the water to where it is needed. The chapter discusses the location, use, and preparation of water sites and the use of mobile water supply apparatus. The use of alternate water supply sources helps a community meet its water supply needs in time of emergency.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on alternate water sources

discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 220, *Standard on Types of Building Construction*
NFPA 1002, *Standard for Fire Apparatus Driver /Operator Professional Qualifications*
NFPA 1142, *Standard on Water Supplies for Suburban and Rural Fire Fighting*
NFPA 1901, *Standard for Automotive Fire Apparatus*

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Planning for Water Supply and Distribution in the Wildland/Urban Interface—Operation Water, NWCE, 1992.
Building Interagency Cooperation: A Six-Step Process to Help You Improve Your Fire Protection Effectiveness, National Wildland/Urban Fire Protection Initiative, National Fire Protection Association, Quincy, MA, 1990.

Chapter 5

Wildland Fire Management

Revised by
James C. Smalley

Chapter Contents

Brief History of U.S. Wildland Fires
Challenges to Managing U.S. Wildlands
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Wildland Fire Organizations
Legislation and Policy
Federal Agencies That Affect Public Fire Safety
Fire Detection, Suppression, and Resources
Fire Prevention
Research

Key Terms

aerial fuel, fire fighter safety, fire triangle, Firewise, forest fire, ground fuel, heat transfer, Miramichi and Maine fire, Peshtigo fire, prescribed fire, Smokey Bear, spot fire, topography, wildland, wildland/urban interface

Wildland fires occur in every state of the United States at some time during the year. Information from the U.S. Department of Agriculture (USDA) and the U.S. Department of the Interior shows the yearly pattern of wildfires during "normal peak fire seasons" in the 1990s. But following a decade of increasingly severe wildfires, it is now becoming difficult to define "normal peak fire seasons." Eight to ten years ago, a wildland fire exceeding 100,000 acres (40,470 ha) was the sign of an unusually severe fire season. Today, these large-scale fires are no longer the exception; they are starting to define what a normal peak fire season may be for years to come.

As debate over "prescribed fire"—that is, how much, where, when, and at what cost to use—continued, the price of suppression systems for tackling wildfires climbed and more unprotected homes and structures were lost, even though federal and state land management agencies treated millions of acres to reduce the fire risk using prescribed fire and mechanical means (such as cutting and clearing). Fires in largely untreated areas were the problem.

This chapter provides a brief summary of past wildland fires and their significance. The historic review will set the stage for the current challenges that accumulating forest fuels, increased public recreation in state and national lands, and the threat of unwanted fires present to federal, state, and local fire agencies and residents in and near forested and grassy plains areas. After establishing both the usual and unusual characteristics of wildland fire, the chapter explores the many ways (e.g., prevention, education, research, legislation, and suppression) that we seek to prevent disasters, save lives, protect the environment, share the responsibilities of protecting our natural environment, and continue to enjoy safely the beauty of national and state forests, parks, rivers, and wildlife.

See also Section 1, Chapter 7, "Protecting Against Extreme Events"; Section 2, Chapter 1, "Physics and Chemistry of Fire"; and Section 13, Chapter 1, "Fireground Operations."

BRIEF HISTORY OF U.S. WILDLAND FIRES

General Trends

Multiple large forest fires, such as the one shown in Figure 13.5.1, involving hundreds of thousands of acres, are starting to define what a normal peak fire season may be for years to come. Fire seasons have been worsening for several years. In 2003, however, the numbers were down from the 10-year average. In 2003, the numbers of fires (62,000) and acres burned (3.8 million acres [1.5 million ha]) were below the average of 64,000 fires and 4.6 million acres (1.9 million ha) (see Figures 13.5.2 and 13.5.3). In the same year, less acreage burned than in recent years, but what did burn was acreage in populated areas.

Although the numbers may vary from year to year, the longer-term trends are important, and a definite and troubling trend is becoming evident. Although the number of fires appears to be dropping, the affected acreage is growing. This trend may mean fewer fires in the future but the fires may involve increasingly larger acreage. Larger fires may also have a significant future impact on the environment, fire suppression resources, fire fighter safety, and structural loss.

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FIGURE 13.5.1 Large Forest Fire (Photo: James C. Smalley)

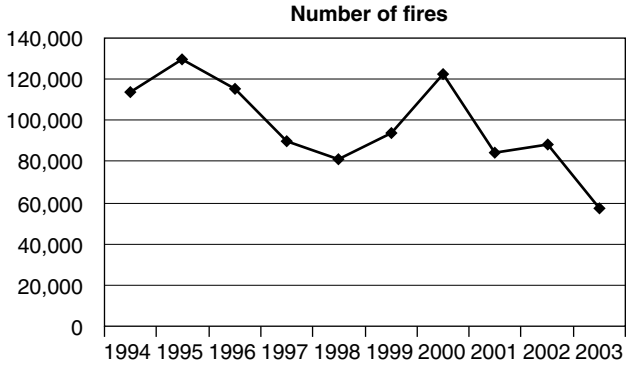

FIGURE 13.5.2 Number of Wildland Fires in the United States, 1994 to 2004

Considered the worst fire season in 80 years, 2000 was a landmark year, perhaps most remembered by the "escaped prescribed" fire in Bandelier National Monument near Los Alamos, New Mexico, that burned 47,650 acres (19,284 ha) and destroyed 235 homes. A moratorium on prescribed fire was put into effect following the blaze. The Cerro Grande fire was a harbinger of one of the most difficult seasons in the last half century. In 2002, the National Interagency Fire Center's annual summary included an average "worst" summary, noting that, based on previous years' activities, fire seasons of 85,000 fires and 6 million acre (2,428,200 ha) damage could be expected in the future.[1]

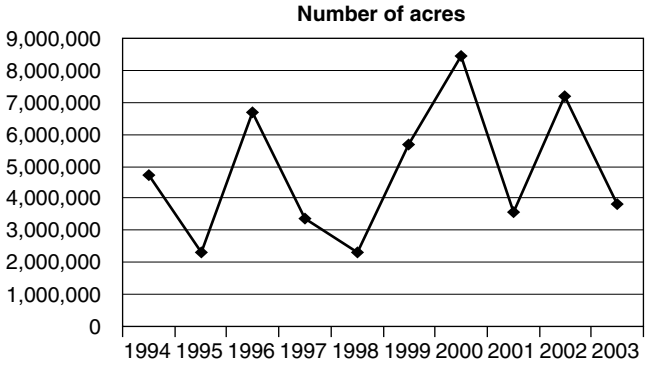

FIGURE 13.5.3 Number of Acres Burned in the United States, 1994 to 2003

Significant Historical Fires

Possibly the largest wildfires (known as the Miramichi and Maine fires) occurred in October 1825, burning from Maine through New Brunswick, Canada. A group of loggers ignited a fire in a drought area that soon burned out of their control and eventually destroyed 3 million acres (1.2 million ha) of forest and killed more than 160 people. The most devastating fire in U.S. history in terms of human lives and property lost was in Peshtigo, Wisconsin, in 1871. The fire killed over 1500 people in a single night and burned more than 1 million acres (404,700 ha). Other significant historical fires are summarized in Table 13.5.1.

CHALLENGES TO MANAGING U.S. WILDLANDS

There are 747 million acres (302,300,175 ha) of forestland in the United States, about 71 percent as much as there was in 1630. Today, the United States has about the same amount of land (or slightly less) covered by trees as in 1907. Over half (54%) of America's forests are owned by private individuals, 37 percent are under the management of public agencies, and 9 percent are owned by private industries.[2] With mixed ownership and changing expectations for public use and future of those lands, national policies regarding the management of those forests have changed dramatically over the last 100 years.

Four Threats to U.S. Forests

With progress in understanding better how fire shapes ecosystems, including watersheds, technology has made remarkable advances in assisting land managers and fire professionals in fire management through geographic information systems

TABLE 13.5.1 Significant Historical Fires

Year/Month	*Name*	*Location*	*Acres (ha)*	*Significance*
1871/October	Peshtigo	Wisconsin and Michigan	3,780,000 (1,529,760)	1500 dead in Wisconsin
1881/September	Michigan	Michigan	1,000,000 (404,700)	169 dead
1894/September	Hinckley	Minnesota	Undetermined	418 dead
1894/September	Wisconsin	Wisconsin	Several million	Undetermined, some dead
1902/September	Yacoult	Washington and Oregon	1,000,000 + (404,700)	38 dead
1903/April	Adirondack	New York	637,000 (257,790)	Large amount of acreage burned
1910/August	Great Idaho	Idaho and Montana	3,000,000 (1,214,100)	85 dead
1918/October	Cloquet-Moose Lake	Minnesota	250,000 (101,175)	450 dead
1933/August	Tillamook	Oregon	311,000 (125,861)	1 dead; same area burned again in 1939
1947/October	Maine	Maine	205,678 (83,238)	16 dead, 9 towns leveled, 3500 displaced, 2500 homeless, 851 homes and 397 summer homes destroyed, 20,000 fire fighters engaged in fire suppression
1949	Mann Gulch	Montana	4,339 (1,756)	13 smoke jumpers killed
1967	Sundance	Idaho	56,000 (22,663)	50,000 acres burned in just 9 hours
1961/November	Bel Air	California		505 homes destroyed
1970/September	Laguna	California	175,425 (70,995)	382 structures destroyed
1977/July	Sycamore	California	805 (326)	234 structures destroyed
1980/November	Panorama	California	23,600 (9,551)	325 structures destroyed
1985/May	Black Friday Fires	Florida	110,000 (44,517)	1 dead, at least one fire in nearly every county of the state, 600 homes lost (400 of those lost in 1 day)
1987	Siege of '87	California	640,000 (259,000)	Valuable timber lost on the Klamath and Stanislaus National Forests
1988	Yellowstone	Montana and Idaho	1,585,000 (641,450)	Large amount of acreage burned
1988	Canyon Creek	Montana	250,000 (101,175)	Large amount of acreage burned
1990/June	Painted Cave	California	4,900 (1,983)	641 structures destroyed
1990/June	Dude Fire	Arizona	24,174 (9,783)	6 dead, 63 homes destroyed
1991/October	Oakland Hills	California	1,500 (607)	25 dead and 2,900 structures destroyed
1992/August	Foothills Fire	Idaho	257,000 (104,000)	1 dead
1994/July	South Canyon Fire	Colorado	1,856 (751)	14 dead
1994/July	Idaho City Complex	Idaho	154,000 (62,324)	1 dead
1996/August	Cox Wells	Idaho	219,000 (88,629)	Largest fire of the year
1996/June	Millers Reach	Alaska	37,336 (15,110)	344 structures destroyed
1997/July	Inowak	Alaska	610,000 (246,867)	Threatened 3 villages
1998	Volusia Complex	Florida	111,130 (44,570)	Thousands of people evacuated from several counties
1998	Flagler/St. John	Florida	94,656 (38,307)	Forced the evacuation of thousands of residents
1999/August	Dunn Glen Complex	Nevada	288,220 (116,643)	Largest fire of the year
1999/August–November	Big Bar Complex	California	140,947 (57,041)	Series of fires caused several evacuations during a 3½-month period
1999/September–November	Kirk Complex	California	86,700 (35,087)	Hundreds of people evacuated by this complex of fires that burned for almost 3 months
2000/May	Cerro Grande	New Mexico	47,650 (19,284)	Originally a prescribed fire, 235 structures destroyed and Los Alamos National Laboratory damaged
2003/October	19 fires throughout the state	California	730,000 + (295,431)	More than 3,600 homes destroyed, 22 people dead, more than 200 injured, more than 500 farms and commercial properties damaged

Source: National Interagency Fire Center, Boise, Idaho, and the Insurance Services Offices, Jersey City, New Jersey.

(GIS), globally positioned satellites (GPS), remote sensing of weather and fire conditions, fire and related land management simulation models, and the Internet. A major consideration in the twenty-first century is what Americans want and expect from their national forests and grasslands.

In a presentation to the Idaho Environmental Forum in 2004, USDA Forest Service Chief Dale Bosworth pointed out four major threats to the forestlands in the United States: fires, invasive species, loss of open space, and unmanaged outdoor recreation.[3]

Fires. Since 2000, the United States has had some of the worst fire seasons in 50 years. In 2002, record-breaking fires burned in four different states, and a fifth came close to breaking past records. In 2003, the fire season in southern California resulted in the deaths of at least 20 people and more from the debris flows that followed when rains fell on slopes where fires had burned away the vegetation.

Because many of the nation's fire-dependent ecosystems have become overgrown and unhealthy, the proper response is to reduce fuels *before* the big fires break out. The use of thinning techniques and the effective and safe reintroduction of fire into the ecosystem will help reduce the damage that fire makes each year in nearly every state.

Invasive Species. Plant species that evolve in one place and show up in another, where the ecological controls they evolved with are missing, take advantage of their new surroundings to crowd out or kill off native species, destroying habitat for native wildlife. Where cheatgrass takes over, for example, the range loses forage value for deer and elk, affecting the nation's heritage at a cost of billions of dollars.

Loss of Open Space. Every day, America loses about 4000 acres (1619 ha) of open space to development, about 3 acres (1.2 ha) per minute, and the rate of conversion is accelerating. In some places, the loss is to large, relatively undisturbed forests that provide needed habitat for animals like marten, bear, and cougar. In other places, the loss is to rangeland needed by many other animals and plants. Where private open space is lost, recreational pressures on public lands tend to grow.

Unmanaged Outdoor Recreation. Ninety-nine percent of recreational users are careful to protect the land. However, with millions of users, even a tiny percentage of problem use becomes relatively huge. Each year, the national forests and grasslands get hundreds of miles of unauthorized roads and trails due to repeated cross-country use. Every season, more erosion, water degradation, and habitat destruction occur. Conflicts between users and among land managers are rising. The challenge is to improve land management in order to get the most desirable and responsible recreational use based on sound outdoor ethics.

Causes of Wildland Fires

Leading Causes. Causes of forest fires differ from region to region but nationally they maintain a consistent ranking within percentage ranges (Table 13.5.2).[4] The leading cause of wildfires in the United States is intentional burning, or arson, which accounts for one-quarter to one-third of the fires and burned-over area. Debris burning accounts for an additional one-fourth of the fires, whereas lightning accounts for another one-tenth to one-seventh of the fires but affects a larger share of the burned area. Other prominent causes of fires include equipment use, careless smoking, children playing with matches, campfires, and railroad use.[5]

Nearly all of these fires are controlled at a size of 100 acres (40 ha) or less. However, roughly 2 percent of fires result in two-thirds of the total burned-over area. Altogether, hundreds of thousands of wildfires occur each year in the United States, burning millions of acres of forest, brush, and grass-covered lands.

The relative importance of the fire causes just mentioned varies considerably among the different geographical regions of the country. In terms of the number of fires and burned areas, lightning is the leading cause in the northwestern part of the country, as well as in Arizona and New Mexico. For the entire eastern half of the United States, intentional burning, or arson, and debris burning are the chief causes. In California, equipment use and arson rank highest, and debris burning and lightning are the main problems in the central Rockies. Alaska's wildfires can be blamed chiefly on debris burning and lightning.

In Canada, thousands of wildfires occur each year, burning millions of acres of wildlands. About one-third of these fires are caused by lightning, although fires started by lightning account for most of the burned-over area.

Role of Lightning. On a global scale, lightning is common; 8 million cloud-to-ground discharges occur per day around the world. One percent of these strikes results in wildland fires. In fact, dry lightning is responsible for 80 percent of all fires in wildland areas. Dry lightning occurs during thunderstorms when the humidity is so low (the air is so dry) that rain evaporates before it reaches the ground. Even though the rain does not reach the ground, the lightning does. Although the energy per lightning bolt varies greatly, 250 kilowatt-hours is a good estimate of the average energy discharged in each stroke. Almost 75 percent of a lightning bolt's energy is converted to heat during discharge. This is more than sufficient to ignite most fuels.

There are two types of discharge: cold and hot stroke. Cold strokes exhibit high voltage of short duration, generally with

TABLE 13.5.2 Causes of Wildland Fires

Cause	*Percentage Range*
Arson	25–39
Trash burning	18–23
Careless smoking	17–19
Miscellaneous/unknown	10–14
Lightning	9
Machine use	7–8
Railroads	5
Campers	3–6

mechanical or explosive effects. Hot strokes discharge a lesser current for a longer duration, thus starting more fires. Approximately 21 percent of all lightning moves from cloud to ground. Of this amount, 20 percent is hot stroke, according to studies in the northern Rockies. Therefore, in the northern Rockies, one stroke in 25 has the electrical characteristics to start a fire, depending on where or what it strikes and on the local weather conditions.

PRINCIPLES OF COMBUSTION

Fire is a chemical reaction in which energy is produced. When forest material burns, the oxygen in the air combines chemically with wood, pitch, and/or other burnable elements in the fuel. In the forest, several stages in the fire process are normally encountered: first, the igniting spark; then a period of smoldering; and, finally, the more rapid combustion of fuels. This process may continue to involve leaping flames, dense smoke, intense heat, loud noises, and occasional explosions. Throughout its life, the action of a fire is governed by certain natural laws or principles of combustion. An understanding of these principles is basic in judging the effect of various environmental factors on fire behavior.

The Fire Triangle

Three elements—heat, oxygen, and fuel—are required in proper combination for ignition and combustion to occur.* If any one of the three is absent or if they are not in proper balance, ignition or combustion will not occur. Variations in balance among heat, oxygen, and fuel govern the violence of a fire and determine whether the fire will smolder and spread slowly or flame brightly and travel rapidly.

Heat. Because of the variation in the nature of forest fuels, specifying the amount of heat required to ignite the fuels is difficult. Vegetative material is high in carbon content and ignites at relatively low temperatures, provided the moisture content is low and the substance is freely exposed to the air. During the forest fire season, a large part of the vegetative matter in a forest—duff, dead limbs, pine needles, tree branches, rotted logs, and so on—is dry enough to be ignited easily. The temperature requirement for ignition of forest fuels varies from approximately 500 to 750°F (260 to 399°C). Many common ignition sources can provide the required heat, including a burning match, a glowing cigarette, or a lightning bolt.

Ignition often depends on the length of time the fuel is exposed to heat. Dry pine needles may be ignited in a few seconds by the heat from a flaming match. Moist pine needles also may be ignited by a match if subjected to the heat for several minutes. When wood fuels are exposed to heat for a long time, the normal ignition temperature may be lowered. Studies have shown that wood exposed to a temperature of 400°F (204°C) for approximately 30 minutes may ignite.

The ease of ignition of forest fuels exposed to heat for a considerable time has an important influence on fire behavior. In a coniferous forest, a hot fire burning in a tangle of downed logs and dry limbs may generate enough heat to make the green tree crowns above the fire easily ignitable. All that is needed to cause the tree crowns to ignite is a flying ember and a gust of wind. Similarly, a fire smoldering in a pile of leaves may generate enough heat to lower the normal ignition temperature of the entire pile. When the leaves are stirred up, the whole pile breaks into flame. The stirring of the pile lets in enough oxygen for the preheated leaves to be ignited easily.

Oxygen. The atmosphere is about 21 percent oxygen and since most wildland fires burn in a free-burning state in an uncontained environment (unlike structure fires), removing the oxygen side of the triangle (smothering the fire) is usually impractical to extinguish a wildland fire. In the forest, there is usually enough oxygen to permit ignition and combustion. However, some of the forest fuels may be arranged so that oxygen is not available in sufficient amount to support a fire. In deep, tightly compacted duff, only the top particles can get enough air to permit a fire to burn. In this situation, a fire will burn from the top down as each layer is exposed to the air. By contrast, in a very loose layer of pine needles, the entire mass is fairly well exposed to air and, consequently, combustion will take place rapidly.

The air mass near a fire, as represented by weather elements that can be measured, is perhaps the most variable component of the fire environment.[2] When wind blows on a fire, it usually speeds up the combustion process. Wind forces oxygen around fuel particles where the flow of air normally may be restricted. In addition, wind has a physical reaction on the flames, often bending them into positions that create more favorable situations for the spread of the fire.

Fuel. Under forest conditions, fuel is a major variable in the fire triangle. The fire fighter must become acquainted with the general nature of forest fuels to understand their burning characteristics.

The ease of ignition and rate of combustion of forest fuels depend mainly on the type of fuel—is it logging slash or dense duff in a green forest? On fuel continuity—is the fuel distributed more or less evenly over the area, or is it only present in patches? On moisture content—does it feel damp when touched, or does it crackle and appear very brittle? On fuel temperature—is the fuel exposed to the heat of the sun, or does it lie in cool shade?

Combustion Process. When fuels are heated to their ignition temperature, they produce gases that will ignite if combined with oxygen. When a log burns, the flames may appear to be coming directly from the fuel. Actually, the flames come from the ignited fuel gases emerging from the heated log.

In forest fires, the two common stages of combustion are smoldering and flaming. In the smoldering stage, heat is

*Although it is recognized that there is a fourth component involved in the combustion process (a chemical chain reaction), for the purposes of this chapter only, the components that make up the commonly referred to "fire triangle"—heat, fuel, and oxygen—will be addressed. The process of breaking the chemical chain reaction is not normally addressed in relation to wildland fire suppression methods. For a discussion relating to the fire tetrahedron and the chemical chain reaction process, see Section 2, Chapter 1, "Physics and Chemistry of Fire."

liberated, and a rise in fuel temperature occurs, whereas flames are absent or appear only intermittently. The absence of flames is caused by insufficient oxygen or by moisture in the fuels, which slows the oxidation process.

When a fire is in the flaming stage, all the elements of the fire triangle—that is, heat, oxygen, and fuel—are in proper combination for rapid oxidation to occur. The flames of very hot fires may be observed intermittently in the smoke at a considerable distance above the fire. This occurs when oxygen is consumed so rapidly near the base of the fire that combustion of the gases is incomplete. As these superheated gases rise, they reach a fresh oxygen supply and break into flames, giving the appearance that the smoke itself is flaming.

Reignition of apparently dead fires is an important factor in forest fuels. Although neither flames nor smoke may be observed, a fire can break out again if sufficient heat remains. Reignition occurs easily where fuels have been subjected to heat for a considerable length of time. To prevent reignition, an experienced fire fighter feels out fuels by hand before leaving the area. If heat continues to be present, the danger of reignition exists, and the control job remains incomplete.

Breaking the Fire Triangle

In fire control operations, the objective is to prevent combustion by breaking the fire triangle. If a sufficient volume of water is applied, the fuel temperature can be lowered below the ignition point. Smothering fires with dirt deprives them of oxygen. Building a line in which all flammable material is removed from the path of the fire prevents further spread by robbing the fire of fuel.

In forest fire fighting, the actual method of suppression is often dictated by the equipment and fire fighters available. The most effective methods for each stage of a suppression operation can be determined by keen observation of the combustion process.

Reducing Heat. Water being used to reduce fuel temperatures should be applied directly on the fuels being consumed. It is a mistake to apply water on the flames rather than the fuels. If the liberation of these gases is to be stopped, the fuels themselves must be cooled by the water. Although some of the water played on the flames may reach the fuels, a large part will either miss its mark or be lost through vaporization. If water is being used for cooling purposes, the ultimate target is always the fuel.

In a very hot fire accompanied by leaping flames, the nozzle user may not be able to get close enough to the fuels to apply water directly on the trouble spot. In such cases, a fog nozzle should be used to knock down the flames. The water particles help cool the heated gases being liberated by the fuels. Once the flames have been knocked down, the water should be used to thoroughly cool the heated fuels that are generating flammable gases.

Reducing Oxygen. Fires burning in forest fuels are difficult to smother completely. Soil thrown on burning forest materials may retard combustion by shielding portions of the fuel surface from the air, but the porous nature of most soils makes it difficult to completely shut off the supply of oxygen in this manner. Throwing dirt on a fire is nevertheless an important means of reducing the rate of combustion, after which the control operation may be continued by attacking one of the other legs of the fire triangle.

In very fine fuels such as dry grass, the oxygen supply may be reduced easily. Fuels of this nature do not retain heat for long periods and, therefore, combustion normally may be checked by temporarily shielding the fuel surface from the air. Gunnysacks, fire swatters, and a shovelful of dirt correctly applied are effective implements in smothering grass fires. When larger accumulations of flammable materials, such as dead stems and leaves, lie beneath a stand of grass, the danger of reignition exists. The understory material may hold enough heat to cause the fire to reignite once an adequate supply of oxygen becomes available. This danger can be determined by the careful observation and "feeling out" of the fuel.

Removing Fuel. In wildland fire suppression, the removal of fuel from the path of the fire is a common method of attacking the fire triangle. The fire continues to burn until its fuel is consumed, but it is prevented from spreading any further. A slowly advancing fire burning in sparse ground fuels may be checked simply by constructing a fireline down to mineral soil (soil with little humus or organic matter). A hot or fast-running fire may require several fuel removal operations. Snags of trees or tall brush that could cause spot fires may have to be felled. Thickets of reproduction or dry brush may need to be weeded out. Low-hanging limbs may have to be removed to prevent the build-up of a crown fire. Concentrations of limbs and logs may have to be broken up. The objective of these operations is to remove or reduce the flammable substances that could allow the fire to either build in intensity or continue to spread.

Heat Transfer

The rate and amount of heat transferred influence the rate of spread and the intensity of a fire. Combustion cannot be sustained unless heat continues to be transferred. Heat transfer occurs by three means: radiation, convection, and conduction.

Radiation. In forest fires, radiation is the most significant means of transferring heat from burning fuels to exposed fuels. The location and width of firelines must be governed, in part, by the rate of radiant heat transfer. Potentially hot fires and spots where dangerous flare-ups might occur can often be prevented by the breaking up of the fuels to reduce the radiant heat transfer between them.

The degree of slope influences the amount of radiant heat transmitted to fuels upslope and downslope of the fire. Most forest fires will burn in the direction of the wind, partly due to the effects of radiant heat. Wind influences radiant heat transfer in two ways: (1) it increases the rate of combustion, thus creating a hotter fire; and (2) it bends the flames, thus decreasing the distance between the heat source and the fuels lying in the path of the fire. The dual effect of the hotter fire and the bent-over flames dries and heats the fuels laying ahead to such an extent that rate or spread may be greatly accelerated.

Often a fire will burn into the wind because the wind increases combustion to such a degree that a large amount of ra-

diant heat may be transmitted to the fuels lying on the upwind side. On the upslope side of a fire, the fuels receive more radiant heat, which is one reason fires often spread more rapidly up steep slopes than on level ground.

Convection. In a forest fire, the fuels lying in the path of convection currents are heated and, thus, transformed into a more ignitable condition. The hot air mass rising from a surface fire transfers a large amount of heat to the tree crowns, thus bringing them nearer to the ignition temperature.

When fires break out in tree crowns and in other aerial fuels, heat transfer by convection is usually increased. Sparks and burning embers (firebrands) from burning tree crowns and snags will also drop and start new fires in fuels on the ground. As these ground fires gain in intensity, more hot air masses rise through the aerial fuels, and a type of chain reaction may be created. Fire fighters must always be alert to the danger of hot surface fires burning underneath a forest canopy. These surface fires must be cooled promptly, and fuel masses must be broken up to reduce convective heat transfer.

Heat transfer through convection is also increased by wind, which moves hot masses of air ahead of the fire. Wind both increases the rate of combustion and accelerates the transport of hot air masses. When driven by wind, the hot convection currents may move closer to the ground fuels and, thus, create more flammable conditions in the understory vegetation of the forest.

Fuels located above the fire on steep slopes also receive heat by the movement of convection currents up the slope and are, thus, subjected to an accelerated rate of heating and drying. This fact is one more reason why fires often burn very rapidly up the sides of steep slopes.

Conduction. Wood is a poor conductor of heat, and the conduction method of heat transfer is relatively minor in evaluating forest fire behavior.

TOPOGRAPHY

Topography provides a useful and easily recognized indicator of fire behavior. Fires often have distinctive behavior characteristics according to aspect, elevation, position on slope, steepness of slope, and shape of the surrounding countryside. These topographic features are usually easy to identify in the field and, thus, are important factors in the evaluation of fire behavior.

Differences in topography may cause local variations in climate and day-to-day weather conditions. These variations, in turn, influence the character of forest growth and the flammability of fuels. In rough terrain, such as the northern Rocky Mountains, topography has a great influence on fire behavior.

Aspect

Aspect, sometimes referred to as exposure, describes the direction a slope faces. Fire conditions vary greatly according to aspect because different aspects receive varying amounts of sunshine and wind.

In general, southern and southwestern slopes provide favorable conditions for the ignition and spread of fires. Because these slopes receive direct sunshine, the air and fuel temperatures are somewhat higher and cause snow to melt earlier on southern slopes. For these reasons, vegetation on south-facing slopes is not only sparser but also drier and more flammable than vegetation on north-facing slopes.

There are also variations in temperature and relative humidity on northern and southern slopes. On south-facing slopes, the average July through August temperature is higher, and the relative humidity is lower. The time of day is also critical. South- and west-facing slopes are most dangerous in the afternoon and early evening. When the combined effects of aspect and elevation are considered, some striking indicators of fire behavior become evident.

Elevation

In the Rocky Mountains, there is a vertical difference of more than 10,000 ft (3048 m) between the lowest valleys and the highest mountains. At Lewiston, Idaho, the elevation is only 757 ft (231 m) above sea level. Along the Continental Divide, there are many peaks over 10,000 ft (3048 m), and in northwestern Wyoming, some peaks are over 13,000 ft (3962 m) above sea level. Between these extremes of elevation is a variety of weather and fuel conditions that creates distinctive fire control problems.

Position of Fire on Slope

Fire behavior at various positions on a slope may be influenced not only by aspect and elevation but also by the magnitude of the fuel body and by topographic barriers. When a fire starts at the bottom of a slope, an entire mountainside of fuels may lie in its path. Once a fire starting at the base of a slope gains headway, the availability of a continuous fuel body makes a large burn possible.

Steepness of Slope

Other conditions being equal, fires burn more rapidly on steep slopes. In general, as the steepness of the slope increases, the rate of fire spread increases. As explained previously, combustion is accelerated on steep slopes primarily due to increased heat transfer through radiation and convection. A fire will double in rate of spread on a 30 percent slope. On a 55 percent slope it will double again.

Shape of Country

In rugged, mountainous areas, the shape of the country is of great importance to the fire fighter who must evaluate fire behavior. Narrow canyons, side drainages, sharp ridges, and massive, irregular slopes all have a bearing on the direction of travel, rate of spread, and general behavior of fires.

Experience has shown the following topographic features to be of special importance:

- *Narrow canyons.* Wind direction normally will follow the direction of the canyon. Wind eddies and strong upslope air movement may be expected at sharp bends in a canyon. Radiant heat transfer from one slope to another is great and, as a result, fires may spot across the canyon easily. Near the bottom of the

canyon, there is little difference between conditions on various aspects.

- *Wide canyons.* Prevailing wind direction will not be altered to any great extent by the direction of the canyon. Cross-canyon spotting of fires is not common except in high winds. Strong differences will occur between general fire conditions on northern and southern aspects.
- *Box canyons.* Fires starting near the base of box canyons will react similarly to a fire in a stove. Air will be drawn in from the canyon bottom, thus creating very strong upslope drafts. These same conditions may occur at the heads of narrow canyons and at the heads of high mountain valleys.
- *Ridges.* Fires burning along lateral ridges may change direction when they reach a point where the ridge drops off into a canyon. This change of direction is caused by the flow of air in the canyon. In some cases, a whirling motion by the fire may result from a strong flow of air around the point of a ridge.

FUELS

Keen observation of variations in forest fuels is essential in reliably estimating fire behavior. Fuel is the material of primary concern to fire control agencies. A good fire fighter must be able to evaluate flammability and difficulty of control in the various fuel situations encountered in a forest area.

Flammability Analysis

In a forest, great differences exist in the character of flammable materials. Deep duff, newly fallen dead leaves, clumps of grass, litters of dry twigs and branches, downed logs, low shrubs, green tree branches, hanging moss, snags, and many other types of material are present. Each of these materials has distinctive burning characteristics. The flammability of a particular fuel body is governed by the burning characteristics of individual materials and by the combined effects of the various types of materials present.

Before flammability can be analyzed, the physical characteristics of combustible forest materials must be classified. Such a classification permits the identification of the fuel factors that influence flammability. After the fuel has been classified properly, topographic and weather factors must be considered before the rate of spread and the general behavior of fires in that fuel can be determined.

Because forest fuels are so varied and complex, developing a systematic approach to flammability analysis is necessary. First, the fuel body is subdivided into two broad classes: ground fuels and aerial fuels. Then each of these classes is evaluated according to the arrangement, compactness, continuity, volume, and moisture content of the principal materials involved. Aspect also affects the flammability of fuels. Southwest-facing slopes heat up to a greater extent. With practice, this procedure can be performed quickly and easily.

Ground Fuels

Ground fuels include all flammable materials lying on or immediately above the ground or in the ground. The principal materials are duff, tree roots, dead leaves, grass, fine deadwood, downed logs, stumps, large limbs, low brush, and reproduction or young stands of timbers.

Duff. Duff is composed of partially decayed vegetative matter found on the forest floor. Duff seldom has a major influence on the spread rate of fire as it is typically moist and tightly compressed so that little of its surface is freely exposed to air and its rate of combustion is slow. In forest fires, most of the duff is consumed down to mineral soil. Occasionally, duff contributes to the rate of spread by furnishing a path for the fire to creep along between patches of more flammable material.

The smoldering characteristics of duff fires make them somewhat difficult to control. Firelines must be dug down to mineral soil in duff areas unless the lower layers of duff are too wet or too tightly compressed to burn. Duff fires inside a fireline are best mopped up by turning over the duff with a shovel, loosening the material for better exposure to air, and allowing it to burn out. Water may be used effectively, but great care must be taken to stir the fuel to ensure that all particles are thoroughly soaked. Extinguishing duff fires by smothering them with dirt is very difficult to accomplish.

Tree Roots. Tree roots are not an important factor in rate of fire spread, as the greatly restricted air supply prevents rapid combustion. However, fires can creep slowly in roots—in fact, some fires have escaped control because a root provided an avenue for the fire to cross the control line. The most flammable roots are the large laterals stemming from dead snags. Root fires are controlled simply by cutting the root where it crosses the fireline. Mop-up of persistent fires may require complete excavation of roots.

Dead Leaves. As leaves decay on the ground, they gradually become part of the duff layer. Before this decay takes place, however, leaves are a highly flammable material and should be considered separately in evaluating ground fuels. In northern Rocky Mountain forests, the cover of dead leaves on the ground is composed primarily of needles dropped from coniferous trees. Ponderosa pine needles are the most flammable because their large size and shape lead to a loose arrangement allowing free circulation of air. Smaller needles, such as those from Douglas fir, are generally less flammable as they are more tightly compacted on the ground.

Needles that are still attached to dead branches are especially flammable because they are exposed freely to air and are not typically in direct contact with the more moist material on the ground. Needles remaining on fallen limbs form highly combustible kindling for larger material. For this reason, logging slash containing dry needles is dangerous fuel.

Many techniques are necessary to control fires for which leaves or needles are the primary fuel. The advance of a fast-running fire may be checked temporarily by smothering it with dirt or by cooling it with water. Only a light cover of dirt thrown with the sweeping motion of a shovel is necessary to slow down a needle fire.

When water is used to check the advance, a spray or fog-type stream is most effective, with the water being aimed at the base and directly in front of the flames. A penetrating straight stream of water is most effective for mopping up a needle fire. Careful

stirring of all flammable material is required. A fireline is essential around all fires burning in a continuous cover of needles.

Grass. Grass, weeds, and other small plants are important ground fuels that influence the rate of fire spread. The key factor in these fuels is the degree of curing. Succulent green grass acts as a fire barrier. During the course of a normal fire season, however, grass gradually becomes drier and more flammable until the stems and leaves die due to lack of moisture. At this time, the major part of the grass cover becomes highly flammable. Cured grass, if present in large and uniform volume, provides the most flammable ground fuel in the region.

Grass and other small plants occur on the floor of almost all forests. Fire fighters need to observe the volume and continuity of the grass cover. In dense forests where little sunlight reaches the ground, very little grass is found. In more open forests, such as in mature stands of ponderosa pine, there may be a large amount. If there is a more or less continuous cover of dry grass on the forest floor, the spread rate of a fire will be governed largely by that cover rather than by the heavier fuels normally associated with a forest.

The ease with which fires in dry grass can be controlled depends mainly on the volume of grass. When the volume is low, the fire is often cool enough to permit fire fighters to work near the edge of the flame front. When the volume of grass is great, however, the resulting hot fire may prevent work close to the fire front.

In grass fires, smothering with dirt or swatters and cooling with a spray or fog stream of water are effective control methods. Both methods require follow-up to ensure that no hangover fires remain. Wherever forest material, such as a mat of dead pine needles, twigs, or small limbs, is intermixed with the stand of grass, a fireline dug down to mineral soil is usually required.

Fires in dry grass often have high rates of spread. For this reason, special safety measures need to be observed.

Fine Deadwood. Fine deadwood consists of twigs, small limbs, bark, and rotting material. Normally, the fine deadwood classification is confined to material with a diameter of less than 2 in. (50.8 mm). These fine dead ground fuels are among the most important of all materials influencing the rate of fire spread and general fire behavior in forest areas. Fine deadwood ignites easily and often provides the main avenue for carrying fire from one area to another. It is the kindling material for larger, heavier fuels.

In areas where a great volume of fine deadwood exists, a fire can rapidly develop tremendous heat. The greatest volume of fine deadwood is usually found in areas containing logging slash. Under dry conditions, fires in such areas burn violently, and the strong convection currents created by the intense heat pick up burning embers and throw them out ahead, causing spot fires beyond the main fire front. In some areas, the occurrence of fine deadwood may be spotty. Troublesome situations may be avoided by breaking up the worst bunches of fine deadwood before a fire reaches them.

Granulated dry rotten wood, although not an especially important factor in the rate of fire spread, is a highly ignitable fuel. Flying embers from the main fire often cause spot fires in rotten wood lying on the ground or in hollow places on old logs or stumps. Fire fighters searching for spot fires should seek out and carefully check these areas.

In most forest fires, the control job must be aimed largely at checking the spread of fires in fine deadwood and in the associated material—that is, duff and leaves—lying underneath. Unless a large volume of dry grass is present, the fine deadwood is the most important fuel and should receive the first and most concentrated attention. If the fire is very hot, the first action may be to smother it with dirt or cool it with water. Final control requires a fireline dug down to mineral soil in nearly all cases.

Downed Logs, Stumps, and Large Limbs. Heavy fuels, such as downed logs, stumps, and large limbs, require long periods of hot, dry weather before they become highly flammable. When such material reaches a dry state, however, very hot fires may develop. The most dangerous heavy fuels are those containing stringers of dry wood, shaggy bark, or many large checks and cracks. Smooth-surfaced material is less flammable as it dries out more slowly, has little surface exposed to air, and contains less attached kindling fuel. Extremely hot fires may develop in piles of downed logs and large limbs or in crisscrossed windfalls as the various fuel components radiate heat to each other. Individual limbs and logs will not burn very hot unless the fire is supported by large accumulations of fine deadwood.

The control of an advancing fire seldom rests on the fire fighters' ability to suppress the fire in heavy fuels. Usually, fires will not advance from log to log unless finer fuels are present or the area is covered with logs that radiate heat to each other.

Once a fire becomes well established in heavy fuels, complete suppression becomes difficult. A control line around the area is essential. Smothering with dirt or cooling with water is effective, but both these methods require very large volumes of suppression agent. In some cases, it is necessary to allow the fire to burn out until the heat has subsided sufficiently to permit final mop-up operations to take place. When a fire is allowed to burn out in logs containing stringers of bark, a careful lookout must be kept for spot fires caused by embers carried in the strong convection currents. If at all possible, hot fires in such areas should be cooled promptly by any available means.

Low Brush and Reproduction. Low brush, tree seedlings, and small saplings are classified as ground fuels because they are so closely intermixed with the flammable material on the forest floor. This understory vegetation may either accelerate or slow down the spread rate of a fire. During the early part of a fire season, the shade normally provided by understory vegetation prevents other ground fuels from drying out rapidly. As the season progresses, however, continued high air temperature and low relative humidity dry out both the fuel lying on the ground and the understory vegetation. When this happens, most of the low vegetation, particularly small coniferous trees, becomes fire carriers.

The understory vegetation in a forest often provides a link between ground fuels and aerial fuels. The crowns of small trees may catch fire and, in turn, spread the fire to aerial fuels in the forest canopy. Either thickets of reproduction or dead brush may provide the first means for a surface fire to flare up and spread into the crowns of the overstory trees. In anticipation of this

possibility, alert fire fighters break up reproduction thickets and dead brush along the fireline or, wherever possible, locate control lines to prevent fire from spreading into these danger areas. It is not uncommon for fire to creep through ground fuels under low brush or reproduction during periods when there is a low burning index, such as during the night. Heat from the creeping fires dries out the leaves and stems of the low brush and reproduction. Then, on the following day, as the burning index increases, a reburn occurs. Often on the reburn, the dried, low vegetation burns hotly and carries the fire to the aerial fuels, causing a crown fire.

Aerial Fuels

Aerial fuels include all green and dead materials located in the upper forest canopy. The main aerial fuel components are tree branches, crowns, snags, tree moss, and high brush.

Tree Branches and Crowns. The live needles of coniferous trees are a highly flammable fuel. Their arrangements on the tree branches allow free circulation of air. In addition, the upper branches of trees are more freely exposed to wind and sun than most ground fuels. These factors, plus the volatile oils and resins in coniferous needles, make tree branches and crowns important components in aerial fuels.

Tree branches and crowns are fuels that can flash quickly with changes in relative humidity. Crown fires seldom occur when relative humidity is high. However, coniferous needles dry out quickly when exposed to hot, dry air. The dryness of needles is influenced by the transpiration process in a tree. When the ground is moist, trees pump a large amount of moisture into the air through the leaves. As the ground becomes drier, the transpiration process slows and, as a result, leaves and branches become drier and more flammable.

Dead branches on trees are an important aerial fuel. Concentrations of dead branches, such as those found in insect- or disease-killed stands, may cause fire to spread from tree to tree. Concentrations of dead branches on the lower trunks of trees may provide an additional avenue for fires to spread from ground fuels into tree crowns. The most flammable dead branches are those still containing needles.

Fires in the upper crowns of trees are extremely difficult to control. The main control method must be aimed at suppressing the fire in ground fuels and preventing the fire from entering the tree crowns. Removal of limbs on the lower trunks of trees is one method of preventing crown fires. Limbs should be removed wherever a concentration of ground fuels makes a crown fire likely.

Snags. Snags, or tree stumps, are one of the most important aerial fuels that influence fire behavior. Although green trees greatly outnumber snags in most forests, more fires start in snags because they are drier and are arranged for easier ignition.

Snags vary widely in character and, consequently, in their effect on fire behavior. Smooth, solid snags that contain very little bark and few checks or cracks are not highly flammable. On the other hand, broken-topped, shaggy-barked, or partially decayed snags ignite easily and have a major influence on the spread of fires. Burning embers blown from shaggy-barked snags are prolific starters of spot fires. In areas containing large numbers of snags, fire may spread from one trunk to another because of the intense radiation of heat.

Fires in burning snags must be controlled promptly. Wherever possible, the main control effort on the fire must be designed to prevent the blaze from getting into snags. When fires become established in snags, the control method usually requires that the snags be felled. Snag felling is especially important if shaggy bark might be carried from the burning trunk by wind or strong convection currents.

Tree Moss. Moss hanging on trees is the lightest and flashiest of all aerial fuels. Moss is important principally because it provides a means of spreading fires from ground fuels to other aerial fuels or from one aerial component to another. Like other light fuels, moss reacts quickly to changes in relative humidity. During dry weather, crown fires may develop easily in heavily moss-covered stands. Methods of controlling moss fires are aimed primarily at breaking up ground fuels to prevent fire from entering the tree crowns through hanging moss. In addition, lower limbs containing tree moss should be removed at all danger spots.

High Brush. Crowns of high brush are classified as aerial fuels because they are separated distinctly by distance from ground fuels. In the northern Rocky Mountain region, heavy stands of brush may develop in old burns, and they often form the principal vegetative cover in such areas. Crown fires in brush fuels ordinarily do not occur unless heavy ground fuels are present to develop the required heat. In some brush stands, however, a high proportion of dead stems may create a sufficient volume of fine dead aerial fuels to permit very hot and fast-spreading crown fires. Key factors in evaluating the behavior of fires in high brush are volume, arrangement, the general condition of ground fuels, and the presence of fine dead aerial fuels.

Fuel Conditions

Fuel Continuity. Fuel continuity describes the distribution of fuels in a given area. Fuel continuity is an important factor in fire behavior because the distribution of fuels influences the potential area where a fire may spread, as well as the rate of spread. If a dangerous fuel is uniformly distributed over an entire area, a high potential exists for a complete burn to occur at a rapid rate of spread. If the fuel body is broken up by patches of bare ground or much less flammable material, both the potential area of the burn and the rate of fire spread are reduced.

A wide range of fuel continuity conditions is found in most forest areas. For the sake of simplicity in making fire behavior estimates, the following two broad fuel continuity classes are recognized:

- *Uniform fuels.* Uniform fuels include all fuels distributed continuously over the area being evaluated. Areas containing a network of stringers, or blocks, which connect with each other to provide a continuous path for the spread of fire, are included in this classification.

- *Patchy fuels.* Patchy fuels include all fuels distributed unevenly over the area being evaluated. Definite breaks should be present, such as patches of rocky outcropping or plots where the dominant vegetation is of much lower flammability than the main fuel body.

Volume. As the amount of flammable materials in a given area increases, the amount of heat a fire produces also increases. The hottest fires, as well as those most difficult to control, occur in areas containing the greatest quantity of fuel.

In evaluating fuel volume, fire fighters should observe the quantity of both small- and large-sized fuel components. A great volume of small materials, such as fine deadwood, indicates ample kindling for the ignition of other fuels. A great volume of either small- or large-sized material indicates a high potential for a hot fire. Where fires develop in areas containing a great volume of large-sized material, there is intense radiation of heat to fuels lying in the path of the fire.

Fuel Compactness. Fuel compactness—that is, the number of individual fuel particles per unit of volume—varies greatly in all kinds of fuel, but it is significant principally in duff and dead leaves lying on the ground. Fires burn rapidly in loosely compacted fuels because more of the individual fuel particles are freely exposed to air.

Live Fuel Moisture. Two conditions of fuel moisture have major influence on the rating of fuel types. One concerns the greenness, or curing stage, of vegetation. The other relates to the shade and protection furnished by green timber.

In grass fuels, moisture content is a critical factor in determining flammability. Fires spread only at a low rate, or not at all, in grasses that are green, but when the same grasses become cured and dry, fires will race through them at an extremely rapid rate. The degree of curing of grass is difficult to evaluate and requires keen observation of the grass stand. For purposes of considering fire behavior, the moisture content of grass can be judged according to the state of curing, as follows:

- *Green.* The condition can be recognized by the green color and the cool, moist feel when crushed in the hand.
- *Curing.* As hot, dry weather prevails, grasses ordinarily progress through a period of gradual curing. This stage is detected by close observation of the individual grass clumps or stems. For cheatgrass, the curing stage is typified by a lavender tinge commonly referred to as "the purple stage." For most other grasses, the curing stage begins when the tips of grass blades become tan or brown, or when individual grass blades take on a cured appearance.
- *Cured.* In the cured stage, grasses are dried completely to a tan or brownish hue, and the stems feel dry or crackly when crushed or rubbed in the hand.

Soils influence curing primarily because of soil moisture relationships. In the deep, moist soils bordering creeks, curing is much slower than in the thin soils on slopes. Some grasses seldom reach a dangerous cured condition. The shade and protection afforded by timber stands influence fuel type ratings due to the favorable fuel moisture conditions that are created. In a dense forest, ground fuels are protected from the sun and wind. Temperatures and wind velocities are lower so that moisture does not evaporate as rapidly from the dead fuels on the ground. Lower ratings are assigned to fuels situated beneath dense timber canopies.

The moisture content of fuels is influenced also by aspect, altitude, time of year, time of day, and other factors. For the purpose of fuel type classification, these factors are disregarded, and fuel types are classified on the basis of the physical characteristics of the fuels themselves.

Dead Fuel Moisture. Dead fuel moisture is changed by the moisture content of the air. Time lag is the time it takes for the moisture content of the dead fuels and the surrounding air to equalize. Time lag is expressed as a rate (usually in hours) (Table 13.5.3).

SPECIAL FIRE BEHAVIOR FACTORS

Spot Fires

The development of spot fires depends not only on topographic and weather factors but also on the character of the fuels in the main fire and fuels beyond the main fire. In the main fire, rotten, shaggy-barked snags, such as broken-topped hemlock snags, and large quantities of ground fuels, such as heavy logging slash, are the fuels most likely to cause spot fires. Spot fires frequently are started by crown fires. Widespread crown fires, with their intense heat and strong convection currents, can throw burning embers far out ahead of the main fire. In many wildland/urban interface fires, significant structure loss occurs primarily from ember (firebrand) exposure.

Fuels that are ignited most readily by embers thrown out ahead of the main fire, listed in order of susceptibility, include the following:

1. Rotten wood on the ground, on logs, and in snags
2. Moss and lichens in treetops
3. Slash, particularly when compacted in tight piles
4. Duff
5. Cured grass

Spot fires become more frequent and severe with lower fuel moisture and increased wind. On an average dry, late summer afternoon, the smallest sparks quickly ignite rotten wood or tree moss. In compacted slash, in duff, and in cured grass, larger

TABLE 13.5.3 Dead Fuel Moisture: Time Lag Relationship to Fuel Size

Size Time Lag	*Diameter of Fuel*	*Examples*
1 hr	Less than ¼ in.	Annual grass
10 hr	¼ to 1 in.	Coastal sage, juniper, and chaparral
100 hr	1 to 3 in.	Logging slash
1000 hr	3 to 8 in.	Logs and mature standing timber

Note: For SI units: 1 in. = 25.4 mm.

burning embers are required to start spot fires unless sufficient wind exists to fan smoldering material into flames.

Crown Fires

Many forests contain a combination of aerial and ground fuels that favors the development of crown fires. Fuel conditions that influence the probability and character of crown fires include the following:

- Volume and arrangement of the timber canopy
- Volume and arrangement of fine dry aerial fuels, such as moss and dead twigs
- Position of aerial fuels above ground fuels
- Character of ground fuels

In open forests where single trees or small clumps of trees are well isolated from each other, crown fires are usually confined to single trees or to small groups of trees. Crowning, in such cases, increases rate of spread by intensifying heat and causing spot fires, but it will not result in racing crown fires like those that sometimes occur in dense forests.

When the timber canopy is sufficiently dense and continuous to carry broadcast crown fires, the severity of the crown fire is influenced by the quantity, character, and arrangement of dry fuels in the air and on the ground.

An important consideration in evaluating fuel conditions is the likelihood of reburns in tree crowns over previously burned ground fuels. A combination of fuel, weather, and topographic conditions may confine a fire to ground fuels for a considerable period of time. While the fire is burning on the ground, the aerial fuels may be scorched and singed and may become critically dry. If conditions change, a crown fire may develop and sweep back over the area. This type of crown fire may develop rapidly and burn more explosively because the aerial fuels have been dried by surface fire.

WILDLAND/URBAN INTERFACE (WUI)

Wildland/Urban Interface (WUI) Defined

The potential dangers of the wildland/urban interface (WUI) depend on a specific set of physical conditions that vary according to season (time of year), weather (humidity, winds), vegetation, and the structures in proximity of vegetation (construction, density). Attempts to define the interface as a geographic location or locations fail to account for the other factors that contribute to the potential for significant fire losses and unusual fire behavior. As defined in NFPA 1144, *Standard for Reducing Structure Ignition Hazards from Wildland Fire,* the wildland/urban interface is the "presence of structures in locations in which the AHJ [authority having jurisdiction] determines that topographical features, vegetation fuel types, local weather conditions, and prevailing winds result in the potential for ignition of the structures within the area from flames and firebrands of a wildland fire."

WUI as a National Concern

The destruction of an average of more than 900 homes per year over the last three decades is the result of the wildland/urban fire interface. Although of growing concern and attention, the problem is not new. Significant home destruction and numerous human fatalities had occurred for over a century before 1984. Historical records indicate that for the years between 1921 and 1984, over 5000 homes were destroyed by wildfires. During the 50 years prior to that (1870–1920), thousands of lives were lost and numerous communities were destroyed.[6]

In 1985, more than 1400 homes were lost to wildfires burning primarily in two states, California and Florida. Of the 1400 homes destroyed, 600 were in Florida, and 400 of the 600 were destroyed in 1 day. Never in the twentieth century had a loss of this magnitude occurred in a southeastern state.

As tragic as wildfires seem, today's wildland/urban fire losses are not as economically significant as other natural events, such as hurricanes and earthquakes, and the life and property losses from individual residential fire events. Severe hurricanes that impact urban areas do more damage in a matter of hours than severe wildfires do in a matter of days or weeks. Property damages and loss of life from even the most severe wildland/urban fire seasons do not come close to the magnitude of America's annual structural and life losses from even residential fires.* But there is more to the modern issue of wildfire disaster than just the economic impact of homes burning, because communities are more than homes and subdivisions. These communities include the surrounding natural environment, which allows and supports the economic, ecological, and social mechanics of a functioning community.

After these significant structural losses and resulting environmental damages from wildfires in California and Florida, wildland/urban fire received national attention from federal and state lands and forestry agencies, researchers, planners, insurance companies, and other key fire and safety organizations.[7] Since that time, the momentum has evolved into a national program, highlighted by Firewise Communities™, supported by numerous agencies from wildland/forestry and structural fire services, to emergency management and national security. Other regional/state programs like FireSafe Councils (California and Nevada) and FireFree (central Oregon) have been organized and funded to educate and implement programs to reduce community losses and damages from wildfire.

The term "wildland/urban interface" can distort the perception of the primary issue, directing attention to *where* homes are located (e.g., at the edge of communities near wildlands) rather than *if they are ignitable.* And that distraction may often result in a concentration on factors that won't make a big difference in reducing home loss (i.e., how fire fighters and equipment get there, what type of fire equipment is needed, road signs). In other words, knowing the width of roads and the location of hydrants is of little value if more homes are at risk than equipment is available to protect them or if it's too dangerous for fire fighters to be safely there in the first place. The wildland/urban interface is a set of conditions that may exist in many communities. The community illustrated in Figure 13.5.4, which is located in the Pine Barrens area of central New Jersey, escaped an 1800 acre fire through a quick response

*Comparison of data available from Insurance Service Offices, NFPA, and the Institute for Business & Home Safety.

FIGURE 13.5.4 Community in New Jersey That Escaped 1800 Acre Fire Through Quick Fire Fighter Response and Adequate Separation Between Vegetation and Structures (Photo: James C. Smalley)

FIGURE 13.5.5 Increasing Residential Density Resulting from Development into Formerly Wild or Rural Areas That Creates Volatile Interface Conditions (Photo: James C. Smalley)

by fire fighters and adequate separation between the vegetation and structures.

The essence of the wildland/urban interface issue is not where homes and domestic landscapes adjoin wildlands but rather the location, density, and availability of ignitable homes. A meaningful question, then, is: which homes are at greatest risk? Ignition-resistant homes closely bordering the wildlands are at less risk than a dense subdivision with wood shingle roofs several miles away from wildland fuels.

WUI Conditions

The wildland/urban interface fire problem is a volatile set of conditions leading to loss of life, property, and resources in the United States every year. These conditions include the following:

- Residential density is increasing. This condition is resulting from the rapid movement of development into formerly wild or rural areas, without consideration of how the potential of wildfire will impact this development (Figure 13.5.5). When a wildfire occurs, public perception tends to be that the fire came from federal or state agency-managed lands that have fire-fighting resources and that the losses are someone else's responsibility and outside a resident's authority and control.
- Community infrastructure, supporting rapid and expanding growth, is aging. This condition is placing pressures on basic protective aspects, such as roads for evacuation, water supplies for fire suppression, and storm water drainage.
- Inadequate planning and construction techniques plague existing homes and communities in the wildland/urban interface.
- Property owners and residents in the wildland/urban interface practice poor landscaping and landscape maintenance.
- Wildland conditions, including drought, insect infestation, invasive species, and overgrowth, contribute to more frequent and intense wildfires. A perception that needs our continued scrutiny is that all trees and forests are "natural" and should not be cut, thinned, or altered in any way. This thinking leads to overcrowded forest stands of native and nonnative tree species that bring with them a variety of undesirable consequences, including reduced water tables and stressed trees prone to insect and disease infestations and vulnerable to dangerous and devastating wildfires.
- Extreme weather events are being brought about by global climate changes over time. Long-term ecosystem changes have altered natural fuel beds and now severe wildfires burn outside natural fire regimes and can damage soils and the natural cycles of plant succession. For instance, when excessive wildland vegetation is allowed to grow unchecked for long periods of time, a fire that would normally burn surface fuels under the canopies of trees may ignite ladder fuels and reach the tree canopies, becoming a crown fire that causes devastating tree and forest mortality.

Sequence of Events in WUI Fire Disasters

The term "disaster" is a defining event in which resources have become overwhelmed and economic loss, property damage, or loss of life occurs. When lightning starts a severe wildland fire in a remote area, well away from communities (i.e., human presence), it is seen as a natural event rather than a disaster. The definition of today's wildland/urban interface fire disaster seems to depend on fire fighters being unable to prevent homes from burning.

A sequence of events typifies most WUI fire disasters. Although some variation exists in each severe occurrence, the following sequential elements are generally always present and the impacts are consistent time after time:

1. *Severe fire conditions exist.* Certainly, home loss from wildfires can occur without severe fire conditions and behavior, but the large-loss disasters most always occur under severe conditions—that is, the worst-case combination of fuels, weather, and/or topography.

2. *Wildland fire occurs.* Once a fire ignites under the worst-case conditions, it can spread rapidly through vegetation with growing intensity.

3. *Wildland fire becomes an urban fire.* The change from wildland to urban fire is the point in the combustion process that fuel types move from vegetation to constructed materials (i.e., homes). It is the point at which a "wildland fire" becomes a "wildland/urban interface fire." Preventing the ignition of those constructed materials is the best opportunity to prevent the inevitable disaster. If the homes don't burn, there is no interface disaster.

4. *Fire suppression resources are overwhelmed.* During extreme fire conditions with dry wildland fuels and high winds, fire fighters, equipment, and water supplies can become depleted as numerous homes ignite and burn. Fire-fighting forces struggle to position themselves to stop large flames pushed by strong winds. Suppression effectiveness is dramatically reduced in these conditions as tactics shift and fire-fighting forces initiate life/safety procedures by evacuating the public.

5. *Fire protection effectiveness is reduced.* Fire engines and crews cannot simultaneously evacuate residents and effectively take suppression action in a subdivision of homes igniting within a few minutes of each other. With multiple ignitions, the effectiveness of fire protection forces in these situations becomes compromised.

6. *Disaster!* In these disaster scenarios, when fire protection forces are overwhelmed and standard operating procedures fall short, fire protection forces cannot stop the large flames from these intense wildland fires from entering a residential area and cannot prevent numerous homes from becoming ignited. Valiant efforts may save a few homes but, most often, hundreds of homes are threatened or destroyed in a matter of hours and numerous lives may be lost.

Preventing the Disaster

When individual homes ignite or a single wildland ignition occurs, local fire agencies' standard operating procedures (SOPs) are very effective. The success rate in containing these ignitions is routinely in the 98 to 99 percent range. When ignitions occur in dense fuels (whether structural or vegetative) during periods of severe fire conditions, numerous homes may become involved. Rapidly spreading fire cannot be stopped and suppression efforts are dramatically reduced. The world sees the resulting "wildland/urban fire disaster."

Disaster Prevention Factors. Future wildfires will continue to enter communities, but homes and adjacent vegetative fuel beds do not have to ignite. A community made up of ignition-resistant homes, healthy surrounding forests, and noncontinuous fuels (i.e., breaks in the fuels from vegetation to single homes to multiple homes) becomes less vulnerable to encroaching wildfire. Vegetation doesn't combust near homes, houses don't ignite from firebrands, and severe structural property losses and human fatalities are dramatically reduced or potentially eliminated.

Fire Fighter Safety and Suppression Effectiveness in the WUI. Standard fire suppression operations are largely ineffective against severe wildland fire behavior, driven by high winds and producing huge flames, along with intense heat and showering firebrands. Often, during these situations, fire fighters must "fall back" to implement their own necessary life safety procedures. Because fire suppression strategies and tactics in interface fires may differ from those employed during structure fires or forest fires individually, fire departments join with forestry agencies to provide basic wildland fire training and to hold joint training sessions.

WUI Fire "Watch-Out Situations." Because of the ways that vegetation and structures interact in a fire in the wildland/urban interface, the following additional cautions for "watch-out situations"[8] were developed for both wildland and structural fire crews and officers:[9]

- Poor access and narrow one-way roads
- Bridge load limits
- Wooden construction and wood shake roofs
- Power lines, propane tanks, and HazMat threats
- Inadequate water supply
- Natural fuels 30 feet or closer to structures
- Structures in chimneys, box canyons, narrow canyons, or on steep slopes (30% or greater)
- Extreme fire behavior
- Strong winds
- Evacuation of public (panic)

Reducing Home Ignitions in WUI Fires. Case studies and experimentation by the USDA Forest Service and other organizations point to some general aspects of house construction and landscaping that can minimize risk of ignition. One of the most critical aspects is roofing. Findings from California studies have indicated that houses with flammable roofing have an 81 percent chance of being destroyed in wildfires, whereas the ratio of houses with nonflammable roofing is much lower at 30 percent. Moreover, 62 percent of houses without a maintained vegetation clearance of at least 30 ft (9 m) were destroyed as opposed to those (22%) whose vegetation clearance is maintained to at least 30 ft (9 m). In all, the effect of these two elements together provides the minimum guidance for homeowners, developers, and builders.[9,10] The combined effects are displayed in Table 13.5.4.

FIREWISE AND FIREWISE COMMUNITIES/USA

Development of the Firewise Programs

After the extreme fire season of 1985, representatives of NFPA and the USDA Forest Service met to discuss the increasing trend of wind-driven fire in populated areas and formed what is now the National Wildland/Urban Interface Fire Program. In 1992, the advisory group for the program adopted the term "Firewise" to describe the state of being knowledgeable and prepared for wildfire in residential or urban settings. In 1999 the advisory group became the Wildland/Urban Interface (WUI) Working Team of the National Wildfire Coordinating Group, which oversees the National Wildland/Urban Interface Fire Program and its Firewise Communities program. The Firewise website was launched in 1996, and the national workshop series began

TABLE 13.5.4 Effects of Roofing and Vegetation on Destruction of Structure in Wildfire

Factor	*Percent of Houses Destroyed*
Flammable roof and vegetation clearance not maintained	96
Nonflammable roof and maintained vegetation clearance	14

in 1999. Today, the Firewise Communities team continues its mission of wildland/urban interface fire education through its website, workshop series, community recognition program, and information resources.

Firewise Approach

The best approach to wildfire preparedness involves utilizing the wide range of Firewise practices that individuals and communities can take to reduce their vulnerability to wildfire. The National Firewise Communities Program offers a series of practical steps and/or supporting documents in the following areas:

- Land use and community development planning
- Improved planning for fire protection infrastructure
- Cooperative approaches to forest management adjacent to wildland/urban interface communities
- Regulation, codes, deed restrictions
- Improved education of interface residents (including landscaping and home construction and design)
- Response to and evacuation of interface areas
- Firewise Communities and Firewise Communities/USA Recognition Program

By implementing at least one recommended mitigation measure or planning element, individuals and communities can begin to protect against the risk of fire in the wildland/urban interface. Examples of Firewise techniques for property owners include the following:

- Creating a defensible space around residential structures by thinning trees and brush
- Choosing fire-resistant plants
- Selecting ignition-resistant building materials
- Positioning structures away from slopes
- Working with fire fighters to develop emergency plans

Firewise Communities Workshops

From 1999 through 2003, the National Firewise Communities Program offered national workshops and continues to support regional and local organizations interested in hosting Firewise workshops using materials supplied by the national program. Firewise Communities workshops prepare community leaders and fire service professionals to recognize WUI fire hazards, make homes and landscapes Firewise, deliver fire education to residents, and incorporate Firewise planning into existing and developing areas of communities. These dynamic workshops can feature interactive discussions, mapping, and wildfire simulations. Firewise workshops are most successful when they are attended by a variety of community representatives, such as planners, business leaders, homeowner association members, and emergency service professionals.

Firewise Communities/USA Recognition Program

To facilitate local solutions to wildfire preparedness goals, the Firewise Communities/USA program recognizes communities for working together to protect residents and property from fire in the wildland/urban interface. To be recognized as a Firewise Communities/USA site, local communities must create and implement a local plan with cooperative assistance from state forestry agencies and local fire staff. In addition, communities are required to continue regular maintenance and education to retain recognition status.

Community Definition. Homeowner associations and towns of 500 residents or fewer are the most appropriate venue for the Firewise Communities/USA Recognition Program. Individual homeowner commitment is the cornerstone of a successful Firewise Communities/USA program. Residents of a smaller geographic unit can more easily create and execute a plan that reflects the needs of its specific locale. The program is intended to engage residents in playing an active role in shaping and implementing the neighborhood plan and supporting the larger Community Wildfire Protection Plan (CWPP).*

Recognition Criteria. Working with local wildland fire staff, communities can earn an annually renewable Firewise Communities/USA status by meeting the following criteria:†

- Enlist a wildland/urban interface (WUI) specialist to complete a community assessment and work together to create a plan that identifies agreed-upon achievable solutions to be implemented by the community. Development of a local WUI plan may take up to 6 months.

*The Healthy Forest Restoration Act of 2003 (HFRA) (P.L. 108-148) recommended that interface communities develop, in cooperation with local, state, and federal fire agencies, a Community Wildfire Protection Plan (CWPP). The HFRA provides communities with an opportunity to influence where and how federal agencies implement fuel reduction projects on federal lands. A CWPP is the most effective way to take advantage of this opportunity. Communities with CWPPs in place will be given priority for funding of hazardous fuels reduction projects carried out under the auspices of the HFRA. The "communities" involved in a CWPP are political jurisdictions ranging in size from small incorporated towns to largely urbanized counties. A handbook on developing CWPPs is available from the Society of American Foresters (http://www.safnet.org). The handbook outlines how to convene other interested parties, what elements to consider in assessing community risks and priorities, and how to develop a mitigation or protection plan to address those risks.

†Becoming a Firewise Communities/USA recognition site begins with the community itself. A community representative completes an online request form on the Firewise Communities/USA website or contacts the state forestry agency. Applications and renewal forms are downloadable in PDF format at http://www.firewise.org/usa.

- Organize a multidisciplined Firewise board/committee. The team should include homeowners and fire professionals. Participation by planners, land managers, urban foresters, and/or members of other interest groups is also encouraged.
- Observe a Firewise Communities/USA Day each year that is dedicated to a local Firewise project.
- Invest a minimum of $2.00 per capita annually in local Firewise projects. The investment may be met through financial donations, state grants, or an equivalent amount of volunteer labor. Work by municipal employees or volunteers using municipal and other equipment can be included, as can state/federal grants dedicated to that purpose. A specialist can work with the community to identify and seek project implementation funds, should they be necessary.
- Submit an annual report to Firewise Communities/USA that documents continuing compliance with the program.

WILDLAND FIRE ORGANIZATIONS

Public Land Agencies

In the United States, wildland fire protection is handled by federal, state, county, and in some cases, city agencies, as well as by private corporations and career/volunteer fire departments. The U.S. Forest Service protects about 200 million acres (81 million ha) of national forest and other lands. Approximately 587 million acres (236 million ha) of other federal lands, mostly in the public domain, are protected by the Department of the Interior agencies: Bureau of Land Management (BLM), the National Park Service (NPS), the U.S. Fish and Wildlife Service, and the Bureau of Indian Affairs.

States, local governments, corporations, and career/volunteer fire departments protect about 840 million acres (340 million ha) of the country's essentially undeveloped lands. About 158 million acres (64 million ha), or roughly 9.5 percent, of the wildlands in the United States are not protected.[11]

In Canada, wildland fire protection is handled by 10 provinces, 2 territories, and Parks Canada, as well as by private corporations and career/volunteer fire departments.

U.S. and Canadian Coordinating Organizations

Wildland Fire Leadership Council (WFLC). The Wildland Fire Leadership Council (WFLC) was established in April 2002 by a Memorandum of Understanding between the Secretaries of Agriculture and the Interior. The purpose of the council is to support the implementation and coordination of the National Fire Plan and the Federal Wildland Fire Management Policy.

WFLC is a cooperative interagency organization dedicated to achieving consistent implementation of the goals, actions, and policies in the National Fire Plan and the Federal Wildland Fire Management Policy. WFLC provides leadership and oversight to ensure policy coordination, accountability, and effective implementation of the National Fire Plan and the Federal Wildland Fire Management Policy. Since its inception in 2002, the council has been successful through its collaborative work at reducing the interdepartmental differences for a seamless delivery of a coordinated fire protection program.

National Wildfire Coordinating Group (NWCG). The National Wildfire Coordinating Group (http://www.nwcg.gov) is made up of the USDA Forest Service; four agencies of the Department of the Interior: Bureau of Land Management (BLM), National Park Service (NPS), Bureau of Indian Affairs (BIA), and the U.S. Fish and Wildlife Service (FWS); and state forestry agencies through the National Association of State Foresters. The purpose of NWCG is to coordinate programs of the participating wildfire management agencies so as to avoid wasteful duplication and to provide a means of constructively working together. Its goal is to provide more effective execution of each agency's fire management program. The group provides a formalized system to agree on standards of training, equipment, qualifications, and other operational functions. Policies, standards, and procedures are implemented directly through regular agency channels.

The NWCG operates through subject- or task-focused "working teams," a concept that provides a means for the exchange of knowledge about all dimensions of fire management. Each working team is small (8 to 10 persons), interagency in nature, and geographically balanced. The current teams work in key areas, such as training, incident operations, fire use, fire equipment, wildland fire education, safety and health, incident business practices, information resource management, fire danger, fire weather, social science (task group), and the wildland/urban interface.

There are several avenues in which individuals or agencies can interface with the NWCG to retrieve information, make recommendations, or raise issues. Contact with NWCG can be made through agency representatives of the parent group and/or the working teams, working team chairpersons, or the executive secretary.

National Interagency Coordination Center (NICC). The National Interagency Coordination Center (NICC) is the focal point for coordinating the mobilization of resources for wildland fire and other incidents throughout the United States. Located in Boise, Idaho, the NICC also provides products designed to be used by the internal wildland fire community for wildland fire and incident management decision making.

Wildfire suppression is built on a three-tiered system of support—the local area, one of the 11 geographic areas, and the national level. When a fire is reported, the local agency and its fire-fighting partners respond. If the fire continues to grow, the agency can ask for help from its geographic area. When a geographic area has exhausted all its resources, it can turn to NICC at the National Interagency Fire Center (NIFC) for help in locating what is needed, from air tankers to radios to fire-fighting crews to incident management teams.

The center coordinates activities through 11 geographic-area coordinating centers: Southern Eastern, Northern Rockies, Rocky Mountain, Southwest, East Basin, West Basin, Northwest, Alaska, Northern California, and Southern California.

National Multi-Agency Coordination Group (NMAC). The NMAC comprises representatives from the Bureau of Land Management, Bureau of Indian Affairs, National Park Service, Forest Service, U.S. Fish and Wildlife Service, Federal Emergency

Management Administration, and the State Foresters. The NMAC group at NIFC prioritizes and allocates resources when there are critical shortages of national resources such as smoke jumpers, air tankers, or Type 1 incident management teams (IMTs).

Canadian Interagency Forest Fire Centre (CIFFC). CIFFC was opened on June 2, 1982, with a mandate to provide operational forest fire management services to member agencies that would, by agreement, gather, analyze, and disseminate fire management information to ensure a cost-effective sharing of resources. It would also actively promote, develop, refine, standardize, and provide services to member agencies in order to improve forest fire management in Canada.

CIFFC operates as a private, nonprofit corporation with two levels of management that direct the operation. The board of corporate trustees is made up of deputy-ministers responsible for forestry representing each of the provinces, territories, and the federal government. This group sets policy, gives direction, and approves annual budgets for CIFFC. The board of directors is made up of the directors responsible for forest fire management for each of the provinces, territories, and a representative of the federal government. This group prepares budgets and policies and controls the operation and expenditures of CIFFC. CIFFC staff operate and implement programs approved by the board of directors and the board of corporate trustees. In addition, CIFFC coordinates and directs working groups assembled to address specific tasks.

LEGISLATION AND POLICY

National Fire Plan (NFP)

Following a landmark wildland fire season in 2000, the National Fire Plan was developed with the intent of actively responding to severe wildland fires and their impacts to communities while ensuring sufficient fire-fighting capacity for the future. The NFP addresses five key points: fire fighting, rehabilitation, hazardous fuels reduction, community assistance, and accountability.

The National Fire Plan provides invaluable technical, financial, and resource guidance and support for wildland fire management across the United States. Together, the USDA Forest Service and the Department of the Interior work to successfully implement the key points outlined in the National Fire Plan by taking the following steps:

1. Assuring that necessary fire-fighting resources and personnel are available to respond to wildland fires that threaten lives and property
2. Conducting emergency stabilization and rehabilitation activities on landscapes and communities affected by wildland fire
3. Reducing hazardous fuels (dry brush and trees that have accumulated and that increase the likelihood of unusually large fires) in the country's forests and rangelands
4. Providing assistance to communities that have been or may be threatened by wildland fire[12]
5. Committing to the Wildland Fire Leadership Council, an interagency team created to set and maintain high standards for wildland fire management on public lands

Healthy Forests Restoration Act of 2003

The Healthy Forests Restoration Act of 2003 (P.L. 108-148) (HFRA) became law in December 2003. HFRA includes provisions to speed up hazardous-fuel reduction and forest-restoration projects on specific types of federal lands at risk of wildland fire and/or of insect and disease epidemics. The HFRA was designed to help states, tribes, rural communities, and landowners restore healthy forest and rangeland conditions on their respective lands. The provisions of HFRA can be applied to as many as 20,000,000 acres (8.1 million ha) of land managed by the Forest Service and the Bureau of Land Management.

With direct respect to hazardous fuels reduction and wildfire protection, HFRA provisions include the authority for expedited vegetation treatments on certain types of Forest Service and Bureau of Land Management lands that (1) are at risk of wildland fire, (2) have experienced windthrow, blowdown, or ice-storm damage, (3) are currently experiencing disease or insect epidemics, or (4) are at imminent risk of such epidemics because of conditions on adjacent land. The act also requires the Forest Service and Bureau of Land Management to maximize retention of larger trees in areas other than old-growth stands and to ensure that the agencies' actions are consistent with the objective of restoring fire-resilient stands and protecting "at-risk" communities and federal lands through collaboration among federal agencies and local communities, particularly when Community Wildfire Protection Plans (CWPPs) are prepared. At least 50 percent of the funding allocated to HFRA projects is to protect areas adjacent to communities at risk of wildland fire, with performance of these actions to be monitored when agencies conduct hazardous-fuel reduction projects. Multiparty monitoring is encouraged especially in projects that include communities and other diverse stakeholders (i.e., interested citizens and tribes).

In addition, HFRA encourages biomass removal from public and private lands following fuel reduction projects and provides technical, educational, and financial assistance to improve water quality and address watershed issues on nonfederal lands.

FEDERAL AGENCIES THAT AFFECT PUBLIC FIRE SAFETY

U.S. Department of Agriculture (USDA)

The fire protection programs of the U.S. Department of Agriculture (http://www.usda.gov) are aimed at fire prevention and education in rural areas; they are carried out by the USDA Forest Service and the Rural Housing Service.

USDA Forest Service. Known to millions through its familiar symbol Smokey Bear, the USDA Forest Service (http://www.fs.fed.us) provides fire protection to more than 200 million acres of forests, grasslands, and nearby private lands (National Forest System), conducts research and develops improved methods in forest fire management, provides technical and financial assistance to state forestry organizations to improve fire protection efficiency on nonfederal wildlands, and provides international

assistance in formulating policy and coordinating U.S. support for the protection and sound management of the world's forest resources.

Rural Housing Service (RHS). The Rural Housing Service (http://www.rurdev.usda.gov/rhs) operates a range of programs formerly administered by the Farmers Home Administration to support affordable housing and community development in rural areas. An agency in the U.S. Department of Agriculture, the RHS distributes loans and grants to improve housing and community facilities, including police stations and fire stations.

U.S. Department of the Interior (DOI)

The U.S. Department of the Interior (http://www.doi.gov) is composed of the Bureau of Land Management, the Bureau of Indian Affairs, the U.S. Fish and Wildlife Service, and the National Park Service (NPS).

Bureau of Land Management (BLM). The Bureau of Land Management (http://www.blm.gov) provides protection against wildfires on over 630 million acres (255 million ha) of public land, natural resources, and other values. It services and supports the National Interagency Fire Center in Boise, Idaho.

Bureau of Indian Affairs (BIA). The responsibility of the Bureau of Indian Affairs (http://www.doi.gov/bureau-indian-affairs.html) is the administration and management of 55.7 million acres (22.5 million ha) of land held in trust by the United States for American Indians, Indian tribes, and Alaska Natives. There are 562 federally recognized tribal governments in the United States. Developing forestlands, leasing assets on these lands, directing agricultural programs, protecting water and land rights, and developing and maintaining infrastructure and economic development are all part of the agency's responsibility.

U.S. Fish and Wildlife Service (FWS). The mission of the U.S. Fish and Wildlife Service (http://www.fws.gov) is to conserve, protect, and enhance fish, wildlife, and plants and their habitats. The service manages the 93-million-acre National Wildlife Refuge System of more than 520 National Wildlife Refuges and thousands of small wetlands and other special management areas; operates 66 National Fish Hatcheries, 64 fishery resource offices, and 78 ecological services field stations; and enforces federal wildlife laws.

National Park Service (NPS). The National Park Service (http://www.nps.gov) provides presuppression and suppression services and administers law enforcement, structural and wildland fire protection, and emergency medical services to protect visitors, national park employees, resources, and facilities.

National Interagency Fire Center

The National Interagency Fire Center (http://www.nifc.gov), located in Boise, Idaho, provides logistical support for the USDA Forest Service, the Department of Commerce's National Oceanic and Atmospheric Administration (NOAA), and the BLM, BIA, NPA, and FWS services of the Department of the Interior.

FIRE DETECTION, SUPPRESSION, AND RESOURCES

Fire Detection

In many wildland areas, lookouts in fire towers and aircraft patrols are the ones who discover, locate, and report fires. Additionally, travelers, campers, woodcutters, hunters, and others annually report thousands of fires. In the western United States and parts of Canada, lightning strikes are routinely detected electronically and their locations plotted by computer. Computer programs have been developed to assess the likelihood of ignition at various locations, as well as the characteristics of the strikes themselves. Automated fixed-point infrared detection systems have been developed but they have yet to be used extensively in North America, although they are used in some European countries. Although fire detection from satellites is technically feasible, the complication of discriminating between legitimate heat sources and incipient fires has not yet allowed the practical use of this technology.

Fire Suppression

Fire suppression includes all work to extinguish or confine a fire, beginning with its discovery. Suppressing or fighting a fire is usually difficult work that is inherently dangerous. However, knowing and applying safety principles and fire-fighting tactics serve to increase the safety and effectiveness of operations.

How agencies respond to a reported incident is well organized and planned in advance. As the incident requires, additional resources are dispatched from the local agency. Once the incident goes beyond the local agency's ability to continue supplying resources, requests for additional resources are forwarded to the nearest geographical area coordination center (GACC).

Suppression of Small Fires. Wildland fire management strategies are aimed at prompt, safe, aggressive suppression action of all wildfires. Small fires pose the same kind of suppression problems and require the same kind of practices as larger fires. Effective suppression of small fires involves the following steps: first attack, line location, line construction, burning out, mop-up, patrol, and declaring the fire out. Suppression strategies range from prompt control at the smallest acreage possible to containment using a combination of fireline and natural or constructed features, to merely ensuring that the fire remains confined to a defined geographical area.

Principles of Attack. The following principles of initial attack include sizing up a fire, selecting a point of attack and making an attack, mopping up, patrolling, and declaring the fire out:

- *Sizing up a fire.* Going around the fire as quickly and safely as possible or inspecting it from a vantage point. Fire fighters should not, however, go around the head of the fire if it is moving rapidly because entrapment is likely. Sizing up a fire should be performed from a vantage point or from the flanks of the fire.
- *Selecting a point of attack and making an attack.* The universal rules are to take prompt action on an attack point, to stay

with the fire, to take the most effective action possible with the available forces and equipment, to inform the dispatcher of the situation by radio, and to continue to work day or night, if night work can be done safely.

- *Mopping up.* After primary line construction work is completed and a fire is called "controlled," many things remain to be done to make the fireline "safe" and put the fire out. This work is called mop-up (Figure 13.5.6). The objective of mop-up is to put out all embers or sparks to prevent them from crossing the fireline. A certain amount of mop-up work is done while building the control line. Mop-up becomes an independent part of fire fighting as soon as the spread of the fire has been stopped and all lines have been completed. Ordinarily, mop-up is composed of two actions: putting the fire out and disposing of fuel, either by burning it to eliminate it or by removing it so it cannot burn.
- *Patrolling.* Patrolling is that portion of the mop-up job that consists of moving back and forth over the control line and the edges of burn areas to check for and put out any fire that may burn or blow across the line and, at the same time, to check for and put out spot fires outside the line.
- *Declaring the fire out.* Before abandoning a fire, and as a follow-up, the incident commander should take steps to ensure that the fire has been extinguished and that any fireline that has been constructed is adequate should a flare-up occur within the fireline.

Wildland Fire-Fighting Resources

Most agencies have full-time fire fighters but also hire a fair number of employees on a seasonal basis (generally from May to September). Almost without exception, regardless of the type of work seasonal employees are hired to do, everyone receives basic fire fighter training. During seasons when there are a lot of fires, people who have had basic fire training are called on to help organize fire crews.

FIGURE 13.5.6 Mop-Up, or Extinguishment of All Embers, Subsurface Fires, and Sparks, Being Performed by Fire Fighters to Ensure Safety of Fireline (Photo: James C. Smalley)

Hotshot Fire Crews. Hotshot fire crews are highly trained, skilled, and experienced crews made up of fire fighters who have had at least one season of experience as a wildland fire fighter. There are 68 hotshot crews nationwide—a total of 1360 fire fighters. These fire fighters are generally given assignments on the toughest part of a fire and use a variety of specialized hand tools, including chainsaws and fireline explosives. The crew members serve in all phases of wildland fire fighting—building firelines, burning out, setting backfires, and mopping up. Hotshot crew members are employed for a minimum of 130 days.

Smoke Jumpers. Smoke jumpers are airborne fire fighters who parachute from planes to attack wildland fires in remote and inaccessible areas. Generally, smoke jumpers are the initial attack force on remote, inaccessible fires. Competition for smoke jumper jobs in recent years is resulting in applicants with four to five seasons of wildland fire-fighting experience competing for the very limited number of jobs that become available each year.

Engine Crews. Engine crews are made up of three to five wildland fire fighters. A typical wildland fire engine is a heavy-duty off-road vehicle able to carry up to 800 gallons (3028 liters) of water. Engines also carry foam to use on wildland fuels. The foam can also be used to protect the exterior walls of a structure.

Hand Crews. Hand crews consist of about 20 individuals who have been organized and trained and are supervised principally for operational assignments on an incident (Figure 13.5.7). Generally, these crews are made up of people who have been trained to fire fight, but whose everyday job is something other than fire fighting, that is, timber, wilderness rangers, recreation, range management. There are approximately 500 hand crews in the United States.

Helitack Crew. Helitack crews are specially trained in the tactical and logistical use of helicopters for fire suppression. These crews can be rapidly deployed and are often the first to respond

FIGURE 13.5.7 Hand Crew Members Clearing Vegetation to Create a Fireline (Photo: James C. Smalley)

to a wildland fire. Helitack crews are also trained to rappel from a hovering helicopter in areas where the terrain or vegetation does not allow the helicopter to land. A primary job for the crew is to load and unload slings of equipment and supplies needed for fire fighting.

Aircraft Used in Wildland Fire Suppression

Helicopters. In a typical year, there are 15 to 20 heavy and medium helicopters under contract in the United States for wildland fire-fighting purposes. Also, there are 175 additional helicopters under contract on a call-when-needed basis. Helicopters support fire fighters on the ground by dropping water, foam, or retardant on flaming trees, brush, and even structures to cool hot spots and prevent a fire from spreading (Figure 13.5.8).

SEAT. The single engine air tanker (SEAT) is one of the newer tools in aerial fire fighting. The SEAT is a small agricultural "crop duster" airplane that has been modified to drop 500 to 800 gallons (1893 to 3028 liters) of fire retardant on wildfires (ideal for use on smaller, incipient fires). These aircraft are designed to fly low and slow, which is ideal for dropping retardants to slow or retard the spread of the fire.

Air Tankers. Air tankers are large planes fitted with tanks for transporting and dropping fire retardant or water. Their capability ranges from 2000 gallons (7,571 liters) to the larger aircraft that are capable of delivering 3000 gallons (11,356 liters). Air tankers drop their load in a long string, creating a line of retardant. The purpose of the retardant is to slow the fire down in order to give ground support forces the opportunity to build firelines. A pink dye is added to give the pilot an idea of where the drop landed. In a typical year, 40 to 50 air tankers are under contract to state and federal agencies for wildland fire-fighting purposes.

FIGURE 13.5.8 Helicopter Supporting Fire Fighters on the Ground by Dropping Water, Foam, or Retardant on Trees, Brush, and Structures to Cool Hot Spots and Prevent Fire from Spreading (Photo: James C. Smalley)

Modular Airborne Fire-Fighting System (MAFFS). A MAFFS unit is a pressurized 3000 gal (11,356 L) tank system containing either water or a water-based retardant designed to fit into a C-130 aircraft. Air tankers equipped with pressurized discharge systems are used to drop retardant or water on fires, under the direction of incident managers and guided by small aircraft known as lead planes. MAFFS units can only be utilized when there is imminent danger to life and property and other aerial resources are exhausted or committed (Figure 13.5.9).

Lead Planes. Lead planes, also called bird dogs, are used to lead the air tankers to and through their retardant drops and are also used for aerial reconnaissance of fire areas.

Infrared Aircraft. Infrared aircraft are equipped with highly specialized infrared mapping systems (Figure 13.5.10). The infrared scanners locate hot spots inside and outside a fire's perimeter. Infrared scanners can pinpoint a 6 in. (15 cm) hot spot from an altitude of 8000 feet (1.5 miles or 2.4 km) above ground

FIGURE 13.5.9 Air Tanker Equipped with Pressurized Discharge System Dropping Retardant on Fire (Photo: James C. Smalley)

FIGURE 13.5.10 Infrared Mapping System in Light Aircraft Used to Locate Hot Spots (Photo: James C. Smalley)

level and can cover almost 1 million acres (404,700 ha) in 1 hour. Flights are generally flown after sunset and before sunrise when temperatures between the terrain and the fire differ the most, making it easier to pinpoint heat sources.

Other Wildland Fire-Fighting Resources

Other wildland fire-fighting resources include incident management teams and remote automated weather stations (RAWSs).

Incident Management Teams. An incident management team is a team of highly trained, experienced individuals who are organized to manage large and/or complex incidents.

Remote Automated Weather Stations (RAWSs). Remote automated weather station (RAWS) units collect, store, and forward six critical weather elements hourly, via a geostationary operational satellite (GOES) 22,300 miles (35,887 km) above the equator, to a computer system located at the National Interagency Fire Center in Boise, Idaho. There are approximately 1150 RAWSs strategically positioned throughout the United States. The types of weather information involved include wind speed and direction, wind gusts, precipitation, air temperature, relative humidity, and fuel moisture. Resource managers also use RAWSs to monitor environmental conditions and air quality. Some RAWS units are used as early-alert warning systems for floods, mud slides, or hazardous material levels.

Fire Fighter Hand Tools. Most of the hand tools used by fire fighters are combination tools; that is, they have more than one purpose or use. Hand tools used by fire fighters must be effective, efficient, versatile, portable, simple, easy to maintain and repair, and standardized, so they can be pooled, traded, and transported quickly. The following are among the handtools that are repaired, sharpened, and stockpiled at the base camp for crews to use on the fireline:

- *Pulaski.* A Pulaski is a combination tool, ax, and mattock invented by Ed Pulaski in 1910. This tool enables fire fighters to cut trees and limbs with the ax side and to dig and scrape with the mattock side. Figure 13.5.11 shows cutting tools like Pulaski tools and shovels being sharpened.
- *McLeod.* The McLeod, a heavy-duty combination rake-and-hoe tool, is named after Ranter Malcolm McLeod. Fire fighters use this tool to cut through matted litter and duff and clear loose surface materials.
- *Ax.* Axes, the most common ones being the double-bitted, are used for cutting trees and limbs. The single-bitted or poleax is common in the East and is used for cutting trees and limbs and for driving wedges.
- *Shovel.* The shovel is a combination tool. The edges are sharpened so that the user can chop down small trees and cut limbs and roots. Fire fighters also use shovels to scrape away needles and other duff as they construct firelines down to mineral soil. They are specifically designed for fire use.
- *Drip torch.* Fire fighters use drip torches for igniting backfires or burnouts.
- *Backpack pump.* Fire fighters carry backpack pumps (Figure 13.5.12), usually made from collapsible neoprene, during mop-up operations. They are effective for cooling down hot spots.

FIGURE 13.5.11 Cutting Tools Like Pulaski Tools and Shovels Being Sharpened (Photo: James C. Smalley)

FIGURE 13.5.12 Fire Fighter Using a Backpack Pump to Cool Down a Hot Spot (Photo: James C. Smalley)

Wildland Fire Fighter Training and Safety

Two reports, eight years apart, to the U.S. Congress about the roles of volunteers in protecting lives, property, and resources illustrate that the need for training is essential.[2] *Rural Fire Protection in America: A Challenge for the Future,* published by the National Association of State Foresters in 1994, listed training as the third most pressing problem and the second priority for any federal funding received by small rural fire departments. The report found that many communities have no funds to pay for the training and that most volunteers do not have the money to afford such training.

A more recent report by NFPA and the U.S. Fire Administration, *A Needs Assessment of the U.S. Fire Service: A Co-operative Fire Department Study,* confirmed that training

remains a problem. It showed that 30 to 50 percent of uncertified and untrained structural fire fighters are serving communities of 2500 or less. Consistently, both reports found over 40 percent of the rural fire fighters had no wildland fire training. Although some instances may have improved, a wide gap remains in attaining a trained fire-fighting force for small communities across America.

To help meet the need for wildland fire training in these small fire departments, the National Wildland/Urban Interface Fire Program[3] produced a three-part training program targeted at small community and volunteer fire departments, designed to raise the fire fighter's awareness of his or her surroundings in an interface fire. The program, complete with videotapes or DVDs, computer presentations, and handouts, was distributed free of charge to fire departments in over 10,000 small communities in the United States. It will eventually be offered as a Web-based, self-study course on the Firewise website (http://www.firewise.org).

Ten Standard Fire Orders. The 10 Standard Fire Orders* were developed in 1957 by a task force studying ways to prevent fire fighter injuries and fatalities. The standards discuss fire behavior, fireline safety, and organizational control and are delineated as follows:[9]

Fire Behavior

1. Keep informed on fire weather conditions and forecasts.
2. Know what your fire is doing at all times.
3. Base all actions on current and expected behavior of the fire.

Fireline Safety

4. Identify escape routes and make them known.
5. Post lookouts when there is possible danger.
6. Be alert. Keep calm. Think clearly. Act decisively.

Organizational Control

7. Maintain prompt communications with your forces, your supervisor, and adjoining forces.
8. Give clear instructions and ensure they are understood.
9. Maintain control of your forces at all times.

If 1–9 are considered, then . . .

10. Fight fire aggressively, having provided for safety first.

Eighteen Watch-Out Situations

Shortly after the 10 Standard Fire Orders were incorporated into fire fighter training, the 18 Situations That Shout Watch Out were developed. These following 18 situations are more specific and cautionary than the 10 Standard Fire Orders and describe situations that expand the 10 points of the fire orders:[9]

1. Fire not scouted and sized up
2. In country not seen in daylight
3. Safety zones and escape routes not identified
4. Unfamiliar with weather and local factors influencing fire behavior
5. Uninformed on strategy, tactics, and hazards
6. Instructions and assignments not clear
7. No communication link between crew members and supervisors
8. Constructing line without safe anchor point
9. Building line downhill with fire below
10. Attempting frontal assault on fire
11. Unburned fuel between you and the fire
12. Cannot see main fire, not in contact with anyone who can
13. On a hillside where rolling material can ignite fuel below
14. Weather gets hotter and drier
15. Wind increases and/or changes direction
16. Getting frequent spot fires across line
17. Terrain or fuels make escape to safety zones difficult
18. Feel like taking a nap near fireline

If fire fighters follow the 10 Standard Fire Orders and are alerted to the 18 Watch-Out Situations, much of the risk of fire fighting can be reduced.

Fire Fighter Fatalities

A very serious concern will continue to be the risk to fire fighters. Of the 999 fire fighters who died on duty between 1996 and 2005, 159 (or 15.9%) died as a result of wildland fires or control burns. As shown in Figure 13.5.13, the number of deaths in any one year was as low as 8 and as high as 26. Over the period, 25.5 percent of all fireground deaths occurred at wildfires and control burns. This examination of wildfire deaths was prompted by the large number of wildfire-related fire fighter fatalities in 2003 (26 of the 106 fire fighter deaths).[8]

The unusually high number of deaths among fire-fighting aircraft personnel, particularly in 2003, and the subsequent grounding of aircraft due to safety reasons in early 2004, may place more pressure on initial attack crews. In many cases, initial attack responders are from small community and volunteer fire departments. In addition, without traditional air support, ground crews may be expected to work harder, covering more acreage in shorter times at each fire. The concerns for fire fighter safety are extremely grave but, at the same time, may result in new methods of training in the future.

Wildland fire fighters carry special tent shelters, meeting the requirements of NFPA 1977, *Standard on Protective Clothing and Equipment for Wildland Fire Fighting.* In Figure 13.5.14, a fire fighter has deployed the shelter, stepped into the bottom, and is falling to the ground as a wildfire approaches. The deployment of shelters is a last resort and each deployment is recorded and investigated for the purpose of improving safety on the fireline.

Common Denominators of Fire Behavior

Four major common denominators of fire behavior have been noted in fires where a fire fighter has been killed or from which

*During the years since their inception, the Ten Standard Fire Orders were rearranged to provide fire fighters a mneumonic learning aid, so that the first letter of the first word of each order spelled out F-I-R-E-O-R-D-E-R-S. In May 2002, the NWCG approved the revision of the Ten Standard Fire Orders in accordance with their original arrangement. The original arrangement of the orders are logically organized to be implemented systematically and applied to all fires.

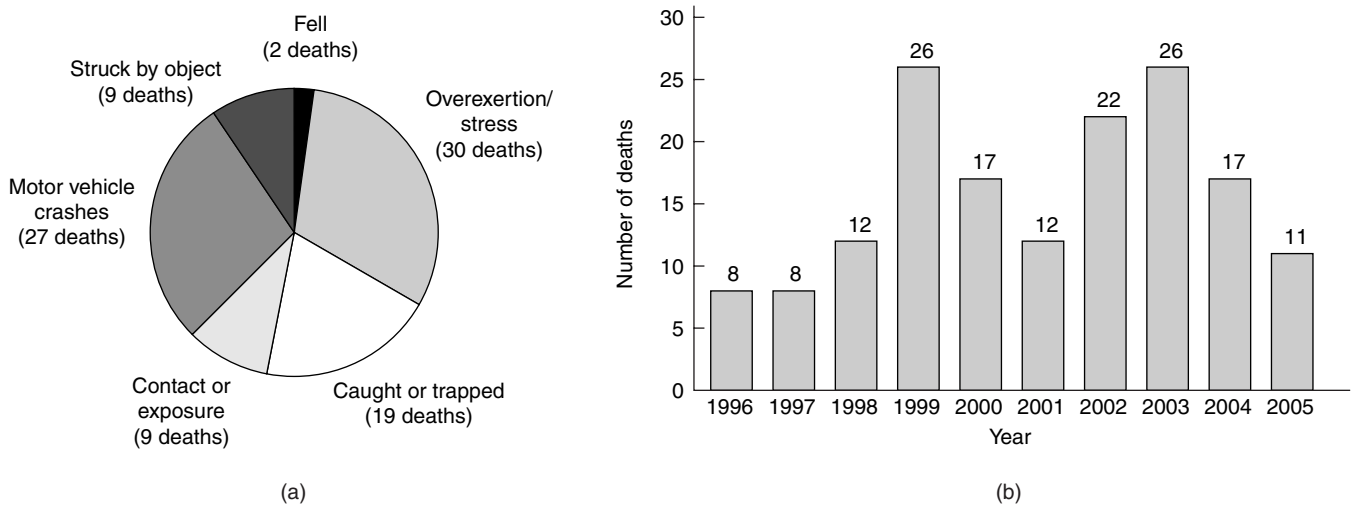

FIGURE 13.5.13 Fire Fighter Fatalities in Wildland Fires, 1996–2005: (a) On the Fireground, by Cause of Death; (b) by Year

FIGURE 13.5.14 Wildland Fire Fighter Deploying Special Tent Shelter (Photo: James C. Smalley)

fire fighters narrowly escaped. Such situations often occur in the following conditions:

1. On relatively small or deceptively quiet areas of large fires
2. In areas with relatively light fuels, such as grass, herbs, and light brush
3. When there is an unexpected shift in wind direction or wind speed
4. When the fire responds to topographic conditions and runs uphill

These factors should not be considered all-inclusive. For example, a sudden change of wind may change the direction of fire spread, regardless of topography. Each set of circumstances has the potential for creating a tragedy or near-miss fire. Often human behavior is the determining factor. Sociologists Jon Driessen, Lisa Outka-Perkins, and Leslie Anderson in their report, "Two Entrapment Avoidance Projects: Studying Crew Cohesion as a Social Human Factor," studied crew cohesion and how a breakdown in the crew affects the level of fatalities and injuries to wildland fire fighters.[13] Fire fighters who remain calm when the wind direction changes and move back into a burned area should survive. Those who try to outrun a fire under similar conditions may die. The difference between a tragic fire and a near-miss fire may be due to luck, skill, and/or advance planning. In all cases, it is important to be alert and aware of conditions that may signal a sudden change in fire behavior. In a few words, be alert and watch out for light fuels, wind shifts, steep slopes, and "chimneys." Those who remain alert and on the lookout for possible trouble have the best chance of survival.

FIRE PREVENTION

Challenge of Prevention

In the United States, about 2.5 million acres (1 million ha) of developed lands and wildlands burn every year. Often the carelessness of people leads to fires in wildlands. Some wildland fires are caused by campers who neglect to properly extinguish campfires. Other wildland fires result from lit cigarettes tossed onto the dry ground. Unwanted fires threaten valuable resources and, for this reason, fire prevention is an ongoing job. Fire prevention is one of the most important parts of a fire protection agency's responsibilities.

Smokey Bear Program

One of the most effective educational programs in the United States since 1944 has been Smokey Bear (Figure 13.5.15). This program has been a major factor in the prevention of thousands of unwanted human-caused fires, saving millions of dollars in damages and fire suppression costs. Nine out of every 10 wildfires is human caused. The program is managed by the partnership of the USDA Forest Service, the Ad Council, and National Association of State Foresters.

FIGURE 13.5.15 Smokey Bear (Source: U.S. Forest Service)

Following a series of changes in fire management policies and practices over the past decade, Smokey's message subtly changed from preventing forest fires to preventing wildfires, recognizing that unwanted fires on forests and grasslands (particularly those that destroy homes) are now the targets of prevention.

Over time, the Smokey program developed partnerships to reach new groups. Such partnerships include the American cowboy, pro-sports figures, and amateur athletes, all of whom have joined with Smokey to get the fire prevention message to the public. In 2005, Smokey Bear partnered with the Disney Corporation to deliver a fire prevention message with the DVD release of the Disney movie *Bambi.*

Specific prevention programs have been developed by different agencies and areas of the country. The Keep Washington Green Program, California Fire-Safe Councils, and central Oregon's Free Program are examples of programs developed to meet regional needs. Other individual states have very active wildfire prevention programs.

RESEARCH

Both Canada and the United States maintain fire research programs whose ultimate goals are to reduce the loss of life, property, and forest resources from wildfires and to introduce prescribed fire to achieve forest and range management objectives at reduced costs.

Joint Fire Science Program

The Joint Fire Science Program (JFSP), a partnership of six federal wildland and fire and research organizations, was established in 1998 to provide scientific information and support for fuel and fire management programs. All JFSP projects require scientist-manager partnerships along with strong emphasis on transferring research findings to the field. Guidance for the program includes the following four original principal purposes, all related to wildland fuels:

- Fuels inventory and mapping
- Evaluation of fuels treatments
- Scheduling of fuels treatments
- Development of protocols for monitoring and evaluation

Digital mapping (Figure 13.5.16) helps build inventories of forest health issues, fire-fighting resources, fuels, wildland/urban interface developments at risk from wildfire, and other forest and land management concerns. Mapping also provides the opportunity for spatial relationships to be examined, for example, the relationships between watersheds, wildlife habitat, and either a wildfire or the impact of a prescribed fire in the area.

In 2001, Congress further directed JFSP to expand its research efforts in postfire rehabilitation and stabilization, local assistance, and aircraft-based remote sensing. JFSP research also examines air quality, smoke management and social aspects of fire, and fuels management. In setting priorities for funding, the program responds to congressional direction, recommendations from advisory committees and member agencies, along with collective input from key agency personnel, workshops, and informational meetings. The program focus is on short-term, applied research that provides information and tools to specialists and managers, helping them make the best possible decisions and develop sound, scientifically valid plans.

Fire Behavior Research

Current U.S. Research. Current U.S. fire research is being conducted at six forest and range experiment stations. Much of the work is done at forest fire laboratories located in Macon, Georgia; Missoula, Montana; and Riverside, California. Major research projects include the following:

- *Fire behavior.* Fundamental studies in fuel chemistry, combustion and ignition processes, fire spread mechanisms, time-temperature heat flux interrelationships, and effects of fuel moisture, wind, and slope; development of systems to aid fire and land managers in dealing with the growth of large fires,

FIGURE 13.5.16 Digital Mapping Used to Provide Information on Forest and Land Management Concerns (Photo: James C. Smalley)

fuel consumption and energy release, probability of ignition by lightning, and fire spread in nonuniform fuels

- *Fire suppression.* Development of real-time and planning guidelines for individual suppression activities related to primary fuel and fire variables; integration of production rate knowledge into real-time and planning guidelines for fire suppression strategies and tactics; and development of design criteria for chemical formulations and for aerial and ground delivery systems for primary strategies and tactics
- *Fire effects, use, and ecology.* Research to determine how, when, and where prescribed fire may be used to improve tree growth, provide better wildlife habitat, reduce fire hazard, and accomplish other forestry goals; includes studies on soil to ascertain biological responses, impacts on soil, stand structure, and so on
- *Fire management planning.* Studies to relate wildland fires and social benefits desired from wildlands; to determine the effectiveness of fire prevention activities; to determine the influence of weather and climate on fire occurrence, control, and effects; and to determine the productivity and effectiveness of air tanker systems
- *Other.* Additional research projects involving smoke management for prescribed fires, reducing residues from forestry activities, evaluating the economics of fire protection systems, and aiding managers with systems for applying knowledge gained through research projects

Canadian Research. The Canadian Forestry Services (CFS) of Canada's Department of the Environment is the principal research organization in Canada. Its forest fire research program is centered at the Petawawa National Forestry Institute in Chalk River, Ontario. Fire research work is also carried out at regional forest research centers in Victoria, British Columbia; Edmonton, Alberta; and Sault Ste. Marie, Ontario. These research programs address the following six major areas:

1. *Fire behavior.* Fuel moisture physics, fire spread physics, prediction of fire danger by forest type, fire/weather interactions, fire danger rating system, and spatial weather models
2. *Fire ecology.* Postfire forest regeneration mechanisms, cyclic forest development from fire to fire, predictors of postfire forest development, and age-class distribution in fire-cycled forests
3. *Fire suppression.* Performance testing of fire management equipment, air tankers, fire retardant and water additives, aerial ignition devices, backfiring methods, and new suppression methods
4. *Prescribed fire.* Tree damage and mortality, use of fire for slash removal, seedbed preparation and vegetation control, design of prescriptions for proper burning conditions, and operational techniques
5. *Economics.* Estimation of values at risk, effect of fire on timber supply, relation between fire management costs and burned area, allowable cut effect, and ultimate impact on the forest economy
6. *Fire management systems.* Remote sensing applications; computerized systems for integrating weather, fuel type, and terrain into fire spread and growth models; prediction of lightning and human-caused fires; air patrol routing; resource deployment; and fire management strategies

Social Science Research. As national policies and practices changed over the past decade, a renewed interest developed in learning how the public would react to changes in fire policy, accepting the concept of good fire on the landscape and smoke in the air. To better understand and explain the interrelationships between people and natural environments, social research has been a focus of the U.S. Forest Service and other agencies in examining how people relate to, value, and impact the environment, that is, how the severity of forest and rangeland fires can be reduced through human interaction. Analogous to physical research that examines how fuel moisture in various types of vegetation affects flame lengths, social research examines the dynamics of changing values, public policies, and forest use, productivity, and management practices.

For more information on the overall research agenda, consult *Burning Questions: A Social Science Research Plan for Federal Wildland Fire Management.* In July 2000, the National Wildfire Coordinating Group commissioned an interagency research plan for understanding the human dimensions of federal wildland fire management. The resulting report describes the applicability of social science to wildland fire management problems, articulates high-priority needs for social science research, and organizes a research agenda that the NWCG advocates. This report is the foundation for NWCG's participation in the further development of a strong social science base to federal wildland fire management.

Programs such as Firewise Communities are based on steps that communities can take to reduce their risk from wildfire. Even in areas not traditionally considered at high fire risk, storm events, changing climate, and pest/disease outbreaks have focused attention on the potential for catastrophic fire. In addition, in areas where fire is viewed as a natural part of the ecosystem, the fact that more and more people choose these places to live means that there is a greater potential for significant fire impacts.

In research funded by the National Fire Plan, the North Central Research Station of the USDA Forest Service has found that actions to increase wildfire preparedness are affected by decisions made by individuals and the community. Individuals have resources that influence and are used to implement decisions regarding the siting of structures, building materials, landscaping, access, and other factors that impact wildfire preparedness. Communities also have resources that influence and are used to implement their decisions relating to zoning, planning, education, and other activities that impact wildfire preparedness. Agencies within these communities have resources that influence and are used to implement their decisions relating to the purchase and availability of equipment and gear, scheduling and conduct of training, and implementation of protocols. Decisions made at both the individual and community levels come together in a set of actions aimed at increasing wildfire preparedness. Figure 13.5.17 indicates that, as a result of these actions, communities can minimize losses from wildfire, and recovery or restoration following a fire will be quicker and more effective.

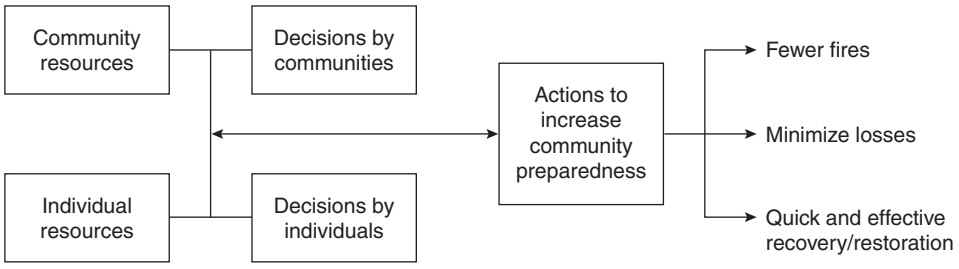

FIGURE 13.5.17 Model for Understanding Community Preparedness for Wildfire

Based on pilot studies in northern Minnesota on the Gunflint Trail; Bend, Oregon; and Waldo, Florida, to test the model, the focus turned to the following five community resources or characteristics that are critical to wildfire preparedness:

- *Social capital.* The community characteristics that contribute to collective social action; communities that are described as having social capital would have strong leadership within the community, networks to encourage coordination and cooperation, and the ability to mobilize resources
- *Human capital.* Knowledge and skills an individual obtains through education and training
- *Cultural capital.* Knowledge and skills possessed by individuals because of their heritage, experience, and attachment to place
- *Agency involvement.* Agency involvement (one agency working alone, a couple of agencies working separately but toward a common goal, or multiple agencies truly integrating their activities) was important in affording the local community access to the myriad of public programs providing funding and materials for wildfire preparedness; agencies also provide expertise and skills to the community to aid in wildfire preparedness
- *Landscape.* Vegetation and topography that have a huge influence on fire frequency and risk; there are also social aspects to landscape, for example, land ownership as a social characteristic of landscape that affects wildfire preparedness

The product of this and related research will be a more detailed understanding of the relationship of humans to the environment and recommendations for actions to increase wildfire preparedness based on the ecological characteristics of the landscape and the social characteristics of the community. The outcome of this research will be communities that, if they experience a wildfire, will minimize their losses and recover and restore their communities more quickly because they have taken steps to increase wildfire preparedness and have identified the necessary resources to implement these steps.[14]

SUMMARY

The historic and potential loss of human life, the financial impact on the national economy, and the increased value of natural resources make it undesirable to lose thousands of acres of valuable timber, rangeland, and watersheds. Continuing efforts to mitigate accumulating forest fuels, to guide growth of residences near forests, to prepare fire managers and fire fighters to use the beneficial aspects of prescribed fire, and the control of unwanted fires are growing in importance.

Because mitigating strategic fuels around communities requires action largely on private property, most fire agencies support and complement the national Firewise Communities program. The overarching objective of Firewise is, in a sense, to transfer the responsibility for mitigation and preparation for wildfires from the public sector to the private sector—that is, the homeowners and residents in hillside and grassy plains communities everywhere. Firewise Communities is a highly successful program emphasizing individual responsibility for fire hazard mitigation on community and private property through land use planning, building methods and materials, creative landscaping, intelligent zoning, and innovative community fire protection planning. The Firewise program educates and supports community leaders, fire professionals, planners, and individuals on wildland/urban interface fire issues; maintains an educational website; and provides varied assistance to organizations and individuals for wildland fire mitigation.

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14. For more information, refer to the North Central Research Station website http://www.ncrs.fs.fed.us.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on wildland fire management discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1051, *Standard for Wildland Fire Fighter Professional Qualifications*
NFPA 1143, *Standard for Wildland Fire Management*
NFPA 1144, *Standard for Reducing Structure Ignition Hazards from Wildland Fire*
NFPA 1906, *Standard for Wildland Fire Apparatus*

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Chapter 6

Public Fire Protection and Hazmat Management

Michael S. Hildebrand ■ Gregory G. Noll

Chapter Contents

Definition of a Hazardous Material
Hazardous Materials Prevention and Enforcement Programs
Federal Hazardous Materials Laws
Hazardous Materials Regulations
Voluntary Consensus Standards

Key Terms

Clean Air Act, hazardous material, Hazardous Waste Operations and Emergency Response (HAZWOPER) Standard, Resource Conservation and Recovery Act, Superfund, Superfund Amendments and Reauthorization Act (SARA)

Public interest in the environment and major catastrophes involving hazardous materials (hazmats) have resulted in promulgation of a wide range of laws, regulations, and standards that mandate fire department involvement. Many laws created at the federal level assign overlapping responsibility for public safety to federal, state, and local agencies. Organizing an effective hazardous materials prevention and enforcement program within a fire department can be a difficult task. Consider the fact that the U.S. Congress has passed six major pieces of legislation concerning hazardous materials and public safety. These laws have produced seven different major federal agency regulations that contain no fewer than six different legal definitions for a hazardous material. Add the fact that there are also 50 individual state codes and over 70 different voluntary consensus standards, and it is easy to see why the code enforcement issue can be confusing.

This chapter has been written for the fire department prevention and enforcement specialist who wants to learn the fundamentals of hazardous materials laws, regulations, and standards. It begins by defining what a hazardous material is and provides an overview of the major elements of a hazardous materials prevention and enforcement program. The chapter provides an in-depth overview of the key elements of each of the major federal laws and regulations, as well as a general summary of the primary hazardous materials codes and standards.

See also Section 7, Chapter 5, "Hazardous Waste Control"; and Section 13, Chapter 8, "Managing the Response to Hazardous Material Incidents."

DEFINITION OF A HAZARDOUS MATERIAL

The first step in understanding hazardous materials from a prevention and enforcement perspective is to define what a hazardous material actually is. Many of the commonly used hazardous materials terms are sometimes used interchangeably, but they have distinctively different meanings. Various state and federal regulations govern the manufacture, transportation, storage, use, and cleanup of chemicals in the United States and Canada, and use numerous terms, definitions, and lists to convey information.

Hazardous materials: Any substance or material in any form or quantity that poses an unreasonable risk to safety and health and property when transported in commerce (U.S. Department of Transportation, 49 CFR 171).

Hazardous substances: Any substance designated under the Clean Water Act and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) as posing a threat to waterways and the environment when released (U.S. Environmental Protection Agency [EPA], 40 CFR 302). It should be noted that the term "hazardous substances," as used within Occupational and Safety Health Administration (OSHA) 1910.120, refers to any substance defined by EPA within Section 101 of CERCLA; any biological agent or other disease-causing agent as defined by EPA within Section 101 of CERCLA; any substance listed by Department of Transportation (DOT) as

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a hazardous material; and any hazardous waste, as defined by EPA in 40 CFR 261.3 or by DOT in 49 CFR 171.8.

Extremely hazardous substances (EHS): Chemicals determined by the EPA to be extremely hazardous to a community during an emergency spill or release as a result of their toxicities and physical/chemical properties (U.S. EPA, 40 CFR 355).

Hazardous chemicals: Any chemical that would be a risk to employees if exposed in the workplace (U.S. OSHA, 29 CFR 1910). Examples of a "physical hazard" are combustible liquids, compressed gases, explosives, flammables, organic peroxides, oxidizers, pyrophorics, unstables (reactives), or water-reactives. "Health hazard" means a mixture of chemicals or a pathogen for which there is statistically significant evidence, based on at least one study conducted in accordance with established scientific principles, that acute or chronic health effects may occur in exposed employees. The term "health hazard" includes chemicals that are carcinogens, toxic or highly toxic agents, reproductive toxins, irritants, corrosives, sensitizers, hepatoxins, nephrotoxins, neurotoxins, agents that act on the hematopoietic system, and agents that damage the lungs, skin, eyes, or mucous membranes.

Hazardous wastes: Discarded materials regulated by the EPA because of public health and safety concerns. Regulatory authority is granted under the Resource Conservation and Recovery Act (RCRA) (U.S. EPA, 40 CFR 260–281).

Marine pollutant: Materials that have an adverse impact on the marine environment.

Dangerous goods: An internationally used term under the International Maritime Dangerous Good Code (IMDG). In Canadian transportation, the U.S. term "hazardous materials" has basically the same meaning as "dangerous goods."

HAZARDOUS MATERIALS PREVENTION AND ENFORCEMENT PROGRAMS

A comprehensive and integrated public safety hazardous materials program should consist of four major program elements: (1) prevention, (2) preparedness, (3) response, and (4) recovery. The prevention program element usually consists of four subelements: (1) construction and design standards; (2) an inspection and enforcement program; (3) a public education program; and (4) handling, notification, and reporting requirements.

Process, Container Design, and Construction Standards

Almost all hazardous materials facilities, containers, and processes are designed and constructed to some engineering standard. This standard may be based on voluntary consensus standards, such as those developed by the National Fire Protection Association (NFPA) and the American Society for Testing and Materials (ASTM) or on government regulations. Many major petrochemical companies, hazardous materials companies, and industry trade associations have also developed their own respective engineering standards and guidelines.

All containers used for the transportation of hazmats are designed and constructed to both specification and performance regulations established by the U.S. DOT. These regulations are referenced in Title 49 of the Code of Federal Regulations (CFR). In certain situations, hazmats may be shipped in non-DOT-specification containers that have received a DOT exemption.

Inspection and Enforcement

Fixed facilities, transportation vehicles, and transportation containers are subject to some form of hazardous materials inspection. Fixed facilities will commonly be inspected by state and federal OSHA and EPA inspectors in addition to state fire marshals and local fire departments. It should be recognized that many of these inspections will focus on fire safety and life safety issues and may not adequately address either environmental or process safety issues.

Transportation vehicle inspection is generally based on criteria established within Title 49 CFR. The enforcing agency is usually the state police; however, some local fire departments and state fire marshal's offices are also involved in inspecting hazardous materials cargo tank trucks. This will vary according to the individual state, the hazardous materials being transported, and the mode of transportation.

Among the U.S. DOT agencies with primary hazardous materials regulatory responsibilities are the following.

U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA): Responsible for safe and secure movement of hazardous materials to industry and consumers by all transportation modes, including the nation's pipelines.

Federal Motor Carrier Safety Administration (FMCSA): The mission of FMCSA is to improve truck and bus safety on the nation's highways and to reduce hazardous materials security risks that could potentially harm the public and the environment.

Federal Railroad Administration (FRA): Responsible for enforcement of regulations relating to hazardous materials carried by rail or held in depots and freight yards.

Federal Aviation Administration (FAA): Responsible for the enforcement of regulations relating to hazardous materials shipments on domestic and foreign carriers operating at U.S. airports and in cargo-handling areas.

U.S. Coast Guard (USCG): Responsible for the inspection and enforcement of regulations relating to hazmats in port areas and on domestic and foreign ships and barges operating in the navigable waters of the United States.

Public Education

Hazardous materials are a concern not only for industry but also for the community. The average homeowner contributes to this problem by improperly disposing of substances such as used motor oil, paints, solvents, batteries, and other chemicals used in and around the home. As a result, many communities have initiated full-time household chemical waste awareness,

education, and disposal programs. In other instances, communities have established used motor oil collection stations and chemical cleanup days in an effort to reclaim and recycle these materials.

Handling, Notification, and Reporting Requirements

These guidelines actually act as a bridge between planning and prevention functions. There are many federal, state, and local regulations that require those who manufacture, store, or transport hazmats and hazardous wastes to comply with certain handling, notification, and reporting rules. Key federal regulations include the facility reporting requirements of Superfund Amendments and Reauthorization Act (SARA), Title III, and the release notification requirements of CERCLA (Superfund). There are also many state regulations that are similar in scope and that often exceed the federal requirements.

FEDERAL HAZARDOUS MATERIALS LAWS

Laws are primarily created through an act of Congress or by individual state legislatures. Laws typically provide broad goals and objectives, mandatory dates for compliance, and established penalties for noncompliance. Federal and state laws enacted by legislative bodies usually delegate the details for implementation to a specific federal or state agency. For example, the U.S. Occupational Safety and Health Act enacted by Congress delegates rule making and enforcement authority on worker health and safety issues to the Occupational Safety and Health Administration.

History shows that hazardous materials laws have been enacted by Congress in response to specific catastrophes, such as Love Canal, New York; Bhopal, India; and the terrorist attacks of 9/11. Laws now regulate everything from finished products to hazardous waste.

Because of their lengthy official titles, many simply use abbreviations or acronyms when referring to these laws. The following summaries outline some of the more important laws impacting hazardous materials emergency planning and response.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

Known as "Superfund," this law addresses hazardous substance releases into the environment and cleanup of inactive hazardous waste disposal sites. It also requires those individuals responsible for the release of the hazardous materials (commonly referred to as the responsible party) above a specified "reportable quantity" to notify the National Response Center.

In 1980, Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and established a fund of $1.6 billion called the "Superfund" (PL 96-510) to be administered by the EPA. Under this legislation, the EPA is authorized to inventory all uncontrolled hazardous waste sites in the nation. If the substances at these sites pose an immediate danger to public health and/or the environment, and those responsible for the contamination cannot be identified or cannot pay for the cleanup, the EPA can use the Superfund to clean up chemical spills or toxic wastes.

Resource Conservation and Recovery Act (RCRA)

In 1976, Congress passed major legislation establishing a uniform national policy for hazardous and solid waste disposal. This act is called the Resource Conservation and Recovery Act (RCRA). Congress intended that states assume responsibility for implementing RCRA, with oversight from the federal government. The rationale was that states are more familiar with the regulated community and are in a better position to administer the programs and respond to specific state and local needs most effectively. The state program must be fully equivalent to the federal program. However, states may impose requirements that are "more stringent" or "broader in scope" than the federal requirements.

There are four major programs established under RCRA: (1) solid waste, (2) underground storage tanks, (3) medical waste, and (4) hazardous waste.

Solid Waste. Subtitle D of the act encourages states to develop and implement solid waste management plans. These plans, among other purposes, are intended to promote recycling of solid wastes and require closing or upgrading of all environmentally unsound dumps.

Underground Storage Tanks. Subtitle I of the act regulates petroleum products and hazardous substances (as defined under Superfund) stored in underground tanks. The objective of this section is to prevent leakage to groundwater from tanks and to clean up past releases. There are also performance standards for new tanks and regulations for leak detection, prevention, closure, financial responsibility, and corrective action at all underground tank sites.

Medical Waste. Subtitle J addresses the problem of medical waste mismanagement. Included are requirements pertaining to medical waste generation, treatment, destruction, and disposal.

Hazardous Waste. Subtitle C establishes a program to manage hazardous wastes from "cradle to grave." The objective of the program is to ensure that hazardous waste is handled in a manner that protects human health and the environment. These regulations cover the generation, transportation, and treatment, storage, or disposal of hazardous wastes. Any facility generating more than a minimum amount of hazardous waste must follow the RCRA requirements for storage, transportation, and disposal.

Regulations of both the DOT and the EPA govern the transportation of hazardous wastes. A hazardous waste manifest system, among other purposes, ensures that the material is properly identified; states the place of origin and destination for treatment, storage, or disposal; classifies the waste; provides the quantity and flashpoint of the substance; and gives special

handling instructions. Each shipper handling a hazardous waste cargo must sign the manifest certifying acceptance.

Comprehensive guidelines have been established by the EPA for tracking the movement, treatment, storage, and disposal of these waste products. Among the provisions of the guidelines are the following:

1. Identification and listing of materials classified as hazardous waste
2. A system of record keeping and labeling
3. Procedures for providing correct information regarding hazardous waste contents to and by persons transporting, storing, or disposing of this waste
4. A manifest and permit system regulating the transport of wastes to authorized sites
5. Requirements that transporters of hazardous wastes properly label hazardous waste shipments and carry them only to treatment, storage, or disposal sites licensed under RCRA
6. Requirements that operators of toxic storage disposal (TSD) facilities maintain records and comply with the manifest system. Only EPA-approved methods of treatment, storage, and disposal can be used as indicated in the permit issued by the EPA.
7. A mandate for producers and site operators to develop contingency plans in the event of a hazardous waste emergency. The plans must be the result of consultations with local fire, police, and hospital officials. These organizations must be included as part of the local response team. Contingency plans provide detailed information, such as the industrial site plan, the on-scene coordinator's phone number, and types of hazards present.
8. Encouragement for states to develop and manage their own hazardous waste programs consistent with RCRA guidelines. In the absence of a state plan, RCRA authorizes EPA to impose a federal plan for the state.

RCRA also requires hazardous waste generators to do the following:

1. Consult the list of hazardous and toxic organic and inorganic compounds published by the EPA to determine if a chemical waste is hazardous.
2. Subject all unlisted wastes to chemical analysis to determine if they possess any of the hazardous waste characteristics established in the regulations.
3. Declare a waste hazardous (based on knowledge of the material or processes used in its production).
4. Obtain an EPA identification number by filing with the EPA's regional administrator. Fire officials and local emergency-planning committees can obtain a list of hazardous waste generators in their area by contacting their EPA regional office. This list is updated on a regular basis and will provide the name and address of the facility, its EPA identification number, and its hazardous waste generator classification. Hazardous waste generators are classified in one of three categories, as follows:
   a. *Large-quantity generator (LQG).* Generates more than 2200 lb (1000 kg) of hazardous waste or more than 2.2 lb (1 kg) of acutely hazardous waste in a month. Once the first 2200 lb (1000 kg) has been accumulated, the waste must be shipped within 90 days. There is no limit to the amount that can be accumulated.
   b. *Small-quantity generator (SQG).* Generates less than 2200 lb (1000 kg) of hazardous waste in a month and/or less than 2.2 lb (1 kg) of acutely hazardous waste as listed by the EPA.
   c. *Conditionally exempt small-quantity generator (CESQG).* Generates less than 220 lb (100 kg) of hazardous waste or less than 2.2 lb (1 kg) of acutely hazardous waste in a month.
5. Apply for a facility permit if waste is accumulated on the generator's site for more than 90 days. The waste is considered to be stored at the site when it remains on the generator's property for more than 90 days. If this condition continues, the generator must secure a facility permit for storage of hazardous wastes, under RCRA Section 3005.
6. Treat, store, or dispose of hazardous wastes on site subject to requirements under RCRA Sections 3004 and 3005.
7. Transport hazardous wastes to other locations for use, storage, treatment, or disposal in properly labeled and approved containers, and prepare a hazardous waste manifest.

On November 8, 1984, Congress passed the Hazardous and Solid Waste Amendments Act of 1984, which modified waste-management practices and strengthened RCRA by:

1. Establishing tighter requirements for hazardous waste land disposal
2. Regulating underground storage tanks for new or waste products under RCRA
3. Bringing small-quantity generators (i.e., those generating between 220 and 2200 lb [100 and 1000 kg] of hazardous waste per month) under RCRA's authority
4. Giving the authority to order corrective action at RCRA-regulated facilities to the EPA
5. Setting forth "minimum technological standards," such as double liners, two-leachate collection systems, and groundwater monitoring, for new land-disposal facilities, as well as requiring interim-status facilities to either be retrofitted or stop receiving, storing, or treating hazardous waste
6. Establishing new requirements for delisting hazardous wastes

Clean Air Act (CAA)

This act establishes requirements for airborne emissions and the protection of the environment. The Clean Air Act Amendments of 1990 addressed emergency response and planning issues at certain facilities with processes using highly hazardous chemicals. This included the establishment of a national Chemical Safety and Hazard Investigation Board; EPA's promulgation of 40 CFR, Part 68, "Risk Management Programs for Chemical Accidental Release Prevention"; and OSHA's promulgation of 29 CFR 1910.119, "Process Safety Management of Highly Hazardous Chemicals, Explosives, and Blasting Agents." In addition, certain facilities are required to make information available to the general public regarding the manner in which chemical risks are handled within a facility.

Superfund Amendments and Reauthorization Act of 1986 (SARA)

SARA has had the greatest impact on hazardous materials emergency planning and response operations. As the name implies, SARA amended and reauthorized the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA or Superfund). Although many of the amendments pertained to hazardous waste site cleanup, SARA's requirements also established a national baseline with regard to hazardous materials planning, preparedness, training, and response.

Title I of this act required OSHA to develop health and safety standards covering numerous worker groups who handle or respond to chemical emergencies and led to the development of OSHA 1910.120, "Hazardous Waste Operations and Emergency Response (HAZWOPER)."

Most familiar to the emergency response community is SARA, Title III. Also known as the Emergency Planning and Community Right-to-Know Act (EPCRA), SARA, Title III, led to the establishment of the State Emergency Response Commissions (SERC) and the Local Emergency Planning Committees (LEPC).

The Right-to-Know Act of 1986 includes four major sections affecting public safety. These include (1) Sections 301 through 303: emergency planning; (2) Section 304: emergency release notification; (3) Sections 311 and 312: community right-to-know reporting requirements; and (4) Section 313: toxic chemical release inventory.

Emergency Planning (Sections 301 through 303). Sections 301 through 303 of the act required the governor of each state to appoint a state emergency response commission (SERC) that, in turn, was required to designate local emergency planning districts and appoint a local emergency planning committee (LEPC) for each district. Membership in the LEPC is required to include elected state and local officials; members of fire, police, civil defense, and public health organizations; environmental, hospital, and transportation officials; and representatives of industry, business, the community, and the media.

The primary responsibility of the LEPC is to develop a comprehensive emergency response plan and submit it to the SERC. After being reviewed by the SERC, the plan is returned to the LEPC with approval or recommendations for revision. This emergency response plan is required to be revised and updated annually. The plan must include the following:

1. The identification of specific sites and transportation corridors in which extremely hazardous materials are stored, used, or transported
2. Emergency response procedures
3. Designation of a community coordinator and facility coordinator to implement the emergency plan
4. Emergency notification procedures
5. Procedures for determining the occurrence of a chemical release and the probable area and population that will be affected
6. Description of community and industrial emergency response equipment and resources and the identity of personnel responsible for them
7. Evacuation plans
8. Description and schedule of a chemical emergency response training program
9. Method and schedule for conducting emergency response plan exercises

Emergency Release Notification (Section 304). Section 304 requires facility owners or operators to give immediate notification to the community emergency coordinator of the LEPC, and to the SERC, of any release of a listed hazardous substance or its vapor that will extend beyond the facility's property and possibly endanger the general public. In most communities, the initial notification point will be to the emergency 9-1-1 telephone number or the local equivalent.

Under Section 304, the term "facility" means any building, structure, installation, equipment, pipe or pipeline (including any pipe into a sewer or publicly owned treatment works), well, pit, pond, lagoon, impoundment, ditch, storage container, motor vehicle, rolling stock, or aircraft, or any site or area where a hazardous substance has been deposited, stored, disposed of, or placed, or otherwise come to be located; this, however, does not include any consumer product use or any waterborne vessel.

Releases that result only in exposure to persons solely within the site on which the facility is located are not required to be reported to the LEPC or SERC but may require the owner or operator to notify the National Response Center, under Section 103(a) of CERCLA. Hazardous substances that are subjected to these reporting requirements can be found on a list of approximately 360 extremely hazardous substances that was published by the EPA in the Federal Register (40 CFR 355) or on a list of approximately 725 substances subject to emergency notification requirements, under CERCLA, Section 103(a), 40 CFR 302.4. There are additions and deletions to these lists on a periodic basis, and some of the substances can be found on both lists.

Initial emergency notification of a release by the owner or operator can be made by telephone, radio, or in person. To the extent it is known at the time of the notice, and as long as it does not result in a delay in responding to the emergency, the notification must include the following information:

1. The name or identity of the involved substance or substances
2. An indication of whether the substance or substances are on the extremely hazardous list
3. An estimate of the quantity of the substance or substances released into the environment
4. The time and duration of the release
5. The medium or media (air, land, water) into which the release occurred
6. Any known or anticipated acute or chronic health risks associated with the emergency, and, if necessary, advice regarding medical attention for exposed individuals
7. Proper precautions to take as a result of the release, such as evacuation
8. The name and telephone numbers of the person or persons to be contacted for further information

As soon as possible after a release that requires notice, the owner or operator must provide a written follow-up emergency

notice. As more information becomes available, the owner or operator must update the information originally required and include additional information with respect to the following:

1. Actions taken in responding to and containing the release
2. Any known or anticipated acute or chronic health risks associated with the release
3. When appropriate, advice regarding medical attention necessary for exposed individuals

Notification of releases of hazardous substances during transportation or during storage relating to the transportation of such substances must be reported by dialing emergency 9-1-1 or, in the absence of a 9-1-1 emergency telephone number, by calling the operator.

Community Right-to-Know Reporting Requirements (Sections 311 and 312). Section 311 requires that the owner or operator of a facility prepare or have available a material safety data sheet (MSDS) for each hazardous chemical covered under the Occupational Safety and Health Act of 1970 (and any regulations promulgated under that act) and submit an MSDS to each of the following:

1. The local emergency planning committee
2. The state emergency-response commission
3. The fire department with jurisdiction over the facility

If the hazardous chemical is a mixture, the owner or operator of the facility can fulfill the requirements of Section 311 by submitting an MSDS for, or identifying on a list, each element or compound in the mixture that is a hazardous chemical. The owner or operator may also submit an MSDS for, or identify on a list, the mixture itself.

In lieu of an MSDS, the owner or operator may submit a list of the hazardous chemicals grouped in categories of health and physical hazards according to OSHA or in terms of groups of hazardous chemicals that present similar hazards in an emergency, as designated by the EPA administrator. The list of hazardous chemicals must include (1) the chemical name or common name of each substance, as provided on the MSDS and (2) any hazardous component of each substance, as provided on the MSDS.

An MSDS or revised list must be provided when new hazardous chemicals become present at a facility in quantities at or above established threshold levels. Upon request by the local emergency planning committee, an owner or operator who submits a list of chemicals must provide the appropriate MSDS for any chemical on that list. If requested by any member of the general public, the LEPC must make available to that person an MSDS for any hazardous chemicals required to be submitted to them. This information may be given at a location designated by the LEPC during normal working hours.

Within three months following the discovery by an owner or operator of significant new information concerning an aspect of a hazardous chemical for which an MSDS was previously submitted to the LEPC, a revised MSDS must be provided to the LEPC.

Section 312 stipulates that owners or operators of a facility who are required to prepare or have available an MSDS for each hazardous chemical covered under the Occupational Safety and Health Act of 1970 (and any regulations promulgated under that act) prepare and submit an emergency and hazardous chemical inventory form to the local emergency planning committee, the state emergency response commission, and the fire department with jurisdiction over the facility.

The inventory form must include all hazardous chemicals above specified thresholds that were present at the facility at any time during the previous calendar year. The EPA has established threshold quantities for hazardous chemicals covered by Section 312. If the quantities of hazardous chemicals are below that set forth by EPA, a report is not required. Current threshold quantities are as follows:

1. For extremely hazardous substances: 500 lb (227 kg) or the threshold planning quantity, whichever is lower
2. For all other hazardous chemicals that meet or exceed 10,000 lb (4450 kg) for which OSHA requires an MSDS; it should be noted that there are over 500,000 chemicals and mixtures for which OSHA requires an MSDS be maintained

Facilities may file either a Tier I or Tier II inventory form. Tier I reporting requires owners or operators to submit the following information for each of the hazard categories set forth under OSHA regulations:

1. Fire, sudden release of pressure, reactivity, acute health hazard, chronic health hazard
2. An estimate (in ranges) of the maximum amount of hazardous chemicals in each category present at the facility at any time during the preceding calendar year
3. An estimate (in ranges) of the average daily amount of hazardous chemicals in each category present at the facility at any time during the preceding calendar year
4. The general location of hazardous chemicals in each category

The EPA administrator may modify the OSHA categories of health and physical hazards by requiring information to be reported in terms of groups of hazardous chemicals that present similar hazards in an emergency or require reporting on individual hazardous chemicals of special concern to emergency response personnel. Tier I inventory forms are required to be submitted on or before March 1 of each year and contain data with respect to the preceding calendar year.

Tier II inventory reporting forms are required if requested by a state emergency response commission, an LEPC, or a fire department with jurisdiction over the facility. If an owner or operator of a facility files a Tier II inventory form, a Tier I form is not required, as long as the same deadlines are followed. The public may also request Tier II information from the LEPC or SERC. Tier II information must include the following:

1. The chemical name or common name of each chemical, as provided on the MSDS
2. An estimate (in ranges) of the maximum amount of hazardous chemicals present at the facility at any time during the preceding calendar year
3. An estimate (in ranges) of the average daily amount of hazardous chemicals present at the facility at any time during the preceding calendar year

4. A brief description of the manner of storage of the hazardous chemical
5. The location at the facility of the hazardous chemical
6. An indication of whether the owner elects to withhold location information of a specific hazardous chemical from disclosure to the public

Upon request by a fire department with jurisdiction over any facility that files an inventory form under Section 312, the owner or operator must allow the fire department to conduct an on-site inspection of the facility and must provide to the fire department specific location information on hazardous chemicals at the facility.

Toxic Chemical Release Inventory (Section 313). Section 313 requires owners or operators of certain facilities to file an annual Toxic Chemical Release Inventory Form (Form R) with the EPA and to those officials designated by the governor of the state on or before July 1 of each year. A release is defined as any spilling, leaking, pumping, pouring, emitting, emptying, discharging, injecting, escaping, leaching, dumping, or disposing into the environment (including the abandonment or discarding of barrels, containers, and other closed receptacles) of any toxic chemical. Section 313 applies to facilities that have 10 or more full-time employees, fall under the Standard Industrial Classification (SIC) Codes 20 through 39, and that manufactured, processed, or otherwise used a listed toxic chemical in excess of specified threshold quantities during the previous calendar year. The threshold quantity is 25,000 lb (11,350 kg) per year for toxic chemical manufacturing or processing. The threshold quantity with respect to use at a facility is 10,000 lb (4450 kg) of toxic chemical per year. The initial List of Toxic Chemicals subject to the provisions of Section 313 was published in August 1986 for the Senate Committee on Environment and Public Works. Through rule making, the EPA has modified this list to date by adding nine chemicals and delisting six. Chemicals may be added to the list if there is sufficient evidence to establish any one of the following:

1. The chemical is known to cause, or can reasonably be anticipated to cause, significant adverse acute human health effects at concentration levels that are reasonably likely to exist beyond facility site boundaries as a result of continuous, or frequently recurring, releases.
2. The chemical is known to cause, or can reasonably be anticipated to cause, cancer or teratogenic effects, or serious or irreversible reproductive dysfunction, neurological disorders, heritable genetic mutations, or other chronic health effects in humans.
3. The chemical is known to cause, or can reasonably be anticipated to cause, because of its toxicity, its toxicity and persistence in the environment, or its toxicity to bioaccumulate in the environment, a significant adverse effect on the environment of sufficient seriousness, in the opinion of the EPA, to warrant reporting under Section 313.

The EPA has established and maintains a national toxic-chemical inventory database (TRI database) on the information submitted. The computer database is accessible by the public and government officials via computer telecommunications and is intended to help answer questions about toxic chemical releases in a community. The EPA is using the data to target problem pollution areas and as a screening tool for the development of regulations, guidelines, and standards. Researchers from the government or universities conducting environmental analysis can also access the data.

Toxic Substances Control Act (TSCA)

The Toxic Substances Control Act (TSCA—pronounced Tosca), passed by Congress in 1976, establishes regulations with respect to the inventory and testing of all chemical substances manufactured or processed in the United States. This act makes the EPA the central implementation arm of the federal government. TSCA authorizes the EPA to do the following:

1. Develop a uniform listing of all chemical substances.
2. Establish a testing procedure for chemicals already in use and any one of approximately 1000 new chemicals developed each year.
3. Determine if these chemicals present an unreasonable risk to the public's health or the environment.
4. Prohibit or limit the manufacture, processing, use, application, and concentration of such chemicals.
5. Recall or seize by civil action hazardous substances that are determined to be imminently harmful to the public's health or the environment.

Federal Water Pollution Control Act (FWPCA)

In 1970, the Federal Water Pollution Control Act (PL 92-500) was amended in Section 311 to include oil and hazardous spills. Through this legislation, both the EPA and the U.S. Coast Guard are mandated to regulate spills of oil and/or other hazardous substances that threaten coastal waters and inland waterways.

Spill Prevention, Control, and Countermeasure Plan (SPCC)

This regulation was issued by the EPA in 40 CFR 112 and applies to facilities engaged in drilling, producing, gathering, storing, processing, refining, transferring, distributing, or consuming oil and oil products, which due to location could reasonably be expected to discharge oil in quantities that may be harmful into or upon navigable waterways or adjoining shorelines, or upon the waters on the contiguous zone.

Owners or operators of these facilities must prepare a Spill Prevention, Control, and Countermeasure (SPCC) plan that includes appropriate containment and/or drainage control structures or equipment to prevent discharged oil from reaching navigable water before cleanup occurs.

Facilities that are excluded from being required to have a SPCC plan are facilities that do not have an aboveground storage capacity of at least 1320 gal (4996 L) of oil. No single container at these facilities can hold more than 660 gal (2498 L) of oil.

Oil Pollution Act of 1990 (OPA)

Commonly referred to as OPA, this act amended the Federal Water Pollution Control Act. Its scope covers both facilities and

carriers of oil and related liquid products, including deepwater marine terminals, marine vessels, pipelines, and railcars. Requirements include the development of emergency response plans, regular training and exercise sessions, and verification of spill resources and contractor capabilities. The act also requires the establishment of Area Committees (AC) and the development of Area Contingency Plans (ACP) to address oil and hazardous substance spill response in coastal zone areas.

HAZARDOUS MATERIALS REGULATIONS

Regulations, sometimes called "rules," are created by federal or state agencies as a method of providing guidelines for complying with a law that was enacted through legislation. A regulation permits individual governmental agencies to enforce the law through inspections, which may be conducted by federal and state officials.

Laws delegate certain details of implementation and enforcement to federal or state agencies that are then responsible for writing the actual regulations that enforce the legislative intent of the law. Regulations will either (1) define the broad performance required to meet the letter of the law (i.e., performance-oriented standards) or (2) provide very specific and detailed guidance on satisfying the regulation (i.e., specification standards).

Federal Regulations

The following summary includes several of the more significant federal regulations that affect hazardous materials emergency planning and response.

Hazardous Waste Operations and Emergency Response (29 CFR 1910.120). Also known as HAZWOPER, this federal regulation was issued under the authority of SARA, Title I. The regulation was written and is enforced by OSHA in those 23 states and two territories with their own OSHA-approved occupational safety and health plans. In the remaining 27 "non-OSHA" states, public sector personnel will be covered by a similar regulation enacted by the EPA (40 CFR Part 311).

The regulation establishes important requirements for both industry and public safety organizations that respond to hazardous materials or hazardous waste emergencies. This includes fire fighters, law enforcement, emergency medical personnel (EMS), hazardous materials responders, and industrial emergency response team (ERT) members. Requirements cover the following areas:

1. Hazardous materials emergency response plan
2. Emergency response procedures, including the establishment of an incident management system, the use of a buddy system with backup personnel, and the establishment of a safety officer
3. Specific training requirements covering instructors and both initial and refresher training
4. Medical surveillance programs
5. Postemergency termination procedures

Of particular interest to hazardous materials managers and responders are the specific levels of competency and associated training requirements identified within OSHA 1910.120(q)(6).

First Responder at the Awareness Level. These are individuals who are likely to witness or discover a hazardous substance release and who have been trained to initiate an emergency response notification process. The primary focus of their hazardous materials responsibilities is to secure the incident site, recognize and identify the materials involved, and make the appropriate notifications. These individuals would take no further action to control or mitigate the release. First responder–awareness personnel must have sufficient training or experience to objectively demonstrate the following competencies:

1. An understanding of what hazardous materials are and the risks associated with them in an incident
2. An understanding of the potential outcomes associated with a hazardous materials emergency
3. The ability to recognize the presence of hazardous materials in an emergency and, if possible, identify the materials involved
4. An understanding of the role of the first responder–awareness individual within the local emergency operations plan; this would include site safety, security and control, and the use of the *Emergency Response Guidebook* (ERG)
5. The ability to realize the need for additional resources and to make the appropriate notifications to the communications center

The most common examples of first responder–awareness personnel include law enforcement and plant security personnel, as well as some public works employees. There is no minimum hourly training requirement for this level; the employee would have to have sufficient training to objectively demonstrate the required competencies.

First Responder at the Operations Level. Most fire department suppression personnel fall into this category. These are individuals who respond to releases or potential releases of hazardous substances as part of the initial response for the purpose of protecting nearby persons, property, or the environment from the effects of the release. They are trained to respond in a defensive fashion without actually trying to stop the release. Their primary function is to contain the release from a safe distance, keep it from spreading, and protect exposures.

First responder–operations personnel must have sufficient training or experience to objectively demonstrate the following competencies:

1. Knowledge of basic hazard and risk assessment techniques
2. Knowledge of how to select and use proper personal protective clothing and equipment available to the operations-level responder
3. An understanding of basic hazardous materials terms
4. Knowledge of how to perform basic control, containment, and/or confinement operations within the capabilities of the resources and personal protective equipment available

5. Knowledge of how to implement basic decontamination measures
6. An understanding of the relevant standard operating procedures and termination procedures

First responders at the operations level must have received at least 8 hours of training or have had sufficient experience to objectively demonstrate competency in the previously mentioned areas, as well as the established skill and knowledge levels for the first responder–awareness level.

Hazardous Materials Technicians. These are individuals who respond to releases or potential releases for the purposes of stopping the release (Figure 13.6.1). Unlike the operations level, they generally assume a more aggressive role, in that they are often able to approach the point of a release in order to plug, patch, or otherwise stop the release of a hazardous substance.

Hazardous materials technicians are required to have received at least 24 hours of training equal to the first responder–operations level and have competency in the following established skill and knowledge levels:

1. Capable of implementing the local employers' emergency operations plan
2. Able to classify, identify, and verify known and unknown materials by using field survey instruments and equipment (direct reading instruments)
3. Able to function within an assigned role in the incident management system
4. Able to select and use the proper specialized chemical personal protective clothing and equipment provided to the hazardous materials technician
5. Understand hazard and risk assessment techniques
6. Able to perform advanced control, containment, and/or confinement operations within the capabilities of the resources and equipment available to the hazardous materials technician
7. Understand and implement decontamination procedures
8. Understand basic chemical and toxicological terminology and behavior
9. Understand termination procedures
10. Understand basic chemical and toxicological terminology and behavior

Many communities and facilities have personnel trained as emergency medical technicians (EMT) who nevertheless do not have the primary responsibility for providing basic or advanced life support medical care. Similarly, hazardous materials technicians may not necessarily be part of a hazardous materials response team. However, if they are part of a designated team as defined by OSHA, they must also meet the medical surveillance requirements within OSHA 29 CFR 1910.120.

Hazardous Materials Specialists. These are individuals who respond with, and provide support to, hazardous materials technicians. Their duties parallel those of the technician, but they require a more detailed or specific knowledge of the various substances they may be called on to contain. This individual

FIGURE 13.6.1 Hazardous Materials Technicians Donning EPA Level A Personal Protection Clothing

would also act as the site liaison with federal, state, local, and other governmental authorities, with regard to site activities.

Similar to the technician level, hazardous materials specialists must have received at least 24 hours of training equal to the technician level and have competency in the following established skill and knowledge levels:

1. Capable of implementing the local emergency operations plan
2. Able to classify, identify, and verify known and unknown materials by using advanced field survey instruments and equipment (direct reading instruments)
3. Have knowledge of the state emergency response plan
4. Able to select and use the proper specialized chemical personal protective clothing and equipment provided to the hazardous materials specialist
5. Understand in-depth hazard and risk assessment techniques
6. Able to perform specialized control, containment, and/or confinement operations within the capabilities of the resources and equipment available to the hazardous materials specialist
7. Able to determine and implement decontamination procedures
8. Able to develop a site safety and control plan
9. Understand basic chemical, radiological, and toxicological terminology and behavior

Whereas the hazardous materials technician possesses an intermediate level of expertise and is often viewed as a "utility person" within the hazardous materials response community, the hazardous materials specialist possesses an advanced level of expertise. Within the fire service, the specialist will often assume the role of the safety officer or hazardous materials branch. Furthermore, the specialist must meet the medical surveillance requirements outlined within OSHA 129 CFR 1910.120. The reader should note that a hazardous materials specialist, as defined by OSHA, is different from "specialist employee," as defined by NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents.* The differences in these terms is often a source of confusion among industrial emergency responders. They are two different titles and have different levels of competency.

On-Scene Incident Commander. Incident commanders, who will assume control of the incident scene, must receive at least 24 hours of training equal to the first responder operations level. In addition, the employer must certify that the incident commander has competency in the following areas:

1. Know and be able to implement the employer's incident management system
2. Know how to implement the employer's emergency operations plan
3. Understand the hazards and risks associated with working in chemical protective clothing
4. Know of the state emergency response plan and of the federal regional response team
5. Know and understand the importance of decontamination procedures

Skilled Support Personnel. These are personnel who are skilled in the operation of certain equipment, such as cranes and hoisting equipment, and who are needed temporarily to perform immediate emergency support work that cannot reasonably be performed in a timely fashion by emergency response personnel. It is assumed that these individuals will be exposed to the hazards of the emergency response scene.

Although these individuals are not subject to the HAZWOPER training requirements, they must be given an initial briefing at the site prior to their participation in any emergency response effort. This briefing must include elements such as instructions in using personal protective clothing and equipment, the chemical hazards involved, and the tasks to be performed. All other health and safety precautions provided to emergency responders and on-scene workers must be used to ensure the health and safety of these support personnel.

Specialist Employees. These are employees who, in the course of their regular job duties, work with and are trained in the hazards of specific hazardous substances and who will be called on to provide technical advice or assistance to the incident commander at a hazardous materials incident (Figure 13.6.2). This would include industry responders, chemists, and related professional or operations employees. These individuals must receive training or demonstrate competency in the area of their specialization annually. Appendix E in 29 CFR 1910.120, *Hazardous Waste Operations and Emergency Response,* provides nonmandatory guidelines for an effective training curriculum.

Hazard Communication Standard (29 CFR 1910.1200). The Hazard Communication Standard (HCS) was originally issued by OSHA in November 1983. OSHA's most recent revision of the HCS was issued on March 11, 1994, and covers manufacturers, importers, distributors, and users of hazardous chemicals. The Hazard Communication Standard is commonly called the right-to-know law or HAZCOM.

HAZCOM is a federal regulation that requires hazardous materials manufacturers and handlers to develop written material safety data sheets (MSDSs) on specific types of hazardous chemicals. These MSDSs must be made available to employees who request information about a chemical in the workplace. Examples of information on an MSDS include known health hazards, the physical and chemical properties of the material, first aid, fire-fighting and spill control recommendations, protective clothing and equipment requirements, and emergency telephone contact numbers. Under HAZCOM, hazmat health exposure information should be provided to emergency responders during the termination phase of an emergency, and all exposures should be documented. The basic responsibilities are outlined in Table 13.6.1.

Hazard Determination. Chemical manufacturers and importers are required to review the scientific information on the chemicals they produce or import and to report the information they find to their employees and to employers who distribute or use their products. Downstream employers can rely on the evaluations performed by the chemical manufacturers or importers to establish the hazards of the chemicals they use.

FIGURE 13.6.2 Specialist Employees Working with Specific Hazardous Substances

TABLE 13.6.1 Responsibilities Outlined by Hazardous Communications Standard

Chemical Manufacturers/ Importers	*Determine the Hazards of Each Product*
Chemical manufacturers/ importers/ distributors	Communicate the hazard information and associated protective measures downstream to customers through labels and MSDSs
Employers	Identify and list all hazardous chemicals in their workplace Obtain MSDSs and labels for each hazardous chemical Develop and implement a written hazard communication program, including labels, MSDSs, and employee training Communicate hazard information to employees through labels, MSDSs, and formal training programs

The chemical manufacturers, importers, and any employers that choose to evaluate hazards are responsible for the quality of the hazard determinations they perform. Each chemical must be evaluated for its potential to cause adverse health effects and its potential to pose physical hazards, such as flammability. In addition, chemicals that have been evaluated and found to be suspected or confirmed carcinogens must be reported as such.

Written Hazard Communication Program. Employers that fall under the requirements of HAZCOM must develop, implement, and maintain a written hazard communication program that includes provisions for container labeling, collection, and availability of MSDSs and employee training. It also must contain a list of the hazardous chemicals in the workplace, the means the employer will use to inform employees of the hazards of nonroutine tasks, and the hazards associated with chemicals in unlabeled pipes. If the workplace has multiple employers on-site (e.g., a construction site), HAZCOM requires these employers to ensure that information regarding hazards and protective measures be made available to the other employers on-site, where appropriate.

Labels and Other Forms of Warning. Chemical manufacturers, importers, and distributors must be sure that containers of hazardous chemicals leaving their facilities are labeled, tagged, or marked with the identity, appropriate hazard warning, and the name and address of the manufacturer or other responsible party.

In the workplace, each container must be labeled, tagged, or marked with the identity of the hazardous chemicals contained within and must show hazard warnings appropriate for employee protection. The hazard warning can be any type of message, words, pictures, or symbols that convey the hazards of the chemical(s) in the container. Labels must be legible, in English (plus other languages, if desired), and prominently displayed.

Material Safety Data Sheets. Chemical manufacturers and importers must develop a material safety data sheet (MSDS) for each hazardous chemical they produce or import and must provide the MSDS automatically at the time of the initial shipment of a hazardous chemical to a downstream distributor or user. Distributors must also ensure that downstream employers are similarly provided an MSDS.

Each MSDS must be in English and include information regarding the specific identity of the hazardous chemical(s) involved and the common names. In addition, information must be provided on the physical and chemical characteristics of the hazardous chemical, known acute and chronic health effects and related health information, exposure limits, whether the chemical is considered to be a carcinogen, precautionary measures, emergency and first-aid procedures, and the identification of the organization responsible for preparing the MSDS.

Copies of the MSDS for hazardous chemicals in a given work site are to be readily accessible to employees in that area. Although OSHA has developed a model MSDS format (OSHA form 174), there is currently no specific MSDS form required by the regulation. OSHA's model MSDS is divided into nine separate sections: (1) chemical identity, (2) hazardous ingredients, (3) physical and chemical characteristics, (4) fire and explosion hazard data, (5) reactivity details, (6) health-hazard information, (7) precautions for safe handling, (8) use of the material, and (9) any control measures to be taken.

The American National Standards Institute (ANSI) has developed a standard on the preparation of MSDSs. ANSI Z400.1, *Hazardous Industrial Chemicals, Material Safety Data Sheet—Preparation,* is used by many chemical manufacturers as a standardized format for MSDS preparation.

Employee MSDS training must include methods and observations that may be used to detect the presence or release of a hazardous chemical in the work area (e.g., monitoring conducted by the employer, continuous monitoring devices, visual appearance, or odor of hazardous chemicals when released). Physical and health hazards of the chemicals used and measures that the employees can take to protect themselves from these hazards must be covered, as well as specific procedures the employer has implemented to protect employees from exposure to hazard.

Trade Secrets. A "trade secret" is something that gives an employer an opportunity to obtain an advantage over competitors who do not know about the trade secret or who do not use it. For example, a trade secret may be a confidential device, pattern, information, or chemical makeup. Chemical industry trade secrets are generally formulas, process data, or a "specific chemical identity." The last is the type of trade secret information referred to in the Hazard Communication Standard. The term includes the chemical name, the chemical abstract services (CAS) registry number, or any other specific information that reveals the precise designation. It does not include common names.

The HCS standard strikes a balance between the need to protect exposed employees and the employer's need to maintain confidentially of a bona fide trade secret. This is achieved by providing limited disclosure to health professionals who are furnishing medical or other occupational services to exposed employees, or employees and their designated representatives, under specified conditions of need and confidentiality.

Medical Emergency. The chemical manufacturer, importer, or employer must immediately disclose the specific chemical identity of a hazardous chemical to a treating physician or nurse when the information is needed for proper emergency or first-aid treatment. As soon as circumstances permit, the chemical manufacturer, importer, or employer may obtain a written statement of need and a confidentiality agreement.

Hazardous Materials Transportation Regulations (49 CFR 100 through 199). This series of regulations is issued and enforced by DOT. The regulations govern container design, chemical compatibility, packaging and labeling requirements, shipping papers, transportation routes and restrictions, and so on. The regulations are comprehensive and strictly govern how all hazardous materials are transported by highway, railroad, pipeline, aircraft, and water. There are some local fire departments that routinely perform inspections of hazardous materials cargo tank trucks using DOT regulations.

Retention of DOT Markings, Placards, and Labels (29 CFR 1910.1201). In 1994, OSHA issued requirements that those facilities that receive containers of hazardous materials, which are required to be marked, labeled, or placarded in accordance with DOT regulations, retain those markings, labels, or placards on the container until the container is sufficiently cleaned of residue and purged of vapors to remove any potential hazards.

National Contingency Plan (NCP) (40 CFR 300, Subchapters A through J). The National Contingency Plan (NCP) outlines the policies and procedures of the federal agency members of the National Oil and Hazardous Materials Response Team, also known as the National Response Team (NRT). The regulation provides guidance for emergency responses, remedial actions, enforcement, and funding mechanisms for federal government response to hazardous materials incidents. The NRT is chaired by the EPA, whereas the vice-chairperson represents the U.S. Coast Guard (USCG).

Each of the 10 federal regions also has a Regional Response Team (RRT) that mirrors the makeup of the NRT. RRTs may also include representatives from state and local government and Indian tribal governments.

When the NRT or RRT is activated for a federal response to an oil spill or hazardous materials incident, a federal on-scene coordinator (OSC) will be designated to coordinate the overall response. The OSC will represent either the EPA or the USCG, based on the location of the incident. If the release or threatened release occurs in coastal areas or near major navigable waterways, the USCG will usually assume primary OSC responsibility. If the situation occurs inland and away from navigable or major waterways, the EPA will serve as the OSC. Local emergency responders should contact EPA and USCG personnel within their region to determine which agency has primary responsibility and will act as the federal OSC for their respective area.

If the incident is a terrorism-related event, the Federal Bureau of Investigation (FBI) will assume the role as Federal On Scene Coordinator during the emergency response phase; the Department of Homeland Security/Federal Emergency Management Agency (FEMA) would assume the role for the postemergency response.

Process Safety Management of Highly Hazardous Chemicals (29 CFR 1910.119). Issued by OSHA in 1992, this regulation

applies mainly to hazardous materials manufacturing facilities, such as refineries and chemical plants. Other affected sectors include natural gas liquids, farm product warehousing, electric, gas, and sanitary services.

The requirements apply to companies that deal with any of more than 130 specific toxic and reactive chemicals in EPA-listed quantities. It also applies to flammable liquids and gases in quantities greater than 10,000 lb (4540 kg).

The regulation includes the following major requirements:

1. *Process safety information* must include information on the hazards of the highly hazardous chemicals used or produced by the process, information on the technology of the process, and information on the equipment in the process.
2. *Process hazards analysis* must include an initial process analysis (hazard evaluation) appropriate for the complexity of the process and must identify, evaluate, and control the hazards involved.
3. *Written operating procedures* must be developed and implemented that provide clear instructions for safely conducting activities involved in each process. Procedures must address initial startup and shutdown, operating limits, and safety and health considerations.
4. *Employee participation* must be solicited on the conduct and development of process management.
5. *Training programs* must include initial employee training on health and safety hazards, refresher training provided at least every three years on current operating procedures, and a training documentation program. The regulation also applies to contractors performing maintenance, repair, renovation, or specialty work on a process.
6. *Prestartup safety review* must be provided for new facilities and for modified facilities when the modification is significant enough to require a change in process safety.
7. *Mechanical integrity* must be provided for pressure vessels and storage tanks, piping systems, relief and vent systems and devices, emergency shutdown systems, controls and alarms, and pumps.
8. *Management of change* must be provided for written procedures to manage changes to process chemicals, technology, equipment, and so on.
9. *Incident investigation* must include a thorough investigation of incidents to identify the chain of events and causes, so that corrective measures can be developed and implemented.
10. *Emergency planning and response procedures* must be provided for handling spills and releases at the facility.
11. *Compliance audit* must be provided that includes mandatory process safety management reviews every three years to verify that procedures are adequate and being followed.

Risk Management Programs for Chemical Accidental Release Prevention (40 CFR Part 68). Promulgated under amendments to the Clean Air Act, this regulation requires that facilities that manufacture, process, use, store, or otherwise handle certain regulated substances above established threshold values develop and implement Risk Management Programs (RMPs). The regulation is similar in scope to the OSHA Process Safety Management (PSM) standard, with the primary focus being community safety as opposed to employee safety.

Risk Management Programs consists of the following three elements:

1. *Hazard assessment* of the facility, including the worst-case accidental release and an analysis of potential off-site consequences
2. *Prevention program,* which addresses safety precautions, maintenance, monitoring, and employee training; EPA believes that the prevention program should adopt and build upon the OSHA Process Safety Management standard
3. *Emergency response considerations,* including facility emergency response plans, informing public and local agencies, emergency medical care, and employee training

State Regulations

Each of the 50 states and the two U.S. territories maintain an enforcement agency that has responsibility for hazardous materials. The three key players in each state usually consist of the (1) state fire marshal, (2) state Occupational Safety and Health Administration, and (3) State Department of the Environment (sometimes known as Natural Resources or Environmental Quality). Although there are many variations, the state fire marshal is typically responsible for the regulation of flammable liquids and gases, due to the close relationship between the flammability hazard and the fire prevention code; the state environmental agency would be responsible for the development and enforcement of environmental safety regulations.

Most states have the equivalent of the federal OSHA. Approximately 23 states and two U.S. territories have adopted the federal OSHA regulations as state law. State governments also maintain an environmental enforcement agency that usually enforces the federal RCRA, CERCLA, and CAA laws at the local level. Increased state involvement in hazardous materials waste regulatory enforcement has significantly increased the number of hazardous materials incidents reported. This increase is expected to continue in the future and will generate more fire service activity at the local level in both enforcement and response.

VOLUNTARY CONSENSUS STANDARDS

Voluntary consensus standards are normally developed through professional organizations or trade associations as a method of improving the individual quality of a product or system. Within the emergency response community, NFPA is recognized for its role in developing consensus standards and recommended practices that impact fire safety and hazardous materials operations. In the United States, standards are developed primarily through a democratic process, whereby a committee of subject specialists representing varied interests writes the first draft of the standard. The document is then submitted to either a larger body of specialists or the general public, who then may amend, vote on, and approve the standard for publication. This procedure is known as the consensus standards process.

When a consensus standard is completed, it may be voluntarily adopted by government agencies, individual corporations, or organizations. Many hazardous materials consensus standards are also adopted as a reference in a regulation. In effect, when a federal, state, or municipal government adopts a consensus standard by reference, the document becomes a regulation.

Standards developed through the voluntary consensus process play an important role in increasing both workplace and public safety. Historically, a voluntary standard improves over time, as each revision reflects recent field experience and adds more detailed requirements. As users of the standard adopt it as a way of doing business, the level of safety gradually improves over time.

Voluntary consensus standards provide a way for individual organizations and corporations to self-regulate their business or profession. All of the national fire codes in the United States are developed through the voluntary consensus standards process; the two most active associations are (1) NFPA and (2) Western Fire Chiefs Association. Standards developed by these two associations address many hazardous materials issues, including hazardous materials storage and handling, personal protective clothing and equipment, and hazardous materials professional competencies.

NFPA Standards

NFPA has over 60 individual hazardous materials–related voluntary consensus standards. These standards are developed through the committee process, according to NFPA rules and procedures.

NFPA's hazardous materials standards are widely used by both industry and public safety organizations as recommended practices for inspection, safe handling, and installation, and so on. They do not have the force of law unless they are adopted by a government agency. For example, state governments that have approved state OSHA plans under Section 18b of the Occupational Safety and Health Act of 1970 must adopt standards to enforce requirements that are at least as effective as federal requirements.

The current OSHA regulations on flammable and combustible liquids adopt NFPA 30, *Flammable and Combustible Liquids Code,* by reference. Consequently, although NFPA does not specifically write regulations, NFPA standards often result as law through a similar adoption process.

Unfortunately, the pace of revising and updating federal and state regulations lags behind the development and approval of revised NFPA standards. Many state regulations that have adopted NFPA standards, such as NFPA 30 and NFPA 58, *Liquefied Petroleum Gas Code,* have adopted editions that are 5 to 10 years behind current editions. Most consensus standards reflect current and accepted practices, as opposed to "cutting-edge" technology, practices, and procedures. This means that an organization that adopts a 2003 edition of a standard, as a local or state regulation, is actually adopting a standard that may not be based on the most recent technology.

The following list summarizes current NFPA hazardous materials–related standards. They have been categorized by the authors for easier reference by the standards users and are not necessarily grouped by committee responsibility.

Flammable Liquids Related Standards

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*
NFPA 34, *Standard for Dipping and Coating Processes Using Flammable or Combustible Liquids*
NFPA 326, *Standard for the Safeguarding of Tanks and Containers for Entry, Cleaning, or Repair*
NFPA 329, *Recommended Practice for Handling Releases of Flammable and Combustible Liquids and Gases*
NFPA 385, *Standard for Tank Vehicles for Flammable and Combustible Liquids*

Flammable Gases Related Standards

NFPA 51A, *Standard for Acetylene Cylinder Charging Plants*
NFPA 54, *National Fuel Gas Code*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 59, *Utility LP-Gas Plant Code*
NFPA 59A, *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*
NFPA 306, *Standard for the Control of Gas Hazards on Vessels*

Dusts and Powders Related Standards

NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*

Explosives and Reactive Chemicals Standards

NFPA 35, *Standard for the Manufacture of Organic Coatings*
NFPA 51, *Standard for the Design and Installation of Oxygen–Fuel Gas Systems for Welding, Cutting, and Allied Processes*
NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres*
NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 430, *Code for the Storage of Liquid and Solid Oxidizers*
NFPA 432, *Code for the Storage of Organic Peroxide Formulations*
NFPA 490, *Code for the Storage of Ammonium Nitrate*
NFPA 495, *Explosive Materials Code*
NFPA 498, *Standard for Safe Havens and Interchange Lots for Vehicles Transporting Explosives*
NFPA 655, *Standard for Prevention of Sulfur Fires and Explosions*
NFPA 1124, *Code for the Manufacture, Transportation, Storage, and Retail Sales of Fireworks and Pyrotechnic Articles*

Nuclear Standards

NFPA 801, *Standard for Fire Protection for Facilities Handling Radioactive Materials*

NFPA 805, *Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants*

Facilities and Related Manufacturing Standards

NFPA 30B, *Code for the Manufacture and Storage of Aerosol Products*
NFPA 32, *Standard for Drycleaning Plants*
NFPA 36, *Standard for Solvent Extraction Plants*
NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 820, *Standard for Fire Protection in Wastewater Treatment and Collection Facilities*

Electrical Standards

NFPA 70, *National Electrical Code®*
NFPA 77, *Recommended Practice on Static Electricity*
NFPA 79, *Electrical Standard for Industrial Machinery*
NFPA 110, *Standard for Emergency and Standby Power Systems*
NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment*
NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*
NFPA 499, *Recommended Practice for the Classification of Combustible Dusts and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*
NFPA 780, *Standard for the Installation of Lightning Protection Systems*

Emergency Response Standards

NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents*
NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents*
NFPA 473, *Standard for Competencies for EMS Personnel Responding to Hazardous Materials Incidents*
NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*
NFPA 1991, *Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies*
NFPA 1992, *Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies*

Relevant Standards

NFPA 72®, National Fire Alarm Code®
NFPA *101®*, *Life Safety Code®*
NFPA 434, *Code for the Storage of Pesticides*

Hazardous Materials Emergency Response Standards. Within the hazardous materials community there are three major consensus standards that have been widely accepted as the baseline standard for hazardous materials response teams, as follows:

1. NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents*
2. NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials Incidents*
3. NFPA 473, *Standard for Competencies for EMS Personnel Responding to Hazardous Materials Incidents*

As the titles imply, these standards primarily address the emergency response and field operational aspects of hazardous materials. Nevertheless, they provide an excellent basis for developing hazardous materials inspection and enforcement personnel.

NFPA 471, Recommended Practice for Responding to Hazardous Materials Incidents. The document covers planning procedures, policies, and application of procedures for incident levels, personal protective clothing and equipment, decontamination, safety, and communications. The purpose of NFPA 471 is to outline the minimum requirements that should be considered when dealing with responses to hazardous materials incidents and to specify operating guidelines.

NFPA 472, Standard for Professional Competence of Responders to Hazardous Materials Incidents. The purpose of NFPA 472 is to specify minimum competencies for those who will respond to hazardous materials incidents. The overall objective is to reduce the number of accidents, injuries, and illnesses during response to hazardous materials incidents and to prevent exposure to hazardous materials to reduce the possibility of fatalities, illnesses, and disabilities affecting emergency responders.

It is important to recognize that NFPA 472 covers all hazardous materials emergency responders from both the public and private sector.

NFPA 472 provides competencies for the following levels of hazardous materials responders. These levels parallel those listed within OSHA 1910.120, with the exception that the hazardous materials specialist has been deleted and the specialist employee has been expanded on and clarified, as follows:

1. *First responders at the awareness level.* These are individuals who, in the course of their normal duties, may be the first on scene of an emergency involving hazardous materials. They are expected to recognize the presence of hazardous materials, protect themselves, call for trained personnel, and secure the area.

2. *First responders at the operations level.* These are individuals who respond to releases or potential releases of hazardous materials as part of the initial response to the incident for the purpose of protecting nearby persons, the environment, or property from the effects of the release. They must be trained to respond in a defensive fashion to control the release from a safe distance and keep it from spreading.

3. *Hazardous materials technicians.* These are individuals who respond to releases or potential releases of hazardous materials for the purpose of controlling the release. Hazardous materials technicians are expected to use specialized chemical protective clothing and specialized control equipment (Figure 13.6.3).

4. *Incident commander.* This is the person who is responsible for directing and coordinating all aspects of a hazardous materials incident.

FIGURE 13.6.3 Hazardous Materials Technicians Cleaning Up a Spill in EPA Personal Protective Clothing

5. *Private sector specialist employee.* These are individuals who, in the course of their regular job duties, work with or are trained in the hazards of specific materials and/or containers. In response to incidents involving chemicals, they may be called on to provide technical advice or assistance to the incident commander relative to their area of specialization. The following are three levels of private sector specialist employees:

a. Level C are those persons who may respond to incidents involving chemicals and/or containers within their organization's area of specialization. They may be called on to gather and record information, provide technical advice, and/or arrange for technical assistance consistent with the organization's emergency response plan and standard operating procedures. The individual is not expected to enter the hot/warm zone at an incident.
b. Level B are those persons who, in the course of their regular job duties, work with or are trained in the hazards of specific chemicals or containers within their organization's area of specialization. Because of their education, training, or work experience, they may be called on to respond to incidents involving chemicals. The Level B employee may be used to gather and record information, provide technical advice, and provide technical assistance (including working within the hot/warm zone) at the incident consistent with the organization's emergency response plan and standard operating procedures and the local emergency operations plan.
c. Level A are those persons who are specifically trained to handle incidents involving chemicals and/or containers for chemicals used in their organization's area of specialization. Consistent with the organization's emergency response plan and standard operating procedures, the Level A employee must be able to analyze an incident involving chemicals within the organization's area of specialization, plan a response to that incident, implement the planned response within the capabilities of the resources available, and evaluate the progress of the planned response (Figure 13.6.4).

NFPA 473, Standard for Competencies for EMS Personnel Responding to Hazardous Materials Incidents. The purpose of NFPA 473 is to specify minimum requirements of competence and to enhance the safety and protection of response personnel and all components of the emergency medical services system. The overall objective is to reduce the number of EMS personnel accidents, exposures, injuries, and illnesses resulting from hazardous materials (HM) incidents. The following are the two levels of EMS/HM responders:

1. *EMS/HM Level I.* Persons who, in the course of their normal duties, may be called on to perform patient care activities in the cold zone at a hazardous materials incident. EMS/HM Level I responders provide care to only those individuals who no longer pose a significant risk of secondary contamination. Level I includes different competency requirements for basic (BLS) and advanced life support (ALS) personnel.

2. *EMS/HM Level II.* Persons who, in the course of their normal duties, may be called on to perform patient care activities in the warm zone at a hazardous materials incident. EMS/HM Level II responders may provide care to those individuals who still pose a significant risk of secondary contamination. In addition, personnel at this level must be able to coordinate EMS activities at a hazardous materials incident and provide medical support for hazardous materials response personnel. Level II includes different competency requirements for basic (BLS) and advanced life support (ALS) personnel.

NFPA Technical Committee on Hazardous Materials Protective Clothing and Equipment (NFPA 1991, NFPA 1992, NFPA 1994). This technical committee is responsible for the development of standards and documents pertaining to the use of personal protective clothing and equipment (excluding respiratory protection) by emergency responders at hazardous materials incidents. The committee scope includes personal protective equipment (PPE) selection, care, and maintenance.

The following three hazmat protective clothing standards have been developed:

FIGURE 13.6.4 NFPA 472 Level A Private Sector Specialist Employees Handling a Hazardous Materials Incident

1. NFPA 1991, *Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies*
2. NFPA 1992, *Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies*
3. NFPA 1994, *Standard on Protective Ensembles for First Responders to CBRN Terrorism Incidents*

Other Standards Organizations

There are many other important standards-writing bodies that develop hazardous materials safety and emergency response–related standards. The more significant organizations include the American Society of Mechanical Engineers (ASME), the American Society for Testing and Materials (ASTM), the American Petroleum Institute (API), the Compressed Gas Association (CGA), and the Safety Equipment Institute (SEI). Each of these organizations approves or creates standards, ranging from hazardous materials container design to personal protective clothing and equipment. Standards produced by these groups usually follow the standards development guidelines of the American National Standards Institute (ANSI). ANSI is an approval body and is recognized by the International Organization for Standardization (ISO).

SUMMARY

This chapter is aimed at the fire department prevention and enforcement specialist who needs to understand the fundamentals of hazardous materials laws, regulations, and standards. The chapter began by defining the term *hazardous materials* and continued with a discussion of the key elements of a hazardous materials prevention and enforcement program. The rest of the chapter was devoted to an overview of the major federal laws and regulations governing hazardous materials and the main hazardous materials codes and standards

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Chapter 7

Aircraft Rescue and Fire Fighting (ARFF)

Jack Kreckie

Modern aircraft have evolved from the early days when gliders were crafted of wood and stretched fabric. This evolution has occurred rather swiftly since the Wright Brothers' first successful flight from Kitty Hawk in 1903. In a century, aviation has evolved from wind-powered aircraft (gliders), to man-powered aircraft (using pedals or cranks), to piston engine-driven propellers, to turbo props and jets. The days of supersonic transport (SST) have given way to the era of new large aircraft (NLA). These mammoth aircraft can be configured to carry over 800 passengers in double-deck cabins. Statistically, aviation is very safe. There are, however, certain risks associated with air travel. Mechanical failure, human error, and weather add an undeniable risk that a small percentage of commercial aircraft will be involved in aircraft incidents and accidents. The primary responsibility of aircraft rescue and fire-fighting (ARFF) personnel is to provide for the safety of all aircraft passengers at aircraft incidents that occur at an airport. This specialized career continues to become increasingly more complex.

This chapter discusses the mission of aircraft rescue fire fighters and provides an explanation of the tools, techniques, agents, and objectives that are used to satisfy that mission. Also provided is a review of the regulations and industry standards that influence the levels of training, staffing, and equipment at airports as well as information to help the reader gain an understanding of typical aircraft emergencies and ARFF response procedures.

See also Section 6, Chapter 2, "Combustion Products and Their Effects on Life Safety"; and Section 13, Chapter 2, "Organizing Rescue Operations."

OVERVIEW

Aircraft Rescue and Fire-Fighting (ARFF) Mission

Federal regulations and industry standards determine the minimum requirements for aircraft rescue and fire fighting (ARFF) at airports. ARFF fire fighters put these regulations and standards to practical use. The primary ARFF mission is to protect the lives of the flying public. However, airport fire fighters work under a variety of structures. Some are members of municipal or state-run fire departments that serve the community in which the airport is located. The airport assignment might be a bid position or one attained through seniority. Other airport fire departments are staffed by employees of the Airport Authority or Port Authority that holds the operating certificate for the airport. Private-contract fire departments are also used by a small number of airports, whereas military or federal fire fighters staff bases and mixed military-civil airfields.

In terms of total mission, there are several variables as well. Small airports might support the ARFF requirements using employees who serve dual roles. Maintenance, security, or airport operations personnel are often cross-trained to satisfy the requirements of the regulations governing

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Key Terms

aircraft accident, aircraft fire fighting, aircraft rescue, aircraft rescue and fire-fighting (ARFF), aircraft rescue and fire-fighting vehicle, airport fire fighter, Federal Aviation Administration (FAA), International Civil Aviation Organization (ICAO), National Transportation Safety Board (NTSB), personal protective equipment (PPE), practical critical fire area (PCA), rapid response area, response time, theoretical critical fire area (TCA)

ARFF. Some airport departments are responsible for "all hazards," including structural, EMS, hazmat, confined space, technical rescue, and water rescue. Other departments handle only the ARFF response and depend on off-airport response for other types of emergencies. Dual-role departments, typically called public safety officers, provide both law enforcement and fire department functions. The argument as to which approach is better will never be satisfied. Regardless of how the service is provided, all ARFF fire fighters and the apparatus they depend on must meet the qualifications and requirements of the regulatory authority having jurisdiction.

The underlying mission of aircraft rescue fire fighters has not changed. Fire fighters, by their very nature, will exhaust every resource and their last ounce of energy to rescue the people they are sworn to protect. What has evolved over time, however, are the methods, agents, expertise, and equipment they use to satisfy that mission.

Aircraft Construction Design and Materials

The "jet age" arrived in 1958. Pan American Airways led the way with the introduction of the Boeing 707 as the first U.S. passenger jet. The B-707 burned kerosene fuel, which was half the cost of the high-octane gasoline used in more traditional planes of the era. The jet engines proved more reliable than the piston-driven engines and could carry up to 180 passengers traveling at speeds of up to 550 miles per hour.

The evolution of this new era continued with the introduction of wide-body (two aisles) jets. The Boeing 747 arrived in 1969, followed by the MacDonnell Douglas DC-10 and the Lockheed L-1011 in 1970. With the introduction of jet aircraft, injury and fatality rates relative to survivable accidents have increased. This increase was found to be largely attributable to seats, overhead bins, cabin partitions, and other cabin interior furnishings breaking loose at relatively low-impact loads. An example of a low-impact load incident could be a controlled descent terminating in a landing without landing gear deployed or a landing in a field or on other nonpaved irregular terrain. The resulting conditions injured or trapped occupants, thereby impeding or preventing their escape.

Since the arrival of the jet age, a great deal of attention has been paid to increasing survivability through aircraft construction design and materials. Composite materials have been developed that provide increased strength at lower weight; interior fabrics and finishes must meet more stringent flammability testing; and a layer of fire-resistive fabric has been added in seat construction to further reduce the risk to passengers in the event of a cabin fire.

Modern aircraft are now built with a number of redundant systems. Designs that incorporate redundant systems provide a margin of safety for incidents or accidents caused by mechanical failure. In such cases when a mechanical failure occurs, a backup system takes over, and the flight terminates safely.

Hazards and Risk

The hazards associated with aircraft vary with the size and type of loading of the particular flight. As is the case in structures, the risk is increased or decreased depending on the aircraft's contents and occupancy. Each offers its own set of unique challenges and risks for its occupants and for ARFF responders. Large aircraft carrying hundreds of passengers, small military aircraft carrying ordinance, cargo aircraft loaded with freight that may include manifested or unmanifested hazardous materials, general aviation, helicopters, and ultralights are all in the air, and all experience in-flight emergencies on a regular basis (Figure 13.7.1).

The one element that exists in every powered aircraft is fuel. The fire service prepares for the worst-case scenario based on greatest risk. This risk for occupants of a survivable crash is exposure to fire and the products of combustion from a fuel fire.

Escape Time and Survival Time

For passengers on board an aircraft involved in fire, time is the enemy. From the time of the crash or the outbreak of fire, the survival clock begins ticking. Human tolerance is a measurable effect. In 1965, Don W. Conley prepared a report for the Federal Aviation Administration (FAA) titled, " Post Crash Fire Fighting

(a)

(b)

FIGURE 13.7.1 (a) American Airlines, Boeing 757 Beginning Its Takeoff Roll at Boston Logan International Airport; (b) Aircraft Lining Up on Taxiway Awaiting Their Turn for the Departure Runway (Source: Courtesy of Rudy Chiarello)

Studies on Transport Category Aircraft."[1] Among the research items presented is a study on the parameters of human tolerance. ARFF fire fighters know it is crucial to remove victims from a toxic or dangerous environment or to remove the dangers and toxins from the victim's environment before the limits of human tolerance are reached. Understanding what those limits are is helpful for a better understanding of the urgency and complexity of the ARFF mission.

Escape Time. In a number of documented survivable crashes involving fire, occupants have escaped the hostile environment by their own means. Those surviving the impact have a certain period of time during which they can escape before being overcome by one of the life-threatening hazards of a postcrash fire. The amount of time available, which has been termed *escape time*, varies depending on the type of aircraft, the crash severity, and a variety of other conditions. Escape time is defined in the Conley study as "the elapsed time from the instant fire began to the instant when a human tolerance limit (based on heat or carbon monoxide) was reached that could cause an inability to escape on the part of the would-be occupant." The study calculates escape time and survival time in a number of categories. Each illustrates how little time an ARFF fire fighter has to effectively rescue an occupant who was unable to escape on his or her own.

Survival Time. The most dramatic of the findings relative to human tolerance levels or unbearable pain were data taken from a crash test program conducted by the National Advisory Committee on Aeronautics (NACA) in the early 1950s and referenced in the Conley study. During a fire test on a C-97, the temperature inside the aircraft cabin remained at 70°F (21.1°C) while the spill fire burned for 2 minutes. This occurred as a result of cabin insulation and closed major hatches. At 130 seconds, burn-through occurred and the temperatures soared. At 138 seconds, the temperature reached unsurvivable temperatures.

Many efforts have been made since the days of the Conley study to improve aircraft construction, insulation, and fire block material. In modern transport aircraft, the sidewall panels, partitions, overhead bins, and ceiling panels are typically composite assemblies with a Nomex core, phenolic-impregnated fabric facesheets, and colored thermoplastics. Seat fire-blocking is often polybenzimiazole or a blend of Nomex and Kevlar. All of these efforts are dedicated to improving cabin safety and increasing survival time. Ultimately, once the fire enters the cabin as a result of impingement and burn-through, an open door, or a hull fracture from the impact, the survival clock ticks faster than one can act.

With this in mind, it is understandable why the mission of an ARFF fire fighter is so critical and why lifesaving actions are measured in seconds. Seconds saved through training, technology, methods, and skills translate into lives saved at an aircraft accident.

ARFF REGULATORY AND STANDARD-DEVELOPING ORGANIZATIONS

As aircraft evolve, obviously so must the regulations that identify the minimum standard for ARFF equipment, personnel, and fire-fighting agents at airports around the world.

Federal Aviation Administration (FAA)

In 1970, the FAA administrator was given the statutory authority to issue airport operating certificates. This authority, found in Title 49, United States Code (U.S.C.) Section 44706, Airport Operating Certificates, was used to establish minimum safety standard requirements for the operation and certification of certain U.S. airports. Title 14, Code of Federal Regulation (CFR) Part 139 (14 CFR 139), *Certification and Operations: Land Airports Serving Certain Air Carriers*, spells out these requirements.

This statutory authority, which was limited to land airports serving passenger operations of an air carrier conducted with aircraft having a seating capacity of more than 30 passengers, was broadened by the FAA Reauthorization Act of 1996. The act allowed the FAA to certificate airports that serve any scheduled passenger air carrier operations operating aircraft designed for more than nine passenger seats. Alaska, however, is exempt from this authority.

International Civil Aviation Organization (ICAO)

In addition to the FAA for U.S-certificated airports, the International Civil Aviation Organization (ICAO), a specialized agency of the United Nations, was created on December 7, 1944, at the convention on International Civil Aviation in Chicago, to set international aviation standards. One of ICAO's principal goals is the establishment of international standards, recommended practices, and procedures covering the technical fields of aviation including aircraft rescue and fire fighting (ARFF), search and rescue, and aircraft accident investigation. These standards (related to ARFF) are under constant review and amended, as necessary, by the ICAO Rescue and Fire Fighting Study Group (RFFSG).

National Fire Protection Association (NFPA)

The NFPA develops standards relative to ARFF but the NFPA standards are not always in total agreement with the minimum standards set forth by the FAA. At every meeting of the groups that review federal aviation regulations, NFPA standards, and ICAO standards, there is a desire to harmonize the documents. Given the differences in the documents, it is difficult to have standardized equipment or training for all airports. Manufacturers of ARFF equipment struggle with different requirements for FAA-funded equipment and international customers.

REGULATORY REQUIREMENTS AND STANDARDS

Title 14 Code of Federal Regulations Part 139[2] lists the current U.S. requirements for ARFF personnel, agent quantities, response times, and related topics. "The Rule" is issued by the FAA and compliance is measured by the FAA's regional office, which dispatches a certification inspector to evaluate ARFF equipment, personnel, and training records. Failure to meet the minimum standards of 14 CFR Part 139 could threaten an airport's operating certificate.

Some of the key sections of Part 139 that are specifically related to ARFF are the airport certification manual, personnel requirements, and airport index determination. Comparisons of key differences between FAA, ICAO, and NFPA requirements and guidance are shown in Table 13.7.1.

Airport Certification Manual (ACM)

As set forth in Section 139.205, maintaining an ACM is one of the requirements for an airport certificate holder. The ACM must contain a description of how each requirement of Part 139 is satisfied. Included in that list of requirements are:

- A grid map or other means for identifying airport locations and terrain features that are significant for emergency operations
- A description of facilities, equipment, personnel, and procedures for meeting the rescue and fire-fighting requirements in Sections 139.317 and 139.319
- Procedures for complying with the requirements of Part 139.321, relating to hazardous materials and substances
- An emergency plan, as required by Section 139.325

Personnel

"The Rule" does not prescribe specific minimum staffing numbers. Section 139.303 does, however, require

That sufficient rescue and fire fighting personnel be available during all air carrier operations to operate the vehicles, meet the response times, and meet the minimum fire fighting agent discharge rates specified within the regulation.

Airport Index

As set forth in Section 139.315, an airport index is currently determined with a formula based on the overall length of the aircraft servicing the airport and the number of daily departures of that aircraft. If there are five or more average daily departures of air carrier aircraft in a single group serving that airport, the longest index group with an average of five or more daily departures is the index required for the airport.

If there are less than five average daily departures of air carrier aircraft in a single index group serving that airport, the next lower index from the longest index group with air carrier aircraft in it is the index required for the airport. The minimum designated index is Index A. The airport index (A through E) is determined through this formula; the minimum number of ARFF vehicles and quantities of agent carried are based on the index. A provision in 14 CFR Part 139.319 (ARFF Operational Requirements) allows for a reduction in rescue and fire-fighting capabilities.

TABLE 13.7.1 Comparison of ARFF Index Requirements of FAA, ICAO, and NFPA

FAA Index	*Aircraft Length*	*ICAO Cat.*	*Aircraft Length up to But Not Including*	*Aircraft Width up to But Not Including*	*NFPA Cat.*	*Aircraft Length up to But Not Including*	*Aircraft Width up to But Not Including*	*Sample Aircraft*
GA-1	NA	1	29 ft (9 m)	6.6 ft (2.00 m)	1	30 ft (9.0 m)	6.6 ft (2.00 m)	Cessna 182
GA-1	NA	2	39 ft (12 m)	6.6 ft (2.00 m)	2	39 ft (12.0 m)	6.6 ft (2.00 m)	Cessna Caravan
GA-2	NA	3	59 ft (18 m)	9.8 ft (3.00 m)	3	59 ft (18.0 m)	9.8 ft (3.00 m)	Cessna 404
A	<90 ft (28.0 m)	4	78 ft (24 m)	13.1 ft (4.00 m)	4	78 ft (24.0 m)	13.0 ft (4.00 m)	EMB120
A	<90 ft (28.0 m)	5	91 ft (28 m)	13.1 ft (4.00 m)	5	90 ft (28.0 m)	13.0 ft (4.00 m)	CRJ-200, Saab 340
B	90–126 ft (28–39 m)	6	127 ft (39 m)	16.4 ft (5.00 m)	6	126 ft (39.0 m)	16.4 ft (5.00 m)	DC-9, A320
C	126–159 ft (39–49 m)	7	160 ft (49 m)	16.4 ft (5.00 m)	7	160 ft (49.0 m)	16.4 ft (5.00 m)	B757-200; B767-200ER
D	159–200 ft (49–61 m)	8	200 ft (61 m)	22.9 ft (7.00 m)	8	200 ft (61.0 m)	23.0 ft (7.00 m)	A300, B757-300
E	>200 ft (61 m)	9	249 ft (76 m)	22.9 ft (7.00 m)	9	250 ft (76.0 m)	23.0 ft (7.00 m)	A340-600, B777
		10	295 ft (90 m)	26.2 ft (8.00 m)	10	295 ft (90.0 m)	25.0 ft (8.00 m)	AN-225, A380

Source: *Final Recommendation to ARAC, Airport Certification Issues Group Relative to 14 CFR Part 139, Subpart D, March 2004 (6),* Table 2; Paper produced for the U.S. Department of Transportation, Federal Aviation Administration, by the Aviation Rulemaking Advisory Committee, Airport Certification Issues Group, ARFF Requirements Working Group.

> (c) During air-carrier operations with only aircraft shorter than the Index aircraft group required by paragraph (a) of this section, the certificate holder may reduce the rescue and fire fighting to a lower level corresponding to the Index group of the longest air carrier aircraft being operated.

This reduction in requirements is known as the remission factor. The remission factor was incorporated into regulatory language to reduce the financial burden for airports that have a low frequency of flight operations for the longest aircraft conducting scheduled operations at that airport. In January 2005, ICAO eliminated the remission factor from its standard. NFPA 403, *Standard for Aircraft Rescue and Fire-Fighting Services at Airports,* has no provision for remission. Table 13.7.1 provides comparisons among the requirements of the FAA, ICAO, and NFPA.

ARFF AGENTS

Original Quantity-Determining Formula

Determining the quantities of agent required to control or extinguish an aircraft fire must be approached using science, logic, historical data, and repeatable tests. Formulas derived from this process must be adaptable to different-sized aircraft. The theoretical critical area (TCA)/practical critical area (PCA) methodology has survived the test of time and remains the standard over three decades after its introduction. This is not to say that these formulas are adopted by every regulation or standard.

Current debate may require some expansion or modifications to these formulas. Some form of change needs to be brought about to sufficiently provide agent quantities for new large aircraft (NLA). Full-length, double-deck aircraft, like the Airbus Industries A-380, have drawn attention to the fact that the formula assumes a standard height when the number of gallons required for ARFF is determined. This assumption is not reasonable.

The Boeing 747 was the first aircraft with a double deck cabin. However, the original double deck was seen as a "bump" on the front of the fuselage, with a spiral staircase leading to a lounge or small seating area. It was seen as a novelty and never raised a flag as to whether tactical ARFF challenges or minimum agent requirements needed to be reconsidered. Typically, these aircraft flew into only larger airports, which usually maintain more than the minimum required quantities of agent.

Over the years, Boeing introduced new models of the 747, and the second deck grew to greater lengths. Finally, with the introduction of the A-380, the ARFF industry realized it could no longer treat variations in height as rare exceptions of no practical significance.

The number of ARFF vehicles and the minimum quantities of agent required at each index or category of airports are directly related to the ARFF departments' ability to control and/or extinguish an aircraft fire. FAA requirements and requirements mandated in standards established by the NFPA and ICAO differ significantly. To understand the rationale used to determine the actual quantities needed, a review of the historical and technical basis of TCA/PCA methodology employed by the NFPA since the early 1970s is helpful.

Theoretical Critical Area/Practical Critical Area (TCA/PCA) Methodology

Critical Fire Area. The critical area concept was used as a method for determining a level of protection for aircraft of every size. This was the minimum area that was to be protected post-crash to permit safe evacuation of the occupants of an aircraft. The critical fire area is a rectangle with its size determined by using a formula based on the length and width of the aircraft. This method of determining minimum agent quantities does not consider tactical fire attack challenges or conditions. It is simply a repeatable formula that could be applied to any category of aircraft. It is not intended to represent the minimum, average, or maximum fire area based on spill size. NFPA 403 defines *theoretical critical area (TCA)* as

> The fire area adjacent to the aircraft that must be controlled to ensure temporary fuselage integrity and to provide an occupant escape area.

The theoretical critical area served only to categorize aircraft by size and the area of the potential fire hazard that could become involved.

The data on hand indicated that the practical critical area (PCA) was approximately two-thirds of the TCA. NFPA 403 defines *practical critical area (PCA)* as

> The area used to calculate minimum agent quantities and flow rates. The PCA is defined as 2/3 of the size of the TCA, as determined by the ICAO RFFP-II committee.

Discharge and Application Rates. Once the area to be protected was determined, the ICAO RFFP-1 (Rescue and Fire Fighting Panel) began to focus on discharge rates and extinguishing agents during its first meeting in March 1970.[3] In order to determine quantities of agent needed, it was necessary to calculate the rate of discharge and the time required to control and/or extinguish the fire. The RFFP-1 determined that control and extinguishment needed to be considered separately. *Control time* is defined as the time required from the arrival of the first fire-fighting vehicle to the time the intensity of the fire is reduced by 90 percent. *Extinguishment time* is the time required from the arrival of the first fire-fighting vehicle to the time the fire is completely extinguished.

At the time of these studies, protein fire-fighting foam was typically carried. The committee based its recommendations on protein foam but acknowledged that when dual-agent attacks were utilized (foam and dry chemical, CO_2, or a halocarbon), a reduced application rate could be used.

In June 1972, the ICAO Rescue and Fire Fighting Panel met for a second time (RFFP-2). During these deliberations, an application rate of 0.13 U.S. gpm/ft^2 for aqueous film-forming foam (AFFF) was found to be suitable.[4] This application rate is still used for AFFF. The RFFP-2 also confirmed the application rate of 0.15 U.S. gpm/ft^2 for protein foam that was recommended by RFFP-1.

Additional Quantity-Determining Formulas

In determining the quantities of agent(s) required, additional formulas were agreed upon. The quantities required for each milestone in a tactical event are identified and calculated separately. These quantities are expressed as *Q1* and *Q2*.

Quantity *Q1*. Quantity *Q1* is the quantity required to obtain a 1-minute control time in the PCA. The formula for the water required for control (*Q1*) in the PCA is expressed as

$$Q1 = PCA \times R \times T$$

where

PCA = Practical critical area

R = Rate of application for specific foam

T = Time of application

Quantity *Q2*. Quantity *Q2* is the quantity required for maintaining control of the fire after the first minute, or as required for total extinguishment, or both. The RFFP-2 recognized that the exact quantity for *Q2* could not be accurately determined without considering a number of variables. These variables, expressed as *f* in calculating formulas, were assigned values for each category airport based on maximum gross weight, maximum passenger loads, maximum fuel loads, and analysis of previous aircraft rescue and fire-fighting operations.

$$Q2 = f \times Q1$$

The RFFP-2 used these factors (*f*) to determine *Q2* values for each airport category. The range of values for *f* ranged from 3 percent to 170 percent for Category 1 through Category 8 airports, respectively.

Quantity Q3. This general process is still in use today with revisions made over the years. The most significant revision was the introduction of Q3 quantities needed for interior fire-fighting operations.

The values of Q3 are based on accepted waterflow requirements for the type of fire-fighting operations to be experienced when combating an interior aircraft fire. They are determined as follows:

Airport Category	*Q3 Equals (U.S. gal)*
1	0
2	0
3	60 gpm 5 min = 300 gal
4	60 gpm 10 min = 600 gal
5	125 gpm 10 min = 1250 gal
6	125 gpm 10 min = 1250 gal
7	125 gpm 10 min = 1250 gal
8	250 gpm 10 min = 2500 gal
9	250 gpm 10 min = 2500 gal
10	500 gpm 10 min = 5000 gal

Agent Quantity Totals (*Q*). NFPA standards define the total quantity of water (*Q*) as

$$Q = Q1 + Q2 + \text{Q3}$$

Beyond this basic introduction of calculating agent quantities, additional factors are introduced to calculate area based on actual aircraft size and category. NFPA 403 provides a comprehensive description of the process. Table 13.7.2 compares the agent quantities as required (or recommended) by the FAA, ICAO, and NFPA. The quantities listed under NFPA are the only quantities that include gallons required for Q3. It should be noted that, although ICAO used the PCA/TCA formulas to calculate agent quantities required, it reduced its quantities in Category 5 through Category 10 by 1000 gallons. This reduction was made to lessen the financial impact on airports.

TABLE 13.7.2 Agent/Quantity Comparison

		Water (U.S. Gallons)			
Category	*Index*	*ICAO Q1 + Q2*	*FAA Q1 + Q2*	*NFPA Q1+ Q2 + Q3*	*Example Aircraft*
1	GA-1	61	—	120	Cessna 206
2	GA-1	177	—	200	Cessna 414
3	GA-2	317	—	670	Beech 1900
4	A	634	100	1340	DHC-8-100
5	A	1427	100	2760	ATR-72
6	B	2087	1500	3740	B737-300; Emb-145
7	C	3197	3000	4880	B757
8	D	4808	4000	7780	A300; B767-300
9	E	6419	6000	9570	B747-200; A340-400
10		8533	—	14,260	AN-225; A380

Note: NFPA Agent Quantities include gallons required for Q3.

Source: *Final Recommendation to ARAC, Airport Certification Issues Group Relative to 14 CFR Part 139, Subpart D, March 2004 (6),* Table 4; Paper produced for the U.S. Department of Transportation, Federal Aviation Administration, by the Aviation Rulemaking Advisory Committee, Airport Certification Issues Group, ARFF Requirements Working Group.

Complementary Agent Requirements

In addition to the requirements for water and foam, complementary agent must also be carried. Every index airport is required to carry a minimum of 500 lb of dry chemical powder or 500 lb of clean (halogenated) streaming agent, Halon 1211, or Halotron.

Dry Chemical Agents. Dry chemical fire-extinguishing agents are available in a variety of chemical compounds. Potassium bicarbonate and potassium bicarbomate–based powders have proven effective in quickly extinguishing flammable liquid fires when applied at the proper rate and with the proper technique.

Halogenated/Halon Alternative Agents. Halogenated agents are hydrocarbons that have had one or more hydrogen atoms replaced by atoms from the halogen series, usually fluorine (F), bromine (Br), or chlorine (Cl). The extinguishing mechanism of halogenated agents seems to interfere with the combustion process. Halogenated agents are discharged as a liquefied gas, which allows excellent penetration of difficult-to-access areas. Because it leaves no residue, it is an excellent choice for fighting fires in avionics compartments, electronic or electrical components, and engine fires.

ARFF VEHICLES AND EQUIPMENT

Apparatus Features

Fire apparatus is designed to satisfy the needs of the particular mission it primarily serves. Aircraft rescue and fire-fighting apparatus is specifically designed to satisfy its primary mission, namely, response to aircraft incidents and accidents. ARFF vehicles must be designed and built to be compliant with the standards required by the customer. If the apparatus is being funded by the FAA, it must be in compliance with the FAA Advisory Circular 150/5220-10D, "Guide Specification for Aircraft Rescue and Fire Fighting Vehicles." Most U.S. manufacturers will not build a truck that is not compliant with the relevant NFPA standard, in this case, NFPA 414. ARFF vehicles have a number of specialized features that are not typically on structural fire apparatus.

Large Water Tanks. Large water tanks are a functional requirement of the ARFF mission. Because of the critical relationship between time and survival factors, establishing water supply prior to initiating fire attack is not practical. Fire hydrants are not readily available on most runway systems. A hydrant is considered an obstruction near a runway and, for safety purposes, must be located a distance away from the runway. Underground hydrants are available on some airfields but are not practical during initial fire attack because of their inaccessibility and time delays in opening manholes, as well as groundwater and drainage issues. ARFF crews "bring their water with them"; apparatus manufactured today are available with tank sizes ranging from 1000 to 4500 gal. Each truck also has foam quantities commensurate with the water tank size. The standards call for a double shot of foam, so that ARFF vehicles can discharge two tanks of water without having to reservice the foam tanks (Figure 13.7.2).

Aqueous film-forming foam (AFFF) is the standard foam used at airports. The FAA now requires the foam used at certificated airports to meet mil specification MIL-F-24385. The primary reason for this is to guarantee compatibility of foam concentrates. Ensuring compatibility is important for both bulk foam storage tanks and apparatus-mounted foam tanks.

Many ARFF departments have bulk foam storage tanks tied into rapid reservice facilities. In order to maintain sufficient reserve quantities of foam concentrate, the tanks are never emptied. When the reorder level is reached, the tank is topped off. If the foam concentrates are not compatible, all the foam in the tank could become contaminated through a reaction of the two products.

This same logic is used in the refill of apparatus-mounted foam tanks. Many training, testing, or fire-fighting evolutions will consume foam concentrate but not empty the foam tank. As the vehicle is reserviced, the foam tank is topped off. If the foam being added is not guaranteed to be compatible (as mil spec foam is), it is possible to contaminate all of the foam in the tank.

AFFF foam is mixed with water, using foam-proportioning systems installed on the apparatus. These systems automatically proportion the foam to the selected percentage based on the discharge or discharges opened. Foam discharges on an ARFF vehicle can include primary turret (Figure 13.7.3), secondary turret, high-reach extendible turret (HRET), piercing nozzles, hand lines, hose reels, and undertruck nozzles. The nozzles used are both aerated and nonaerated, per airport choice.

With regard to the debate on the environmental concerns of the use of this foam, all AFFF on the market is currently in compliance with EPA requirements. However, the FAA is looking for a "greener" alternative to AFFF, but so far nothing else is as effective.

FIGURE 13.7.2 Massport Fire Rescue Engine 7, Oshkosh T-B 3000 ARFF Vehicle with 3000-Gallon Water Tank and 420-Gallon Foam Tank Carrying 3 Percent AFFF Foam Concentrate (Source: Jack Kreckie)

FIGURE 13.7.3 Oshkosh T-1500 ARFF Vehicle Discharging Through Its Primary Roof Turret at a Training Fire (Source: Jack Kreckie)

TABLE 13.7.3 ARFF Vehicle Requirement Comparison

		Vehicles			
Category	*Index*	*ICAO*	*FAA*	*NFPA*	*Example Aircraft*
1	GA-1	1	NA	1	Cessna 206
2	GA-1	1	NA	1	Cessna 414
3	GA-2	1	NA	1	Beech 1900
4	A	1	1	1	DHC-8-100
5	A	1	1	2	ATR-72
6	B	2	1–2	2	B737-300; Emb-145
7	C	2	2–3	3	B757
8	D	3	3	3	A300; B-767-300
9	E	3	3	4	B747-200; A340-400
10		3		4	AN-225; A380

Source: *Final Recommendation to ARAC, Airport Certification Issues Group Relative to 14 CFR Part 139, Subpart D, March 2004 (6),* Table 7; Paper produced for the U.S. Department of Transportation, Federal Aviation Administration, by the Aviation Rulemaking Advisory Committee, Airport Certification Issues Group, ARFF Requirements Working Group.

"Pump and Roll" Capability. ARFF vehicles have "pump and roll" capability. This feature allows ARFF fire fighters to begin agent application prior to stopping the apparatus. The vehicle can be driven around the fire while agent is being discharged through turrets or undertruck nozzles. It also allows the truck to continue to pump for protection if a flowing fuel fire threatens the apparatus and its occupants and an escape becomes necessary.

Turrets. Traditionally, the primary turret on ARFF vehicles was located on the roof of the apparatus facing forward. Over the years, testing has been completed to evaluate the effectiveness of a low-attack, high-volume turret. These low-attack turrets, which are mounted below the windshield, have proven to be more effective than roof-mounted turrets. Fire fighters operating the newer turrets benefit by seeing the origin of their stream as well as the target. It also reduces the amount of agent falling on the windshield and obscuring the view.

Piercing Nozzles. Piercing nozzles are used to introduce agent into a fuselage without introducing oxygen to the fire through opening a door. Piercing nozzles are available as handheld tools attached to attack lines or mounted on high-reach extendible turrets (HRETs) operated by means of a joystick from the ARFF vehicle cab.

Vehicle Requirements

The number of vehicles required at an airport is driven by several factors. The minimum requirement of the regulatory authority provides a number based on the airport index or category, as illustrated in Table 13.7.3. If only the minimum number of vehicles is maintained at the airport, however, no provision exists for taking a piece of apparatus out of service for maintenance, repairs, or training. The size of the airport is a major factor. Some airports with large airfields maintain the minimum requirement of vehicles at each station in order to satisfy the timed response requirements for each runway.

RESPONSE TIME REQUIREMENTS

The successful mitigation of the effects of an aircraft accident depends on the successful completion of a number of actions. Swift notification with accurate location and conditions is critical. Time is the single most important factor to increase survivability of the occupants of an aircraft involved in a major accident. Requirements for response times to the scene of an accident are difficult to define or measure. Requirements for response are measured using known distances and conditions to demonstrate ability. The FAA, ICAO, and the NFPA all use different standards to establish response time requirements.

ICAO Standards and Recommendations

ICAO's International Standards and Recommended Practices (SARPs) for Annex 14 to the Convention on International Civil Aviation, Aerodromes[5] states:

> The operational objective of the rescue and fire fighting service *shall* be to achieve a response time not exceeding three minutes to any point of each operational runway, in optimum visibility and surface conditions.

In addition to these standards, ICAO also publishes recommendations. The following recommendation follows the preceding standards in the SARP.*

> The operational objective of the rescue and fire fighting service *should* be to achieve a response time not exceeding two minutes to any point of each operational

*The key words *shall* and *should* point out the difference between standards and recommendations.

> runway, in optimum visibility and surface conditions. The operational objective of the rescue and fire fighting service *should* be to achieve a response time not exceeding three minutes to any other part of the movement area in optimum visibility and surface conditions. . . . Any other vehicles required to deliver the amounts of extinguishing agents specified *should* arrive no more than one minute after the first responding vehicle(s) so as to provide continuous agent application.

NFPA 403, *Standard for Aircraft Rescue and Fire-Fighting Services at Airports*

Of the three sources, NFPA 403 is certainly the most stringent, as well as the clearest:*

> The demonstrated response time of the first responding vehicle to reach any point on the operational runway shall be 2 minutes or less and to any point remaining within the on-airport portion of the rapid response area shall be no more than 2½ minutes, both in optimum conditions of visibility and surface conditions. Other ARFF vehicles necessary to achieve the required discharge rate shall arrive at intervals not exceeding 30 seconds.

FAA's 14 CFR Part 139

The U.S. government has chosen not to adopt NFPA 403 and has filed differences to ICAO Annex 14 with respect to response time. The current response requirements from 14 CFR Part 139.319(h)(2) state

> (i) Within three minutes from the time of the alarm, at least one required airport rescue and firefighting vehicle shall reach the midpoint of the farthest runway serving air carrier aircraft from its assigned post, or reach any other specified point of comparable difference on the movement area which is available to air carriers, and begin application of agent;
>
> (ii) Within four minutes from the time of the alarm, all other required vehicles shall reach the point specified (above) from their assigned post and begin application of agent.

ARFF TRAINING REQUIREMENTS

Each airport must develop its own ARFF fire fighter training program that is designed to prepare the fire fighter for the specific mission of the airport. The program should be carefully developed to meet the qualifications and requirements of NFPA 1003, *Standard for Airport Fire Fighter Professional Qualifications,* and NFPA 405, *Standard for the Recurring Proficiency of Airport Fire Fighters.*

**Rapid response area* is defined by the NFPA as a rectangle 500 ft to either side of a runway centerline and extending 1650 ft beyond each runway end, remaining within the airport property line.

Fire Fighter Training

In 14 CFR Part 139.319(i)(2), the FAA requires that

> all rescue and firefighting personnel are properly trained to perform their duties in a manner authorized by the administrator. Such personnel must be trained prior to initial performance of rescue and firefighting duties and receive recurrent instruction every 12 consecutive calendar months. The curriculum for initial and recurrent training must include at least the following areas: airport familiarization; aircraft familiarization; rescue and firefighting personnel safety; emergency communications; use of fire hoses, nozzles and appliances; application of extinguishing agents; emergency aircraft evacuation assistance; firefighting operations; adapting structural firefighting equipment for ARFF; aircraft cargo hazards including haz mat; and ARFF responsibilities within airport emergency plan.

Each ARFF fire fighter must participate in at least one live-fire drill that simulates an aircraft fire of the size typical to the airport index certificate (Figure 13.7.4).

Training Records

Training records must be maintained by the airport fire department training officer for each member. During the annual airport certification inspection, the FAA inspector inspects the records for compliance. Inspectors can evaluate or test any member for proficiency in any or all of the training requirements. They will also conduct a surprise test run to see a demonstration of the department's ability to satisfy the response test requirements of 14 CFR Part 139.319.

Airport Emergency Exercise

14 CFR Part 139.325 requires all Class 1 airports to hold a full-scale airport emergency exercise at least every 36 months. This

FIGURE 13.7.4 Live-Fire Training Exercises (Source: Jack Kreckie)

FIGURE 13.7.5 Tri-Annual Emergency Response Exercise Being Conducted at Allentown Bethlehem International Airport (Source: Jack Kreckie)

exercise is required to test the airport emergency plan and to demonstrate the ability of those with responsibilities under the emergency plan to fulfill their obligations (Figure 13.7.5).

ARFF PERSONAL PROTECTIVE EQUIPMENT (PPE)

For years there has been debate in the industry relative to the proper personal protective equipment (PPE) for ARFF fire fighters. This issue is primarily raised by departments that serve dual roles of ARFF and structural. Many fire fighters felt that traditional ARFF PPE "silvers," or proximity fire-fighting ensembles (Figure 13.7.6), were too stiff and cumbersome and that they were safer in gear that allowed more freedom of movement. The opposition was typically from departments that were primarily dedicated to ARFF and spoke of the value of reflecting the heat away from the fire fighter.

Many research sources are available to understand the debate but, more importantly, to understand the laws that govern ARFF. The single most important factor is fire fighter safety. If the level of protection is lower than that which is required, fire fighter safety and level of effectiveness will not be maximized.

OSHA Requirements

In the United States, the Department of Labor's Occupational Safety & Health Administration (OSHA) oversees the safety of workers. OSHA standards are federal laws. On July 15, 1997, an Interpretation Record[6] was issued to interpret OSHA's position on proximity gear for ARFF fire fighters in Standard Number 1910.120; 1910.156:

- If a firefighter's primary job is crash and rescue, he or she must be adequately protected for that job (NFPA 1971, proximity protective ensemble). This is true even for those large combined fire departments with multiple tasks where personnel are rotated from station to station and expected to perform crash and rescue duties.
- If a firefighter's primary job is structural, then he or she must be adequately protected for that job (NFPA 1971, structural protective ensemble). This does not preclude being trained for incidental response to aircraft crashes as crashes do occur in unexpected locations.

FIGURE 13.7.6 ARFF Fire Fighter in Silvers (Source: Jack Kreckie)

An example given in the memo referred to the San Diego combined fire department. It stated that all 300 members can be tasked to do any type of fire fighting at any time (usually on a rotational basis). OSHA determined that in this case, all 300 members would have to be equipped to fight any type of fire. In another example where aircraft crash and rescue was less than 5 percent of the tasking, proximity fire fighting was incidental and not the primary job.

FAA Recommendations

FAA Advisory Circular 150/5210-14B, Airport Rescue and Fire Fighting Personnel Protective Ensemble for Proximity Fire Fighting,[7] identifies the standards for design, performance, testing, and safety of personal protective ensembles for proximity fire fighting. This document serves as a recommendation by the FAA for all airports. It is mandatory for PPE purchased under

federally funded projects and serves as an acceptable means of compliance with 14 CFR Part 139 as it pertains to PPE for airport fire and rescue personnel. It states:

> If ARFF personnel engage in any fire and rescue activity where there is any hazard or potential hazard of high radiant heat fuel fire, then the operational consideration and risk assessment mandates the use of proximity protective clothing.
>
> *Recommendations from Advisory Circular:*
> a. Proximity Protective Ensemble
> 1) Design, Performance, Testing and Certification Standards. Proximity Protective Ensembles as a minimum shall meet the most recent edition of NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting.*
> 2) For Safety and Health Standards, Proximity Ensemble, as a minimum, shall meet the requirements of NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program.*

AIRCRAFT EMERGENCIES

The vast majority of responses by ARFF departments for aircraft emergencies are precautionary. Aircraft are designed and built with a number of redundant critical systems and can fly safely with certain systems shut down. Although the aircraft are capable of these things, it is still not considered normal, and failure of a system will cause an aircraft to return and land (if it occurs shortly after takeoff) and notify the tower of the problem. In order to provide appropriate levels of protection for the landing aircraft, the authority having jurisdiction (AHJ) at each airport must have established procedures to provide the necessary level of response to all types of aircraft emergencies.

Aircraft Emergencies with Prior Warning

The majority of aircraft emergency responses for ARFF departments are announced prior to the landing of the aircraft. There is often several minutes' warning that the aircraft is inbound and a description of the problem is provided. The calls are typically received from the air traffic control tower (ATCT) or flight service center (FSS).

Problem Information Provided. In most cases, the following information is provided:

- Make, model, and flight number of the aircraft
- Problem reported by the pilot
- Landing runway
- Number of "souls" on board (SOBs)
- Quantity of fuel on board
- Whether or not the pilot is "declaring an emergency" or "requesting the equipment" (requesting ARFF vehicles at the runway)
- Estimated time of arrival (ETA)

Response Objectives. Response to calls with advance warning results in apparatus response to designated runway standby positions. Runway hold-off positions should be designed to accommodate a number of objectives. These objectives are satisfied more easily at airports with multiple pieces of apparatus responding:

- Minimize delays in reaching burning aircraft in the event the aircraft crashes or has a fire on board.
- Provide observation points from different angles and sequences of landing to observe unsafe or reportable conditions.
- Minimize risk to ARFF personnel and vehicles by not locating several assets together. (An aircraft skidding off the runway could wipe out several vehicles if co-located.)
- Provide strategic locations planning for prestaging to include tactical consideration for rapid access to all sides of the aircraft as well as factoring in wind and terrain.

Aircraft Emergencies with No Prior Warning

Some ARFF responses to aircraft emergencies occur with little or no warning. Crashes due to catastrophic failures during landing and takeoff are examples. Another scenario would be an aircraft that experiences an emergency on takeoff roll or on short final (i.e., immediately prior to becoming airborne or immediately upon touchdown). A call from the tower might say, "He just aborted takeoff due to a bird strike! He's at the departure end of Runway 9. He's requesting equipment!" or "Aircraft is on Final for 4R, he has a Fire Warning Light for Number 1 engine. Pilot's declaring an emergency! He's over the numbers now!" (indicating the aircraft is still airborne but about to touch down). In these scenarios, the ARFF vehicles would respond directly to the aircraft rather than to runway standby positions.

ARFF ACTIONS

Size-Up/Set-Up

Initial Observations Reported. Every vehicle approaching an aircraft incident or accident should immediately perform a quick size-up. Initial observations reported to other responding units as well as the aircraft cockpit are among the most critical initial actions. Visible smoke, fire, physical damage, and fuel spills should all be reported immediately. These are items that will factor into decision making in the cockpit as to whether the aircraft should be evacuated or not.

Incident Action Plan. This information is also taken into consideration by the incident commander (IC). At a small airport, there may only be one truck and one person responding. In any case, the IC needs to make a decision based on the initial size-up. He or she must gather the assessment information and develop an incident action plan based on the resources available. The operational priorities for an aircraft accident are no different from any other emergency response:

1. Rescue
2. Fire control

3. Loss control
4. Environmental consideration

Set-Up Factors. The positioning of arriving ARFF vehicles is critical to the success of the mission. In many cases, the positioning of the first arriving piece dictates the position of the remaining apparatus. There are a number of factors to be considered in the set-up phase. Wind, grade, terrain, exposures, spilled fuel, passenger evacuation, and limitations of the apparatus all need to be considered. In addition, each piece of apparatus or specialized equipment needs to have access to the area it was designed to service. If a high-mounted engine is on fire, the best area for tactical deployment of a high-reach extendible turret or aerial device should be left accessible. If the department has a mobile stair truck, the rescue side of the aircraft must be determined and the safest door for deplaning must be left accessible for the stairs.

The decision as to where to position must be made within seconds. Once in position, it is difficult to move vehicles around due to their size and other vehicles at the scene. Although the decisions are made very quickly, the video from media helicopters and long-range lenses will be on display forever with subject matter experts and attorneys questioning every step and criticizing every decision. Decisions made relative to the positioning of apparatus need to be deliberate and for good reason. Training evolutions and critiques of incidents will help ARFF fire fighters develop good instincts and make rapid decisions at the next incident.

Aircraft Cabin Fires Requiring Aircraft Evacuations

Time Requirement. Interior fires on aircraft, whether postcrash or in-flight fires, pose obvious life-threatening hazards to occupants. In either case, the immediate objective of the aircraft crew is to evacuate the occupants of the aircraft. The certification of the aircraft includes a requirement that the aircraft design is such that a full evacuation of the aircraft using half of the exits is accomplished in 90 seconds or less. This ability must be demonstrated prior to certification for revenue service.

Escape Slide. According to an FAA study relating to aircraft cabin fire safety:[8]

> Accident data studies indicate that, in most survivable air transport crashes to date, occupant survival has been largely determined by the ability of uninjured passengers to leave their seats and find an exit before being overcome by fire or smoke.

Air carrier aircraft that make use of escape slides depend on them to satisfy the evacuation requirement. These inflatable devices are not fail-safe. They are subject to failure for mechanical reason or to damage due to the landing or crash. They are designed to be effective for an aircraft sitting on a runway, up on all of its gear. If the attitude of the aircraft is affected, or the gear collapsed upon landing, the value of the slides is reduced or negated. The slides are also affected by heat and wind.

During an emergency evacuation, fire fighters should be positioned at the base of the slides to secure them, help passengers to their feet, and direct them to a safe area of refuge. Fire fighters anchoring the slides from the effects of wind, providing a fire-free escape area, and assisting passengers to areas of safety will help to minimize injuries.

On June 27, 2000, the National Transportation Safety Board (NTSB) adopted a safety study entitled "Emergency Evacuation of Commercial Airplanes." This study collected data from accident investigations and from crew and passenger interviews from 46 emergency evacuations involving 2846 occupants that occurred between September 24, 1997, and January 24, 1999. During this period, an evacuation occurred on average, every 11 days. In the 46 study cases, 92 percent (2614) of the 2846 occupants were uninjured, 6 percent (170) sustained minor injuries, and 2 percent (62) sustained serious injuries.[9]

Removal from Hazardous Atmosphere. Postcrash aircraft accident fatalities are typically due to exposure to products of combustion. For the effects of such exposure, see Section 6, Chapter 2, "Combustion Products and Their Effects on Life Safety." In addition to the effects of the toxic atmosphere, the survival of the occupants depends on the level of air temperature in the aircraft cabin. In postcrash fires, the cabin air temperatures can increase as a result of the ignition of interior cabin components or as a result of fire gases entering the fuselage from outside fires.

To increase the chance for survival, occupants need to be removed from the hazardous atmosphere before they suffer effects of exposure to toxins in the atmosphere and prior to the air temperatures reaching the limits of human tolerance. The other option is to make the atmosphere in the cabin safe for occupants. This may be the only alternative if extrication is required for trapped victims.

Interior Fire Attack and Ventilation

According to the International Fire Service Training Association (IFSTA),[10] ARFF fire fighters should try to determine the location and extent of the fire prior to attempting entry. Ventilation should be immediately initiated to allow the smoke and steam created by interior fire attack to escape. Applying water to the fire will quickly cause the limited space in the cabin to fill with smoke and steam. This condition compounds the difficulty for rescuers making entry and puts occupants and rescuers at risk for steam burns. Making entry and initiating fire attack should be simultaneous to ventilation efforts. Entry, search and rescue, and interior fire attack should be initiated from the unburned side of the aircraft (Figure 13.7.7).

In order to affect interior fire attack in time periods that will increase survivability, efforts must be initiated immediately. The ability to immediately launch exterior fire-fighting efforts to protect escape paths, begin ventilation, and perform interior rescue and fire-fighting actions requires that properly trained and equipped teams be on hand very quickly. It also means that water supply to satisfy *Q1, Q2,* and Q3 quantities must also be available. The personnel and equipment required for these operations need to be on airport or prestaged to arrive in the first few critical minutes if they are to be effective.

FIGURE 13.7.7 Fire Fighters at Orlando International Airport Being Trained on Making Entry Through Emergency Over-Wing Exit (Source: Jack Kreckie)

ARFF personnel at certificated airports should be equipped, trained, and capable of interior aircraft fire fighting. Such operations should be performed in accordance with OSHA, as detailed in 29 CFR Part 1910.134(g)(4). The standard details certain procedures for interior structural fire fighting to ensure respiratory protection and safe practices when entering atmospheres that are immediately dangerous to life and health (IDLH):

> At least 2 employees enter the IDLH atmosphere and remain in visual or voice contact with one another at all times; At least two employees are located outside the IDLH atmosphere; and all employees engaged in interior structural firefighting use Self-Contained Breathing Apparatus (SCBAs)[11]

An interior fire on an aircraft is certainly IDLH. This OSHA regulation is known in the industry as the "two-in/two-out" rule. Federal Aviation Regulation FAR Part 139 certificate holders should develop and implement policies addressing aircraft firefighting operations.

CARGO AIRCRAFT

ARFF Requirements

Currently the FAA authority and, therefore, the applicability of Part 139 extend only to passenger-carrying aircraft under 49 USC 44706. This means that the U.S. requirements for index determination, agent/vehicle quantities, and aircraft training do not include cargo aircraft. To illustrate the point, an airport could conduct flight operations all day long with Boeing 747 cargo aircraft, but the FAA would not require any ARFF coverage.

Although there may not be any legal responsibility on the part of the certificate holder to provide ARFF coverage for these flight operations, most airports realize that they have a moral obligation to protect the aircraft occupants, the airport, and the surrounding communities. In some cases, the costs associated with providing this protection are carried by the cargo operators.

Cargo Aircraft Hazard

Cargo aircraft contain the same fuel loads as passenger aircraft of the same size or class; therefore, the potential for fire and associated damage on the ground is the same, regardless of whether the aircraft is configured for cargo operations or passenger service. Cargo aircraft may actually provide a greater risk for those on the ground since cargo aircraft frequently carry hazardous materials not permitted in passenger operations. Morally to suggest that the lives of the occupants of a cargo aircraft are not eligible for the protection or benefit provided by ARFF services is reprehensible. Human life must always remain the highest priority, regardless of the primary mission of the aircraft these individuals occupy.

Occupant Evacuation

Fires on cargo aircraft offer different challenges from those on passenger aircraft. The life hazard for occupants is obviously less due to the fewer number of people on board. Crew members will attempt to escape through normal exit doors or through the emergency exits in the cockpit. After determining that all occupants have escaped from the aircraft, all efforts can be placed on protecting exposures and attacking the aircraft fire.

Interior Fire Attack

In an intact fuselage, access through normal doors may not provide access to the area of the fire. "Space" on a cargo aircraft is the commodity from which cargo carriers generate their revenue. The intention of the cargo carrier is to fill every space with freight. An open aisle down the center of the fuselage is like flying a passenger aircraft with mostly empty seats. Profits depend on full aircraft. This factor complicates interior fire attack because of the access problem. Opening a cargo bay loading door on an aircraft with an interior fire may intensify the fire due to the introduction of oxygen and not provide any access to extinguish the fire due to the cargo load itself. On most fully loaded cargo aircraft, there are only a few inches between the cargo containers and the fuselage.

Incident Action Plan. Before initiating interior fire attack, crews should attempt to determine the quantities and types of hazardous materials on board. The airway bills and manifests are stored on board the aircraft, usually in the cockpit or adjacent to the main loading door. Aircraft that carry quantities or types of dangerous goods that are not allowed on passenger aircraft are usually stored in designated areas in the forward portion of the cargo bay. If the dangerous goods are in smaller quantities and of a class that would be allowed on passenger aircraft, they may be mixed throughout the aircraft. In all incidents involving a fire on a cargo aircraft, a hazardous materials team should be on site and involved in developing the incident action plan.

Aircraft Skin-Piercing Nozzles. The use of aircraft skin-piercing nozzles may be the best tactic to attack an interior fire on a cargo aircraft. The use of forward-looking infrared (FLIR) cameras is helpful in determining the location and severity of the interior fire. Penetrations in the skin, using handheld piercing

nozzles or those installed on ARFF vehicles equipped with high-reach extendible turrets, are an efficient way of introducing agent to an area that is not accessible due to cargo loading (Figure 13.7.8). It also minimizes the amount of air introduced to small holes punched in the fuselage by the piercing tip. The effectiveness of the fire attack can be monitored through the FLIR camera, which is focused on the "bloom," or heat signature, from the onboard fire. In most cargo aircraft fires, venting occurs when the fire burns through the roof of the fuselage. If the fire is attacked prior to burn-through, ventilation will have to be factored into the incident action plan.

ACCIDENT INVESTIGATION AND SCENE PRESERVATION

Fire Department and Law Enforcement Responsibilities

An aircraft accident is considered a crime scene until proven otherwise. Following ICS/NIMS protocol, the fire department is in charge until all rescue has been completed, the fire is extinguished, and the scene is made safe. At that time, command of the incident is handed over to law enforcement. Local, state, and federal law enforcement agencies are responsible for securing the scene, debris field, personal effects, cargo, and mail. They will collect documentation, gather intelligence, record the scene, and begin analysis of the accident site. Law enforcement looks specifically for anything that might have been a criminal or intentional act or an act of war or terrorism.

Fire fighters need to remain aware that when the scene is declared safe, every inch will be studied and scrutinized by trained investigators. Every bit of damage will be evaluated to determine the specific cause. Damage caused by rescuers during fire fighting, forcible entry, or extrication efforts should be documented for the investigation that will follow. The location of every piece of debris may be an important clue in determining the cause of the accident. The location of personal effects, survivors, bodies, or body parts may be the key to identifying a victim. Care should be taken to touch only things that must be touched to accomplish the critical tasks of the fire fighters' mission.

FIGURE 13.7.8 Oshkosh TI-3000 ARFF Vehicle with High Reach Extendible Turret (HRET) with Piercing Tip (or Snozzle®) (Source: Jack Kreckie)

National Transportation Safety Board (NTSB)

The National Transportation Safety Board (NTSB) investigates every civil aviation accident in the United States. In compliance with international treaties, it also provides investigators to serve as U.S.-accredited representatives for aviation accidents overseas involving U.S.-registered aircraft or involving aircraft or major components of U.S. manufacture. The NTSB launches teams from its headquarters in Washington, DC, or from one of the ten regional offices in the United States. The NTSB maintains the U.S. government's database on civil aviation accidents. The NTSB Accident Incident Database is available to the public at http://www.ntsb.gov/avdata.

AIRCRAFT TECHNOLOGY ADVANCES

Aircraft technology advances, such as aircraft cabin-zoned waterspray systems and emergency locator transmitters (ELT), would increase survivability and are, therefore, justified from a safety or survival standpoint. The associated costs of some of these advances, however, are prohibitive and thus not likely to be implemented at this time.

Aircraft Cabin-Zoned Waterspray Systems and Aircraft Cabin Sprinklers

In the United States, building a structure designed for public assembly, which would accommodate up to 800 people, without fire sprinklers would be unthinkable. Yet in the twenty-first century, new aircraft carry these numbers of people. The area of assembly (the fuselage) is nestled between two wings that are loaded with jet fuel. This area of assembly is then lifted off the ground by powerful jet engines and travels at 30,000 to 40,000 ft above the ground at 500 mph. Based on a study performed by the FAA, "Fire Management/Suppression Systems/Concepts Relating to Aircraft Cabin Fire Safety" (Oct. 1983),[8] the cost of an aircraft cabin-zoned waterspray system for a wide-body jet was estimated to add $86,000 (approximately $140,000 in 2006 dollars) to the cost of the aircraft. The study indicated that, historically, major losses have occurred in postcrash or emergency landing fires.

Unfortunately, this initial cost is the least significant expense to be considered. The weight of a zoned waterspray system for a wide-body jet is 1190 gross lb. This weight is multiplied by the total number of miles flown throughout the anticipated life of the aircraft. The fuel cost and space allowance, combined with annual maintenance, inspection, and repair, reveal the actual cost to the airline. Although the concept of aircraft suppression systems has great merit in the areas of survivability and

loss reduction, it is difficult to calculate a favorable cost/benefit analysis due to the limited number of incidents on which to base benefits. Weight is money in aviation, and automatic suppression systems are not mandated by the FAA, so it is not likely such systems will be installed unless concerns for the number of people at risk in the new large aircraft (NLA) bring back the debate on this issue.

Smart ELT Technology

The key to survival for the occupant of an aircraft involved in a survivable crash is time. The occupant needs to be removed from the fuselage, which is rapidly filling with smoke and fumes (products of combustion), or the atmosphere of that space must be made safe. The elements of response for rescue crews include notification, activation, response, and control time. Notification of emergency crews is usually handled by the air traffic control tower (ATCT) that was handling the flight. Depending on location, visibility, weather, and other factors, this report might have very specific accident location, last known location, or perhaps best estimate location. In cases of survivable crashes, where delays in response and arrival are caused by the inability of the ATCT to provide specific accident location, survival risks are increased. American Airlines Flight 1420, Little Rock, Arkansas, is a perfect example. The following conclusion was published in the NTSB Abstract of the accident report:[12]

> A crash detection and location technology would help expedite the arrival of emergency responders at an accident scene, thus maximizing the possibility for saving lives and reducing the severity of injuries.

Most light aircraft are equipped with emergency locator transmitters (ELT). These ELTs transmit an emergency radio signal that can be tracked to help locate a downed aircraft. Commercial vessels are required by the U.S. Department of Transportation to be equipped with a Category I emergency position indicating reporting beacon (EPIRB). If a ship sinks, the EPIRB will separate itself from the vessel and float to the surface, as it sends out a signal to search and rescue assets.[13]

Technology exists today that combines ELT technology with differential global positioning systems. This smart ELT could be activated manually by the pilot or automatically by deceleration forces and could send out aircraft identification and location information.

Fire Fighter Preparedness

Post–9/11 thinking further complicates everything done in the fire service. On September 11, 2001, aircraft became weapons of mass destruction and airports became their launching pads. It is speculated that these terrorists, who have forever changed life in the United States, spent years watching U.S. airports, studying the system, and flying on airplanes. Much like ARFF fire fighters walking through parking garages and airport terminals on building familiarization, these terrorists walked the same routes. They found every weakness in the system and used it to cause thousands of deaths. Fire fighters everywhere need to reassess every incident they approach; complacency is the enemy. For every routine incident response, there are additional concerns that must be factored into the assessment:

- Could this be a diversion?
- Could there be a secondary device?
- Could this fire be a dispersal method for radiation or other weapons of mass destruction (WMD)?

Incident action plans and SOPs must always hold contingencies for the "what ifs." Transportation centers are critical infrastructure; therefore, airports are high-risk targets for terrorist acts. ARFF fire fighters are the front-line level of protection to minimize threats and mitigate effects of these acts.

There are no federal regulations or industry standards that prepare ARFF fire fighters for what could occur at airports, but they will be the first on the scene. In a multiple-hit scenario, additional events may occur in the cities outside the airport. These are the same cities that provide mutual aid to airports. In these cases, there may be no help coming. It has been said that the only difference between a WMD release and a hazmat incident is intent. The same could be said of a gas explosion in a terminal complex or airport hotel and improvised explosive devices (IEDs) detonated by suicide bombers in the middle of security checkpoints. The bottom line is simply that preparedness is key.

SUMMARY

The challenges presented in a survivable aircraft accident are great. ARFF fire fighters, through training and experience, will exhaust all available resources in an attempt to rescue every occupant. The enemy in this event is time. Most ARFF departments are not staffed with sufficient numbers of personnel to accomplish all the tasks critical to the survival of the occupants in the time allowed. Continued training and development of faster, more capable fire-fighting technology will contribute to their success, but advances in aircraft safety technology might provide the additional edge needed. This chapter discussed a number of pieces of technology, such as aircraft cabin-zoned waterspray systems or emergency locator transmitters, that would further increase survivability but have not been introduced to the fleet mix. Although it is clear that these items can be justified from a safety or survival standpoint, the associated cost will probably prevent their introduction.

This chapter discussed the mission of the aircraft rescue fire fighter and followed it by a review of the evolution of the aircraft itself. As the aircraft evolved, so did the regulations and consensus standards that ARFF protection at airports is modeled around. Basic ARFF response procedures as well as specific hazards to fire fighters and aircraft occupants alike were reviewed. For the ARFF fire fighter, all of the information provided and referenced here is nothing more than "ARFF 101." The basic requirements of the regulations that govern ARFF departments are a foundation for the knowledge base each ARFF fire fighter must develop to be proficient in his or her mission.

Responsibilities change daily with changes in fleet mix, passenger load factors, unknown cargo loads, and the new age threat of the day.

A simple review of the scenario that every ARFF fire fighter trains and prepares for shows how important proficiency in every required skill set is to the survival of the occupants of an aircraft involved in a survivable crash. Consider this:

- According to a study released in 1996,[14] which examined NTSB reports from 60 survivable aviation accidents, 78 percent of all fatalities occurred after impact, and 95.4 percent of them resulted from smoke inhalation or burns.
- In postcrash fires, cabin air temperatures can rise from both the ignition of the cabin interior and from fire gases entering the fuselage through open doors or fractured fuselage. In an FAA study,[8] the cabin air temperature at the ceiling reached 1300°F (704.4°C) in 50 seconds with open doors. Closing all but one door retarded the flow of heat, which still reached 400°F (204°C) in the same time.

Statistically, therefore, the fatalities that occur in a survivable crash will occur postcrash. The fire that is likely to occur will rapidly create an environment that cannot support life for those unable to escape by themselves. The lives of surviving occupants are totally dependent on the swift actions of highly trained and properly equipped ARFF fire fighters. Every action, every second spent or saved, from the moment of the impact until all survivors are safe will have an effect on who lives and who does not. For ARFF fire fighters, the minimum standard is never enough. Commitment to mission, training, coordination, and cooperation is the key to successful incident accident plans.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on aircraft rescue and fire fighting discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 402, *Guide for Aircraft Rescue and Fire Fighting Operations*
NFPA 403, *Standard for Aircraft Rescue and Fire-Fighting Services at Airports*
NFPA 405, *Standard for the Recurring Proficiency of Airport Fire Fighters*
NFPA 412, *Standard for Evaluating Aircraft Rescue and Fire-Fighting Foam Equipment*
NFPA 414, *Standard for Aircraft Rescue and Fire-Fighting Vehicles*
NFPA 1003, *Standard for Airport Fire Fighter Professional Qualifications*
NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*
NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*

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Chapter 8

Managing the Response to Hazardous Material Incidents

Charles J. Wright

Chapter Contents

Definitions
Hazard Classes and Divisions
Analyzing the Hazardous Material Problem
Planning the Response
Implementing the Planned Response
Evaluating Progress and Adjusting Accordingly

Key Terms

bulk packaging, damage assessment, decontamination, elevated temperature material, emergency, *Emergency Response Guidebook,* hazard class, hazardous material, hazardous material data sheet, incident management system (IMS), personal protective equipment, shipping paper, weapons of mass destruction (WMD)

Hazardous materials may be an important part of our high standard of living, but when a release occurs, it can harm people, including response personnel, property, and the environment. It can disrupt critical systems, damage reputations, and create a residual fear of hazardous materials. The effective management of hazardous materials and other chemicals in the community requires (1) prevention, (2) preparedness, (3) response, and (4) recovery activities. This chapter focuses on a risk-based response process, but the underlying concepts apply to the other hazardous material management activities as well.

The purpose of the response effort is "to change the sequence of events constituting the emergency before it has run its course naturally and to minimize harm that would otherwise occur."[1] To accomplish this purpose, the following four duties are undertaken (Figure 13.8.1):

1. Analyze the problem.
2. Plan the response.
3. Implement the planned response.
4. Evaluate progress and adjust accordingly.

Each duty involves a series of tasks and steps that must be considered and resolved by decisions and actions. These duties, when supported by the response community, are the framework for an appropriate, survival-oriented response to hazardous material incidents. Reasoned decisions based on this approach will minimize the harm resulting from a hazardous material incident and reduce the risk to responders.

See also Section 7, Chapter 5, "Hazardous Waste Control"; and Section 13, Chapter 6, "Public Fire Protection and Hazmat Management."

DEFINITIONS

The following terms are used in this chapter.

Bulk packaging is any containment system, including transport vehicles and freight containers, having a capacity meeting one of the following criteria: liquid—internal volume of more than 119 gal (450 L); solid—capacity of more than 882 lb (400 kg); or compressed gas—water capacity of more than 1000 lb (454 kg).

Containment systems (or containers) are a combination of a container and its closures used to isolate the contents from the surrounding environment. A closure is a device for closing the openings in a container.

Elevated temperature material (DOT) means a material that, when offered for transportation or transported in a bulk packaging, is (1) in a liquid phase and at a temperature at or above 212°F

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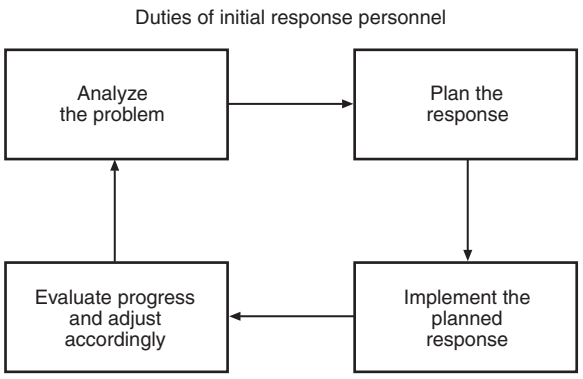

FIGURE 13.8.1 Response Duties Associated with Emergencies Involving Hazardous Materials

(100°C), (2) in a liquid phase with a flashpoint at or above 100°F (37.8°C) that is intentionally heated and offered for transportation or transported at or above its flashpoint, or (3) in a solid phase and at a temperature at or above 464°F (240°C).

Emergency is the term used for a sudden, generally unexpected disruption in a normal sequence of events requiring immediate action.

Hazardous material, for the purpose of this chapter, is a substance that on release has the potential of causing harm to people, property, or the environment, including weapons of mass destruction (WMD).

Hazardous material (DOT) means a substance or material that has been determined by the Secretary of Transportation to be capable of posing an unreasonable risk to health, safety, and property when transported in commerce, and that has been so designated. Table 13.8.1 lists the internationally accepted hazard classes and divisions associated with hazardous materials in transportation. This definition includes hazardous materials, hazardous substances, hazardous wastes, elevated temperature materials, marine pollutants, and dangerous goods internationally.

Hazardous substance (DOT) means a material, including its mixtures and solutions, in a quantity, in one package, that equals or exceeds the reportable quantity (RQ) listed in DOT's Hazardous Materials Regulations (49 CFR, Parts 171–172).

Hazardous waste (DOT) means any material that is subject to the Hazardous Waste Manifest Requirements of the U.S. Environmental Protection Agency (EPA) specified in 40 CFR, Part 262.

Hazardous material incident is an emergency involving the release or potential release of hazardous materials/weapons of mass destruction (WMD) with or without fire.

Marine pollutant (DOT) means a material that is harmful to aquatic life (listed in 49 CFR 172.101, Appendix B).

Nonbulk packaging is any containment system having a capacity meeting one of the following criteria: liquid—internal volume of 119 gal (450 L) or less; solid—capacity of 882 lb (400 kg) or less; or compressed gas—water capacity of 101 lb (454 kg) or less.

Outcomes are the direct and indirect results or consequences associated with an emergency. Direct outcomes include death, injury, property damage, and environmental damage. Indirect outcomes include system disruption, damaged reputations, and residual fear of hazardous materials.

Response community is composed of those individuals, agencies, or companies who have resources and can become involved in handling a hazardous material incident. These may include fire service personnel, law enforcement personnel, rescue and emergency medical personnel, private sector response personnel (carriers, manufacturers, and contractors), and local, state and federal government response personnel.

Weapons of mass destructions (WMD) are defined in NFPA 472, *Standard for Competence of Responders to Hazardous Materials/Weapons of Mass Destruction Incidents*, as (a) any destructive device, such as any explosive, incendiary, or poison gas, bomb, grenade, rocket having a propellant charge of more than four ounces (112 grams), missile having an explosive or incendiary charge of more than one quarter ounce (7 grams), or device similar to the above; (b) any weapon involving toxic or poisonous chemicals; (c) any weapon involving a disease organism; (d) any weapon that is designed to release radiation or radioactivity at a level dangerous to human life.

HAZARD CLASSES AND DIVISIONS

The following list presents the internationally accepted definitions of the nine numbered hazard classes and divisions. These definitions should not be used to determine compliance with the regulations, because they do not indicate the exceptions and specificity found in the regulations in all cases.[2]

Class 1 *(Explosives and Blasting Agents)*

Explosive means any substance or article, including a device, that is designed to function by explosion (i.e., an extremely rapid release of gas and heat) or that, by chemical reaction within itself, is able to function in a similar manner even if not designed to function by explosion. Explosives in Class 1 are divided into six divisions. Each division will have a letter designation (compatibility group letter.)

Division 1.1. Consists of explosives that have a mass explosion hazard. A mass explosion is one that affects almost the entire load instantaneously.

Division 1.2. Consists of explosives that have a projection hazard but not a mass explosion hazard.

Division 1.3. Consists of explosives that have a fire hazard and either a minor blast hazard or a minor projection hazard or both, but not a mass explosion hazard.

Division 1.4. Consists of explosive devices that present a minor explosion hazard. No device may contain more than 0.9 oz (25 g) of a detonating material.

Division 1.5. Consists of very insensitive explosives. These substances have a mass explosion hazard but are so insensitive that there is very little probability of initiation or of transition from burning to detonation under normal conditions of transport.

TABLE 13.8.1 International Hazard Classes and Divisions

Classes and Divisions	*Examples of Materials (by Hazard Class or Division)*	*General Hazard Properties (Not All-Inclusive)*
Class 1—Explosives and blasting agents		Explosive; exposure to heat, shock, or contamination could result in thermal and mechanical hazards
Division 1.1—explosives with mass explosion hazard	Dynamite, TNT, black powder	
Division 1.2—explosives with projection hazard	Projectiles with bursting charges	
Division 1.3—explosives with fire, minor blast, or minor projection hazard	Propellant explosives, rocket motors, special fireworks	
Division 1.4—explosive devices with minor explosion hazard	Common fireworks	
Division 1.5—very insensitive explosives	Ammonium nitrate–fuel oil mix, blasting agent	
Division 1.6—extremely insensitive explosives		
Class 2—Gases		Under pressure; container may rupture violently (fire and nonfire); may be flammable, poisonous, corrosive, asphyxiant, and/or thermally unstable
Division 2.1—flammable gases	Propane, butadiene, acetylene, methyl chloride	
Division 2.2—nonflammable, nonpoisonous (nontoxic) gas	Carbon dioxide, anhydrous ammonia	
Division 2.3—poisonous (toxic) gas by inhalation	Arsine, phosgene, chlorine, methyl bromide	
Class 3—Flammable liquids *(flashpoint less than 141°F [60°C])*	Acetone, amyl acetate, gasoline, methyl alcohol	Flammable; container may rupture violently from heat/fire; may be corrosive, toxic, and/or thermally unstable
Class 4—Flammable solids and reactive liquids and solids		Flammable, some spontaneously; may be water reactive, toxic, and/or corrosive; may be extremely difficult to extinguish
Division 4.1—flammable solids	Nitrocellulose, matches	
Division 4.2—spontaneously combustible materials	Phosphorus, aluminum alkyls, charcoal	
Division 4.3—dangerous when wet materials	Calcium carbide, potassium	
Class 5—Oxidizers and organic peroxides		Supplies oxygen to support combustion; sensitive to heat, shock, friction, and/or contamination
Division 5.1—oxidizers	Ammonium nitrate fertilizer	
Division 5.2—organic peroxides	Dibenzoyl peroxide	
Class 6—Toxic (poisonous) materials		Toxic by inhalation, ingestion, and skin/eye contact; may be flammable
Division 6.1—poisonous (toxic) material	Aniline, arsenic, tear gas, carbon tetrachloride	
Division 6.2—infectious substances	Anthrax, botulism, tetanus	
Class 7—Radioactive materials	Cobalt, uranium hexafluoride	May cause burns and biologic effects; may be in form of energy or matter
Class 8—Corrosive materials	Hydrochloric acid, sulfuric acid, sodium hydroxide	Disintegration of contacted tissues; may be fuming and/or water reactive
Class 9—Miscellaneous hazardous materials	Adipic acid, molten sulfur, dry ice, PCBs	

Division 1.6. Consists of extremely insensitive articles that do not have a mass explosion hazard. These articles contain only extremely insensitive detonating substances and demonstrate a negligible probability of accidental initiation or propagation.

Class 2 *(Gases)*

Division 2.1. *Flammable gas* means any material that is a gas at 68°F (20°C) or less and 14.7 psi (101.3 kPa) of pressure, or

a material that has a boiling point of 68°F (20°C) or less at 14.7 psi (101.3 kPa) that meets either of the following criteria:

1. Is ignitible at 14.7 psi (101.3 kPa) when in a mixture of 13 percent or less by volume with air
2. Has a flammable range of at least 12 percent in air at 14.7 psi (101.3 kPa) regardless of the lower limit

Division 2.2. Nonflammable, nontoxic (nonpoisonous) compressed gas, including compressed gas, liquefied gas, pressurized cryogenic gas, and compressed gas in solution means any material (or mixture) that exerts in the packaging an absolute pressure of 41 psi (280 kPa) at 68°F (20°C).

A *cryogenic liquid* means a refrigerated liquefied gas having a boiling point colder than –130°F (–90°C) at 14.7 psi (101.3 kPa) absolute.

Division 2.3. *Toxic (poisonous) gas* means a material that is a gas at 68°F (20°C) or less and a pressure of 14.7 psi or 1 atm (101.3 kPa), that has a boiling point of 68°F (20°C) or less at 14.7 psi (101.3 kPa), and that has either of the following characteristics:

1. Is known to be so toxic to humans as to pose a hazard to health during transportation
2. In the absence of adequate data on human toxicity, is presumed to be toxic to humans because, when tested on laboratory animals, it has an LC_{50} value not more than 5000 ppm

Class 3 *(Flammable Liquids)*

Flammable liquids are any liquids having a flashpoint of not more than 140°F (60°C).

In the United States and Canada, an additional worded hazard class, *combustible liquids,* has been added to designate liquids with flashpoints above 140°F (60°C) and below 200°F (93°C). Actually, the U.S. regulations allow shippers to reclassify liquids with flashpoints above 100°F (38°C) as *combustible liquids.*

Class 4 *(Flammable Solids and Reactive Liquids and Solids)*

Division 4.1. *Flammable solid* means any of the following three types of materials:

1. *Wetted explosives*. Explosives wetted with sufficient water, alcohol, or plasticizers to suppress explosive properties
2. *Self-reactive materials*. Materials that are liable to undergo, at normal or elevated temperatures, a strongly exothermal decomposition caused by excessively high transport temperatures or by contamination
3. *Readily combustible solids*. Solids that may cause a fire through friction and any metal powders that can be ignited

Division 4.2. *Spontaneously combustible solid* means either of the following materials:

1. *Pyrophoric material*. A liquid or solid that, even in small quantities and without an external ignition source, can ignite within 5 minutes after coming in contact with air
2. *Self-heating material*. A material that, when in contact with air and without an energy supply, is liable to self-heat

Division 4.3. *Dangerous-when-wet material* means a material that, by contact with water, is liable to become spontaneously flammable or to give off flammable or toxic gas at a rate greater than 1 L/kg of the material, per hour.

Class 5 *(Oxidizers and Organic Peroxides)*

Division 5.1. *Oxidizer* means a material that may, generally by yielding oxygen, cause or enhance the combustion of other materials.

Division 5.2. *Organic peroxide* means any organic compound containing oxygen (O) in the bivalent -O-O- structure and that may be considered a derivative of hydrogen peroxide, whereby one or more of the hydrogen atoms have been replaced by organic radicals.

Class 6 *(Toxic or Poisonous Materials and Infectious Substances)*

Division 6.1. *Toxic (poisonous) material* means a material, other than a gas, that is either known to be so toxic to humans as to afford a hazard to health during transportation, or in the absence of adequate data on human toxicity, is presumed to be toxic to humans.

Division 6.2. *Infectious substance* means a viable microorganism, or its toxin, that causes or may cause disease in humans or animals. Infectious substance and etiologic agent are synonymous.

Class 7 *(Radioactive Materials)*

Radioactive material is any material containing radionuclides where both the activity concentration and the total activity of the shipment exceed specific values.

Class 8 *(Corrosive Materials)*

Corrosive material means either a liquid or solid that causes visible destruction or irreversible alterations in human skin tissue at the site of contact, or a liquid that has a severe corrosion rate on steel or aluminum.

Class 9 *(Miscellaneous Hazardous Materials)*

Miscellaneous hazardous material means a material that presents a hazard during transport, but that is not included in another hazard class, including the following:

1. Any material that has an anesthetic, noxious, or other similar property that could cause extreme annoyance or discomfort to a flight-crew member so as to prevent the correct performance of assigned duties
2. Any material that is not included in any other hazard class (a hazardous substance or a hazardous waste)

ORM-D Materials

In the United States, the hazard class ORM-D material (Other Regulated Materials-D) is used to designate materials, such as consumer commodities and some small arms ammunition, that present a limited hazard during transportation, due to their form, quantity, and packaging.

Other Definitions

The following are *hazard zones* associated with gases (Class 2) and listed as poison-inhalation hazards:

- *Hazard zone A*. LC_{50} less than or equal to 200 ppm
- *Hazard zone B*. LC_{50} greater than 200 ppm and less than or equal to 1000 ppm
- *Hazard zone C*. LC_{50} greater than 1000 ppm and less than or equal to 3000 ppm
- *Hazard zone D*. LC_{50} greater than 3000 ppm and less than or equal to 5000 ppm

The following are *hazard zones* associated with liquid and listed as poison-inhalation hazards in Classes 3, 4, 5, 6, and 8:

- *Hazard zone A*. LC_{50} less than or equal to 200 ppm
- *Hazard zone B*. LC_{50} greater than 200 ppm and less than or equal to 1000 ppm

Forbidden means prohibited from being offered or accepted for transportation. Prohibition does not apply if these materials are diluted, stabilized, or incorporated in devices.

ANALYZING THE HAZARDOUS MATERIAL PROBLEM

Background

Responding to emergencies involving hazardous materials is not easy. Just the sheer numbers of these materials present an intimidating list for those who respond to the emergencies they create. Consider the following examples:

1. A review of the Chemical Abstract Service's (CAS) list indicates that out of 1.5 million chemicals or chemical formulations found outside of the laboratory, more than 63,000 are considered hazardous.
2. The U.S. Department of Transportation (DOT) regulates the transportation of some 4000 hazardous materials.
3. The Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor regulates about 600 hazardous substances on the basis of occupational exposure.

A national study by Industrial Economics, Inc., sponsored by the U.S. Environmental Protection Agency (EPA),[3] and subsequent regional studies indicate that the most commonly released chemical is vehicle fuel. The following are two other findings that are of interest:

- 49.5 percent of the rest of the releases involved only 10 chemicals in addition to vehicle fuels. (Table 13.8.2 lists these chemicals.) These additional 10 chemicals are typically produced in the largest volume.
- 74.8 percent of the releases occurred in facilities (production, storage, and use) whereas the remaining 25.2 percent occurred in transportation.

Regional differences from this national study may change the makeup of the list locally.

Overview

The process of analyzing the hazardous material problem (sizeup) provides a way of determining the specific hazards and the potential magnitude of the problem in terms of outcomes. An understanding of the magnitude of the problem is the basis for subsequent decisions on the handling of an incident. Failure to consider all the hazards increases the responder's risk.

The analysis process begins when a responder receives notification of a problem and continues throughout the incident, typically at the scene threatened by any hazardous materials involved. Pre-emergency planning, following the same tasks and steps, lessens the time expended to achieve a safe and cost-effective response at a hazardous material incident, and also increases the available response options for that response.

An analysis of the hazardous material problem involves completing the following tasks (Figure 13.8.2):

1. Detect presence of hazardous material.
2. Initiate command and control activities.
3. Survey hazardous material incident.
4. Collect and interpret hazard and response information.
5. Assess extent of damage to containment system.
6. Predict likely behavior of containment system or contents.
7. Estimate potential outcomes within engulfed area.

Detecting the Presence of Hazardous Materials

The first task in analyzing, and ultimately understanding and solving, hazardous material problems is that of recognizing

TABLE 13.8.2 Most Commonly Released Hazardous Materials with Percentage of Releases and Percentage of Deaths and Injuries Associated with the Material[3]

Chemical Name	*Percentage of Releases*	*Percentage of Deaths and Injuries*
PCB (polychlorinated biphenyls)	23.0	2.8
Sulfuric acid	6.5	4.7
Anhydrous ammonia	3.7	6.8
Chlorine	3.5	9.6
Hydrochloric acid	3.1	5.6
Sodium hydroxide	2.6	1.9
Methyl alcohol	1.7	0.4
Nitric acid	1.7	1.5
Toluene	1.4	2.4
Methyl chloride	1.4	0.0

Source: Based on Industrial Economics, Inc., database.

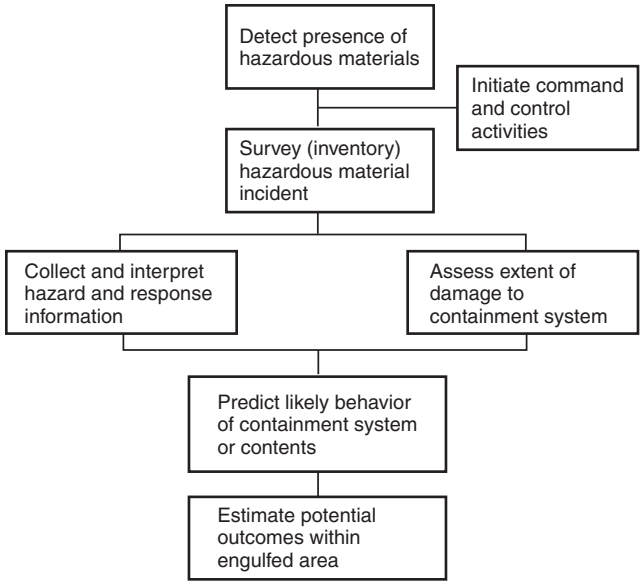

FIGURE 13.8.2 Tasks Associated with Analyzing a Hazardous Materials Problem

those situations where hazardous materials are present. This recognition task begins with the receipt of the initial notification of an emergency and continues throughout the handling of an emergency. Any emergency should be approached from a direction that will provide protection if hazardous materials are present. As with all tasks in the analysis process, detection should be performed from a safe location—upwind, uphill, and upstream, if possible.

The following steps should be taken when responding to any emergency:

1. *Review the initial information received for indications of hazardous materials.* Clues to the presence of hazardous materials may be provided by the caller or dispatcher.

2. *Review the occupancy, location, or local planning documents for indications of hazardous materials.* Planning documents, such as local emergency response plans, industry site-specific plans, and fire service pre-emergency response plans, may indicate the presence of hazardous materials. During pre-emergency planning activities, typical occupancies and locations where hazardous materials are manufactured, transported, stored, used, or disposed of in the community are identified.

3. *Look for containment system characteristics that indicate hazardous materials.* The hemispherical ends on the container or the protective housing around the fittings on top of a pressure tank car are indications of hazardous materials. An awareness of the various types of hazardous material containment systems is useful.

4. *Look for facility and transportation markings and color that indicate hazardous materials.* The use of color is not consistent nationwide; however, color markings may be consistent in local areas. Various markings indicate the presence of hazardous materials. Some examples are as follows.

Identification numbers are four-digit numbers assigned to a specific hazardous material or group of hazardous materials. They are used to cross-reference the name of a material in order to access hazard and response information for that material. In transportation, identification numbers must be displayed on the following:

- Nonbulk packages of hazardous materials (except limited quantities) printed adjacent to the required labels on the package
- Bulk packages of hazardous materials, such as cargo tanks, portable tanks, tank cars, and other bulk shipments; on bulk packages, identification numbers can be displayed on an orange panel, in the center of the appropriate placard, or in the center of a placard-sized, square-on-point white display (Figure 13.8.3)

On shipping papers, identification numbers are preceded by the prefix "UN" (United Nations) for domestic and international shipments or "NA" (North American) for shipments considered hazardous only within North America.

NFPA 704 *markings* are diamond-shaped symbols used within facilities to alert people to the type and degree of

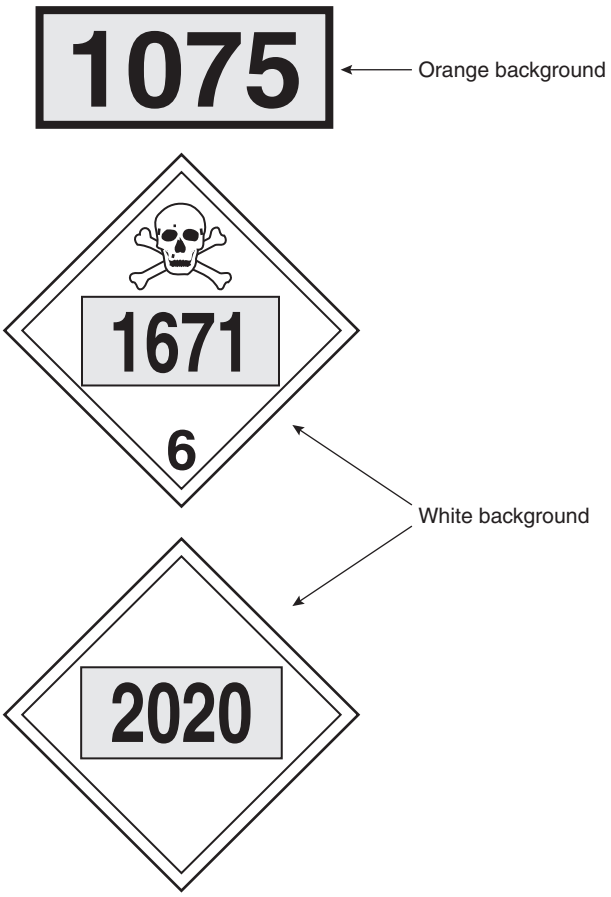

FIGURE 13.8.3 Identification Numbers. The rectangular box has an orange background. The diamonds have white backgrounds.

hazard. (See NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response.*) They may be found on nonbulk packages; however, they are not used on transport vehicles. The diamond-shaped symbol is divided into four color-coded quadrants (Figure 13.8.4). The blue in the left quadrant refers to the health hazard; the red in the top quadrant indicates the flammability hazard; the yellow in the right quadrant refers to the reactivity hazard; and the bottom quadrant carries special information, such as "OX" for oxidizers or "W" for water-reactive materials. Each quadrant contains a number from 0 to 4 that represents the relative degree of hazard (0 is low; 4 is high) (Figure 13.8.5).

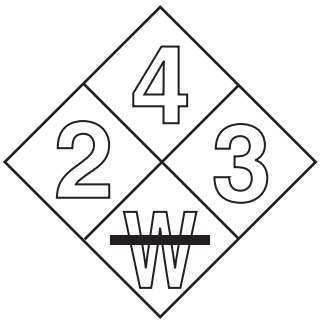

FIGURE 13.8.4 Sample NFPA Marking (Source: 2007 edition of NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*)

NFPA 704 Marking System

Scale	Health Hazard	Flammability Hazard	Instability Hazard
4	Materials that, under emergency conditions, can be lethal	Materials that will rapidly or completely vaporize at atmospheric pressure and normal ambient temperature or that are readily dispersed in air and that burn readily	Materials that in themselves are readily capable of detonation, explosive decomposition, or explosive reaction at normal temperatures and pressures. This includes materials that are sensitive to localized thermal or mechanical shock at normal temperatures and pressures.
3	Materials that, under emergency conditions, can cause serious or permanent injury	Liquids and solids that can be ignited under almost all atmosphere and temperature conditions. Materials in this degree produce hazardous atmospheres with air under almost all ambient temperatures or, though unaffected by ambient temperatures, are readily ignited under almost all conditions	Materials that in themselves are capable of detonation, explosive decomposition, or explosive reaction but that require a strong initiating source or that must be heated under confinement before initiation
2	Materials that, under emergency conditions, can cause temporary incapacitation or residual injury	Materials that must be moderately heated or exposed to relatively high ambient temperatures before ignition can occur. Materials in this degree would not under normal conditions form hazardous atmospheres with air but under high ambient temperatures or under moderate heating might release vapor in sufficient quantities to produce hazardous atmospheres with air.	Materials that in themselves undergo violent chemical change at elevated temperatures and pressures
1	Materials that, under emergency conditions, can cause severe irritation	Materials that must be preheated before ignition can occur. Materials in this degree require considerable preheating, under all ambient temperature conditions before ignition and combustion can occur.	Materials that in themselves are normally stable but that can become unstable at elevated temperatures and pressures
0	Materials that, under emergency conditions, would offer no hazard beyond that of ordinary combustible materials	Materials that will not burn. This includes any material that will not burn in air when exposed to a temperature of 1500°F (816°C) for a period of 5 minutes.	Materials that in themselves are normally stable even under fire conditions

FIGURE 13.8.5 Significance of Numbers on NFPA 704 Marking System (Source: 2001 edition of NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*)

Military markings are used to indicate hazardous materials for military shipments.

Special hazard communication markings are used in facility situations to indicate hazardous materials.

Warning labels indicate the presence of hazardous materials using words such as *warning, danger, caution,* and *poison.*

Pipeline markers mark the location of pipelines, especially where the pipeline crosses a street.

Container markings, such as the stenciled name of the contents, also may indicate the presence of hazardous materials.

5. *Look for placards and labels.* Placards and labels are diamond-shaped symbols that are used internationally to communicate the presence of hazardous materials in transportation. Placards 10.8 in. by 10.8 in. (273 mm by 273 mm) are required on some bulk packages, such as transport vehicles (e.g., cargo tanks, portable tanks, tank cars, and hopper cars). Labels, 4 in. by 4 in. (102 mm by 102 mm) or smaller for cylinders, are found on some nonbulk packages. Placards and labels convey information by their color, symbol, hazard class and division number, and either the hazard class wording or four-digit identification number. DOT Chart 12 provides examples of U.S. and Canadian placards and labels (Figure 13.8.6).

Transport vehicles and freight containers could contain up to 1000 lb (454 kg) of certain hazardous materials without a placard being applied. Limited-quantity, Division 6.2 (infectious substance/etiologic agents), and ORM-D shipments do not require placards. To determine load/empty status, use the shipping papers. Square white backgrounds are used behind Division 1.1, Division 1.2, Division 2.3, Division 6.1 Packing Group I Zone A, and Class 7 placards to indicate special handling. The dangerous placard indicates a mixed load of several classes of hazardous materials.

6. *Obtain and review facility documents or shipping papers.* Shipping papers accompany each shipment during transportation and provide detailed information about the contents of the shipment. These shipping papers are used in the various modes of

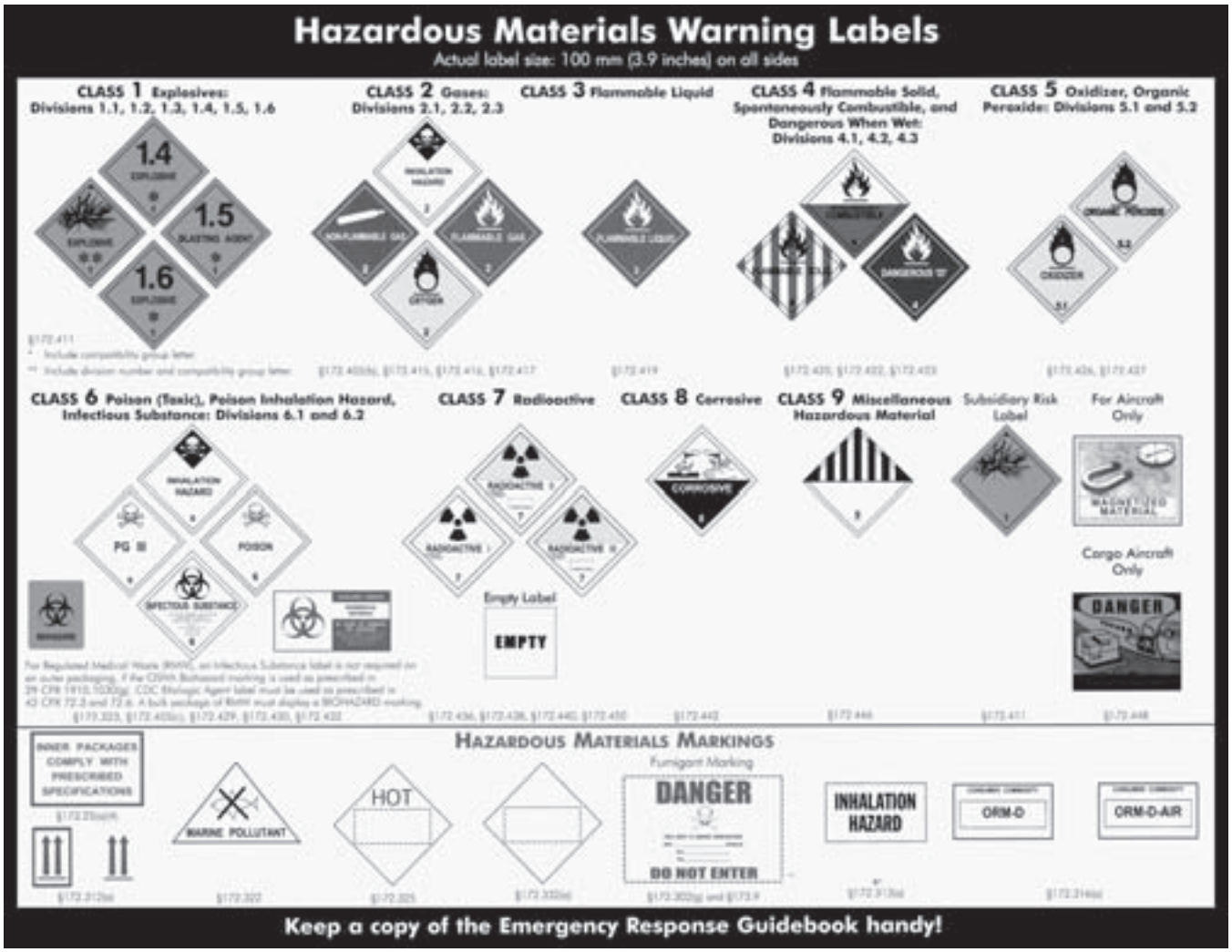

FIGURE 13.8.6 DOT Chart 12 Depicting Hazardous Materials Marking, Labeling, and Placarding

TABLE 13.8.3 Shipping Papers by Mode of Transportation, Title of Shipping Paper, Location, and Responsible Person

Mode of Transportation	*Title of Shipping Paper*	*Location of Shipping Papers*	*Responsible Person*
Highway	Bill of lading or freight bill	Cab of vehicle	Driver
Rail	Train list or train consist and/or waybill	With member of train crew (conductor or engineer)	Conductor
Water	Dangerous cargo manifest	Wheelhouse or pipelike container or barge	Captain or master
Air	Air bill with shipper's certification for restricted articles	Cockpit (may also be found attached to the outside of packages)	Pilot

transportation (highway, rail, water, and air) and are listed in Table 13.8.3 by mode of transportation, title of shipping paper, location of shipping papers, and the person responsible. Shipping papers may indicate the presence of hazardous materials through a variety of required entries (all of which are not always present). The most common entries include the proper shipping name, hazard class or division, identification number, packing group, and the total quantity (by weight, volume, or as otherwise appropriate).

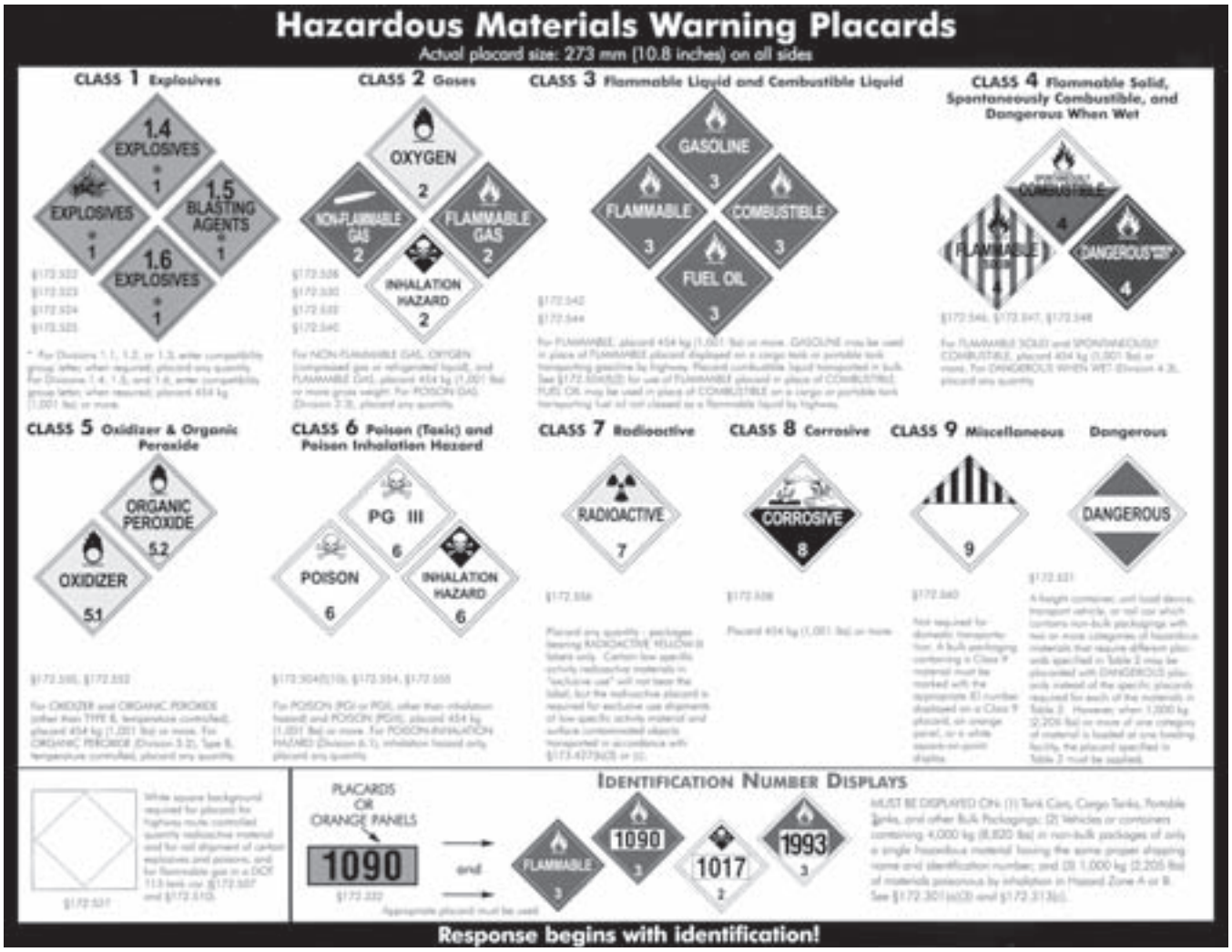

FIGURE 13.8.6 Continued

Additional entries may include technical and chemical group names, the letters RQ (reportable quantity notation) POISON—INHALATION HAZARD, LIMITED QUANTITY notation, DANGEROUS WHEN WET notation, and shipper contact information. Shipping papers also include telephone number and emergency-response information for the specific commodity.

Facility documents include the material safety data sheet (MSDS). The MSDS is a document that provides information about the composition, physical and chemical properties, health and safety hazards, emergency response, and waste disposal of materials required by OSHA in 29 CFR 1910.1200.

7. *Identify clues (other than occupancy/locations, container shape, markings/color, and placards/labels) that use sight, sound, and odor to indicate hazardous materials.* Sensual indications include chemical odors, dead animals and fish, vapor clouds, flames or smoke, irritation of the skin or eyes, the hiss of escaping gas, or the sound of an explosion.

As soon as the presence of hazardous materials is detected, move to the next task in the analysis process.

Initiating Command and Control Activities

Although not part of the analysis process, command and control activities should be initiated on detecting the presence of hazardous materials and simultaneously with the initial survey of the situation. These command and control actions are taken: (1) to protect the responder and others during completion of analysis and planning duties, (2) to provide for a command structure at the incident, and (3) to provide for notification of resources required to handle the situation. Specific procedures for initiating command and control activities are found in the local emergency response plan or organization's standard operating procedures.

To initiate command and control activities, take the following steps:

1. *Implement an incident command system.* This step provides organization of the incident scene and may begin prior to arrival on the scene.
2. *Locate personnel at a safe distance from the problem.* With consideration of the terrain and weather conditions, response personnel should stop at a safe location from the incident—uphill, upwind, and upstream. Suggested minimum "safe" distances should be specified in the local emergency response plan or the organization's standard operating procedures. At this point, the analysis process is not complete, and sufficient information is not available to determine safe distances.
3. *Initiate the notification process.* Specific procedures and contacts for notification of required resources should be developed prior to an emergency and listed in the local planning documents.
4. *Control access to the site.* Prevent unauthorized persons from entering the area to reduce the negative outcomes in the incident.

The command and control actions taken depend on both the responder's level of training and the resources available. They should be attempted without risk to the responder.

Surveying the Hazardous Materials Incident

After detecting the presence of hazardous materials in an emergency, and while initiating command and control activities, the next task is to survey or inventory the hazardous material incident. Completion of this task provides an inventory of the containment systems and materials involved, materials released, and surrounding conditions. This incident survey should be conducted from a safe distance, using aided vision, without exposure to the released materials.

The following steps should be completed during the survey of a hazardous material incident:

1. *Identify each containment system by type, identifier, and size.* Containment systems fit into one of three types: (1) nonbulk, (2) bulk, or (3) facility containment systems (Table 13.8.4). The containment system identifier (e.g., facility or carrier name and number) is used to differentiate one containment system from another and to allow tracking of that container throughout the incident. The quantity within, or capacity of, the containment system can be obtained from markings on the container or entries on the shipping papers or facility documents. The quantity information will help indicate the magnitude of the problem.

2. *Identify the name, identification number, or placard applied to each hazardous material containment system.* This information provides a means of accessing various sources of hazard and response information.

For facilities. Sources for identifying the material include pre-emergency planning document, markings and color, contact with the facility manager, and review of appropriate MSDS.

TABLE 13.8.4 Types of Nonbulk, Bulk, and Facility Containment Systems[4]

Transportation		*Facility Containment Systems*
Nonbulk	*Bulk*	
Bags	Bulk bags	Buildings
Bottles	Bulk boxes	Machinery
Boxes	Cargo tanks	Open piles (outdoors and indoors)
Carboys	Covered hopper cars	Piping
Cylinders	Freight containers	Reactors (chemical and nuclear)
Drums	Gondolas	Storage bins, cabinets, or shelves
Jerricans	Intermediate bulk containers (IBCs)	
Multicell	Pneumatic hopper trailers	
Tanks and storage vessels packages	Portable tanks and bins	
Wooden barrels	Protective overpacks for radioactive materials	
	Tank cars	
	Tank containers	
	Ton containers	
	Van trailers	

In transportation. The identity of the hazardous material can be determined from the identification number, commodity stencil, type of placard or label applied, shipping paper entries, and manufacturer, shipper, or consignee contacts using the 24-hour emergency telephone number on the shipping papers. Pipeline markers provide the name of the commodity or at least the name and telephone number of the pipeline company.

3. *Identify leaking containment systems.* Clues indicating leakage include material on the outside of the containment system, taste or smell, the presence of vapor clouds, or the operation of a pressure relief valve. If possible during the survey, note the form of the released material (solid, liquid, or gas) and the location of the release.

4. *Identify the surrounding conditions.* Surrounding conditions should be noted when surveying hazardous material incidents. These conditions include topography, land use (including utilities and fiber optic cables), accessibility, weather conditions, bodies of water (including recharging ponds), public exposure potential, and the nature and extent of injuries. If a facility is involved, look for information about floor drains, ventilation ducts, air returns, and so on, as appropriate.

For ease of collection, recording, and interpretation of information obtained during the survey of an incident, a hazardous material incident survey form or similar form may prove helpful (Figure 13.8.7).

Finally, the information collected in the incident survey should be reviewed to verify its accuracy. For example, if the shipping paper identifies the material as a gas and a solid is being released, some of the information obtained may not be correct. An understanding of the characteristics of various containment systems will help to verify information on the contents.

Collecting and Interpreting Hazard and Response Information

Once a hazardous material is identified, information about the material's hazards, behavior characteristics, and suggested response options is collected. This information, which may be collected simultaneously with determining the extent of containment system damage, is used to predict the behavior of that material. The information to be collected is divided into six basic groups: (1) material identification information, (2) physical properties, (3) chemical properties, (4) physical hazards, (5) health hazards, and (6) response information. The task of obtaining, recording, and interpreting hazardous material information can be lengthy and rigorous. Various forms are being used to record hazard and response information (Figure 13.8.8).

A number of resources are available for this task, including the following.

Printed Materials. Printed materials include various response guides and MSDSs.

Various *response guides* are available for use in obtaining hazard, behavior, and response information. A listing of the sources of the most common response guides is found in Table 13.8.5. As one will note from the X's in Table 13.8.6, no one printed material source provides all the information. Therefore, more than one resource may have to be consulted to obtain the needed information. An understanding of the type of information available from each resource is important. These references augment personal knowledge and experience.

Material safety data sheets (MSDSs) are available at facilities from the manager or other facility personnel and may be found in transportation. CHEMTREC, the Chemical Transportation Emergency Center, has more than 500,000 MSDSs on file if one is not available locally. MSDSs typically provide the following types of information:

1. Physical and chemical characteristics
2. Physical hazards of the material
3. Health hazards of the material
4. Signs and symptoms of exposure
5. Routes of entry
6. Permissible exposure limits
7. Responsible party contact
8. Precautions for safe handling (including hygiene practices, protective measures, and procedures for cleanup of spills or leaks)
9. Applicable control measures including personal protective equipment
10. Emergency and first aid procedures

Technical Resources. A number of technical resources are available, including the following:

1. CHEMTREC is part of the American Chemical Council (ACC). CHEMTREC operates around the clock to receive toll-free calls from the United States and Canada through a wide-area telephone service number (800) 424-9300. If in Washington, DC, or Alaska, call (202) 483-7617. CHEMTREC can usually provide immediate hazard information from the CHEMTREC files. CHEMTREC will also contact the shipper; therefore, be prepared to provide CHEMTREC with the following information when available:

- Caller's name and phone number where caller can be reached
- Name of the carrier, shipper, manufacturer, or facility operator
- Nature, location, and time of the incident
- Name of the material (or other identifying information)
- Container type, railcar or truck number, vessel name, or other identifying information such as a railcar's reporting marks (initials) and number

CHEMTREC can also provide a teleconferencing bridge, connecting technical specialists with those needing technical information.

2. *National Response Center* (NRC), operated by the U.S. Coast Guard, receives reports required from spillers of hazardous substances. The NRC also acts as the notification, communications, technical assistance, and coordination center for the National Response Team. After receiving a report, the NRC will immediately relay the information to the responsible, predesignated, federal on-scene coordinator and other resources of

Hazardous Material Incident Survey Form

Location _____

Date ___ - ___ - ___ Time: ___ : ___ ___ Weather Conditions _____

Terrain _____

Closest Populated Buildings _____

Closest Bodies of Water _____

Closest Other Buildings _____

No. Deaths _____ No. Injuries _____ Remedial Actions Taken _____

Containment System			Material Identification			Release		
Container Type	Container ID No.	Qty	DOT ID No.	Placard	Name of Material	Yes	Form	Location
						☐	☐ Solid ☐ Liquid ☐ Gas	
						☐	☐ Solid ☐ Liquid ☐ Gas	
						☐	☐ Solid ☐ Liquid ☐ Gas	
						☐	☐ Solid ☐ Liquid ☐ Gas	
						☐	☐ Solid ☐ Liquid ☐ Gas	
						☐	☐ Solid ☐ Liquid ☐ Gas	

Sketch of scene

FIGURE 13.8.7 Hazardous Material Incident Survey Form. This worksheet is used for recording information collected during the task of surveying a hazardous material incident.[5]

Hazardous Material Data Sheet

Containment System ID.

Material Name _____ DOT ID Nº _____ STCC Nº _____

Synonyms _____

Hazard Class _____

NFPA 704 Marking: Health _____ Flammability _____ Reactivity _____ Other _____

Physical Properties

Form	Color	Odor	Chemical Formula	Molecular Wt.
☐ Solid ☐ Liquid ☐ Gas				

Chemical Properties

Actual Temp.	Boiling Point	Melting Point	Vapor Pressure	Expansion Ratio	Specific Gravity	Vapor Density	Soluble?	Degree of Solubility
							☐ Yes	

Physical Hazards

Flammable (heat/fire)	☐ Yes
Cryogenic (cold)	☐ Yes
Oxidizer (supports combustion)	☐ Yes
Explosive	☐ Yes
Reactive	☐ Yes
To What? _____	

Actual Temperature	Flashpoint	Ignition Temperature
Actual Concentration	**Flammable Range**	**Toxic Products of Combustion**

Health Hazards

Acute Health Hazards:

Poisonous	☐ Yes
Corrosive	☐ Yes
To What? _____	
Asphyxiation	☐ Yes
Etiologic	☐ Yes
Radiation	☐ Yes
Type: alpha beta gamma	

Chronic Health Hazards:

Carcinogen	☐ Yes
Mutagen	☐ Yes
Teratogen	☐ Yes
Aquatic Hazard	☐ Yes

Actual Concentration	Non–Life Threatening Exposure Limits		
	TLV-TWA(PEL)	TLV-C	TLV-STEL
Odor Threshold	**Life Threatening Exposure Limits**		
	IDLH	LC_{50}	LD_{50}

Route of Entry	☒ = YES	Toxicity Rating	Notes
Inhalation	☐	1 2 3 4 5 6	
Dermal	☐	1 2 3 4 5 6	
Ingestion	☐	1 2 3 4 5 6	

Response Information

Evacuation Distances _____

First Aid _____

_____

Personal Protective Equipment _____

Decontamination _____

Extinguishing Agents _____

Neutralizing Agents _____

FIGURE 13.8.8 Hazardous Material Data Sheet. This worksheet is used for recording information obtained during the task of collecting and interpreting hazard and response information.[5]

TABLE 13.8.5 Common Reference Guides for Collecting Hazardous Response Information and Their Sources

Printed Information	*Source*
Emergency Response Guidebook	U.S. Department of Transportation Research and Special Programs Administration Washington, DC 20590
Fire Protection Guide to Hazardous Materials, National Fire Protection Association (NFPA 325, NFPA 49, and NFPA 491M)	National Fire Protection Association 1 Batterymarch Park Quincy, MA 02269
Emergency Handling of Hazardous Materials in Surface Transportation (EH) *Emergency Actions Guides* (EAG)	Association of American Railroads 50 F Street, NW Washington, DC 20001
U.S. Coast Guard CHRIS Manual Series (CHRIS) *Hazardous Chemical Data* CG-446-2	Superintendent of Documents U.S. Government Printing Office Washington, DC 20402
Farm Chemicals Handbook (FCH)	Meister Publishing Company 37841 Euclid Avenue Willoughby, OH 44094
NIOSH/OSHA References (NIOSH) *Pocket Guide to Chemical Hazards*	Superintendent of Documents U.S. Government Printing Office Washington, DC 20402
Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices	American Conference of Governmental Industrial Hygienists Kemper Woods Center 1330 Kemper Meadow Drive Cincinnati, OH 45240

Abbreviations Used for References

Primary Resources		*Secondary Resources*	
ERG	*Emergency Response Guidebook*	**EAG**	Association of American Railroads' *Emergency Action Guides*
NIOSH	*Pocket Guide to Chemical Hazards*	**EH**	Association of American Railroads' *Emergency Handling of Hazardous Materials in Surface Transportation*
		NFPA	National Fire Protection Association's *Fire Protection Guide to Hazardous Materials*
		CHRIS	U.S. Coast Guard's *Hazardous Chemical Data*
		ACGIH	American Conference of Governmental Industrial Hygienists' *Threshold Limit Values and Biological Exposure Indices*
		FCH	*Farm Chemicals Handbook*
		MSDS	Material safety data sheet

Source: Ericksen, Keffer, and Wright.[5]

the federal government. The NRC can be contacted by calling (800) 424-8802.

3. *Local poison control center.* For consumer products, comprehensive hazard information is available through regional poison control centers. The local planning documents should contain the telephone number.

4. *Manufacturer's technical medical staff.* For bulk industrial chemicals, assistance may be available from the technical medical staff of the manufacturer. CHEMTREC will make the contact.

5. *Agency for Toxic Substances and Disease Registry (ATSDR).* For chemical mixtures or wastes, when a second opinion is required or when the chemical is unknown, a preferred source of information is the ATSDR, a part of the Centers for Disease Control and Prevention of the U.S. Department of Health and Human Services. ATSDR can be reached by calling (404) 498-0120.

6. *Department of Energy.* For radioactive materials, contact the Department of Energy by calling (202) 586-8100.

TABLE 13.8.6 A Cross-Reference of Information Available in Common Reference Guides[5]

	Primary Resources		Secondary Resources						
Required Information	*ERG*	*NIOSH*	*EAG*	*EH*	*NFPA*	*CHRIS*	*ACGIH*	*FCH*	*MSDS*
DOT ID No.	X	X	X	X		X			X
STCC No.			X	X					
Synonyms		X	X		X	X		X	X
Hazard class			X	X	X	X		X	X
NFPA 704 marking			X		X	X			
Form		X	X	X	X	X		X	X
Color		X	X	X	X	X		X	X
Odor		X	X	X	X	X		X	X
Chemical formula		X	X		X	X		X	X
Molecular weight		X	X			X			X
Boiling point		X	X		X	X		X	X
Melting point		X	X			X		X	X
Vapor pressure		X	X			X			X
Expansion ratio									
Specific gravity			X	X	X	X			X
Vapor density			X	X	X	X			X
Soluble		X	X	X	X	X		X	X
Degree of solubility		X	X	X	X	X		X	X
Flashpoint		X	X	X	X	X		X	X
Ignition temperature			X		X	X			X
Flammable range		X	X		X	X			X
Toxic products of combustion			X			X		X	X
Reactive to what	X	X	X	X		X			X
Odor threshold			X			X			X
IDLH		X				X			X
LD_{50}						X		X	X
LC_{50}								X	X
TLV-C		X				X	X		X
TLV-STEL			X			X	X		X
TLV-TWA		X	X				X		X
PEL		X							X
Route of entry	X	X	X	X	X	X		X	X
Toxicity rating					X	X			
Evacuation distances	X		X	X		X			X
First aid	X	X	X	X		X		X	X
Personal protective equipment	X	X	X	X	X	X		X	X
Decontamination	X	X	X					X	X
Extinguishing agents	X		X	X	X	X		X	X
Neutralizing agents			X	X		X			X

Note: An "X" in the intersection of the resource and the required information indicates that the information is typically found in that publication.

Source: Ericksen, Keffer, and Wright.[5]

7. *Hazardous material emergency response teams.* Assistance from these sources ranges from immediate telephone advice to the dispatching of emergency teams to actual assistance in field operations. Some common examples include the following:

- Pesticide Safety Team Network
- CHLOREP Teams
- U.S. Coast Guard Strike Teams
- Carrier Response Teams

- U.S. Environmental Protection Agency Regional Response and Technical Assistance Teams
- Association of American Railroads, Bureau of Explosives

On contact with these resources, provide as much information as possible; especially the full name, form, use, and concentration of the chemical, when available. An occupational-health physician may be required to obtain or interpret information from any of these sources. Assistance in contacting many of these technical resources may be obtained from CHEMTREC or the NRC, if not listed in the local planning documents.

Assessing the Extent of Containment System Damage

Information on the types and extent of damage to a containment system is used in predicting the likely behavior of the containment system and its contents. This task can be initiated simultaneously with collecting information about the materials involved. Provide appropriate personal protective equipment for the response personnel if they could be exposed to released materials. Contact technical personnel with knowledge of the type of containment systems involved for assistance.

The following steps will help determine the extent of damage to a containment system:

1. *Identify containment systems that are damaged.* Indications of damage include abnormal orientation or position of the containment system, damage to other containment systems in the area, or a change in shape of the containment system.

2. *Determine the construction of the damaged containment system.* Before inspecting the damaged containment system, review the containment system's basic design, construction, and secondary containment features.

3. *Determine the type and location of closures on the containment system.* Review the closures on the containment system by name and purpose. Use of standard terminology will help describe the problem to the technical resources.

4. *Determine the type and location of any damage to the container or its closures.* Dents, cracks, gouges, scores, corrosion, and punctures should be noted. Using appropriate personal protective equipment when necessary, the containment system must be evaluated for signs of failure or potential failure. If the containment system has not already failed, it may have been weakened and result in failure.

5. *Determine the extent of the damage to the container or its closures.* Information on the extent of damage (e.g., the radius of curvature for dents or the depth of scores and gouges on pressure tank cars) should be determined. It may be necessary to determine the pressure in a bulk packaging or facility containment system using either a pressure gauge or the temperature of the contents.

6. *Estimate the release rate.*

Figure 13.8.9 provides an example of a form used for determining the extent of damage to tank cars.

Predicting Likely Behavior

After information on the characteristics of the material and the extent of damage to the containment system has been collected, the next task is to predict their likely behavior. This prediction, or "mental movie," is used throughout the response activity as a reference point. A mental movie is made for each containment system and hazardous material involved and is based on the worst possible case. As additional information is obtained, the mental movie is modified. The steps for predicting the behavior of the containment system and its contents include the following:

1. *Identify the types of stress or potential stress on a containment system and/or its contents.* Stress is the applied force or system of forces that tend to strain or deform a body (either the containment system or the contents). The types of stress include thermal, mechanical, chemical, irradiation, and etiologic. Thermal, mechanical, and chemical stresses can typically be identified visually, whereas irradiation and etiologic are more difficult to identify. Considerations include type and characteristics of the containment system, type of stress, amount of stress applied, intensity of stress, and duration of stress.

2. *Predict the way in which the containment system will breach.* A breach is an opening (failure) caused by damage to the containment system through which matter and/or energy can or does escape. The types of breach include disintegration, runaway linear cracking, closures that open up, punctures, and splits or tears. Considerations include type and duration of the stress being applied, behavior of the containment system under the stresses applied, behavior of the contents, location of the applied stresses, force of opening of the containment system, size of breach, and speed of the breach event. Even if the containment system has already breached, this prediction step must be considered in light of a further breach.

3. *Predict the way in which the contents will be released.* Release is the escape of the contents through a breach in a containment system. The types of release include *detonation*—the disintegration of the containment system and/or detonation of the contents; *violent rupture*—the runaway cracking of the containment system or the rapid expansion of the contents that burst the containment system abruptly; *rapid relief*—pressurized flow of the contents through closures, splits or tears, and punctures; and *spill or leak*—gradual flow through closures, splits or tears, and punctures. Considerations include type of breach, location of breach, quantity of contents, flow characteristics of contents, release rate, length of release, and weather conditions.

4. *Predict the dispersion pattern that will create the engulfed area.* Dispersion is the scattering of the matter and/or energy (from the point of release) to form an engulfed area. The engulfed area is the actual or potential area of exposure from a hazardous material or its containment system. The types of dispersion patterns include hemisphere, cloud, plume, cone, stream, pool, and irregular. Considerations include type of release, form of the released contents, weather conditions, topography, release rate, solubility of material, secondary reactions,

Tank Car Damage Assessment

Car Initials & Number	
Material	

Tank Car Characteristics/Features

Type of Car: ☐ Non-pressure ☐ Pressure ☐ Cryogenic ☐ Other _____

Specification No:	**Tank Test Pressure:**	**Tank Capacity:**
Build Date:	**Underframe:** ☐ Continuous ☐ Stub Sill	
Jacketed: Y N	**Thermal Protection:** J Jacketed T Sprayed on	**Insulated:** Y N
Construction Material: *Type/Grade* _____ *Thickness* _____		**Stress:** T M C O N

Fitting Damage

Type Fitting	Damage	Description Damage/Leak
☐ Liquid Valve	Y N ☐ Leaking	
☐ Vapor/Air Valve	Y N ☐ Leaking	
☐ Bottom Outlet Type: _____	Y N ☐ Leaking	
☐ Pressure Relief Device Type: _____	Y N ☐ Leaking	
☐ Vacuum Relief Valve	Y N ☐ Leaking	
☐ Gauging Device Type: _____	Y N ☐ Leaking	
☐ Manway Cover Plate	Y N ☐ Leaking	
☐ Fill Hole	Y N ☐ Leaking	
☐ Sample Line	Y N ☐ Leaking	
☐ Thermometer Well	Y N ☐ Leaking	
☐ Washout	Y N ☐ Leaking	
☐ Sump	Y N ☐ Leaking	
☐ Other Type: _____	Y N ☐ Leaking	

Jacket, Tank, and Head Damage

Indicate location and severity of damage (punctures, cracks, scores, gouges, wheel burns, dents, rail burns, underframe, and leaks) on the appropriate diagram(s).

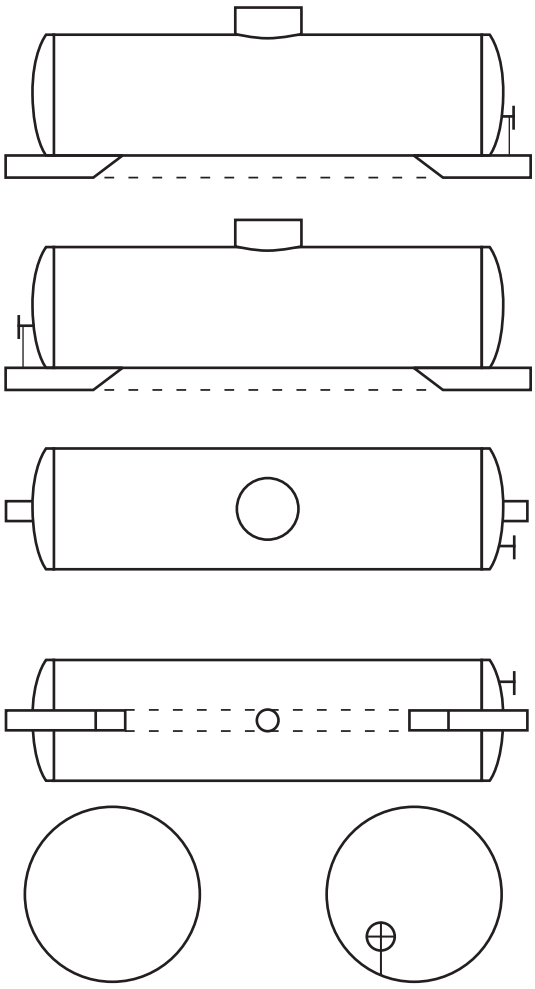

FIGURE 13.8.9 Tank Car Damage Assessment. This worksheet is used for recording results of damage assessment for rail tank cars.

melting point, freezing point, boiling point, vapor density, specific gravity, secondary containment, vapor pressure, and expansion ratio. For fixed facilities, consider tank spacing, impoundment and diking, tank venting and flaring systems, transfer operations, monitoring and detection systems, and fire protection systems.

5. *Predict the length of contact that exposures will have with the released contents. Contact* means to be exposed to something undesirable or injurious. Type of contact is considered in relation to time: short term refers to minutes and hours; medium term is associated with days, weeks, and months; and long term is in terms of years and generations. Considerations include form of the material on release, dispersion pattern, weather conditions, topography, distance to exposure, barriers or shielding, speed of dispersing materials, and quantity released.

6. *Predict the hazards that will cause harm.* Harm is the injury or damage caused by being exposed to the hazards of the released contents. Types of hazards include physical hazards, including thermal and mechanical effects; and health hazards, including chemical (poisonous, corrosive, and asphyxiation), radiation, and etiologic effects. Considerations include hazards associated with the released contents, concentrations of released materials, duration of contact, and how often the exposures will come into contact with the released materials.

To assist in predicting the behavior of the containment system and its contents, a behavior model form is suggested (Figure 13.8.10).

If unable to make all the predictions necessary to analyze the incident, seek help from the following resources: manufacturer, shipper and consignee, carrier, and federal, state, and local agencies involved with hazardous materials. A number of response guides also indicate the effects of mixing various chemicals.

Estimating Outcomes

This final task in the analysis process results in an indication of the magnitude of the problem in terms of outcomes within the engulfed area. The engulfed area is the actual or potential area of exposure from a hazardous material. The following steps should be taken to estimate outcomes in the engulfed area:

1. *Determine the dimensions of an engulfed area.* Using the Table of Initial Isolation and Protective Action Distances in the *Emergency Response Guidebook,* planning documents, or dispersion modeling programs, identify the potential size of the dispersion pattern (Table 13.8.7). Considerations include wind speed and direction and topography.

2. *Estimate the number of exposures within the engulfed area.* Exposures include people, property, the environment, and critical systems. Considerations include direction of wind, time of day, day of the week, setting (rural or urban), occupancies in area (schools, businesses, industry, transportation), bodies of water, sewer systems, and essential services.

3. *Determine the concentrations of a released hazardous material within the engulfed area.* Resources, such as monitoring equipment, computer dispersion modeling systems, toxic chemical release reporting forms, and a programmable calculator with equations, are available for this step. Information about odor may provide an insight on the level of concentration, but not without risk.

In some cases, monitoring equipment may be used to identify or classify unknown materials, verify the identity of hazardous materials, or determine the concentration of the hazardous materials. Monitoring equipment includes, but is not limited to, the following:

- Colorimetric tubes
- CO meter
- Combustible-gas meter
- Organic-vapor analyzer
- Oxygen meter
- Passive dosimeter
- Personal air-monitoring equipment
- Photoionization detectors
- pH papers and strips
- Radiation-detection instruments

Where monitoring equipment is available, personnel should be able to select the appropriate monitoring equipment considering its limitations, perform field testing procedures, operate the equipment to collect data, and record and interpret the results. If monitoring equipment is not provided, the potential sources of monitoring equipment and personnel to operate the equipment should be identified as part of the pre-emergency planning activities.

4. *Predict the extent of physical, health, and safety hazards within the engulfed area under the current conditions.* Predicting health hazards requires an understanding of the various exposure limits, including (1) immediately dangerous to life and health value (IDLH), (2) lethal concentrations (LC_{50}), (3) lethal dose (LD_{50}), (4) permissible exposure limit (PEL), (5) threshold limit value-ceiling (TLV-C), (6) threshold limit value-short-term exposure limit (TLV-STEL), and (7) threshold limit value-time weighted average (TLV-TWA).

5. *Predict the areas of potential harm within the engulfed area.* Considerations address likely concentrations, lethal concentrations, length of contact, frequency, and intensity of harm.

6. *Estimate the outcomes within an engulfed area* (Figure 13.8.11). Considerations include number of exposures in the engulfed area, age and condition of the exposures, anticipated reaction of exposures on contact with material, and weather conditions.

The purpose of analyzing the hazardous material problem is to determine the likely magnitude of the problem in terms of outcomes. Although time consuming, this process is an essential part of managing a hazardous material incident. As the incident conditions change, analysis information must be reviewed and updated. When decisions regarding protective actions and control measures are made before completing the analysis process, the risk to the responder is greater.

Behavior Model	Containment System ID.

Material: _____ Quantity: _____

Form of Released Material: ☐ Gas ☐ Liquid ☐ Solid

Containment System Type: _____

Weather Conditions: Ambient Temperature: _____° Wind Speed: _____ m.p.h. Rain ☐ Snow ☐

Terrain: _____

Event Sequence

Stress	Breach	Release	Engulf	Contact	Harm

Prediction Steps

Identify the Type of Stress	Predict the Type of Breach	Predict the Type of Release	Predict the Dispersion Pattern	Predict the Length of Exposure	Predict the Hazard Causing the Harm

Behavior Options

Thermal Mechanical Chemical	Disintegration Runaway linear cracking Closures open up Punctures Splits or tears	Detonation Violent rupture Rapid relief Spill or leak	Hemisphere Cloud Plume Cone Stream Pool Irregular	Short term Medium term Long term	Physical *Thermal* *Mechanical* Health *Poisonous* *Corrosive* *Asphyxiation* *Radiation* *Etiologic*

FIGURE 13.8.10 Behavior Model. This worksheet is used for predicting the behavior of a containment system and its contents in a hazardous material incident (Source: Adapted from Ludwig Benner's *Hazardous Materials Emergencies,* 1978[6])

TABLE 13.8.7 Sample of Table of Initial Isolation and Protective Action Distances

		Small Spills (from a small package or small leak from a large package)						Large Spills (from a large package or from many small packages)					
		First **ISOLATE** in All Directions		Then **PROTECT** Persons Downwind during—				First **ISOLATE** in All Directions		Then **PROTECT** Persons Downwind during—			
				Day		Night				Day		Night	
ID No.	*Name of Material*	*Feet*	*(Meters)*	*Miles*	*(Kilometers)*	*Miles*	*(Kilometers)*	*Feet*	*(Meters)*	*Miles*	*(Kilometers)*	*Miles*	*(Kilometers)*
1005	Ammonia, anhydrous	100 ft	(30 m)	0.1 mi	(0.2 km)	0.1 mi	(0.2 km)	200 ft	(60 m)	0.3 mi	(0.5 km)	0.7 mi	(1.1 km)
1005	Ammonia, anhydrous, liquefied												
1005	Ammonia, solution, with more than 50% ammonia												
1005	Anhydrous ammonia												
1005	Anhydrous ammonia, liquefied												
1008	Boron trifluoride	100 ft	(30 m)	0.1 mi	(0.2 km)	0.4 mi	(0.6 km)	700 ft	(215 m)	1.0 mi	(1.6 km)	3.2 mi	(5.1 km)
1008	Boron trifluoride, compressed												
1016	Carbon monoxide	100 ft	(30 m)	0.1 mi	(0.2 km)	0.1 mi	(0.2 km)	400 ft	(125 m)	0.4 mi	(0.6 km)	1.1 mi	(1.8 km)
1016	Carbon monoxide, compressed												
1017	Chlorine	100 ft	(30 m)	0.2 mi	(0.3 km)	0.7 mi	(1.1 km)	900 ft	(275 m)	1.7 mi	(2.7 km)	4.2 mi	(6.8 km)
1023	Coal gas	100 ft	(30 m)	0.1 mi	(0.2 km)	0.1 mi	(0.2 km)	200 ft	(60 m)	0.2 mi	(0.3 km)	0.3 mi	(0.5 km)
1023	Coal gas, compressed												
1026	Cyanogen	100 ft	(30 m)	0.2 mi	(0.3 km)	0.7 mi	(1.1 km)	1000 ft	(305 m)	1.9 mi	(3.1 km)	4.8 mi	(7.7 km)
1026	Cyanogen, liquefied												
1026	Cyanogen gas												
1040	Ethylene oxide	100 ft	(30 m)	0.1 mi	(0.2 km)	0.1 mi	(0.2 km)	200 ft	(60 m)	0.3 mi	(0.5 km)	1.1 mi	(1.8 km)
1040	Ethylene oxide with nitrogen												
1045	Fluorine	100 ft	(30 m)	0.1 mi	(0.2 km)	0.3 mi	(0.5 km)	600 ft	(185 m)	0.9 mi	(1.4 km)	2.5 mi	(4.0 km)
1045	Fluorine, compressed												
1048	Hydrogen bromide, anhydrous	100 ft	(30 m)	0.1 mi	(0.2 km)	0.3 mi	(0.5 km)	400 ft	(125 m)	0.7 mi	(1.1 km)	2.1 mi	(3.4 km)
1050	Hydrogen chloride, anhydrous	100 ft	(30 m)	0.1 mi	(0.2 km)	0.4 mi	(0.6 km)	600 ft	(185 m)	1.0 mi	(1.6 km)	2.7 mi	(4.3 km)
1051	AC (**when used as a weapon**)	200 ft	(60 m)	0.1 mi	(0.2 km)	0.3 mi	(0.5 km)	1500 ft	(460 m)	1.0 mi	(1.6 km)	2.4 mi	(3.9 km)

Source: *2004 Emergency Response Guidebook.*[7]

Estimating Loss and Salvageable Amount Worksheet

Exposures	Estimated Exposed	Estimated Type of Harm	Estimated Outcomes	Amount Already Lost	Amount That Could Be Saved
People	#	Deaths	#		
		Injuries	#		
Property	$	Damage	$		
Environment	$	Damage	$		

FIGURE 13.8.11 Worksheet for Estimating Loss and Salvageable Amount. A worksheet is used for estimating both the outcomes in an emergency and the amount that could be saved.

PLANNING THE RESPONSE

Overview

Based on the magnitude of the problem, appropriate preventive measures and control actions are identified. Control actions include containment, confinement, and extinguishment. The potential impact (benefits and losses) to people, property, equipment, and the environment of each decision is considered.

The result of the planning process is the direction that the response effort will take to influence the sequence of events in the emergency and favorably change the outcome. Response planning is a process for identifying and evaluating response objectives (strategy) and response options (tactics). This process considers the available resources (e.g., personnel, personal protective equipment, and other tools and equipment). The planned response should be consistent with the local emergency response plan and the organization's standard operating procedures.

The planning process begins as part of the pre-emergency response planning efforts prior to the incident and continues on the scene of the incident, again from a safe location. Federal, state, and local agencies, industry, and carrier personnel may be called on to help.

The process of response planning is based on the following tasks:

1. Determine the response objectives.
2. Determine the available response options that could favorably change the outcomes.
3. Identify the personal protective equipment for the response options.
4. Identify an appropriate decontamination process for each response option.
5. Select the response options within the response community's capabilities that will most favorably change the outcomes.
6. Develop a plan of action including safety considerations.

Determining the Response Objectives (Strategy)

The first task in planning the response is to determine the response objectives (strategy) based on the estimated outcomes. The response objectives, based on the stage of the incident, are the strategic goals for stopping the event now occurring or keeping future events from occurring. The following two basic principles apply to these decisions:

1. One cannot influence events that have already happened or change the outcomes of those events.
2. The earlier that the event sequence can be interrupted, the more acceptable the loss.

The following steps should be taken when determining response objectives:

1. *Estimate the exposures that could be saved.* The level of response and the acceptable risk associated with a response is based on the exposures that can be saved. The number of exposures that could be saved is based on the estimated outcomes minus the exposures already lost (Figure 13.8.11).

2. *Determine the response objectives.* The response objectives, based on the stage of the incident, are the strategic goals for stopping the event now occurring or keeping future such events from occurring. Decisions should focus on changing the actions of the stressors, the containment system, and the hazardous material.

Determining Response Option (Tactics)

Two types of response options are available. Corrective actions are taken to resolve the immediate problem, whereas preventive actions are taken to prevent the immediate problem from escalating. The following actions are intended to keep losses to a minimum:

1. *Determine the potential response options available by response objective.* Response options are the tactical activities for stopping the event now occurring or keeping a predicted event from occurring. Response options are associated with the specific events in the emergency (Figure 13.8.12). An understanding of the procedures, equipment, and safety precautions for each technique is critical to this decision. Response options include one of the following types: defensive, offensive, and nonintervention. Control options involve either containment or confinement options. The responder must determine which type is appropriate for the incident based on the analysis of the problem.

Response Objective Analysis Form	Containment
	Material

Event Sequence

Stress	Breach	Release	Engulf	Contact	Harm

Response Objectives

Change Applied Stresses	Change Breach Size	Change Quantity Release	Change Size of Danger Zone	Change Exposures Contacted	Change Severity of Harm

Sample Response Options

Move stressor Move stressed system Shield stressed system	Chill contents Limit stress levels Activate venting devices Mechanical repair	Change container position Minimize pressure differential Cap off breach Remove contents	Barriers Dikes and dams Adsorbents Absorbents Diluents Reactants Overpack	Provide sheltering Begin evacuation Personal protective equipment	Rinse off contaminant Increase distance from source Provide shielding Provide prompt medical attention

FIGURE 13.8.12 Response Objective Analysis Worksheet. This worksheet is used for identifying response options in a hazardous material incident by response objective (Source: Adapted from Ludwig Benner's *Hazardous Materials Emergencies,* 1978[6])

2. *Estimate how each response option will affect the outcomes.* Before a response option is selected, the effect of that response option or combination of response options on the sequence of events and ultimately the outcomes should be reviewed (Figure 13.8.13).

The response options must be based on their expected effect on the outcomes.

Identifying Appropriate Personal Protective Equipment (PPE)

The purpose of identifying appropriate personal protective equipment for each response option is to determine the equipment required to implement the various response options identified. Again, pre-emergency planning cannot be overemphasized in the selection of personal protective equipment.

Estimating Effect of Each Response Option Worksheet

Exposures/Harm	Amount that could be saved	Amount that could be saved with option 1	Amount that could be saved with option 2	Amount that could be saved with option 3	Amount that could be saved with option 4	Amount that could be saved with option 5	Amount that could be saved with option 6
People death	#	#	#	#	#	#	#
People injuries	#	#	#	#	#	#	#
Property damage	$	$	$	$	$	$	$
Environ. damage	$	$	$	$	$	$	$

FIGURE 13.8.13 Worksheet for Estimating Effect of Each Response Option. This worksheet is used for estimating the effect of each response option on the outcomes of the incident.

The following PPE-related definitions are used for the purpose of this chapter.

Personal protective equipment is protective clothing and respiratory protection used to shield or isolate a person from the chemical and biological, physical, or thermal hazards that may be encountered at a hazardous material incident. No single combination of personal protective equipment is capable of protecting against all hazards. Personal protective equipment should be used in conjunction with other protective methods, such as medical monitoring and environmental surveillance. For any given situation, personal protective equipment should be selected to provide an adequate level of protection. Both overprotection and underprotection can be hazardous and should be avoided.

Protective clothing includes those pieces of apparel that are designed to protect the wearer from dermal (skin and eye) contact with the hazardous material. Protective clothing is divided into the following types:

Chemical-protective clothing

- Liquid splash-protective clothing
- Vapor-protective clothing

High temperature-protective clothing

- Proximity suit
- Entry suit

Structural fire-fighting protective clothing

Respiratory protection is the equipment designed to protect the wearer from inhaling the hazardous material. Respiratory protection is divided into the following six types:

1. Positive pressure self-contained breathing apparatus (SCBA)
2. Positive pressure air-line respirators with required escape unit
3. Closed circuit SCBA
4. Powered air-purifying respirators (PAPR)
5. Air-purifying respirator (APR)
6. Particulate respirator

Breakthrough time is the time it takes for the hazardous material to move through the protective material.

Penetration is the movement of a chemical through zippers, stitched seams, or imperfections, such as pinholes, in a protective equipment material.

Permeation is the process by which the chemical dissolves in and moves through a protective clothing material on a molecular level.

Degradation is the physical decomposition of the material due to exposure to chemicals, use, or ambient conditions, such as sunlight.

The identification of appropriate personal protective equipment requires completion of the following steps:

1. *Determine the name, concentration, and hazards of each of the materials involved.* This information should have been developed during the process of analyzing the hazardous material problem.

2. *Predict the types of exposure associated with each response option.* The types of exposure include the following:

- Immersion (e.g., standing in or handling the chemical)
- Splash (e.g., splash of a liquid from a drum or decontaminating people or equipment coming in direct contact)
- Airborne (e.g., exposure to airborne chemicals as a result of sampling)

3. *Determine the level of personal protective equipment required.* This step provides a list of the required pieces of personal protective equipment, including suits, gloves, and boots. If the chief threat is through liquid contact, the protective clothing should resist chemical degradation and penetration. For a threat from vapor contact, the protective clothing may have to be airtight and impermeable. The minimum requirement for respiratory protection, set by OSHA in 29 CFR 1910.120, for emergency conditions at hazardous material incidents (until concentrations have been determined) is positive-pressure self-contained breathing apparatus.

The U.S. Environmental Protection Agency identifies the following four levels of protection:

- *Level A* is the highest level of protection and should be worn when respiratory, skin, eye, and mucous membrane protection is needed.

- *Level B* is the second highest level of protection and should be worn when a lesser level of skin and eye protection is needed. It is the minimum level recommended for initial site entries until the hazards have been determined by monitoring, sampling, or other reliable methods of analysis.
- *Level C* is the third highest level of protection and may be worn only when the type of airborne substance is known, concentration measured, criteria for using air-purifying respirators met, and skin and eye exposure is unlikely. Periodic monitoring of the air must be performed while working in level C.
- *Level D* is the lowest level of protection and is primarily a work uniform. It should not be worn on any site where respiratory or skin hazards exist.

Responders must understand the advantages, limitations, and use of each of the levels of protection at hazardous material incidents. If the appropriate level of protection is not available, arrange to obtain it from other resources.

4. *Identify chemically compatible materials for the chemicals involved.* Look for breakthrough times of at least 2 hours. A breakthrough time of 2 hours represents the normal physical limits of a responder's capacity for effective work in protective equipment. Resources for identifying chemically compatible materials include *Guidelines for the Selection of Chemical Protective Clothing*[8] or the *Quick Selection Guide to Chemical Protective Clothing,*[9] various emergency response guides, and chemical compatability charts provided by the manufacturers of chemical protective clothing.

Figure 13.8.14 provides a worksheet for recording chemically compatible materials identified.

5. *Match the material requirements with personal protective equipment provided or available.* Using chemical-compatibility charts provided with the protective equipment available, identify the available equipment that provides the required protection. Multiple materials can be layered to provide the appropriate level of protection.

6. *Identify the appropriate personal protective equipment needed for each response option.* Keep in mind the requirement for the buddy system and backup personnel. Considerations include availability of sufficient equipment in the appropriate sizes and the potential of multiple layers providing required protection. The use of personal protective equipment itself can create significant responder hazards, such as heat stress, physical and psychological stress, as well as impaired vision, mobility, and communication.

Identifying Appropriate Decontamination Procedures

With the potential that personnel, personal protective equipment, apparatus, and tools and equipment may become contaminated in a hazardous material incident, a decontamination (contamination reduction) process is established.

Decontamination (Contamination Reduction). This is the act of removing or neutralizing contaminants from equipment or personnel to preclude the occurrence of foreseeable adverse health effects outside the engulfed area. Possible decontamination options include absorption, adsorption, chemical degradation, dilution, neutralization, or solidification.

Decontamination procedures should be tailored to the specific hazards of the incident. They may vary in complexity and number of steps, depending on the level of hazard and the level of exposure to the hazard. The steps to be taken to select an appropriate decontamination (contamination reduction) process include the following:

1. *Identify what needs to be decontaminated.* This includes injured persons, response personnel, personal protective equipment, other equipment, and emergency-care facilities.

Chemically Compatible Materials Identification Worksheet

Chemical	Chemical concentration	Chemically compatible clothing material required		
		> 8 hr	> 2 hr	Less than ½ hr

FIGURE 13.8.14 Chemically Compatible Materials Identification Worksheet. This worksheet is for recording the chemically compatible protective clothing materials by hazardous material.

2. *Determine the contaminant and the type and amount of contamination.* Considerations include whether the material is organic or inorganic, in the solid, liquid, or gas form, a dermal or inhalation hazard, a local or systemic material, and whether the contaminant is life threatening, injurious, or irritating. Another consideration is whether physical trauma is involved.

3. *Seek appropriate advice.* Immediate decontamination guidelines are found in the *Emergency Response Guidebook*[7] (under first aid on the numbered guide pages), the NIOSH *Pocket Guide to Chemical Hazards,*[10] or local planning documents. Follow-up guidance can be obtained from local poison control centers, the shipper or manufacturer through CHEMTREC, or the Agency for Toxic Substances and Disease Registry.

4. *Identify methods for isolating and securing and then disposing of clothing and equipment that cannot be decontaminated.* The local emergency response plan or the organization's standard operating procedures provide guidelines on decontamination (contamination reduction) procedures. Other resources should be identified in pre-emergency planning activities. Follow-up resources include the Agency for Toxic Substances and Disease Registry, poison control centers, and the shipper or manufacturer through CHEMTREC.

Selecting Response Options

The selection of response options to change the outcomes favorably must be consistent with the local emergency response plan and the organization's standard operating procedures and also within the capability of available personnel, personal protective equipment, and control equipment. The steps to be taken in selecting the response options include the following:

1. *Determine the required resources to implement each response option.* Required resources include the time to implement the option, availability of sufficient personnel with the appropriate training, and appropriate personal protective equipment, materials for decontamination (contamination reduction) activities, and control equipment.
2. *Inventory the resources available and identify those resources available.* These resources should be readily accessible.
3. *Determine how to obtain the needed resources.* A review of the planning documents should provide these answers.
4. *Select the response option(s) consistent with the available resources.* Evaluate the potential reaction of the hazardous material to the control action and the ability to contain the side effects of the response option. Surrounding conditions, including topography and weather conditions, and response times can also affect the decision to select the response options.

Developing a Plan of Action

After selecting the response option for a hazardous material incident, a plan of action including safety and health considerations should be developed. This plan of action describes the response objectives and options and the personnel and equipment required to accomplish the objectives. The plan provides a permanent record of the decisions made at the incident. An organization's standard operating procedures provide the basis of this plan of action. Input from all segments of the response community is considered in developing the plan. Based on the specific incident conditions, the standard operating procedures are modified without having to write an entire plan for each incident.

A plan of action also outlines the safety and health procedures to protect responders and the public from the potential hazards at an incident. These procedures should address incident management, communications protocol (both internal and external), control zones for incident security, personal protective equipment use, decontamination procedures, and documentation. They also include designation of a safety sector and a safety officer, emergency medical care procedures, environmental monitoring, emergency procedures, and personnel monitoring.

Components for a typical plan of action include the following:

1. Site description
2. Entry objectives
3. On-scene organization and coordination
4. On-scene control
5. Hazard evaluation
6. Personal protective equipment
7. On-scene work assignments
8. Communication procedures
9. Decontamination procedures
10. On-scene safety and health considerations including designation of the safety officer, emergency medical care procedures, environmental monitoring, emergency procedures, and personnel monitoring

Response personnel at a hazardous material incident must recognize and understand the potential hazards associated with the incident. They must also be familiar with the procedures contained in the plan of action. Therefore, prior to working on-scene, all personnel must be provided a safety briefing. The safety briefing will describe the assigned tasks and their potential hazards, coordinate activities, identify methods and precautions to prevent injuries, and plan for emergencies. The plan of action can serve as a guide to this safety briefing.

The result of planning a response to a hazardous material incident is a plan of action consistent with the local emergency response plan and the organization's standard operating procedures and within the capability of the resources available. Development of a written plan ensures that all safety aspects of the response are thoroughly examined. Plans should be modified as necessitated by changing conditions on the scene.

IMPLEMENTING THE PLANNED RESPONSE

Overview

Once the plan of action is determined, response personnel must implement the response options in that plan. The following tasks are associated with implementing the planned response to a hazardous material incident:

1. Implement the incident management system (IMS).

2. Implement the selected protective actions.
3. Establish and enforce scene-control procedures.
4. Implement planned control actions.

Initiating the Incident Management System

The incident management system (IMS) is an organized approach to control and manage operations effectively at an emergency through a system of roles, responsibilities, and standard operating procedures. The incident management system should be developed as part of pre-emergency planning efforts, including the local emergency response plan and an organization's standard operating procedures.

One individual is in charge of managing the incident. This individual may delegate responsibility for performing various tasks to others on the scene. All communications are routed through the command post. Delegation of tasks may be by location or by function. Some of the functions include: medical services, evacuation, water supply, resources, media relations, safety, and site control. The incident management system reduces confusion, improves safety, organizes and coordinates actions, and facilitates effective management of the incident.

The National Incident Management System (NIMS) provides an example that includes the following elements of an incident management system used to coordinate response activities:

1. Common terminology
2. Modular organizations
3. Integrated communications
4. Unified command structure
5. Consolidated action plans
6. Manageable span of control
7. Predesignated incident facilities
8. Comprehensive resource management

Responders should understand the roles and responsibilities of the various positions in the local incident management system as defined in the local emergency response plan or the organization's standard operating procedures.

The incident management system includes the procedures for notification and use of other than local resources, including private, state, and federal government personnel. The incident commander should be familiar with and comply with the requirements of the following plans:

1. Organization's emergency response plan
2. Organization's standard operating procedures
3. Local emergency response plan
4. State emergency response plan
5. Regional emergency response plan, including the resources available from the regional response team
6. Federal emergency response plans

Response personnel should be aware of the primary local, state, regional, and federal government agencies and understand the scope of their regulatory authority (including the regulations) pertaining to the production, transportation, storage, and use of hazardous materials and the disposal of hazardous wastes. They should also be aware of private sector resources offering assistance during a hazardous material incident and identify their role and the type of assistance or resources available.

The incident management system should provide a focal point for information transfer to the media and local elected officials. A public information officer should be designated to provide appropriate information to the media and local, state, and federal officials.

Implementing Selected Protective Actions

Protective measures are those taken to preserve the health and safety of emergency responders and the public during an incident involving the release of hazardous materials. Protective actions include the following:

1. *Isolate the hazard area and deny entry.* Keep all persons away from the area if they are not directly involved in emergency response operations. Unprotected emergency responders should not be allowed within the isolation area. Planning documents should include techniques to isolate the hazard area and deny entry to unauthorized persons at hazardous material incidents.

2. *Evacuate persons in the threatened area.* Evacuation is defined as a process to "move all people from the threatened area to a safer place."[7] To perform an evacuation, there must be enough time for people to be warned, to get ready, and to leave the area. Even after people are evacuated, they should not be allowed to congregate on the perimeter of the control zones. Evacuees should be sent upwind to a definite place, by a specific route, far enough away so that they will not have to be moved again if the conditions change.

3. *Protect persons who cannot be evacuated in place.* In-place protection is defined as a "means to direct people to quickly go inside a building and remain inside until the danger passes."[7] Certain protective actions must be taken inside the building. In-place protection is used when evacuating the public would cause greater risk than directing them to stay where they are or when an evacuation cannot be performed.

Establishing and Enforcing Scene-Control Procedures

Scene-control procedures must be implemented quickly. Control zones (Figure 13.8.15), decontamination (contamination reduction) activities, and communication must be established and maintained throughout the incident. Personnel should move between control zones through access control points.

Scene control is established through the use of control zones based on safety and the degree of hazard. The hot zone is the area surrounding a hazardous material incident. It extends far enough to prevent adverse effects from hazardous material releases to personnel outside the zone. The warm zone is the area where personnel and equipment decontamination (contamination reduction) takes place. The cold zone is the area containing the command post and other support functions. Access to various zones is determined by need and level of personal protection provided as specified in the plan of action.

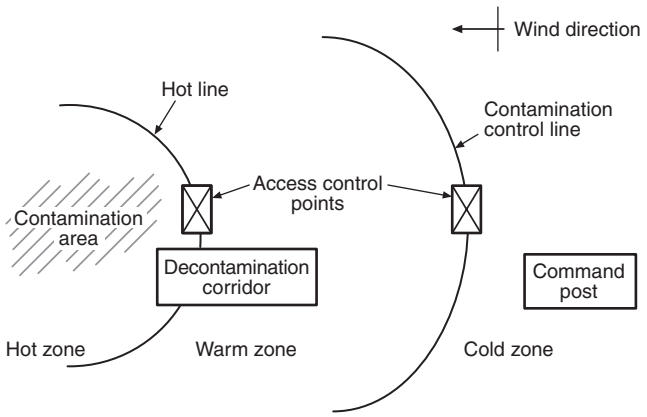

FIGURE 13.8.15 Control Zones

Extreme caution is necessary when providing emergency medical care to victims of hazardous material incidents.

Performing Control Functions

Responders are expected to perform control functions identified in the plan of action. They will have to select the tools, equipment, and materials for the tasks assigned. They should also understand the precautions for controlling releases from the containment systems involved.

In conjunction with their ability to use personal protective equipment, response personnel should be able to identify the symptoms of heat and cold stress. Response personnel should be aware of the physical and psychological stresses that can affect users of personal protective equipment. Personnel should be able to identify the signs and symptoms of exposure to any hazardous material involved. Response personnel should be able to record the use, repair, and testing of chemical protective clothing.

EVALUATING PROGRESS AND ADJUSTING ACCORDINGLY

The fourth and final duty in responding to hazardous material incidents is to evaluate the progress of the planned response—whether it stabilizes, intensifies, or otherwise changes. This duty evaluates the effectiveness of the following:

1. Personnel being used
2. Personal protective equipment
3. Established control zones
4. Decontamination process
5. Selected action options

A comparison of the actual behavior to that predicted indicates the effectiveness of the operations. Negative feedback initiates a re-evaluation of the situation, including another analysis of the problem, response objectives and options, and a modified plan of action. Positive feedback indicates successful operations; however, modification of the plan may still be necessary.

Termination

Termination of a hazardous material incident is that portion of incident management in which personnel are involved in documenting safety procedures, site operations, hazards faced, and lessons from the incident. Termination is divided into three phases: (1) debriefing the responders, (2) postincident analysis, and (3) critiquing the incident.[11]

Debriefing the responders is the process of reviewing a hazardous material incident focusing on the following factors:

1. Informing responders of any potential exposure to hazardous materials and the signs and symptoms associated with that exposure
2. Identifying equipment damage and unsafe conditions
3. Assigning information-gathering responsibilities for a critique
4. Summarizing the activities performed

Postincident analysis is the reconstruction of the incident to establish a clear picture of the events that took place during the incident. The postincident analysis focuses on four key topics: (1) command and control, (2) tactical operations, (3) resources, and (4) support services.

Critiquing the incident—emphasizing successful and unsuccessful operations—should be conducted with all response community members. The procedures for conducting a critique of a hazardous material incident should be in the local emergency response plan or the organization's standard operating procedures including written reports to management that suggest ways to improve future operations.

At the termination of the emergency phase, authority may be transferred to those responsible for the recovery activity in the incident. The local emergency response plan or the organization's standard operating procedures outline the steps for terminating the emergency phase of the incident.

Providing Reports and Subsequent Documentation

Responders to hazardous material incidents must comply with the reporting requirements of federal, state, and local agencies. All reports and other incident documents should be consistent with the local, state, and federal requirements.

Training records, exposure records, incident reports, and critique reports should become part of the file for the incident. An activity log and detailed exposure records should be maintained on each hazardous material incident. Typically, requirements for filing documents and maintaining records are found in the local emergency response plan and the organization's standard operating procedures.

SUMMARY

As with any emergency, favorably changing the outcomes requires a logical sequential process involving four duties: (1) analysis, (2) planning, (3) implementation, and (4) evaluation. Each of these duties is made up of tasks that need to be accomplished to complete that duty. Each task requires that

certain steps be performed to complete the task. The topics in this chapter describe the duties, tasks, and steps associated with managing the response to hazardous material incidents.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on managing response to hazardous material incidents discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents*
NFPA 472, *Standard for Professional Competence of Responders to Hazardous Materials/Weapons of Mass Destruction Incidents*
NFPA 704, *Standard System for the Identification of the Hazards of Materials for Emergency Response*
NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*
NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services*
NFPA 1991, *Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies*
NFPA 1992, *Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies*
NFPA 1994, *Standard on Protective Ensembles for First Responders to CBRN Terrorism Incidents*

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Technical Guidance for Hazard Analysis (EPA, FEMA, DOT).
Title 40 CFR Part 261.33 (EPA).
Title 40 CFR Part 302 (EPA).
Title 40 CFR Part 355 (EPA).
Title 49 CFR Parts 170–179 (DOT).

Chapter 9

Emergency Medical Services and the Fire Department

Jack J. Krakeel

Chapter Contents

Fire Department's Role in EMS
EMS-Involved Organizations
EMS Organizational Models
System Performance Evaluation
Performance Evaluation Organizations
System Design Elements and Performance

Key Terms

advanced life support (ALS), ambulance service, basic life support (BLS), benchmarking, emergency medical responder, emergency medical services, emergency medical technician (advanced), emergency medical technician (basic), EMS coordinator, enhanced 9-1-1, medical control, medical director, medical first responder, paramedic, patient transport, process performance indicator index (PPII), response time performance

The fire service plays a significant role in the delivery of emergency medical services (EMS). During the past 50 years, fire service–based emergency medical services (EMS) has grown to be the principal operational delivery program in the majority of fire departments. In 2004, the 14.1 million EMS calls by local fire departments constituted 62 percent of total emergency responses, and the EMS share grows every year. In 2005, 67 percent of fire departments reported that they provide EMS response, up slightly from 65 percent in 2001. These departments protected 86 percent of the population, as most departments not providing EMS coverage were all-volunteer departments protecting rural communities. The term *cross-trained dual-role fire fighter* is generally being replaced by the recognition that fire fighters are the personnel who respond to the needs of their communities irrespective of the nature of the emergency.

As is the case with other fire department programs and responsibilities, the manner and degree of EMS system involvement is predicated to a great extent on the community being served. The recognition that "all EMS is local" is offset by the fact that common elements are applicable to all EMS systems. The core components of EMS systems were defined in legislation passed by Congress over 40 years ago. Since that time efforts by individual groups, including the American Ambulance Association (AAA), the International Association of Fire Chiefs (IAFC), the International Association of Fire Fighters (IAFF), the National Association of State EMS Directors (NAEMSD), the National Association of EMS Physicians (NAEMSP), the National Fire Protection Association (NFPA), and others, have expanded the understanding of EMS systems and the factors that define and influence the effectiveness and efficiency in the delivery of emergency medical services.

EMS is not a fast ride to an emergency room by ambulance nor is it singularly delivered by the fire department. It is a complex set of coordinated activities and responsibilities working in unison to deliver optimum service to a citizen in need of emergency medical care. NFPA 450, *Guide for Emergency Medical Services and Systems,* defines an EMS system as

> A comprehensive, coordinated arrangement of resources and functions which are organized to respond in a timely, staged manner to medical emergencies regardless of their cause.

Irrespective of the role of a fire department, from functioning as a first responder providing basic life support to one providing advanced life support critical care transport services, the adherence to accepted standards and measures of performance is essential to ensuring optimum patient care.

This chapter intends to provide the reader with an understanding of the role of emergency medical services delivery by fire departments. In addition, it identifies the various factors, standards, and performance measures that can be utilized by fire departments in their analysis and improvement of the emergency medical services program.

For related topics see also Section 12, Chapter 4, "Managing Fire-Rescue Departments"; Section 13, Chapter 2, "Organizing Rescue Operations"; and Section 13, Chapter 7, "Aircraft Rescue and Fire Fighting (ARFF)."

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FIRE DEPARTMENT'S ROLE IN EMS

Historical Background

The delivery of emergency medical services by fire departments must be viewed within the historical and modern context of the fire service. Although the current nomenclature of prehospital or, if preferred, out-of-hospital emergency medical services was not defined until the genesis of modern EMS systems over 40 years ago, fire agencies across the country have routinely responded to rescues of all types since their founding with the delivery of first-aid services to those in need. The fire service's history in EMS is well documented within the history of departments such as Phoenix, Arizona, Chicago, Illinois, Columbus, Ohio, Miami, Florida, and others.

During the past 40 years, the evolution of the fire service to include EMS as an element of its core mission, "saving lives and property," has been the result of multiple factors, not singularly and simply the decline of fires. As early as 1976, communities across the country witnessed the lifesaving heroic actions of Squad 51 as the television series *Emergency* showcased the capabilities of trained Los Angeles County fire fighters delivering emergency medical care. The publication *EMS Agenda for the Future,* considered by many to be the second white paper in EMS, credits the show with being one of the influential factors of modern EMS system design.[1] The term *white paper* denotes the importance attached to the document in serving as a catalyst for change. The first white paper, published in 1967 and titled *Accidental Death and Disability: The Neglected Disease of Modern Society,*[2] functioned as the principal document from which modern EMS system improvements were generated.

Federal Funding. Whereas the period from the 1960s to the 1970s was known for the vast amount of federal funding committed to the development of EMS systems, the decade of the 1980s reversed that trend and placed the responsibility of supporting emergency medical services squarely on the shoulders of local government. Demand for service coupled with declining federal grant revenues resulted in many local governments turning to their fire departments for the delivery of EMS programs and services. Table 13.9.1 provides a summary of funding for the development of EMS systems.

Patient Transport. The consolidation of the patient transport industry during the decade of the 1990s resulted in further development of fire service–based systems as large corporate organizations shed nonprofitable transport service markets to focus attention on those environments conducive to corporate growth and consolidated market share.

The first few years of the new millennium have seen further strengthening of the fire department's role in EMS, specifi-

TABLE 13.9.1 Summary of Funding for EMS Systems

Legislation	*Time Period*	*Source*	*Amount*	*Explanation*
National Highway Safety Act of 1966 (Public Law 89-564, 23 U.S.C. 401)	1966–1973	Department of Transportation	Approx. $48 million	
National Highway Safety Act of 1966 (Public Law 89-564, 23 U.S.C. 401)	1966–1973	Department of Health, Education and Welfare (HEW)	Approx. $73 million	
Emergency Medical Services (EMS) Systems Act of 1973 (42 U.S.C. 300d)	1973–1976	Department of Health, Education and Welfare (HEW)	Approx. $50 million	
Emergency Medical Services (EMS) Systems Act of 1973 (42 U.S.C. 300d)	1973–1976	Health Resources Administration	Approx. $15 million	
	1974–1978	Robert Woods Johnson Foundation (private philanthropic foundation)	Approx. $14 million	Grants for the improvement of EMS systems
Omnibus Budget Reconciliation Act of 1981 (Public Law 97-35)	1981			Transferred federal funding of EMS to states through preventative health and health services block grants

cally through the absorption of third service municipal transport systems. Beginning during the mid-1990s, local governments' efforts to achieve cost savings through various economies of scale merged these agencies into their fire departments. Highly publicized mergers included those in New York, San Francisco, and St. Louis.

Development of 9-1-1 and E-9-1-1. Contributing to the multiple factors that influenced the widespread inclusion of emergency medical services within fire departments is the recognition of the development of 9-1-1 and enhanced 9-1-1 (E-9-1-1) systems throughout the country. As of late 2005, 98.5 percent of U.S. local fire departments, protecting 99.4 percent of the U.S. population, had some type of 9-1-1 service. What is more, 70.6 percent of U.S. local fire departments, protecting 86.7 percent of the U.S. population, had E-9-1-1 service. The growth of both 9-1-1 and E-9-1-1 since 1967 has resulted in this service being recognized as a fundamental and essential local government service. Responsibility for direct access to the EMS system through 9-1-1 has local governments and their elected leadership intrinsically involved in the EMS system design decision-making process.

The fire service has grown to be the largest provider of emergency medical care throughout the continuum of the EMS system from education and prevention, to system entry, through first response, and ultimately patient transport to a definitive care facility during the last 50 years. In light of the major demographic shifts (aging of the population) and new risks (terrorism, pandemics), there do not appear to be any major influences that will significantly alter the role of the fire service in responding to the emergency medical needs of their constituents.

Factors Influencing EMS Development

The emergence of modern prehospital emergency medical services and the widespread inclusion of fire departments in EMS can be traced to the middle of the twentieth century as a result of various factors that coalesced to define EMS as it is known today. These factors included (1) innovations and technological developments, (2) battlefield medical experience, (3) fire service attributes, (4) cardiac research, and (5) federal legislation and grant funding.

Innovations and Technological Developments. During the 1950s, Dr. Peter Safer, a noted physician trained in surgery and pathology, introduced the concept of airway control and artificial ventilation combined with external chest compressions that resulted in the lifesaving skill of cardiopulmonary resuscitation. In his groundbreaking work, Dr. Safer demonstrated that by training first responders and citizens in CPR, the opportunity for someone to survive cardiac arrest outside of traditional medical institutions could be improved. Dr. Safar authored the text *ABC of Resuscitation* in 1957.

Following the development of CPR and mass instruction to first responders and the lay community, researchers led by cardiologist Dr. Frank Pantridge from the Royal Victoria Hospital in Belfast, Ireland (1966), expanded on the work of researchers at Johns Hopkins Hospital in the development of portable cardiac defibrillators. Their innovation led to the institution of mobile coronary care units in Belfast. His efforts are generally considered to have led to the first mobile-based advanced life support (ALS) units to serve the general public.[3]

Battlefield Medical Experience. Concurrent with these innovations and technological developments were the experiences of military emergency physicians who served on the battlefields of Korea and Vietnam. They questioned why many of the lessons learned from the successes they witnessed in the combat theater, where early care was provided at the point of injury and forward medical bases (MASH) were used, could not be transferred to the civilian community. Drawing on their experiences, these physicians defined the country's failures for prompt and effective emergency care through a study conducted by the National Academy of Sciences, National Research Council's Committees on Trauma, Shock, and Anesthesia. Their publication was entitled *Accidental Death and Disability: The Neglected Disease of Modern Society.*[2] The first paragraph of the publication summed up the gravity of their findings:

> In 1965, 52 million accidental injuries killed 107,000, temporarily disabled over 10 million and permanently impaired 400,000 American citizens at a cost of $18 billion. This neglected epidemic of modern society is the nation's most important environmental health problem. It is the leading cause of death in the first half of life's span.[2]

Demonstrating the paucity of adequate ambulance services, the study stated:

> Adequate ambulance services are as much a municipal responsibility as firefighting and police services. . . . Very few communities provide sufficient financial support for adequate ambulance services. Where they are provided, they are usually maintained by the fire or police department. . . . First class ambulance service exists in few cities. Some such as the City of Baltimore employ highly trained full-time ambulance attendants with up-to-date vehicles and equipment as a separate mission of the fire department.[2]

Although many of the recommendations for improving care to the injured centered on hospital-based initiatives, some were specific to the out-of-hospital environment and applicable to the fire service community including the following:

- Extension of basic and advanced first aid training to greater numbers of lay population
- Preparation of nationally accepted texts, training aids, and courses of instruction for rescue squad personnel, police, fire fighters, and ambulance attendants
- Implementation of traffic safety legislation to ensure completely adequate standards for ambulance design and construction, for ambulance equipment and supplies, and for the qualifications and supervision of ambulance personnel
- Adoption at the state level of general policies and regulations pertaining to ambulance services

- Adoption at district, county, and municipal levels of ways and means of providing ambulance services applicable to local conditions, control and surveillance of ambulance services, and coordination of ambulance services with health departments, hospitals, traffic authorities, and communication services
- Delineation of radio frequency channels and of equipment suitable to provide voice communication between ambulances, emergency departments, and other health-related agencies at community, regional, and national levels
- Day-to-day use of voice communication facilities by the agencies serving emergency medical needs[2]

Fire Service Attributes. Individual fire agencies understood that they were uniquely positioned to embody many of the recommendations made by this pivotal study, recognizing that their organizations offered the following attributes in support of delivering emergency medical services:

- Dedicated and trained workforce
- Defined and practiced command/control functions
- Established communication systems
- Ability to function under emergency conditions
- Geographic deployment of assets and resources to respond in a time-sensitive manner
- Day-to-day involvement of responding to medical emergencies
- Public trust and confidence
- History of EMS service

Cardiac Research. Cardiac researchers in the United States, eager to expand the work of Pantridge, et al., engaged fire departments in their communities for the implementation of advanced mobile coronary care units. Cities and fire departments such as Seattle, Jacksonville, Los Angeles, Dayton, and others pioneered the concept of delivering advanced cardiac life support during this era. In 1966, the Columbus, Ohio, Fire Department introduced the concept of the "Heartmobile," considered to be one of the first advanced cardiac life support units (Figure 13.9.1). In their article on the evolution of prehospital care in the United States, the authors state: "Most of the early paramedic programs were based in fire departments."[4] In 1969, under the direction of Dr. Eugene Nagel, the Miami, Florida, Fire Department started the nation's first paramedic program.

Federal Legislation and Grant Funding. The publication of *Accidental Death and Disability: The Neglected Disease of Modern Society* served as the stimulus for the emergence of the federal government's role in EMS. Concurrently with the inclusion of payment for ambulance transport services in the Social Security Act of 1967, the focus on improving emergency medical care in the United States gained momentum, culminating with the passage of legislation designed to provide funding and guidance for the development of EMS systems across the country.

The first of the federal efforts to improve emergency care came about as a result of the passage of the National Highway Safety Act of 1966 (Public Law 89-564, 23 U.S.C. 401). Confronted with the reality that many of the injuries and deaths were directly attributable to automobile accidents, federal responsibility for EMS was placed within the Department of Transportation (DOT). Although there have been changes during the last 50 years, the principal federal agency charged with EMS responsibilities continues to reside within the agency responsible for roadway safety, the National Highway Transportation and Safety Administration (NHTSA). The National Highway Safety Act charged the DOT with the development of training texts and curriculum for basic emergency medical technicians (EMTs).

FIGURE 13.9.1 Heartmobile (Source: Courtesy of Columbus, Ohio, Fire Department)

Generally regarded as the most comprehensive EMS legislation passed was the Emergency Medical Services Act (EMS) Systems Act of 1973 (42 U.S.C. 300d). This landmark legislation promoted the development of regional EMS councils with specific responsibility for the coordination of EMS within their regions including ensuring adequate staffing, training, emergency facilities, communication, and transportation capabilities for persons in need of EMS services in their area. The 15 core elements or components of an EMS system were defined in the act. To receive federal block grant funding, the regional councils were required to meet the requirements of these 15 elements. The core components of EMS defined in 1973 continue to this day to serve as the basic building blocks of an effective and efficient EMS system design.

During the decade from 1966 to 1976, it is estimated that the federal government provided approximately $200 million for the improvement of EMS. The majority of this funding, administered by multiple federal agencies, was in the form of grants to states and local communities. Access to grant funds paved the way for the emergence of local government involvement in emergency medical services. Many local governments took advantage of the historic 75 percent federal and 25 percent local match grant program. This funding allowed for the acquisition of ambulances and equipment leading to a greater role of the fire service in delivering EMS within their communities. By 1976, morticians who prior to 1966 provided more than 50 percent of ambulance service in the country, had essentially been replaced by an array of public, private, and volunteer ambulance services.[4]

In addition to making grant funding available, the federal government developed the first series of ambulance design specifications. Currently known as KKK-1822E and administered through the Government Services Administration, the specifications and standards that continue to be used by the industry include vehicle style, design, and construction; performance characteristics; specifications for individual components such as the electrical system, oxygen delivery system, communication system; and optional and required medical equipment. The earliest units constructed in compliance with the first set of standards were marked with the distinctive "Omaha" orange stripe (Figure 13.9.2).

EMS-INVOLVED ORGANIZATIONS

During the 1980s, as the federal government's role in and funding for EMS systems waned, national organizations emerged to provide leadership for EMS systems and issues. Through collaboration and consensus-based processes, these and other organizations have essentially provided many of the standards and performance measures currently utilized by the industry.

International Association of Fire Chiefs (IAFC) and International Association of Fire Fighters (IAFF)

The International Association of Fire Chiefs (IAFC) was established in 1873 and has approximately 13,000 members. The organization provides leadership to chief officers and consists of both national and international membership. The association formed its first EMS committee in 1985; by 1991 the EMS committee had evolved as one of the largest sections within the organization. The International Association of Fire Fighters (IAFF) represents fire fighters in more than 3500 communities in the United States and Canada. Its membership of more than 274,000 members includes full-time professional fire fighters and paramedics who protect the lives and property of 85 percent of the nation's population. In 1991, the IAFC and the IAFF signed a joint memorandum of understanding (MOU) that defined the role of the fire service in the delivery of EMS.[5] The MOU initiated a series of collaborative efforts by both labor and management on emergency medical services issues of common concern to the fire service (Figure 13.9.3).

FIGURE 13.9.2 1970s Era Ambulance with Required Horizontal Orange Stripe (Source: Courtesy of Glenside Fire Protection District)

Commission on Fire Accreditation International

In 1995, the Commission on Fire Accreditation International was formed and included EMS as a core program that identified criteria and core competencies and performance indicators relative to EMS. Collaborative organizational fire service efforts with respect to EMS included transforming federal legislation that had the potential for inhibiting the role of fire departments in the delivery of emergency medical services. Of specific concern to the industry was the application of the 7K overtime exemption to medical services performed by fire departments. The Fair Labor Standards Act was amended in 1999 after joint efforts by the IAFC and the IAFF to reflect the role of fire fighters in the delivery of EMS. Historically, fire fighters were exempt from overtime compensation only in the performance of actual fire-fighting duties. Congress amended the act as a result of a redefinition of a fire fighter's duties by the Department of Labor that included emergency medical care. Known as Section 203(y), it states:

> "Employee in fire protection activities" means an employee, including a firefighter, paramedic, emergency medical technician, rescue worker, ambulance personnel, or hazardous material worker, who—
>
> (1) is trained in fire suppression, has the legal authority and responsibility to engage in fire suppression, and is employed by a fire department of a municipality, county, fire district, or State; and,
>
> (2) is engaged in the prevention, control and extinguishment of fires or response to emergency situations where life, property or the environment is at risk.[6]

In 2000, in a survey of its membership, the IAFC found that over 90 percent of fire departments participated in the delivery of emergency medical services.[7] This participation extended throughout the continuum of EMS care, including basic and advanced life support first responder services as well as over 50 percent of responding departments providing advanced life support transport services. These statistics are confirmed in the *Journal of Emergency Medical Services* (*JEMS*) publication in which its annual survey reflects that over 50 percent of the 200 most populated cities have fire department transport services and nearly all have either basic or advanced life support first responder services.[8]

National Association of State EMS Directors

In 2006, the National Association of State EMS Directors officially became the National Association of State EMS Officials, representing various state EMS agencies and their officials,

THE INTERNATIONAL ASSOCIATION OF FIRE CHIEFS
and
THE INTERNATIONAL ASSOCIATION OF FIRE FIGHTERS
JOINT RESOLUTION ON EMERGENCY MEDICAL SERVICES

WHEREAS, Pre-hospital emergency medical service is a major service provided by America's fire service, and;

WHEREAS, As first responders to most emergency situations, it is imperative that the fire service continue to provide pre-hospital medical care, and;

WHEREAS, The fire service has been hampered by lack of public recognition and support for its vital role in providing emergency medical care;

THEREFORE BE IT RESOLVED, That the leadership of the International Association of Fire Fighters and the International Association of Fire Chiefs agrees that America's fire service must continue to provide pre-hospital emergency medical care, and;

BE IT FURTHER RESOLVED, That the International Association of Fire Fighters and the International Association of Fire Chiefs urge all elected officials, professional associations and health care providers to recognize and support the provision of emergency medical care by the fire service.

Adopted by

Chief David W. Hilton, President
International Association of Fire Chiefs

Alfred K. Whitehead, President
International Association of Fire Fighters

FIGURE 13.9.3 IAFC/IAFF Joint Resolution on Emergency Medical Services

including state directors, medical directors, and training coordinators. It is considered a leading national organization for EMS, serving as an advocate for the development of effective, integrated, community-based, universal, and consistent EMS systems. In 2003, the National Association of State EMS Directors conducted a national EMS survey. The survey, completed by state EMS directors, reflected that with respect to EMS systems, approximately 48.6 percent are nonfire, non–hospital based, 44.9 percent are fire based, and 6.5 percent are hospital based.[9] Nonfire, non–hospital based services include private providers, volunteer agencies, and governmental services not affiliated with a fire department. State EMS agencies have fundamental responsibilities for the certification and recertification of EMS providers and the licensure of ambulance services.

EMS Standard-Developing Organizations

Between 1984 and 2005, the National Fire Protection Association (NFPA) developed and published various standards and guides for fire agencies specific to EMS. During this time period, other organizations made significant contributions to EMS. The American Ambulance Association developed the Commission on Accreditation of Ambulance Services. Its standards are utilized primarily by patient transport providers in an effort to be officially accredited by the agency. The National Association of EMS Physicians serves as the principal platform for the involvement of physicians certified in emergency medicine. Its initial efforts focused on the role, training, and certification of the medical director. The National Association of State EMS Directors and others took on a more visible role addressing the issues facing its constituencies, as examined earlier.

EMS ORGANIZATIONAL MODELS

Fire departments have generally been organized along functional lines of program and service delivery. The complexity of the organizational matrix depends on various factors, including agency size, community size, services being provided, and fiscal capability. Depending on these factors, an EMS organization within the fire department generally follows one of two matrices, which are delineated by the level of EMS being provided. A shared common element that exists between both transport and nontransport systems is that of medical direction. Service levels typically define the role of the agency within the system and represent either first response, transport, or both. Service levels are further defined based on level of care being provided, which generally parallels individual provider certification.

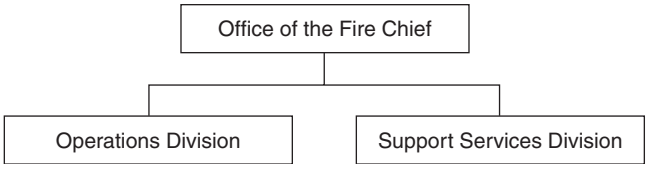

FIGURE 13.9.4 Typical EMS Organizational Model in Medical First Responder Fire Departments

Medical First Responder Fire Departments

In simple, less complex, and typically smaller organizations, such as those often found in rural and small municipal environments, duties and responsibilities for EMS administration and management are generally shared by existing personnel, both administratively and operationally (Figure 13.9.4).

Consistent with other operational programs, in this organizational model responsibility for EMS administration resides within the office of the fire chief. The fire chief has agency-wide responsibility for administrative functions, including planning, directing, controlling, and organizing the various aspects of EMS. In this model, the fire chief usually has a direct relationship with the medical director.

The operations division is generally responsible for the delivery of field programs such as fire suppression, hazmat, rescue services, and emergency medical services. Consistent with these duties are the day-to-day management of individual stations and companies.

The support services division includes all of the responsibilities to ensure that field programs have the essential resources and capabilities to fulfill their primary mission, including such functions as training, facility and fleet management, and supply and equipment management.

Patient Transport–Based Fire Department

The scope of responsibilities for EMS management and administration changes dramatically when the agency has responsibility for EMS transport services, irrespective of agency size. The complexities of patient transport require additional staff for the coordination of associated responsibilities, including medical direction and coordination, quality assurance, training and certification, billing, inventory control, equipment maintenance, and procurement. In smaller organizations that provide patient transport services, the position of an EMS coordinator is generally found within the support services division (Figure 13.9.5).

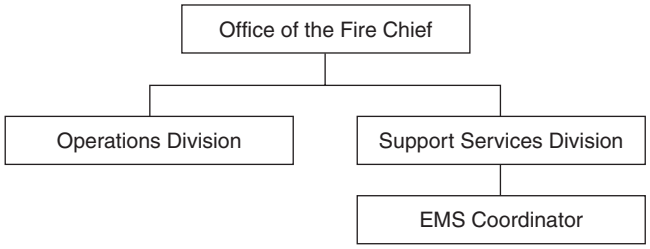

FIGURE 13.9.5 Typical EMS Organizational Model in Smaller Patient Transport–Based Fire Departments

Depending on agency size, the position of the EMS coordinator generally consists of a dedicated full-time position. In smaller organizations, it may be a shared position that includes EMS training in addition to coordinating the various aspects associated with patient transport activities. Organizations following this model are typically found in smaller communities and less densely populated environments.

In more complex organizations serving larger populations the organization typically reflects a divisional structure. These organizations are prevalent in urban and suburban environments (Figure 13.9.6).

The responsibilities for EMS administration and management are predicated on the recognition that certain functions must be carried in order for the system to be able to meet the demands of the population.

EMS Service Levels

The terms *service levels* and *level of care provided* are often used synonymously. Although there are parallels, service levels generally reflect the level of service being provided to a patient, which can consists of basic life support, advanced life support, or critical services. Service levels can be applied to both first responder as well as transport providing agencies.

Level of care can be defined as the provision of patient care services as determined by provider certification and licensure. Certification and licensure of personnel to perform within their specific scope of practice levels lie within the domain of

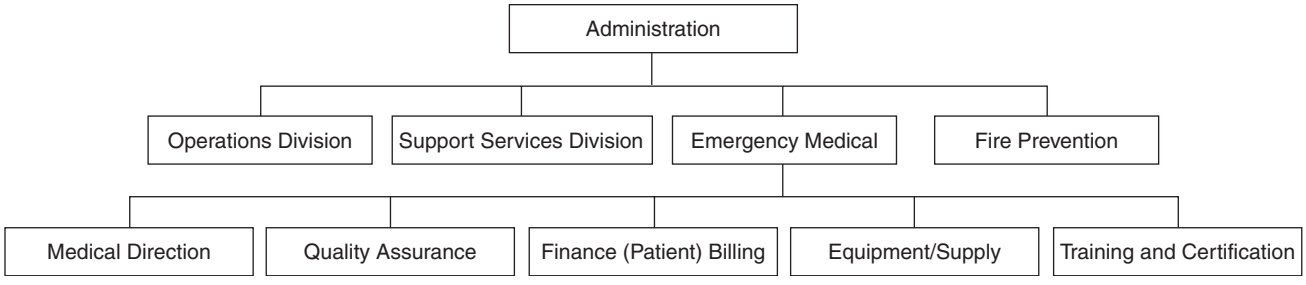

FIGURE 13.9.6 Typical EMS Organizational Model in Larger Patient Transport–Based Fire Departments

state and territory regulatory agencies. In addition, certification state and territorial agencies also govern the ability of agencies to provide services at a specified level and, depending on location, may include the authority to provide first response or patient transport services. These regulations and licensure requirements vary from state to state and are one of the reasons for the variation in EMS service delivery through the country. Although there are differences between the states and territories, certification levels include the following:

First responder
Basic emergency medical technician
Intermediate emergency medical technician
Paramedic

In addition to state and territorial rules and regulations, the Centers for Medicare Services also describe service levels for the purpose of patient transport reimbursement.[10] The establishment of the National Fee Schedule for Ambulances in 2002 defined CMS service levels as follows:

- *Basic Life Support Non-Emergency.* Scheduled transfer of patients from one facility to another requiring only basic life support services
- *Basic Life Support Emergency.* 9-1-1 call or equivalent response to a request for assistance requiring only basic life support services
- *Advanced Life Support Non-Emergency.* Scheduled transfer of patients from one facility to another requiring advanced life support services
- *Advanced Life Support Level 1.* 9-1-1 call or equivalent response to a request for assistance requiring advanced life support assessment services
- *Advanced Life Support Level 2.* Response to a request for assistance requiring advanced life support services that includes provision of at least one invasive procedure or administration of at least three separate medications
- *Critical Care Transport.* Provision of patient care services that exceed capabilities of a paramedic without additional training and certification

Within the fire service, there may be a single role such as that of a first responder or additional roles to include ambulance transportation. The level of care that certified fire fighters are capable of providing may encompass the entire spectrum from first responder certification to paramedic certification.

As of late 2005, 98 percent of U.S. local fire departments providing EMS service had all of their involved personnel certified to at least the first responder level. Also, 26 percent had all of their involved personnel certified to at least basic life support, and 87 percent had at least some involved personnel certified to that level. In addition, 3 percent had all their involved personnel certified to at least advanced life support, and 50 percent had at least some involved personnel certified to that level. Finally, no departments had all involved personnel certified to the level of paramedic, but 18 percent had at least some personnel certified to that level. For additional discussion and information on fire departments and organizational structures, refer to Section 12, Chapter 4, "Managing Fire-Rescue Departments."

SYSTEM PERFORMANCE EVALUATION

Performance Measures and Standards

The goal of any fire department should include a commitment to quality in its delivery of services. The quality process encompasses a number of activities, including the institution and use of various criteria by the department to measure its progress in achieving quality or modifying its program. These criteria may encompass performance measures, benchmarks, or standards.

Performance Measurement. According to the Joint Commission on Accreditation of Health Care Organizations (JCAHO):

> Performance measurement is used internally by health care organizations to support performance improvement and externally, to demonstrate accountability to the public and other interested stakeholders. Performance measurement benefits the health care organization by providing statistically valid, data-driven mechanisms that generate a continuous stream of performance information. This enables a health care organization to understand how well their organization is doing over time and have continuous access to objective data to support claims of quality. The organization can verify the effectiveness of corrective actions; identify areas of excellence within the organization; and compare their performance with that of peer organizations using the same measures. Similarly, performance data can be used by external stakeholders to make value-based decisions on where to seek quality health care.[11]

Benchmarking. Benchmarking is the process of emulating another agency's level of performance or excellence. Benchmarking can be valuable to an agency when comparative analysis reflects similar organizational attributes or service levels. Using benchmarking techniques reduces the time needed to implement best practices and reduces the potential for error in program implementation or modification.

Standard. A standard is generally defined as an accepted industry practice based on a consensus process that employs affected stakeholders in the development of the standard. Requirements may or may not be based on scientific research.

Efforts at developing performance measurements and standards within EMS that are designed to measure performance or serve as a basis for system improvement have been undertaken by various regulatory and nonregulatory agencies and organizations. The vast majority of these efforts have focused on consensus-based processes involving regulators, educators, practitioners, providers, and physicians.

System Performance Criteria

Efforts at developing system performance criteria have focused on how the system and the elements that define a system are functioning. EMS system evaluation can be conducted at the national, state, regional, and local levels.

EMS Performance Audit. The National Highway Transportation Safety Administration (NHTSA) routinely provides state EMS regulatory agencies with a process for evaluating their EMS system from a state perspective utilizing the core components of system design. Known as an EMS performance audit, the agency contracts with emergency medical service experts to conduct the audit of the state EMS administrative agency and through its efforts provide a blueprint for state EMS system improvement.

NFPA Standards and Guides. The National Fire Protection Association between 1984 and 2005 developed and published various standards and guides for fire agencies specific to EMS. These standards and documents include the following:

- NFPA 450, *Guide for Emergency Medical Services and Systems*
- NFPA 473, *Standard for Competencies for EMS Personnel Responding to Hazardous Materials Incidents*
- NFPA 1581, *Standard on Fire Department Infection Control Program*
- NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*
- NFPA 1999, *Standard on Protective Clothing for Emergency Medical Operations*

In 2001 the National Fire Protection Association established an EMS technical committee. As stated in NFPA 450, the committee's scope recognizes that it

> shall have primary responsibility for documents on the training and education requirements for personnel, personal protective equipment, health and safety programs, and quality assurance programs which incorporate physicians and the community in the planning process. It shall also be responsible for documents relating to emergency medical services, except those covered by other NFPA committees that have primary responsibility.

The committee's first effort resulted in the development of a comprehensive guide designed to assist individuals and agencies with a process for evaluating their EMS system. The application of NFPA 450 from a system's perspective can encompass local and regional systems. Although any analysis of an EMS system must recognize the core elements that have historically been defined to constitute an EMS system, other factors must be taken into consideration, including system design, finance, and medical direction.

NFPA 450 recognizes the following components as essential elements of an EMS system that are intrinsically linked and should therefore be coordinated:

- System regulation and policy
- Analysis and planning
- Finance
- Medical direction
- Quality management, clinical quality
- Public information, education, and relations
- Communications
- Equipment and facilities
- Human resources
- Operations

System Relationships

EMS organizations do not exist in a vacuum. Their success and ability to provide effective and efficient services are dependent on the various relationships the fire department has within the system's local domain. This system consists of multiple entities that impact the organization's ability to deliver quality services. Some of these relationships are reflected in Figure 13.9.7. As one can discern, these relationships are dependent on each other and any change in one can have an effect on the rest of the system. In order to quantify changes and their impacts, system analysis from both an historical as well as a prospective basis should be undertaken by the agency on a regular basis.

Response Time Performance. To illustrate the impact of the relationships that exist in a system when there is a lack of coordination, one can view the performance element of response time. Response time performance standards have existed for many years in the EMS industry, yet in many systems the ability to differentiate the contributions to response time from the various participants that make up a system's overall response time

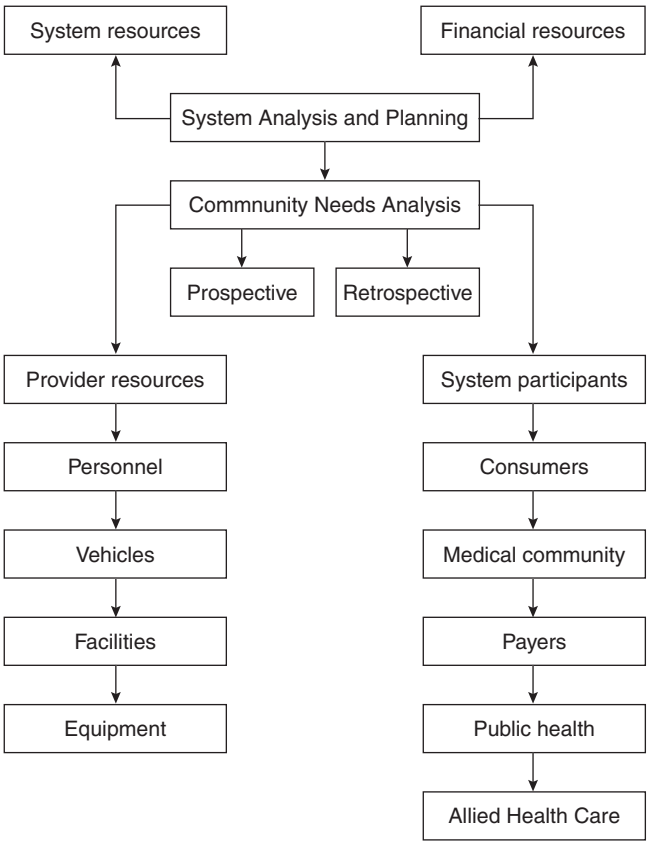

FIGURE 13.9.7 EMS System Relationships

do not exist or are not analyzed in the context of the contributing agencies. Without system coordination, analysis, and review, the time it takes a dispatch center to process a call, the turnout time of a first responder, the travel time to the scene of a transport unit, or the time it takes to turn a patient over to definitive care has little value in determining whether the system is performing consistent with expectations. Failure of any element of the agencies that contribute to response time performance can have a detrimental effect with respect to system performance.

Process Performance Indicator Index (PPII). Other efforts at developing a comprehensive identification of performance measures are ongoing. The Open Source EMS Initiative, an organization devoted to the collection of best practices and resource information for EMS agencies, has developed a draft of a comprehensive collection of areas for which EMS performance indicators should be established, including the following:[12]

- Administration/leadership
- Field operations
- Clinical care
- Medical direction
- Human resources
- Fleet management
- Supply management
- Dispatch and communications
- Information services
- Support services
- Prevention, community education, and access
- Special events and services
- Financial services
- Safety and risk management
- Research
- System measures

EMS Agenda for the Future

The *EMS Agenda for the Future,* a published federal document, consisted of a joint effort by the National Association of EMS Physicians and the National Association of EMS Directors to produce a vision for the future of EMS. The effort was funded through grants provided by NHTSA and the U.S. Department of Health and Human Services' Maternal Health Services Division. Utilizing experts from the industry, the *EMS Agenda for the Future* established a visionary blueprint for the progression and improvement of EMS in the United States. The document has been widely used by the federal government as its road map for providing a federal focus and improving EMS from a national perspective. Building on the efforts of the agenda, a companion document entitled *Emergency Medical Services Agenda for the Future Implementation Guide*[13] provides specific strategies, objectives, and responsibilities for implementing the vision. Other documents emanating from the agenda include the *Emergency Medical Services Education Agenda for the Future: A Systems Approach*[14] and the *National EMS Research Agenda.*[15] Both of these publications provide a blueprint for activities to improve EMS within their respective domains from a national perspective.

PERFORMANCE EVALUATION ORGANIZATIONS

During the last 20 years several accrediting bodies have been developed that wholly or partly have EMS-specific elements. Their efforts focus primarily on the individual agency. Generally included within their documents are requirements with respect to external relationships. The agency is required to demonstrate how they interact with organizations that impact their service delivery. Departments can voluntarily undertake accreditation as demonstration of compliance with accepted industry standards and performance and recognition of excellence.

Commission on Fire Accreditation International (CFAI)

Initiated by the International Association of Fire Chiefs and the International City-County Management Association, the Commission on Fire Accreditation International (CFAI) accredits fire departments internationally when they complete a self-assessment and peer review process of compliance with its criteria and performance standards. The accrediting body currently resides within the Center for Public Safety Excellence, Inc., an organization that also administers the Commission on Professional Credentialing. Provision of EMS as a core program of a fire department is included within the document. The Tempe, Arizona, Fire Department was the first agency to achieve CFAI accreditation. An essential component of the accreditation process is the development of a "Standard of Cover" document, which defines the agency's performance measurements for the various service delivery programs provided by the department.

Compliance with recognized performance measures can occur only when true system coordination exists and the individual participants in the system, from dispatch through definitive care, recognize their contribution and the critical role each plays to ensure the overall welfare of the patient needing emergency medical care. It should follow that the discussion of performance measures or standards for the various elements that constitute EMS should correlate to the progression of the medical event, the resources utilized to manage the critical care needs of the patient, and the contributors that provide resources and personnel in ensuring that the system is effective. Without ensuring that coordination exists in the various elements that make up an EMS system, ensuring quality or making improvements to the system would be difficult to achieve.

Commission on Accreditation of Ambulance Services (CAAS)

The first effort to accredit ambulance services was initiated by the American Ambulance Association. In May 1984, the AAA Board of Directors formed a committee on accreditation and standards. The standards developed by the committee represented a consensus-based process involving EMS officials from throughout the country. The efforts of the committee resulted in the formation of an independent Commission on Accreditation of Ambulance Services (CAAS) in 1990.

CAAS accreditation is based on the agency's seeking accreditation to demonstrate compliance with various standards and performance measures specific to the individual agency. The accreditation is focused on patient transport providers. In 1999, the Lubbock, Texas, Fire Department became the first fire-based transport provider to be accredited by CAAS. One of the most widely utilized performance measurements by the EMS industry identified in the document is 90 percent compliance with a response time performance of 8 minutes, 59 seconds (8:59) to life-threatening calls for service. This performance measurement is frequently used as a core requirement in contracts for patient transport services.

International Association of Fire Fighters (IAFF)

The International Association of Fire Fighters (IAFF) has developed a collection of performance measures specific to fire department–based EMS programs. Included are measures for call processing, turnout time, travel time, staffing, deployment, geographic coverage, protocol compliance, patient outcomes, availability of defibrillation, extrication capability, frequency of employee illness or injury, employee turnover rate, quality programs, and multicasualty response plans.

American Heart Association

According to its mission statement, the American Heart Association "is a national voluntary health agency whose mission is to reduce disability and death from cardiovascular diseases and stroke." Founded in 1924, the association has developed various programs specifically addressing cardiac care in the prehospital environment. The association, although not a standards-setting body, does publish peer-reviewed scientific journals and recommends changes to cardiac care based on scientific research. Within the prehospital environment, the American Heart Association offers specialty certification courses such as advanced cardiac life support, pediatric cardiac life support, as well as basic life support.

American Ambulance Association

The American Ambulance Association, founded in 1979, represents ambulance services across the United States. It is estimated that the association's membership serves over 75 percent of the U.S. population with emergency and nonemergency care and medical transportation services. The organization provides leadership services to its members and services as a voice and clearinghouse for ambulance services across the nation. The American Ambulance Association developed the "Contracting Guide for Ambulance Services," a document that contains various performance criteria for agencies involved in providing patient transport services. In addition, the document is designed to provide information on alternative system design and efficiencies.

American Society for Testing and Materials (ASTM) International

American Society for Testing and Materials (ASTM) International, one of the largest voluntary standards development organizations in the world, is a trusted source for technical standards for materials, products, systems, and services. The committee responsible for the development of these standards is known as the F30 Committee. ASTM has been developing EMS standards for the last 20 years, including the following:

- F1086-94(2002), *Standard Guide for Structures and Responsibilities of Emergency Medical Services Systems Organizations*
- F1149-93(2003), *Standard Practice for Qualifications, Responsibilities, and Authority of Individuals and Institutions Providing Medical Direction of Emergency Medical Services*
- F1224-89(2004)e1, *Standard Guide for Providing System Evaluation for Emergency Medical Services*
- F1268-90(2003), *Standard Guide for Establishing and Operating a Public Information, Education, and Relations Program for Emergency Medical Service Systems*
- F1286-90(2002), *Standard Guide for Development and Operation of Level 1 Pediatric Trauma Facilities*
- F1288-90(2003), *Standard Guide for Planning for and Response to a Multiple Casualty Incident*
- F1339-92(2003), *Standard Guide for Organization and Operation of Emergency Medical Services Systems*
- F1493-93(2003), *Standard Guide for Financing and Financial Accountability of Medical Transportation Systems*
- F1629-95(2007), *Standard Guide for Establishing Operating Emergency Medical Services and Management Information Systems, or Both*
- F1652-95(2007), *Standard Guide for Providing Essential Data Needed in Advance for Prehospital Emergency Medical Services*

SYSTEM DESIGN ELEMENTS AND PERFORMANCE

The Emergency Medical Services Systems Act of 1973 defined the essential elements of EMS system design. Although the core components have been modified, they stand largely intact as the fundamental elements of an EMS system. Performance measures and standards generally correlate to these elements. They include the following elements, some of which will be discussed here: public information and education, communications, human resources training, public safety, transportation, access to care, facilities, critical care, patient transfers, financial control, medical direction, quality management, resource deployment, record keeping, evaluation, disaster preparedness, mutual aid, and consumer participation.

Recognizing that there are multiple contributors to any EMS system, development of performance measures and standards has been predicated to a great extent on the contribution that each participant provides to the system and by the organizations that generally represent a specific professional constituency.

Public Information and Education

In the United States, the fire service has largely been successful in educating the general public and modifying the public's

behavior to reduce illness or injuries. Fire prevention efforts have been highly successful in reducing fire deaths and injuries. Similarly, efforts toward reducing injuries and death from non-fire-related causes have also been proven successful.

The role of the fire service in illness and injury prevention has progressed significantly in recent years. Although fire prevention continues to be a fundamental effort, programs such as NFPA's *Risk Watch*® that focus on injury prevention and reduction have been instituted in many communities, with the fire department often taking a leadership role.

Advances in technology, especially in the area of automatic external defibrillators, provide opportunities for departments to serve as the focal point for the institution of community automatic external defibrillator (AED) programs.

Benchmarking these and other similar programs provides the fire service with an excellent opportunity to expand its role in community education and prevention measures that focus on illnesses and injuries.

During the past five years, professional organizations such as the IAFC have expanded their role in providing leadership to fire departments by means of publications addressing preparedness for organizational and community health concerns. The impetus for the development of these documents varies, but the overall goal is to expand organizational awareness of the issues that departments and communities may face within the health care arena.

The first of these documents, published in 2001, is the *Fire Department Guide to Smallpox.*[16] The second document, published in 2005, is the *Fire Department Guide to Pandemics.*[17] Both of these documents provide organizational leaders with information and education to assist organizations in preparing for and managing health care crises in their communities.

Communications

The success of 9-1-1 to access public safety services and emergency medical care since the first system went into service in Haleyville, Alabama, in 1967[18] has been unparalleled from a public education perspective. The communication and dispatch centers serve as the primary access point for emergency medical care in most communities. Given this enormous responsibility, these centers and the personnel in their employ are recognized as being critical to ensuring that the appropriate resources and medical assistance are provided to constituents in need of EMS.

The *EMS Agenda for the Future,* a visionary document on how the future of emergency medical services may be constructed, utilizes the communication process diagram shown in Figure 13.9.8 to describe potential alternative decisions that could be made available in the future for EMS dispatch centers in order to optimize scarce response resources while simultaneously ensuring that callers' medical needs are appropriately met.

Dispatcher Certification. Various standards and performance criteria have been developed specific to the communication and dispatch function. In 1987, the NHTSA developed the curriculum for emergency medical dispatcher certification. The certification available through state training agencies provides the essential skills and knowledge base for individuals charged with the responsibilities of providing emergency medical care instructions prior to the arrival of response units.

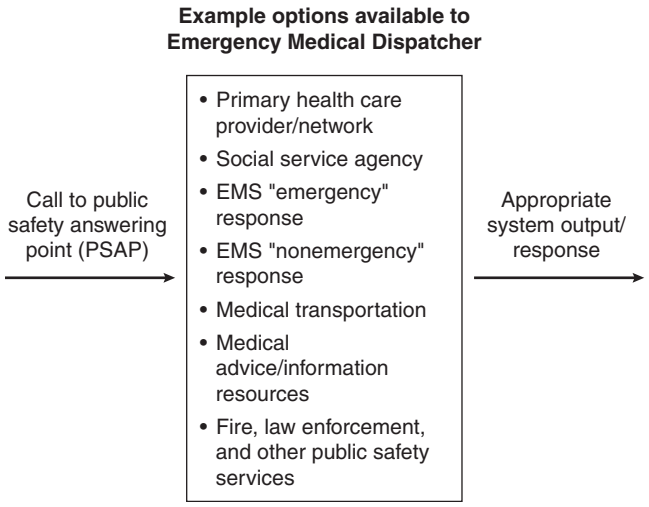

FIGURE 13.9.8 Sample Emergency Medical Dispatcher Options

Dispatching Protocols. Subsequent to the creation of the dispatcher curriculum, independent efforts have resulted in the development of standardized dispatching protocols designed to provide a hierarchical process for determining patient criticality and correlating prehospital care instructions. In 1987, Dr. Jeffrey Claussen developed a proprietary card system process that the dispatcher uses to ask specific questions. Based on the answers to the questions, the dispatcher is able to determine whether to dispatch basic or advanced life support units. The system also provides instructions in patient care for the dispatcher to relay to the patient or bystanders.

Using a process that allows for the identification of appropriate resource allocation is critical not only from a cost-containment perspective but also to ensure that the provider of transport services can recover revenues consistent with the dispatch of resources. The Centers for Medicare Services, through its modification of payment policies for Medicare patient transports in 2001, allows for the payment of advanced life support if the initial information provided to the dispatch agency indicated a need for an advanced life support response even though the patient may have needed only basic life support services.

Communication Standards and Performance Measures Resources. The principal organizations providing communication standards and performance measures include the following:

- *Association of Public-Safety Communications Officials (APCO).* The APCO Institute provides an Emergency Medical Dispatch program that is based on the *NHTSA National*

Standard Curriculum for EMD as well as ASTM International guidelines in a comprehensive EMD package. Emergency Medical Dispatch is a structured and sequential program that enables communication personnel to properly determine the nature and priority of an emergency medical call, dispatch the appropriate response, and provide the caller with specific medical self-help instructions to assist the patient until EMS personnel arrive.

- *National Fire Protection Association (NFPA).* NFPA 1221, *Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems,* is a standard for communication systems and facilities.
- *Commission on Accreditation of Law Enforcement Agencies* (*CALEA*). In 1996, CALEA and APCO collectively developed an accreditation program for public safety communications agencies. The CALEA *Accreditation Standards Manual* contains 216 standards designed to include the following categories: organization, direction and authority; human resources; recruitment and selection; training; and operations.
- *Commission on Fire Accreditation International* (*CFAI*). The CFAI, established in 1996, provides a voluntary accreditation program to fire departments encompassing 10 program categories that include performance indicators.

Response Time Performance Measurements

The ability to reach a victim of an accident or illness within time-sensitive parameters has long been a hallmark of the fire service. Strategically deployed resources throughout a community allow for rapid response to any emergency event. The single performance measurement most frequently utilized to measure an EMS system's performance is that of response time. The American Heart Association considers critical components of EMS systems to include appropriate access by citizens as well as timely dispatch of responders. According to the American Heart Association:

> Passage of time drives all aspects of emergency cardiac care and determines patient outcomes.[19]

Development of Response Time Standards. Initial efforts to establish response time standards were developed during the late 1970s by Dr. Michael Eisenberg. In his studies he found that patients who received CPR during the first 4 to 6 minutes followed by advanced emergency medical care in 8 minutes had a statistically higher probability of survival.[20] Since that time, the 8 minute standard for advanced life support has been universally adopted and reflected in community EMS system requirements and accreditation programs. In 1995, the Commission on Accreditation of Ambulance Services (CAAS) clarified its 8:00 minute standard to represent 8 minutes, 59 seconds.

NFPA 450 provides a comprehensive listing and definitions for response times including discrete time stamps, process intervals, and functional intervals. The identification of these measurements was established in an effort to create uniformity in how agencies define response time as well as the elements that constitute response time. In addition, acceptance and utilization of these values will facilitate system-to-system comparison and analysis.

Discrete Time Stamps. Discrete time stamps are identified as fixed points in time that can be captured electronically throughout the continuum of an EMS call. The value of these fixed points lies in the recognition that multiple system participants contribute to the overall lapse of time from the initial call to definitive care. These baseline points can then be aggregated and analyzed to determine system response time performance improvements as shown in Table 13.9.2.

Functional Intervals. Functional intervals represent the span of time during which specific functions are performed by system participants. The analysis of functional time intervals allows agencies and system administrators to determine whether any particular modification is necessary and designates the agency and personnel responsible for making improvements.

Process Intervals. Process intervals are designed to capture the time for the completion of specific elements within the system in accomplishing their objectives. The compilation and analysis of process intervals provide additional insight into overall system performance and whether there are unique circumstances or environments that have an impact on system performance.

Response Time Standards and Performance Measures Resources. The principal organizations providing response time standards and performance measures include the following:

- *Commission on Fire Accreditation International* (*CFAI*). CFAI's accreditation standard requires performance compliance of 60 seconds for turnout of personnel in urban and suburban communities to an emergency event.
- *National Fire Protection Association* (*NFPA*). NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments,* establishes a 4 minute response time for the arrival of a unit with first-responder or higher capability to EMS calls and 8 minutes or less for an arrival of an advanced life support unit when such service is provided by the fire department. The standard further allows a 1 minute turnout time. Call processing time is covered by NFPA 1221, *Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems,* and requires that calls be handled in 60 seconds or less 95 percent of the time.
- *Commission on Accreditation of Ambulance Services* (*CAAS*). CAAS's accreditation standard allows 8 minutes, 59 seconds for arrival of advanced life support ambulance in urban and suburban communities from point of response unit notification of the event to life-threatening emergencies.
- *Centers for Medicare Services* (*CMS*). CMS provides a definition of an emergency response as one in which resources are mobilized and responding within the first 5 minutes from notification of the event. Definition is utilized to qualify for the payment of an emergency response versus a nonemergency request for Medicare-eligible patient transports.

TABLE 13.9.2 EMS Time Template

Column A *Discrete Time Stamps*	*Column B* *Function Intervals*	*Column C* *Process Intervals*
1. Event occurs	Recognition interval (1 to 2)	Call processing (4 to 11)
2. Discovery of event	System access interval (2 to 3)	System response (4 to 13)
3. Call for help	Switching interval (3 to 4)	Agency response (6 to 13)
4. Phone rings in 1st PSAP	Answer interval (4 to 5)	Unit response (11 to 13)
5. Phone "off hook" answered in 1st PSAP	Routing interval (5 to 6)	Patient contact (14 to 17)
6. Secondary dispatch phone rings (if appropriate)	Answer Interval (6 to 7)	Event to treatment (1 to 14)
7. Secondary dispatch phone "off hook" answered (if appropriate)	Interrogation interval (7 to 8)	On-scene management (13 to 15)
a. Interview begins	Resource selection interval (8 to 9)	Citizen reaction (1 to 3)
b. Pre-arrival instructions begin	Alert interval (9 to 10)	Unit cycle (11 to 18)
c. Pre-arrival instructions end	Acknowledgment interval (10 to 11)	Event elapsed (1 to 18)
8. Interview ends	Turn-out interval (11 to 12)	
9. Response resources identified	Travel interval (12 to 13)	
10. Dispatch time	Patient access interval (13 to 14)	
11. Unit acknowledgment	Scene management interval (14 to 15)	
12. Wheels turning (en route to scene)	Transport interval (15 to 16)	
13. Wheels stopped (arrived at scene)	Care transfer interval (16 to 17)	
14. Patient contact	Unit-ready interval (17 to 18)	
15. Wheels turning (en route to hospital)		
16. Wheels stopped (arrived at hospital)		
17. Transfer of care		
18. Available for service		

Source: NFPA 450, 2004 edition, p. 450-22.

Human Resources

The role of establishing educational criteria has largely been within the domain of the federal government through the National Highway Traffic Safety Administration (NHTSA). This statutory responsibility can be found in the Emergency Medical Services Systems Act of 1973.

Provider Level Skills and Knowledge. Since its initial development of the basic EMT curriculum, the NHTSA has undertaken various efforts to expand on the essential training and education for EMS personnel. In 1992, NHTSA developed the National Practice Blueprint designed to identify the essential skills and knowledge for each provider level:

- *First Responder.* Provision of care consistent with the guidelines prescribed in the *National Practice Blueprint for First Responder.* This certification level generally is limited to provision of basic first aid and CPR.
- *Basic EMT.* Provision of care consistent with the guidelines prescribed in the *National EMS Education and Practice Blueprint* for basic EMTs. This certification level is considered to be the minimum level of certification requirement to function on an ambulance. Many fire departments utilize this certification level as a requirement for their personnel in the same manner as NPQ FFI is required.
- *Intermediate EMT.* Provision of care consistent with the guidelines prescribed in the *National EMS Education and Practice Blueprint* for intermediate EMTs. This certification level serves to bridge the practice skills and capabilities of Basic EMTs and those of paramedics. Use of Intermediate EMTs is especially prevalent in areas where there is a lack of paramedics.
- *Paramedic.* Provision of care consistent with the guidelines prescribed in the *National EMS Education and Practice Blueprint.* The care and skills capability of this certification allows for the administration of various medications and invasive procedures such as intubation, pleural decompression, manual cardiac defibrillation, and other procedures as permitted under medical direction.

National Scope of Practice Model. In 2000, The National Highway Traffic Safety Administration convened a stakeholders' meeting to review EMS education comprehensively. Patterned after the highly successful *EMS Agenda for the Future,* the task force developed the *EMS Education Agenda for the Future.* Included in its findings and recommendations was the development of a *National EMS Scope of Practice Model.*[21] The work toward developing a National Scope of Practice Model was concluded in 2005. The model has recommended a new continuum of EMS providers that includes the following:

Emergency Medical Responder
Emergency Medical Technician
Paramedic
Advanced Practice Paramedic

The development of these new provider levels was based on a consensus process; thus the federal government does not have

any regulatory authority to require their adoption. Whether there will be widespread acceptance and adoption of the recommendations from the Scope of Practice task force will be determined by individual state regulatory agencies that generally have statutory authority over provider training, certification, and licensure.

Many states utilize testing and certification conducted by the National Registry of EMTs. The organization established in 1980 conducts comprehensive task analysis of provider skills. Through this analysis, the registry established testing materials and provides initial certification. Approximately 47 states and territories currently use the National Registry testing and certification process for personnel within their respective geographic areas.

Human Resource Standards and Performance Measurement Resources. The principal organizations providing human resource standards and performance measures include the following:

- International Association of Fire Fighters

  EMS Performance Measures
- State EMS Regulatory Agencies
- National Registry of Emergency Medical Technicians
- National Fire Protection Association

  NFPA 473, *Standard for Competencies for EMS Personnel Responding to Hazardous Materials Incidents*

Financial Control

Without appropriate financial controls and adherence to sound financial practices, EMS systems are subject to undue risk and potentially their demise. According to NFPA 450, EMS systems should have a comprehensive method for determining the cost of the EMS system. At a minimum the document recommends the establishment of an EMS financial plan that includes a cost analysis, short-term and long-term financial plans, and a financial reporting system.

Cost Analysis. A cost analysis should be conducted to study start-up costs, ongoing costs, and indirect costs:

Start-up costs. Generally include equipment, vehicles, supplies and materials, and personnel—including primary and support staff and training costs

Ongoing costs. Include equipment, vehicles, fuel, supplies and materials, communication systems, and personnel—including the cost of benefits, education/training, and certification costs

Indirect costs. Include insurance, legal services, medical oversight, contract services, regulatory compliance, billing services, and information management costs

Short-Term and Long-Term Financial Plans. Consistent with proper fiscal planning, the document identifies the development of a short-term financial plan, which consists of both an operating budget and a capital budget. A long-term financial plan should also be developed to insulate the agency from changes that can affect the organization fiscally. This plan should reflect new programs or services that are anticipated in the future, potential reimbursement changes, revenues, and cash flow projections. A contingency plan should be constructed if any of the analysis determines that the organization is at risk.

Financial Reporting System. Agencies that provide patient transport services should have a financial reporting system that provides the agency with information on the efficacy of revenue generation. Agencies should be able to identify and calculate gross billings, collection rate, payer mix, billing mix for advanced life support (ALS) and basic life support (BLS), scheduled and unscheduled transports, and miles per transport. The agency should be capable of determining bad debt expense, contractual allowances, write-offs, net revenue, revenues per transport, and accounts receivable turnover rate.

Finance Standards and Performance Measures Resources. The principal organizations providing finance standards and performance measures include the following:

- National Fire Protection Association

  NFPA 450, *Guide for Emergency Medical Services and Systems*
- American Ambulance Association

  Contracting Guide for Ambulance Services
  Medicare Compliance Manual
- Governmental Accounting Standards Board

Medical Direction

Medical direction is central to an agency's ability to provide patient services. Although there are exceptions, EMS personnel providing patient care are usually considered to be an extension of the physician and therefore require physician authority for the services they provide. Historically, physicians have provided their medical oversight services on a voluntary basis in the interest of patient care. However, with increasing demands on their time for the multitude of services being required of medical directors, the trend throughout the industry is to contract for and subsequently provide payment for medical director services.

The National Association of EMS Physicians (NAEMSP) and the American College of Emergency Physicians (ACEP) have been the principal agencies providing leadership and guidance for medical direction. In 2000, NHTSA in conjunction with NAEMSP and ACEP developed the National Standard Curriculum for Medical Direction.

Medical Oversight. Medical oversight provided by physicians encompasses the entire range of patient care activities provided by the EMS organization. The two principal functions of these services are online services and off-line services. Online services generally refer to medical control decisions affecting patient care at the time those services are provided. Off-line services refer to the additional services that the medical director

is engaged in, including protocol development, education and evaluation of personnel, administrative services, patient advocacy, medical community liaison, and participation in quality review and management processes.

Medical Direction Standards and Performance Measures Resources. The principal organizations providing medical direction standards and performance measures include the following:

- National Highway Transportation Safety Administration (NHTSA)
- National Association of EMS Physicians
- American College of Emergency Physicians
- National Fire Protection Association (see NFPA 450, *Guide for Emergency Medical Services and Systems*)

Quality Management

The process for ensuring that patient care services are delivered consistent with community expectations and organizational standards is known as quality management. The core component that drives the quality management program is the ability to generate meaningful data that can be analyzed, measured, and compared to established organizational expectations.

EMS Quality Management Elements. Elements of an effective EMS quality management program include conducting or measuring patient outcomes, effective review of clinical care, analysis and evaluation of system participant integration, human resource activities, data collection validation, and performance standard compliance. The process of quality management is ongoing, recognizing that changes based on the evaluation and analysis process require that change itself is monitored and evaluated to determine whether the desired results have been achieved.

Quality Management Standards and Performance Measures. The principal organizations providing quality management standards and performance measures include the following:

- National Fire Protection Association
  - NFPA 450, *Guide for Emergency Medical Services and Systems*
- National Highway Transportation Safety Administration (NHTSA)
  - *National EMS Information System*
  - *A Leadership Guide to Quality Improvement for EMS Systems*
  - *Uniform Pre-Hospital Data Elements and Definitions*
- National Institute of Standards and Technology
  - Malcolm Baldrige National Quality Award

Resource Deployment

The management of assets and resources in an EMS system is critical in ensuring effective and efficient delivery of services. In fire-based systems, resources are, with few exceptions, deployed from a fixed location. These locations are generally fire stations whose locations are routinely predicated on time and distance studies to meet specific response time objectives.

Deployment Models. In addition to fixed deployment models, variable deployment models are also used by the industry. These models are predicated on moving ambulance transport resources to various locations based on volume and location analysis. Time-of-day and computer-generated predictability patterns for call locations are also used to shift resources to predetermined points in the service area. This model of resource deployment, referred to as system status management, is routinely used by the private sector and by third-party service providers responsible for high-volume systems.

Tiered Response. The use of multiple agencies for the delivery of EMS is commonly referred to a tiered response. In a single-tier system, one organization has responsibility for response and care at a single level of care. Fire-based EMS transport systems fall into the single-tier category because they provide both the initial response as well as the patient transport at usually the advanced life support level of care. Multiple-tiered response systems are those in which an agency provides first response and initial care but delegates patient transport responsibilities to another entity. There are various types of multitiered systems; the most common is a fire-based first response system supported by a separate patient transport system provider, either public or private.

Resource Deployment Standards and Performance Measures. The principal organizations providing resource deployment standards and performance measures include the following:

- National Fire Protection Association
  - NFPA 450, *Guide for Emergency Medical Services and Systems*
  - NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*
  - NFPA 1710, *Standard for the Organization ad Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*
- American Ambulance Association
  - *Contracting Guide for Ambulance Services*
- International Association of Fire Fighters
  - *Effectiveness of Fire Based EMS*
  - *IAFF Performance Measures*
- American Society for Testing and Materials
  - ASTM F1224-89(2004)e1, *Standard Guide for Providing System Evaluation for Emergency Medical Services*
  - ASTM 1339-92(2003), *Standard Guide for Organization and Operation of Emergency Medical Services Systems*
  - ASTM F1517-94(2007), *Standard Guide for Scope of Performance of Emergency Medical Services Ambulance Operations*

SUMMARY

The evolution of EMS during the last 50 years has resulted in fire departments being the dominant provider of emergency medical care in their communities. The fire department's integration of EMS is not based singularly on a reduction in fire suppression activity but as a result of multiple factors. The factors responsible for the evolution of EMS and the fire service have been varied but are representative of local, state, and national issues. Fire departments have changed in concert with the environment in which they operate.

Successful delivery of EMS services by the fire department in the local community is dependent on the successful integration of multiple partners and a committed adherence to established standards and performance measures. As such, fire departments occupy a central role in responding to the emergency medical care needs of their constituents. Although changes are certain to occur in the industry, the delivery of EMS by fire departments is established and will continue to reflect a major operational program of the local fire department.

ACKNOWLEDGMENT

The late James O. Page is regarded as the "Father of Fire-Based EMS." His devotion and commitment to and advocacy of emergency medical services, particularly as a core service element of the fire department, are well known to those in the industry. He was a friend and mentor and his untimely passing will no doubt leave a great void in our profession.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on medical services and the fire department discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 450, *Guide for Emergency Medical Services and Systems*
NFPA 473, *Standard for Competencies for EMS Personnel Responding to Hazardous Materials Incidents*
NFPA 1581, *Standard on Fire Department Infection Control Program*
NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*
NFPA 1999, *Standard on Protective Clothing for Emergency Medical Operations*

SECTION

14

Detection and Alarm

Shane M. Clary

14.1 Fire Alarm Systems
14.2 Automatic Fire Detectors
14.3 Notification Appliances
14.4 Fire Alarm System Interconnections
14.5 Inspection, Testing, and Maintenance of Fire Alarm Systems
14.6 Household Fire Warning Equipment
14.7 Fire Protection Surveillance and Security Services
14.8 Gas and Vapor Detection Systems and Monitors
14.9 Carbon Monoxide Detection in Residential Occupancies
14.10 Security and Intrusion Detection Systems

Historically, detection and alarm have been fire protection's first line of defense after an ignition has occurred. As technology has improved, fires and their by-products have been detected earlier and earlier. More recently, various forms of detection and alarm have become interconnected. At the same time, the fields of fire protection and security have grown closer together.

Section 14 of the *Fire Protection Handbook*® reflects the evolution of detection and alarm technologies. The 19th edition included the first chapter on carbon monoxide detection in residential occupancies. In this 20th edition, the section has been expanded to include a new chapter entitled "Security and Intrusion Detection Systems."

Chapter 1, "Fire Alarm Systems," describes types of signals and basic system components before explaining the basic types of systems: protected premises, central station, proprietary, remote station, and auxiliary. The chapter also discusses emergency voice/alarm communication systems and a new concept for the alerting of individuals, mass notification systems.

Chapter 2, "Automatic Fire Detectors," has been expanded to include video-based smoke and flame detection. After describing several types of detectors (heat, smoke, gas, radiant energy, and multisensor), the chapter discusses detector selection, installation, maintenance, and testing.

Chapter 3, "Notification Appliances," concentrates on notification devices that *NFPA 72*®*, National Fire Alarm Code*®*,* defines as fire alarm system components, such as bells, horns, speakers, and light or text displays that provide audible, tactile, or visible outputs (or any combination of those outputs). Mass notification systems and intelligibility are discussed.

Chapter 4, "Fire Alarm System Interconnections," presents the interface of process monitoring and building management systems (such as elevator control, door control, and heating, ventilating, and air-conditioning control) and fire protection systems.

Chapter 5, "Inspection, Testing, and Maintenance of Fire Alarm Systems," explains reliability analysis and prediction, as well as topics such as acceptance and reacceptance testing, a design lifetime, and sensitivity measurement. Schedules for system and component inspection, testing, and maintenance are presented.

Chapter 6, "Household Fire Warning Equipment," discusses why household fire warning systems are needed, the history of residential fire warning systems, research into system effectiveness, the importance of having a system in the home and how to make the best use of it, and the importance of an effective escape plan. Types of systems and detectors are covered, along with installation and testing guidelines.

The section considers the human element of detection and alarm in Chapter 7, "Fire Protection Surveillance and Security Services." This chapter discusses topics such as the management of security services, communications equipment, security service functions and supervision, security officers, and patrol routes and rounds.

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Chapter 8, "Gas and Vapor Detection Systems and Monitors," addresses the detection of flammable, combustible, or toxic gases and vapors that represent a hazard to the occupants or the facility.

The physical properties, sources, and hazards of CO are described in Chapter 9, "Carbon Monoxide Detection in Residential Occupancies." The chapter then outlines carbon monoxide standards and detection technologies and provides a discussion of fire service response to carbon monoxide alarms.

The section closes with a new subject in Chapter 10, "Security and Intrusion Detection Systems." This chapter provides a brief overview of premises security systems that are covered by two NFPA documents first approved in 2005: NFPA 730, *Guide for Premises Security,* and NFPA 731, *Standard for the Installation of Electronic Premises Security Systems.*

Chapter 1

Fire Alarm Systems

Wayne D. Moore

Chapter Contents

Selecting the System
Making the System Work
Types of Signals
Fire Alarm System Basics
Protected Premises System
Emergency Voice/Alarm Communication System
Central Station Fire Alarm System
Proprietary System
Remote Station System
Auxiliary System

Key Terms

auxiliary fire alarm system, central station fire alarm system, emergency voice/alarm communications, fire alarm control unit, fire alarm signal, fire alarm system, fire barrier, fire detection system, mass notification system, McCulloh system, proprietary supervising station fire alarm system, protected premises, remote supervising station fire alarm system, supervisory signal, trouble signal

A fire detection and alarm system is a key element among the fire protection features of any building. Because most fire deaths in the United States result from building fires, the use of fire detection and alarm systems in buildings can help to significantly reduce the loss of life from fire. Also, if properly specified, designed, manufactured, installed, maintained, tested, and used, a fire alarm system can help limit property fire losses in buildings, regardless of occupancy.

Strictly adhering to the requirements of *NFPA 72®*, *National Fire Alarm Code®*, is fundamental to maintaining an appropriate level of quality control through the steps that lead to the successful provision of a fire detection and alarm system. This document, working in concert with NFPA 70, *National Electrical Code®*, particularly Article 760 on wiring for fire alarm systems, forms the basis for requirements that have been created through the consensus standards-making process. These requirements represent the combined experience and professional judgment of the members of the eight technical committees that write the various chapters of *NFPA 72*.

This chapter discusses the philosophical basis for fire alarm system design, as well as the major operational characteristics of the various types of fire alarm systems currently in use.

For related topics see Section 14, Chapter 2, "Automatic Fire Detectors"; Section 14, Chapter 3, "Notification Appliances"; Section 14, Chapter 4, "Fire Alarm System Interconnections"; Section 14, Chapter 5, "Inspection, Testing, and Maintenance of Fire Alarm Systems."

SELECTING THE SYSTEM

In making the basic decision regarding what type of fire alarm system is needed for a particular building, certain questions must be answered. In answering these questions, one must bear in mind that the most successful approach to the overall protection of life and property is a holistic approach—an approach that relies on the fact that the protection provided by the sum of the individual components of the fire protection system will always be much greater than if one was to rely on each individual component alone. Thus, effective protection is a combination of interlocking, interrelated fire protection systems, designed to function in concert with each other to provide the desired level of protection.

It is not a matter of whether or not automatic sprinklers or a fire alarm system should be provided. Rather, automatic sprinklers, a fire alarm system, and proper building construction features such as fire barriers along with a host of other valuable prevention and protection features, all built on a foundation of management commitment to fire prevention and control, can assure a building owner or occupant that a facility is safe.

With this foundational truth in mind, fire alarm system selection must be based on answering the question: "What are the protection goals?" Is the building owner attempting to provide a level of life safety that will meet the needs of the people occupying the building and satisfy the requirements of the local building code and local authority having jurisdiction (AHJ)? Or is the building owner intent on providing a needed level of property protection? Or is the building owner trying to ensure that the mission of the facility is not interrupted by fire? Other protection goals include cultural/heritage preservation, environmental protection, and first responder safety. In most cases the development of the owner's fire protection goals will require a risk analysis of the property. A

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risk analysis involves identifying the most probable fire threats to the owner's property and then analyzing the impact of those fire threats on the building and operation.

The final answer may be "yes" to one or more of these questions. And, with each "yes" answer, the building owner will be guided to select the fire alarm system that will meet the needs of the facility.

MAKING THE SYSTEM WORK

Just as building fire protection is most effective when it consists of a series of interlocking, interrelated fire protection systems, ensuring the mission effectiveness or operational reliability of a fire alarm system is the result of specific attention given to a series of interlocking, interrelated steps:

- Specify
- Design
- Manufacture
- Install
- Maintain
- Test
- Use

Determining Goals

The user of the fire alarm system must define the reason why the system is being provided. This definition step will identify the protection goals of the user and also the external factors that may influence the fire alarm system installation. The user may determine that the protection goal is the preservation of the lives of the persons occupying the building. Such a *life safety goal* and the protection features it dictates will help determine the type of fire alarm system. Or the user may determine that the protection goal is the preservation of the physical building and its contents. Such a *property safety goal* and the protection features unique to this goal will also help determine the type of fire alarm system that can most effectively provide protection.

In analyzing the particular needs of a facility, the user may determine that the protection goal is the preservation of the ability to produce a product or provide a service. Such a *mission protection goal* will help determine the type of fire alarm system needed at the facility.

It may even be that the user determines that the protection goal actually embraces a combination of all three primary goals: (1) life safety, (2) property protection, and (3) mission protection. An analysis of how fire will affect the mission (business impact) involves identifying the critical business functions within the organization and determining the impact of a fire incident on that business function and whether or not the business can recover from the expected fire incident. Once the protection goals are clearly defined, the features of the fire alarm system can be determined. If the user simply wants to build his or her building to be compliant with the minimum requirements of the codes in force in the jurisdiction, the designer must still understand how the codes may combine to be able to properly design the fire alarm system to meet the user's needs.

Additionally the user may be a representative of the federal government and want a mass notification system (MNS) to be integrated with the fire alarm system. Care must be taken to ensure that the MNS and the fire alarm system operate as required. The MNS is the only system allowed to interrupt a fire alarm system to allow additional safety information to be announced to the occupants.

Generally speaking the user will not develop this information without consulting a fire protection engineer. The engineer will review the features selected to develop a clear and concise written set of specifications. These specifications will include the needed features and will include statements as to how the quality of the installation is to be ensured, including the initiating device, notification appliance, and signaling line circuit performance. This document will guide the system supplier in making recommendations regarding particular equipment, as well as guide the supplier by providing the required quality control measures.

Based on the specifications, a fire protection engineer working either as a consultant to the user or as an employee of, or consultant to, the system supplier can develop a detailed system design. *NFPA 72,* recognizes the need for trained designers and installers and provides guidance for both the owner and authority having jurisdiction to assist in determining if these individuals are qualified. Certification by a national organization is one of the recommendations of the code. By exercising care to ensure that the design meets both the specifications and the requirements of *NFPA 72,* the designer will greatly enhance the overall quality of the fire alarm system.

Meanwhile, the manufacturer of fire alarm system components has been studying the needs of fire alarm users and has developed products with a wide variety of features. The manufacturer will provide products of high quality that can meet the requirements of *NFPA 72* and pass the tests of the nationally recognized testing laboratories, such as Underwriters Laboratories Inc. (UL) and FM Global Research.

A qualified fire alarm system installer can now take the manufacturer's equipment that satisfies the user's specifications and the fire protection engineer's design and install a fire alarm system. The process of installation must also meet the requirements of *NFPA 72.* Quality assurance during installation is critical to the long-term usefulness and stability of the fire alarm system. There are several ways of ensuring installation quality and meeting the mission effectiveness goals.

Ensuring Installation Quality

To help ensure installation quality, UL has developed two fire alarm certificate programs. One certificate is for central station fire alarm systems. The other is for local, auxiliary, remote station, proprietary, and emergency voice alarm/communication systems. UL-listed contractors may apply to UL for a certificate covering the installation of a fire alarm system at a specific protected premises. The certificate describes the system, and states that the contractor has met the requirements of *NFPA 72* and the relevant UL standards. It further states that the contractor has a contract with the user for periodic testing and routine maintenance of the fire alarm system to ensure quality continuity. Periodically, UL representatives inspect a statistical sampling of certificated installations of each contractor to check on the accuracy of the information supplied on the certificate and to verify compliance with *NFPA 72* and relevant UL standards.

FM Global Research has developed a placard that the contractor may post at the fire alarm installation, stating that the

system has been installed to comply with the requirements of *NFPA 72* and the relevant FM requirements. When FM representatives visit facilities insured within the FM system, they look for this placard as an indication that standard fire alarm service has been provided.

Some AHJs require that installers demonstrate competency to install systems. Competency may be demonstrated by achieving certification through the National Institute for Certification in Engineering Technologies in fire protection, subfield fire alarms. The International Municipal Signaling Association also has an interior fire alarm certification program that has minimum competency requirements. Alternately, some AHJs may have developed an examination of their own that installers must pass. Many states, although not all, require that installers of fire alarm systems be licensed in that specialty in order to install these systems.

To ensure continuity of quality, a fire alarm system must be tested and maintained. *NFPA 72* sets forth the requirements for maintenance and testing in Chapter 10. Once again, the competency of the persons performing the testing and maintenance is critical to achieving an appropriate level of quality. (See Section 14, Chapter 5, "Inspection, Testing, and Maintenance of Fire Alarm Systems.")

Finally, just as the components of the fire alarm system must be listed by a nationally recognized testing laboratory for the specific use, the way the fire alarm system is used must conform to the requirements of *NFPA 72.* By carefully working through the steps (i.e., specify, design, manufacture, install, maintain, test, and use), the user of the fire alarm system will have a system that will serve the facility well for many years to come.

TYPES OF SIGNALS

Fire alarm systems may provide three types of signals: (1) alarm, (2) supervisory, and (3) trouble.

An *alarm signal* is a warning of fire danger that requires immediate action.

A *supervisory signal* indicates that action is needed in connection with the operation of other fire protection systems that are being monitored by the fire alarm system. Such systems may include extinguishing or suppression systems, such as automatic sprinkler systems, carbon dioxide systems, dry chemical systems, foam systems, and gaseous agent systems. They may also include the supervision of guards who make fire patrol tours throughout the protected premises. A supervisory signal may be either an "off-normal" signal, indicating a condition requiring attention; or a "restoration-to-normal" signal, indicating the condition that initiated the original off-normal signal has been resolved.

A *trouble signal* indicates a fault in a monitored circuit or component of the fire alarm system or the disarrangement of the primary or secondary power supply.

FIRE ALARM SYSTEM BASICS

Fire alarm systems are classified according to the functions they are expected to perform. Their installation, maintenance, and use are specified in *NFPA 72.*

The basic components of each system are:

1. A system control unit (Figure 14.1.1)
2. A primary, or main, power supply
3. A secondary, or standby, power supply
4. One or more initiating device circuits or signaling line circuits to which manual fire alarm boxes, sprinkler waterflow alarm initiating devices, automatic fire detectors, and other fire alarm initiating devices are connected
5. One or more fire alarm notification appliance circuits to which audible and visible fire alarm notification appliances, such as bells, horns, stroboscopic lamps, and speakers, are connected
6. Many systems also have an off-premises connection to a central station, proprietary supervising station, remote supervising station, or public fire service communication center by means of an auxiliary fire alarm system

FIGURE 14.1.1 Fire Alarm System Control Unit (Source: Mircom Ltd., Toronto, CN; Mammoth Fire Alarms, Lowell, MA)

Primary and Secondary Power Supplies

The primary and secondary power supplies at both the protected premises and at a subsidiary or supervising station must meet the requirements of *NFPA 72*. The primary power is usually supplied by a connection to utility-generated electric power. The connection must be from a branch circuit dedicated to the fire alarm system. The circuit and connections must be mechanically protected. The circuit disconnecting means must have a red marking, be accessible only to authorized personnel, and be identified as "Fire Alarm Circuit Control." Inside the fire alarm system control unit, a permanent legend must identify the location of the electrical panel board that contains the circuit disconnecting means.

Very remote areas may not have utility-generated power available. In these cases, electricity is usually supplied by generators on the site of the facility. Most often more than one generator is provided, each operated for a number of hours at a time to help ensure the reliability of the electric power. Primary power for fire alarm systems at geographically remote facilities is, therefore, supplied by generators.

Secondary power supply for a fire alarm system is required to automatically supply the energy to the system within 30 seconds whenever the primary power supply is not capable of providing the minimum voltage required for proper system operation.

The size of the secondary supply usually is measured in the amount of time that the secondary supply will operate the system, followed by a prescribed time period for the system to operate in an alarm condition. Local (protected premises), central station, remote station, proprietary, and auxiliary systems must have 24 hours of standby power, followed by 5 minutes of alarm. Emergency voice/alarm communication systems must have 24 hours of standby power, followed by 2 hours of emergency operation. To allow calculation of the power required for 2-hour emergency operation, *NFPA 72* specifies that the 2 hours of emergency operation are the equivalent of 15 minutes of operation under full load (i.e., with all input devices and output appliances operating).

The required capacity of the secondary power can be supplied by storage batteries; storage batteries with 4 hours of capacity in conjunction with an engine-driven generator; or multiple engine-driven generators, each of which must be capable of supplying the entire standby power load. This generator is considered "dedicated" to the fire alarm system. This means that the reason the generator was installed was to supply secondary power to the fire alarm system. Of course, if the generator has a greater capacity than is needed by the fire alarm system, it may also be used to supply loads related to the fire alarm system, such as lighting or air-conditioning equipment serving the room where the fire alarm system is located.

Engine-driven generators used to provide secondary power for a protected premises fire alarm system must comply with NFPA 110, *Standard for Emergency and Standby Power Systems,* Section 2.2, requirements for a Type 10, Class 24, Level 1 System. Installation must be in accordance with the *NEC,* Article 700. In addition, where survivability of circuits is required by Chapter 6, equal protection must be provided for power supply circuits.

Circuits

Fire alarm systems have three basic types of circuits: (1) initiating device circuits (IDC), (2) notification appliance circuits (NAC), and (3) signaling line circuits (SLC).

All fire alarm system cable and the wiring installation must conform to Article 760 of the *NEC* and the additional requirements of *NFPA 72*.

Initiating device circuits connect conventional (nonaddressable) fire alarm and supervising initiating devices to the system control unit. Notification appliance circuits connect notification appliances (audible and visible) to the system control unit. The term *signaling line circuits* is used to define circuits over which two-way data communications take place. This communication can take place between an addressable device and system control unit or the system control unit and the off-premises connection, such as a central station, a public fire service communications center, a remote station, or a proprietary supervising station.

There is at least one manufacturer that has the capability of using an SLC for the notification appliance circuit. The feature is software driven and permits selective area evacuation using the same SLC. When a Class B circuit is allowed, the notification appliances can be "T-Tapped" off the SLC and still meet the code requirements for monitoring of wiring and appliance integrity. The addressable controller for the appliances constantly polls the appliances to verify communications. Using short circuit fault isolators also helps to ensure survivability of the circuit.

NFPA 72 provides the fire alarm system designer with various circuit configurations that provide different levels of operation and integrity. The circuit configuration can only be defined when both the fire alarm control unit operation and the wiring configuration are known.

A typical circuit used in many fire alarm systems consists of a two-wire circuit with an end-of-line resistor. Initiating devices, with normally open contacts, are connected in parallel. A small amount of electrical current flows through the wire to monitor the wiring integrity. A break in the wire causes a trouble condition at the system control unit. Everything electrically beyond the break in the wiring is out of service until repairs are made to the circuit. Operation of an initiating device shunts the resistor, thus increasing the current, which causes the system control panel to respond in an alarm condition.

A two-wire circuit configuration that operates up to the single fault (open-circuit or ground-fault condition) is labeled a Class B circuit. A circuit configuration that requires the wiring to be returned to the system control unit, where the system control unit is configured to allow a device or appliance to operate on either side of a single open-circuit or ground-fault condition, is labeled a Class A circuit. Both of these designations can be applied to initiating device circuits, notification appliance circuits, and signaling line circuits.

Many fire alarm system control units have more than one initiating device circuit, so that the fire location can be indicated on an annunciator panel by floor, wing, subsection, or room. The annunciator can be built into the control unit or located in a lobby, maintenance area, telephone switchboard room, or some other location where it is accessible to building and fire service personnel.

Depending on the size of the building and the fire alarm system, addressable and addressable analog systems will have

one or two signaling line circuits. The code does not require more signaling line circuits than the number of connected devices dictates. However, it is prudent to "not put all of your eggs in one basket" and to use a minimum of two signaling line circuits for all except the smallest of systems.

Annunciation is principally designed to serve the fire department. Therefore, coordination with the fire department is important if the annunciation of alarms is to be effective. With the new liquid crystal display (LCD) annunciators and addressable technology, it is tempting to annunciate each point at a remote annunciator. This tactic results in too much information that will tend to confuse rather than help first responders.

NFPA 72 has Annex A material that details the guidelines for a standard fire service interface. Annunciators, information display systems, and controls for portions of the fire alarm system provided for use by the fire service should be designed, arranged, and located in accordance with the needs of the organizations intended to use the equipment.

Where annunciators, information display systems, and controls for portions of the fire alarm system are provided for use by the fire service, these should have a common design and operation to avoid confusion for users. The standard fire service interface uses an icon-based design that can be implemented in various manners on a range of system sizes and still maintain sufficient familiarity so that fire service personnel, with training, should be able to use effectively any variation that follows the guidelines presented in the Annex material.

NFPA 72®, National Fire Alarm Code®, Format

NFPA 72 comprises 11 chapters presented in the following format:

- Chapter 1 Administration
- Chapter 2 Referenced Publications
- Chapter 3 Definitions
- Chapter 4 Fundamentals of Fire Alarm Systems
- Chapter 5 Initiating Devices
- Chapter 6 Protected Premises Fire Alarm Systems
- Chapter 7 Notification Appliances for Fire Alarm Systems
- Chapter 8 Supervising Station Fire Alarm Systems
- Chapter 9 Public Fire Alarm Reporting Systems
- Chapter 10 Inspection, Testing, and Maintenance
- Chapter 11 Single- and Multiple-Station Alarms and Household Fire Alarm Systems

In *NFPA 72* the requirements for fire alarm systems that provide household fire warning have their own chapter (Chapter 11), and the requirements for fire alarm systems for all other occupancies are contained in Chapters 1 through 10.

In *NFPA 72* a fire alarm system that meets the requirements of Chapters 4 and 6 forms the basic fire alarm system "building block." A protected premises fire alarm system, whether it is used to notify the occupants so they may safely evacuate, used to actuate a fire suppression or extinguishing system, or used to oversee conditions at a facility and report status changes to a supervising station, must meet the requirements of these two chapters. The initiating devices and notification appliances connected to the protected premises fire alarm system must meet the requirements contained in Chapters 5 and 7, respectively. A supervising station fire alarm system must meet the requirements contained in Chapter 8. And a protected premises fire alarm system, its initiating devices and notification appliances, along with a supervising station fire alarm system, must all meet the testing and maintenance requirements contained in Chapter 10.

Because of the familiarity and wide usage of industry terms that have evolved over the years, *NFPA 72* has retained such terminology. One example of this terminology is the system designations: protected premises system, emergency voice/alarm communication system, central station system, proprietary system, remote station system, public fire reporting system, and auxiliary system.

PROTECTED PREMISES SYSTEM

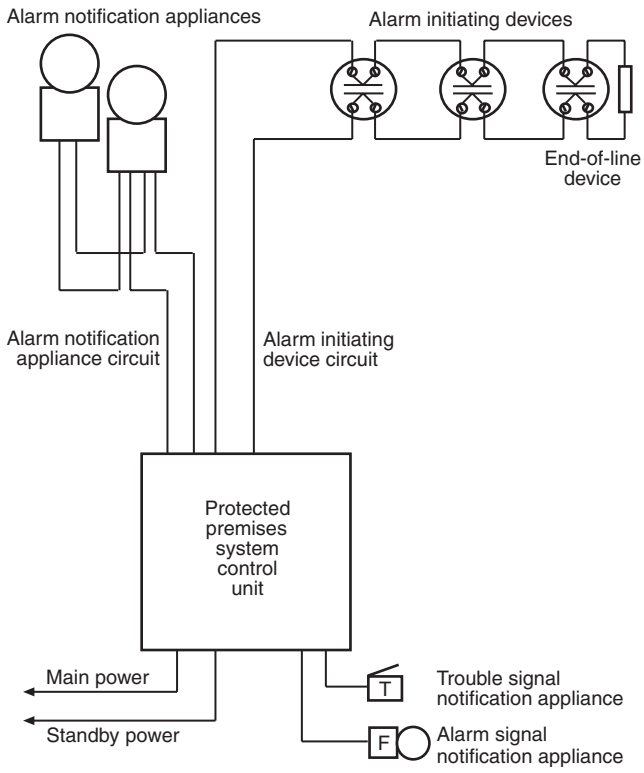
The main purpose of a protected premises fire alarm system is to activate local audible and visible alarm notification appliances to notify the occupants that they must evacuate the protected building (Figure 14.1.2). Such a system could be limited to the basic features described earlier. The system could also interface with other protective systems that would help make the building safer in case of fire. Such features might include, for example, the operation of a fire-extinguishing or suppression system; the recall of elevators; the unlocking of doors; the closing of smoke barrier doors; the control of heating, ventilation, and air-conditioning (HVAC) equipment; or the operation of smoke control systems.

In a protected premises system, the alarm is not relayed automatically to a fire department. Instead, when the alarm sounds, someone must use some other means to notify the fire department. If the building is unoccupied at the time of the alarm, fire department response would depend on a neighbor or passerby hearing or seeing the audible and/or visible fire alarm notification appliances and telephoning the fire department.

Additionally a fire alarm system may be interfaced with a smoke control system. When such an interface occurs, the fire protection engineer and mechanical engineer must coordinate their efforts to ensure that the design and operation of the combined systems will work as expected by the authority having jurisdiction. Many jurisdictions now have a policy that the system design must be submitted with a narrative describing the system interface and operation of the systems, both individually and as combined systems.

EMERGENCY VOICE/ALARM COMMUNICATION SYSTEM

This system is used in occupancies, such as high-rise buildings and large assembly occupancies, where it is necessary to relocate occupants to areas of refuge rather than evacuate them (Figure 14.1.3). The voice/alarm system consists of a series of high-reliability speakers located throughout the building. They are connected to, and controlled from, the fire alarm communication console located in an area designated as a building fire command station. From the building fire command station, individual speaker zones or the entire building can be selected to receive an alert tone followed by a voice message that gives specific instructions to the occupants. Some systems have fire



(a)

(b)

FIGURE 14.1.2 (a) Typical Arrangement of a Local Fire Alarm System; (b) Local System Control Unit (Source: Mircom Ltd., Toronto, CN; Mammoth Fire Alarms, Lowell, MA)

FIGURE 14.1.3 Emergency Voice/Alarm Communication System. A fire officer gives building occupants specific instructions during a fire. (Source: SimplexGrinnell Company)

warden telephone stations on each floor, or within each fire zone, to which a fire warden would report to assume local command and pass on specific evacuation instructions.

A trained building employee usually operates the fire command station until the fire department arrives, at which time the officer in charge takes over. The fire warden telephone stations may also be used during fire-fighting operations for communication with the fire fighters whose hand-portable two-way radios may not function properly in the high-rise building. *NFPA 72* recognizes that the installation of two-way, in-building radio communications enhancement systems will ensure that fire department radios will work in all areas of a high-rise building. A bidirectional amplifier is an example of such a system. The two-way, in-building radio communications enhancement system is permitted to be monitored by the building fire alarm system.

One important aspect of a voice/alarm communication system is that, since complete building evacuation is not always feasible, it can instruct occupants to relocate to areas of ref-

uge where they can safely wait for the fire to be brought under control. In such cases, communication with these relocated occupants must be maintained to keep occupants informed and, therefore, more comfortable with the soundness and safety of decisions that leave them still inside a burning building.

The most recent edition of the *National Fire Alarm Code* allows mass notification systems (MNS) to be integrated with emergency voice/alarm communication systems. The MNS can be a stand-alone system that interfaces with the fire alarm system to allow the MNS system to stop all alarm notification in the building while more specific instructions can be given. A typical example would be a terrorist event when occupants may be instructed to stay inside the building. The MNS can also be integrated with the fire alarm system using the same speakers as the fire alarm system. Annex material is provided in the *National Fire Alarm Code* to assist the designers, installers, and authorities having jurisdiction in understanding mass notification systems.

CENTRAL STATION FIRE ALARM SYSTEM

A central station fire alarm system is designed to receive signals from a protected premises at a constantly attended location operated by a company whose purpose is providing central station service. This operating company must be listed by either UL or FM Global Research. Central station installations must have either the UL certificate or FM Global Research placard; whichever means of verifying the character of the installation is required by the AHJ. It may be expected that central station service will be provided for only industrial and commercial facilities of relatively high value. In such cases, the central station fire alarm system is intended to enhance the property protection aspects of a facility in order to satisfy the recommendations submitted by a highly protected risk property insurance company acting in its role of AHJ for matters relating to property insurance.

In some cases, a central station operating company may collect signals from a specific geographic area at a subsidiary station and then transmit the signals to a central station for handling. Although the subsidiary station is not normally staffed, *NFPA 72* requires that it be capable of being staffed in an emergency. Such an emergency might include the failure of the communication channels between the subsidiary station and the central station.

There are eight elements of central station service: four at the protected premises and four at the central station. The four at the protected premises are installation, testing, maintenance, and runner service. The four at the central station are management or oversight of the system, monitoring of signals from the protected premises, retransmission of fire alarm signals to the public fire service communication center, and record keeping. Of course, a listed central station is allowed to contract for other services that do not include the eight points described previously. A central station may simply provide monitoring for alarm, supervisory, and trouble signals such as provided by a remote station.

Central station service may be provided entirely by a listed central station operating company, by a listed central station operating company that contracts one or more elements of central station service at the protected premises to a subcontractor, or by a listed local fire alarm installation company that will provide the four elements at the protected premises and subcontract the four elements at the central station to a listed central station operating company.

Signals may be transmitted from a protected premises using a variety of transmission technologies stated in *NFPA 72,* Chapter 8. Such technologies include active multiplex system encompassing leased line, optical fiber cable, private microwave radio system, and telephone-company-provided derived local channel system; digital alarm communicator system; digital alarm radio system; McCulloh system (the code now states that unless accepted by the authority having jurisdiction, McCulloh systems are not permitted to be installed after June 2003); two-way RF multiplex system; one-way private radio alarm system; or a directly connected noncoded system.

When they receive fire alarm, supervisory, or trouble signals, operators at the central station take actions prescribed by *NFPA 72.* In addition to notifying the public fire service communication center in the case of a fire alarm signal, the central station operators must notify designated persons either at the protected premises or at their homes. The operators must also dispatch a runner or service technician when equipment at the protected premises must be reset by someone from the central station. This runner must reach the premises within 1 hour.

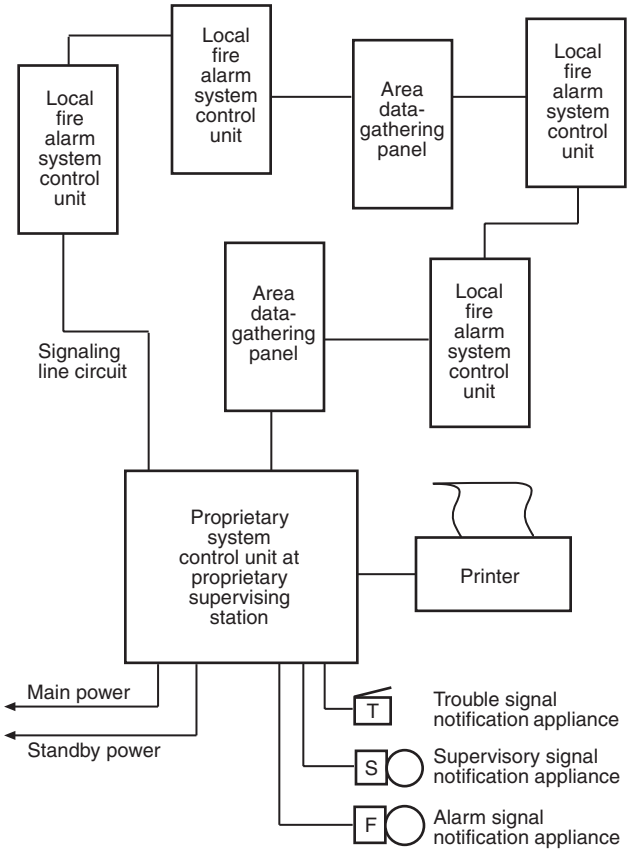
Similarly, supervisory signals and trouble signals also require a runner response. Unresolved guard tour signals require a runner response within one-half hour of the expiration of a 15-minute grace period. Other unresolved supervisory signals require a runner to reach the protected premises within 1 hour. In the case of a trouble signal, the service technician must arrive at the protected premises within 4 hours and begin making repairs to the fire alarm system.

PROPRIETARY SYSTEM

The proprietary fire alarm system is widely used in large commercial or industrial occupancies (Figure 14.1.4).

Signals transmitted over a proprietary system are received and automatically and permanently recorded at a constantly attended proprietary supervising station located either at the protected premises or at another location of the property owner. In very simplistic terms, a proprietary system is similar to a central station system but with the supervising station owned and operated by the property owner and located at the protected premises or another location of the property owner.

Many existing proprietary systems have separate initiating device circuits for each building zone or subsection, similar to local, auxiliary, and remote station systems. However, due to the increasing use of electronics, newer proprietary systems for larger buildings often have signal multiplexing and built-in minicomputer systems. These systems receive all signals from the protected building over one or more communication paths and determine the exact location of the fire by use of digitally coded information. Figure 14.1.5 shows the complexity and interrelationships among the many facets of a modern



(a)

(b)

FIGURE 14.1.4 (a) Typical Arrangement of a Proprietary Protective Signaling System; (b) Central Supervisory Station. An attendant constantly monitors the proprietary protective signaling system. The printer on the desk provides a permanent record of signaling traffic. (Source: SimplexGrinnell Company)

computer-controlled proprietary fire alarm system serving one large building. Proprietary systems can be used in one building as shown in Figure 14.1.5 or serve multiple campus-style such as shown in Figure 14.1.4(a).

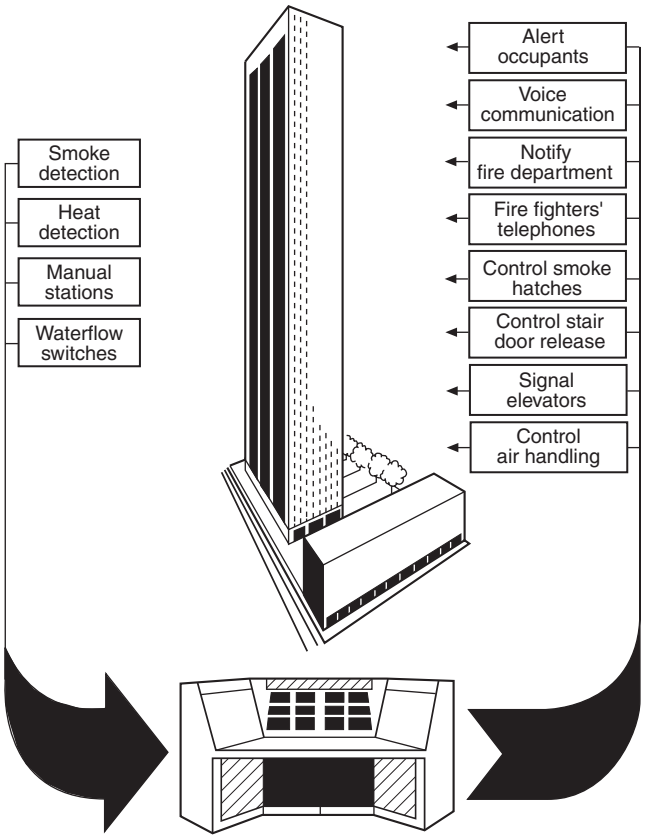


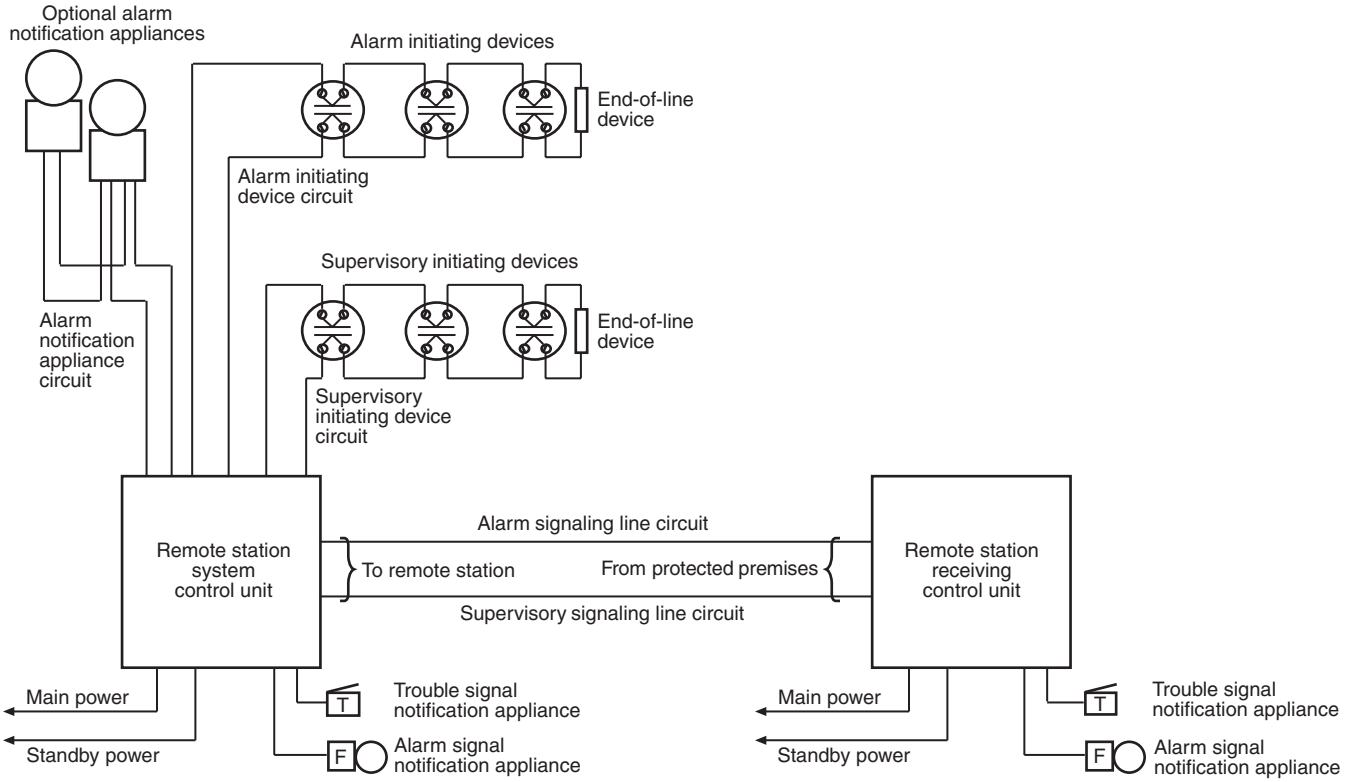
FIGURE 14.1.5 Modern Computer-Controlled Proprietary Fire Alarm System

Proprietary control units are required to transmit alarm, supervisory, and trouble signals to the supervising station. Signals may be transmitted from a protected premises using a variety of transmission technologies as stated in *NFPA 72,* Chapter 8. Such technologies include active multiplex system encompassing leased line, optical fiber cable, private microwave radio system, and telephone-company-provided derived local channel system; digital alarm communicator system; digital alarm radio system; McCulloh system (the code now states that unless accepted by the authority having jurisdiction, McCulloh systems are not permitted to be installed after June 2003); two-way RF multiplex system; one-way private radio alarm system; or a directly connected noncoded system.

Upon receipt of fire alarm signals, supervisory signals, or trouble signals, a runner must be dispatched to investigate. Fire alarm signals must also be retransmitted to the public fire service communication center.

REMOTE STATION SYSTEM

A remote station fire alarm system connects the outputs from a building fire alarm control unit and transmits them to a remote location (Figure 14.1.6). *NFPA 72* specifies that fire alarm signals must be received at the public fire service communication center, at a fire station, or at the location of the public



(a)

(b)

FIGURE 14.1.6 (a) Typical Arrangement of a Remote Station Fire Alarm System. Note that, if a direct circuit connection is used, fire alarm and supervisory signals must be transmitted over separate signaling line circuits. (b) Remote Station Receiving Control Unit. Upon receipt of a remote station sprinkler waterflow alarm, the fire dispatcher prepares to retransmit the alarm to the fire companies that will respond.

agency that has the responsibility to receive fire alarms from the public.

If the public agency is unwilling to receive the remote station fire alarm signals, or if that agency is willing to allow another organization to receive those signals, then the signals may be received at a location acceptable to the AHJ that is attended by trained personnel 24 hours a day, such as a central station or monitoring company that will contract to provide the services required of a remote station. Upon receipt of fire alarm signals, the personnel retransmit the signals to the public fire service communication center.

In some cases, the public agency receiving fire alarm signals may also be willing to receive supervisory signals and trouble signals. In most cases, supervisory signals and trouble signals are transmitted to a constantly attended location acceptable to the AHJ, such as a monitoring company or a central station.

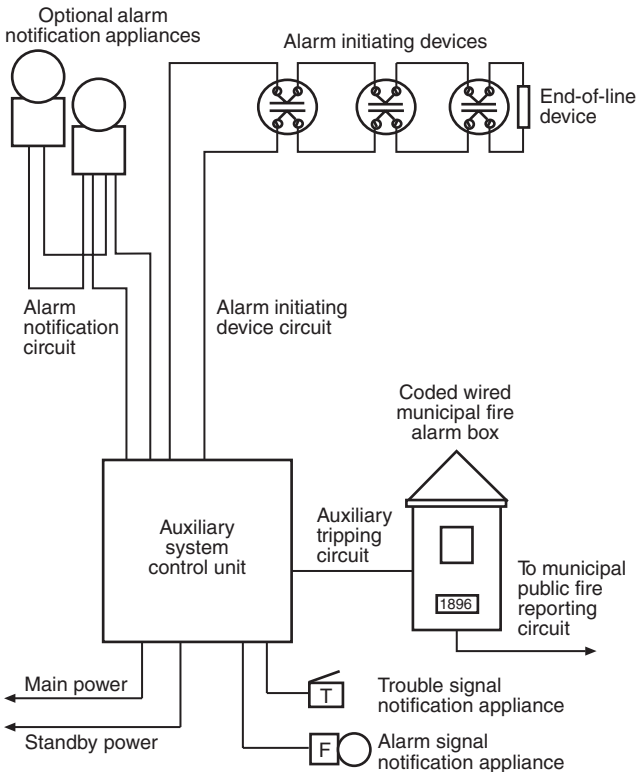
Signals may be transmitted from a protected premises using a variety of transmission technologies stated in *NFPA 72,* Chapter 8. Such technologies include active multiplex system encompassing leased line, optical fiber cable, private microwave radio system, and telephone-company-provided derived local channel system; digital alarm communicator system; digital alarm radio system; McCulloh system (the code now states that unless accepted by the authority having jurisdiction, McCulloh systems are not permitted to be installed after June 2003); two-way RF multiplex system; one-way private radio alarm system; or a directly connected noncoded system.

AUXILIARY SYSTEM

An auxiliary fire alarm system provides the interface between a protected premises fire alarm system and a public fire reporting system (Figure 14.1.7). *NFPA 72* states requirements for public fire reporting systems in Chapter 9. *NFPA 72* also states requirements for auxiliary fire alarm systems in Chapter 9. If a community does not have a public fire reporting system, then a protected premises within that community cannot have an auxiliary fire alarm system.

The transmission technology employed between the protected premises and the public fire service communication center is determined by the type of public fire reporting system (i.e., coded wired, coded radio, series telephone, or parallel telephone). The auxiliary fire alarm system interface may be a shunt-type or local energy-type connection to a coded wired, coded radio, or series telephone master fire alarm box (Figure 14.1.8). Or the auxiliary fire alarm system may be directly connected to a parallel telephone system circuit.

NFPA 72 states that only fire alarm signals may be transmitted by an auxiliary fire alarm system. In cases where the protected premises fire alarm system must also cover supervisory signals, these are usually transmitted by a remote station system or a central station contracted to receive supervisory signals as a remote station. Trouble signals are either received only at the protected premises, or they are transmitted by a remote station system or a central station contracted to receive trouble signals as a remote station.



(a)

(b)

FIGURE 14.1.7 (a) Typical Arrangement of an Auxiliary Fire System; (b) Auxiliary System Control Unit (Source: SimplexGrinnell Company)

SUMMARY

Fire alarm systems play an essential role in protecting property and lives from fire. An effective system is a combination of individual components designed to work together to provide the

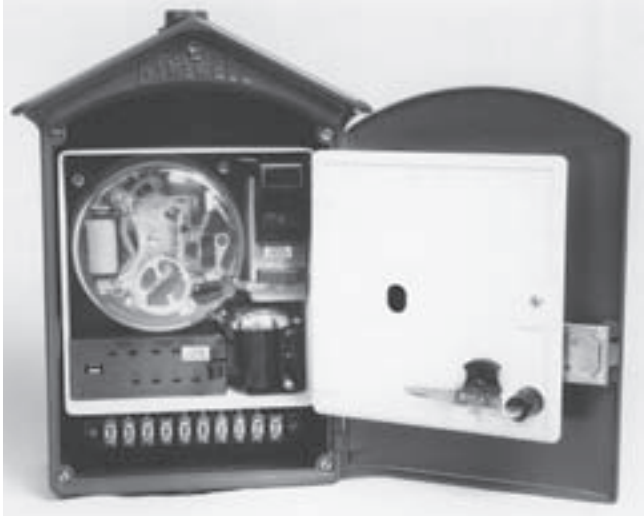


FIGURE 14.1.8 Local Energy-Type Masterbox That Connects the Protected Premises Fire Alarm System to the Public Fire Reporting System (Source: Gamewell-FCI, Div. Honeywell Inc.)

desired level of protection. The user of the fire alarm system must define the goal of the system, for example, whether the priority is life safety or property safety, in order to select the appropriate system. Once installed, the fire alarm system needs to be properly maintained and tested in order to ensure it will function as intended during an emergency.

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Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire alarm systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 70, *National Electrical Code®*
NFPA 72®, National Fire Alarm Code®
NFPA *101®, Life Safety Code®*
NFPA 5000®, Building Construction and Safety Code®

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Chapter 2

Automatic Fire Detectors

Revised by
Kenneth W. Dungan

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Heat Detectors
Smoke Detectors
Gas-Sensing Fire Detectors
Multisensor and Multicriteria Detectors
Radiant Energy–Sensing Fire Detectors
Video-Based Flame Detection
Selection of Detectors
Detector Installation
Detector Maintenance and Testing

Key Terms

air sampling–type detector, combination fixed-temperature/rate-of-rise detector, electronic spot-type heat detector, fire signature, fixed temperature heat detector, flame detector, heat detector, infrared absorption detector, ionization smoke detector, multisensor detector, optical density, photoelectric smoke detector, rate compensation heat detector, rate-of-rise heat detector, smoke detector, spark/ember detector, thermal lag, video-based detection

Fire produces a variety of environmental changes called "fire signatures," which help make its presence known. Human beings are excellent fire detectors when able to effectively use the senses of smell, sight, and so on. However, human senses can be impaired by sleep, disability, illness, or distractions, so that timely, effective warning may not result. Beginning in the mid-nineteenth century, a number of mechanical, electrical, and electronic devices have been developed to substitute for human senses in detecting the environmental changes created by fire.

The fire signatures most often used as the basis for detection are heat, smoke (aerosol particulates), and radiant energy (IR, visible, UV). Several factors complicate the ability of any detector to sense fire reliably. (1) Different types of fires can have widely divergent fire signatures. For example, some materials burn intensely with little or no smoke, whereas smoldering fires have no visible flame and generally very low heat output. (2) The environmental change(s) being monitored must reach the fire detector and must exceed a threshold amplitude and/or rate of change before alarm can occur. (3) Nonfire conditions can produce ambient changes that mimic fire signatures and that may cause false (nuisance) alarms.

Most building codes require what amounts to partial coverage by detection systems, meaning some rooms or spaces do not have detectors in them. Designers must be aware that this can substantially delay detection and alarm because fire signatures become weaker as the distance from the fire to a detector increases, especially if there are any physical barriers between them. A minimum code design may not meet expectations.

The proper selection and location of automatic fire detectors are essential for achieving protection objectives. For example, the use of spot-type smoke detectors on a very high ceiling will delay detection of a fire until it grows very intense. In addition, detector access for testing, cleaning, or replacement may also be very difficult. In this particular application, the use of projected beam-type smoke detectors may be much more suitable.

Every application of detectors needs to be properly evaluated. This begins with a clear understanding of the protection objectives, likely fire scenarios, and the expected environment in each protected space. With that knowledge, the fire protection engineer can (1) evaluate the fire signatures expected from potential hostile fires at various times in their growth, (2) determine the effect of ambient conditions on various detector options, and (3) select the detector type(s) that will offer the best balance of fire response and discrimination (avoidance of nuisance alarms from nonfire ambient conditions). This chapter will help designers understand how the various types of automatic fire detectors operate, their performance capabilities, and how they are applied.

See also Section 2, Chapter 6, "Fundamentals of Fire Detection"; Section 14, Chapter 4, "Fire Alarm System Interconnections"; and Section 14, Chapter 5, "Inspection, Testing, and Maintenance of Fire Alarm Systems."

HEAT DETECTORS

Heat detectors are the oldest type of automatic fire detection device. They began with the development of automatic sprinklers in the 1860s and have continued to the present with a

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proliferation of various types of devices. A sprinkler can be considered a combined heat-activated fire detector and extinguishing device when the sprinkler system is provided with waterflow indicators connected to the fire alarm control system. Waterflow indicators detect either the flow of water through the pipes or the subsequent pressure change upon actuation of the system.

Heat detectors are very reliable and have the lowest false alarm rate of all automatic fire detectors. They are best suited for fire detection in small confined spaces where rapidly building high-heat-output fires are expected, in areas where ambient conditions would not allow the use of other fire detection devices, or where very early warning of fire is not required.

Heat detectors are generally located on or near the ceiling and respond primarily to the convected thermal energy of a fire. They operate either when the detecting element reaches a predetermined fixed temperature or when a specified rate of temperature change occurs.

Operating Principles of Fixed-Temperature Heat Detectors

Fixed-temperature heat detectors are designed to alarm when the temperature of the operating element reaches a specified point. The air temperature at the time of alarm can be considerably higher than the rated temperature (depending on the fire growth rate), because it takes time for the air to raise the temperature of the operating element to its set point. This condition is called *thermal lag*. Fixed-temperature heat detectors are available to cover a wide range of operating temperatures—from about 135°F (58°C) on up. Higher temperature detectors are necessary so that detection can be provided in areas normally subjected to high ambient temperatures (i.e., boiler rooms, attics, etc.) or in special applications requiring detectors that operate only if close to the fire.

Fusible-Element Type. Eutectic metals—alloys of bismuth, lead, tin, and cadmium that melt rapidly at a predetermined temperature—can be used as operating elements for heat detection. The most common use is the fusible element in an automatic sprinkler. Fusing of the element allows the cover on the orifice to fall away, water to flow in the system, and the alarm to be initiated.

Eutectic metals may also be used to actuate electrical heat detectors. Often they are used as a solder to secure a spring under tension. When the element fuses, the spring action closes contacts and initiates an alarm (Figure 14.2.1). Devices using eutectic metals cannot be restored; either the device or its operating element must be replaced following operation.

Continuous Line Type. As alternatives to spot-type fixed-temperature detection, various methods of line-type detection have been developed. The detector shown in Figure 14.2.2 uses a pair of steel wires in a normally open circuit. The conductors are held apart by a heat-sensitive insulation. The wires, under tension, are enclosed in a braided sheath to form a single cable assembly. When the design temperature is reached, the insulation melts, the two wires contact, and an alarm is initiated. Following an alarm, the fused section of the cable must be replaced to restore the system.

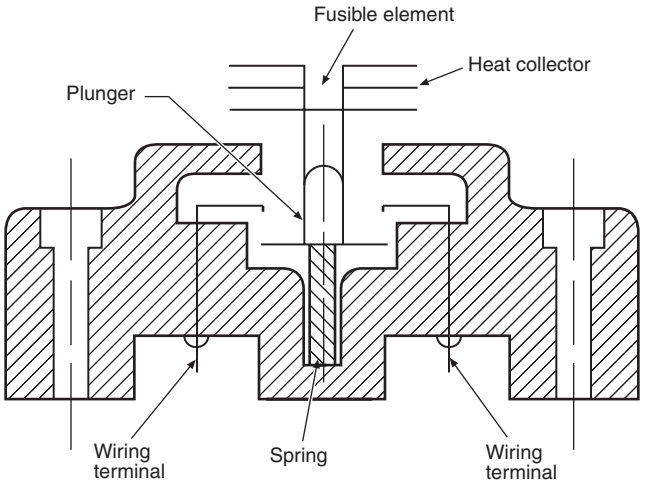


FIGURE 14.2.1 Fixed-Temperature Heat Detector, Spot-Type, Fusible Element

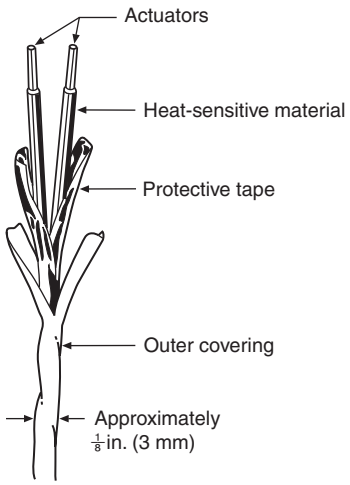


FIGURE 14.2.2 Line-Type Heat Detector

A similar alarm device utilizing a semiconductor material and a stainless steel capillary tube has been used where mechanical stability is also a factor (Figure 14.2.3). The capillary tube contains a coaxial center conductor separated from the tube wall by a temperature-sensitive glass semiconductor material. Under normal conditions, a small current (i.e., below alarm threshold) flows in the circuit. As the temperature rises, the resistance of the semiconductor decreases, allows more current flow, and initiates the alarm.

Bimetallic Type. When two metals with different coefficients of thermal expansion are bonded together and then heated, differential expansion causes bending or flexing toward the metal having the lower expansion rate. This action closes a normally

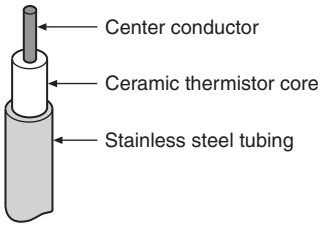


FIGURE 14.2.3 Construction of the Continuous Thermal Sensor Showing Outer Tubing, Ceramic Thermistor Core, and Center Wire

open circuit. The low-expansion metal commonly used is Invar™, an alloy of 36 percent nickel and 64 percent iron. Several alloys of manganese-copper-nickel, nickel-chromium-iron, or stainless steel may also be used for the high-expansion component of a bimetal assembly. Bimetals are used for the operating elements of a variety of fixed-temperature detectors. These detectors are generally of two types: (1) the bimetal strip and (2) the bimetal snap disc.

As it is heated, a bimetal strip deforms in the direction of the contact point. With a given bimetal, the width of the gap between the contacts determines the operating temperature: the wider the gap, the higher the operating point. The operating element of a snap disc device is a bimetal disc formed into a concave shape in its unstressed condition (Figure 14.2.4). Generally, a heat collector is attached to the detector frame to speed the transfer of heat from the room air to the bimetal. As the disc is heated, the stresses developed cause it to suddenly reverse curvature and become convex. This provides a rapid positive action that closes the alarm contacts. The disc itself usually is not part of the electrical circuit. All heat detectors using bimetal elements are automatically self-restoring after operation, when the ambient temperature drops sufficiently below the operating point.

Rate Compensation Detectors

A rate compensation detector is a device that responds when the temperature of the surrounding air reaches a predetermined level, with the rate of temperature rise having minimal effect on response (low thermal lag). This makes them rather sensitive fixed-temperature detectors (Figure 14.2.5).

A typical example is a spot-type detector with a tubular casing of metal that tends to expand lengthwise as it is heated, and an associated contact mechanism that will close at a certain point in the elongation. A second metallic element inside the tube exerts an opposing force on the contacts, tending to hold them open. The forces are balanced so that, with a slow rate of temperature rise, there is more time for heat to penetrate to the inner element. This inhibits contact closure until the total device has been heated to its rated temperature level. However, with a fast rate of temperature rise, there is less time for heat to penetrate to the inner element. The element, therefore, exerts less of an inhibiting effect, so contact closure is obtained when the total device has been heated to a lower level. This, in effect, compensates for thermal lag.

Thermal detectors using expanding metal elements are also automatically self-restoring after operation, when the ambient temperature drops to some point below the operating point.

Rate-of-Rise Detectors

One effect that a flaming fire has on the surrounding area is to rapidly increase air temperature in the space above the fire. Fixed-temperature heat detectors will not initiate an alarm until the air temperature near the ceiling exceeds the design operating point. The rate-of-rise detector, however, will function when the rate of temperature increase exceeds a predetermined value, typically around 12 to 15°F (7 to 8°C) per minute. Rate-of-rise detectors are designed to compensate for the normal changes in ambient temperature (less than 12°F [6.7°C] per minute) that are expected under nonfire conditions.

When applying rate-of-rise heat detectors, use care to avoid locating them in areas where temperatures might normally be expected to rise as much as 12 to 15°F (7 to 8°C) in 1 minute (or less) in order to avoid unwanted alarms. These include commercial kitchens, laundries, or dishwashing areas, truck or construction equipment repair facilities, in front of ceiling-mounted space heaters or air diffusers, near the outside doors of air-conditioned facilities, and in attics. Remember that these detectors will respond for the prescribed rate-of-rise in temperature, even if the current ambient temperature is frigid.

Rate-of-rise detectors that operate by pneumatic action have been manufactured for decades. In a pneumatic fire

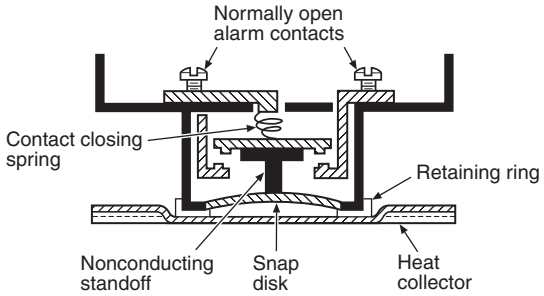


FIGURE 14.2.4 Spot-Type Fixed-Temperature Snap Disc Detector

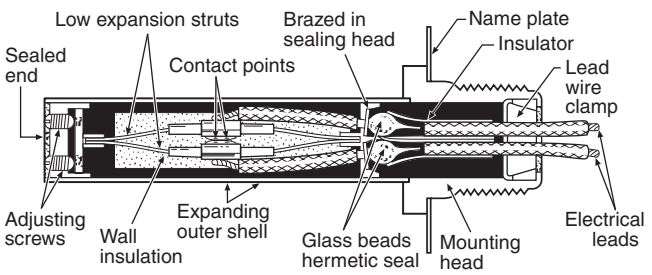


FIGURE 14.2.5 Section of Spot-Type Rate Compensation Detector

detector, air heated in a tube or chamber expands, increasing the pressure in the tube or chamber. This exerts a mechanical force on a diaphragm that closes the alarm contacts. If the tube or chamber were hermetically sealed, slow increases in ambient temperature, a drop in the barometric pressure, or both, would cause the detector to initiate an alarm regardless of the rate of temperature change. To overcome this, pneumatic detectors have a small orifice to vent the higher pressure that builds up during slow increases in temperature or during a drop in barometric pressure. The vents are sized so that when the temperature changes rapidly, as in a fire, the rate of expansion exceeds the venting rate and the pressure rises. When the temperature rise exceeds 12 to 15°F (7 to 8°C) per minute, the pressure is converted to mechanical action by a flexible diaphragm. Pneumatic heat detectors are available for both line- and spot-type detectors. A schematic of a spot-type pneumatic heat detector is shown in Figure 14.2.6, and a line type is shown in Figure 14.2.7.

Line Type. The line type consists of metal tubing, in a loop configuration, attached to the ceiling or side wall near the ceiling of the area to be protected (see Figure 14.2.7). Lines of tubing are normally spaced not more than 30 ft (9.1 m) apart, not more than 15 ft (4.5 m) from a wall, and with no more than 1000 ft (305 m) of tubing on each circuit. Also, a minimum of at least 5 percent of each tube circuit or 25 ft (7.6 m) of tube, whichever is greater, must be in each protected area. Without this minimum amount of tubing exposed to a fire condition, insufficient pressure would build up to achieve proper response.

In small areas where the line-type tube detectors might have insufficient tubing exposed to generate sufficient pressures to close the alarm contacts, air chambers or rosettes of tubing are often used. These units act like a spot-type detector by providing the volume of air required to meet the 5 percent or 25 ft (7.6 m) requirement. Since a line-type rate-of-rise detector is an integrating detector, it will actuate either when a rapid heat rise occurs in one area of exposed tubing or when a slightly less rapid heat rise takes place in several areas where tubing on the same loop is exposed.

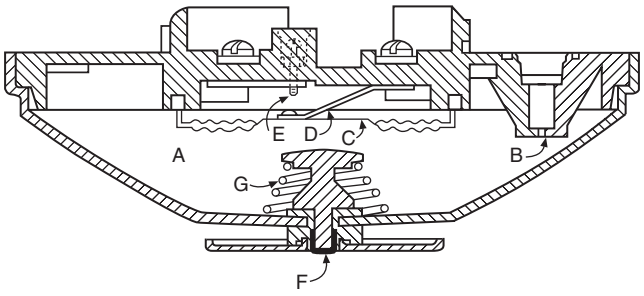


FIGURE 14.2.6 A Spot-Type Combination Rate-of-Rise, Fixed-Temperature Detector. The air in chamber A expands more rapidly than it can escape from vent B. This causes pressure to close electrical contact D between diaphragm C and contact screw E. Fixed-temperature operation occurs when fusible alloy F melts, releasing spring G, which depresses the diaphragm closing contact points.

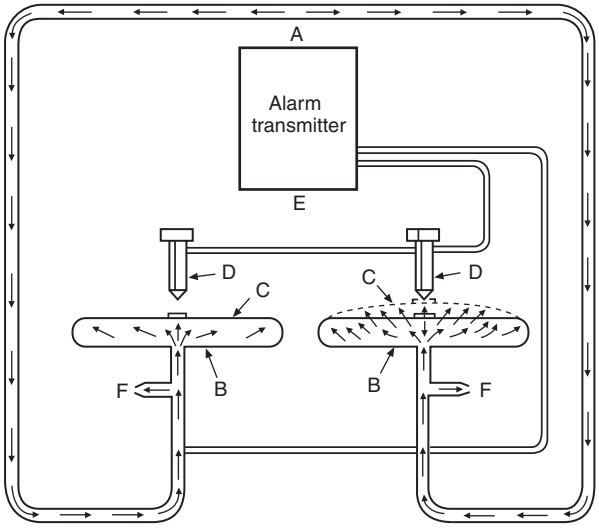


FIGURE 14.2.7 Line-Type Rate-of-Rise Heat Detector. The copper tubing A is fastened in a continuous loop to ceilings or walls and terminates at both ends in chambers B having flexible diaphragms C, which control electrical contacts D. When air in the tubing expands under the influence of heat, pressure builds within the chambers, causing the diaphragms to move and close a circuit to alarm transmitter E. Vents F compensate for small pressure changes in the tubing brought about by small changes in temperature in the protected spaces.

Spot Type. The pneumatic principle is also used to close contacts within spot detectors (see Figure 14.2.6). The difference between the line- and spot-type detectors is that the spot type contains all of the air in a single container rather than in a tube that extends from the detector assembly to the protected area(s).

Combination Fixed-Temperature/ Rate-of-Rise Detectors

Combination fixed-temperature/rate-of-rise detectors contain more than one element that responds to a fire. These detectors may be designed to respond from either element or from the combined partial or complete response of both elements. An example of the former is a heat detector that operates on both the rate-of-rise and fixed-temperature principles. Its advantage is that the rate-of-rise element will respond quickly to a rapidly developing fire, while the fixed-temperature element will respond to a slowly developing fire when the detecting element reaches its set point temperature. The most common combination heat detector uses a vented air chamber and a flexible diaphragm for the rate-of-rise function, while the fixed-temperature element is usually leaf-spring restrained by a eutectic metal (see Figure 14.2.6). When the fixed-temperature element reaches its design

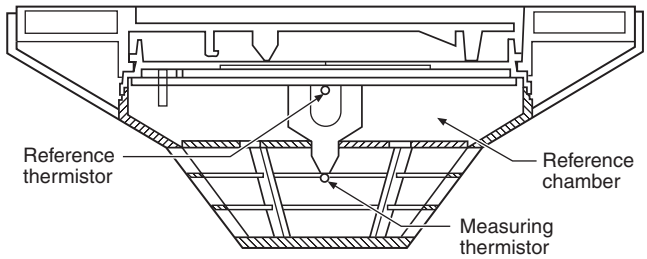
operating temperature, the eutectic metal fuses and releases the spring, which closes the contacts.

Electronic Spot-Type Heat Detectors

A thermoelectric effect detector is a device that utilizes a sensing element consisting of one or more thermistors, which produce a change in electrical resistance in response to an increase in temperature (Figure 14.2.8). This resistance change is monitored by associated electronic circuitry, and the detector responds when the resistance changes at an abnormal rate (rate-of-rise type) or when the resistance reaches a specific value (fixed-temperature type).

The very low mass of the sensing elements used in electronic spot-type heat detectors gives them low thermal lag (for faster response), and their analog outputs can be analyzed by complex signal processing algorithms to further improve performance. This makes them the technology of choice for use in multisensor smoke detectors, discussed later in this chapter.

Rate-of-rise detectors of this type use two thermistors. One is exposed to changes in atmospheric temperature. When the temperature rapidly changes as in a fire situation, the temperature of the exposed thermistor increases faster than the temperature of the unexposed reference thermistor, generating a net change in resistance causing the detector to go into alarm condition. Most rate-of-rise detectors are designed with a fixed-temperature backup feature so that, should the temperature rise be slower than 15°F (8°C) per minute, the detector will operate when the exposed thermistor has reached a predetermined fixed temperature.



(a)

(b)

FIGURE 14.2.8 Solid-State Electronic Heat Detector with Dual Thermistor Sensing Circuit (Source: System Sensor®)

SMOKE DETECTORS

A smoke detector detects most fires much more rapidly than a heat detector. Smoke detectors are identified by their operating principle as being either (1) ionization, (2) photoelectric, or (3) video. As a class, ionization smoke detectors are spot-type detectors, which provide somewhat faster response to high-energy (flaming) fires, since they respond to the number density of smoke particles, and such fires produce large numbers of relatively small particles. Photoelectric smoke detectors, as a class, provide superior response to low-energy (smoldering) fires, since they respond to the optical density of smoke, and such fires produce a preponderance of visible size range smoke particles. Their performance advantage for detecting smoldering fires is substantial; this can result in much earlier warning when the fire growth rate is slow. They may equal or even surpass ionization detector response to flaming fires when the fire is not in close proximity, such as in duct smoke detector applications. For these reasons, photoelectric smoke detectors have captured an increasing share of the market in recent years. Photoelectric smoke detectors can be spot type, beam type, or air sampling type. Video-based smoke detection uses video cameras and computer software to analyze changes in the recorded images. Since this method of detection does not require transport of the smoke to a detector or a sampling port, it offers advantages in large open and high-ceiling spaces.

For decades, virtually all smoke detectors were nonanalog,* meaning they had only two operating states: normal and alarm. Typically they were not addressable devices, meaning they did not provide their specific identification or location information to the control unit, except as part of a zone (protected area) consisting of multiple detectors on a common fire alarm initiating circuit. Their ability to avoid false (nuisance) alarms was hampered by their fixed sensitivity and limited on-board signal processing ability. Some jurisdictions even required these smoke detectors to have a specified minimum sensitivity level in order to avoid excessive alarms from transient nonfire conditions such as smoking.

The advent of low-cost microprocessors and surface-mount electronics technology enabled detector manufacturers to utilize new smoke detector concepts, including the use of analog technology to monitor conditions in the protected space. Another advance was to make them addressable, meaning they individually communicate with the fire alarm control unit (FACU), so the specific device reporting is displayed. The data produced by these new technology smoke detectors are analyzed using complex signal-processing algorithms that are either on board the detectors or in the FACU. Some detectors offer a choice

*Nonanalog detectors have commonly been called "conventional" smoke detectors. However, because most new system installations now utilize analog-addressable smoke detectors, "nonaddressable" is the preferred term for those older technology devices.

of several field-selectable algorithms for specific applications (ambient conditions).

Microprocessors also make comprehensive self-diagnostics possible. The sensitivity of most analog-addressable smoke detectors can automatically be monitored by the control unit and adjusted over time as needed to hold a constant sensitivity, despite the effects of dust buildup, component drift, or gradual changes in ambient conditions. The FACU can also arrange individual detectors to have different sensitivity settings for day and night or weekend to take advantage of different ambient conditions when the business is closed. Some detector models use distributed intelligence so that several capabilities like this reside within the detector itself to reduce communication traffic on the signaling line circuit. This may permit less stringent wiring methods to be used.

Addressable devices are constantly polled by the control unit, typically every few seconds, and immediate notice is given if a detector fails to report or needs servicing. Some multisensor smoke detectors are able to report as many as 20 to 30 specific trouble conditions to the FACU. The substantial performance advantages and unique features offered by analog-addressable smoke detectors make them the sensor of choice for most smoke detection applications. Nonaddressable smoke detectors are now primarily used for replacement purposes in existing or very small systems.

Ionization Smoke Detectors

As stated, smoke detectors utilizing the ionization principle are usually of the spot type. An ionization smoke detector has a very small amount of radioactive material (an alpha emitter) that ionizes the air in the sensing chamber, rendering the air conductive and permitting a minute current flow through the air between two charged electrodes. This gives the sensing chamber an effective electrical conductance. When smoke particles enter the ionization area, they decrease the conductance of the air by attaching themselves to the ions, causing a reduction in ion mobility. The current flow is monitored and when conductance is below a predetermined level, the detector is in alarm (Figure 14.2.9). With analog-addressable detectors, this alarm threshold can be varied to compensate for ambient conditions.

Photoelectric Smoke Detectors

The presence of suspended smoke particles generated during the combustion process affects the propagation of a light beam

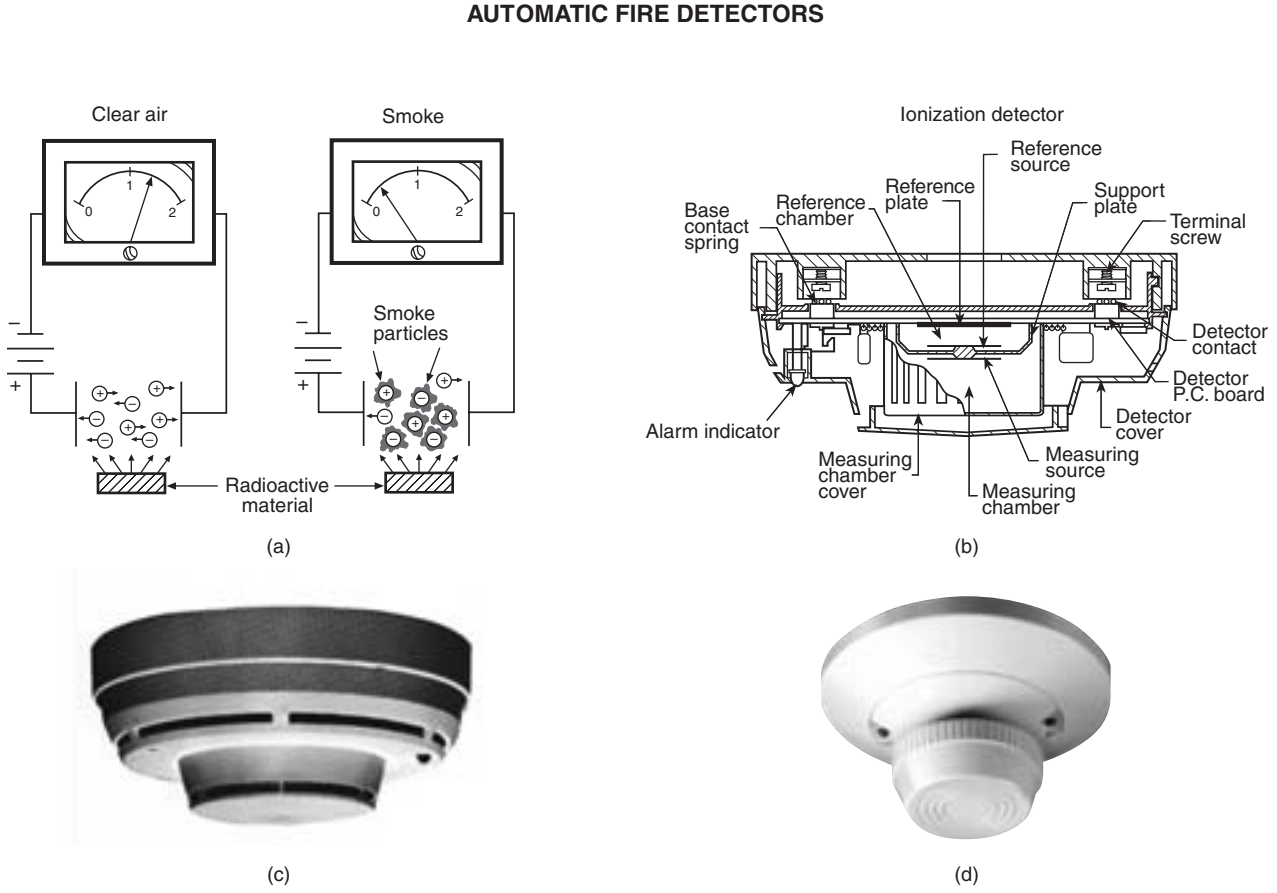


FIGURE 14.2.9 (a) Principle of Operation for Ionization Smoke Detector; (b) Cross-Sectional View of an Ionization Smoke Detector; (c) Ionization Smoke Detector (Source: Siemens Building Technologies, Fire Safety Division); (d) Ionization Smoke Detector (Courtesy of Gamewell-FCI)

passing through the air. The effect can be utilized to detect the presence of a fire in two ways: (1) obscuration of light intensity over the beam path or (2) scattering of the light beam.

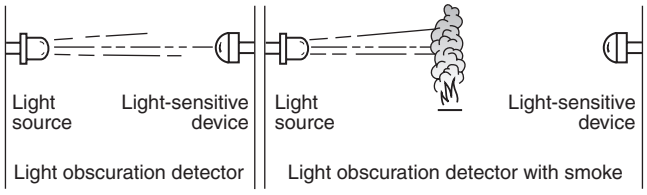
Light Obscuration Principle. Smoke detectors that operate on the principle of light obscuration consist of a light source, a light beam collimating system, and a photosensitive device. When dense smoke obscures part of the light beam, or less dense smoke obscures more of the beam, the light reaching the photosensitive device is reduced, and this initiates the alarm (Figure 14.2.10).

Most light obscuration smoke detectors are the beam type and are used to protect rather large spaces such as atriums, auditoriums, manufacturing areas, and so on. Each projected beam smoke detector is equivalent to a row of spot-type smoke detectors along the beam path. They are installed with the transmitter (pulsed IR light source) at one end of the area to be protected and the receiver (photosensitive device) at the opposite end.

The transmitter and receiver must have a completely unobstructed view of each other that cannot normally be blocked. In the event of any sudden accidental blockage, the detector generates a trouble signal rather than an alarm, since smoke buildup from a fire would not cause a sudden, complete blockage of the beam. If multiple parallel sets of these smoke detectors are installed, it may be prudent to alternate the transmitter and receiver locations to avoid possible cross-talk between adjacent units. Some models may also be sensitive to intense flashing lights, such as on large machinery or vehicles, if the source is close to their optical axis.

Projected beam smoke detectors have a permitted operating range, for example, 33 to 330 ft (10 to 100 m). This range varies from model to model, as does the permitted minimum mounting distance below the ceiling, and so on. They require very stable mounting surfaces, so that alignment of the IR light beam can be maintained. This becomes more important at longer ranges and less so when the beam's throw distance is shorter. In all cases the manufacturer's detailed instructions for installation and beam alignment must be followed.

Light-Scattering Principle. When smoke particles enter a light path, scattering results. Smoke detectors utilizing the photoelectric light-scattering principle are usually of the spot type. They contain a light source and a photosensitive device arranged so the light rays normally do not fall onto the device. When smoke particles enter the light path, light strikes the particles and is scattered onto the photosensitive device, causing the detector to respond (Figure 14.2.11).



(a)

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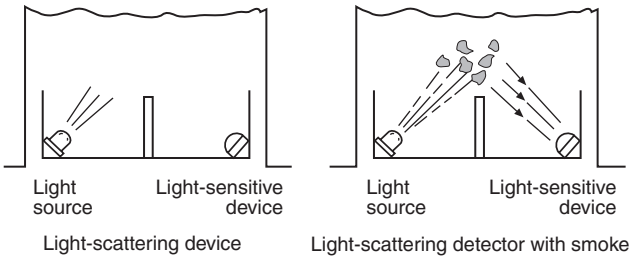
FIGURE 14.2.10 (a) Principle of Operation for Photoelectric Obscuration Smoke Detector; (b) Typical Photoelectric Obscuration–Type Smoke Detector (Source: System Sensor®)



(a)

(b)

(c)

FIGURE 14.2.11 (a) Cross-Sectional View of a Photoelectric Scattering Smoke Detector; (b) Photoelectric Smoke Detector (Source: System Sensor®); (c) Photoelectronic Smoke Detector (Courtesy of GE Security)

The photosensitive device used in scattering detectors usually is a photodiode or a phototransistor. The light source is typically an infrared light-emitting diode (LED), pulsed to reduce power drain. However, several manufacturers recently introduced a photoelectric spot-type smoke detector utilizing a very sharp laser beam. Because the laser beam is so intense, more light is reflected into the sensing chamber than with a standard LED. A signal-processing algorithm is used to discriminate between airborne dust particles and smoke particles entering the sensing chamber. These attributes enable it to have up to 100 times the sensitivity of LED units and still be very stable. It's intended for special applications, like cleanrooms, telecommunications hubs, archives, and computer rooms, where very early warning of incipient fires is essential.

Air Sampling–Type Smoke Detectors

As the name implies, air sampling–type smoke detectors draw in air from the protected space and analyze it for smoke particles. The fact that air is mechanically transported to the sensor permits the use of filters to remove most dust particles, a common source of false alarms for ordinary nonaspirating smoke detectors. Almost all air sampling–type smoke detectors utilize the photoelectric light-scattering principle, enhanced by various means to give it the capability for very high sensitivity. However, there are at least three rather different design approaches.

Continuous Air-Sampling Smoke Detection. These devices use a network of tubing or piping (with spaced intake ports) and an aspirating fan to draw a sample of air from the protected area. Their photoelectric detector has an intense light source, either a pulsed laser or a xenon strobe, to increase the amount of light that any smoke particles will forward scatter toward a photosensitive element. This makes these units capable of very high sensitivity, surpassing all spot-type smoke detectors, except the laser source design previously discussed.

The use of a tubular network to draw air back to the detector permits the sensor to be located out of harm's way, for applications such as prisons and mental hospital isolation rooms. Typically, these devices also have several user-definable alert and alarm levels to take advantage of their capability for high sensitivity and, for special applications like computer room fire suppression system control, to initiate various actions, including gaseous agent release.

There are limitations imposed on the application of these devices as a result of the method of sampling air and transporting it back for analysis. (1) Transport time limits the length of the sampling network and, therefore, the size of the area covered by the detector. (2) Smoke dilution reduces their inherent high sensitivity, proportional to the number of sampling ports in the network, and this fact must be considered in design. (3) The piping network is supervised for breakage or blockage but the airflow condition of an individual sampling port usually cannot be sensed. (4) The ability to zone these systems is limited, but some models can monitor several different piping networks, on a rotating basis (using air valves), as long as each network is within the permitted length.

Cloud Chamber Principle Air-Sampling Smoke Detection. These devices also use a network of tubing or piping (with spaced intake ports) and an aspirating fan to draw individual samples of air from the protected area. After being filtered to remove dust particles, it enters a humidifier where distilled water is used to raise the relative humidity to approximately 100 percent. Then the sample of air is subject to some reduction in air pressure, using a vacuum pump, so that it becomes supersaturated. If any smoke particles are present, they act as condensation nuclei for water droplets, triggering formation of a cloud in the sensing chamber. The density of the cloud is measured by a photoelectric light-scattering detector, which will respond if a threshold alert or alarm value is exceeded.

This phenomenon is effective for detecting the submicron particles that are produced in abundance by thermal decomposition during the pyrolysis or precombustion phase of incipient fires. For example, an electric motor that is "cooking out" releases large numbers of decomposing molecules from insulation on the winding, long before there is any visible smoke or flame. This gives cloud chamber principle smoke detectors unsurpassed ability to provide very early warning of incipient fire.

The need to transport the sampled air back to the unit through a piping network imposes the same limitations on these devices as previously discussed. In addition, they require more frequent servicing than other types of smoke detectors, including replenishment of the distilled water supply. They are most often used where the protected space has very high value or mission-critical contents that demand very early warning of incipient fires and justify the expense.

Spot-Type Aspirating Smoke Detection. This design combines the technology of spot-type photoelectric smoke detection with filtered, periodic aspiration. The objective is to detect smoke reliably in very dusty environments where regular spot-type detectors cannot be used.

Air is sampled by a small on-board fan, which cycles on and off to reduce power drain. The time between samples is less than a minute, and airflow (filter status) is verified every few hours. The filter is replaceable and the time between filter clogs can vary from a few months up to several years, depending on ambient conditions. Typical applications are heated stables, paper plants, cotton and textile mills, commercial laundries, food processing areas, and so on. A separate power supply is required for fan power. They are not intended for outdoor use, nor for locations with potential explosion hazard.

Video-Based Smoke Detectors

Video-based smoke detectors operate on the principle of identifying changes in the digitized video image from a camera or series of cameras. Closed-circuit TV (CCTV) cameras view an area and the images that are within the field of view of the cameras are transmitted to a computer. The computer looks for areas of change as it digitizes the images. Only those pixels that show a change are further processed to discriminate the particular characteristics of smoke. These cameras work in the visible light range and therefore need an illuminated space. The use of video cameras also provides a visual image to an operator monitoring

the system, which can provide very useful input to emergency management decisions. The software allows masking of portions of the field of view to minimize unwanted alarms from ambient sources of smoke or dust. As previously stated, these devices can offer significant advantages in large open facilities, where transport of smoke to other means of smoke detection can cause delays in identifying and locating a fire condition. Examples of such applications include the turbine hall of electrical generating facilities, large assembly plants, or aircraft hangars.

GAS-SENSING FIRE DETECTORS

Many changes occur in the gas content of the environment during a fire. It has been observed that detectable levels of gases are reached after detectable smoke levels and before detectable heat levels. One of three operating principles, that is, semiconductor, catalytic element, or infrared absorption, may be used in a gas-sensing fire detector or in a combination (multisensor) detector.

Semiconductor Principle

Fire-gas detectors of the semiconductor type respond to either oxidizing or reducing gases by creating electrical changes in the semiconductor. The subsequent conductivity change of the semiconductor causes actuation of the detector.

Catalytic Element Principle

Fire-gas detectors of the catalytic element type contain a material that, in itself, remains unchanged, but that accelerates the oxidation of combustible gases. The resulting temperature rise of the element causes detector actuation.

Infrared Absorption Principle

Carbon dioxide, carbon monoxide, water vapor, and hydrocarbons absorb different frequencies of infrared light. This principle can be used to measure the presence of and concentration of one or more of these gases from a fire.

MULTISENSOR AND MULTICRITERIA DETECTORS

The combination of sensors placed in a single spot-type detector has been a common practice for decades. The early devices were combinations of a heat detector with a smoke detector. *NFPA 72®*, *National Fire Alarm Code®*, required that any heat detector combined with a smoke detector should have a listed spacing of 50 ft (15.25 m). For these devices both sensors act independently, carry independent listings, and require independent testing of each element.

With the development of analog-addressable or "intelligent" detectors, the use of multicriteria detectors was introduced. These devices are typically smoke detectors that integrate the response of two or more sensors to achieve greater sensitivity (early response) without sacrificing stability (increasing unwanted alarms). These devices can incorporate a thermal sensor with a smoke sensor or multiple smoke sensors (e.g., ion and photo). The signal from each sensor is analyzed and combined using proprietary algorithms to establish alarm thresholds. Development is under way by some manufacturers to incorporate gas sensors such as CO or CO_2 to improve the performance of smoke detectors.

RADIANT ENERGY–SENSING FIRE DETECTORS

Radiant energy–sensing devices sense the radiant energy (electromagnetic radiation) emitted as a by-product of the combustion reaction, which obeys the laws of optics. This includes radiation in the ultraviolet, visible, and infrared portions of the spectrum, emitted by flames or glowing embers. They are categorized as flame detectors and spark/ember detectors.

The selection of the radiant energy–sensing detector requires that the device's spectral response be matched to the spectral emissions of the potential fire to be detected. The fire protection engineer must also evaluate any nonfire radiant energy sources in the area to be protected to determine if they could cause nuisance alarms in the detector being considered.

All flame and spark/ember detectors respond in accordance with the inverse square law, which defines the fire size versus distance curve for the detector. Therefore, if the distance from the detector to the fire is doubled, the signal received drops to $(½)^2 = ¼$ of what it previously was. Sensitivity also drops off as the source of radiant energy being detected is displaced from the optical axis of the detector. Each detector model will have manufacturer's data on its effective (normalized) sensitivity versus angular displacement (Figure 14.2.12)

Because these detectors are line-of-sight devices, they must be positioned so that no point requiring detection in the hazard

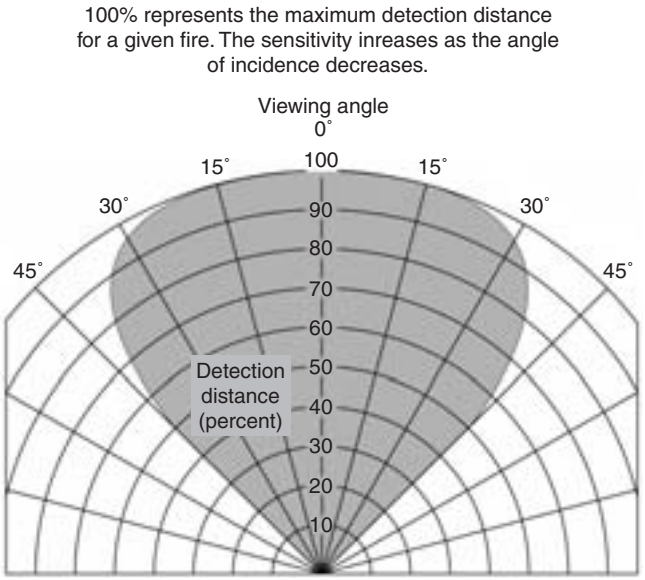


FIGURE 14.2.12 UV Fire Detector Cone of Vision (Courtesy of Detector Electronics Corporation)

area is obstructed or outside the field of view of at least one detector. Spacing will depend on the overall protection objectives of the system, including the minimum size of flaming fire or spark/ember that must be detected and the response time required.

An additional consideration for all applications of radiant energy–sensing fire detectors is the effect of the medium between the anticipated fire and the sensor. Different wavelengths of radiant energy are absorbed with varying degrees of efficiency by materials suspended in the air or that may accumulate on the optical surfaces of the detector. Some examples include atmospheric humidity, smoke, dust, aerosol film, fog, rain, and snow. Detector lens clarity must be assured between maintenance intervals by electronic monitoring or inspection, possibly augmented by a lens air purge device. Protective housings (behind glass, plastic, etc.) should not be used unless listed for the purpose, because some optical materials are absorptive at the wavelength(s) used by these detectors.

FIGURE 14.2.13 Typical UV Detector Assembly (Courtesy of Detector Electronics Corporation)

Flame Detectors

Other than video-based flame detectors, discussed later in the chapter, flame detectors operate in the UV and/or IR portion of the spectrum. Most such flame detectors exhibit some kind of fuel specificity and are qualified based on a defined fire under specific conditions. When employing these detectors for fuels other than the defined fire, the designer should make appropriate adjustments to the maximum distance between the detector and the fire. The various types of UV/IR flame detectors and their principles of operation follow.

Ultraviolet Flame Detectors. The ultraviolet spectrum comprises wavelengths ranging from approximately 0.1 μm to 0.35 μm. UV detectors typically use a vacuum photodiode Geiger-Muller tube to detect the ultraviolet radiation that is produced by a flame. The photodiode allows a burst of current to flow for each UV photon that hits the active area of the tube. When the number of current bursts per unit time reaches a set level, the detector initiates an alarm. A special control unit is required to monitor the count rates from UV detectors and initiate alarm (Figure 14.2.13).

UV detectors are sensitive to most fires, including hydrocarbons (liquids, gases, and solids), ammonia, sulfur, hydrogen, hydrazine, and metals such as magnesium. However, the smoke produced by combustion of middle and heavy fraction petroleum distillates is highly absorptive in the UV end of the spectrum, and this must be compensated for in system design if UV detectors are used.

Potential sources of UV detector nuisance alarms include lightning, arc welding, X rays (used in industrial nondestructive testing of metals), and radioactive materials.

Infrared Flame Detectors. The total infrared spectrum comprises wavelengths ranging from approximately 0.76μm to 220 μm. IR detectors basically comprises a filter and lens system used to screen out unwanted wavelengths and focus those remaining on a photovoltaic or photoresistive cell sensitive to IR energy. They can respond just to the resulting net IR component of the flame or in combination with a flame flicker sensor (typically looking for a flicker rate of 5 to 30 Hz).

Although almost all materials that participate in flaming combustion emit UV radiation to some degree during such combustion, only carbon-containing fuels emit significant radiation in the 4.35 μm (carbon dioxide) band used by many IR detectors to sense flame (Figure 14.2.14). This means that IR flame detectors are not responsive to carbon-free fuels, such as hydrogen and sulfur.

Potential sources of nuisance alarms from infrared flame detectors include gas (oxy-acetylene) welding in their field of view and solar radiation from sunlight (a strong IR source). Several measures are available to prevent sunlight from being a problem, including the use of multiple wavelength technology. This design (commonly referred to as an IR/IR detector) employs filters to pass radiation from different portions of the infrared spectrum to separate IR sensors. The two outputs are

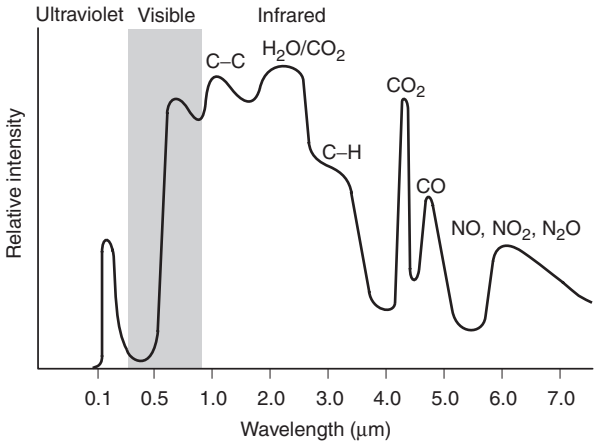


FIGURE 14.2.14 Spectrum of a Typical Flame (free-burning gasoline)

continuously compared and an alarm is initiated when the relationship between them indicates a fire.

Ultraviolet/Infrared Flame Detectors. Combination UV/IR devices sense radiation from portions of both spectrums and use the resulting signal to indicate a fire. They typically require both UV and IR sensor response to cause an alarm, resulting in better false alarm rejection than either UV or IR detectors alone. (In circuit design this is called an "AND" circuit because it requires condition A and condition B to exist before declaring that an alarm should sound. If either the UV or the IR sensor could trigger an alarm, that would invoke an "OR" circuit.) An AND circuit makes the system subject to the combined limitations of both technologies.

Spark/Ember Detectors

Spark/ember detectors are primarily installed to detect sparks and embers that could, if allowed to continue to burn, precipitate a much larger fire or even an explosion. They are typically mounted on a duct or conveyor to monitor the fuel as it passes by. Usually it is necessary to enclose the portion of a conveyor where the spark/ember detectors are located, because they normally require a dark environment to operate properly.

Radiant energy from an ember is primarily of infrared and, to a lesser degree, visible wavelengths. In general, embers do not emit significant ultraviolet energy until their temperature reaches approximately 3240°F (1727°C).

Spark/ember detectors are often used to control in-duct fire-extinguishing systems for woodworking plant dust collectors or textile plant ventilation. For example, sawdust or textile fiber embers may be traveling past the unit at 328 ft/sec (100 m/sec), and their detection triggers a very brief burst from a downstream water spray nozzle. Typically, a subsequent detector further downstream verifies extinguishment and, if necessary, repeats the spray burst at another point in the duct. For applications such as this, spark/ember detectors are required to have a very fast response time.

Common sources of nuisance alarms include incident light, electrostatic discharge in the fuel stream, and electromagnetic interference (EMI/RFI).

VIDEO-BASED FLAME DETECTION

Operating Principles and Applications

Video-based flame detection operates in the visible light range and as with video-based smoke detection previously described uses video cameras. The images from one or more cameras are processed by computer software to look for and identify the characteristics of a flame. The cameras also provide a video image of the area to assist the operators in managing the emergency. The detectors/cameras are enclosed in explosionproof electrical enclosures. Since they view visible light, they are not affected by UV or IR sources and can be enclosed behind a glass or plastic view port. As with video-based smoke detectors, portions of the camera field of view can be masked to eliminate ambient sources of unwanted alarms. Commercially available models are capable of detecting a 10 kW flaming fire (one ft^2 [0.093 m^2] gasoline pan fire) at a distance of 65 ft (20 m) and can operate in temperatures ranging from –40°F (–40°C) to 158°F (70°C). Examples of applications of video-based flame detection include offshore petroleum facilities (e.g., platforms and vessels) and land-based petrochemical facilities (Figure 14.2.15).

Combination Video Technologies

The combination of smoke and flame video technologies is also being applied. As the software matures and field experience grows, the advantages of video camera technology will broaden their application.

SELECTION OF DETECTORS

When a fire detection system is being planned, the choice of detectors is critical for ensuring proper performance. Numerous factors must be considered in order to make the right choice. This is true whether the design is prescriptive (per a regulatory formula), is performance based (the usual case for flame or spark/ember detection systems), or uses some elements of both. Regardless of the design method, the following basic steps should normally be included in the selection of automatic fire detectors:

1. Determine the specific fire protection goals for the system, such as life safety, property protection, continuity of operations, and compliance with building codes, statutes, and criteria of the authority having jurisdiction (AHJ).

FIGURE 14.2.15 Video-Based Flame Detector (Source: Micropack Detection (Americas) Inc.)

2. Obtain stakeholder input to quantify these goals as explicitly as possible.
3. Develop general design objectives that outline how the preceding goals will be met.*
4. Evaluate the fire threat, including possible ignition sources, the type and quantity of fuels available, their expected growth rate, whether a fire suppression system is present, and so on. For example, very different threats would be posed by a petrochemical processing area, a hotel, and a woodworking shop.
5. Determine what fire signature(s) would be presented by potential fires at various points in their growth and what the area's normal ambient conditions would be (without fire present).
6. Weighing the foregoing factors, select fire detectors on the basis of their sensitivity to the fire signatures, response time (signal processing time), and relative immunity to false alarms in the anticipated ambient conditions (or their discrimination ability).

There is normally an inverse relationship between the sensitivity/speed of detection and the detector's ability to discriminate between fire and nonfire conditions. In general, heat detectors have the lowest false alarm rate but the slowest response time. Because the heat generated by small fires tends to dissipate fairly rapidly, heat detectors are best used to protect confined spaces or installed directly over hazards where flaming fires could be expected. They are typically installed in a grid pattern at their listed spacing or at reduced spacing for faster response. The operating temperature of a fixed temperature heat detector should be at least 25°F (14°C) above the maximum expected ambient temperature in the area protected. (For application information on rate-of-rise–type heat detectors, see previous comments in the corresponding portion of this chapter.)

Smoke detectors normally have much faster response times than heat detectors. The fire plume (buoyancy effects), air currents from HVAC, and diffusion may all be involved in transporting smoke. The response time advantage of smoke detectors becomes larger as the size of the space increases. Although frequently installed in a grid pattern, at a uniform recommended spacing, they are more properly located by considering the sources of potential fires and how the smoke would be transported. (For application information on the various types of smoke detectors, see previous comments in the corresponding portion of this chapter.)

Radiant energy–sensing detectors generally offer extremely fast response to any source of radiation within the spectrum they monitor. However, this can result in high false alarm rates if they are applied improperly. Since most are listed for NFPA 70, *National Electrical Code®*, Class I or II locations, they are well suited to protecting areas where potentially explosive or flammable vapors or dusts may be present. (For application information on the various types of radiant energy–sensing detectors, see previous comments in the corresponding portion of this chapter.)

*For performance-based design these design objectives are explicitly stated and quantified and then are used to develop specific performance criteria for the system, stated in fire protection engineering terms. See *NFPA 72®*, *National Fire Alarm Code®*, Annex B, for a more thorough description of the performance-based design process.

DETECTOR INSTALLATION

After selection of the most suitable detectors to use, the next step is to determine where to locate them within the space to be protected. Video-based smoke and flame detection offer distinct advantages in large open spaces. The potential to detect fires before the transport of smoke to a high ceiling and the ability to view and record the visual images of the area can provide additional benefits over spot-type or beam-type smoke detectors. Likewise the visual image provided with the video flame detectors provides an additional emergency management tool.

Detector Placement

Spot-type detectors are usually installed on the ceiling, not less than 4 in. (0.1 m) from the wall. If their listing permits, they are also permitted to be installed on the wall, with their highest edge no less than 4 in. (0.1 m) and no more than 12 in. (0.3 m) from the ceiling (Figure 14.2.16).

Where subject to mechanical damage, detectors must be protected. Any mechanical guard used with a smoke or heat detector must be listed for use with the detector. Otherwise, sensor performance may be degraded. Smoke detectors are often required to be set at higher sensitivity when used with plastic or perforated metal guards due to their effect on smoke entry. One manufacturer has a unique metal guard that looks like the series of smoke detectors it protects and that is engineered not to affect detector sensitivity.

Smoke detectors should not be installed in an air stream from an HVAC supply grill, because that will inhibit smoke from a fire in the protected space from reaching the detector. (The smoke detector would be bathed in a clean air stream when the HVAC supply fan is running.) This can also affect heat detector performance, usually to a lesser degree. Locations adjacent to a return air grill should also be avoided, because returns can affect air circulation patterns in the room so as to inhibit the detection of smoke from low-energy fires.

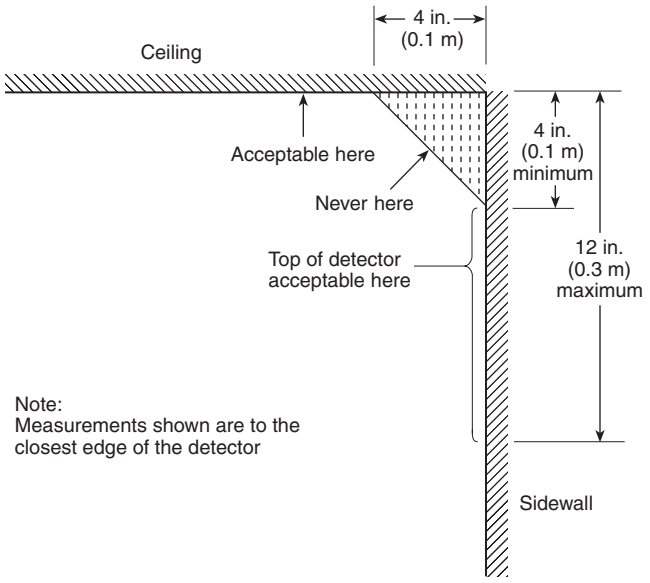


FIGURE 14.2.16 Mounting of Spot-Type Detectors

Where ceilings are high or ceiling construction is not smooth, the spacing of smoke or heat detectors should be reduced appropriately. Specific information on the treatment of joisted, beamed, and sloped ceilings can be found in *NFPA 72*.

When heat detectors are installed at their listed spacing, detection times will approximately equal the operating times of standard 165°F (74°C) sprinklers. If a faster response is desired, detector spacing should be reduced.

Spacing of Heat Detectors on High Ceilings

The hot air in a fire plume is diluted by entrainment with cooler air as it rises. Therefore, it had generally been assumed that heat detectors should be spaced more closely together on a high ceiling to achieve the same response time that they would provide on a standard 8 ft to 10 ft (2.5 to 3.0 m) high ceiling. To determine how much closer the detectors should be, a series of full-scale fire tests was funded by the Fire Detection Institute. These tests explored different ceiling heights in addition to several other design parameters. The data clearly showed that heat detectors must be spaced more closely together on a high ceiling to achieve the same response time that they would have on a 10 ft (3 m) ceiling (Table 14.2.1).[1]

Annex B of *NFPA 72* was developed from these tests and presents a performance-based design approach that can be used to determine the effect of changes in various design parameters on heat detectors in a flaming fire scenario only (plume-dependent response). The formulas it contains take into account the detector's listed spacing and temperature rating, the ceiling height, the design fire size, the fire growth rate, the normal ambient temperature, and the response time index (RTI) of the device. The thermal response characteristics of a heat detector describe how fast heat is transferred to the sensor. The plunge test used characterizes this as a response time index. The RTI allows the calculation of the time it takes for the heat-sensing element to reach its alarm threshold, based on the temperature and velocity of the fire plume or ceiling jet passing by the device.[2]

TABLE 14.2.1 Heat Detector Spacing Reduction Based on Ceiling Height

Ceiling Height Above		Up to and Including		*Multiply Listed Spacing By*
ft	*m*	*ft*	*m*	
0	0.00	10	3.05	1.00
10	3.05	12	3.66	0.91
12	3.66	14	4.27	0.84
14	4.27	16	4.88	0.77
16	4.88	18	5.49	0.71
18	5.49	20	6.10	0.64
20	6.10	22	6.71	0.58
22	6.71	24	7.32	0.52
24	7.32	26	7.93	0.46
26	7.93	28	8.54	0.40
28	8.54	30	9.14	0.34

The formulas can be used by entering a set of known values and design objectives and then calculating for one unknown, such as the required detector spacing in a given situation.

Spacing of Smoke Detectors

Nationally recognized testing laboratory approval (listing) tests for smoke detectors do not yield a listed spacing as they do for heat detectors. However, because the largest spacing evaluated in the fire test room used for these tests is 30 ft (9.1 m), manufacturers use that figure as the normal recommended spacing when smoke detectors are installed on a flat, smooth ceiling. Reductions in spacing may be required to address factors that can affect response, including ceiling height, beamed or joisted ceilings, and high rates of air movement (such as in a computer room). Room size, corridor width, and beam pocket size must also be considered. Calculations have demonstrated that in corridors and in small rooms, reduced spacing for nonsmooth ceilings may not be required.[3]

In design applications where predicting the response of smoke detectors is not critical, the prescriptive criteria in the body of *NFPA 72* should provide sufficient information to design a basic smoke detection system. The performance-based design methodology of Annex B can also be used for smoke detector design calculations. Again, this applies only to the flaming fire scenario, where fire plume and ceiling jet flows are major factors in smoke transport to the sensor. Thus, it cannot be used for low-energy (smoldering) fires. There are other limitations resulting from the fact that smoke detector response varies for different burning materials, and the properties of smoke itself change as it ages. These limitations will continue to affect the ability of fire protection engineers to more accurately predict smoke detector response until such time that testing laboratories are able to determine (and publish) meaningful performance metrics for all smoke detectors.

Special Applications

Duct smoke detectors are installed in the return and/or supply ducts of HVAC systems in buildings to prevent smoke from a fire being spread throughout the building by its recirculating HVAC system. Return duct smoke detectors, where required, are permitted to be replaced by total coverage smoke detection in the area served by the HVAC system or by spot-type smoke detectors located in each return air opening. Upon the detection of smoke, the HVAC system either shuts down or transitions to a smoke control mode such as 100 percent exhaust and/or 100 percent outside fresh air. The detection of duct smoke is made difficult by its dilution with return air from other spaces (away from the fire) and possibly with outside fresh air. Also, when the HVAC system fan is not running, smoke may not reach the duct detector. For these reasons, air duct smoke detectors must never be considered as a substitute for open area protection.

Smoke detectors are also used to initiate the closure of smoke doors in buildings to limit the spread of combustion products in the event of fire. This can be accomplished with detectors located near each controlled door or by door frame mounted hold-open devices with integral smoke detectors.

Smoke and/or heat detectors are often used for control of fire suppression systems such as gaseous (clean agent) and

preaction or deluge sprinkler installations. The design of these special systems should be undertaken only by fire protection engineers or other qualified individuals.

DETECTOR MAINTENANCE AND TESTING

A systematic program of preventive maintenance and regular testing is essential to ensure the continuous, proper performance of detectors. Analog-addressable detectors have an inherent advantage in this regard due to their on-board diagnostics and constant reporting for each roll call. Whereas a nonaddressable detector could be dead for months and not found until the next scheduled test, failure of an analog-addressable detector would be known in seconds. However, it is still necessary to periodically inspect smoke detectors and test them with smoke or equivalent aerosol to ensure that their smoke entry remains unaffected by such possibilities as conduit stack effect, HVAC air streams (supply diffuser changes), or even the detector being painted, taped up, or bagged. (See Section 14, Chapter 5, "Inspection, Testing, and Maintenance of Fire Alarm Systems" and *NFPA 72* chapter on inspection, testing, and maintenance.)

SUMMARY

Automatic fire detectors are activated by environmental changes known as fire signatures, principally heat, smoke, and radiation. Various types of systems have been developed to detect these divergent fire signatures, including heat detectors, smoke detectors, gas-sensing fire detectors, and radiant energy–sensing fire detectors. The type of fire detection system installed depends on several factors, including reliability, sensitivity, and environmental characteristics. The detectors must be properly installed, positioned, maintained, and tested to ensure dependable fire protection.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on automatic fire detectors discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following document.)*

NFPA 72®, National Fire Alarm Code®

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Chapter 3

Notification Appliances

Robert P. Schifiliti

Chapter Contents

Operating Modes for Notification Appliances
Audible Signaling
Visible Signaling
Combination Audible/Visible Units

Key Terms

audible appliance, fire alarm system, household fire-warning equipment, notification appliance, temporal code-three signal, visible signal

Fire alarm systems and household fire-warning equipment protect life by automatically indicating the need for the occupants to evacuate or relocate to a safe area. They may also notify emergency forces or other responsible persons who may then assist the occupants or assist in controlling and extinguishing the fire. Emergency communication systems (ECS) and mass notification systems (MNS) are used to provide information to occupants of a building or area for a variety of threats and emergencies. Audible and visible notification appliances alert the occupants, and, in some cases, emergency forces, and convey information to them.

A fire alarm system that simply sounds an audible signal and flashes strobe lights in a space is conveying a single bit of information—fire alarm. Systems that send voice announcements or that use text or graphic annunciators typically convey multiple bits of information. They may signal a fire alarm or other threat and give a specific location and information on how and where to evacuate or relocate. As the cost of emergency voice/alarm systems (EVAC) comes down closer to conventional systems, they are being used more and more by designers. They are almost always required by codes in high-rise buildings but can also be effectively used in smaller buildings. When provided with detailed information about a fire or other emergency, people tend to evacuate or respond to the information more quickly and effectively than to alarms that merely produce an audible signal or flash. The audibility requirements for voice systems are the same as for conventional systems except that it is only an alert tone, not the actual voice that is measured for proper audibility. In addition to audibility, the intelligibility of the signal content becomes important.

Audible and visible appliances may also be used to indicate a trouble condition in the fire alarm system or they may be used as supervisory signals to indicate the condition or status of other protection systems, for example, automatic sprinklers.

For related topics see Section 12, Chapter 15, "Public Emergency Services Alarm, Dispatch, and Communications Systems"; Section 14, Chapter 1, "Fire Alarm Systems"; and Section 14, Chapter 5, "Inspection, Testing, and Maintenance of Fire Alarm Systems."

OPERATING MODES FOR NOTIFICATION APPLIANCES

There are two operating modes for alarm notification appliances: (1) public operating mode and (2) private operating mode. In the public operating mode, audible and visible signaling is intended for the occupants or inhabitants of the area protected by the fire alarm system, emergency voice/alarm systems (EVAC), emergency communication systems (ECS), or mass notification systems (MNS). In the private operating mode, audible and visible signaling is intended only for persons directly concerned with implementation and direction of emergency actions in the area protected by the system. For example, in a bank or shopping mall, the fire alarm is intended to alert all occupants and convey the need for them to evacuate. This scenario describes a public mode system. If an EVAC or ECS system is used, it may be used to convey information to all occupants or to some subset of the occupants, but would still be considered to be in the public mode. In a prison or

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hospital, the system may be designed to notify only the trained staff. They will then initiate emergency procedures, including assisting occupants who might not otherwise be able to evacuate or relocate. This scenario describes a private mode system. Similarly, a supervisory signal at a guard's station indicating an off-normal status of a fire pump is considered to be private mode signaling.

The operating mode of the system affects the selection and placement of notification appliances. In general, the requirements for private mode signaling are less stringent, because they are intended for a professional staff that has been trained to look and listen for that signal and to immediately take certain actions when it is seen or heard.

AUDIBLE SIGNALING

Audible notification appliances are the most common method for signaling a fire alarm or other emergency condition in a building or area. There are two factors that affect the performance of audible notification systems. Here performance is defined as the ability to alert and convey information. The first is the rating of the audible appliance. Typically, audible appliances are rated by measuring the sound pressure level (SPL) at a fixed distance in a special room.

Rating of Audible Appliances

Without giving the exact mathematical definition, sound pressure level is a measurement of how loud something is. The measurement is expressed in decibels (dB). For almost all emergency alarm applications, the sound pressure level is expressed in dBA (i.e., decibels, A-weighted). A sound pressure level expressed in dBA has been adjusted to account for the way the human ear perceives different frequencies. Typically, high-pitched sounds (high frequency) are heard better than low frequency, bass, sounds. The A-weighting adjustment corrects for this so that the loudness of sounds that are composed of different frequencies can be compared.

Audible appliance ratings are usually stated as a certain sound pressure level (SPL) at a distance of 10 ft (3.05 m). This is a starting point for the design or analysis of audible signaling systems. Because the rating is measured in a room with certain reverberation characteristics, the actual performance will vary depending on the field conditions. In a room or hallway with concrete block walls, a sheetrock ceiling, and a tile floor, the actual SPL at 10 ft (3.05 m) will probably be greater than the rating of the audible appliance. However, in an acoustically soft situation, such as a room with wood walls, carpet on the floors, and an acoustical tile ceiling, the SPL may be less than the appliance's rating.

The second factor affecting the performance of audible notification systems is the net sound pressure level produced throughout all of the building or area served by the system. As one moves away from an audible appliance, the SPL decreases. As one gets closer, the SPL increases. In a wide-open space where the sound does not reflect off any surfaces (no reverberation), the SPL decreases by roughly 6 dB every time the distance from the source is doubled. This condition is called the free-field condition. An anechoic chamber, designed to absorb all sound waves, simulates a free-field condition. In almost all other situations there is some reverberation. Nevertheless, the 6 dB rule can be used when designing a system or analyzing the expected performance of a system. Note that dBA is used when expressing an absolute SPL that has been adjusted using the A-weighting scale. However differences are always expressed as dB.

For example, if an appliance has a rating of 90 dBA at 10 ft (3.05 m) and the distance is doubled to 20 ft (6.1 m), one would expect to measure an SPL of approximately 84 dBA (Figure 14.3.1). At a distance of 40 ft (12.2 m), one would expect an SPL of 78 dBA. At 80 ft (24.4 m), the SPL would be approximately 72 dBA.

When there are multiple audible appliances in a space, their combined SPL is greater than any one, but the individual SPLs are not simply added together to get the result. For example, consider two appliances rated 90 dBA at 10 ft (3.05 m) that are spaced 40 ft (12.2 m) apart. Alone, each unit would produce about 84 dBA (90 – 6) in the center (20 ft [6.1 m] from each). With both units operating, a measurement taken between the two at 20 ft (6.1 m) from each would be about 87 dBA (3 dB greater than a single unit). Fire alarm designers usually ignore this effect so that their designs are conservative.

This type of analysis works well in open spaces. However, sound loss through walls and doors requires more complex calculation methods. Of course, in an existing building a temporary audible appliance can be used to study sound transmission and attenuation throughout the space and through the walls and doors. By measuring sound loss from one side of a door/wall assembly, designers can obtain representative values for a structure to be used in later design and analysis of the fire alerting system. The *SFPE Handbook of Fire Protection Engineering*[1] contains calculation methods that can be used in design and analysis of audible alerting systems.

Fire Alarm Audibility Design Goals

How loud should an alerting system be? Obviously, the audible signals must be louder than the ambient noise in a space. So, the first step is to measure the ambient noise. When designing new systems, tables of ambient noise levels may be used as an estimate. Annex A of *NFPA 72®, National Fire Alarm Code®*, contains such a table. Two different ambient noise levels are required to complete a system design: (1) the average SPL dur-

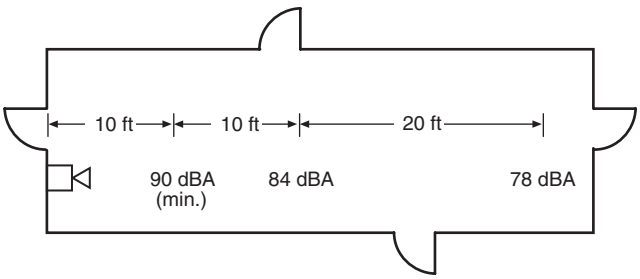

FIGURE 14.3.1 Example of 6 dBA Rule (1 ft = 0.305 m)

ing the time the area is occupied, and (2) the maximum SPL that lasts 60 seconds or more.

Fire alarm audibility goals are dependent on the mode of operation. In the public operating mode, the fire alarm system must produce a sound pressure level that is 5 dB above any ambient noise that lasts 60 seconds or more, or 15 dB above the 24 hour average, whichever is greater. In the private operating mode, the fire alarm system must produce a sound pressure level that is 5 dB above any ambient noise that lasts 60 seconds or more, or 10 dB above the average, whichever is greater. In either case, if the area will be used for sleeping, the minimum SPL required of the fire alarm system is 75 dBA. When designing an EVAC or MNS system, the same goals should be used for the audibility of the system's alert tone.

A fire alarm or other emergency tone signal may have the same SPL or less, measured in dBA, than the ambient noise and still be clearly heard. This occurs when the two signals (ambient and alarm) operate at different frequencies. In high noise occupancies such as manufacturing plants, it might be more effective to conduct a frequency analysis of the ambient noise and then design a fire alarm signal at frequency bands not occupied by noise. See Figure 14.3.2 for an example. The figure shows a one-third octave band analysis of noise and an alarm signal in a compressor room. The loudness of each frequency band is measured in dB (*Y* axis). The *X* axis shows the center frequency for each band measured in Hertz (Hz = cycles per second). The frequency bands range from low, bass-level frequencies on the left through midrange tones and up through very high-frequency tones. (Middle C on a piano is approximately 262 Hz.) On the far right, L_P represents the logarithmic sum of all the frequency bands while L_A is the logarithmic sum adjusted using the A-weighting scale to correct for how the human ear hears different frequencies. The noise can be thought of as a picket fence. To hear a fire alarm signal above the background noise, it does not have to be louder than all the component frequencies added together; it just has to be louder than one. As long as one of the alarm signal's frequency bands (pickets) is taller than the corresponding noise picket, you will hear the signal, even if the total broadband sound pressure level of the noise is greater than the total broadband sound pressure level of the signal. Consult *NFPA 72,* ISO, or an audio design text for more information.

Because building codes require residential and other sleeping-type occupancies to have a minimum degree of soundproofing, they represent the most challenging scenarios for fire alarm system design. Given the high SPL that must be achieved to alert a sleeping person, it has been shown that audible appliances are almost always needed in each sleeping room.[1] In other occupancies, such as offices and schools, it may be sufficient to place audible appliances in the corridors only. In any case, careful design is needed to ensure that audibility requirements are met.

Audibility Requirements. Once the system is installed, a complete test, including SPL measurements, must be done to prove that the system meets the signaling requirements. Various types of sound level meters are available for use in testing system audibility. Some are very expensive and have many features for special system analysis, and others are very inexpensive, yet serve the purpose. It is important that the meter have an A-weighting scale for measurement of the ambient and fire alarm SPLs.

In addition to the minimum sound pressure levels that a fire alarm must produce, there is a maximum allowable SPL of 100 dBA. This is below the threshold of pain, which occurs at about 130 dBA, and is intended to reduce the chances of damaging someone's hearing. It is possible to achieve fire alarm audibility requirements by using a few very loud appliances or a larger

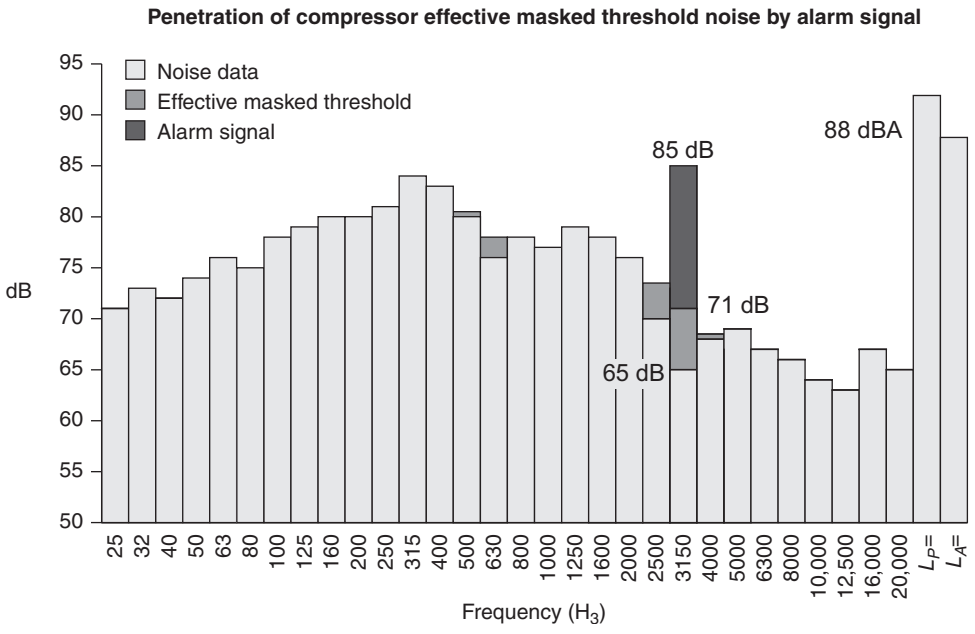

FIGURE 14.3.2 One-Third Octave Band Analysis

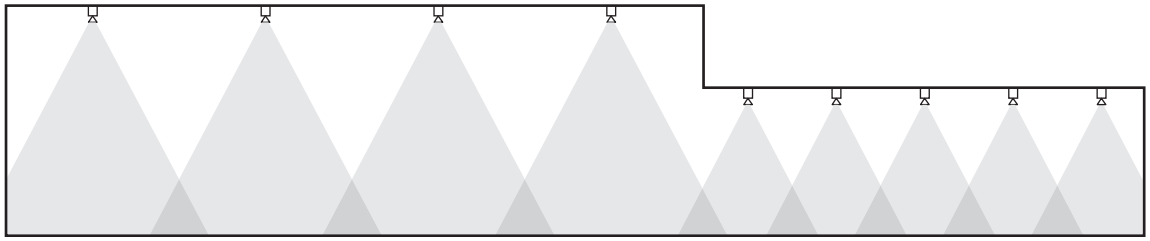

FIGURE 14.3.3 Spacing Between Textual Audible Appliances for Direct Field Coverage

number of units at a lower SPL rating. In general, system reliability is better with a larger number of lower SPL units. Also, the cost may be lower using a larger number of lower SPL units.

Intelligibility Requirements. If the system is being designed to transmit voice messages, the design should use a larger number of low-power units so that the voice message is intelligible. If only a few high-power speakers are used, reverberation or echoes of the sound may make it difficult to understand the message.

For voice communication, a sufficient audible level does not guarantee that the message will be intelligible. There are many factors affecting speech intelligibility in addition to the audible level. Some of the factors are a part of the audio system design and installation; others are a part of the architectural/acoustical environment. In addition, the talker and the listener are also a part of intelligibility, although they are generally taken to be "average" or slightly below "average."

For systems used to reproduce voice, specifying a louder system may result in degradation of the intelligibility of the message. One of the basic concepts in the design of intelligible voice systems is to have all listeners in the direct field of a single speaker, and to avoid having the system so loud that sound reverberates from other locations to the listener. If a person is in the direct field of two speakers, the sound from the farther one arrives some time after the sound from the closer speaker. The same effect occurs when the sound bounces off a wall and comes back to the listener (reverberation). The degree of impact on intelligibility depends on the time difference between the first arrival of the word or sound and the arrival from the second source. Distributing the speakers to reduce or eliminate the overlap of the direct field sound is the best design practice. Though at first counterintuitive to many fire alarm system designers, the lower ceiling height requires a smaller spacing between the speakers (see Figure 14.3.3). For additional information about the factors affecting speech intelligibility and their effects on system design, consult *NFPA 72* and "Understanding Speech Intelligibility and the Fire Alarm Code," by Kenneth Jacob.[2]

Audible Emergency Evacuation Signal. *NFPA 72* requires all audible evacuation signals to comply with ANSI S3.41, *Audible Emergency Evacuation Signal.*[3] (Note: *NFPA 72* does not itself require existing systems to comply with current requirements.) That signal is commonly referred to as a temporal code-three signal. The pattern consists of an "on" phase (a) lasting 0.5 seconds ± 10 percent, followed by an "off" phase (b) lasting 0.5 seconds ± 10 percent, for three successive "on" periods, which is then followed by an "off" phase (c) lasting 1.5 seconds ± 10 percent. The signal should be repeated for a period appropriate for the building, but not less than 180 seconds. A single-stroke bell or chime sounded at "on" intervals lasting 1 second ± 10 percent, with a 2 seconds ± 10 percent "off" interval after each third "on" stroke, is acceptable (Figures 14.3.4, 14.3.5, and 14.3.6.). The

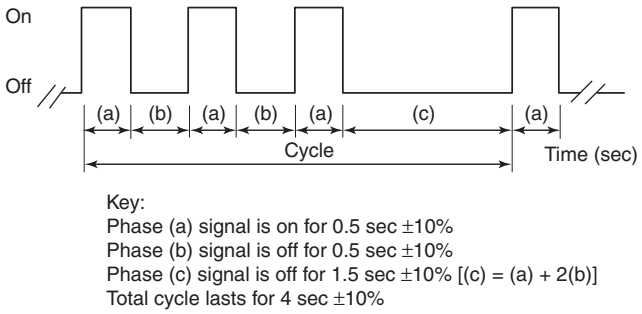

FIGURE 14.3.4 Temporal Pattern Parameters (Source: *NFPA 72®, National Fire Alarm Code®*, Figure A.6.8.6.5.1(a), 2007, p. 72-150)

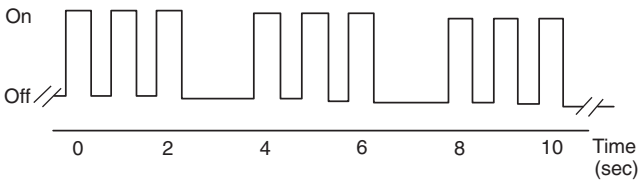

FIGURE 14.3.5 Temporal Pattern Imposed on Audible Notification Appliances That Otherwise Emit a Continuous Signal While Energized (Source: *NFPA 72®, National Fire Alarm Code®*, Figure A.6.8.6.5.1(b), 2007, p. 72-150)

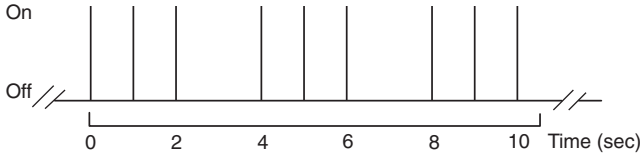

FIGURE 14.3.6 Temporal Pattern Imposed on a Single-Stroke Bell or Chime (Source: *NFPA 72®, National Fire Alarm Code®*, Figure A.6.8.6.5.1(c), 2007, p. 72-150)

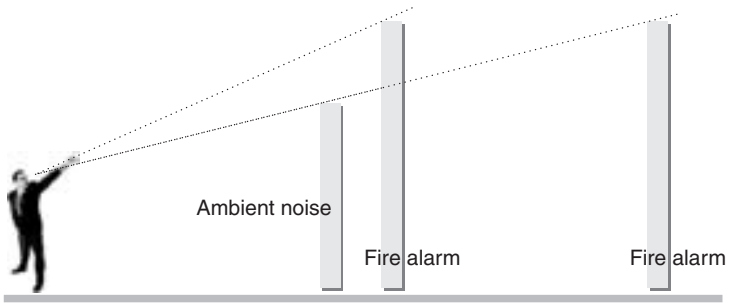

FIGURE 14.3.7 Effect of Ambient Noise on Ability to Perceive an Alarm

type of signal is not important; it may be a bell, horn, chime, whoop, or any other sound, provided it is not used for any purpose other than fire alarm. The intent is that the pattern of the sound will be standard from system to system. Systems intended to relocate people or to simply alert them of a nonfire emergency must not use the standard evacuation signal.

Importance of Location

The farther your ear or sound meter is from a sound source, the less loud it will be. Basic design practice is to analyze or estimate the ambient noise and then select and place alarm appliances to overcome that background noise. The picket fence analogy is useful here again (Figures 14.3.7 and 14.3.8). It is possible to hide a larger object that is farther away with a smaller object close by. Similarly, when you are at a certain location and the noise is at a certain level, there is a distance at which an alarm signal will be clearly heard, and there is a distance at which it will not be heard. Also, for set levels of noise and alarm and for set distance between their sources, there is a point where you can be so close to the noise that it will mask the alarm, as shown in Figure 14.3.8.

VISIBLE SIGNALING

Visible fire alarm notification appliances are often intended only to augment audible appliances. However, when it is expected that hearing-impaired persons may be in the protected area or when ambient noise levels are high, visible appliances may be the primary means of occupant notification that a fire emergency exists. Increasingly, visible appliances are being used as an integral part of occupant notification systems. For MNS or EVAC systems, simple visible appliances, such as strobes, are used to signal the need to "get additional information." Other types of visible appliances, such as scrolling signs, annunciators, and displays may be used to convey visible information during an emergency.

Building codes, NFPA *101*®, *Life Safety Code*®, and *NFPA 72,* as well as state and federal laws, all contain requirements for the use of visible notification appliances under certain circumstances. At present, only the use of strobe lights is addressed by *NFPA 72*. Other appliances and systems, such as revolving beacons or the flashing of building lights, have also been shown to be effective under certain circumstances. However, requirements necessary to ensure their availability and effectiveness are not addressed by the code at this time.

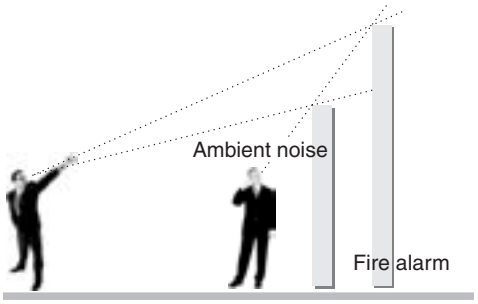

FIGURE 14.3.8 Effect of Proximity on Ability to Perceive an Alarm

Factors Affecting Performance of Visible Appliances

Visual signaling and notification using strobe lights involve a large number of complex variables. For this reason, *NFPA 72* uses prescriptive code language to provide simple, preengineered solutions. As with audible appliances, *NFPA 72* addresses two factors affecting the performance of visible notification appliances: (1) source intensity and (2) illumination at some distance from the source.

Source intensity is a measure of the light output of the appliance. The unit of measure is the candela (cd). (This unit was formerly called "candlepower." There is a one-to-one relationship between candela and candlepower.) As one moves away from any light source, the illumination it provides decreases. Illumination is measured in units of lumens (lm) per ft^2, or lumens per m^2 (also called "lux"). Formerly, the unit used to describe illumination was the "footcandle." One footcandle equals one lumen per ft^2. One lumen per m^2 equals 0.926 footcandles. Figure 14.3.9 shows the relationship between source intensity and illumination.

The inverse square law is used to determine the illumination, E, at some distance, d, from a source of intensity, I (i.e., $E = I/d^2$).

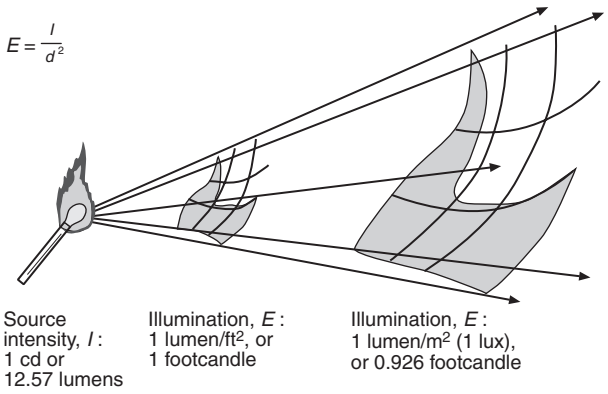

FIGURE 14.3.9 Visible Intensity Versus Illumination

Because strobe lights flash for a very brief period of time, the perceived brightness can vary depending on the actual peak source strength and duration of the flash (Figure 14.3.10). One appliance might reach a peak intensity of 1000 candelas in 0.1 second, while another might reach 750 candelas in 0.2 second. Nevertheless, the human eye might perceive both as being equally bright. A complex mathematical relationship is used to relate the perceived brightness of a strobe light to that of a constantly burning light. The result is called the "effective intensity" (candela effective [cd eff]).

The design of visible notification systems involves many additional factors beyond those discussed herein. Many other factors, such as how much light is absorbed versus how much is reflected by a surface, the angle that the light strikes a surface, and the color of the surface, affect the performance of the notification system. For instance, as light strikes a surface at some angle, only a portion of that light is reflected back to the human eye. The term used to describe the reflected light is "luminance." Thus, a certain intensity appliance produces a certain illumination at some distance on a surface, but a person looking at that surface sees a certain luminance.

To simplify the process of designing and evaluating visible notification systems, *NFPA 72* contains prescriptive requirements for the intensity and spacing of visible appliances that are sufficient in almost all applications to alert persons. In essence, *NFPA 72* provides preset designs that can be used for a variety of actual field conditions.

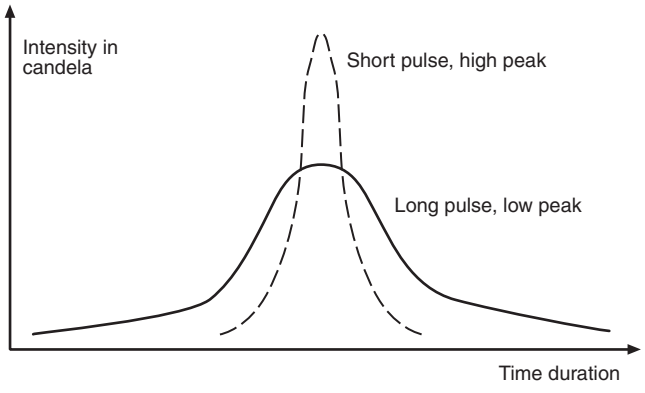

FIGURE 14.3.10 Visible Peak Versus Effective Intensity

The prescriptive requirements contained in *NFPA 72* are based, in part, on tests performed by Underwriters Laboratories Inc. (UL).[4] The tests were conducted in real classrooms and test facilities with similar size characteristics. Use of *NFPA 72* methods for larger spaces may not be valid. For example, in large stores or warehouses, it is not known if these methods will be conservative or ineffective.

Fire Alarm Visibility Design Goals

NFPA 72 contains tables listing the minimum intensity strobe required in certain size rooms to alert the occupants. For instance, a single 15 cd eff strobe can be used when centered on one wall of a 20 ft × 20 ft (6.1 m × 6.1 m) room. There are also listings for use of multiple units in a single room. Using the 20 ft × 20 ft (6.1 m × 6.1 m) room as an example, the illumination on the opposite wall would be $15/20^2 = 0.0375$ lumens per ft^2. *NFPA 72* permits a performance-based design approach using this level of illumination as the requirement. See *NFPA 72* and the *SFPE Handbook of Fire Protection Engineering* for examples.

Occupancies where hearing-impaired persons may sleep must have higher strobe intensities than for nonsleeping areas to ensure that the hearing-impaired person can be awakened. A 110 cd eff strobe no more than 16 ft (4.9 m) from the pillow was sufficient to awaken hearing-impaired persons. Other methods, such as bed shakers or fans, may be used to supplement visible signaling. In practice, a bedroom strobe light is often combined with a smoke detector. In that case, the strobe light must have an even higher intensity (177 cd eff) to overcome potential obscuration by a smoke layer at the ceiling.

Some spaces, such as corridors, can be treated differently from those rooms where a person may have his or her face turned away from a strobe light. In corridors, a person's view path is more concentrated, and the person is usually moving. Recognizing this, *NFPA 72* allows the use of 15 cd eff strobes at longer distances than what would be required for rooms. The luminous intensity required is actually less, given that a person is likely to directly see the appliance or to see more surfaces illuminated by the strobe.

When designing the audible part of an occupant-notification system, it is best to use a greater number of lower-power SPL units. The opposite is true for visible appliances. The use of a lower number of higher-intensity units will usually be more cost-effective. Furthermore, with fewer appliances, the distance between them is greater, and the chances of a person directly viewing more than two units at a time is reduced or eliminated. That, in turn, reduces the likelihood of triggering a seizure in a person who has photosensitive epilepsy.

When choosing and placing visible appliances, every effort should be made to place the unit in the concentrated viewing path of the target audience. For example, in a meeting room or classroom, the appliance should be on the wall that the majority of people face. This, however, is not a requirement of the code, since the entire methodology for signaling in rooms is based on having sufficient illumination for indirect alerting. Further-

more, a mounting height of 6.5 to 8 ft (2.03 to 2.44 m) ensures that the visible appliance is unlikely to be blocked by common furnishings.

In spaces such as large auditoriums the use of high-intensity indirect signaling may be warranted. This method of indirect signaling uses much higher-intensity strobes that must be located so that they cannot be directly viewed by the human eye (they could temporarily or permanently impair vision). The light from the strobes is used to illuminate large areas of walls and ceilings. The UL research used indirect illumination. However, the illumination was on a wall in front of the test subjects, and the maximum intensity was low enough to allow direct viewing of the appliance's element. Another possible method of visible signaling in such high-challenge spaces is to flash some or all of the building lights. Although these methods may prove effective, at this time there are few test data to support specific performance requirements for these notification methods. It should be noted that the authority having jurisdiction (AHJ) must approve any type of alternate arrangement that is not directly covered by code requirements.

In the past, guidelines for meeting the visible signaling requirements of the Americans with Disabilities Act (ADA)[5] have cited strobe intensities and distances different from those specified in *NFPA 72*. However, through a process called "equivalent facilitation," the requirements of *NFPA 72* have been shown to meet or exceed the original ADA "Accessibility Guidelines" (ADAAG). The ADAAG have been revised to follow *NFPA 72* requirements.

Visible Signaling in Warehouse Stores

In large warehouse spaces and large distribution spaces such as superstores, it is possible to provide visible signaling using strobe appliances. However, mounting strobe lights at a height of 2.0 to 2.4 m (80 to 96 in.) along aisles with rack storage subjects the lights to frequent mechanical damage by forklift trucks and stock.

Tests of systems in large warehouse/superstores designed using ceiling-mounted strobes, and the prescriptive approach of *NFPA 72*, showed that the systems worked because of both indirect and direct signaling effects.[6] The signal-to-noise ratio produced by the operating strobes was low in many locations due to high ambient light. However, with strobes located over the aisles or unobstructed by stock, indirect and some direct notification was sometimes achieved. Direct notification can occur even when occupants do not look up toward the ceiling-mounted strobes due to the extended cone of vision shown in Figure 14.3.11.

Tests showed that the strobe intensity and spacing resulting from the prescriptive design were generally sufficient for occupant notification by a combination of direct and indirect signaling. The best performance was achieved where strobes were directly over aisles or where strobes in adjacent aisles were not obstructed by stock. The performance-based design method will almost always result in aisles not having a line of strobes in them, since the spacing of strobes can be greater than the spacing of aisles. Also, it is recognized that aisles may be relocated after installation of the system. Good design practice is to place strobes over aisles, especially those that are likely to remain unchanged such as main aisles and over checkout areas. Where reorganization of aisles results in strobes not in or over an aisle, or where that is the base design, it is important to have a clear view from that aisle to a nearby strobe (Figure 14.3.12). Some spaces may have marginal strobe effect (direct or indirect). However, occupants in these large stores and storage occupancies move frequently and place themselves in a position where they receive notification via the strobes.

COMBINATION AUDIBLE/VISIBLE UNITS

To meet the requirements of ANSI S3.41, *Audible Emergency Evacuation Signal,*[3] some systems will require separate circuits for audible and visible appliances. Some combination audible/visible appliances may be available that can be installed on a common circuit. In any case, it will be important to size the circuit to handle the expected load. Greatest flexibility is obtained by putting fewer than the maximum number of units on a circuit when the system is first designed or installed. In this way, if the acceptance test shows deficiencies in some areas, additional units can be added without overloading the circuits or the system.

Most codes do not require audible and visible appliances to be on separately controlled circuits. However, if they are, the audible circuits can be silenced after a building has been completely evacuated, and the visible appliances can be left

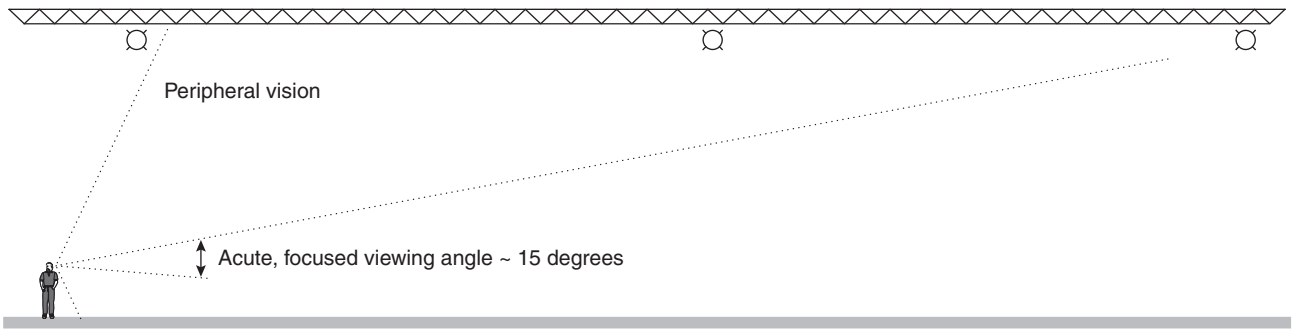

FIGURE 14.3.11 Occupant Perception of Notification Through Extended Cone of Vision

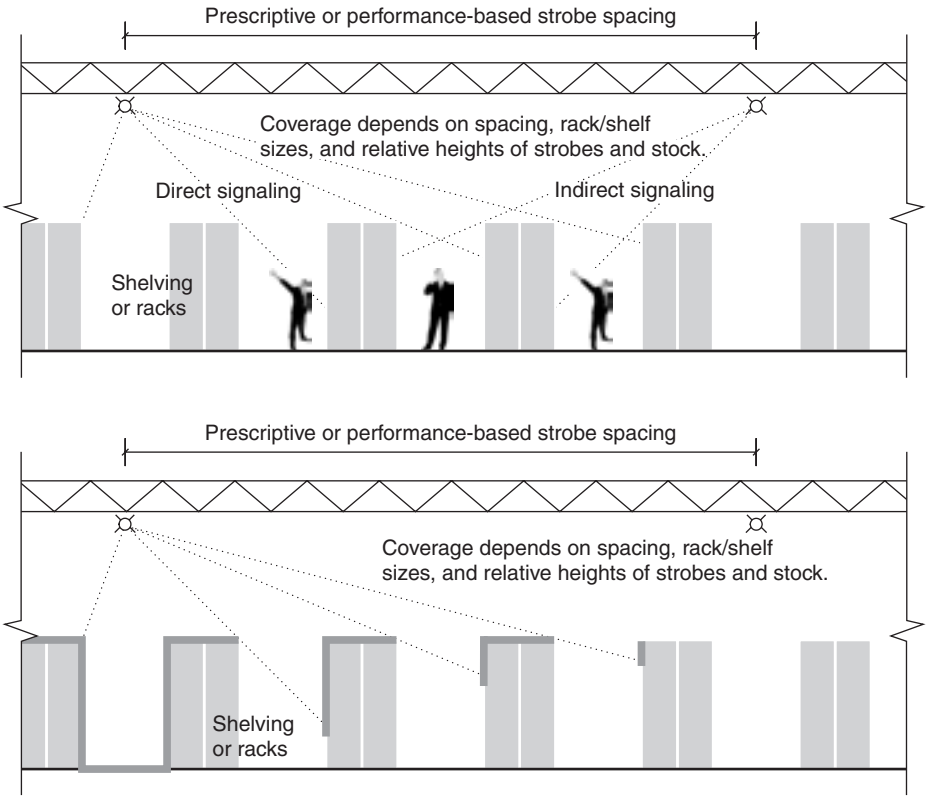

FIGURE 14.3.12 View of Strobe from Aisle

in operation. This is a way of telling people not to reenter the building or space. Similarly, good design practice is to include an audible and a visible appliance on the outside of the building to assist arriving fire fighters in locating the building or building entrance. Placing appliances on each side of a building or at each entrance also helps inform persons that they should not enter the building or space.

When designing or installing occupant notification systems utilizing both audible and visible appliances, it is best to determine the locations of the visible units first. This is because their location is more dependent on viewing angles, intersections of corridors, and blockage by furnishings. Once the visible appliances have been placed, audible appliances can be located so that some or all of the units can be combination audible and visible appliances. The use of combination units may reduce installation costs slightly. Figure 14.3.13 shows examples of both visible and combination audible/visible notification appliances.

FIGURE 14.3.13 Typical Visible and Combination Audible/Visible Notification Appliances (Source: Gentex Corp.)

SUMMARY

Audible and visible notification appliances are used to alert occupants of a building that they need to evacuate or relocate to a safe area. In addition, they may alert emergency personnel or indicate a problem in the fire alarm system or other protection system, such as automatic sprinklers. When used in the public operating mode, the notification appliance will alert the occupants of an area, such as a shopping mall, that they need to evacuate. In the private operating mode, the notification appliance is intended for trained staff responsible for undertaking emergency actions in locations such as hospitals or prisons.

Audible notification appliances are the type most commonly implemented, and their placement, decibel setting, frequency, and length of signal are calculated according to numerous factors, including the physical parameters of the area being protected. Visible notification appliances are usually used to supplement the audible alarm system, but in certain cases

(such as loud ambient noise) they may be the primary alarm system. As with audible systems, the design of visual notification appliances must use many calculations based on a variety of factors, including the physical properties of light.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on notification appliances discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 72®, National Fire Alarm Code®
NFPA *101®*, *Life Safety Code®*

Chapter 4

Fire Alarm System Interconnections

Fred Leber

Chapter Contents

Automatic Sprinkler Systems
Automatic Sprinkler System Waterflow Alarms
Automatic Sprinkler System Supervision
Other Automatic Fire Suppression Systems
Fire Safety Function Interfaces
Interconnected Fire Alarm Control Units
Interfaced Equipment
Testing Interfaced Systems

Key Terms

automatic sprinkler system, building automation system, fire alarm control unit, fire alarm system, interconnection, protected premises, waterflow alarm

Many fire protection systems, fire safety control functions, process monitoring systems, and building operation and control systems can contribute to life safety in a building. A significant benefit can be obtained if these systems are interfaced with the building fire alarm system. *NFPA 72®*, *National Fire Alarm Code®*, requires that all fire protection systems in a protected property be connected to the protected premises (local) fire alarm system. Many interface strategies are now also required by building codes and (other) relevant standards.

The integration of commercial fire and nonfire protection systems has existed for many years. In addition to the benefits to life safety, the combination of systems was an attempt to conserve valuable construction dollars through systems integration. In other cases, systems integration was seen as a necessity for ease of building management—for example, combination security/access control and fire alarm systems or building automation and fire alarm systems.

There are some commercially available combination systems that are tested, listed, and manufactured to serve as combination systems. However, many systems provide some form of protection or management of a building, such as elevator control, door control, and heating, ventilating, and air-conditioning (HVAC) control, which can benefit by being integrated or interfaced with the fire alarm system. These systems are not necessarily manufactured, tested, or listed as a single integrated system. Their interface with fire protection systems will be presented in this chapter.

See also Section 2, Chapter 6, "Fundamentals of Fire Detection"; Section 14, Chapter 1, "Fire Alarm Systems"; Section 14, Chapter 10, "Security and Intrusion Detection Systems"; and Section 16, Chapter 3, "Automatic Sprinkler Systems."

AUTOMATIC SPRINKLER SYSTEMS

The fire protection system that will provide the most obvious benefit by interfacing to a fire alarm system is the automatic sprinkler system, which can be monitored both for waterflow alarms and for disablement of system components or water supply. Fire and building codes as well as other relevant standards identify the specific system functions that must initiate alarm and supervisory signals. In addition, "good engineering practice" may conclude that certain functions or devices should be supervised.

The value of installing an automatic sprinkler system for life safety and property protection has been well documented over many years of service in a variety of specific applications. It is obviously necessary to ensure that the automatic sprinkler system is maintained in such a condition that it is always ready to discharge water on a hostile fire, holding the fire to its area of origin, and helping to control smoke development.

One way of making certain that an automatic sprinkler system remains fully in service is to supervise its operational features as well as the availability of water supplies. At the same time, it is necessary to initiate an alarm signal whenever the sprinkler system does operate so that personnel

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may respond promptly and take whatever action is needed. Thus, these two functions—waterflow alarm and automatic sprinkler system supervision—are vital elements of an overall fire protection program.

AUTOMATIC SPRINKLER SYSTEM WATERFLOW ALARMS

Notification Functions

Notification of a waterflow alarm may be as simple as a hydraulically operated water motor gong serving a single sprinkler riser (see Section 16) or as complex as a multiplex proprietary fire alarm system monitoring several hundred sprinkler risers at a very large industrial facility. In either case, there are certain basic functions that must be provided by whatever waterflow alarm equipment is installed, including the following:

1. The prompt detection of the discharge of a certain number of gallons per minute (L/min) at nominal pressure that would be equivalent to the amount of water discharged from a single operating sprinkler having the smallest orifice of those sprinklers installed in that particular system
2. The reliable operation of a suitable audible alarm notification appliance; the exact nature of the particular appliance will depend on the purpose of the specific waterflow alarm system
3. The provision of suitable facilities to test the operation of the waterflow alarm device, preferably by an actual flow of water equivalent to the discharge from a single automatic sprinkler having the smallest orifice of those sprinklers installed in the system

Notification of waterflow alarms can be categorized according to their purpose and according to their method of operation. For example, the notification of a waterflow may be an alarm signal to alert someone either outside the building or in the immediate area protected by the sprinkler system riser. Such a signal would normally be produced by the operation of either a hydraulically operated or electrically operated bell. The waterflow alarm system also may be installed to provide an alarm signal that will sound throughout the protected building. This will normally be achieved by connecting the waterflow alarm initiating device to a protected premises (local) fire alarm system.

The waterflow alarm signal may transmit the signal off-premises to a constantly attended location by means of a signaling system for central station service, an auxiliary fire alarm system, or a remote station fire alarm system. The waterflow alarm signal may provide a signal that will be transmitted to a constantly attended location on the protected premises or to another location of the same owner. This will normally be accomplished by connecting the waterflow alarm initiating device to a proprietary fire alarm system.

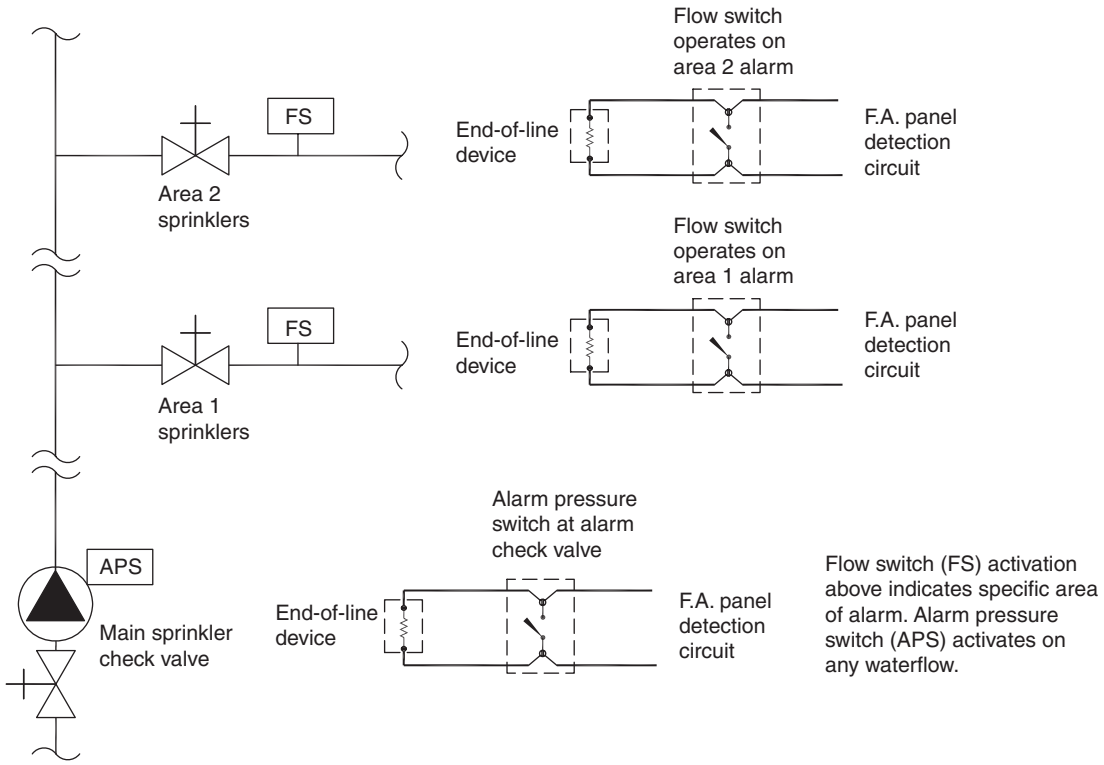

FIGURE 14.4.1 Alarm Pressure Switch Connection

Electrically Operated Waterflow Alarms

Waterflow alarms may be signaled using electrically operated fire alarm notification appliances, such as vibrating bells, horns, sirens, chimes, and several varieties of flashing lights. Such signals usually are initiated by electrical switches incorporated into some type of pressure- or flow-operated device.

Waterflow Alarms for Wet Pipe Automatic Sprinkler Systems

For wet pipe automatic sprinkler systems, the flow of water is generally detected hydraulically by an alarm check valve or by a vane-type waterflow alarm initiating device. The alarm check valve and waterflow alarm initiating device cause an electrical contact closure when waterflow is detected. This contact is connected to the fire alarm system. Either of these would be installed at the point the water supply piping enters the building from the underground. Supplementary vane-type devices could also be installed at various points in the piping system, for example, on each floor of a high-rise building. This allows a more precise determination of the location where water is flowing and subsequently aids in obtaining a timely response to the emergency.

Alarm Check Valves

Depending on the specific design, alarm check valves are generally referred to as being either "plain type" or "differential type." (See Section 16, Chapter 3, "Automatic Sprinkler Systems," for more information on alarm check valves.) The basic design of most alarm check valves incorporates a clapper that lifts from its seat when water is discharged from sprinkler system piping above the valve. The movement of the clapper is used to allow waterflow into an "alarm port." This port can be connected to electrical or mechanical devices that initiate an alarm at the fire alarm system. Since the clapper may be subject to movement as a result of sudden changes in water pressure, a retard mechanism is installed that takes up the water surge and prevents clapper movement and subsequent false alarms.

Pressure-Operated Switch Waterflow Alarm Initiating Devices

A pressure-operated switch could be mounted on a fitting connected to the alarm port of the alarm check valve, as long as there is no shutoff valve in the connection. In such a case, it would normally be necessary to provide an electronic or electropneumatic retard mechanism, either built into the pressure-operated switch or installed at the fire alarm system control unit, if one exists. A pressure-operated switch so located could be used to initiate a fire alarm signal on a central station, local, auxiliary, remote station, or proprietary fire alarm system (Figure 14.4.1).

Vane-Type Waterflow Alarm Initiating Devices

Far and away the most common electrically operated waterflow alarm initiating device is the vane-type waterflow switch

FIGURE 14.4.2 Vane-Type Waterflow Alarm Switch

(Figure 14.4.2), which is designed to be inserted into the riser just above the point at which the water supply piping enters the building from underground. Even if the wet pipe system has been equipped with an alarm check valve, a vane-type waterflow alarm initiating device may still be used. In this case, it normally would be installed just above the alarm check valve.

A small hole approximately 1 in. (25 mm) in diameter is drilled into the riser. The drill bit has a special piece of spring steel wire that captures the metal center of the hole, which is called the "coupon." Once the coupon is removed from the drill bit, it is usually attached to one of the mounting bolts of the waterflow alarm initiating device to show future inspectors that it was not left inside the pipe where it might possibly move upward into the sprinkler system and become an obstruction to the proper operation of the sprinkler system. The plastic or thin metal vane is rolled up and inserted into the riser. Once it resumes its original shape, it forms a thin barrier that covers almost all of the interior of the riser. When a sprinkler fuses, water flowing past the vane will push the vane upward, actuating a switch. When the switch contacts close, they initiate an alarm by activating the fire alarm system.

Two problems that may occur occasionally with vane-type waterflow alarm initiating devices are leaks around the point of entrance into the riser and detached vanes. The laboratories that test and list such devices require that each vane have a supplementary means of attaching the vane to the device so that, even if the vane breaks off, it will be retained near its original point of connection.

Waterflow Alarms for Dry Pipe, Preaction, and Deluge Automatic Sprinkler Systems

Automatic sprinkler systems equipped with dry pipe valves, preaction valves, or deluge valves also must have appropriate waterflow alarms. Each of these types of valves has a passageway that is uncovered when the clapper of the valve trips into the open position. Since these three types of valves are not affected generally by surges in the water system, no retard chamber is necessary. Piping connected to the outlet from the alarm passageway of these valves may be attached to a water motor gong or to a pressure-operated switch.

Vane-type waterflow alarm initiating devices are not permitted to be used for dry pipe valve, preaction, or deluge sprinkler systems. This prohibition comes from concern that the hydraulic shock occurring when these valves trip would increase the possibility that the vane might become detached.

Drop-in-Pressure Waterflow Alarms

An alternative arrangement designed to initiate a waterflow alarm, even if the main automatic sprinkler system control valve is shut, is the drop-in-pressure waterflow alarm. The supervision of all fire protective system control valves 2½ in. (63.5 mm) nominal size or larger is considered very important, especially when a fire alarm system is used to supplement or supplant standard guard service. Occasionally, it is simply not possible to obtain this valuable supervision. In such cases, it is essential that some method of detecting sprinkler system waterflow be used that will initiate an alarm even if the sprinkler control valve is shut. One method of accomplishing this is to use a waterflow alarm initiating device that detects a drop in sprinkler system pressure as a means of detecting the discharge of water from the system.

Such devices may use an ancillary storage chamber connected to the sprinkler system through a restricted orifice. Under normal conditions, the pressure in the ancillary chamber is the same as that in the sprinkler system. When system pressure drops, the pressure stored in the chamber acts on a diaphragm to activate an alarm initiating switch. Other such devices may employ a pressure-sensing transducer and associated electronic circuitry to detect the rate of pressure change in the system. A slow rate of change is reported as a trouble signal, whereas a rapid rate of change is reported as an alarm.

The most common drop-in-pressure waterflow alarm initiating device uses a pressure switch to sense the pressure in the system and, for wet pipe systems, employs a small riser-mounted excess pressure pump (Figure 14.4.3). (An excess pressure pump is not needed for dry pipe systems.) When the water pressure in a wet pipe system or the air pressure in a dry pipe system drops to a predetermined pressure setting, the pressure switch initiates an alarm signal. The automatic excess pressure pump maintains a pressure of 29 to 47 psi (200 to 325 kPa) in excess of the water supply pressure above an alarm check valve. A continuous white pilot light, controlled by a differential switch, indicates when the pressure in the sprinkler system is more than 29 psi (200 kPa) above the supply pressure. Should the water supply fail, a low-pressure switch shuts off the current

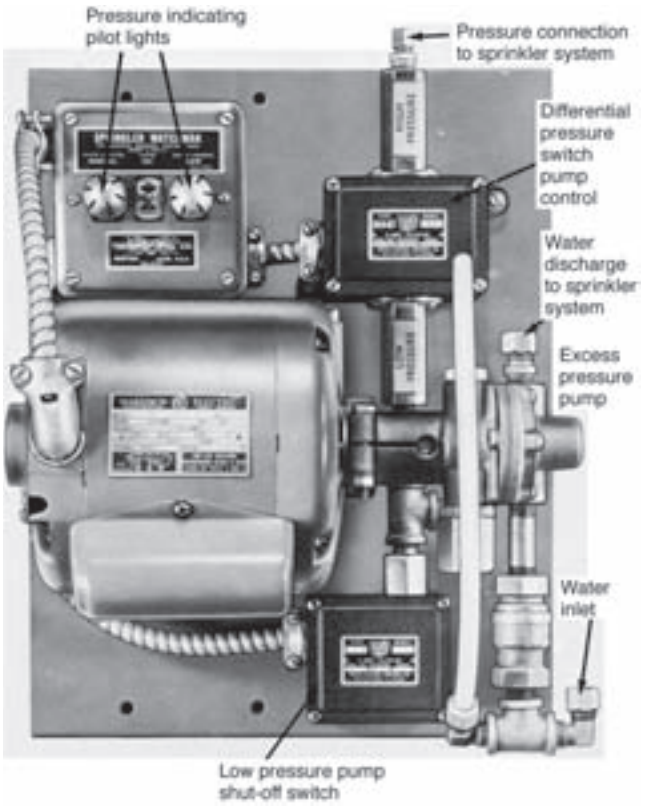

FIGURE 14.4.3 Excess Pressure Pump for Installation on a Wet Pipe Sprinkler System (Source: The Gamewell Co.)

to the pump so that it will not run without water. This switch also controls a red pilot light to show when the supply pressure drops below 29 psi (200 kPa). A second pressure switch on the sprinkler system (not a part of the pump unit) is connected into the sprinkler system alarm circuit and gives an alarm if system pressure fails completely (e.g., a closed water control valve) when a sprinkler operates. A third pressure switch gives a warning by a local bell or other means in the event the pressure pump fails to maintain system pressure within the established excess pressure range.

Drop-in-pressure-type waterflow alarm initiating devices should be connected to the sprinkler system through an automatic stop-and-waste valve. Such a valve automatically "wastes" the pressure trapped between the valve and the device to the atmosphere. Thus, a signal is initiated whenever the valve is closed. This eliminates the possibility of tampering with the device without producing a signal.

Testing Waterflow Alarm Initiating Devices

The piping connected to the alarm outlet from alarm check valves, dry pipe valves, preaction valves, or deluge valves usually is connected also through a normally closed valve to a point of water supply below the alarm check valve, dry pipe valve, preaction valve, or deluge valve. Opening this test bypass valve will allow water to flow into the alarm piping, actuating the water motor gong or pressure-operated switch. Unless

the dry pipe valve, preaction valve, or deluge valve is going to be performance tested with a full actuation of the system, opening the alarm test bypass valve is the only way to test the alarms.

In the case of a dry pipe valve, care must be taken to be certain that the automatic velocity drain from the intermediate chamber of the dry pipe valve is not stuck in the closed position and that the check valve at the alarm outlet from the dry pipe valve intermediate chamber is not stuck in the open position. The combination of these two faults will most likely cause the dry pipe valve to trip when the alarm test bypass valve is opened. This tripping occurs when water from the test bypass valve flows back into the intermediate chamber of the dry pipe valve, destroying the differential between the air seat and the water seat inside the valve.

For wet pipe automatic sprinkler systems, the only proper way to test the operation of a vane-type waterflow alarm initiating device, and the preferable way to test all other types of waterflow alarm initiating devices, is to open the valve at the inspector's test connection. This valve, installed on a 1 in. (25 mm) piece of pipe—for older installations, it is often located at the most remote point of the sprinkler system, and, for more modern installations, it is often located at the top of the riser—terminates outside the building in an orifice that can simulate the discharge from a single sprinkler having the smallest orifice used by those sprinklers installed on the system. Thus, opening the inspector's test connection will simulate the fusing of a single sprinkler.

Last but not least, it is important to consider the consequences of a test when systems are interfaced. The testing of a sprinkler system could, for example, cause an unnecessary building evacuation. This could lead to injury as well as disruption of building operations. In addition, other interfaced systems such as heating and cooling equipment and elevators may be actuated or de-energized inadvertently, again creating potential risk to building occupants. Where testing is conducted and interfaced systems are disconnected temporarily, it is absolutely necessary to reconnect any bypassed functions on completion of the test. Interfaced system functions must also be tested but this should be done deliberately, with full knowledge of consequences, and not by negligence.

AUTOMATIC SPRINKLER SYSTEM SUPERVISION

Supervisory Initiating Devices

To ensure that an automatic sprinkler system is ready to discharge water on a hostile fire and hold the fire to its area of origin, a central station, local, remote station, or proprietary fire alarm system may be connected to supervisory initiating devices that will supervise critical operating features of the sprinkler system. Fire and building codes as well as other relevant standards identify the specific equipment required to be supervised and must be considered when assessing an existing system or designing a new one. As well, good engineering practice may conclude that certain functions or devices should be supervised.

Functions or Devices to Be Supervised

Supervision may include the following devices or functions:

1. *The position of sprinkler water shutoff valves.* Normally, only those valves that are 2½ in. (63.5 mm) or larger are supervised. This supervision is provided by mounting a supervisory initiating device on the valve that will initiate an off-normal signal whenever the valve is operated into a closed position and that will initiate a restoration-to-normal signal whenever the valve is returned to a fully open position.

When mounting an initiating device where it will come in contact with the threaded shaft of the valve, care must be taken that the device is adjusted so that it will not falsely initiate a restoration signal if the shaft stops turning with the sensing portion of the device between two of the threads. This is a particularly troubling problem with larger sizes of control valves (Figures 14.4.4 and 14.4.5).

FIGURE 14.4.4 Valve Supervisory Switch for an Outside Screw and Yoke (OS&Y) Valve

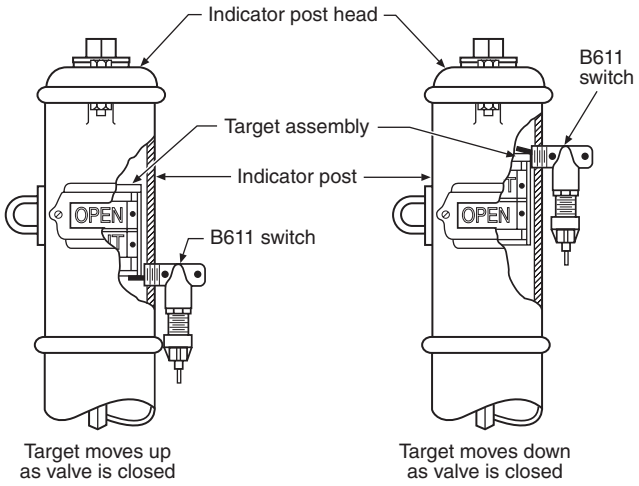

FIGURE 14.4.5 Valve Supervisory Switch for a Postindicator Valve (PIV)

FIGURE 14.4.6 Low-Temperature Switches for a Water Storage Tank

Some systems employ a metal or other loop attached to the water shutoff valve. One end of the loop plugs into an electrical switch mechanism such that a turn of the valve requires removal of the loop from the switch mechanism. These are not generally allowed in new systems because they can be plugged into the switch once the valve is closed, thereby allowing the fire alarm system supervisory circuit to return to normal unless latching circuitry is used in the monitor circuit.

2. *The air pressure in a dry pipe sprinkler system or water pressure tank and the supervisory air pressure in a preaction sprinkler system.* Connecting an air pressure supervisory initiating device to the system being supervised allows it to be monitored. Such a device is designed to initiate a supervisory off-normal signal whenever the air pressure climbs above or drops below a designated set point. Conversely, the device will initiate a restoration-to-normal signal whenever the air pressure is restored to the valve at which the device is set.

During installation, it is important that provision be made to allow testing of the device by simulating its operation during abnormal conditions. One method of accomplishing this is to connect the device to the sprinkler system through a stop-and-waste valve. When operated, such a valve automatically "wastes" the pressure trapped between the valve and the device to the atmosphere. Thus, whenever the valve is closed, a signal is initiated. This eliminates the possibility of tampering with the device without producing a signal.

3. *Low temperature in a building equipped with a wet pipe automatic sprinkler system, in a closet protecting a dry pipe valve, preaction valve, or deluge valve from freezing, or of the water inside a storage tank.* Mounting a temperature supervisory initiating device at the location to be supervised allows it to be monitored. Such a device is designed to initiate a supervisory off-normal signal whenever the temperature drops below a designated set point. Conversely, the device will initiate a restoration-to-normal signal whenever the temperature is restored to the value at which the device is set (Figure 14.4.6).

4. *The level of the water in a storage tank.* Mounting a water-level supervisory initiating device in a storage tank allows the water level to be supervised. Such a device is designed to initiate a supervisory off-normal signal whenever the water level rises above or drops below a designated set point. Conversely, the device will initiate a restoration-to-normal signal whenever the water level is restored to the value at which the device is set. During installation, it is important that provision be made to allow testing of the device by simulating its operation during abnormal conditions (Figure 14.4.7).

5. *The operation and integrity of a fire pump.* Connecting supervisory initiating device circuits to the "remote signal" contacts inside the fire pump controller allows it to be monitored. When an electric motor–driven fire pump operates into a running condition or when the power to the motor is interrupted, distinct supervisory signals are initiated. Similarly, when an engine-driven fire pump operates into a running condition—that is, its main switch is placed in a position other than "automatic start"—the battery charger fails, the engine experiences an abnormal condition or fails to start, or the controller fails, distinct supervisory signals are initiated. Conversely, a restoration-to-

FIGURE 14.4.7 Low-Water-Level Switch for a Water Storage Tank

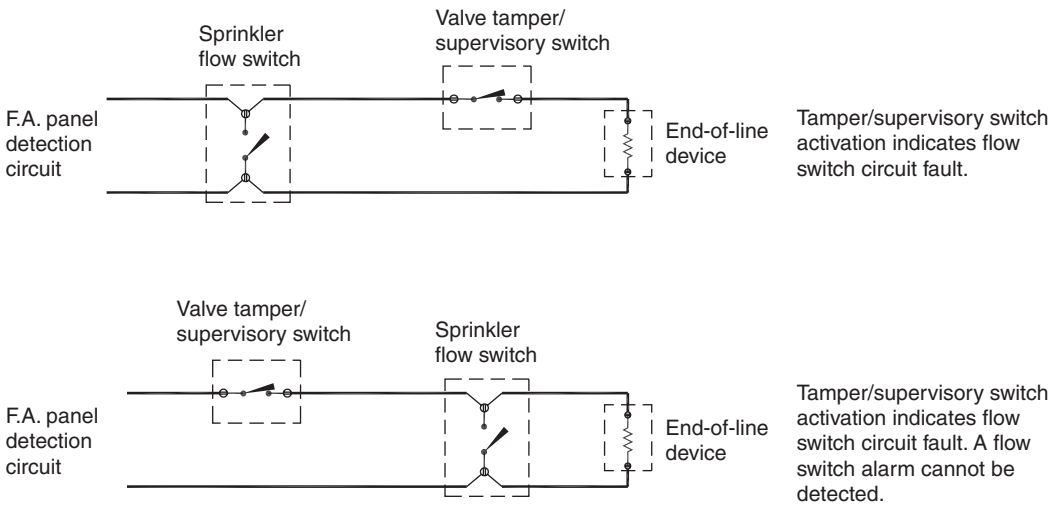

FIGURE 14.4.8 Incorrect Wiring of a Flow Tamper Switch

normal signal will be initiated whenever the particular feature of the fire pump that is off-normal is restored to normal.

6. *Tampering with a waterflow switch cover.* The switch cover may be monitored for removal (tampering that could affect the switch's ability to activate an alarm) by a supervisory switch connected to activate when the cover is removed.

NFPA 72 requires that three signals be identified at the fire alarm control unit: (1) alarm, (2) supervisory, and (3) trouble. In order to comply with that requirement, supervisory initiating devices must not be on the same initiating device circuit as alarm initiating devices. A common wiring configuration has been to install the waterflow alarm initiating device on the same circuit with the supervisory initiating device, for example, an OS&Y supervisory switch (as shown in Figure 14.4.4).

Although electrically this configuration may work, the wiring configuration with both devices on the same circuit will not provide the differentiation between a broken connection (trouble condition) and a closed valve (supervisory condition). If the wiring configuration and panel operation (such as with addressable devices) can provide the signal differentiation required by *NFPA 72,* then the devices can be wired on the same electrical circuit. Refer to Figures 14.4.8 and 14.4.9 for descriptions of incorrect and correct means of connecting these devices to a fire alarm system.

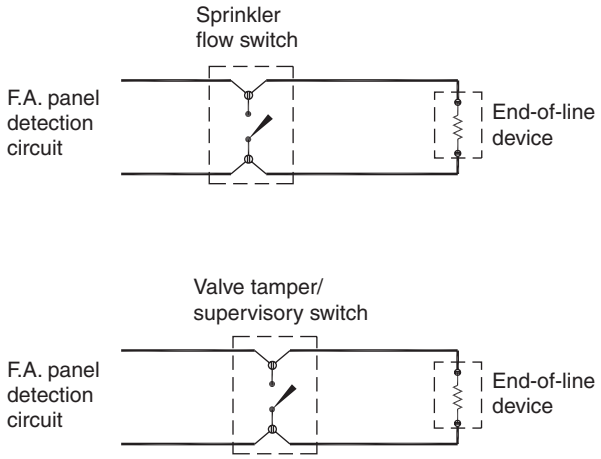

FIGURE 14.4.9 Correct Wiring of a Flow and Tamper Switch

OTHER AUTOMATIC FIRE SUPPRESSION SYSTEMS

There are many other types of fire suppression systems found at protected premises, such as a kitchen hood/duct suppression system or a carbon dioxide or other gaseous suppression system. Each of these fire suppression systems must be connected to the protected premises fire alarm system to initiate an alarm. Each of these systems must also be supervised for proper operation. In most cases, there is an NFPA or other relevant standard describing the respective fire suppression system, and that standard provides information as to interfacing requirements with the fire alarm system. The supervisory devices must be listed for the intended application and installed in accordance with *NFPA 72*.

Automatic fire pumps and special service pumps must be supervised in accordance with the requirements of NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection,* and the authority having jurisdiction (AHJ). Examples of other standards include NFPA 14, *Standard for the Installation of Standpipe and Hose Systems,* NFPA 22, *Standard for Water Tanks for Private Fire Protection,* and NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances.*

FIRE SAFETY FUNCTION INTERFACES

NFPA 72 also provides guidance for installation requirements of fire safety control functions that will be interfaced with fire

alarm systems. These fire safety control functions can include elevator control, door control, building automation system control, and process monitoring and control systems.

General

Fire safety control functions are those functions that contribute in some way to life safety in a building. In many cases these functions are required to be implemented by law. As such and in recognition that they contribute to life safety, it is reasonable to connect these functions to their respective devices with circuits that are monitored for integrity per *NFPA 72* to ensure that someone is notified if they are disabled. Supervised circuits may be provided in a number of ways as illustrated below (Figures 14.4.10 and 14.4.11).

Elevator Control

Fire alarm systems are interfaced to elevator control systems to initiate an elevator recall sequence or to initiate a power shutdown. The interface is generally accomplished by connection from the fire alarm system to a relay that is in turn connected to the elevator controller.

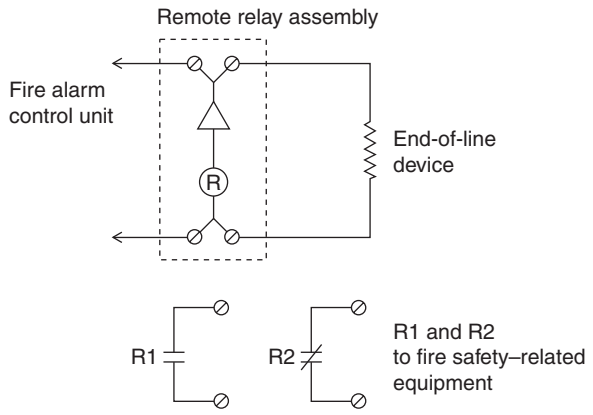

FIGURE 14.4.10 Polarity Reversing Circuit. Note: The remote relay assembly will be mounted within 3 ft (0.9 m) of the controlled fire safety–related equipment.

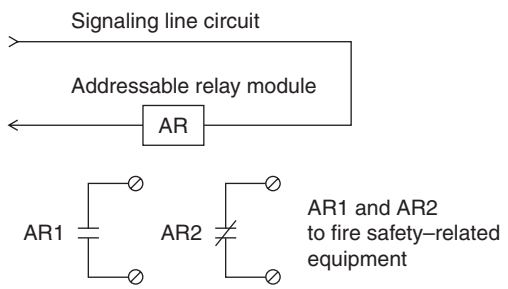

FIGURE 14.4.11 Addressable Circuit. Note: The addressable relay module will be mounted within 3 ft (0.9 m) of the controlled fire safety–related equipment.

Elevator Recall. Fire alarm systems are interfaced to elevator control systems to actuate the elevator recall sequence. The recall sequence and initiation requirements are found in Chapter 3 of *NFPA 72*. In most jurisdictions, only the elevator lobby and machine room smoke detectors are required to initiate recall of the elevators. The standard that originally provided the smoke detector placement requirements and requires the elevators to be recalled is ANSI/ASME A17.1, *Safety Code for Elevators and Escalators.* The ANSI/ASME A17.1 committee has now developed a liaison relationship with the *NFPA 72,* Chapter 3 committee, and all detection and interface requirements are contained in *NFPA 72,* Chapter 3. Additional requirements may be found in local building and fire codes or other elevator codes and standards.

Elevator Shutdown. When the elevator machine room or hoistway is protected with automatic sprinklers, ANSI/ASME A17.1 requires that the power to the elevators be shut down prior to or on discharge of water from the sprinklers. The power shutdown or shunt trip can be accomplished in either of two ways. When heat detectors are used, they must be installed within 2 ft (0.6 m) of each sprinkler, have both a lower temperature rating and a higher sensitivity than the sprinkler head, and be installed in accordance with *NFPA 72,* Chapter 6. When pressure or waterflow switches are used to shut down the elevator power, they must not have a time delay associated with their operation. In either case, it is assumed that elevator recall will have already taken place through the operation of the smoke detectors required for the elevator recall function.

Door Control

Doors may be connected to a fire alarm system for either of two reasons: to release a door normally held open such that it closes automatically or to unlock a door that is normally locked to allow unrestricted egress from a building. The interface is generally accomplished by connection from the fire alarm system to a relay that is in turn connected to either the hold open or locking device mechanism or to a security system that provides door control functions. In each case, the circuit should be arranged to provide a fail-safe operation. In other words, the circuit design must allow release of the door in case of circuit failure, security system failure, or power failure.

Door Release Service. When smoke and fire doors are held in the open position to allow free movement in corridors of buildings, it is required that the doors be released when a fire alarm system is activated. These hold-open devices are commonly magnetic units that are normally powered from a 24- or 120-V ac supply that is interconnected through a relay in a smoke detector or in the fire alarm control unit. *NFPA 72* does not require the door hold-open devices to be connected to the standby power because the units operate in a fail-safe fashion. When power is lost, the hold-open units deactivate and the doors close.

Alternatively, an unnecessary release of the doors (even during a nonemergency power failure) may not be desirable, and in this case the door hold-open devices should be powered from a separate "no-break," battery-supported power supply. The standby time should be equivalent to fire alarm system standby duration if practical.

If it is necessary to use the fire alarm system power supply (which is not encouraged and may not be allowed by the AHJ), then the fire alarm system power supply must not be disabled by any fault in the door hold-open device or related circuit, and the standby battery calculations for the fire alarm system must include the full load power required by the door hold-open devices during the required fire alarm supervisory and alarm periods (Figure 14.4.12).

Door Unlocking Devices. The life safety objectives of NFPA *101, Life Safety Code*®, and local building codes are achieved, in part, by establishing prescriptive requirements intended to ensure that building occupants can freely and promptly evacuate buildings during an emergency. The objective and scope of a security system may differ from the primary occupant life safety objective of the codes. Subjects of security protection may include persons, building assets, or contents. Threats may originate from within the building or from outside. It may therefore be desirable to control movement of persons into, through, and out of buildings. Conflict arises when security systems attempt to control occupant movement in buildings in contravention of the principle of the codes to permit freedom of movement for self-preservation during an emergency. The security system cannot override the code requirements established to provide life safety.

NFPA *101*®, *Life Safety Code*®, requires all stairway exit locked doors be unlocked when an alarm occurs in the building. This is based on the danger of fire deaths occurring in smoke-filled stairways where occupants are trapped after discovering that they have entered an unsafe area and cannot return to the corridor. The proper way to interconnect these unlocking devices (including electromagnetic locks and electric strikes) is so that when power is lost, they unlock. This is a fail-safe operation, and when the unlocking devices are wired in this fashion, the interconnecting wiring does not require monitoring for integrity. This is generally achieved by connecting locking devices through a normally closed contact that opens on fire detection. This contact may be part of a relay controlled by the fire alarm system or a contact within a manual pull box near the locking device.

Sometimes a locking device is connected to a security system that monitors, powers, locks, and unlocks the doors. Even in this case it is prudent to connect the fire-alarm-controlled, normally closed relay contact directly to the locking device by a method allowing fail-safe operation. The security system may fail to respond as required or the connection between the security system and fire alarm system may be lost. In all cases the locking device must release on loss of power to the device (Figure 14.4.13).

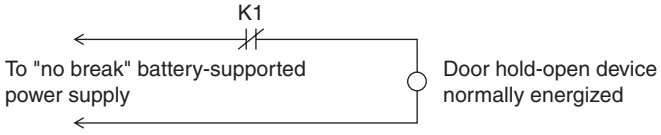

FIGURE 14.4.12 Door Release Control Circuit. Note: K1 is typically operated by fire alarm system activation. This may be supervised conventional relay or addressable relay module.

Building Automation Systems

It has become necessary in many cases to connect building control systems, such as heating and ventilation systems, to the fire alarm system. This has come from recognition that smoke spread can be controlled by use of the building environmental systems and by use of dedicated fans and dampers designed for the purpose. The control of smoke movement and the ability to exhaust smoke aid in providing the time necessary for occupants to leave a building.

Practically speaking, there are many pitfalls in implementing a smoke control strategy. The fire alarm system is generally implemented by a separate contractor with a different skill set than that needed for the mechanical systems employed in smoke control. Also, the systems are generally completed at different times and are commissioned by different people at different times. The fact that there are numerous ways to interface the fire alarm system with building automation and control systems equipment just confirms that this is one of the most difficult systems interface challenges.

The fire alarm system and heating, ventilation, and air-conditioning (HVAC) system may be interfaced by appropriate electrical contacts, digital data interfaces, and other methods listed for the purpose. Appropriate testing of the final interconnected equipment is critical to achieving the building design objectives.

Non-Computer-Controlled Building Systems. Many building HVAC systems are controlled during an emergency by direct connection from the building fire alarm system to the respective fan and/or damper that is to be controlled. Power is generally switched on or off via a relay contact in the fire alarm system or located near the controlled equipment or controlling motor control center (MCC). The wiring for these controls must be monitored for integrity in accordance with *NFPA 72*. In addition, it may be required or desirable to monitor the controlled device to confirm activation or initiate interlocks to prevent undesirable events. Please refer to NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations,* for examples. See Figures 14.4.14 and 14.4.15 for examples of appropriate connections.

Computer-Controlled Building Systems. The computerization of building control systems has led to the integration of these systems with the fire alarm system control unit. Because the fire

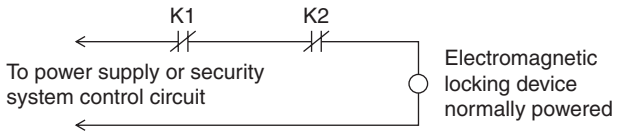

FIGURE 14.4.13 Electromagnetic Lock Control Circuit. Note: K1 is typically operated by fire alarm system activation. This may be by supervised by conventional relay or addressable relay module. K2 is contact operated when manual station at the controlled door is activated.

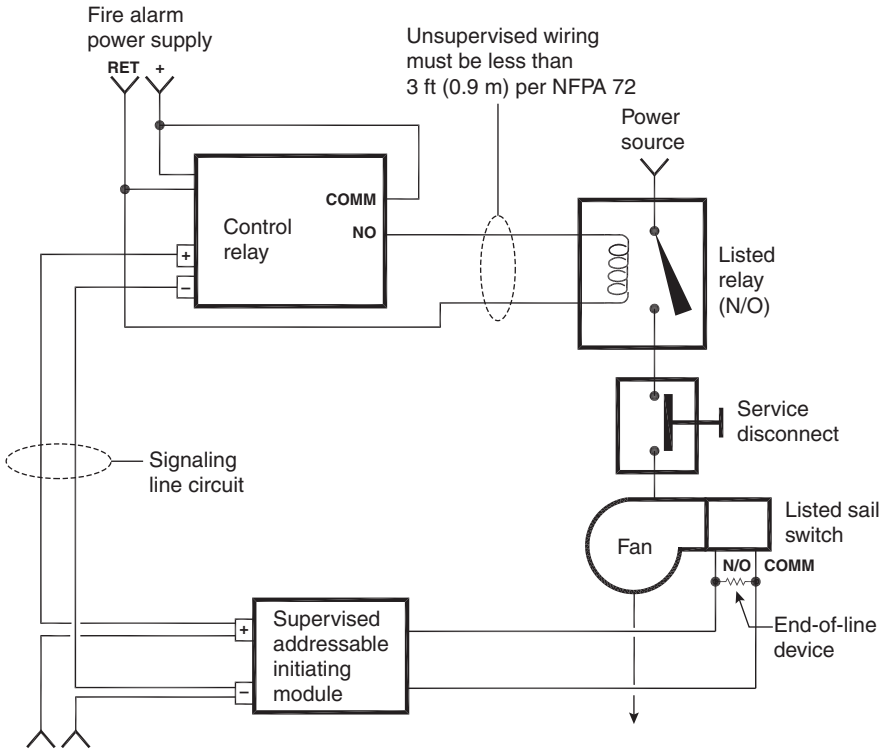

FIGURE 14.4.14 Direct Fan Control with Feedback (Courtesy of SimplexGrinnell, Westminster, MA)

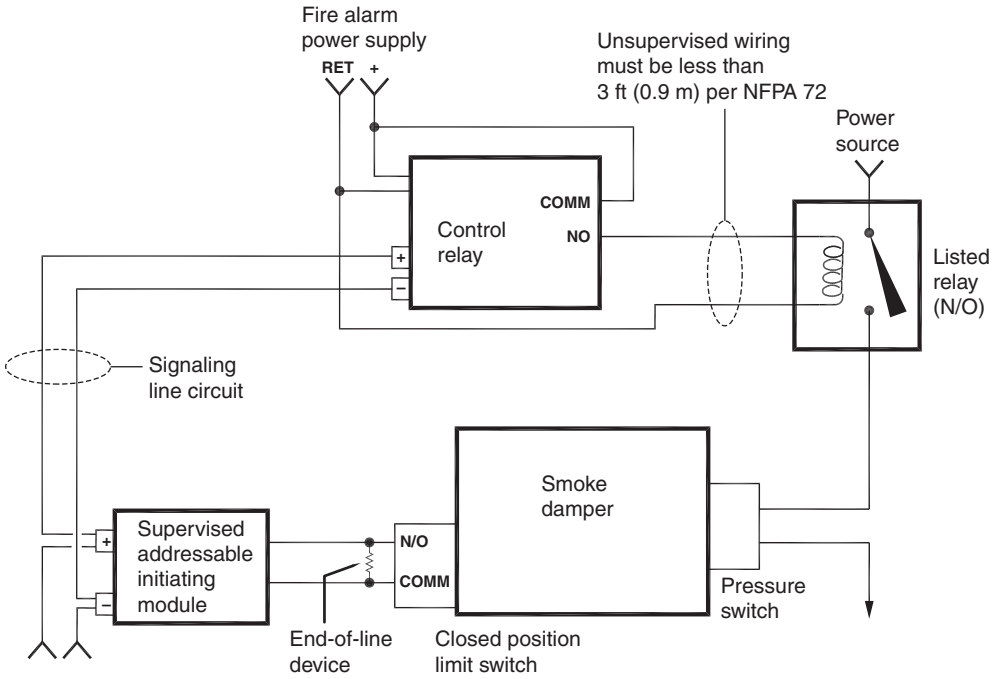

FIGURE 14.4.15 Direct Damper Control with Feedback (Courtesy of SimplexGrinnell, Westminster, MA)

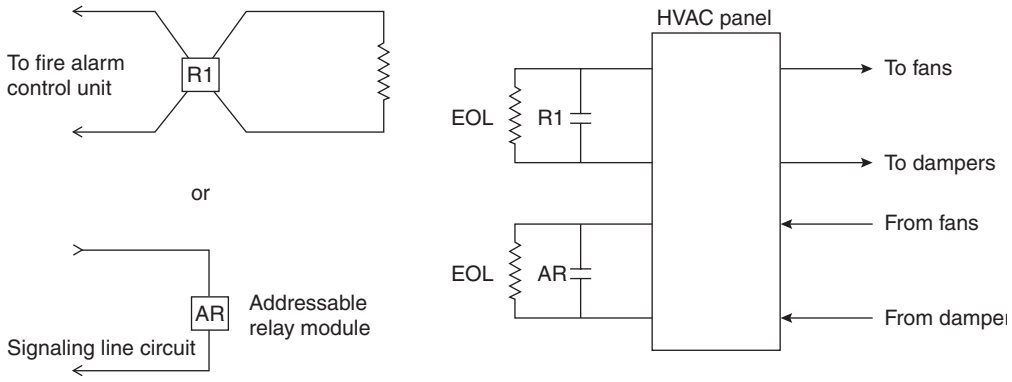

FIGURE 14.4.16 Computer-Controlled Building Systems Relay Interface

safety control function devices must be listed for compatibility with the fire alarm system control unit, so as not to interfere with the fire alarm system's operation, the system designer and the installer must be careful not to interconnect computerized devices together that have not been listed for compatibility. One of the areas that presents this problem is the interconnection of the fire alarm system to the HVAC system direct digital control (DDC) devices used to control fire/smoke dampers. In many cases, the fire alarm system is connected directly to the fire/smoke damper and not to the HVAC system DDC device. This is done instead of connecting the fire alarm system directly to the damper control. This is due to the compatibility requirement and also due to technician/programmers who lack expertise in fire alarm systems working on the interface, the DDC type of interconnections should be approached very carefully.

A computer-controlled HVAC or other building system may be interconnected to the fire alarm system via electrical contacts. These are actuated by the fire alarm system to advise the HVAC system of the fire location such that appropriate HVAC equipment functions can take place. In this case, the relay contact may either activate the fans and dampers directly as described earlier, or the contact may activate an HVAC system–monitored input circuit at an HVAC system control unit.

A computer-controlled HVAC or other building system may be interconnected to the fire alarm system via a digital data interface or via a network connection. Where a fire alarm system is connected to other equipment via a network to share data, this communication must be implemented by means listed for the purpose by a recognized laboratory. The network interconnection must be monitored for integrity and may not interfere in any way with the required operation of the fire alarm system. Data received by the fire alarm system from other equipment may not alter or affect the fire alarm system operation in any way other than to display information for operator use (Figures 14.4.16 and 14.4.17).

INTERCONNECTED FIRE ALARM CONTROL UNITS

There are numerous occasions where it is necessary or required by design to interconnect fire alarm control units. This function may occur during an addition to a building, such as a new wing to a hospital, or during a renovation to an existing building. In the past, there was no guidance as to the proper way to interconnect different manufacturers' control equipment. This created the potential for makeshift interconnections that were improper, unreliable, and unmonitored. *NFPA 72* requires that the interconnected fire alarm control units be connected by listed methods and the interconnection must be monitored for integrity. In addition to monitoring the interconnected system for alarm conditions, the interconnected control must be monitored for conditions that are essential for the proper operation of the interconnected system.

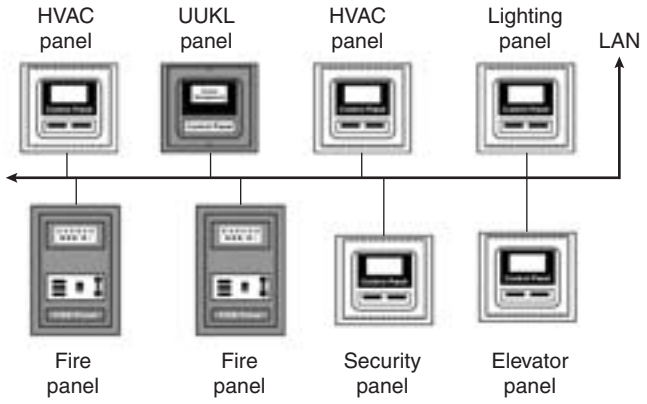

FIGURE 14.4.17 Computer-Controlled Building Systems Interface via LAN (Courtesy of SimplexGrinnell, Westminster, MA)

When an owner or designer suggests that two different manufacturers' control units be interconnected, the AHJ would be wise to ask each manufacturer for a letter indicating the approved interconnection method or drawing showing the approved interconnection method. If the interconnection is being made using relay configurations, the relays used must be listed and compatible with the control units being interconnected.

The objective of the interconnection and its consequences must be carefully considered. Many times it is desirable for one

system to actuate the other. One example is where the systems provide protection and audible signaling for adjacent spaces. When the first system actuates it may cause an alarm condition in the second system. The second system may then actuate the first system in return. Special measures must be taken to allow a reset condition since both control panels must be reset simultaneously or they will continue to actuate each other.

Another example of room for error is the possibility of shared control of fire safety systems by two interconnected fire alarm systems. It may be that the first fire alarm system or one of its components is in close proximity to an exhaust fan for a smoke shaft whereas the second fire alarm system is in close proximity to dampers in the exhaust shaft. If the fan and dampers are connected to different fire alarm systems and the interface between them is compromised, then it is possible for the exhaust fan to start based on an alarm initiation on the first system. Since the second system may not be aware of the alarm, there may not be an open damper in the shaft, which could lead to collapse of the shaft.

Fire alarm system interconnections must be carefully considered and designed to ensure only desirable operations. Where the connection between two fire alarm systems is deemed necessary, the design of the resulting system should emulate the operation and control of a single system. Consideration must also be given to the final commissioning and annual testing protocols that will be used. System failure can almost be guaranteed if, over time, different service companies work on the interconnected systems.

INTERFACED EQUIPMENT

Nonfire Alarm Interfaced Equipment

There are times when an owner may wish to interconnect a process monitoring system or some other type of nonfire alarm system to the fire alarm system. Caution should be exercised, and the AHJ should be consulted. If the system being interfaced is monitoring conditions affecting the life safety of occupants or protection of the property, then it may be required to have that system initiate an alarm condition on the fire alarm system. Otherwise, these nonfire signals must be considered supervisory in nature.

Interface Areas of Concern

The most important areas of concern when interfacing the fire alarm control unit with a fire safety function control device are that (1) the relay used to initiate control must be located within 3 ft (0.9 m) of the controlled circuit or device; (2) the relay, digital data interface, or other interface method must be listed for the intended purpose; (3) the relay, digital data interface, or other interface method must be compatible with the fire alarm control unit; (4) the wiring between the fire alarm control unit and the relay, digital data interface, or other interface method must be monitored for integrity, unless the control device is connected in a fail-safe manner; and (5) the relays, digital data interfaces, or other listed means of providing fire safety functions must not interfere with other operations of the fire alarm system.

TESTING INTERFACED SYSTEMS

Whether the interfaced system is a security system or a special hazard suppression system, care must be taken when performing acceptance and periodic testing of the fire alarm system. The technicians performing the tests must be totally familiar with all of the systems interfaced to the fire alarm system or must have other technicians present for the test who are familiar with the interfaced systems.

Interfaced systems equipment connections must be tested by operating or simulating the operation of the equipment being supervised. Signals required to be transmitted must be verified at the control panel. The test frequency for the interfaced equipment is governed by the applicable NFPA standard(s) for the equipment being supervised by the fire alarm system.

The system's test protocol, required sequence of operation, and test results must be documented to assure appropriate ongoing testing and system reliability. The testing protocol must recognize that the interconnected systems are designed and installed by different disciplines. Action must be taken to ensure that results are consistent with performance requirements and that connections present during testing remain in place following final commissioning or annual testing.

SUMMARY

The purpose of this section is to make the reader aware of the need to address interface requirements early in the design stage to ensure the reliable operation of both the fire alarm system and the systems being interfaced to the fire alarm system. Ensuring compatibility and correct operation during the acceptance tests is required to achieve reliable operation.

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NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 70, *National Electrical Code®*
NFPA 72®, *National Fire Alarm Code®*
NFPA *101®*, *Life Safety Code®*

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Chapter 5

Inspection, Testing, and Maintenance of Fire Alarm Systems

John M. Cholin

Chapter Contents

Reliability
Electronic Components
Inspection, Testing, and Maintenance Requirements for Signaling Systems and Components
Inspection, Testing, and Maintenance Scheduling for Systems and Components
Household Fire-Warning Equipment
Criticality of Inspection, Testing, and Maintenance on the Effectiveness of the System

Key Terms

acceptance test, design lifetime, failure, fire alarm control unit, fire alarm system, household fire-warning equipment, inspection, maintenance, notification appliance, protected premises, reacceptance test, reliability, reliability prediction, semiconductor, sensitivity measurement, supervising station

With each passing year, improvement in the understanding of fire and its behavior enables designers to better design fire alarm systems to achieve specific objectives and levels of performance rather than compliance with a minimum prescriptive standard. Yet, when designers employ performance-based design, the whole fire protection strategy becomes far more dependent on the fire detection portion of the protection system. This increased reliance on the fire detection and alarm system places a greater importance on maintaining the predictability of the fire detection system response, necessitating an effective inspection testing and maintenance program. Furthermore, no performance-based or objective-oriented design is complete without an explicit quantitative assessment of the level of confidence one can have that the fire alarm system will perform as intended. All computational methods that have been developed to assess this parameter are predicated upon an inspection, testing, and maintenance program at specified regular and predictable times throughout the life of the system. Consequently, without a thorough understanding of the impact the inspection, testing, and maintenance program has on the mission effectiveness of the fire alarm system, one cannot use a performance-based, objective-oriented design approach.

This chapter first develops the concepts of reliability analysis and prediction that form the foundation on which all inspection, testing, and maintenance programs should be based. It then reviews the types of electronic components from which fire alarm systems are constructed. These two background areas form the basis for inspection, testing, and maintenance requirements for fire alarm systems, components, and scheduling. Further, design concepts are applied to the household fire alarm system. Finally, this chapter addresses criticality of inspection, testing, and maintenance on the mission-effectiveness of the system.

This chapter is specifically limited to inspection, testing, and maintenance of fire alarm systems. These are the electronic and electrical systems that are designed (1) to sense a fire, transmit that information to a control unit of some type, and activate personnel warnings, whether for persons occupying the site or at a remote location; and (2) for remedial response, such as the discharge of extinguishing systems and activation of devices designed to enhance the compartmentation of the fire.

This chapter does not cover maintenance of specific remedial response systems. Inspection, testing, and maintenance of these systems are addressed in NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam;* NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems;* NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems;* NFPA 13, *Standard for the Installation of Sprinkler Systems;* NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection;* NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems;* NFPA 17, *Standard for Dry Chemical Extinguishing Systems;* NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection;* NFPA 25, *Standard for the Inspection, Testing, and*

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Maintenance of Water-Based Fire Protection Systems; and NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems.*

For related topics, see the following chapters in Section 14: Chapter 1, "Fire Alarm Systems"; Chapter 2, "Automatic Fire Detectors"; Chapter 3, "Notification Appliances"; Chapter 4, "Fire Alarm Interconnections"; and Chapter 6, "Household Fire Warning Equipment."

RELIABILITY

Murphy's law is familiar. Anything that can go wrong will go wrong. From this truism we can then conclude that any "system" will suffer a failure of one of its constituent components at some moment during its design lifetime. A fire alarm system is a "system" as used in this context. It is also a system on which people rely for life safety, property preservation, and mission continuity. Yet we are assured by Murphy's law that every fire alarm system will experience a failure of some component over the lifetime of the system. This establishes a compelling justification for a regimen of inspection, testing, and maintenance to be employed with every fire alarm system.

Reliability Defined

The reliability of a system includes both the ability to (1) detect and correctly respond to every occurrence of fire and (2) not render a fire alarm indication except when the legitimate fire alarm stimulus actually occurs. For a system to be deemed reliable, alarm signals will occur if, and only if, there is a fire. For the purposes of this chapter, reliability is defined as the measure of the certainty that the system will provide the appropriate response to the conditions that occur, as they occur, during the defined lifetime of the system.

Fire Alarm System Objectives

The driving force behind every inspection, testing, and maintenance program is the need to make system reliability as high as possible. Reliability is essential for fire alarm systems, simply due to mission objectives for these systems. Fire alarm systems are intended to fulfill three essential objectives: (1) ensure life safety, (2) conserve property, and (3) ensure continuity of the mission of the site. The life safety objective is achieved through timely warning of occupants. This is usually the highest priority. Mitigation of property damage is achieved through the timely actuation of automatic fire-extinguishing systems and transmission of fire alarm signals to the fire service. This is generally the second priority. After the first two objectives are met, the third objective, that is, continuity of the mission of the site, becomes attainable. In many cases, the mission objective places greater demands on the fire alarm system. The objectives cannot be attained if the system is unstable, nor can they be attained if the system allows too large a fire to develop prior to the actuation of fire-extinguishing systems. The three objectives can only be achieved when the fire alarm system operates reliably.

System Elements

Experience has shown that reliability of a system is the result of contributions from four system elements: (1) design, (2) installation, (3) equipment, and (4) maintenance. Each of these elements contributes to the overall reliability of the system. Often some "problems" are designed into the system. For example, a smoke detector located above a normally occurring source of aerosols that are not indicative of a fire is a problem that is designed into the system. This represents a reduction of the system reliability that was present during the design process. Other examples of design problems are rate-of-rise heat detectors in an area where rapid and wide fluctuations in temperature are expected, control panels mounted on surfaces that are vibrating, or smoke and heat detectors improperly mounted relative to the ceiling plane. Initial inspection and testing of the system should identify any problems that are designed into the system, so they can be corrected before the system is accepted.

Other problems are introduced during installation. These also deduct from the attainable system reliability. For example, installation problems include substandard wiring, general-purpose conduit and boxes where weathertight materials are needed, insufficient torque on screw terminals, abraded wire insulation, and so on. The initial inspection and test of the system should uncover these types of problems. If they are not corrected prior to acceptance, they will create problems over the operational lifetime of the installation. Furthermore, design and installation problems may not always be apparent during initial inspection. These errors are most likely discovered as a result of a system failure or in the context of the regularly scheduled maintenance program. These examples illustrate the necessity of an initial inspection and test program to uncover problems that are literally designed or installed into the system.

Another source of failures is the equipment itself. Most of today's electronic fire alarm system devices are extremely reliable. They are mature technologies, produced under stringent quality assurance programs that are audited by nationally recognized testing laboratories, such as Underwriters Laboratories Inc. (UL) and FM Global. However, all electronic components manifest a statistical failure rate that results in failures of these devices over time. These failures occur after the system has been accepted and consequently can only be uncovered through a program of regular maintenance and testing.

A program of inspection, testing, and maintenance of fire alarm systems is critical to achieving the design objectives of the system. This is the final element affecting the reliability of every system. It is through the inspection, testing, and maintenance program that errors in product manufacture, system design, and system installation are discovered and corrected. A fire alarm system without an inspection, testing, and maintenance program is every bit as incomplete as a car with only three wheels.

Although inspection, testing, and maintenance schedules have traditionally been developed based on the qualitative judgment of technical committee members, the emergence of performance-based and objective-oriented designs demands a more rigorous method of assessing the reliability of a system. Performance-based design requires that the inspection, testing, and maintenance schedules provide the reliability necessary to

achieve the performance objectives of the design. If reliable performance is to be achieved from a fire alarm system, a rigorous inspection, testing, and maintenance program on a schedule that is derived from the computed reliability of the system and its components is crucial.

Reliability Prediction Techniques for Fire Alarm Systems

The reliability of a fire alarm system, like any electronic system, can be computed using a method developed during World War II by a German rocket scientist named Lusser, who discovered that the reliability of a system was the product of the reliabilities of the individual components. According to the Lusser product law, as the number of components increases, the reliability of each individual component has to be improved commensurately to maintain the reliability of the overall system. The Lusser product law is expressed mathematically by

$$P_T = P_1 \times P_2 \times P_3 \times \cdots \times P_n$$

where

P_T = Probability of successful operation for the system, or reliability

P_n = Probability of successful operation of the nth component

n = The number of constituent components

This equation applies to systems in which the failure of any one component will mean the failure of the system. The probability of successful operation of a system is not directly computable. It is computed from failure rate data for each of the constituent components of that system. Failure rate, that is, the probability of failure, is related to the probability of successful operation by

$$\Lambda_T = 1 - P_T$$

where

Λ_T = Failure rate of the total system

P_T = Probability of successful operation for the system, or reliability

The failure rate, Λ, of a system assembled from components having exponential failure rates, is computed from the sum of the failure rates of each of the components, Λ_n, from

$$\Lambda = q_1\lambda_1 + q_2\lambda_2 + q_3\lambda_3 + \cdots + q_n\lambda_n$$

where

Λ = Failure rate of the total system

q_n = Quantity of the nth component in the system

λ_n = Failure rate of the nth component in the system

The component failure rates are usually expressed as failures per million device operating hours (f/mdoh), and the system failure rate is expressed as failures per million operating hours (f/moh). The previous equation enables one to calculate the reliability of a system based on the failure rates of the constituent components. Each fire alarm system component, that is, a control panel, detector, or notification appliance, has a calculable failure rate and, hence, the system failure rate can be computed. The failure rate of each of these major components is computed from the failure rates of the individual electronic components from which it is made.

Bathtub Curve. Research into the reliability of systems and components has shown that, for most physical systems, when the failure rate is plotted versus time, a curve of familiar shape results from the empirical data.[1,2] This curve is termed the *bathtub curve.* The bathtub curve can be modeled as the sum of two bell-shaped, Gaussian curves, one centered at the time the product is made and called the *turn-on curve,* and the other centered at the design lifetime and termed the *lifetime curve.*[3]

The first, the turn-on curve, shown in Figure 14.5.1(a), describes the rate at which failures can be expected to occur from the date of manufacture, forward over time, due to inherent defects in both constituent components and manufacturing technique. It illustrates the phenomenon known as "infant mortality" in the components and finished product. The second curve, shown in Figure 14.5.1(b), is also a Gaussian distribution, but it is centered at the design lifetime. It describes the distribution of failure rates due to long-term aging.

When the failure rates from the initial turn-on and the lifetime curves are added together (having adjusted the standard

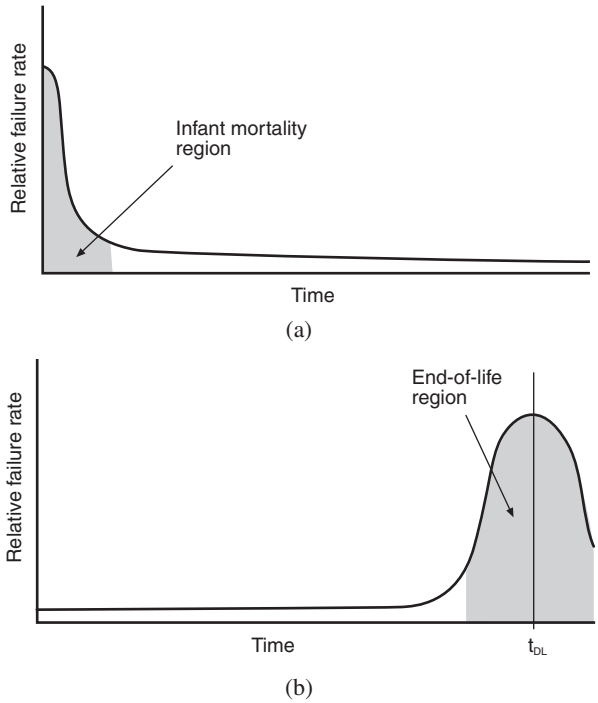

FIGURE 14.5.1 (a) Initial Turn-On Curve Showing Failure Rate of a Component or System at Turn-On; (b) Lifetime Curve Plotting the Failure Rate due to Long-Term Aging of Components and Establishing the Design Lifetime, t_{DL}

deviations for each of the distributions to match the experimentally measured failure rates for each failure mechanism), their sum yields a bathtub curve as shown in Figure 14.5.2.

The bathtub curve is divided into three regions. The leftmost is the "infant mortality" region. This is the initial turn-on phase where failures due to inherent defects in constituent components and manufacturing techniques usually appear. In order to ensure that these failures occur before the product is shipped to a customer, most manufacturers "burn-in" their products for time periods sufficient to allow inherently defective products to fail prior to shipment.

The right-hand portion of the bathtub curve is the "end of useful life" portion. This portion of the curve is used to establish the *design lifetime* of the assembly. The design lifetime of a product is that age at which the probability of operability at the end of the recommended service interval is less than 0.5, due to the acceleration in the frequency of failures resulting from long-term deterioration of constituent components. As the failure rate of the constituent components continues to escalate, it becomes increasingly difficult to maintain the operability of the assembly.

The region of the bathtub curve between the infant mortality region and the design lifetime region is the statistical region, where failures are entirely random. The statistical failure rate region of the curve is very long compared to the infant mortality region and end-of-life region. Over the statistical failure rate region, failures are randomly unpredictable. This region is essentially flat, indicating a fairly uniform failure rate per unit time over this region. Although the actual failure rate may be low, it is always a finite, positive number. Regardless of the time (distance along the x axis) between and the failure rate in the statistical failure region will, to the limits of precision available from the actual data, approach a horizontal line indicating a constant, evenly distributed failure rate. Because this region is flat, one can use the concept of the mean time between failures (MTBF), a quantification of failure rate, to predict the length of time the system can be expected to remain operational. It is a statistical average that is valid over a population of systems, but does not provide any guidance on what will happen with any specific system at any specific time.

Failure Rates. Since the failure rate is essentially constant over the statistical failure rate region of the bathtub curve, the failure rate of any electronic component and, hence, any electronic system assembled from electronic components can be derived from the failure rate data established in *Military Handbook: Reliability Prediction of Electronic Equipment.*[2] This handbook, known as *MIL Handbook 217,* provides experimentally derived failure rate data on electronic components commonly found in electronic assemblies, including fire alarm system components. *MIL Handbook 217* allows the engineer to compute the failure rates of the detectors, notification appliances, control panels, relay panels, interfaces, and other system components. From these failure rates the engineer can then compute the inherent failure rate (IFR) for the system. It is derived from the failure rates of the components from which the system has been assembled. It is important to keep in mind that this inherent failure rate does not include failures due to improper design or installation. Failures caused by design errors or installation errors must be added to the inherent failure rate computed from *MIL Handbook 217* before one can calculate the failure rate of a device or system.

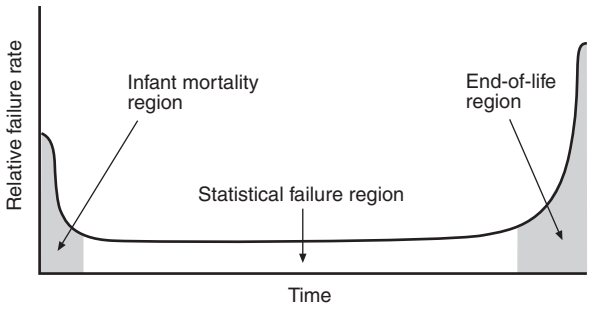

FIGURE 14.5.2 Bathtub Curve, the Sum of the Turn-On and Lifetime Curves

Once the inherent failure rate has been computed, the reliability of the system can be calculated:

$$R = e^{-\Lambda t}$$

where

R = Reliability of the system

e = Napierian logarithm base, 2.71828

Λ = Inherent failure rate of the system

t = Time period for which reliability has been computed[4,5]

This relation allows one to determine the maintenance interval based on the inherent failure rate of the system and the reliability level sought. The factor t is the interval of time between each execution of the inspection, testing, and maintenance procedures for the system. Assuming maintenance restores the entire system to complete operability, the required maintenance interval is computed from

$$t_R = \ln R_R/(-\Lambda)$$

where

$\ln R_R$ = Napierian log of the required reliability, R_R

Λ = Inherent failure rate of the system

t_R = Required maintenance interval to achieve the required reliability

The mathematical relations shown give the engineer the ability to calculate a recommended maintenance interval on a totally new product. It allows the engineer to calculate a maintenance interval that is specifically intended to produce a system with a predetermined reliability. Indeed, most high-technology systems and products have maintenance regimens developed from these relations rather than the consensus committee method used for fire alarms.

An Example Analysis

To illustrate the usefulness of the above computational method, consider the fire alarm system shown in Figure 14.5.3. It consists of 10 smoke detectors, a horn/strobe notification appliance,

and a control panel. Its design objective is to alert the occupants of a fire, enabling them to make safe egress from the facility, with a reliability of 90 percent (0.9). For the purposes of this example only, and with the understanding that these failure rates are not derived from any specific device but are intended to be of the same order of magnitude as commercially available products, use the failure rates in Table 14.5.1.

The inherent failure rate of the system as described is 43.65 f/moh:

$$43.65 \text{ f/moh} = 0.00004365 \text{ failures per hour (f/h)}$$

$$\Lambda = 0.3824 \text{ failures per year}$$

Using the required interval equation

$$t_R = \ln R_R/(-\Lambda)$$

where

$$\ln R_R = \ln 0.90 = -0.11$$

$$\Lambda = 0.3824$$

$$t_R = -0.11/-0.3824$$

$$t_R = 0.288 \text{ yr}$$

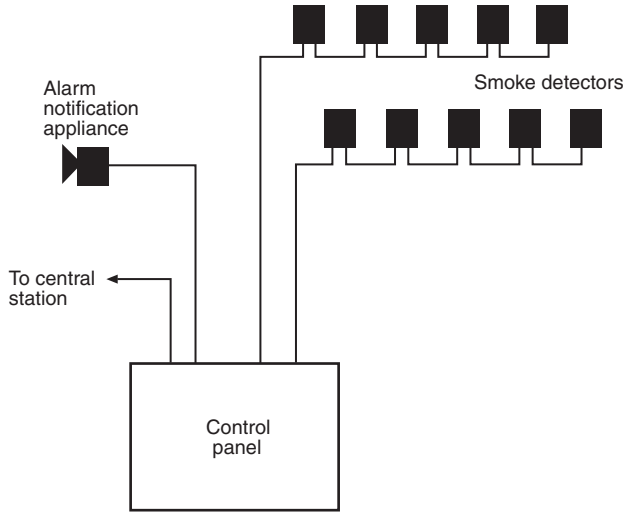

FIGURE 14.5.3 Simplified Example Fire Alarm System

TABLE 14.5.1 Compilation of Computed Failure Rates Providing the Basis for the Reliability Calculation

System Component	*Quantity (q)*	*Failure Rate (λ) (f/mdoh)*	*($q_x\lambda_x$) (f/moh)*
Smoke detectors	10	1.00	10.00
Horn/strobe	1	2.50	2.50
Control panel	1	25.00	25.00
Screw terminals	49	0.10	4.90
Wire segments	25	0.05	1.25
Inherent failure rate, Λ			43.65

This indicates that this system, with the component failure rates used, will require a complete inspection, test, and maintenance routine every 0.288 years in order to maintain at least a 90 percent reliability in achieving its design objectives. As performance-based, objective-oriented designs become more prevalent, reliability predictions for those systems similar to this example will be required to determine the maintenance frequency necessary to achieve the performance criteria. A reliability of 0.9 is a very high reliability, well above that of most systems. It means that there is only a 10 percent chance that there will be any form of failure during the time periods between inspection, testing, and maintenance routines.

The concept of failure is very broad here. Failures include trouble conditions resulting from supervised conditions; spurious alarms; failure to alarm within the design sensitivity or time frame for the design fire; and failures of electronic components, even if the component failure does not cause a system performance malfunction. A reliability of 0.9 (90 percent) is much higher than most owners need. This same system (see Figure 14.5.3 and Table 14.5.1) could achieve a 50 percent reliability with a maintenance schedule of 1.8 years. A maintenance program predicated on an inspection and testing regimen performed every 1.8 years will surely be less expensive than one based on a time interval of every 0.288 years. So how would one determine what target reliability one should use? Clearly, a balance must be achieved between the cost of the service/maintenance program and the inherent reliability of the system. Ideally, the reliability to be achieved should reflect analysis of the cost of failure, which will in turn need to distinguish among different types of failures, as listed above.

The inspection, testing, and maintenance schedules required by *NFPA 72®*, *National Fire Alarm Code®*, are prescriptive in nature and are based on a consensus opinion of what an average system requires. They are not the result of actual reliability calculations. The facility owner/operator must keep in mind that the prescriptive requirements represent the minimum acceptance criteria. There are often circumstances that demand that these minimum criteria be exceeded. It is obvious from the preceding that the larger or more complex the system is, the more frequently it must be inspected and tested if the design performance is to be achieved.

The implications of reliability cannot be overstated. The failure to maintain a system virtually assures the owner/operator of the protected site that the fire alarm system will *not* achieve the design objective.

ELECTRONIC COMPONENTS

The anticipated reliability of an electronic system such as a fire alarm system can be computed because the reliability of the individual electronic components has been thoroughly studied and documented, primarily under the auspices of the U.S. Department of Defense. This prior research has shown that each general type of electronic component exhibits particular and predictable failure modes. Understanding these failure modes leads to understanding the impact such a failure may have on a

fire alarm system component (detector, notification appliance, control unit, or other such system component). It is important for the owner/operator or responsible party to be aware of these failure modes, as the test methods prescribed by *NFPA 72* are intended to uncover those system components that have suffered a component failure.

Semiconductors

Semiconductor devices fail either to a short or open circuit. The semiconductors in use in modern fire alarm systems often include integrated circuits (IC) consisting of hundreds of thousands of simple semiconductor diodes and transistors. This is especially true of the microcomputers at the operational core of the control unit. Regardless of the complexity of the component, most semiconductor failures are catastrophic in nature, meaning that they fail completely and precipitously, often with a little puff of white smoke curling up from the circuit board.

Semiconductor failures are the result of one of three causes: (1) internal flaw, (2) overcurrent, or (3) overvoltage. Internal flaws are becoming less common as semiconductor manufacturing science continues to advance. Nevertheless, occasionally thermal ion migration or die-bond failure, typical internal flaws, cause a semiconductor to fail.

Since microcomputer memory consists of large integrated circuit arrays of transistor memory cells, there is the possibility of a memory failure. Usually, memory failures are catastrophic in nature and the entire device fails. It is rare that a single memory cell (location) or group of cells fails to retain data. Often, control units have diagnostic programs that are executed during the regularly scheduled maintenance to detect memory location failures. Additionally, regular thorough functional tests provide a measure of assurance that there are no memory location failures where the executable programs are stored.

The probability of this type of event is addressed in the reliability calculations presented earlier. Given enough time, a failure of this type is likely to occur, even with the highest-quality electronic equipment. The testing frequency and methods stipulated by the manufacturer and *NFPA 72* are intended to identify these types of failures with a minimum elapsed time period between the occurrence of the failure and its discovery. In other words, the time between failure and its discovery is as short as possible.

Overcurrent and overvoltage failures are usually associated with some other event that places an unintended stress on the system. Occasionally the event is the failure of some other electronic component subjecting adjacent components to the overvoltage or overcurrent. More frequently, overvoltages and overcurrents are the result of wiring and interconnection errors. Regardless, both overvoltages and overcurrents cause severe overheating of the semiconductor die, and the current-carrying portion of the die melts and/or vaporizes. Obviously, this type of damage is irreversible. Usually, these types of failures result in trouble signals and unwarranted activations of parts of the system and generally do not go unnoticed. It is important to correctly identify the source of the failure quickly. Otherwise, it is likely to occur again. Electrical transients caused by lightning, power supply spikes and surges, operation of highly inductive or capacitive equipment in close proximity to the fire alarm system, and even radio frequency interference have been known to cause these types of failures. Generally, the reliability computations presented earlier do not explicitly address the contribution of these external events to the failure rate of the system.

Resistors, Capacitors, and Inductors

These components are classified as "passive" components. They are less likely to fail than semiconductor devices because their structure is much simpler. Usually, these components fail to an open circuit. This generally causes some type of inexplicable action by the system, such as a trouble signal or the unwarranted actuation of some control system function. Rarely do these failures occur, and on those occasions when they do, they are immediately noticed. These failures are included in the reliability computations presented earlier.

Circuit Board Solder Bonds

A major source of electronic system failures occurs in the solder bonds between the electronic components and the circuit board. Solder bonds are occasionally broken during shipping and installation, rendering the unit "dead on arrival." Unfortunately, broken solder bonds do not always show up immediately. Broken solder bonds can behave as either an intermittent or high-resistance connection. Both of these cause spurious operation of portions of the system or intermittent trouble signals. There is no guarantee that these failures will be noticed when they occur. Broken solder bonds are just as likely to allow the unit to "fail silent."

As a system ages, the lead and tin atoms in the solder begin to migrate, allowing the solder to crystallize and become brittle. Variations in temperature, vibrations, and excessive moisture also contribute to the premature failure of solder bonds. A significant percentage of the computed failure rate for a fire alarm system component is derived from the failure rate assigned to each of the hundreds of solder bonds in that component.[2]

Transformers

Transformers are generally very reliable. Furthermore, since most transformers are used in the power supply section of a control unit, their failure will cause obvious indications, making timely repair likely.

Relays

Those switching functions that cannot be accomplished with solid-state (transistor) switches are accomplished with relays. Relays are electromechanical switches that are activated by causing current to flow through an electromagnetic coil situated such that the magnetic attraction developed by the coil pulls a switch from one pole to another. Often several switches are connected together so that the energization of the coil causes all of the switches (poles) to transfer at the same time.

As in any other mechanical component with moving parts, there is a possibility of a mechanical impediment to operation

from dust, corrosion, or wear. There is also the possibility that, even though the electromagnet has mechanically closed the contacts, electrical current fails to flow due to contact contamination by oxide, dirt, or some other material. The continuity of the electromagnetic coil can be lost, rendering the relay inoperative.

With all of these potential failure modes, relays do not provide the level of reliability of solid-state components. Nevertheless, most fire alarm system control units are equipped with relays, because they are very useful for providing a general-purpose switching function, especially for circuits that operate at higher voltages, such as 115 V ac. Although some relays are available in sealed versions, most relays are constructed with simple dust covers. This is usually adequate for normal indoor installations, but extra care must be exercised when testing a unit that is installed where it is exposed to a wide variation in ambient temperature, dust, excessive humidity, or corrosive aerosols. All of these environmental factors have been implicated in relay failures.

When "operation-critical" functions are performed by a fire alarm system with relays, the failure rate of the relay must be included in the reliability computation for the fire alarm control unit. The testing regimen for a fire alarm control unit must test the operability of all of the relays to verify that they are still operable.

Switches

Switches enable an operator to introduce electronic signals into the fire alarm system. The least reliable part of any switching system is the human operator. Nevertheless, once the operator is taken out of the picture, there are two general failure modes for switches: (1) failing to operate when they should and (2) operating when they should not. Since switches are usually mechanical components with moving parts, they suffer relatively high failure rates. The exception to this rule are some of the newer capacitive and membrane switch technologies where the parts do not actually move.

The first failure mode is of lesser concern, because an operator is present and the failure is immediately apparent. It is extremely rare that a fire alarm system is designed requiring that an operator activate a switch in order to secure the life safety and property conservation objectives of the system. Usually, system switches are used to interrupt the automatic functions of the control unit. In this scenario, failure of the switch should result in a safe condition.

The second failure mode usually takes the form of intermittence and generally causes trouble signals. The listing criteria for the nationally recognized testing laboratories require that the off-normal position of any switch result in a trouble signal. This requirement came from years of experience with failures of switches.

Screw Terminals

The least reliable part of a screw terminal is the person with the wire stripper and screwdriver. However, screw terminals do occasionally vibrate loose. *NFPA 72* requires that the wiring to initiating devices and notification appliances be monitored for integrity. However, wiring within the control unit enclosure is not required to be, and is often not, monitored for integrity. Consequently, the failure rate of the screw terminals must be factored into the reliability calculations.

Fuses

Fuses demonstrate one principal failure mode: they fail to an open circuit. This failure mode led nationally recognized testing laboratories to establish a listing criterion requiring that all fuses be monitored for integrity. The failure of any fuse should result in a trouble signal. It is required that monitoring fuses for integrity be done during testing.

Indicator Lamps

The invention of light-emitting diodes (LEDs) ended the reliability problems with indicator lamps. Although it is possible for an LED to fail, it is not a common occurrence. When LEDs fail, they cease making light. LED indicators are generally deemed inherently reliable and are not always monitored for integrity. Their failure rate is included in the reliability prediction for the control unit.

Batteries

Batteries are the most commonly used source of secondary power for fire alarm systems. It is important to understand how batteries fail in order to understand the importance of proper testing. Batteries are designed to provide a specified current for a specified time at a specified voltage. The specified current for a specified time is called capacity. Batteries undergo failure modes where they lose their capacity. Batteries can also lose their output voltage. These two failure modes are separate and distinct, occurring independently of each other.

The loss of capacity cannot be discovered by simply measuring open terminal potential, nor does the loss of terminal potential necessarily imply a loss of capacity. When a totally "dead" battery, that is, one that cannot provide any current at any voltage, is measured with a voltmeter under "open terminal conditions," the meter will usually show very close to nominal potential (voltage). That is because the mechanism of failure which results in the loss of capacity does not necessarily change the open terminal potential of the battery. When a battery is measured with a voltmeter and shows less than nominal open terminal potential, it may still have the ability to provide very large currents in spite of its lower terminal voltage. Consequently, the testing regimen for battery systems must test the ability of the battery to perform its intended function: to store and supply, as needed, electrical energy. A measurement of terminal potential and whether the battery "holds charge" does not provide an adequate assessment of the battery set.

Wires

Wiring is subject to two general classes of failure: (1) breakage of the conductor and (2) loss of insulation. The continuity of wiring conductors used in signaling line circuits, initiating device circuits, and notification appliance circuits is required to be monitored for integrity per *NFPA 72*. When fire alarm control

units are used to actuate extinguishing systems, the wiring to the actuating mechanism and other critical functions should be monitored for integrity also. However, the monitoring circuitry in most fire alarm system control units does not have the ability to distinguish between a normal conductor and one that is damaged. Close visual inspection is necessary on initial acceptance and whenever revisions are made.

The insulation on wiring conductors represents a different problem. Thermoplastic wire insulation behaves much like a supercooled liquid, in that it can flow over time away from a point of compression. This is particularly common when conductors are pulled taut against the edge of a metal enclosure or when pinched between an electrical box and its cover (both indicative of substandard installation practice). Under these conditions, the insulation will slowly flow away from the stress point, eventually allowing the conductor to make electrical contact with the enclosure. This creates a "ground fault."

The nationally recognized testing laboratories require that fire alarm system control units operate completely isolated from earth ground and provide ground-fault detection. These requirements ensure that a single ground fault will be detected, yet will not impair the operation of the system. It is imperative that the first ground fault be corrected before a second one occurs, as the second ground fault introduces a circuit via ground between two separate circuits in the system.

We can see that there is a direct mathematical connection between the reliability of a system and the failure rates of the constituent components. We have also reviewed the types of failures that occur with the types of electronic components that are used in the detectors, notification appliances, and control units in a fire alarm system. If an engineer were given a target reliability level to be achieved, the quantities of each fire alarm system component in the system, complete parts lists for each and every system component, and the failure rate data of each of those electronic components, she/he could, conceptually, calculate a maintenance interval for the system. In actual practice, this is rarely done. Instead, minimum-compliance prescriptive maintenance intervals are used.

INSPECTION, TESTING, AND MAINTENANCE REQUIREMENTS FOR SIGNALING SYSTEMS AND COMPONENTS

The reliability analysis presented earlier establishes the demand that fire alarm systems be maintained. *NFPA 72* establishes this requirement and places the responsibility for the regular inspection, testing, and maintenance on the owner/operator of the site. *NFPA 72* references the manufacturer's instructions, effectively making the manufacturer's instructions part of *NFPA 72* by reference and thus enforceable by the local authorities having jurisdiction (AHJ).

Definitions

To discuss the inspection, testing, and maintenance of fire alarm systems, one must define several terms that are not explicitly defined in *NFPA 72,* but are important in establishing the expected course of conduct.

Inspection. An *inspection* is a close visual observation of the item being inspected without causing the item to perform its intended function. There is said to be a facility manager who insists that the inspector's nose be less than 12 in. (305 mm) from the object to qualify as an inspection. This rule differentiates between a casual glance at a device and an inspection. It works for the manager. An inspection does not require the operation of the device being inspected, but it does require that a written record be made of the observed status of the device. Is it clean? Dirty? Bent? Covered with paint? In "as installed" condition?

Test. A *test* is a process where the device under test is provided a stimulus to determine if it is functional, and a written record of the response of the device under test is made. The term *test* does not necessarily imply that the stimulus is of a similar magnitude to that expected from the fire the unit is intended to detect. However, it does imply that the device has also been inspected while the test was conducted. Many tests require that the system be intentionally impaired to determine if the system properly responds to the impairment. *It is critical that all conditions created in the context of a test be returned to the normal state before the test is deemed completed.* The written record should include both the observed status of the unit and whether it was found to be functional.

Sensitivity Measurement. *Sensitivity measurement* is the quantitative measurement and recording of the stimulus necessary to achieve an alarm signal from an initiating device. This is very different from a test. A test does not imply that the stimulus is of a similar magnitude to that obtained from the design fire. A sensitivity measurement determines how large a stimulus is necessary to cause an alarm response. This measurement is to be compared to the value for the unit as shipped to quantify any change in the performance one can anticipate from the unit. Thus, the sensitivity measurement is intended to assess the ability of the detector to perform its intended function when the design fire occurs. It is understood that initiating devices are also inspected and tested when the sensitivity is measured. The written record should contain the observed status, the sensitivity measurement, and the verification of the functionality of the unit.

Bear in mind that many "intelligent/analog" detectors are actually addressable sensors where the alarm set point is stored in a memory location at the control panel. These systems continuously measure the sensor output and compare it to the value stored in memory for that particular device. These systems often can provide a printout of the current measured values for the initiating devices and their alarm points, thus satisfying the requirements of *NFPA 72*. Observations of physical status and verification of operability are normally associated with measurement of sensitivity, and these must be separately performed when "intelligent/analog" detection is encountered.

Acceptance Test. An *acceptance test* of a system is the process wherein every initiating device is provided an appropriate stimulus that simulates the existence of the design fire, and the

design sequence of operations of each system component in the entire system is verified and recorded in written form. This is usually achieved with a sensitivity measurement, including the functional test to initiate an alarm. Once the alarm is initiated, the technician verifies that all system functions, including interconnections to other building systems, operate as designed. It is preferable to repetitively operate all interconnections for each initiating device rather than verify their operation once and assume that all other initiating device alarms will cause the same operations. Often, problems show up after several operational cycles that would otherwise be missed. Programming errors in some software architectures can lead to problems that can only be uncovered with complete function verifications.

Reacceptance Test. A *reacceptance test* is an acceptance test performed after modifications have been made to the system. Modifications include any change, repair, adjustment to hardware or wiring, or any change in system software. The scope of a reacceptance test can be limited. All components, circuits, system operations, or software functions that are known to be affected by the change in the system must be tested, in addition to 10 percent of the initiating devices (up to a maximum of 50) known to not be directly affected by the change. A reacceptance test does not necessarily imply a complete acceptance test in all cases. However, there are times when a reacceptance test is equivalent to an acceptance test because of the nature of the modifications or repairs performed.

Documentation

Every form of evaluation of a fire alarm system must be completely documented. This includes inspections, tests, sensitivity measurements, acceptance tests, and reacceptance tests. This documentation should be retained in a secure location for future reference. The lack of complete documentation is often viewed by the courts and regulatory authorities as presumptive evidence that the required testing and inspection have not been done. A minimum compliance form for documenting the inspection and testing of a fire alarm system is provided in *NFPA 72*. However, many AHJs require a more complete form as part of a test plan.

Personnel

NFPA 72 establishes qualifications criteria for individuals inspecting and testing fire alarm systems. The facility owner is responsible for making certain that the people performing these functions are qualified. Many fire alarm systems are connected to supervising stations and automatic extinguishing systems. The personnel testing a fire alarm system must be sufficiently familiar with these interconnections to take the appropriate steps to prevent accidental discharge of an extinguishing system or reporting of a fire alarm to the municipal fire service during testing of the system.

Preparation and Coordination of Inspection, Testing, and Maintenance Activities

Many fire alarm systems are connected to off-premises monitoring services, fire pump controllers, special agent extinguishing systems, and building management systems. There are times when the functional testing of a fire alarm system will cause serious interruptions in site operations due to these interconnections. By the same token, it is critical to verify that the interconnections are operative and that the fire management plan for the entire site is achieved when a fire alarm signal occurs.

This presents a dilemma to the facility manager. Should a shutdown be endured, a major problem if the facility is the hub of an online computer network, or should the shutdowns be bypassed, thereby failing to verify complete system operability? Usually the question is not an all or nothing situation, and reasoned decisions must be made regarding which automatic interconnections to bypass and which to allow to operate. The facility manager must recognize that some interconnections actuate extinguishing systems that represent a significant cleanup and/or recharge expense if they are actuated. Understandably, these types of systems must be disabled for routine inspection, testing, and maintenance. However, the portion of the system that is disabled should be as small as possible. For example, many extinguishing system actuators are removable from the extinguishing agent containers, allowing all of the electrical components to be tested. This is a very desirable feature. However, since the electrical supervision cannot recognize this type of impairment, there is the danger that the system will be left with the actuators removed from the agent storage containers. Extra care must be taken to ensure that all of the actuators are properly reinstalled at the conclusion of the inspection, testing, and maintenance program.

Some interconnections, such as smoke management systems, automated process controls, and data processing systems, will interrupt site productivity to the point that the cost of an unwarranted actuation is too high to allow during routine inspection, testing, and maintenance. Systems with these types of interconnections can be designed with built-in disconnect switches that are supervised when in the off-normal state. However, remember that when these functions are disabled, their operability is not verified. It may be reasonable to permit the inspection, testing, and maintenance program to be performed with these types of functions disabled during normal operations time in a site that has experienced no modifications since the initial acceptance tests; however, it is not appropriate if revisions or modifications have been made. If it is critical for a function to occur in order to achieve the design objectives of a fire protection system, then it is equally critical that those functions be inspected and tested.

Finally, off-site reporting and resulting responses must be addressed. These can be effectively managed with prior notification. All impairments must be monitored. Usually, at the beginning of a service visit, the technician places a telephone call to the monitoring entity to advise them that the system is being tested and to disregard alarm and trouble signals. The monitoring entity should be under strict instructions that, when such a call is received, the following are addressed:

1. Call back the facility manager to verify that testing is about to commence.

2. Verify that an alternative procedure to report a fire is in place.
3. Require verification when testing will be completed and deem any signal occurring after that time as a real signal, unless a second call is received rescheduling the estimated completion time.
4. Require a follow-up call on completion of the maintenance visit that confirms the system has been restored to fully automatic status.

System impairments that facilitate inspection, testing, and maintenance should not be granted casually. A system impairment can permit an inconsequential fire to become a large-loss fire. It is also possible for fires to grow to serious proportions because the monitoring entity failed to report the fire. Fire alarm systems should be designed and serviced with these considerations in mind. Every system must be serviced, and often the service activities necessitate disabling portions of the fire alarm system or interconnections. However, the disabling should be limited to the smallest possible portion of the building fire protection assets. Furthermore, if at all possible, those portions that are directly affected by the testing should be disabled individually, thereby keeping operative as many building fire protection assets as possible.

The Test Plan

The inspection, testing, and maintenance regimen for a fire alarm system must stipulate the following:

1. What procedure is to be performed?
2. How it is to be performed?
3. What data are to be recorded in the documentation?
4. How frequently is the specific procedure to be performed?

These four criteria are usually organized into a test plan. A formal test plan is often a very good investment. It establishes a formal procedure to ensure the complete inspection and testing of the system and a record of the results for future reference. Once a test plan has been developed, it is used each time the inspection and test program are performed. Consistency of the presentation of results facilitates identifying problem areas.

NFPA 72, Chapter 10, "Inspection, Testing, and Maintenance," is organized to facilitate the development of a formal test plan. It establishes test methods and then stipulates an inspection and testing frequency. The test methods outline what procedures are to be performed. They are intended to be used in conjunction with the manufacturer's instructions for the specific make and model of equipment involved. Thus the manufacturer's instructions provide the specific "how to" information. The issue of documentation is addressed by *NFPA 72,* Chapter 10, in the section on records.

The frequency of each procedure varies, depending on the general class of device. For example, batteries are inspected more frequently than initiating devices. The frequency of visual inspections is different (i.e., more frequent) than testing. The frequencies provided by *NFPA 72* have been based primarily on experience developed over the recent past rather than reliability data for the fire alarm system components.

Supervising Station Systems

Supervising station systems monitor a number of protected premises fire alarm systems via one or more types of communication paths. The principal concerns during the inspection and testing of these systems is that each communication path is intact and operable and that the supervising station fire alarm control unit is fully operational.

The inspection, testing, and maintenance procedures for specific models of a control unit for a supervising station fire alarm control system are established by the manufacturer. Since supervising station fire alarm systems include many of the same components that make up a protected premises system but organized in a manner that fulfills the design requirements for a supervising station system, the inspection and testing requirements for these components are the same, regardless of the type of system in which they are used.

Protected Premises Systems

There are two general objectives in the testing and inspection of a protected premises fire alarm system. The first is to verify the operability of the system and identify any failures in system components that have failed to a "silent" state. Any failures identified during the course of the inspection and testing must be repaired to restore the system to a fully operational state. The second is to identify changes in the occupancy that render a formerly appropriate system inappropriate, based on the hazard area to be protected. Both objectives affect proper response to a fire.

Fire Alarm Control Unit

The manufacturer for each make and model of fire alarm control unit (FACU) provides a recommended service procedure for the control unit. These procedures are included in *NFPA 72* by reference. However, the fire alarm control unit is one building block in a much larger system, and the manufacturer rarely knows how the overall system is designed. Consequently, there are at least two layers of functions that must be tested. The first layer comprises those functions that are an integral part of the FACU, irrespective of the particular system in which it is used. These functions include supervision of relays, fuses, main power supply, batteries, wiring integrity, alarm indications, trouble indications, supervisory indications, and isolation from ground. The second layer is specific to the facility or system. These are usually in a "sequence of operations" format, establishing the response functions that occur as a result of each input (initiating or supervisory device) signal.

Functions. All functions of the system should be tested. The supervision of all signaling line circuits, initiating device circuits, notification appliance circuits, and signal transmission circuits must be tested. Furthermore, when the FACU is used for the actuation of extinguishing systems, all circuits activating equipment whose operation is critical to successful extinguishment must also be supervised. The testing of these functions consists of creating breaks and ground faults on each circuit

and verifying that the appropriate trouble signal is rendered by the FACU.

The sequence of operations must then be tested to verify the operability of all those functions the control unit is intended to implement specifically for the hazard area it protects. These functions are application specific and vary from one site to another.

Annex C of *NFPA 72* provides specific tests for each type (style) of circuit. Trouble signals can be introduced on signaling line circuits and initiating device circuits by temporarily removing detectors (from their mounting bases) or wiring conductors from detectors. Similar techniques are used for notification appliance circuits. Signaling line circuits are usually interrupted at the FACU screw terminals, with a verification that the trouble signal is received. Alarm signals must be generated on each initiating device circuit or zone by causing a detector to alarm with heat, smoke, or radiant energy, as appropriate, to verify that the design alarm response occurs. The alarm response will include actuation of the notification appliances, alarm indication at the control unit, actuation of interconnected equipment, and signal transmission to the off-premises receiving station.

Conductors on each initiating device, notification appliance, and signaling line circuit must be temporarily grounded to verify that the ground detection circuitry and associated trouble indications are operative. The applications manual for most FACUs stipulates the amount of resistance between conductors and ground that should be detected. A fixed resistor reflecting that criterion should be used to test ground-fault detection.

Special hazards extinguishing systems employ specialized equipment to address the unique needs of the various extinguishing system equipment designs and agent limitations. Each manufacturer is required to provide an engineering manual that addresses the inspection, testing, and maintenance needs of the control unit and ancillary equipment necessary to operate the special hazards extinguishing system. These functions include cross-zone detection, matrix detection, verified detection, sequential detection, detector counting detection, abort switches, solenoid activation (release), and squib actuation (release). When these functions are implemented by the FACU, the specific inspection and testing requirements established by the manufacturer must be observed.

The functional test serves to verify that all of the system interconnects are energized when appropriate and that the system achieves the basic functions it was designed to achieve. However, this type of general "macroscopic" test does not fully evaluate all the system components. There are specific tests to evaluate these components.

Fuses. The listing standards of the nationally recognized testing laboratories require that all fuses be supervised. However, it is possible that the supervisory circuitry could fail and not provide an indication that such a critical component was inoperative. Furthermore, it is conceivable that the fuse may have been replaced with another of the wrong value. Consequently, all fuses must be checked for supervision and correct value. Keep in mind that a fuse cannot be properly checked visually. The only way to check a fuse for continuity is with a volt-ohm meter (VOM) or multimeter.

Indicating Lamps. All indicating lamps must be operated to verify that they are still functional. Modern fire alarm control panels use LEDs for indicator lamps. LEDs are much more reliable than the old incandescent lamps but can still fail. Most fire alarm control units are equipped with a lamp-test switch specifically for this purpose, while others have a key-pad code that performs the lamp-test function.

Main Power Supply. There are electronic component failures that could render the main power supply incapable of supporting the design current load on the system during fires yet not appear under normal, quiescent conditions. The main power supply test entails temporarily disconnecting the secondary supply and applying the maximum design current load to the system while monitoring the output voltage of the system power supply. If the power supply voltage drops below that stipulated in the manufacturer's applications manual, remedial action must be taken.

Engine-Driven Generators. In those instances where an engine-driven generator is used as a required power source, either as a primary or a secondary supply, it must be tested according to the procedures outlined in NFPA 110, *Standard for Emergency and Standby Power Systems.*

Uninterruptable Power Supply (UPS). In those cases where a UPS system is dedicated to the fire alarm system, it must be tested per NFPA 111, *Standard on Stored Electrical Energy Emergency and Standby Power Systems.* Note that a UPS is used for a number of purposes, one of which is the fire alarm system. UPS is treated by *NFPA 72* as being no different than public utility power, and the requirement for a secondary power supply for the fire alarm system is still enforceable.

Secondary Power Supply. The secondary power supply must be able to support the full current load of the fire alarm system when the primary supply is lost. Primary power is often lost during a fire. Testing of the secondary power supply entails temporarily disconnecting the primary power supply and applying the maximum design current load to the system while monitoring the output voltage of the secondary system power supply. If the secondary power supply voltage drops below that stipulated in the manufacturer's applications manual, remedial action must be taken. Additional and more specific testing is required when the secondary power supply consists of a battery set.

Batteries. The lead/acid battery chemistry is the most commonly used type in fire alarm system service. These batteries are typically found as unsealed lead/acid batteries, unsealed calcium grid (lead-calcium) batteries, sealed lead/acid batteries, and gelled electrolyte lead/acid batteries. All of these batteries use a solution of sulfuric acid in water as the electrolyte. These various types require slightly different charging potentials and maintenance. It is imperative that the battery charger be properly matched to the battery, consistent with the listing.

Battery Testing. The testing of a battery set consists of general tests that are performed regardless of battery chemistry and

specific tests for specific types of batteries. A visual inspection is required for all types to discover any terminal corrosion, looseness in terminal connections, or electrolyte leakage. All of these are serious conditions that can cause an increase in the series resistance of the battery set, thus depriving the fire alarm system of the necessary operating potential under large current load conditions.

Batteries exhibit a number of failure modes that result in either a loss of operating potential or a loss of capacity. The exact mechanism of each class of failure mode is dependent on the battery chemistry; nickel/cadmium batteries behave somewhat differently than lead/lead peroxide batteries.

Battery Test Regimens. In general, the test regimen for all batteries includes the following:

1. Battery charger test
2. Discharge test, in which the batteries must support a design current load
3. Load voltage test, in which the voltage is measured while the batteries support a design current load
4. Open circuit test, in which the open-circuit potential of the battery is measured

Battery Discharge Rates. There is a relationship between the output potential of a battery, measured in volts, and the output capacity of the battery, measured in ampere hours (Ah). This relationship is illustrated with a "family" of potential versus discharge time curves for a number of discharge currents, as shown in Figure 14.5.4. When the terminal potential reaches 85 percent of original value, the battery is generally considered effectively depleted. The discharge current multiplied by the length of time it takes to deplete the battery is its capacity (C), measured in Ah (ampere hours). Typically, batteries exhibit smaller capacities when the discharge rates are higher. The battery industry usually uses a 20 hour discharge rate for their specifications. A 10 Ah battery will support a 0.5 A load for 20 hours and be at 85 percent of its fully charged potential after having been discharged at that rate for that time period.

The capacity of the battery is a function of the number of charge carriers stored in the unit. Unfortunately, there are chemical reactions that occur within a battery that "lock up" charge carriers into precipitates, thus removing them from the electrochemical reservoir of available charge carriers. This results in the battery becoming depleted far sooner than expected.

Battery Deterioration. Two symptoms indicate a deterioration of the battery: (1) loss of capacity (Ah) and (2) loss of potential (voltage). These symptoms can usually be traced to the stresses inherent in recharging and maintaining charge. When the battery is being charged, lead sulfate is converted to lead and lead dioxide. As charging continues, hydrogen and oxygen gas are formed from the electrolysis of the water in the electrolyte solution. In the sealed and gelled electrolyte batteries, the hydrogen and oxygen are contained within the battery until sufficient pressure is achieved to cause the battery to vent. In the unsealed type, these gases are allowed to escape. The loss of hydrogen and oxygen represents a loss of water from the electrolyte. This increases the concentration of the acid in the electrolyte. As a result, a lead sulfate and lead sulfite precipitate begins to form, "locking up" the lead in an insoluble and unusable form. This process is called sulfation. Since the capacity of the battery is directly proportional to the quantity of lead available, a sulfated battery cannot support the current load it could before the sulfation occurred.

With unsealed lead/acid batteries the acid concentration is determined by measuring the specific gravity of the electrolyte. As water is lost, the specific gravity of the electrolyte increases. When the specific gravity reaches the upper allowable limit, reagent-grade distilled water is added, restoring the acid con-

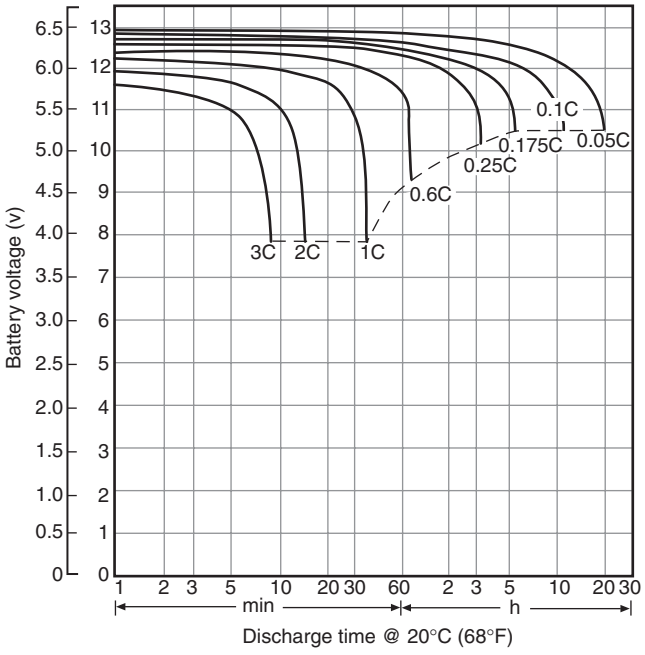

FIGURE 14.5.4 Capacity (C) of a Battery as a Function of Discharge Rate, Time, and Voltage

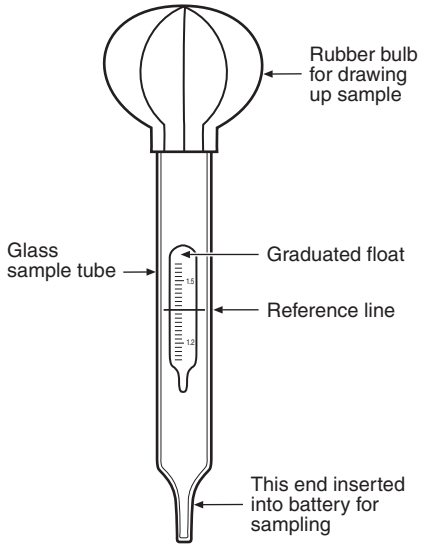

FIGURE 14.5.5 Hydrometer

centration to the design value. The measurement of electrolyte specific gravity is done with a hydrometer, similar to that shown in Figure 14.5.5. Always use one that has a float and a graduated scale.

The sealed lead/acid and gelled electrolyte lead/acid batteries have no provision for returning the electrolyte to the design specific gravity range. These batteries are designed to minimize the loss of hydrogen and oxygen and include design features to offset the effect of the slow leakage that often accompanies continuous float charge. Eventually, the loss of water allows sulfation to occur, with the resultant loss of capacity. If the recharging current is properly matched to the batteries, these types of batteries usually provide reliable service over a time period generally between 3 and 5 years, after which they must be replaced. Figure 14.5.6 shows a typical capacity versus time curve for a sealed or gelled electrolyte lead/acid battery.

Loss of potential failure in batteries comes from either the shorting of a cell or internal deterioration that causes an increase in the internal resistance of the battery. Both of these failure mechanisms result in a battery set that cannot provide sufficient potential for the fire alarm system to operate as intended.

Shorted Battery Cells. Shorted cells usually result from the recharging and maintenance of charge over a period of time. During the recharging of the battery, lead ions move between the lead-dioxide plate and the lead plate. Occasionally a needlelike crystal forms. As it continues to grow, it eventually extends from one plate to an adjacent plate, making an electrically conductive contact between the two. This shorts out the cell, resulting in a battery with a terminal potential 2.2 V lower than originally designed.

When a cell becomes shorted, two serious problems arise. The first is that the battery charger, sensing an inordinately low battery potential, forces a greater charging current into the battery. The increased current overcharges the remaining cells, dehydrating the electrolyte, ultimately causing catastrophic failure. Second, if the fire alarm system loses primary power supply while connected to a battery with a shorted cell, it will not receive an adequate operating potential and will very likely not be able to support the design output load.

Increase of Resistance Within Batteries. Batteries can also lose the ability to maintain output potential due to increases in internal resistance within the battery. During the discharge and recharge of the battery, lead ions migrate through the electrolyte between the plates within the battery. Eventually, electrical resistance within portions of the plate, interconnecting conductor bars, and electrolyte begins increasing. This causes the internal resistance of the battery to increase. This condition only shows up when the battery is required to supply current to a load (the fire alarm system). The larger the current load placed on the battery, the larger the drop in voltage due to internal resistance, and, hence, the easier it is to detect.

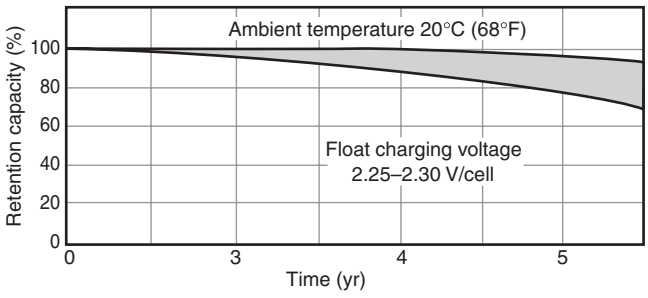

FIGURE 14.5.6 Capacity Versus Time Curve of a Sealed or Gelled Electrolyte Lead/Acid Battery

The likelihood of a shorted cell failure and increased resistance failures increases as the length of time under recharging conditions increases. This fact underscores the importance of using the battery that has been listed for use with the battery charger and of performing the maintenance as prescribed by *NFPA 72*.

Nickel/Cadmium Batteries. Nickel/cadmium battery secondary power supplies are rarely encountered in connection with fire alarm systems, but when they are, it is only as sealed batteries. Sealed nickel/cadmium batteries manifest similar failure modes to the lead/acid units. However, there is an additional failure mechanism called the "memory effect" associated with some nickel/cadmium batteries that is unique to that chemistry. Fire alarm systems are "float-charge" applications. These are applications where the battery is maintained at full charge by a battery charger over long periods of time and, occasionally, are partially discharged, only to be restored to full charge when the primary power is restored. Some nickel/cadmium batteries exhibit a "memory effect," where the usable capacity of the battery declines to that quantity that has been recurrently used.[6] Thus, a 20 Ah battery discharged several times by 2 or 3 Ah will lose the ability to supply more than the 2 or 3 Ah. Nickel/cadmium batteries are much better adapted to cycle charge applications where the unit is completely discharged prior to recharging. This is an additional loss of capacity failure mode that must be addressed in the test program.

Battery Charger and Load Tests. Because the failure modes of batteries are so complex, battery secondary power supplies represent a challenge for any testing program. NFPA 72 provides specific tests for each type of battery. Each type requires a charger test, where the recharge potential of the battery charger is measured with a multimeter to verify that the recharge potential is within acceptable limits. Since most battery failure mechanisms are related to recharging and overcharging, the charger test is essential.

For each type of battery there is a load test. A current load is placed on the batteries and the battery potential is measured. This test is intended to identify batteries that have excessive internal resistances. Consequently, the larger the load, the better. The ideal load is one that is equivalent to the fire alarm system in full alarm with all notification appliances operating, the emergency voice evacuation system operating, and extinguishing system solenoid valves energized. A bank of power resistors can be used to simulate the system load for the battery load test (Figure 14.5.7). One 24 ohm (Ω), 100 W resistor allows 1.0 A to flow at 24 V. Current increases for parallel-connected resistors.

Where the battery is being used for a public fire alarm reporting system, the load tests must be modified and the potential between each side of the battery and earth-ground must be

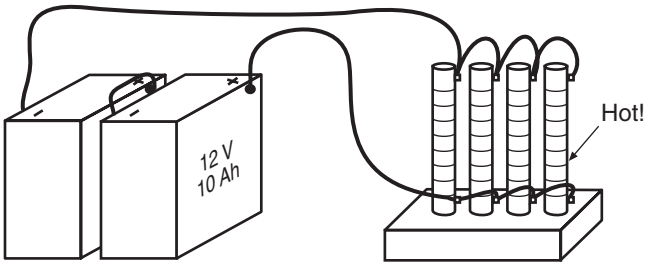

FIGURE 14.5.7 Bank of Power Resistors

included. The standard multimeter cannot be used for testing public fire alarm reporting system power supplies due to the possible erroneous readings caused by voltage differentials in the ground potential. A standard 10-M input impedance meter can be converted to read battery potentials for a public reporting system power supply, with the addition of a properly sized ballast resistor (Figure 14.5.8).

$$R = 100\ \Omega/\text{V} \times \text{Battery voltage}$$

For a 12-V battery

$$100\ \Omega/\text{V} \times 12\ \text{V} = 1200\ \Omega$$

It is important to note that none of these tests actually tests for battery capacity. The load test is used to infer that no serious loss of capacity has occurred. This inference is supported by the observation that loss of capacity is almost always accompanied by an increase in internal resistance. A better inference can be drawn from a timed discharge/recharge test. In this test, a fraction of the battery capacity is discharged and then the battery is returned to the battery charger, while the current is monitored over time. A curve similar to Figure 14.5.9 results. If the capacity returned to the battery, measured in Ah, is no more than 110 percent of the capacity removed, then the battery has retained its design efficiency and one can be more certain that no loss of capacity has occurred. The only sure way to completely verify

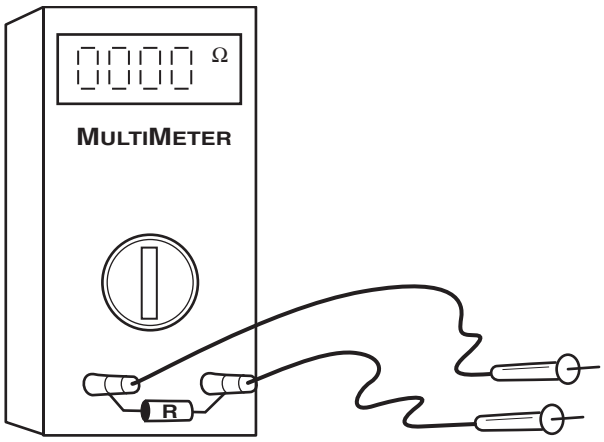

FIGURE 14.5.8 Multimeter

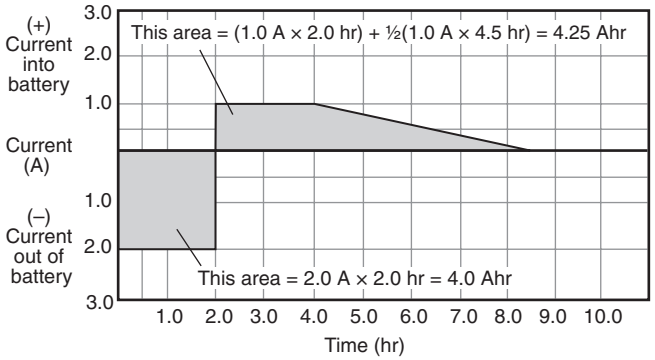

FIGURE 14.5.9 Partial Discharge/Recharge Integration Used to Infer Battery Capacity

design battery capacity is a full, measured discharge of the battery set at the design discharge rates with subsequent monitored recharge.[6]

Recently, meters have become available that purport to measure battery capacity by measuring the dynamic impedance of the battery. While some of the manufacturers of these meters proffer "research reports" supporting the ability of the meter to distinguish batteries with compromised capacity from those with full rated capacity, none of these meters has been listed by UL or FM for this purpose, as of the time this chapter was written.

Transient Suppressors. Since fire alarm systems must maintain isolation from ground and monitor that isolation, they are vulnerable to damage from the electromagnetic pulse (EMP) that occurs during a lightning strike. Transient suppressors are designed to absorb a finite quantity of energy before they overheat and fail, melting to a short circuit or vaporizing to an open circuit. These devices must be tested with a multimeter to verify that they are still intact.

Remote Annunciators. Many fire alarm systems include a remote annunciator to provide information regarding the status of the control unit and the identity of alarm signals at a remote location. Representative signals must be generated at the fire alarm control unit, and correct annunciation verified. Remember that most remote annunciators serve to provide the first responding fire service members with critical information relating to the nature and location of the fire alarm. The presentation of this information must be clear and understandable.

Interface Equipment. Commonly, fire alarm control units are interconnected with other control systems in the protected site. These interfaces must be inspected and tested in a manner consistent with the requirements established by the manufacturer and the expected operation of the interfaced systems.

Off-Premises Signal Transmitters. Fire alarm systems often transmit signals to monitoring stations that are off the immediate premises. The transmitter and the signaling line circuit from the protected premises to the supervising station must be in-

spected and tested as part of the inspection and testing program for the protected premises fire alarm system.

The oldest type of off-premises signaling is the McCulloh system. Where this type of signaling is used, the fire alarm control unit terminals must be regularly inspected for corrosion, and the function must be tested for successful signal transmission, in spite of each of the following four fault conditions:

1. Open circuit in one conductor
2. Ground fault on one conductor
3. Short circuit between the two signal conductors
4. A concurrent open circuit and ground fault

Currently, digital alarm communicator systems are the most commonly provided method for communication to a remote supervising station. Since it is impossible to supervise the entire signal path from protected premises to supervising station, two "numbers" (lines) are used: (1) primary and (2) secondary.

Digital alarm communicator transmitters are tested by verifying that they transmit the appropriate signal to the remote supervising station receiver. When an alarm signal is created in the fire alarm system, it must be verified that the DACT seizes the line and transmits the alarm signal to the supervising station. Similarly, the line seizure and trouble signal transmission must result from a trouble signal on the fire alarm control unit. When either of the signaling lines (numbers) is disconnected, the DACT must transmit a trouble signal on the alternative line within 4 minutes.

Systems similar to the digital alarm communicator are now available using radio communication. These are referred to as digital alarm radio transmitters and receivers (DART and DARR, respectively). These systems must also have provisions for secondary communications paths and must be tested in a similar manner as the DACT/DACR system.

Emergency Voice Communication Equipment. The inspection of the emergency voice communication equipment includes the remote phone jacks, handsets, phone hooks, control panel interface, and amplifiers. These components must be inspected for damage or deterioration due to ambient conditions. The testing includes a verification of the operability of both the primary and backup amplifiers, as well as the switching between them. A verification that the call-in silence, off-hook indication, and the operability of the communication from remote jacks to the base station must be achieved in the testing. Each phone set must be tested and determined to be operable. Finally, system operability with a simulated fire condition communications load, involving the concurrent operation of at least five phone sets, should be conducted to assess the voice quality and clarity of the system.

Guard Tour Monitoring Equipment. When guard tour monitoring equipment is integrated into the fire alarm control unit, it must be added to the inspection and testing schedule for the system. The inspection and testing procedures for this equipment prescribed by the manufacturer should be followed.

Metallic Conductors. Metallic conductors installed in a building are subject to damage and gradual deterioration. The inspection and testing of a fire alarm system must include an evaluation of the wiring. Stray potentials can be introduced into the fire alarm system from a number of sources. These are most often related to leakage currents and electromagnetic interference from high-voltage ac conductors that have been installed in close proximity to the fire alarm system conductors. However, sources of dc leakage currents have also been encountered. The multimeter is used to measure the conductor-to-conductor and conductor-to-ground potentials, both ac and dc, for each fire alarm system circuit. Where the potential differs from that stipulated in the manufacturer's installation manual by more than 1.0 V (ac or dc), the source of the potential must be identified and the problem corrected.

Fire alarm system conductors can also become shorted. There are many circumstances where a shorted circuit will not result in a "trouble" signal at the control panel, because the control unit circuitry does not monitor for short-circuit conditions. Consequently, fire alarm circuits should also be tested with the multimeter to verify the proper impedance on circuits that are not connected to normally closed contacts of other intentionally closed circuits.

Finally, damage to conductors can cause an increase in conductor resistance that will prevent successful operation of the devices served by the circuit. One method to test for this condition is to short the circuit at the end and measure the loop resistance to verify it is within the limits established by the equipment manufacturer. If this method is elected, particular care must be exercised to ensure that no shorting devices can accidentally be allowed to remain in place at the conclusion of the testing. An alternative method requires that detailed records be kept of the loop resistance as installed, including (1) the end-of-line supervisory component and (2) comparing subsequent tests to the as-installed values to identify circuits where the resistance has changed. This method may not be available when testing addressable detector fire alarm systems.

Initiating Devices

Initiating devices sense a fire or a change in the state of some other monitored condition that has an effect on the fire safety of the protected site. These initiating devices, listed in the same order as in *NFPA 72,* include the following:

1. Heat detectors
2. Smoke detectors
3. Radiant energy sensing detectors
4. Sprinkler system waterflow alarms
5. Extinguishing system operation initiating devices
6. Manually activated alarm initiating devices (manual fire alarm boxes)
7. Supervisory signal initiating devices

Each of these devices must be tested to verify that its ability to sense the condition for which it was designed has not deteriorated. The specific test is dependent on the type of device and how it senses the condition it is intended to monitor.

Heat Detectors. A source of failure for heat detection devices is a layer of insulating material between the detector and the fire which retards or prevents response. This can be found in

the form of paint or some other coating. Physical damage can also be found to be a source of problems, causing both spurious alarms as well as failure to alarm.

There is a wide variety of heat sensor designs in common use. *NFPA 72* categorizes heat detectors into various classes based on their general operating characteristics and physical form. Each type has unique features and, hence, specific requirements regarding the inspection, testing, and maintenance of detectors of that type. The method of testing is established by the manufacturer of the detector, and it is reviewed by nationally recognized testing laboratories as part of the listing evaluation. Consequently, it must be followed meticulously for the results to be credible.

Most methods involve the use of a heat source to simulate the flow of heated air and smoke beneath the ceiling across the detector surface. *NFPA 72* requires that restorable, spot-type, and line-type heat detectors be tested by heating them in the manner required by the manufacturer and verifying an alarm within 1 minute. Nonrestorable, spot-type, and line-type detectors, such as those that use a eutectic alloy of specific melting point, are not tested until they are 15 years old, at which time they are either all replaced or a sample is removed and tested by a nationally recognized testing laboratory to substantiate their continued operability. The actuation of nonrestorable heat detectors is simulated by shorting the circuit conductors for verification of the circuit operability.

Smoke Detectors. As with heat detectors, there is a wide variety of smoke detectors using a number of different design concepts. Since smoke detectors exist as spot-type, line-type, and air-sampling-type devices, specific methods must be employed that are appropriate to the detector type. However, all inspection, testing, and maintenance methods relating to smoke detectors are designed to ensure three general criteria:

1. Smoke can enter the sensing "chamber" of the detector.
2. The detector attains the alarm state at the smoke concentration for which the detector was listed.
3. The detector alarm signal is received and processed by the fire alarm system control panel.

Spot-type smoke detectors are available using the ionization technology and the photoelectric technology. In ionization detectors, the accumulation of dust within the sensing chamber over time can interfere with the flow of electrical current through the sensing chamber in a manner similar to the effect of smoke. This tends to render the affected detector more sensitive and, hence, more prone to spurious alarms. The same effect is seen in the photoelectric detectors. The accumulation of dust increases the internal reflectance within the sensing chamber, making it more sensitive and prone to render a spurious alarm. A sensitivity measurement is critical in order to identify units that have suffered a change in sensitivity due to dirt accumulation that is not apparent from an external inspection.

Spot-type detectors are also subject to clogging from airborne dust or, worse yet, paint. The application of paint to the exterior of a spot-type smoke detector permanently changes the smoke entry characteristics of a detector and is prohibited by *NFPA 72*. Detectors must be carefully inspected to ensure that smoke entry is uninhibited. Room air-handling equipment can create airflows of such magnitude that it is impossible for the smoke from the design fire to reach the detectors. Consequently, an "in place" test is required to ensure the continued ability for smoke to reach the detector. Usually, an aerosol can of surrogate smoke or some other method outlined in the manufacturer's instructions is used to simulate the flow of the ceiling jet and access to the detector to verify this criterion.

Line-type smoke detectors are usually of the projected beam, light-obscuration type, which use the protected room as a sampling chamber. These detectors respond when the optical transmission of light across the room is reduced due to the presence of smoke. The accumulation of dust and dirt on the optical surfaces of these units can cause an increase in detector sensitivity. Consequently, they must also be inspected. Since the alarm threshold of the projected beam-type detectors must be adjustable to accommodate different room dimensions, the manufacturers of this type of detector provide a test method that was evaluated during the listing evaluation. The sensitivity of the unit must be measurable. Often, neutral density filters or test screens are placed between the emitter and receiver units of the projected beam detector to simulate the optical effect of a smoke accumulation in the protected space.

Air-sampling smoke detectors use a set of sampling tubes and a fan to convey air from the protected space to the detector unit. Detailed inspection and testing methods for these units are stipulated by the manufacturers. The test methods must verify that all of the air-sampling ports and tubes are operative at their design flow rates and that the detector unit, including the sampling fan, is operating within the parameters established by the listing. This implies a sensitivity measurement similar to that required of all of the other detector types.

Smoke detectors are also often used to monitor the air in heating, ventilating, and air-conditioning (HVAC) ducts. Generally, spot-type detectors are used for this type of service, installed in specially listed housings equipped with sampling tubes that allow air to be sampled from the duct. The inspection, testing, and maintenance for these units include the inspection and testing of the spot-type detector within the housing and the testing of the airflow through the sampling tubes, similar to that required for air-sampling-type units.

Traditionally, smoke detectors were designed with fixed alarm thresholds. However, recently "analog/addressable" detectors have been introduced where the alarm threshold for each detector is a numerical value stored in the fire alarm control panel memory. The control panel sequentially addresses each detector, and the unit responds with a voltage or current that is the analog of stimulus its sensing element is sensing at that moment. The analog voltage or current is compared to the value in memory, and the "alarm" decision is made in the control panel. The sensitivity of this type of detector is determined by the difference between the sensed analog value and the stored threshold value. This type of detector and control panel design minimizes the need for individual detector sensitivity measurements, but does not change the need for regular inspections and maintenance.

Radiant Energy–Sensing Detectors. This category includes flame detectors and spark/ember detectors. These detectors de-

pend on the optical clarity of their lenses and windows, as well as a clear, unobstructed line of sight to the fire. The inspection of these detectors must verify these two critical parameters. The inspection must include a review of the location of the detector and any opaque objects that may have been introduced into the hazard area since the last inspection to verify that the ability of the detector to respond to the design fire has not been impaired.

A close inspection of the detector window/lens must be made to determine if any opaque materials have adhered to the optical surfaces, reducing the sensitivity of the unit. Keep in mind that many materials are transparent in the visible portion of the spectrum but opaque in either the ultraviolet or infrared portions of the spectrum, where the detectors may operate. Many radiant energy–sensing detectors are available with a lens clarity monitoring feature. This feature is often associated with flame detectors using ultraviolet sensing as all or part of the detection method, since very small levels of contamination can have a very significant effect on the effective sensitivity of the unit.

Window clarity monitoring is not a sensitivity measurement. Sensitivity measurement for radiant energy–sensing detectors requires a means by which a radiant emitter, listed for the purpose, is used to provide emissions of the specific wavelengths and intensities representative of the fire the unit is designed to detect. The response of the detector is measured to determine whether a variation in the calibration has occurred.

The measurement of the sensitivity of a radiant energy–sensing detector, whether a flame detector or a spark/ember detector, is a required part of the inspection and testing regimen required by *NFPA 72*. A flame detector equipped with a built-in sensitivity checking and test lamp that performs both functions is shown in Figure 14.5.10. Sensitivity measurements are used to identify which detectors have suffered a loss of sensitivity due to aging of internal electronic components or deterioration of the optical clarity of the detector window or lens. In the author's experience, a common source of performance deterioration in radiant energy–sensing detectors is a loss of clarity in the detector's optical surfaces. Particular attention must be paid to this fact when maintaining these detectors.

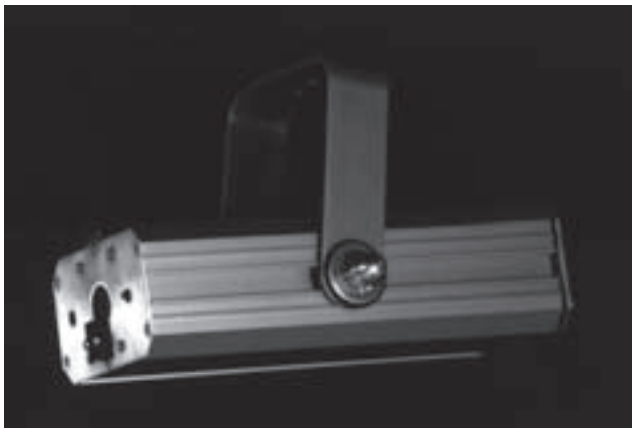

FIGURE 14.5.10 Flame Detector (Source: J. M. Cholin Consultants)

Sprinkler System Waterflow Alarms. Sprinkler system waterflow alarm initiation devices are often the only form of automatic fire detection in the protected site which can render a fire alarm signal during those periods when the building is unoccupied. The flow of water through the sprinkler system is an indication that a serious condition exists. Consequently, failure to render a signal when waterflow occurs is a doubly serious concern. This establishes the background for the aggressive inspection, testing, and maintenance schedules for these devices.

Sprinkler system waterflow alarm initiating devices are tested by operating the valve controlling flow through the inspector's test connection on the sprinkler system. If the waterflow initiating device is monitoring dry-pipe, preaction, or deluge systems, the alarm bypass connection, specifically installed for this purpose, is used for testing of waterflow initiating devices. Operation of the appropriate test connection causes a flow equivalent to the smallest orifice sprinkler head installed in the system. The waterflow alarm initiating device must transmit a signal to the fire alarm control panel within 90 seconds of the start of the waterflow. The delay between the time that flow begins and the time the alarm is transmitted to the fire alarm control panel is necessary to accommodate the oscillatory flows that often occur in large sprinkler systems and, as a result, surges in the public water supply pressure.

Extinguishing System Operation Initiating Devices. These initiating devices usually take the form of discharge switches specifically designed for the particular model of extinguishing system involved. Some of these discharge switches have a means to simulate the pressure of the extinguishing agent and, thus, test the operability of the initiating device. Others do not, and the testing can only be performed by shorting the contacts at their wiring terminations. In either case, each extinguishing system discharge initiating device must be tested as specified by the manufacturer and appropriate system functions verified.

Manually Activated Alarm Initiating Devices. Manually activated alarm initiating devices, commonly called manual fire alarm boxes, have traditionally consisted of a mechanical means to cause an electrical switch to transfer from open to closed, thereby shorting the conductors of the fire alarm initiating device circuit. Two aspects of these devices should be inspected and tested. First, the mechanical portion of the unit should be inspected and the operability should be verified. Recent legislation establishes maximum allowable forces for the operation of manual fire alarm boxes. Any unit that appears to have suffered corrosion, damage, or some other potentially adverse effect should be tested to verify that the operation force is within the limits for the make and model device in question. This is especially important in hazard areas where the walls have been painted subsequent to the installation of the manual station. Second, the manually actuated alarm initiating devices should be actuated to verify that the internal switch contact is electrically operative. Furthermore, many fire alarm systems actuate different responses due to the operation of manual stations in different

areas of the building or facility. The proper sequence of operation must be verified for each area.

Publicly accessible fire alarm boxes, commonly known as street boxes, are addressed in *NFPA 72*. These devices exist in a wide variety of types, connected to a variety of municipal signaling systems. The maintenance of these units is a municipal function, and the appropriate means of inspection and testing is established by the municipality.

Supervisory Signal Initiating Devices. Supervisory signal initiating devices monitor the status of critical fire protection assets. These include sprinkler system control valve status, water pressure status, water level, air pressure, and temperature. It is imperative to recognize that the failure mode and probability of the electrical supervisory initiating device is not related to the probability of failure of the monitored condition. Any coincidence in the frequency and scheduling of the inspection and testing of a supervisory signal initiating device with the supervised device is just that, a coincidence. Control valves do not fail on the same timetable as valve status supervisory signal initiating devices. The failures of valves are due to the compression welding of bronze components, tuberculation of the piping, galvanic corrosion, and the polymerization of seat grease. Failure of status switches is related to the corrosion of electronic contacts and the fatigue of copper wiring conductors and mounting brackets. The inspection and testing of the supervisory signal initiating devices are necessary to ensure that these devices are providing an accurate indication of the status of the supervised equipment and a reliable indication of the change in status of the equipment if and when it occurs.

Inspection and testing of the supervisory signal initiating devices usually involve a close inspection of each device to verify that the ambient conditions have not caused any deterioration in the device, followed by a temporary simulation of a change in status to verify that the supervisory signal initiating device transmits the indication of the change in status to the fire alarm control unit. Once the receipt of the change-in-status signal at the fire alarm system control unit has been verified, the simulated change in status is restored to normal and the receipt of the return-to-normal signal at the control unit is verified. Transmission of a change in status to the fire alarm system control unit should occur without any undue delay. If delays are encountered, the cause should be identified and corrected.

Notification Appliances

The principal objective of every fire alarm system is to ensure timely notification to all building occupants, enabling them to make safe egress from the fire location; therefore, the inspection and testing of the alarm notification appliances are crucial.

The three general types of notification appliances referenced in *NFPA 72* are (1) audible notification appliances, (2) visible notification appliances, and (3) speakers for emergency voice communication. Each type of notification appliance has a test method that verifies that the unit is providing the notification signal at a level consistent with the design objective.

Audible Notification Appliances. These include bells, horns, sirens, chimes, speakers, buzzers, and any other device designed to make a sound other than human speech. They all have a means of converting electrical energy into sound, often involving the making and breaking of an electrical switch contact connected to a bell clapper or a diaphragm and an electromagnet, thus producing a mechanical oscillation and sound. Corrosion, metal fatigue, paint clogging, mechanical damage, electrical contact erosion, and electrical conductor fatigue all can cause a deterioration in the quantity of sound a device produces. Each audible notification appliance must be inspected for signs of deterioration.

The audibility must also be tested to verify that the audibility criteria for the hazard area are still being achieved by the system. Audibility is verified through the measurement of the sound pressure produced by the audible notification appliance. Sound pressure is measured in units of decibels, dBA (the A signifies the A-scale which is designed to weigh sound pressure versus frequency in a manner that approximates human hearing). The sound pressure measurement is made with a sound meter. Only sound meters that comply with ANSI S1.42, *Design Response of Weighting Networks for Acoustical Measurements,*[7] should be used for the assessment of fire alarm systems. Care must also be taken that the sound pressure meter is used as directed by the operating manual to minimize measurement errors (Figure 14.5.11).

Two criteria must be met by the audible notification appliances. First, the system is required to produce a sound pressure level of 15 dBA above the average ambient and 5 dBA above the maximum sound pressure level having a duration of at least 60 seconds, measured 5.0 ft (1.5 m) above the floor in the occupiable area. Because sound intensity usually varies inversely with the distance from the audible appliance, the sound pressure readings are taken at a location furthest from the audible appliance. Generally, if the minimum compliance sound level is achieved at that location, it can be safely assumed that closer locations will also be above the minimum compliance sound level. However, "usually" does not mean always. Occasionally, buildings have unexpected acoustics that affect the sound intensities at various locations within the building. This should be noted when assessing audibility and additional measurements should be taken wherever the audibility seems lower than "normal."

The second criterion is the maximum allowed sound pressure level at the closest occupiable location to the audible

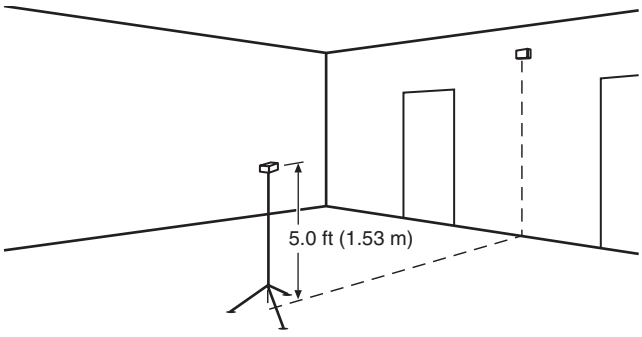

FIGURE 14.5.11 Sound Pressure Meter Mounted on a Tripod for an Audibility Measurement

appliance. This sound level cannot exceed 110 dBA without subjecting the occupant to potential hearing injury, according to the U.S. Occupational Safety and Health Administration (OSHA). System component failures rarely result in higher sound output from audible notification appliances. However, changes in the occupancy, such as installation of catwalks, stairs, mezzanines, and so on, can render a formerly unoccupiable location occupiable. This is consistent with the inspection of all other system components, in that the role of the inspection includes identifying changes in the protected space that may have an impact on the fire alarm system.

Speakers. Emergency voice communication speakers are also audible notification appliances, and they are required to achieve sound levels equivalent to audible notification appliances. The inspection should identify any form of damage, for example, mechanical deformation, corrosion, metal fatiguing, and paint clogging. The testing is similar to that for audible notification appliances. The sound level is measured with an ANSI S1.42–compliant sound level meter.[7] The minimum compliance sound level must be verified throughout the hazard area, and the test must verify that the maximum allowable sound level is not exceeded at any occupiable location.

An additional test criterion, one that is not relevant to other audible notification appliances, is included when emergency voice communication speakers are evaluated. This criterion is the intelligibility or clarity of the voice communication. In the testing of emergency voice communication speakers, the intelligibility of the speech message must be assessed. For existing systems, installed prior to 1999, the intelligibility assessment is essentially qualitative—can the speech message be understood by the intended recipients? Generally, intelligibility is maximized by using more audible notification appliances, so that each dissipates less power rather than using fewer higher-power audible notification appliances.

More recently, the trend has been toward using more quantitative intelligibility assessment methods, especially in acoustically challenging spaces where highly reflective wall, floor, and ceiling surfaces dominate or where very large power levels are needed to attain the requisite sound pressure levels. These challenging spaces include arenas, museums, atria, airport concourses, rail stations, and similar "special-purpose" spaces. An assessment method has been referenced in Annex A of *NFPA 72* and is outlined in Annex A of IEC 60849, *Sound Systems for Emergency Purposes.*[8] The method relies on the measurement of the common intelligibility scale (CIS) for the system. The objective means of determining intelligibility, and hence calculating the CIS, are found in IEC 60268, *The Objective Rating of Speech Intelligibility by Speech Transmission Index.*[9] Subjective techniques are also available, as found in ANSI S3.2-1999, *Method for Measuring the Intelligibility of Speech over Communications Systems.*[10] These methods are generally employed by sound engineers in the design of commercial sound systems and can be applied equally well to fire alarm emergency voice systems.

Visible Notification Appliances. Visible notification appliances are inspected and tested to verify that they are still capable of achieving the design objectives of the fire alarm system. A light meter analogous to the sound-level meter is not in common usage as of this writing. This limits the inspection and testing to those procedures recommended by the manufacturer of the specific visible notification appliance used.

During the inspection and operational testing of the visible notification appliances, particular attention must be paid to any furnishings such as shelves, ornamental plants, lamps, banners, sculptures, and so on, or added construction features, for example, stairs, catwalks, ladders, lighting fixtures, and partitions, that interfere with a clear line of sight to the visible notification appliances. Furthermore, many systems rely on synchronization to ensure that the combined effective light pulse rate does not exceed 4 Hz, a frequency at which there is concern over the effect on those persons prone to seizures. Synchronization is achieved by different means from manufacturer to manufacturer; most manufacturers produce both synchronized and unsynchronized product. Consequently, where the design relies on synchronized visible notification, the inspection must verify that all of the visible notification appliances visible from any single viewing location are still synchronized or are separated by at least 55 ft (16.8 m).

INSPECTION, TESTING, AND MAINTENANCE SCHEDULING FOR SYSTEMS AND COMPONENTS

The requirements regarding the inspection, testing, and maintenance of fire alarm signaling systems must also be scheduled. Since different components have different failure rates, those with the higher failure rates require more frequent inspections and testing if the overall system reliability is to be kept at an acceptable level. Inspection, testing, and maintenance interval recommendations come from both the predicted reliability derived from failure rate analyses and from experience data derived over time. Manufacturers provide specific schedules for the service requirements for their products, and these must be observed where they establish a more frequent regimen of inspection, testing, and maintenance.

The objectives of an inspection program are to identify cases where the hazard area has changed, rendering the existing fire alarm system inappropriate for the hazard area, or some episode of physical abuse has occurred that has damaged the component, rendering it incapable of performing in a manner consistent with the system design. The frequency of these types of conditions is a function of the hazard area, not the inherent reliability of the system components. Consequently, some sites will require more frequent inspections due to the unique nature of the particular site. *NFPA 72* provides the required visual inspection frequencies, reproduced here as Table 14.5.2.

Testing of fire alarm system components occurs on a schedule that is less frequent than the inspections. The testing uncovers failures that are not apparent from a visual inspection and are generally attributable to the combined effect of the ambient conditions and the inherent failure rates of the components. There are applications where the testing frequency established in *NFPA 72* as a minimum compliance criterion is not adequate to achieve the required level of reliability. The effective reliability

TABLE 14.5.2 Visual Inspection Frequencies

Component	*Initial/ Reacceptance*	*Monthly*	*Quarterly*	*Semiannually*	*Annually*
1. Control equipment: fire alarm systems monitored for alarm, supervisory, and trouble signals					
(a) Fuses	X	—	—	—	X
(b) Interfaced equipment	X	—	—	—	X
(c) Lamps and LEDs	X	—	—	—	X
(d) Primary (main) power supply	X	—	—	—	X
2. Control equipment: fire alarm systems unmonitored for alarm, supervisory, and trouble signals					
(a) Fuses	X (weekly)	—	—	—	—
(b) Interfaced equipment	X (weekly)	—	—	—	—
(c) Lamps and LEDs	X (weekly)	—	—	—	—
(d) Primary (main) power supply	X (weekly)	—	—	—	—
3. Batteries					
(a) Lead/acid	X	X	—	—	—
(b) Nickel/cadmium	X	—	—	X	—
(c) Primary (dry cell)	X	X	—	—	—
(d) Sealed lead/acid	X	—	—	X	—
4. Transient suppressors	X	—	—	X	—
5. Fire alarm control unit trouble signals	X (weekly)	—	—	X	—
6. Fiber-optic cable connections	X	—	—	—	X
7. Emergency voice/alarm communications equipment	X	—	—	X	—
8. Remote annunciators	X	—	—	X	—
9. Initiating devices					
(a) Air sampling	X	—	—	X	—
(b) Duct detectors	X	—	—	X	—
(c) Electromechanical releasing devices	X	—	—	X	—
(d) Fire extinguishing system(s) or suppression system(s) switches	X	—	—	X	—
(e) Fire alarm boxes	X	—	—	X	—
(f) Heat detectors	X	—	—	X	—
(g) Radiant energy fire detectors	X	—	X	—	—
(h) Smoke detectors (excluding one- and two-family dwellings)	X	—	—	X	—
(i) Supervisory signal devices	X	—	X	—	—
(j) Waterflow devices	X	—	X	—	—
10. Guard's tour equipment	X	—	—	X	—
11. Combination systems					
(a) Fire extinguisher monitoring device/systems	X	—	—	X	—
(b) Carbon monoxide detectors/ systems	X	—	—	X	—
12. Interface equipment	X	—	—	X	—
13. Alarm notification appliances—supervised	X	—	—	X	—
14. Exit marking audible notification appliances	X	—	—	X	—

TABLE 14.5.2 Continued

Component	*Initial/ Reacceptance*	*Monthly*	*Quarterly*	*Semiannually*	*Annually*
15. Supervising station fire alarm systems—transmitters					
(a) DACT	X	—	—	X	—
(b) DART	X	—	—	X	—
(c) McCulloh	X	—	—	X	—
(d) RAT	X	—	—	X	—
16. Special procedures	X	—	—	X	—
17. Supervising station fire alarm systems—receivers					
(a) DACR*	X	X	—	—	—
(b) DARR*	X	—	—	X	—
(c) McCulloh systems*	X	—	—	X	—
(d) Two-way RF multiplex*	X	—	—	X	—
(e) RASSR*	X	—	—	X	—
(f) RARS*	X	—	—	X	—
(g) Private microwave*	X	—	—	X	—
18. Public fire alarm reporting system transmission equipment					
(a) Publicly accessible fire alarm box	X	—	—	X	—
(b) Auxiliary box	X	—	—	—	X
(c) Master box					
(1) Manual operation	X	—	—	X	—
(2) Auxiliary operation	X	—	—	—	X

*Reports of automatic signal receipt shall be verified daily.

Source: *NFPA 72®, National Fire Alarm Code®,* 2007 ed., Table 10.3.1, pp. 72-93–72-94.

of such a fire alarm system can be improved by implementing a more frequent testing program. *NFPA 72* provides the required testing frequencies, reproduced here as Table 14.5.3.

HOUSEHOLD FIRE WARNING EQUIPMENT

Household fire alarm systems have been implemented in a number of different ways. More recent design concepts correct the performance shortcomings of older design philosophies and reflect the improved performance of modern equipment.

NFPA 72 requires the monthly inspection and testing, per the manufacturer's instructions, of all smoke detectors in a household fire alarm application, regardless of whether those detectors are single-station units, interconnected multiple-station units, or detectors integrated into a complete household fire alarm system. This monthly testing should include a verification that all audible and visible notification appliances are operative. Furthermore, *NFPA 72* requires that household fire alarm systems, that is, systems consisting of detectors, notification appliances, and a control panel, be inspected and tested at least every three years by a qualified alarm technician with a procedure in compliance with the manufacturer's instructions.

UL 217, *Standard for Safety Single and Multiple Station Smoke Detectors,* allows a maximum failure rate of 4.0 f/mdoh for the detector circuitry.[11] This failure rate can be expressed as 1.0 failure per 250,000 device operating hours, or 1.0 failure per 8760 hr/yr × 28.5 yr, or 0.035 failures per year. The battery for the smoke detector can only operate the unit for one and a half years before it is depleted. The depletion of the battery is not included in the failure rate assigned to the battery. The failure rate for the household fire alarm is the failure rate per detector and the depletion rate for the battery multiplied by the number of units in the household. Assuming six detectors in the average house and a failure rate of $1 - (1 - 0.667)(1 - 0.035) = 0.679$, one obtains $6 \times 0.679 = 4.074$ failures per year for Λ. Using the equation developed earlier, that is,

$$R = e^{-\Lambda t}$$

where

R = Reliability of the system

e = Napierian logarithm base, 2.71828

Λ = Inherent failure rate of the system

t = Time period between performing recommended inspection and testing, 1/12 of a year or 0.0833 yr

$$R = e^{-4.074 \times 0.0833}$$

$$= 0.712 \text{ or } 71.2 \text{ percent}$$

TABLE 14.5.3 Testing Frequencies

Component	*Initial/ Reacceptance*	*Monthly*	*Quarterly*	*Semi-annually*	*Annually*	*Table 10.4.2.2 (NFPA 72) Reference*
1. Control equipment—building systems connected to supervising station						1, 7, 16, 17
(a) Functions	X	—	—	—	X	—
(b) Fuses	X	—	—	—	X	—
(c) Interfaced equipment	X	—	—	—	X	—
(d) Lamps and LEDs	X	—	—	—	X	—
(e) Primary (main) power supply	X	—	—	—	X	—
(f) Transponders	X	—	—	—	X	—
2. Control equipment—building systems not connected to a supervising station	—	—	—	—	—	1
(a) Functions	X	—	X	—	—	—
(b) Fuses	X	—	X	—	—	—
(c) Interfaced equipment	X	—	X	—	—	—
(d) Lamps and LEDs	X	—	X	—	—	—
(e) Primary (main) power supply	X	—	X	—	—	—
(f) Transponders	X	—	X	—	—	—
3. Engine-driven generator—central station facilities and fire alarm systems	X	X	—	—	—	—
4. Engine-driven generator—public fire alarm reporting systems	X (weekly)	—	—	—	—	—
5. Batteries—central station facilities						
(a) Lead/acid type	—	—	—	—	—	6b
(1) Charger test (Replace battery as needed.)	X	—	—	—	X	—
(2) Discharge test (30 minutes)	X	X	—	—	—	—
(3) Load voltage test	X	X	—	—	—	—
(4) Specific gravity	X	—	—	X	—	—
(b) Nickel/cadmium type	—	—	—	—	—	6c
(1) Charger test (Replace battery as needed.)	X	—	X	—	—	—
(2) Discharge test (30 minutes)	X	—	—	—	X	—
(3) Load voltage test	X	—	—	—	X	—
(c) Sealed lead/acid type	X	X	—	—	—	6d
(1) Charger test (Replace battery within 5 years after manufacture or more frequently as needed.)	—	X	X	—	—	—
(2) Discharge test (30 minutes)	X	X	—	—	—	—
(3) Load voltage test	X	X	—	—	—	—
6. Batteries—fire alarm systems						
(a) Lead-acid type	—	—	—	—	—	6b
(1) Charger test (Replace battery as needed.)	X	—	—	—	X	—
(2) Discharge test (30 minutes)	X	—	—	X	—	—
(3) Load voltage test	X	—	—	X	—	—
(4) Specific gravity	X	—	—	X	—	—
(b) Nickel/cadmium type	—	—	—	—	—	6c
(1) Charger test (Replace battery as needed.)	X	—	—	—	X	—
(2) Discharge test (30 minutes)	X	—	—	—	X	—
(3) Load voltage test	X	—	—	X	—	—
(c) Primary type (dry cell)	—	—	—	—	—	6a
(1) Age test	X	X	—	—	—	—

TABLE 14.5.3 Continued

Component	*Initial/ Reacceptance*	*Monthly*	*Quarterly*	*Semi-annually*	*Annually*	*Table 10.4.2.2 (NFPA 72) Reference*
(d) Sealed lead/acid type	—	—	—	—	—	6d
(1) Charger test (Replace battery within 5 years after manufacture or more frequently as needed.)	X	—	—	—	X	—
(2) Discharge test (30 minutes)	X	—	—	—	X	—
(3) Load voltage test	X	—	—	X	—	—
7. Power supply—public fire alarm reporting systems	—	—	—	—	—	—
(a) Lead/acid type batteries	—	—	—	—	—	6b
(1) Charger test (Replace battery as needed.)	X	—	—	—	X	—
(2) Discharge test (2 hours)	X	—	X	—	—	—
(3) Load voltage test	X	—	X	—	—	—
(4) Specific gravity	X	—	—	X	—	—
(b) Nickel/cadmium type batteries	—	—	—	—	—	6c
(1) Charger test (Replace battery as needed.)	X	—	—	—	X	—
(2) Discharge test (2 hours)	X	—	—	—	X	—
(3) Load voltage test	X	—	X	—	—	—
(c) Sealed lead/acid type batteries	—	—	—	—	—	6d
(1) Charger test (Replace battery within 5 years after manufacture or more frequently if needed.)	X	—	—	—	X	—
(2) Discharge test (2 hours)	X	—	—	—	X	—
(3) Load voltage test	X	—	X	—	—	—
(d) Wired system—voltage tests	X (daily)	—	—	—	—	7d
8. Fiber-optic cable power	X	—	—	—	X	13b
9. Control unit trouble signals	X	—	—	—	X	10
10. Conductors—metallic	X	—	—	—	—	12
11. Conductors—nonmetallic	X	—	—	—	—	13
12. Emergency voice/alarm communications equipment	X	—	—	—	X	21
13. Retransmission equipment (The requirements of 10.4.9 of *NFPA 72* shall apply.)	X	—	—	—	—	—
14. Remote annunciators	X	—	—	—	X	11
15. Initiating devices	—	—	—	—	—	14
(a) Duct detectors	X	—	—	—	X	—
(b) Electromechanical releasing device	X	—	—	—	X	—
(c) Fire extinguishing system(s) or suppression system(s) switches	X	—	—	—	X	—
(d) Fire-gas and other detectors	X	—	—	—	X	—
(e) Heat detectors (The requirements of 10.4.4.4 of *NFPA 72* shall apply.)	X	—	—	—	X	—
(f) Fire alarm boxes	X	—	—	—	X	—
(g) Radiant energy fire detectors	X	—	—	X	—	—
(h) System smoke detectors—functional test	X	—	—	—	X	—
(i) Smoke detectors—sensitivity testing in other than one- and two-family dwellings (The requirements of 10.4.4.2 of *NFPA 72* shall apply.)	—	—	—	—	—	—

(continued)

TABLE 14.5.3 Continued

Component	*Initial/ Reacceptance*	*Monthly*	*Quarterly*	*Semi-annually*	*Annually*	*Table 10.4.2.2 (NFPA 72) Reference*
15. Initiating devices *(continued)*						
(j) Single- and multiple-station smoke alarms (The requirements for monthly testing in accordance with 10.4.5 of *NFPA 72* shall also apply.)	X	—	—	—	X	—
(k) Single- and multiple-station heat alarms	X	—	—	—	X	—
(l) Supervisory signal devices (except valve tamper switches)	X	—	X	—	—	—
(m) Waterflow devices	X	—	—	X	—	—
(n) Valve supervisory switches	X	—	—	X	—	—
16. Guard's tour equipment	X	—	—	—	X	24
17. Combination systems						
(a) Fire extinguisher monitoring device/systems	X	—	—	—	X	21a
(b) Carbon monoxide detectors/systems	X	—	—	—	X	21b
18. Interface equipment and fire safety functions	X	—	—	—	X	22, 23
19. Special hazard equipment	X	—	—	—	X	17
20. Alarm notification appliances	—	—	—	—	—	15
(a) Audible devices	X	—	—	—	X	—
(b) Audible textual notification appliances	X	—	—	—	X	—
(c) Visible devices	X	—	—	—	X	—
21. Exit marking notification appliances	X	—	—	—	X	16
22. Off-premises transmission equipment	X	—	X	—	—	—
23. Supervising station fire alarm systems—transmitters	—	—	—	—	—	18
(a) DACT	X	—	—	—	X	—
(b) DART	X	—	—	—	X	—
(c) McCulloh	X	—	—	—	X	—
(d) RAT	X	—	—	—	X	—
24. Special procedures	X	—	—	—	X	25
25. Supervising station fire alarm systems—receivers	—	—	—	—	—	19
(a) DACR	X	X	—	—	—	—
(b) DARR	X	X	—	—	—	—
(c) McCulloh systems	X	X	—	—	—	—
(d) Two-way RF multiplex	X	X	—	—	—	—
(e) RASSR	X	X	—	—	—	—
(f) RARSR	X	X	—	—	—	—
(g) Private microwave	X	X	—	—	—	—
26. Public fire alarm reporting system transmission equipment	—	—	—	—	—	—
(a) Publicly accessible fire alarm box	X	—	—	X	—	8a
(b) Auxiliary box	X	—	—	—	X	8b
(c) Master box						8c
(1) Manual operation	X	—	—	X	—	
(2) Auxiliary operation	X	—	—	—	X	

Source: *NFPA 72®, National Fire Alarm Code®,* 2007 ed., Table 10.3.1, pp. 72-106–72-108.

Thus, generally available residential smoke detectors when installed, inspected, and tested monthly per the manufacturer's instructions and *NFPA 72* can be expected to provide a functional reliability of a nominal 71.2 percent.

CRITICALITY OF INSPECTION, TESTING, AND MAINTENANCE ON THE EFFECTIVENESS OF THE SYSTEM

Electronic systems are, at this time, the only systems on which solid reliability data exist in the quantity and quality that allow one to develop a predictive computational method to assess various design alternatives. All physical systems have failure modes, and each system component demonstrates failure at a finite rate over the majority of its operational lifetime. Nonelectrical fire alarm systems are not necessarily more reliable than electronic systems. It is possible to compute the reliability of electrical systems only because good failure rate data exist.

The one concept to be gained from reliability analysis and prediction computations is that all systems are destined to fail, given enough time. It is a probability so high as to approach a *certainty.* A performance-based design cannot be deemed complete until it includes a quantitative assessment of the likelihood that the system will perform as designed. This assessment is dependent on the service and maintenance interval for the system. With long time intervals between inspection and testing procedures, the probability increases that the system will be operating with some type of unnoticed impairment during the intervening time periods. Obviously, the time during which the system is partially and perhaps even completely impaired increases with the increase in the time interval between each exercise of the required inspection and testing. Consequently, no performance- or objective-oriented design is complete without a preventive maintenance program that includes inspection and testing on an interval that is predicated upon the size and complexity of the system itself.

Consider the example fire alarm system presented earlier. A system consisting of 10 smoke detectors, a notification appliance, and a control panel produced a predicted failure rate of 0.3824 failures per year. Table 14.5.4 shows the effect of varying inspection and testing intervals on the reliability of this system. The reliability of the system and, hence, the needed maintenance interval are dependent on the size and complexity of the system. Table 14.5.5 demonstrates the impact that increasing system size has on the needed inspection and testing interval in order to maintain a uniform design reliability of 71.2 percent (0.712). Clearly, as the size or complexity of the system increases, the frequency of the inspection and testing program must be increased to retain a constant reliability. If the inspection and testing frequency is held constant, then the reliability of the system decreases each time the size and complexity of the system are increased.

TABLE 14.5.4 System Reliability Dependent on the Inspection and Testing Interval System (actual values based on the reliability data used in the example)

Inspection and Testing Interval	*Reliability*
Quarterly	0.904
Semiannually	0.826
Annually	0.682
Biannually	0.465

TABLE 14.5.5 Inspection and Testing Interval Necessary to Maintain a 71.2 Percent Reliability as System Size Is Increased (values based on the reliability data used in the example)

System Size	Λ	*Inspection and Testing Interval (yr)*
10 detectors, 1 notification appliance	0.3824	0.93
20 detectors, 2 notification appliances	0.5278	0.68
40 detectors, 4 notification appliances	0.8554	0.42
80 detectors, 8 notification appliances	1.4860	0.24

Tables 14.5.3, 14.5.4, and 14.5.5 demonstrate the importance of the inspection, testing, and maintenance program. A system cannot be expected to achieve the design objectives if the inspection, testing, and maintenance program does not reflect the reliability objectives of the design. The failure to maintain a system in a manner consistent with the design assures the owner/operator of the protected site that the fire alarm system will *not* achieve the design objective.

SUMMARY

The essential objectives of a fire alarm system—life safety, property protection, and continuity of the site's mission—will be achievable in the event of a fire only if the alarm system functions properly. An inspection, testing, and maintenance regimen employed at regular intervals is essential for ensuring the reliable performance of the fire alarm system. Because at some point in its lifetime any system will suffer a failure, a schedule of inspection, testing, and maintenance must be developed based on the size and complexity of the system. The four main system elements—design, equipment, installation, and maintenance—are critical to the reliability of the system and should be the focus of the regimen.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on inspection, testing, and maintenance of fire alarm systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems*
NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 72®, National Fire Alarm Code®
NFPA 110, *Standard for Emergency and Standby Power Systems*
NFPA 111, *Standard on Stored Electrical Energy Emergency and Standby Power Systems*
NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*

Chapter 6

Household Fire-Warning Equipment

Revised by
Daniel T. Gottuk

Chapter Contents

Residential Fire Detector Research
Codes and Standards
Elements of Residential Fire Protection
Types of Systems
Detection System Components
Installation Practices
Maintenance and Testing

Key Terms

heat detector, household fire alarm, Indiana Dunes Report, interconnected smoke alarm, intrusion detection, multiple-station alarm, notification appliance, Operation School Burning, single-station alarm, smoke alarm

America's fire death rate is dominated by fires in U.S. homes. Household warning systems, specifically smoke alarms, provide a rare combination of effectiveness and affordability in reducing the risk of death in home fires. The dominance of U.S. homes in fire deaths is demonstrated each year. In recent years, four of every five deaths have occurred in U.S. homes, as have over 90 percent of fire deaths in structures. Analyses by the National Fire Protection Association (NFPA) indicate that when a fire occurs, having detectors present cuts the chances of dying nearly in half. If every home had an operable smoke alarm, home fire deaths would be reduced by an estimated 36 percent, approximately 1100 lives saved per year.[1]

Although heat detectors for residential use have been available since 1921, field tests have shown that they are not as effective as smoke alarms in detecting fires in the home. Fire tests in residential occupancies have shown that measurable amounts of smoke have preceded measurable amounts of heat in almost all cases. In the other cases, the smoke and heat appeared almost simultaneously. Consequently, codes and standards have mandated the use of smoke alarms because they provide a greater level of protection.

Residential smoke alarms were relatively expensive when they began to appear in the marketplace in the late 1960s. In 1970, however, the introduction of a battery-operated smoke alarm, along with line-powered (AC-powered) smoke alarms, initiated a period of public acceptance of single-station residential smoke alarms. In 2004, 96 percent of U.S. homes had at least one smoke alarm.[2]

This chapter discusses the reasons household fire-warning systems are needed, the history of residential fire-warning systems, research into system effectiveness, the importance of having a system in the home and how to make the best use of it, and the importance of an effective escape plan. The types of systems and detectors will also be covered, along with guidelines for installing and testing household fire warning equipment.

For related topics see the following chapters in Section 14: Chapter 1, "Fire Alarm Systems"; Chapter 2, "Automatic Fire Detectors"; Chapter 3, "Notification Appliances"; and Chapter 9, "Carbon Monoxide Detection in Residential Occupancies."

RESIDENTIAL FIRE DETECTOR RESEARCH

Early Test Programs

Current performance requirements and installation practices for residential fire detectors are the result of knowledge and experience gained from several test programs. The first major test programs using heat and smoke detectors were Operation School Burning and Operation School Burning No. 2, conducted by the Los Angeles (California) City Fire Department in 1959 and 1961, respectively. These tests had a major impact on fire protection and proved two significant points:

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(1) smoke alarms could provide a high level of life safety due to their fast response to a fire, and (2) detectable quantities of smoke usually precede detectable levels of heat.

The next significant test series was conducted by the Bloomington (Minnesota) Fire Department in May 1969. Although all detectors employed in the Bloomington tests were system-connected units, the results of these tests—such as time of detector response, order of response as a function of detector and fire type, and conditions at time of response—correlated well with subsequent tests.

Four Levels of Protection Concept

In 1974 NFPA members adopted a major change to NFPA 74, *Household Fire Warning Equipment.* Prior to this, NFPA 74 required that, in addition to a smoke alarm, a home be protected with a heat detector in every major room of the dwelling. The 1974 edition recognized two facts: (1) the mandatory total system approach was impractical for the majority of the population, and (2) heat detectors were not the most effective detectors for the home. Therefore, an NFPA committee developed a matrix of four "levels of protection" from which the homeowner could choose. The four levels of protection concept was finally adopted by the NFPA membership, but not without a fight. The opposition (principally some fire chiefs and fire marshals) felt that they could not recommend anything less than complete protection, and that effectiveness of Level 4, which provided for one or two smoke alarms in the home, had not been proved by test data.

Indiana Dunes Report and Minneapolis Fire Department Study

Based on this latter argument, the National Bureau of Standards (NBS) (now the National Institute of Standards and Technology [NIST]) contracted with IIT Research Institute and Underwriters Laboratories Inc. (UL) to provide just such test data. The results of the first phase of this test program were published in August 1975 under the title "Detector Sensitivity and Siting Requirements for Dwellings." The study, more commonly known as the Indiana Dunes Report, showed, in fact, that Level 4 coverage was inadequate under certain conditions. The report recommended that at least one smoke alarm on each story of the residence be used as a minimum requirement. This system was referred to as the "every level" smoke detection system. Based primarily on the results of this report, NFPA 74 was revised again in 1978 by dropping the four levels of protection and adopting a minimum required system of one smoke alarm on each story (floor level) of a home. Also, because of the slow response of heat detectors when compared to smoke alarms, NFPA 74 no longer permitted the use of heat detectors as the prime method of fire detection.

Shortly after publication of the first phase of the Indiana Dunes Report, the Minneapolis Fire Department conducted a similar independent study on smoke alarm performance. The Minneapolis and Dunes tests were very similar in that each was conducted in a two-story house with basement, with detectors installed on each floor. Likewise, the conclusions of the Minneapolis and Dunes tests were essentially identical; thus, the Minneapolis tests provided an independent verification of many of the conclusions of the Dunes tests. Over the next quarter century, a number of additional studies would be conducted on the performance of home smoke alarms and all confirmed the earlier studies.[2–4]

CODES AND STANDARDS

It is well known that compliance with strong smoke detection laws offers the potential of significant reduction in loss of life and property from fire. For uniformity, laws adopted statewide are preferable to local ordinances. Most states and communities now require residential occupancies from single-family dwellings to hotels and motels to be equipped with smoke alarms. Although most model building codes and life safety codes include specific requirements for smoke alarms in residential occupancies, the development of these requirements has generally originated from what is now known as *NFPA 72®*, *National Fire Alarm Code®*.

In 1993, NFPA 74 was combined with the other fire alarm system standards and now appears as Chapter 11 of *NFPA 72*. In the latest editions of the code, Chapter 11 was changed to address equipment requirements rather than occupancy-specific requirements; this is reflected in the current technical committee and chapter name, Single- and Multiple-Station Alarms and Household Fire Alarm Systems. Chapter 3 of *NFPA 72* provides definitions for these different types of fire alarm equipment. A single-station alarm is a device that includes a sensor and notification appliance in one unit and a power source that is typically a self-contained battery and/or connection to an AC circuit in the dwelling. A multiple-station alarm is a single-station alarm that has the means to be interconnected to other alarms (that is, when one sounds an alarm signal, all connected devices will sound). A household fire alarm system is different in that it incorporates a fire alarm control panel to power and monitor smoke detectors and often to provide alarm notification through separate appliances. Smoke detectors are different from smoke alarms in that they require a panel to operate, whereas a smoke alarm is a stand-alone device.

In 1989, NFPA 74 added requirements for interconnected smoke alarms in new construction, and in the 1993 conversion of NFPA 74, the requirement for a smoke alarm in each sleeping room in new construction was introduced in *NFPA 72*. This change specifically addressed the protection of the occupant of the sleeping room. Detection of smoke from a fire within the sleeping room by an alarm outside the sleeping room, especially with the door closed, has been a problem. The interconnection of devices located in bedrooms also provided better distribution of the alarm signal, particularly for fires detected by alarms remote from the sleeping area. In 2007, *NFPA 72* was changed to require a uniform set of installation requirements regardless of occupancy age (i.e., new or existing). These changes are partly enabled by several new wireless technologies that permit smoke alarms to be interconnected.

ELEMENTS OF RESIDENTIAL FIRE PROTECTION

The many elements of fire safety and fire protection can be grouped into six elements that need to work together in an integrated system for best results:

1. Fire prevention
2. Prevention of unusually rapid early growth or spread
3. Automatic detection
4. Automatic suppression
5. Compartmentation or containment
6. Evacuation or escape

Each is important individually, and all are interdependent in any successful residential fire protection scheme. From the perspective of household early warning systems, these six elements need to be examined in terms of the essential steps that make the automatic detection element successful and the other fire elements that can render detector protection unsuccessful. Taking them in order, one may focus on prevention of ignition and of rapid early growth or spread under a generic title of minimizing fire hazards.

Although automatic residential sprinkler systems are gaining acceptance for new home construction and are mandated in several jurisdictions, the general consensus among fire safety professionals is also to recommend automatic smoke detection in accordance with *NFPA 72,* Chapter 11, "Single- and Multiple-Station Alarms and Household Fire Alarm Systems," providing a minimum level of life safety protection.

Minimization of Fire Hazards

Preventing a fire before it occurs is always easier than detecting it once it has occurred; therefore, minimizing fire hazards in and around the home is the first key element to minimizing hazards. This prevention includes care in the selection and use of all potential heat sources (e.g., tobacco products, heating and cooking equipment, the electrical system, appliances, lighting appliances) and fuel sources (e.g., furnishings and contents, interior finishes). Preventing rapid early growth or spread implies special attention to removing all unessential flammable liquids and other highly combustible items from the home. Further, it should also mean strict adherence to and enforcement of building and fire codes in the construction of residential occupancies, use of only low-flame-spread materials for interior finish, and use of low-flammability or fire-retardant-treated materials in residential furnishings. Proper compartmentation is also essential to slow the fire as it moves from zone to zone, extending the time to hazardous exposure for most occupants.

It must be realized that, if a fire develops rapidly enough, residential smoke alarms may not provide enough time for the occupants of a dwelling to escape before their exit routes are cut off. Therefore, it is highly dangerous for people to be careless, thinking smoke alarms will protect them from their carelessness.

Installation of Smoke Alarms

Full effectiveness for household warning systems means the right number of smoke alarms, located in the right places and operating properly. As required by *NFPA 72,* Chapter 11, "Single- and Multiple-Station Alarms and Household Fire Alarm Systems," the acceptable minimum consists of one smoke alarm in each bedroom, outside each sleeping area and one on each habitable story, including the basement of the home. It is also recommended that the minimum package be supplemented by additional smoke alarms in other areas as needed. For example, a smoke alarm could be located in living and family rooms, and smoke or heat alarms could be located in the kitchen, attached garage, attic, and furnace room. Each additional alarm could provide more time for the family to escape. When more than one smoke alarm is installed, the alarms should be arranged so all of the devices sound when any one device detects smoke. This chain of alarms can be done by installing either multiple-station smoke alarms or a complete household fire alarm system with smoke detectors, panel, and notification appliances.

Equally as important as the installation are proper care and maintenance of the equipment. Each residential smoke alarm comes with an owner's booklet describing the necessary maintenance procedures. A smoke alarm with a dead or missing battery will be useless in a fire. In fact, NFPA analysis of reported fires has shown roughly one-third of U.S. home smoke alarms are not working when fires occur, typically because of dead or missing batteries. This is a major obstacle to achieving full success with home smoke alarms. Because of the battery problem, *NFPA 72* and many local building codes mandate use of both primary AC and secondary battery power, with an exception in some cases that allows an alarm with a nonrechargeable, nonreplaceable 10 year life battery.

Development of Escape Plan

The last key element in residential fire protection is the development and practice of a family escape plan. Remember, residential smoke alarms can do no more than warn occupants of a fire in the home; they will not extinguish the fire. Also, depending on the speed at which the fire is developing, the amount of time available for escape may be limited. It is critical that all occupants leave the home immediately and *call the fire department once outside the home.* Delay can be fatal if people take extra time, for example, to get dressed, gather valuables, or look for pets. Also, it is important that everyone have an alternative way out of each room in case the primary exit is blocked by fire. There must be a prearranged outside meeting place so everyone will know that the entire family has escaped the fire. Any delay can be fatal, including reluctance to climb out of windows. Any actions that increase the risk of death can be fatal, such as reentering a burning home to look for people who may very well have already escaped.

Information on how to formulate a family escape plan is contained in the homeowner's booklet provided with each residential smoke alarm and by NFPA in its EDITH (Exit Drills in the Home) materials.

TYPES OF SYSTEMS

Residential fire detection may range in size from one single-station smoke alarm in an apartment, manufactured home, or recreational vehicle to a centrally wired system containing numerous detectors and separate alarm notification appliances. The fire detection system may be combined with a burglar alarm system and an emergency medical alert system. It may be connected to an alarm monitoring company by leased telephone lines or by a digital alarm communication transmitter. The number of devices and the complexity of the system are determined, on the low

end, by the minimum acceptable for a given dwelling, and, on the high end, by the extent of the occupant's needs and finances. *NFPA 72* states that the minimum requirements for detection can be met either by the installation of smoke alarms or with a fire alarm system using smoke detectors.

Single- and Multiple-Station Smoke Alarms

A single-station alarm (Figures 14.6.1, 14.6.2, 14.6.3, and 14.6.4) is a self-contained device that consists of a detecting element, electrical control components, an alarm-sounding appliance, and a provision for connection to a separate power supply source (such as the direct AC wiring of a home) or an integral power source or both.

A direct-wired type, when provided with one or more additional wires for interconnection with other similar smoke alarms, is referred to as a multiple-station smoke alarm (Figure 14.6.5). When interconnected according to the instructions provided, an alarm from any one of the interconnected smoke alarms activates the alarm in all the devices. This is important because the smoke alarm near the bedrooms should sound when a smoke alarm located in another area senses smoke. New technologies now allow for wireless interconnected battery-powered smoke alarms, as well as AC-powered ones (Figure 14.6.6). These wire-

FIGURE 14.6.1 Single-Station Photoelectric Smoke Alarm (Source: Gentex Corporation)

FIGURE 14.6.3 Ion Ten-Year Battery Smoke Alarm (Source: Kidde: A UTC Fire and Security Company)

FIGURE 14.6.2 AC Battery Backup Smoke Alarm (Source: Kidde: A UTC Fire and Security Company)

FIGURE 14.6.4 Ion with Backup Battery Smoke Alarm (Source: Kidde: A UTC Fire and Security Company)

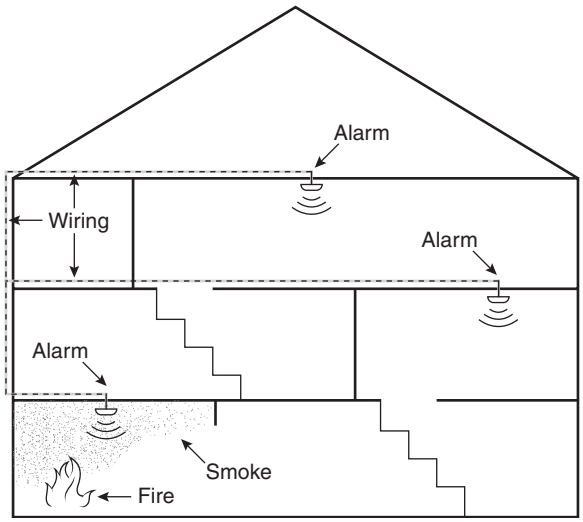

FIGURE 14.6.5 Multiple-Station Smoke Alarms with Hardwired Interconnection (Source: Hughes Associates, Inc.)

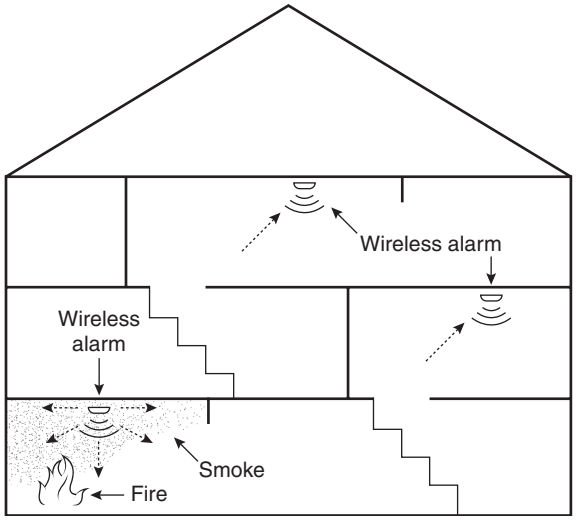

FIGURE 14.6.7 Wireless Interconnected Smoke Alarms (Source: Hughes Associates, Inc.)

FIGURE 14.6.6 Wireless Interconnected Battery-Powered Smoke Alarm (Source: Kidde: A UTC Fire and Security Company)

less interconnected alarms can be easily used in existing homes (Figure 14.6.7), whereas previously to convert to interconnected alarms generally required expensive rewiring of the house. The number of smoke alarms that are permitted to be interconnected is limited to 12 by *NFPA 72,* Chapter 11. Additional multiple-station alarms, other than smoke alarms, are permitted with limitations as specified in Chapter 11 of *NFPA 72.*

NFPA 72, Chapter 11, "Single- and Multiple-Station Alarms and Household Fire Alarm Systems," requires that low-power wireless systems comply with all of the requirements given in *NFPA 72,* Chapter 6, "Protected Premises Fire Alarm Systems."

Wireless systems are composed of smoke alarms with built-in low-power radio transmitters. System operability, including battery condition, is verified by periodic transmission via repeaters, when necessary, to a central receiver. Both repeaters and the central receiver operate from AC power with standby battery, thus providing a reliable system.

Household Fire-Warning System

In addition to single- and multiple-station alarms, there are household fire-warning systems similar in makeup and operation to the local fire alarm systems described in *NFPA 72,* Chapter 6, "Protected Premises Fire Alarm Systems." Such a system typically consists of a fire alarm control unit (panel) that derives main power from the AC house wiring and contains a rechargeable standby battery capable of operating the system for at least 24 hours (Figure 14.6.8). In addition, this system uses smoke detectors and heat detectors of the system-connected type. Some detectors include a self-contained sounder for alarm.

The fire alarm system can also have separate alarm notification appliances, such as bells, horns, or electronic sirens. The control unit also might have provision for connection to an automatic digital dialer, central station, or television cable to transmit the alarm to a point beyond the household. Where the system is connected to a supervising station, *NFPA 72,* Chapter 11, permits the station to verify alarm signals prior to reporting them to the fire service provided that the verification process does not delay the reporting by more than 90 seconds.

The most popular method for such a connection is digital communication. *NFPA 72* permits (1) operation with only one telephone line and (2) programming to call only one digital alarm control receiver (DACR) number.

Combination Systems

Both wired and wireless household fire alarm systems often include intrusion detection in addition to fire alarm functions.

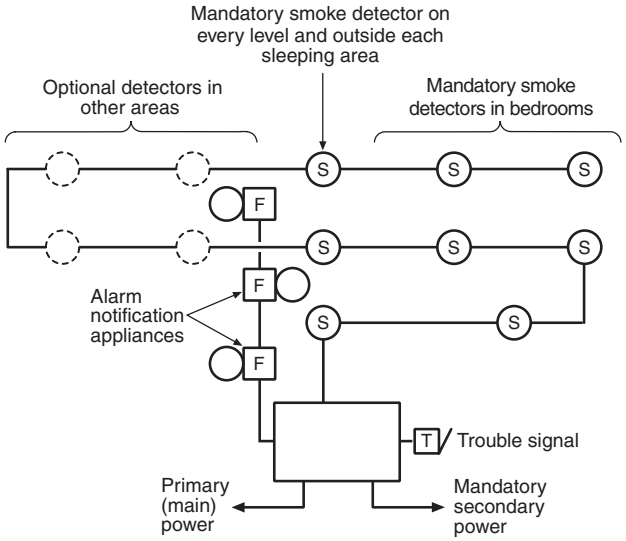

FIGURE 14.6.8 Typical Household Fire Alarm System, with Separate Control Panel

This could make the system more cost effective. In combined systems, the fire alarm signal must take precedence over the intrusion detection alarm signal. The audible alarms are required to be distinctive so the homeowner can immediately discern the difference between a fire and an intrusion. In addition, a system that provides for transmission of alarms to a point beyond the household by means of a digital dialer will sometimes have a medical alert feature that can be used to summon medical help.

DETECTION SYSTEM COMPONENTS

Smoke Alarms

Single- and multiple-station alarms may be of either the ionization or photoelectric type. Tests have shown that listed smoke alarms of either the ionization or photoelectric type should provide adequate warning to the occupants for most residential fires. It might be noted that, as a class, ionization alarms generally respond faster to open flaming fires than photoelectric alarms. Conversely, the photoelectric alarms generally respond faster to smoldering fires. Because residential occupancies experience both flaming and smoldering fires, an extra margin of occupant safety might be achieved if the home were equipped with one alarm of each type. However, the number of potential nuisance alarms may increase. Both types of smoke alarms are subjected to, and must pass, the same test fires for listing by a testing laboratory. Typical test fires are described in UL 217, *Standard for Safety Single- and Multiple-Station Smoke Detectors,* and ANSI/UL 268, *Standard for Safety Smoke Detectors for Fire Protective Signaling Systems.*

Alarm Notification Appliances

A smoke alarm sounds an audible alarm at the device itself. *NFPA 72* requires that a device should provide at least 15 dBA above the maximum ambient sound level at the ear of the sleeping person or at least 75 dBA, whichever is greater. Per the design and listing requirements, the sound level output of an alarm must be at least 85 dBA at a distance of 10 ft (3.05 m). This should be sufficient to meet the *NFPA 72* requirements and to alert most sleeping people as long as the alarms are located per the current code requirements.[5,6]

If alarms are not installed per the current codes (i.e., interconnected and located on every floor and in every bedroom), occupants should be aware of the factors that may impact the effectiveness of alarms to wake people. Long distances between the alarm and the bedroom, closed bedroom doors, a noisy appliance in the bedroom such as an air conditioner or humidifier, or impaired hearing could prevent an occupant from being awakened by the alarm. This possibility is why it is important for alarms to be interconnected and to sound in the bedroom.

A wired or wireless household fire alarm system normally has an alarm-notification appliance circuit for connection of various appliances, such as fire alarm bells, horns, or electronic sirens. These devices can produce higher sound levels and can be located independently of the detectors. They can be clearly audible throughout the house or even outside, where neighbors might hear the alarm. Regardless of the type of devices installed in the home, alarm signals should be measured in each bedroom.

Several studies have examined the response of adult occupants to the smoke alarm signals; Bruck[7] provides a summary of these. In general, an unimpaired sleeping adult will awake quickly to a smoke alarm signal that reaches the occupants at a sound level of 55 to 60 dBA. Recent studies have also shown that most older adults, who as a population group generally experience hearing loss compared to the general population, will wake to smoke alarms installed per the current codes.[6,8] Other studies[9,10] have specifically investigated the waking effectiveness of smoke alarms with children. These studies have shown that a 55 to 60 dBA signal will not reliably wake children between the ages of 6 and 15 years. Even at a sound level of 89 dBA at the pillow, 71 percent of 6- to 10-year-olds and 29 percent of 11- to 15-year-olds slept through alarms. Children under 6 years old would be even less likely to awaken than the 6-year-olds.[11] Due to the deep sleep behavior of children, many simply will not awaken to smoke alarms, even at extremely loud levels of 123 dBA[12] that can be painful to individuals. The key point to understand: children will likely sleep through an alarm and will need assistance to escape from a fire. Though parents typically realize that they have difficulty in waking their children at times, many parents seem quite surprised when presented with these findings. Occupants must plan to help both young children and people with disabilities that will impede waking or escape.

INSTALLATION PRACTICES

Smoke Alarm Location Guidelines

Alarms should be located on the ceiling, at least 4 in. (102 mm) from the wall, or on the side wall, 4 to 12 in. (102 to 305 mm) from the ceiling to the top of the device (Figure 14.6.9). On floors containing bedrooms, the ceiling of the hallway serving

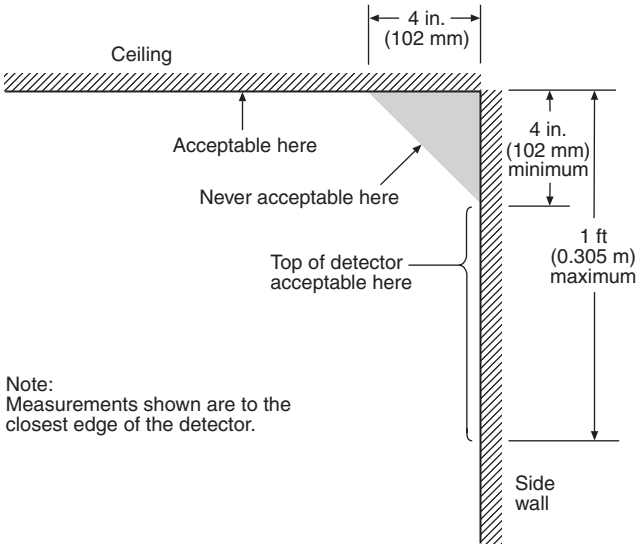

FIGURE 14.6.9 Proper Mounting of Smoke Alarms

the bedrooms is the usual alarm location. On other floors, alarms should be located near the stairways to intercept smoke rising from lower floors. Smoke alarms (indicated by a backward "S" in the figures) must be located on each story (Figure 14.6.10) as well as between the sleeping area and the rest of the family living unit (Figure 14.6.11). A smoke alarm should be provided to protect each sleeping area in addition to smoke alarms required in bedrooms (Figure 14.6.12).

Alarms should be located no closer than 3 ft (0.9 m) from heating vents so that air issuing from the vent will not blow the

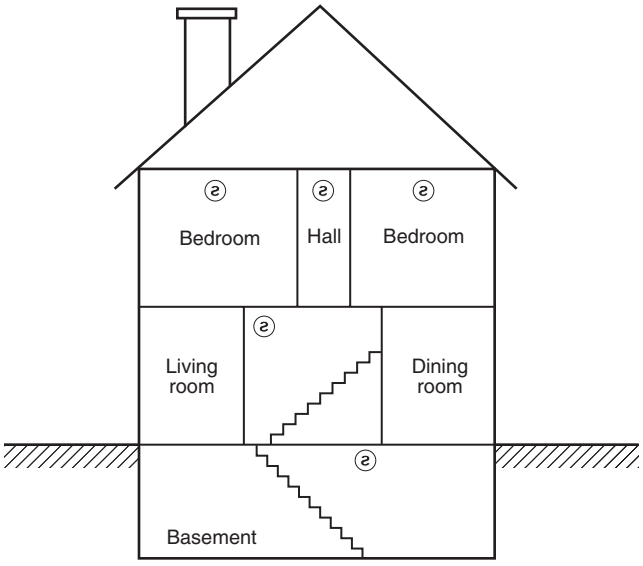

FIGURE 14.6.10 Smoke Alarm to Be Located on Each Story (Source: *NFPA 72®, National Fire Alarm Code®,* 2007 ed., Figure A11.5.1[d])

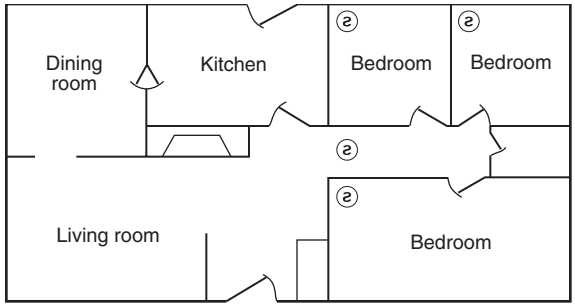

FIGURE 14.6.11 Smoke Alarm to Be Located in Each Bedroom and Between Sleeping Area and Rest of Family Living Unit (Source: *NFPA 72®, National Fire Alarm Code®,* 2007 ed., Figure A11.5.1[b])

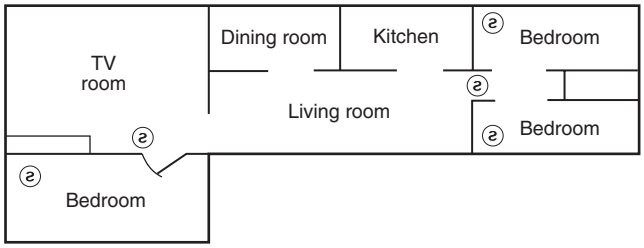

FIGURE 14.6.12 Smoke Alarm to Be Located in Each Sleeping Area as Well as in Each Bedroom (Source: *NFPA 72®, National Fire Alarm Code®,* 2007 ed., Figure A11.5.1[c])

smoke away from the alarm. Some smoke alarms are not suitable for location within kitchens, because of false alarms from cooking vapors. Chapter 11 of *NFPA 72* requires that smoke alarms located within 20 ft (6.1 m) (horizontally) of cooking appliances incorporate temporary silencing (hush) features or be of the photoelectric type. Also, some smoke alarms are not permitted in garages, where automobile exhaust might cause alarms, or in attics or other unheated spaces where extremes of temperature or humidity might affect their operation. Before a smoke alarm is installed in any of these locations, its specifications should be checked to ensure it is appropriate for the intended area.

Another consideration is the temperature of the mounting surface. If a smoke alarm is installed on a surface that can be even a few degrees warmer or cooler than the room temperature, its response may be delayed by the cold or warm air layer at the mounting surface. Smoke alarms should not be installed on uninsulated exterior walls, ceilings below uninsulated attics, or ceilings containing radiant heating coils. If the alarm is colder than the air temperature and if the relative humidity is high, condensation of water vapor may occur in the alarm and either produce a false alarm or disable the alarm. Condensation, dust, and insects are three of the most common things that lead to alarm malfunction.

Special Considerations for the Disabled

In general, households with disabled or elderly occupants need a higher level of protection to provide additional escape time. If the disabled person could not escape without assistance, provisions should be made for someone to provide help. Alarms that signal to remote receivers could be used, for instance, to sound the alarm in a neighbor's home. For hearing-impaired occupants, some alarms can be connected to bed vibrators, flashing strobes (see *NFPA 72,* Chapter 4, "Notification Appliances for Fire Alarm Systems"), or fans to provide tactile or visual as well as aural stimulation (Figure 14.6.13).

MAINTENANCE AND TESTING

Maintenance

Household fire-warning equipment should be maintained in accordance with the recommendations of the equipment manufacturer. In general, this means little more than keeping the equipment clean and free of dust and replacing the batteries when needed. Alarms should never be disconnected due to nuisance alarms. If a smoke alarm sounds a nuisance alarm caused by cooking, the problem can typically be corrected either by moving the alarm to another location, farther from the cooking source, or by replacing it with a smoke alarm that is not as sensitive to cooking smoke.

Testing

The importance of testing smoke alarms cannot be emphasized too strongly. Smoke alarms are basically electronic devices, and, because all devices will fail at some time, the failure rate projection of a smoke alarm can be estimated. From these projections, the life expectancy or the average failure rate of the smoke alarm can be determined. *NFPA 72* requires that smoke alarms in one- and two-family dwellings be replaced when they fail to respond to the operability test (i.e., pushing the test button) or after 10 years from the date of manufacture. This recommendation was developed in part on the estimate that after 10 years there will be a 30 percent chance that a unit will fail.

FIGURE 14.6.13 Combination Photoelectric Smoke Alarm/Strobe Light (Source: Gentex Corporation)

To reduce the period of time that a smoke alarm could be out of service because of failure, the alarm that has failed can best be identified by periodic testing and then replaced. The following example is merely illustrative and is not indicative of currently available units, but it demonstrates the importance of periodic testing of smoke alarms. Assuming a 10-year life of a smoke alarm and a predicted failure rate of 4 failures per million hours of operation (which is the minimum listed design requirement for alarms), if the alarm is never tested, the residents could be unprotected for 276 weeks, or over 5 years. On the other hand, with an alarm that is tested monthly, residents will be unprotected only for at most 5 weeks. This example has a built-in factor of 2 weeks, so a defective alarm can be removed and a replacement can be obtained and installed. However, a defective alarm should be replaced immediately. This example dramatically shows how important it is to test a smoke alarm frequently.

Guidelines for testing smoke alarms can be found in *NFPA 72,* Chapter 10, "Inspection, Testing, and Maintenance," and in the manufacturers' instructions.

SUMMARY

In the United States, fire deaths occur predominantly in the home, and thus household fire-warning equipment is essential for life safety. The types of systems and smoke alarms vary according to minimum standards and the occupants' specific needs. Installation of an adequate fire-warning system and ongoing maintenance and testing ensure that the system will work effectively. Fire protection in the home also involves formulating an escape plan and minimizing fire hazards.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on household fire warning equipment discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 70, *National Electrical Code®*
NFPA 72®, *National Fire Alarm Code®*
NFPA *101®*, *Life Safety Code®*

Chapter 7

Fire Protection Surveillance and Security Services

Lawrence J. Wenzel

Chapter Contents

Fire and Security Services
Management of Security Services
Communications Equipment
Security Patrol Tour Supervision
Security Service Functions
Patrol Routes and Rounds
Security Officers
Evaluating Fire Security Service

Key Terms

fire alarm system, patrol, security, security officer, security tour, surveillance, watchclock

Effective fire protection at a commercial or industrial facility depends on the degree to which the management of the facility is committed to providing an appropriate level of fire loss prevention and fire control. Once the hazards of the facility have been identified and evaluated, and built-in fire protection systems have been provided to offset the impact of those hazards, the protection features must be consistently managed.

A fire alarm system is a management tool that oversees fire protection surveillance. The fire alarm system can monitor the availability of other fire suppression systems. It may also monitor the activities of guards making fire patrol tours.

The fire alarm system should monitor all fire alarm initiating devices. Examples are manual fire alarm boxes; heat, smoke, radiant energy, fire-gas, or other fire detection devices; and the discharge and supervisory device connections for automatic sprinkler systems and other fire suppression or extinguishing systems, such as dry chemical, foam, foam-water, water mist, carbon dioxide, and other gaseous agents.

The fire alarm system should also monitor pertinent supervisory initiating devices for both "off-normal" and "restoration to normal" conditions. These include the following:

- Any automatic sprinkler control valve 2½ in. (63.5 mm) or larger
- Dry pipe or preaction valve high and low air pressure
- Fire protection water tank or reservoir level
- Fire protection water-pressure tank high and low air pressure
- Electric-driven fire pump operation, power failure, loss of phase, and phase reversal
- Diesel-engine-driven fire pump operation, controller switch in a position other than "automatic," engine or controller problems, and failure of the battery charger
- Steam-driven fire pump operation and steam availability
- Low public water system pressure when fire protection systems are fed from a dead-end public water main, or when the public water system is deemed unreliable

In addition, for those geographic areas subject to freezing winter temperatures, the fire alarm system should monitor low temperature for the following:

- Buildings protected by wet pipe automatic sprinklers
- Dry pipe, deluge, or preaction valve closets
- Fire pump rooms
- Fire protection water tanks

Section 14, Chapter 4, "Fire Alarm System Interconnections," discusses these interfaces into the fire alarm system in detail. In order to ensure immediate attention to signals generated by the protected premises fire alarm system, to ensure that management is promptly notified of the nature of these signals, and to keep proper records of signals received, it may be wise to connect the fire alarm system to a central station, proprietary, remote station, or combination auxiliary and remote station fire alarm system. This will ensure that signals receive attention at all times.

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For those facilities where some type of security service is included, and intended to be part of the overall fire protection surveillance, the protected premises fire alarm system can also monitor the patrol tours made by security officers.

For related topics, see the following chapters in Section 14: Chapter 1, "Fire Alarm Systems"; Chapter 4, "Fire Alarm System Interconnections"; Chapter 5, "Inspection, Testing, and Maintenance of Fire Alarm Systems"; and Chapter 10, "Security and Intrusion Detection Systems."

FIRE AND SECURITY SERVICES

Containment of fire to its area of origin involves several factors, one of the most important of which is early detection. During normal business hours, most occupiable areas (i.e., areas other than concealed spaces, exterior surfaces) are continuously or routinely occupied or observed by the people in the areas. (Intermittent occupation might apply to areas such as lavatories, hallways, or closets.) By their presence, the occupants provide fire protection surveillance because they are able to detect a fire when it occurs. A carelessly discarded cigarette, for example, may ignite the contents of a wastebasket; that fire may spread until the entire building is involved. However, someone who discovers the fire while it is still in its incipient stage may be able to extinguish it with a portable fire extinguisher. In some cases, the occupants can also detect conditions, such as a malfunctioning machine, that might lead to a fire. Similarly, increased security surveillance is vital in guarding against fires of incendiary origin.

Security officers generally serve three purposes in helping to protect a property against fire loss: (1) watch the property at times when the management is not present; (2) facilitate and control the movement of persons into, out of, and within the property; and (3) carry out procedures for the orderly conduct of some operations on the property, such as the shipping and receiving functions. Security officers may be facility employees or employees of outside firms that provide these services on a contract basis, or a combination of both. The duties of these individuals may be supplemented or, in some cases, replaced in part by various approved fire and security protective signaling systems.

MANAGEMENT OF SECURITY SERVICES

In conjunction with fire and explosion suppression systems and various other management programs for loss prevention and control, a comprehensive program of fire protection and security surveillance provides a means of (1) continually monitoring the facility for conditions that might lead to a fire or explosion, (2) promptly notifying the public fire department or private fire brigade that a fire or explosion has occurred, and (3) effectively inhibiting unauthorized access to the facility. Management must determine how this surveillance can be best achieved.

In concept, security officers should patrol thoroughly all unoccupied areas of a facility often enough to be able to detect conditions likely to result in a fire or other emergency. These patrols should be supervised in some way so management can verify that the security officer is indeed making the patrol tours.

The highly protected risk (HPR) property insurance carriers generally recommend that the first patrol tour begin within 30 minutes of vacancy and that subsequent patrol tours be made every hour at night and every other hour (bihourly) during the day. Each tour should not exceed 45 minutes in actual length, allowing the security officer at least 15 minutes of rest.

Management Roles

Management should develop a written surveillance plan for both fire protection and security in the facility. To do this, the property manager should determine which areas of the facility are unoccupied during both working and nonworking hours. The property manager should also designate a management representative who will be responsible for overseeing the surveillance program. It is very important that management retain supervisory control of surveillance to maintain program integrity. This representative should review surveillance reports daily and evaluate changes in the facility that might require modification of the surveillance plan.

The facility's fire loss prevention and control manager should be consulted during the establishment of procedures to be followed by security officers. Procedures and instructions to security officers should be geared to the specific actions required. General instructions or superficial training are of little value. Meaningful, specific instructions cannot be prepared, however, without an investment of both time and thought by those who manage the property. Management should also establish a clear line of succession in the event of absences. Even when there are only two security officers employed, one should be designated as the leader.

Supervision of security officers provided under contract with outside firms should be through the designated representatives of the company providing the security service. In the contract for services or supplementary documents, the company should be given details as specific and complete as possible regarding the services expected.

Security Officer Equipment

Management is responsible for providing security officers assigned to patrol a property with adequate equipment and information with which to safeguard their own health and safety. Potential situations that must be considered include the following:

- Sudden illness or injury while the security officer is alone at the property
- Possibility of a security officer being overpowered by an intruder
- Development of a situation requiring management decisions

The first situation can be addressed by equipping security officers with devices for prompt, efficient communication, such as portable two-way radios, which would allow them to summon aid.

In the second situation, an intruder may prevent the security officer from using any communications equipment. It then becomes necessary to have a system or procedure whereby the security officer's failure to transmit a signal or meet a predetermined schedule will be investigated promptly.

Third, situations that require management decisions may arise at times when the property is attended by security officers only. Such decisions may involve conditions ranging from the unscheduled arrival of merchandise or supplies to anonymous bomb threats. Security officers must have instructions and the means for contacting management personnel.

COMMUNICATIONS EQUIPMENT

Security officers should be provided with facilities for communication within and outside the property. A control center should provide a point with which officers may communicate, and the center should have communications facilities to points outside the property. Such a center is needed even when there is very limited security service. For example, in a facility with only one or two officers, this control center might simply be a room with a telephone. Even with a complete fire alarm and security system covering all areas of the property, a control center on the property is necessary.

If an emergency voice/alarm communication fire alarm system is provided, security officers may communicate with the building fire command station by using the fire warden telephones.

Where the equipment for security officer communications, including officers on watch patrol, requires that signals from officers be monitored, the control center should be provided with an operator. Additional operators needed to staff a 24 hour operator service should be provided at the control center, according to the character of security service provided. For some services, runners, or security officers who can be dispatched to investigate signals, should also be provided.

A directory of names and telephone numbers (including any other information to assist in making emergency calls to the outside) should be kept at the control center in a visible index or other quickly accessible form. This directory should give information about the public fire and police departments, key management personnel, and other outside agencies that may have to be contacted in an emergency.

SECURITY PATROL TOUR SUPERVISION

Off-premises security officer supervisory service designed to report the performance of a security officer may be provided by central station, proprietary, or remote station fire alarm systems. Portable watchclocks may also be used to supervise the security officer if centralized, immediate supervision is not required.

Tour supervisory systems generally consist of security officer patrol tour supervisory initiating devices of some type and a means of recording signals initiated from these devices. Many companies refer to this equipment as "guard tour supervisory" devices. Two types of supervisory service systems are (1) compulsory and (2) noncompulsory, based on whether the guard follows a compulsory preset pattern or not.

Compulsory Tour Supervisory Systems

This system involves one or more "active" security patrol tour supervisory initiating devices that are installed in conjunction with several "passive" security patrol tour supervisory initiating devices. These devices are arranged so that the security officer must progress in a fixed route from one station to another. Ordinarily, the officer carries some type of device called a "key," which can be a "wand" that serves as a handheld computer with a memory function. The initiating devices can be arranged so that the passive devices condition the key so that it may operate the next device, whether that device is active or passive. In addition to conditioning the key for the next device, active initiating devices also either transmit a signal to an on- or off-premises central recording location or cause a signal to be recorded inside the key, which indicates the date and time that the active initiating device was operated. This system is particularly useful when, because of the nature of the facility, it is essential that the security officer follow a carefully prescribed route. One disadvantage to this system from a security standpoint is that the tour may not be varied. This is sometimes felt undesirable because a potential intruder who is observing the movement of the security officer might be able to readily discern a pattern to the officer's movement.

In many compulsory tour systems, the security officer initiates a starting signal at the beginning of a round and initiates a finishing or completion signal at the end of the round. All of the other stations in between would be passive initiating devices. A fixed schedule of starting and finishing times is arranged in advance when a compulsory tour is monitored by an off-premises facility. If the security officer fails to either begin or end a round within the prescribed times, on the expiration of a "grace" period of usually no more than 10 or 15 minutes in length, the off-premises monitoring facility will initiate action. Normally, an attempt will be made to contact the security officer by telephone. On failure to reach the officer, the off-premises monitoring facility will normally dispatch the police department and notify the management of the facility that the security officer has failed to respond.

When a compulsory tour system is used in conjunction with a proprietary fire alarm system, the process works much the same, except that, since the receiving location is normally located on the protected premises, the operator at the receiving location will be more readily able to determine why the guard has not begun or ended a round.

Noncompulsory Tour Supervisory Systems

In this system, all of the initiating devices are active. The security officer progresses from station to station, with each initiating device indicating the date and time of the officer operating the station. By following the progression of signals, the off-premises or on-premises monitoring station can follow the progress of the security officer during the course of the round. In some cases, combination manual fire alarm boxes/officer patrol tour

supervisory initiating stations are grouped in the same physical housing. These stations are arranged so that they may be actuated by any person to indicate a fire, but may also be operated by a security officer to indicate the progress of a tour.

Delinquency Reporting Systems

Some compulsory or noncompulsory tour supervisory systems are arranged so that, rather than reporting every time the security officer operates an active initiating device, the system only transmits a signal when the officer has failed to operate the device within a prescribed time period. Such delinquency reporting systems are utilized when it is desired to reduce the amount of signal traffic associated with the officer patrol tour supervisory system. Many remote station fire alarm systems that supervise security officer patrol tours are arranged in this fashion.

Telephone, Radio, and Other Voice Reporting Systems

Occasionally, a security officer patrol tour is supervised by means of the guard reporting from a specific location by means of a voice reporting system. Probably the most common system uses a telephone system equipped with calling subset identification. When the security officer initiates voice communication over such a system, the system indicates and records the specific location from which the officer is calling. Other systems employing means of voice communication, including radio systems, can also be used. In some radio systems, a tour supervisory initiating device must be inserted into the radio before the security officer establishes patrol tour contact. This device transmits a digital code that gives a specific location, thus indicating that the officer is at the prescribed tour station.

Portable Watchclocks

In many cases, management determines that it is not necessary to provide immediate supervision of the security officer patrol tours, and elects to provide retrospective security officer patrol tour supervision by means of a stationary or portable watchclock. Figure 14.7.1 shows a portable watchclock. This clock provides an embossed record tape, made directly from type on the recording key. The tape has 24 ruled segments and is synchronized with the clock mechanism. If a security officer fails to punch in, the omission is indicated by a prominent white space on the tape. This clock indicates when it was opened. The records from these devices must be reviewed the following day to determine that the officer has indeed made the prescribed tours and operated all of the tour supervisory initiating devices. Although this method lacks the immediacy of the other tour supervisory methods, it is sufficiently cost-effective to be the most common tour supervisory method employed. Traditionally, a spring-wound clock mechanism—either at a single location in the case of a stationary watchclock or in a portable case that the guard can carry from location to location—is used to drive some type of recording medium. The most common recording medium is a paper disk or a paper tape. In this case, the tour supervisory initiating devices are embossing keys that must be inserted into the portable watchclock and turned, making their impression on the paper tape. The tour supervisory initiating devices for the stationary clock are usually some type of electric switch or, in at least one design, a magneto that must be operated by the officer, causing the stationary clock to record the specific location.

(a)

(b)

FIGURE 14.7.1 Portable Watchclock: (a) Front view; (b) Interior view (Source: Detex Corp.)

The portable watchclock can be an effective supervisory tool if access to the clock is carefully controlled so that the security officer cannot have access to the internal mechanism of the watchclock. This means that someone in management should actually open the clock and retrieve the record each day. To safeguard against premature opening of the clock, a telltale device places a mark on the paper disk or tape whenever the clock is opened. Even when a security service company provides the security officer patrol tour service, it is advisable to have management supervise the retrieval of records from the watchclock to prevent any collusion between upper-level officers, such as sergeants or lieutenants, and the guards themselves.

Another type of portable watchclock uses computer-based equipment to supervise the route and timing, if desired, of the security officer. As shown in Figure 14.7.2, manufacturers have developed scanners that read the station and store the station's information in the handheld unit carried by the officer. The equipment shown in Figure 14.7.2 is typical of the hardware available for use by security officers, who carries the handheld "wand" unit or a similar device and passes it over data strips or

FIGURE 14.7.2 Computer-Based Equipment for Route Supervision (Source: ProxiGuard)

similar points installed throughout the premises (Figure 14.7.3 and 14.7.4). The use of handheld wands or similar readers is very much the norm for security officers to register their rounds. The handheld unit is then attached to some type of download device for computer storage of the report (Figure 14.7.5).

The security officer can then download the information from the handheld unit to a data-gathering unit designed specifically for this equipment, or in some cases to a computer outfitted with the corresponding program information. Other designs allow the handheld unit to be placed on a base unit that will produce a printed report. Components may be as simple as a bar code strip fixed to a piece of equipment to more sophisticated electronic stations. This type of equipment gives management a number of options to help detail the activities of the security officer.

FIGURE 14.7.3 Security Officer Registering Rounds (Source: ProxiGuard)

FIGURE 14.7.4 Handheld Wand (Source: ProxiGuard)

SECURITY SERVICE FUNCTIONS

A sufficient number of security officers should be provided to accomplish the needed services. If officers are assigned to other part-time duties in addition to their regular security officer services, these duties should be arranged so they will not interfere with regular officer duties.

Control of Pedestrians and Vehicles

Fireguard service can facilitate and control the movement of persons within a property when the property requires such service. Duties in this category include the following:

- Preventing the entry of unauthorized persons who might set a fire or do damage to the facility
- Controlling the activities of people authorized to be on the property, but who may not be aware of procedures established for the prevention of fire
- Controlling pedestrian and vehicular traffic during exit drills, and evacuating the property or parts of it during emergencies
- Controlling gates and vehicular traffic to facilitate access to the property by the public fire department, members of a private fire brigade, and off-duty management personnel in case of fire or emergency

Control of Operations

Security service should be established to carry out certain procedures for the orderly conduct of operations on the property, including procedures for fire loss prevention and control, both by personnel associated with the property and outside contractors. Duties in this category include the following:

- Promptly discovering a fire and calling the public fire department (also the fire brigade of the property, where there is such a brigade)
- Operating equipment provided for fire control and extinguishment *after* giving the alarm and before the response of other persons to the alarm
- Monitoring signals of fire alarm systems
- Patrolling routes chosen by management to ensure surveillance of all the property at appropriate intervals

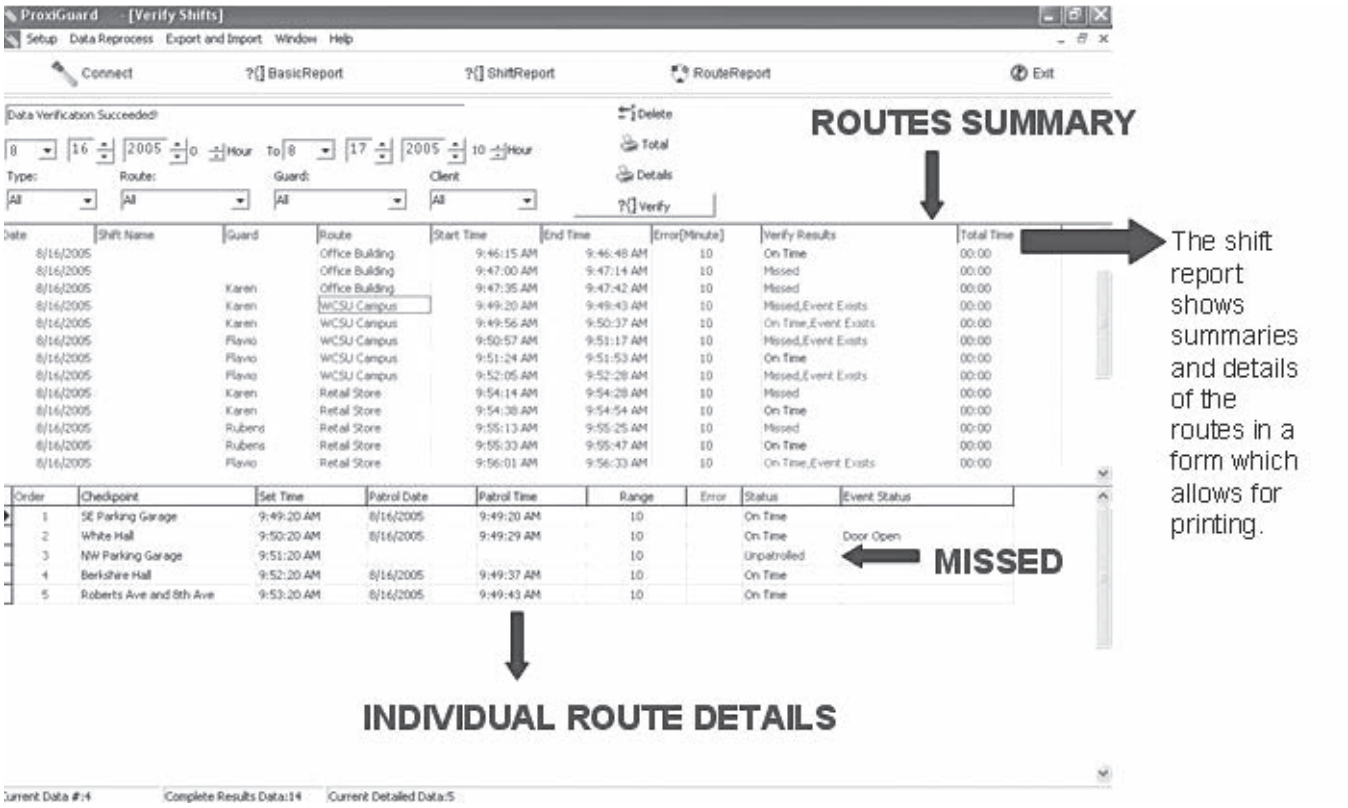


FIGURE 14.7.5 Report Generated from Information Downloaded from Handheld Wand

- Starting up and shutting down certain equipment when no other personnel are provided for this purpose
- Checking permits for "hotwork," including cutting and welding, and standing by to operate fire-extinguishing equipment when necessary
- Detecting conditions likely to cause a fire, such as leaks, spills, and faulty equipment
- Detecting conditions likely to reduce the effectiveness with which a fire may be controlled, such as portable fire extinguishers not in place, sprinkler valves not open, and water supplies impaired
- Performing operations to ensure that fire equipment will function effectively including, for example, testing automatic sprinkler and other fixed fire protection systems, including fire pumps, and other equipment related to these systems and assisting in the maintenance of this equipment; checking portable fire extinguishers and fire hose and assisting in pressure tests and maintenance service on these items; testing fire alarm systems; and checking equipment provided on any fire apparatus and carrying out the periodic tests and maintenance operations required for the apparatus

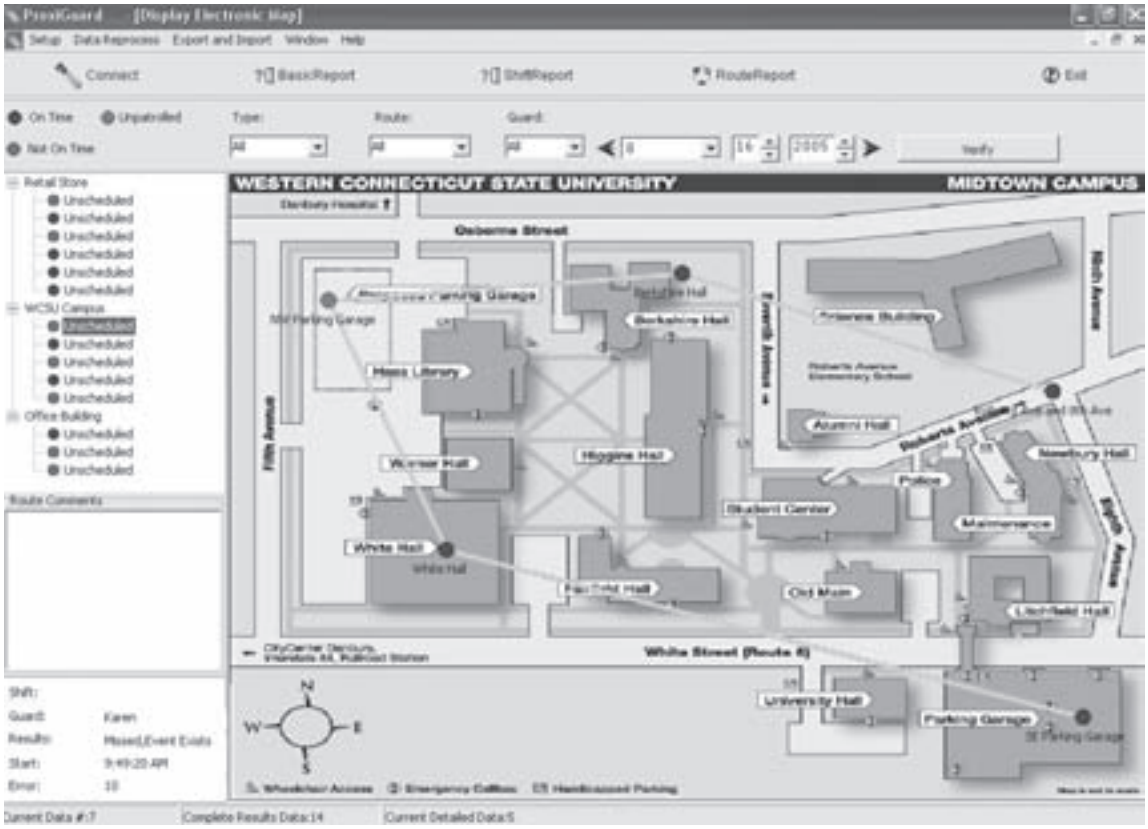
PATROL ROUTES AND ROUNDS

Each route to be patrolled should be laid out by the responsible manager. The security officer responsible for each route should be given instructions on all details of the route, and what is expected in covering it (Figure 14.7.6). The route should be laid out to prevent shortcuts so that the security officer is required to pass through the entire patrol area. A reasonable rest period between rounds must be provided.

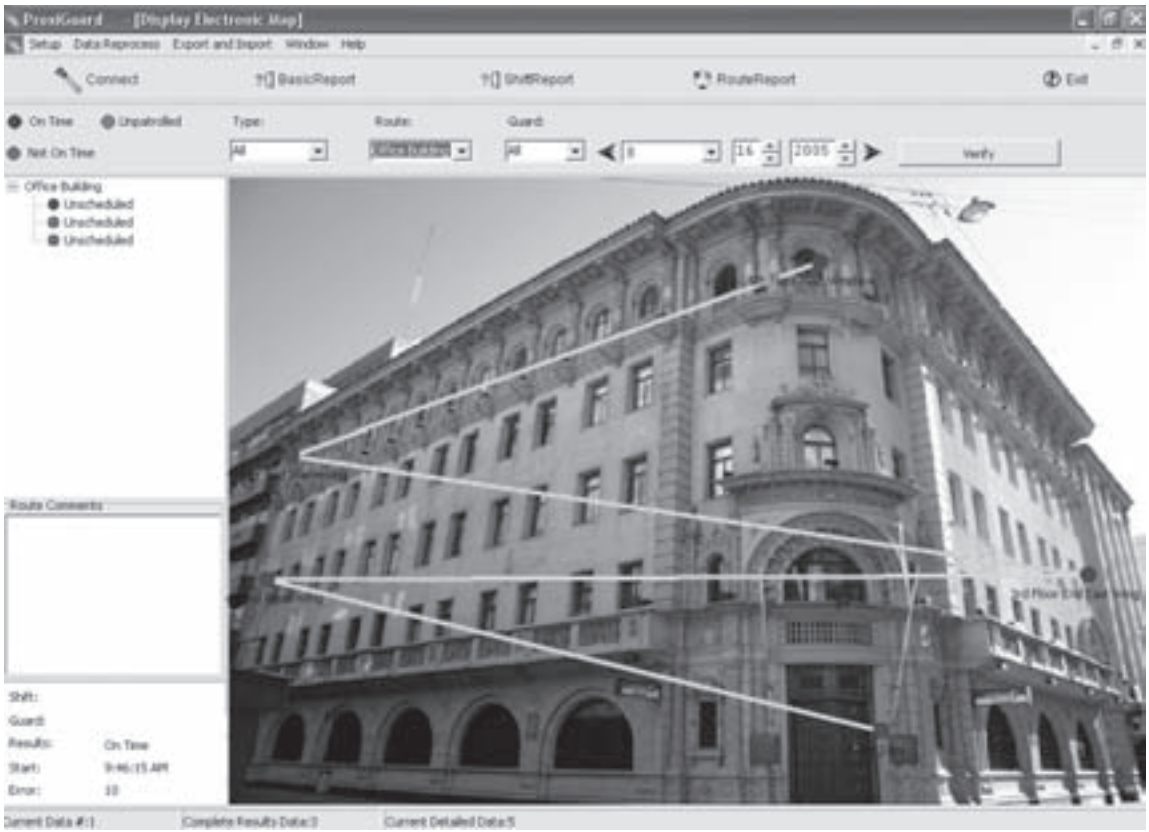
Security officers should make rounds at intervals determined for the particular situation by management. When operations in the property are normally suspended, rounds should be made hourly, unless management is willing to accept rounds at less frequent intervals. When there are special conditions, such as the presence of exceptional hazards or when protection is impaired, management should institute as many additional rounds as necessary to meet the fire safety requirements of such conditions.

The first round of a patrol should begin as soon as possible after the end of activities of the preceding work shift. The officers should be instructed to make a thorough inspection of all buildings or spaces on the route during their first round. Their instructions should cover the following:

- Outside doors and gates should be closed and locked. Windows, skylights, fire doors, and fire shutters should be closed.
- All oily waste, rags, paint residue, rubbish, and similar items should be removed from buildings or placed in approved containers.
- All fire apparatus should be in place and not obstructed.
- Aisles should be clear.
- Motors or machines carelessly left running should be shut off and reported.



(a)



(b)

FIGURE 14.7.6 (a) Route Map of Security Officer Path; (b) Route Map Superimposed on a Building (Source: ProxiGuard)

- All offices, conference rooms, and smoking areas should be checked for carelessly discarded smoking materials.
- All gas and electric heaters, coal and oil stoves, and other heating devices on the premises should be checked.
- All hazardous manufacturing processes should be left in a safe condition. The temperature of dryers, annealing furnaces, and similar equipment that continue to operate during the night, holidays, and weekends should be noted on all rounds.
- Hazardous materials, such as gasoline, rubber cement, and other flammable and highly volatile combustibles, should be kept in proper containers or removed from buildings.
- All normally open sprinkler control valves should be open, with gauges indicating proper pressures. Gauges not open should be reported immediately.
- During cold weather, all rooms should be checked to determine if they are heated properly.
- All water faucets and air valves found leaking should be closed. If leaks cannot be stopped, the condition should be reported.
- Particular attention should be given to new construction or alterations that may be in progress.

SECURITY OFFICERS

Selection and Contracts

Management should require individuals considered for security officer service to satisfactorily pass a character investigation. This investigation should attempt to evaluate the individual's reliability, self-control, and potential loyalty to the employer. Applicants for a security officer position should be fingerprinted and particulars of any police records obtained. The local police should be furnished with this information, should corroborate it, and should ask for checks by other police agencies. The fingerprint data should be cleared with state, national, or appropriate international agencies that maintain clearing facilities for police records. All applicants for a position as a fire or security officer or patrol person should be required to state any military service record and to submit evidence of such service that may assist in an evaluation of the individual's suitability for security officer service.

Contracts for security officer service should include a provision that the company furnishing security officer service will replace any employee who, in the judgment of the company purchasing the service, is not qualified.

Qualifications and Examinations

Management should be satisfied that individuals considered for security officer service are mentally alert and have good powers of observation, intelligence, and judgment. Investigation should attempt to evaluate the individual's personality and temperament. Such an evaluation is more realistic than arbitrarily testing education or intelligence or setting an age limit. Very young people may not qualify because they have not acquired a sense of responsibility or judgment. Very old people may have impaired alertness. Individuals should be sought who are known to be "clear-headed" in an emergency.

Officers should be required to pass an annual written examination dealing with information about the property protected and procedures for fire loss prevention with which they are expected to be familiar. Management should also require that individuals considered for security officer service pass an examination to determine whether they are physically able to perform the guard duties to which they will be assigned. Officers should also be required to pass an annual physical examination. The officers do not need to be athletes, but they should not have a heart condition or other physical ailment that might work to their disadvantage in moments of stress.

Training

Management should establish a continuing training program for its officers. Its scope should be established by the manager or by a fire loss prevention and control manager acting for the manager. Courses for security officers and fire fighters, available through training programs of vocational training agencies, schools, universities, and other training and educational agencies, should be considered in any training program for security officer.

Management should require officers to have completed at least elementary courses of instruction in the use of portable fire equipment and emergency first aid. The time spent in such preliminary training should be a minimum of two working days in each subject. During service, security officers should be given not less than the equivalent of two full working days per year of training to increase their knowledge and experience in the use of portable fire extinguishers, first aid, and other useful training. Officers should be required as part of their training to participate in appropriate meetings devoted to prefire planning with operating personnel. Security officers can help accomplish this by working together with the public fire department when it establishes its plan for the premises.

Management should require security officers to know the location of portable fire extinguishers, hand hoses, standpipes and hydrants, valves controlling sprinkler systems, inside riser valves, post-indicator valves, and sectional valves in the property's own water system. They also should know how to start fire pumps. Officers also need to know the location and purpose of valves controlling water for purposes other than fire protection, and valves controlling steam, gas, and other services. Management should require security officers to know the locations of dangerous machinery or materials and inform them of hazardous manufacturing processes, especially those continuing during the night, holidays, or weekends.

EVALUATING FIRE SECURITY SERVICE

There are several items to be considered when evaluating fire security service.

Tour Records

Management's representative should ensure the following:

- All unoccupied areas of the facility are included in each tour.
- All key stations or tour supervisory transmitters in each tour have been recorded clearly in a regular hourly pattern at night and in a bihourly pattern during the day.
- Tours last no longer than 45 minutes, allowing for a rest period of at least 15 minutes each hour.

- Tours begin within one half-hour of the time the area becomes unoccupied and continue to within one half-hour of the resumption of occupancy.
- The "telltale" of a portable or stationary watchclock is recording each time the clock is opened. Look for indications that the clock has been opened more than once a day or at unusual times. This might indicate that unauthorized persons have access to a clock key.

Basic reports on security officer tours can take many forms. Figure 14.7.7 shows a report generated in spreadsheet format.

Inspecting Tour Supervisory System Initiating Devices

Key stations, tour supervisory transmitters, or intermediate stations should be inspected once a month to ensure they are firmly attached and, if required, sealed with a "tamper" seal, and have not been relocated or removed. The key should be checked for damage. If there is evidence of tampering, the key stations, tour supervisory transmitters, or intermediate stations should be checked more often and suitable action taken.

Evaluating Security Officers

Management should expect, and is entitled to receive, security officer service of the highest quality. Officers must be conscientious in the performance of their duties, note and report all infractions of company regulations, and closely follow the orders given to them. When evaluating security officers, management should consider the following:

1. Security officers hold positions of trust, which require individuals who are physically able, mentally alert, and morally responsible. Therefore, their physical and emotional stability should be evaluated by appropriate management personnel.
2. Security officers must be sufficiently intelligent, calm in the face of an emergency, mature with sound judgment, and possess the physical stamina required for the job.
3. A sufficient number of security officers should be provided to maintain proper surveillance in the facility. It is undesirable for officers to be assigned part-time duties unrelated to surveillance. If they are so assigned, however, these duties must not interfere with surveillance responsibilities.
4. Security officers should receive full support of management in the performance of their duties.
5. When the officers are facility employees, management should establish the scope of the service and provide necessary training and supervision for the guards.
6. If a contract security service is used, management should not assume that it will be adequate. Rather, management should prepare detailed specifications and investigate the ability of prospective contractors to meet these specifications. When

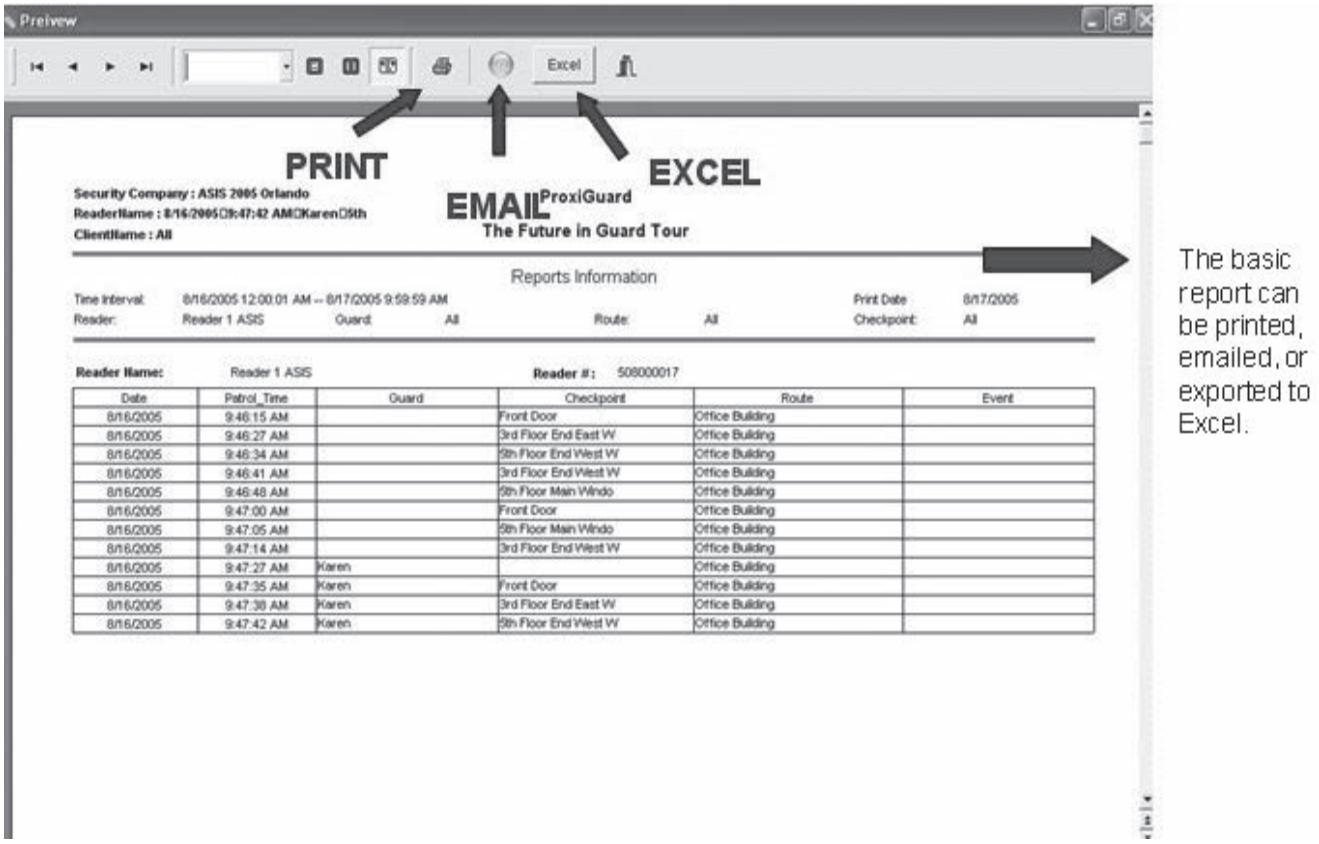


FIGURE 14.7.7 Security Officer Tour Report (Source: ProxiGuard)

the contract has been met, management should make sure that its intent is being carried out.

7. Initial and continued training of officers should be by a formal, comprehensive, written program covering all applicable protection procedures. The following must be met by each guard:
   - Be acquainted with the general nature of the facility's operations and possess specific knowledge of any hazardous operations
   - Be familiar with all of the facility's manual and automatic fire protection equipment. Security officers should be especially aware of the location of all sprinkler valves and know which area each controls. Officers should periodically accompany the person making fire protection equipment inspections, in order to gain a working knowledge of facility protection features and hazards.
   - Be familiar with the location and operation of manual fire alarm boxes and other means of transmitting fire alarms. Such means should be provided throughout the facility so guards can easily report a fire.
   - Be taught to notify the fire department *before* taking any other action
   - Be taught how to admit public fire apparatus to the property and how to direct fire department officers to the location of the fire
   - Be taught to properly notify company officials when an emergency occurs or when potential trouble is observed
   - Be taught to maintain a shift log and to prepare reports to management of observations made and actions taken during tours
8. Security officer service should be integrated into the overall emergency planning program.
9. General and special instructions and other data required by the officers should be written down and kept up-to-date.

Detecting and Reporting Fires

While making regular tours throughout the facility, officers must be alert for all emergencies, paying special attention to known hazardous areas. Security officers are in a position not only to detect and correct unsafe conditions that might develop into or contribute to a serious fire, but also to discover an incipient fire. Therefore, the officers should be familiar with the fundamentals of fire control and with the proper use of all available extinguishing equipment.

The importance of notifying the fire department *before* taking any other action should be stressed in security officer training. Officers should report any situation that may endanger the facility—for example, an exposing fire in adjacent properties. Any unusual condition that the officers cannot correct without assistance must be reported immediately to the proper official so the situation can be remedied without undue delay. Such situations include the interruption of sprinkler service or the failure of heating equipment.

Encountering Natural Hazards

In addition to carefully following written emergency plans, security officers must be resourceful and capable of applying common sense to any unusual conditions, such as "natural" hazard threats, they may encounter. If the facility is being subjected to freezing weather, for example, the guard should be alert to those areas of the facility where fire protection systems or process equipment might be vulnerable to freezing. Such areas should be checked frequently to ensure the heating system is properly maintaining the temperature necessary to avoid damage. If a thermometer is unavailable, a resourceful guard might set out a small container of very cold water to observe whether the area is approaching a dangerously low temperature. See NFPA 601, *Standard for Security Services in Fire Loss Prevention.*

SUMMARY

A fire alarm system in a commercial or industrial facility can monitor a variety of conditions and instruments related to fire protection, including alarm initiating devices, supervisory initiating devices, and environmental conditions such as low temperatures. The fire alarm system can also monitor the patrol tours of the security service. The fire alarm system should be connected to a location that ensures the signals receive immediate attention. The extent of the fire alarm system and security service must be determined by management based on the level of fire protection deemed necessary for the particular facility. The security officers must be supplied with a comprehensive surveillance plan and proper communication equipment in order to perform their duties effectively.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire protection surveillance and security services discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 72®, National Fire Alarm Code®
NFPA 601, *Standard for Security Services in Fire Loss Prevention*

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Chapter 8

Gas and Vapor Detection Systems and Monitors

John M. Cholin

Chapter Contents

Terminology
Sensors
Fixed Gas Detection Systems
Portable Gas Monitoring Instruments

Key Terms

carbon monoxide detector, fire alarm system, flammable gas, flammable vapor, gas detection, hazardous (classified) location, resistive-thermal device, sensor

Two concerns drive the use of gas and vapor detection systems and monitors. First, the existence of flammable gases or vapors represents (1) an elevation in the potential for a fire, either in and of itself as the concentration reaches the critical value sufficient to support a flame; or (2) an indication of a leak, implying an immediate potential of loss of containment of a large quantity of fuel. Second, there is a life safety concern whenever breathing air is contaminated with gases or vapors that are not normal constituents of air. Although one could argue the theoretical position that this second concern is not strictly within the purview of the fire protection engineer, in the context of actual applications it is very rare that these two concerns can be rationally separated from each other. Consequently, the fire protection specialist must have a working knowledge of gas and vapor detection systems and monitors both for flammable and toxic materials.

For many years there was no NFPA standard explicitly establishing requirements for the design, installation, and maintenance of gas and vapor detection systems. Currently, one recommended practice, NFPA 720, *Standard for the Installation of Carbon Monoxide (CO) Warning Equipment in Dwelling Units,* has been adopted. Other than this one document, there are no NFPA standards relating to the design of systems to detect combustible or toxic gases or vapors employed in commercial or industrial occupancies, nor is there a standard for gas monitors. Nevertheless, there are a number of NFPA standards that make reference to gas and vapor detection systems in their requirements. For example, NFPA 86, *Standard for Ovens and Furnaces,* governs the fire protective features of drying ovens such as those where painted parts are cured. NFPA 86 allows reduced airflow rates conditioned on a system for monitoring the concentration of combustible vapor in the ventilation air. Since the fire safety of the curing oven is predicated on the vapor monitoring system, that system becomes a critical part of the fire protection for the site. Failure of the flammable vapor detection system to perform its intended function, whether due to flawed system design, installation error, inadequate maintenance, or component failure, could result in a catastrophic fire loss. This dependence on flammable gas and vapor detection systems to maintain the required level of fire safety argues for the application of sound fire protection engineering in the selection, design, installation, and maintenance of gas and vapor detection systems.

This chapter addresses the detection of flammable, combustible, or toxic gases and vapors that represent a hazard to the occupants or the facility. This hazard can be the risk of fire or deflagration due to ignition of an ignitible concentration of the flammable or combustible gases or vapors. It can also be the physiological threat to the health of the occupants resulting from inhalation or exposure to the vapors or gases. This chapter does not address flammable, combustible, or toxic gases that are the *result* of a fire. The term *fire-gas* was used previously in some fire protection standards and references as part of an effort to distinguish the gaseous components of smoke from the particulate components. Subsequent research and standards derived therefrom found that such a distinction was not particularly helpful and the term has fallen into disuse over the past two decades.

For related topics, see Section 6, Chapter 10, "Gases"; Section 6, Chapter 12, "Flammable and Combustible Liquids"; and Section 14, Chapter 4, "Fire Alarm System Interconnections."

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TERMINOLOGY

The terminology used in the gas and vapor detection community may not be familiar to many fire protection specialists.

Gas. A gas is matter in which the average thermal kinetic energy of the constituent molecules at standard temperature and pressure (STP) exceeds the cohesive forces between them, and consequently the matter expands to occupy the entire containment volume. STP is 77°F (25°C) and 760 mm(Hg) absolute pressure or 1 atm. It is necessary to stipulate temperature and pressure in this definition, because any normally gaseous compound can be compressed and cooled to the point where it will exist in a liquid state.

The gases that are routinely addressed in the context of gas detection, whether flammable gas or toxic gas, include carbon monoxide, carbon dioxide, sulfur dioxide, hydrogen sulfide, hydrogen, methane, ethane, propane, butane, acetylene, ethylene, propylene, silane, germane, diborane, phosphine, arsine, allane, fluorine, and chlorine.

Vapor. Vapor is matter in the gas phase that normally exists at STP as a liquid. This term is not essential. However, it is used too frequently not to be addressed in the context of this chapter. The term is commonly used because of the inference it provides regarding the source of the gaseous matter. Vapors are the result of the evaporation of a liquid and, consequently, are normally associated with a liquid source. There is an equilibrium state at the interface above a pool of liquid and the gas above it. As liquid molecules attain excess thermal energy, they escape the cohesive forces of adjacent molecules and leave the liquid as a gas. When gas molecules lose thermal energy, they condense back into the liquid phase. When vapors are dispersed in air, they behave as gases until a temperature is reached where they begin to condense. The principal distinction between the compounds normally thought of as gases and those as vapors is the temperature and pressure at which they condense.

Combustible/Flammable Gases and Vapors. Combustible/flammable gases and vapors are those gases and vapors that burn in air when the concentration of the gas or vapor is within the range of concentration where combustion can occur. The distinction between combustible and flammable is established in NFPA 30, *Flammable and Combustible Liquids Code.* This distinction is predicated on the flashpoint of the liquid. The flashpoint is the temperature at which the vapor pressure of the liquid is sufficiently high to produce a concentration of gaseous fuel in the air above the liquid in excess of the lower flammable limit (LFL) and, hence, sufficient to support a flame. This distinction has little relevance in the context of detection of molecular species dispersed in the ambient air, except to imply possible origin. Unfortunately, the community of manufacturers and users of gas detection systems and instruments come from an instrumentation background where the term *combustible* has been adopted. In an effort to provide consistency with the terminology and concepts presented in this handbook, this chapter will use the term *flammable gas* to include all chemical species dispersed in the gas phase in ambient air, regardless of source or chemical composition, that will burn in air.

Concentration of flammable gas is typically measured in percent of the lower flammable limit (percent LFL). If the lower flammable limit of a given gas is 4.0 percent, a measurement of 25 percent LFL means that there is 1 percent of that gas by volume in the measured sample of air.

Lower Flammable Limit (LFL). The lower flammable limit is the lowest concentration of a flammable gas in air that will support a flame. Below the LFL there is insufficient fuel per unit of air volume to sustain a flame through the volume. Therefore, when a source of ignition is introduced, the resulting flame will remain at the source of ignition. Once the concentration exceeds the LFL, a flame front will propagate through the air volume. (Note that the term *lower explosive limit (LEL)* was formerly used for this concentration of flammable gas and is occasionally still encountered in older literature.)

Upper Flammable Limit (UFL). The upper flammable limit is the highest concentration of a flammable gas in air that will sustain a flame. As the concentration of flammable gas increases, the oxygen-containing air is displaced. Eventually, the concentration of flammable gas is so high that there is insufficient oxygen remaining to sustain a flame when an ignition source is introduced. (Note that the term *upper explosive limit (UEL)* was formerly used and is occasionally still encountered.)

Toxic Gases and Vapors. Toxic gases and vapors are molecular species dispersed in air in the gas phase that have an adverse effect on living organisms, as defined by the Occupational Safety and Health Administration (OSHA). The concentration of toxic gas is usually measured and displayed as parts per million (ppm) concentration. To convert from percent to parts per million, multiply by the conversion factor of 10,000 ppm/percent. The commonly monitored toxic gases include carbon monoxide, carbon dioxide, hydrogen sulfide, sulfur dioxide, methane, silane, arsine, phosphine, chlorine, and fluorine. Most flammable gases are also toxic at some concentration, but not all toxic gases are flammable.

Oxygen Concentration. Oxygen concentration is the measure of the portion of the air within a space that is oxygen. This is an important life safety and fire protection parameter. The depletion of the oxygen in a gas volume reduces the ability of life to survive in that volume and also reduces the ability of that gas volume to support combustion. The nominal oxygen concentration of air is 23.2 percent oxygen by weight and 21.0 percent oxygen by volume. The difference in the numerical value of the oxygen concentration by weight versus volume comes from the different densities of the constituent gases in the mixture called "air."

Fixed Gas/Vapor Detection System. A fixed gas/vapor detection system is a permanently installed system usually consisting of at least one sensor, transmitter, and display unit (Figure 14.8.1). The sensor is located in the area where the gas or vapor may occur. It produces a minute current or voltage that is pro-

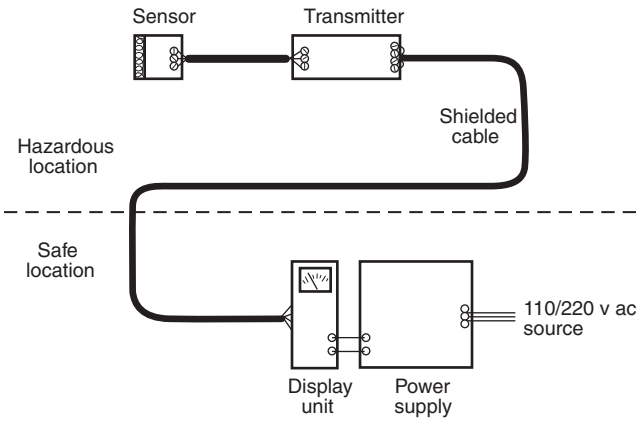

FIGURE 14.8.1 A Fixed Gas Detection System

portional to the concentration of the gas. The sensor is connected via wiring to a transmitter. Generally the distance between the sensor and transmitter is quite limited. The transmitter linearizes the signal from the sensor, corrects it for zero and span (due to variations in sensor output), and converts it into an electrical format that can be transmitted a long distance without interference.

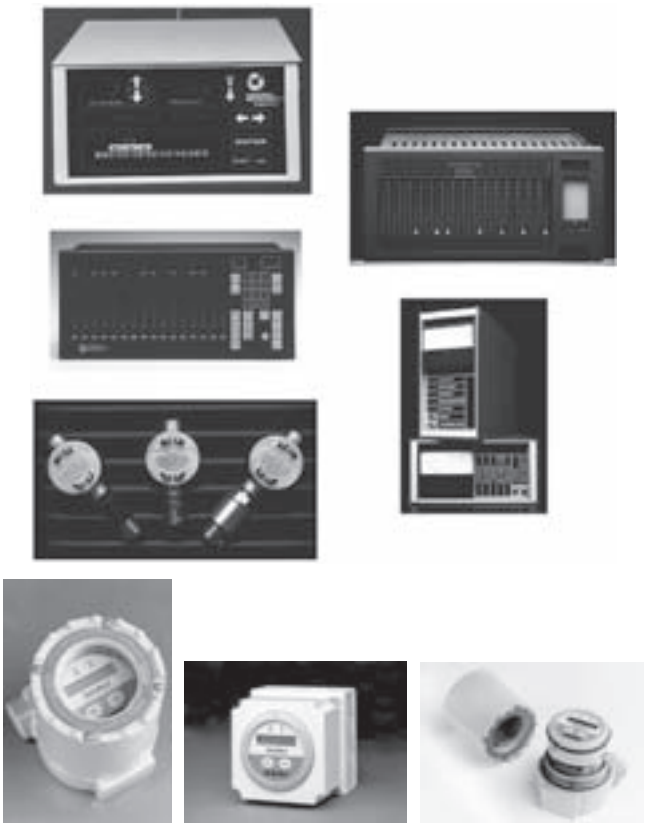

FIGURE 14.8.2 Examples of Modern Fixed Gas Detection Systems and Control Units (Source: Control Instruments® Corp.)

The most popular format is the "4–20 milliampere" format. The transmitter is connected to the display unit via a second set of wires. The maximum wiring distance between the transmitter and the display unit can often be as far as several thousand feet. The display unit expresses the output of the transmitter in a format that is understandable to the operator (Figures 14.8.2 and 14.8.3). Some displays utilize analog meters, whereas others provide bar-graph and numeric displays. Most display units are equipped with output relays that transfer when the measured concentration of gas exceeds pre-established threshold concentrations. This provides for different types of responses as the measured gas concentration increases. For example, a warning response might be activated when the concentration reaches 20 percent LFL, and inerting or shutdown activated when the concentration reaches 50 percent LFL.

Portable Gas/Vapor Monitoring Instrument. Portable gas/vapor monitoring instruments are hand-carried portable instruments, utilizing no external source of power, designed to warn the person carrying it of the presence of dangerous levels of gas or vapor, or dangerously low concentrations of oxygen in the ambient breathing air. Some monitors are simple single gas-warning devices, whereas others are multiple-gas devices. All are designed to measure the gas concentration and warn the user if the concentration begins approaching the threshold limit value (TLV), as established by OSHA, for that particular gas.

FIGURE 14.8.3 Fixed Gas Detection System Using a Sensor and Display Integrated into a Common Unit, Shown Here with the Enclosure Cover Removed (Source: Control Instruments® Corp.)

Hazardous Location. Places where a flammable gas or vapor is able to escape into the surrounding air are considered *hazardous locations.* In the United States hazardous locations are defined in Article 500 of the *NEC* (NFPA 70, *National Electrical Code*®). The *NEC* divides hazardous locations into Class 1, Class 2, and Class 3.

Section 500.5(B) of the *NEC* states that Class 1 hazardous locations are those "in which flammable gases or vapors are or may be present in air in quantities sufficient to produce explosive or ignitible mixtures." Class 2 hazardous locations are those that are hazardous because of the presence of combustible dusts. Class 3 hazardous locations are those that contain ignitible fibers and combustible flyings.

Both flammable gases and vapors and combustible dusts represent an explosion hazard when either is present in the air in sufficient concentration. The NEC further classifies hazardous locations based on the probability that a combustible material will be present at any particular time by assigning a "division" classification to the location. Class 1, Division 1 is assigned to occupancies that (1) contain flammable gases or vapors as part of the normal operating environment, (2) contain flammable gases or vapors frequently due to routine repair, maintenance, or leakage, or (3) contain equipment or processes where breakdown or production upsets could result in both a flammable atmosphere *and* an ignition source.

Class 1, Division 2 is assigned to occupancies where (1) flammable gases or liquids that produce flammable vapors are handled or processed in closed containers or systems and are only subject to release under conditions of equipment malfunction, breakdown, or process upset, (2) the development of a flammable atmosphere is normally prevented by positive mechanical ventilation, the failure of which could lead to a hazardous atmosphere, or (3) areas adjacent to a Class 1, Division 1 location subject to occasional ingress of flammable gas or vapor. Analogous divisions for Class 2 hazardous locations are also established in Article 500 of the NEC for combustible dusts, but these are not relevant to the discussion of gas and vapor detection.

In the European Union a similar hazard classification system has recently been adopted, known as the ATEX Directive. Under the ATEX Directive all process environments that can represent an explosive atmosphere must be so designated by the owner/operator of the facility. Once designated, all equipment used in that environment as well as products and equipment used to manage the hazard must be tested under a set of uniform EU testing standards and found suitable for that environment, as signified by the CE (Communité European) mark on the product labeling. A product that has not been certified by a nationally recognized testing laboratory as being suitable, as evidenced by the CE mark, is prohibited from use within the EU. The hazard classifications under the ATEX Directive are *not* the same as those established by the NEC. Consequently, products must go through two sets of testing if they are to be marketed in both the U.S. and EU markets.

SENSORS

The sensor is the single most critical part of any fixed gas detection system or portable monitoring instrument. The sensor is the portion of either the fixed system or portable instrument that actually does the sensing of the presence of gas in the air. The sensor generates an electrical signal, either current or voltage, proportional to the concentration of gas in the air. The gas detection system can be no better than the sensors used and, consequently, the development of sensors has accounted for much of the research and development effort. As with fire detection, there are a limited number of sensor technologies in common use and then some specialized technologies tailored to the needs of special applications. In general, the design focus has been to develop sensors that are specific to a given gas and that maintain their response characteristics in spite of the presence of other gases.

Most flammable-gas sensors designed to detect the hydrocarbon gases and vapors from hydrocarbon liquids are based on the detection of the heat of combustion of the flammable gas, using resistive-thermal devices (RTDs) and the Wheatstone bridge circuit. An RTD is an electronic component whose resistance varies with temperature. RTDs include metal oxide resistors, resistance wires, and thermistors. These devices can all be wired into a circuit called the Wheatstone bridge, shown in Figure 14.8.4.

The resistors shown as the sample and reference legs of the bridge circuit can be any type of RTD. The sample RTD is coated with a material that acts as a catalyst of the combustion of hydrocarbons. Alloys of both palladium and platinum are often used for this purpose. The reference RTD is enclosed in a manner that prevents contact with the ambient, gas-containing

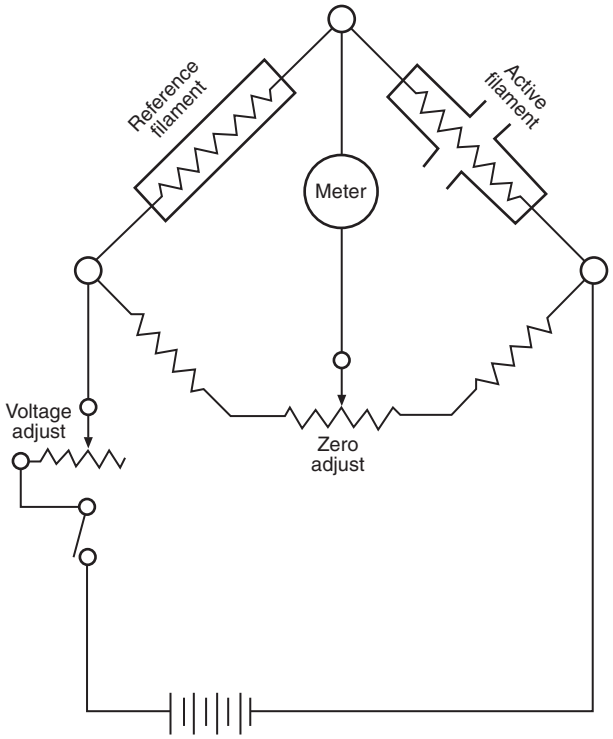

FIGURE 14.8.4 Basic Wheatstone Bridge Circuit as Used in Many Gas Detection Systems

air. Electric current is passed through the bridge circuit, causing all of the legs of the bridge to become warm. When flammable gas impinges upon the sample RTD, the gas oxidizes, releasing heat from the combustion process occurring on the surface of the RTD. This raises the temperature of the sample RTD, and causes the electrical resistance of the sample RTD to change compared to the reference RTD, which remains at normal operating temperature. The change in the sample RTD resistance causes a potential (voltage) difference across the "voltmeter," which is proportional to the concentration of flammable gas.

Theoretically, the heat derived from the combustion of a gas on the surface of a catalyst-coated RTD is dependent on both the concentration and the heat of combustion of the flammable gas. However, the heats of combustion of most chemical compounds encountered in the context of gas detection are very close in value. This allows the heat of combustion term to be considered nominally constant, especially when the gas concentrations are at or below the LFL. This approximation is not perfect. Carbon disulfide vapor yields readings that are lower than the actual concentration under these conditions, while natural gas yields readings that tend to be higher than the actual concentrations. These discrepancies increase as the concentrations increase. However, this is easily addressed with specific calibrations where these gases are present. For most purposes, where the sought-after condition is a hazardous gas–free atmosphere, the differences between various gases disappear as the actual concentration approaches zero.

One of the more popular types of RTD is the catalyst-coated thermistor, called the *catalytic bead.* A *thermistor* is an electrical resistor, fabricated from one of a number of rare-earth ceramics, that exhibits a large change in electrical resistance as a function of temperature, usually referred to as a *temperature coefficient.* Many have a temperature coefficient that is negative, meaning that the electrical resistance goes down as the temperature increases. A *catalyst* is a material, usually a chemical or mixture of chemicals, that facilitates a particular chemical reaction. Certain metals and metal salts catalyze the combustion reaction involving hydrocarbon chemical species. The catalytic effects of such metals and metal salts are often specific for certain hydrocarbon species, meaning that a catalyst that facilitates the combustion of methane would not be particularly effective at facilitating the combustion of butane or gasoline. Coating the thermister of a gas detection sensor with a particular catalyst can make the sensor somewhat selective for particular gases or groups of gases.

Air mixtures containing concentrations of flammable gas much lower than the LFL, approaching zero, will "burn" on the surface of a heated catalytic material, yielding heat in direct proportion to the concentration of the flammable gas. This is called *surface* or *catalytic* combustion. Some RTD designs depend on the flow of electric current through the thermistor bead to generate the requisite operating temperature of the catalyst. Others use a separate resistance heater integrated into the bead. Obviously, the combustion of the flammable gas on the surface of the catalyst could conceivably cause ignition once the concentration exceeded the LFL. Consequently, sensors are contained within a flame arrester of either wire mesh or sintered metal, as shown in Figure 14.8.5, that prevents the propagation of combustion

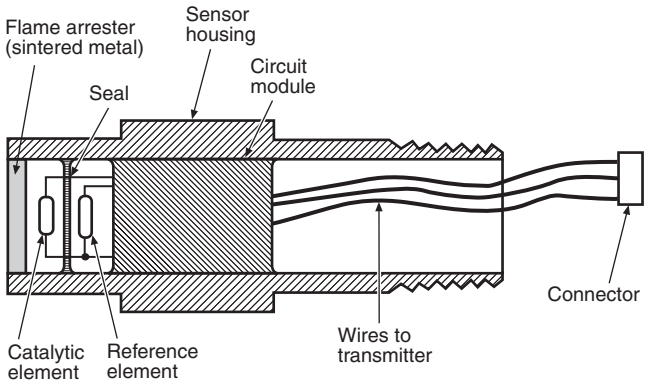

FIGURE 14.8.5 Flammable-Gas Sensor Using Catalytic Bead Technology

outside the sensor. These flame arresters are generally suitable for conventional gas-air mixtures. However, if the atmosphere is oxygen enriched to concentrations greater than 21 percent oxygen by volume, or if the partial pressure of oxygen exceeds 21.27 kPa or 160 mm(Hg), special arresters may be necessary.

Most sensors use a catalyst that is derived from the catalytic properties of platinum, palladium, and nickel. Careful control over the alloying of the catalysts and the operating temperature enables the manufacturer to make sensors that are specific for a particular group of gases. Catalytic beads have a very small mass; therefore, they respond rapidly to the heating produced by the combustion of flammable gas on their surfaces. Response often begins within a few seconds of the introduction of the gas. However, when the influx of flammable gas is large, it may take as long as a minute to attain full-scale response of the sensor. The speed of response of a sensor is an important factor when choosing the best sensor for a given hazard.

Catalytic bead flammable-gas monitoring instruments are designed specifically for measuring combustibles in air. The oxygen in the air is necessary for the combustion of the flammable gas and the generation of heat that the unit senses to infer the presence of flammable gas. These instruments give a reasonably accurate indication of the presence of combustible gas, even when the oxygen concentration has been substantially reduced by oxidation, biological action, or displacement. Generally, one should expect the accuracy of a catalytic-bead sensor to suffer as the ambient oxygen concentration decreases to less than 10 percent. Also note that inerting agents, such as Halon 1301 or the replacement clean agents, interfere with either the combustion reaction on the catalyst surface or increase the heat capacity of air and, hence, reduce the temperature resulting from the combustion of the flammable gas, rendering measurements unreliable when inerting agents are present.

Catalytic bead sensors do suffer from "poisoning" to varying degrees. Poisoning occurs when a noncombustible material impinges upon the bead and only partially burns, leaving a residue on the surface of the bead. The coated surface no longer oxidizes the flammable gas in the air, and the sensor ceases responding to the presence of flammable gas in the air. Although considerable progress has been made in reducing the tendency

for beads to become poisoned, this is a limitation of catalytic sensors that necessitates regular calibration to adjust for the progressive loss of sensing ability over time. Regular field calibration is necessary to adjust the zero and span of the display unit as compensation for drift and aging of the catalytic bead.

Many catalytic bead sensors are supplied with calibration curves showing the response of the particular unit to combustible gases other than that on which the device was calibrated. Calibration curves for one particular model of combustible gas indicator are shown in Figure 14.8.6. Since all manufacturers do not use the same gas for base factory calibrations, the curves for one instrument cannot be used with curves of another type.

Semiconductor (MOS) Devices

Metal oxide semiconductor (MOS) sensors can be used to detect a number of "reducing gases" such as hydrogen, methane, ethane, ammonia, and carbon monoxide. Metal oxide semiconductors can be fabricated with precisely controlled band-gap energies by manipulating the concentrations of the various oxides in the crystal. (This is called "doping.") When a MOS sensor has a voltage across it and a gas with the right chemical structure impinges on it, the current through the sensor changes, indicating the presence of the gas. The semiconductor can be modified to maximize response for a specific gas or group of gases by adjusting the relative concentrations of the constituent oxides (doping) or with the application of specific surface coatings. However, MOS sensors generally cannot be made specific for a single gas and care must be used to ascertain whether an unanticipated gas is causing the response of the sensor. Often, MOS sensors are operated at an elevated temperature to improve the response specificity of the sensor.

Calibration curves for field reference					
Gas or vapor	LEL % by volume	Curve no.	Gas or vapor	LEL % by volume	Curve no.
Acetone	2.5	5	Hydrogen	4.0	1
Acetylene	2.3	3	Methyl alcohol	6.7	2
Benzene	1.4	5	Methyl ethyl ketone	1.8	6
Carbon disulfide	1.0	10	Natural gas	4.8	3
Carbon monoxide	12.5	1	Octane	1.0	9
Ethyl acetate	2.2	7	Pentane	1.4	5
Ethyl ether	1.7	7	Propane	2.2	4
Gasoline	1.3	8	Toluene	1.3	4
Hexane	1.2	7	Xylene	1.0	7

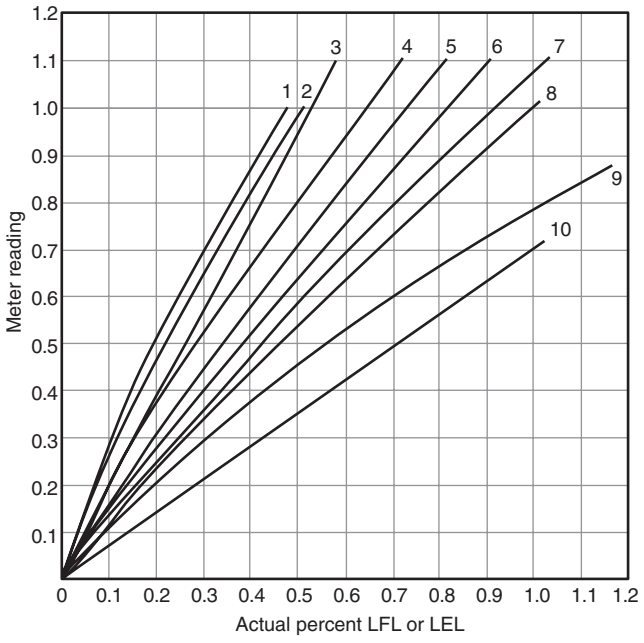

FIGURE 14.8.6 Calibration Curves for a Catalytic Bead Sensor. Note that, despite wide variations at higher concentrations, the error becomes negligible as the zero concentration is approached.

Electrochemical Devices

Electrochemical cells are primarily used for the detection of the toxic gases. The electrochemical cell is designed somewhat like a battery in which air can diffuse into the electrolyte of the cell. If the air contains the toxic gas for which the cell has been designed, an electrochemical reaction takes place, producing a minute voltage within the cell. This voltage causes a current to flow through the sensor electronics. The current is proportional to the concentration of the gas in the air. This enables the concentration to be measured by measuring the current from the cell. The diffusion path and the electrolyte can be varied to limit the response of the sensor to a particular gas.

Electrochemical cells are the predominant method for sensing carbon monoxide, chlorine, nitrogen oxide, sulfur dioxide, and hydrogen sulfide. Electrochemical cells are also used for oxygen-level monitoring by the same means as used for toxic gases. Semiconductor and catalytic bead sensors depend on a level of oxygen in the air in order to provide accurate results, whereas electrochemical cells do not. Furthermore, electrochemical cells usually provide high levels of specificity relative to other technologies.

Flame Cell Devices

When measurement capability for a wide range of hydrocarbon gases and vapors is needed, flame cell technology is often considered. Flame cell sensors are very often employed when LFL monitoring is needed for the atmosphere within an oven where flammable solvent vehicles (vapors) are driven off as part of a curing or finishing operation. This system uses a flame cell that contains a flame fueled by a flammable gas provided by the unit, and ventilated by air sampled from the hazard area. A temperature sensor measures the heat output of the flame. When flammable hydrocarbons are introduced into the hazard area atmosphere, the contaminated air flows from the hazard area to the sensor via sample conveyance tubing to the flame cell. As the hydrocarbon-containing air enters the flame cell, the hydrocarbons burn, adding to the heat available to the temperature sensor. The sensor temperature rises proportional to the concentration of the hydrocarbon gas (vapor) in the air (Figure 14.8.7).

Flame cell sensors are more complex than the other types discussed thus far. However, there are numerous applications where they represent the best cost/benefit solution. They are not affected by poisoning the way catalytic bead sensors are and

(a) (b)

FIGURE 14.8.7 (a) Flame Cell Sensor; (b) Flame Cell Sensor with the Enclosure Open, Showing the Internals (Source: Control Instruments® Corp.)

require far less frequent calibration. However, since sampling tubes convey the sample atmosphere to the detection unit, provisions must be made to ensure that there is no condensation of flammable or combustible vapors on the interior surfaces of the sample conveyance tubing, as this would create serious errors in the flammable gas concentration measurements. The flame cell sensor as a sampling-type device, connected to the hazardous area via a sampling tube, is shown in Figure 14.8.8.

Flame Ionization Devices

In some applications, where a means for detecting very low concentrations of flammable gas is needed, flame ionization detectors are often the sensor of choice. Flame ionization detectors consist of an enclosed flame cell equipped with a high-voltage field. It is fueled from a source of hydrogen, with combustion air coming through the sampling system. When the combustion air includes hydrocarbon molecules, these molecules are pulled apart by the high-voltage electric field, producing ions. These ions flow through the flame to the positive (+) and negative (–) electrodes, creating a current that is directly proportional to the concentration of hydrocarbon gas in the air sample.

Flame ionization sensors, like the flame cell sensors, are more complex than the other spot-type sensors. However, there are numerous applications where they represent the best cost/benefit solution. They are able to measure much smaller concentrations than the other types of gas sensors. They are not affected by poisoning the way catalytic bead sensors are and require far less frequent calibration. Flame ionization sensors (Figure 14.8.9) are installed like the flame cell devices, with a sampling tube that conveys a sample of the hazardous atmosphere to the sensor. Consequently, provisions must be made to ensure that there is no condensation of flammable or combustible vapors on the interior surfaces of the sample conveyance tubing, as this would create serious errors in the flammable gas concentration measurements.

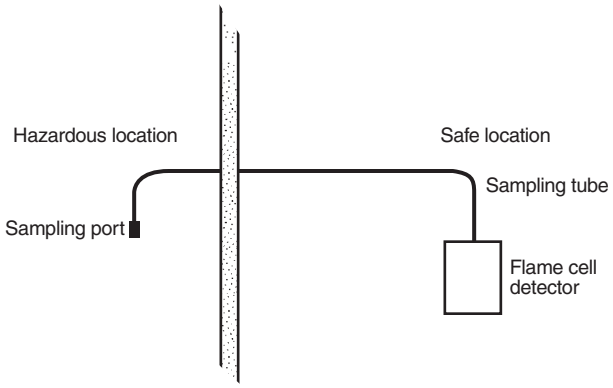

FIGURE 14.8.8 Flame Cell Sensor

Nondispersive Infrared (NDIR) Sensors

Gaseous molecules absorb infrared radiation at specific and characteristic wavelengths. This is analogous to the infrared emission detection that is the basis for many of the advanced technology flame detectors in use today. Infrared gas detectors, using the correlation between specific molecular species and specific wavelengths in the infrared spectrum, have recently been made available. Like smoke detectors, infrared gas detectors are either spot devices or open-path devices analogous to the projected beam smoke detector.

FIGURE 14.8.9 Flame Ionization Sensor (Source: Control Instruments® Corp.)

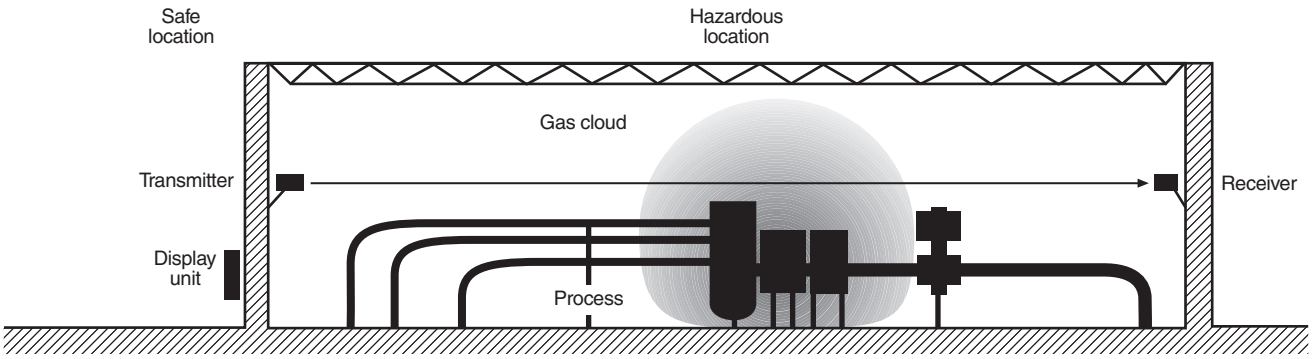

FIGURE 14.8.10 Open-Path Infrared Gas Detector

Open-path gas detectors operate with one or more infrared emitters and one or more receivers. These units compare the optical absorbance of the air in the optical path at two wavelengths, one at which the gas absorbs and a reference wavelength at which the gas does not absorb. The detection system electronics compare the intensities at the two wavelengths. If gas exists along the beam path, it will absorb the sample wavelength while allowing the reference wavelength to pass unattenuated. The difference in received intensities is proportional to the concentration of the gas and the percentage of the path length that contains that concentration. This value is transmitted via the common 4–20 mA analog signal to the display unit. It is displayed as LFL-meters, the product of the percent LFL and the distance. As shown in Figure 14.8.10, the open-path NDIR gas detector covers a large area; however, the reading is the product of the distance and the concentration over that distance.

Spot-type IR gas sensors operate on a similar principle, but the optical path is contained within the detector enclosure. This eliminates the path length as a variable, and they display concentration in simple percent of LFL. The spot-type sensor often contains an integral 4–20 mA transmitter that sends the analog signal to the display unit (Figure 14.8.11).

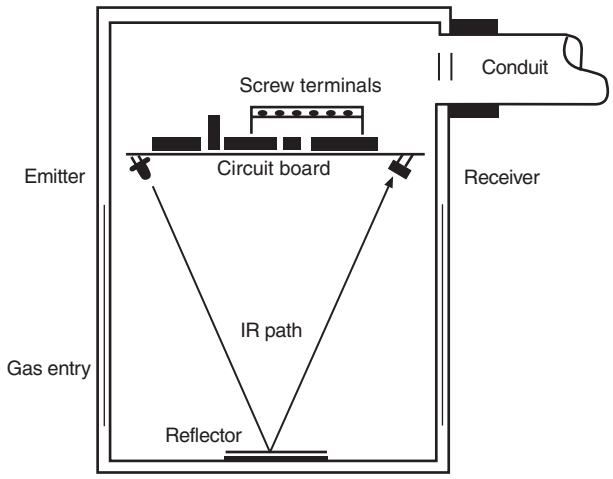

FIGURE 14.8.11 Spot-Type IR Gas Sensor

Infrared gas detectors are reputed to require far less maintenance and calibration than catalytic bead, electrochemical, and semiconductor devices.

FIXED GAS DETECTION SYSTEMS

Throughout modern industry there exist enclosed areas where gaseous contaminants can accumulate. Whether these gases are flammable, toxic, or both flammable and toxic, they represent a serious threat to personnel, the facility, and the operations housed within the facility. Reliable monitoring of known gas hazards is critical if losses are to be prevented.

Where known permanent gas hazards exist, a fixed gas detection system is necessary. These hazards are commonly encountered in public utility electric generating stations; publicly owned water treatment works; petroleum exploration, production, refining, and distribution facilities; pharmaceutical, chemical, and petrochemical production, storage, and distribution facilities; metallurgical facilities; semiconductor fabrication facilities; distilleries; paint and varnish manufacturing facilities; and mines.

Concurrent with the detection of the presence and concentration of both flammable and toxic gases, there is the need to measure the oxygen concentration in the atmosphere in many applications. Measurement of the oxygen concentration is important as a means of evaluating the effectiveness of inerting processes, of protecting personnel from the effects of oxygen deficiency, and of determining that sufficient oxygen is present in the atmosphere to ensure reliable concentration readings from combustible gas detectors.

It is important to note that one cannot use the spacing criteria for smoke detectors in *NFPA 72®*, *National Fire Alarm Code®* as a guide for the location and spacing of gas detectors. The spacing and location criteria in *NFPA 72* for smoke detectors are based on fire plume dynamics in which the heat released by the combustion of the fuel serves as the driving force behind the development of a fire plume and a ceiling jet. No such energy source exists in the context of a gas leak. When a contaminant gas leaks into the surrounding atmosphere, it mixes with the air, changing its density. In a mixture of gases, the density of the mixture is a function of the constituent gases and the portion of the mixture that they represent. Under still air conditions

where there is no ambient air movement, higher concentrations are usually observed at higher locations within the enclosing space when lighter-than-air gases are involved. Conversely, higher concentrations are usually observed at lower locations within the enclosing space when heavier-than-air gases are involved. One can use the specific density of the gas in question to aid in predicting whether the gas in question will tend to rise or sink when a leak occurs (Table 14.8.1).

The data in Table 14.8.1 must be used carefully. It is often necessary to take into account the refrigeration effect that occurs when a gas at high pressure leaks into a region of much lower pressure. The volumetric expansion of the leaking gas causes it to cool the air into which it is flowing. The cooled air is no longer at STP conditions of 77°F (25°C) and 760 mm(Hg) absolute pressure or 1 atm. This cooling causes the air/gas mixture to contract, increasing in density. As the mixture moves from the locus of the leak, it continues to absorb heat from the ambient, and slowly reaches thermal equilibrium with the ambient. These thermodynamics must be observed when using data, such as that in Table 14.8.1, to develop a sensor placement strategy.

Flammable Gas Detection

Most of the fixed gas detection systems in service are designed to measure the concentration of one or more flammable gases.

TABLE 14.8.1 Specific Densities of Commonly Encountered Gases and Vapors*

Standard Conditions of Temperature and Pressure

Gas/Vapor	*Molecular Formula*	*Specific Density, Air = 1.0000*
Air	—	1.0000
Hydrogen	H_2	0.7000
Carbon monoxide	CO	0.9670
Carbon dioxide	CO_2	1.5280
Methane	CH_4	0.5540
Acetylene	C_2H_2	0.9110
Ethane	C_2H_6	1.0490
Hydrogen sulfide	H_2S	0.9109
Phosphine	PH_3	1.1840
Propane	C_3H_8	1.5500
Silane	SiH_4	1.1140
Sulfur dioxide	SO_2	2.2640
Acetone	$(CH_3)_2CO$	2.0
Benzene	C_6H_6	2.8
Carbon disulfide	CS_2	2.6
Cyclohexane	C_6H_{12}	2.9
Ethanol (ethyl alcohol)	CH_3CH_2OH	1.6
Ethyl ether	$CH_3Ch_2OCH_2CH_3$	2.6
Gasoline	mixture	3.4
Mineral spirits	mixture	3.9
Naphtha (VM&P)	mixture	<1.0
Toluene	$C_6H_5CH_3$	3.1

*See NFPA 86, *Standard for Ovens and Furnaces.*

These systems are generally found in petroleum exploration, production, refining, and distribution facilities; power generation plants; water treatment plants; landfills; chemical and pharmaceutical facilities; and numerous industrial processes where flammable solvent (vehicle) vapors are driven off in ovens. Generally, these systems are designed to respond to a broad range of hydrocarbon gases and vapors, such as methane, ethane, propane, butane, ethylene, propylene, acetylene, and similar gases, as well as the vapors from the evaporation of hydrocarbon liquids, such as gasoline, acetone, ethyl ether, methylethyl ketone, methylisobutyl ketone, carbon disulfide, turpentine, and lacquer thinner, to list a few.

The predominant sensor for flammable gas detection in general, normally occupied spaces is the catalytic bead sensor, which is designed to comply with the performance criteria outlined in ANSI/ISA S12.13, *Performance Requirements, Combustible Gas Detectors.*[1] Sensors are situated where there is the probability that gas will accumulate when a leak occurs. When the gas to be detected is methane, natural gas, or other lighter-than-air gases, sensors are generally located above the gas-containing equipment. When propane, butane, and most vapors are involved, the sensors are located low in the air space of the hazard area. Flammable gas sensors must be placed to take advantage of normally occurring air currents and the differences in the density of air and the flammable gas(es) in question. The installation, operation, and maintenance of flammable gas detectors are addressed in ISA RP12.13, Part II-87, *Recommended Practice: Installation, Operation, and Maintenance of Combustible Gas Detection Instruments.*[2]

The gas sensors are connected via multiconductor cable to the appropriate transmitter, which is then connected to the display unit, as shown in Figure 14.8.12. Generally, the distance between the sensor and transmitter is quite limited. The transmitter linearizes the signal from the sensor, corrects it for

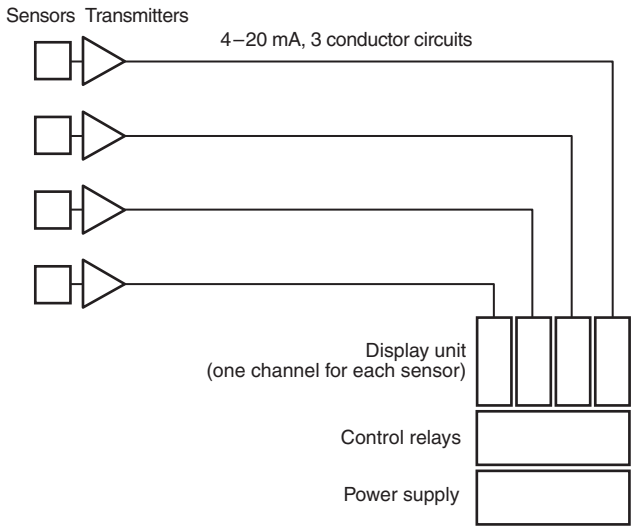

FIGURE 14.8.12 Wiring Architecture for the Traditional and Currently Most Likely Encountered Flammable Gas Detection System

zero and span, and converts it into an electrical format that can be transmitted a long distance without interference. The most popular format is the "4–20 mA" format. A second set of wires connects the transmitter to the display unit. The maximum wiring distance between the transmitter and the display usually can be as far as several thousand feet.

Large numbers of "points" are generally wired to a centrally located display unit where the status of the facility can be monitored by facility staff. The unit displays the output of the transmitter. Some display units utilize analog meters, whereas others provide bar-graph and numeric displays.

Addressable gas detection systems have been introduced that enable the system to be wired in a manner similar to a traditional smoke detector circuit. The transmitter converts the analog data from the sensor into a binary format and transmits it serially along with its identity to the display unit. The display unit presents the analog data in the customary fashion (Figure 14.8.13).

Most display units are equipped with output relays that transfer when the measured concentration of gas exceeds preestablished threshold concentrations. This provides for different types of responses as the measured gas concentration increases. For example, a warning response might be activated when the concentration reaches 20 percent LFL, and inerting or shutdown actuated when the concentration reaches 50 percent LFL.

ANSI/ISA S12.13[1] requires that the flammable (combustible) gas detection system supervise for the following:

1. The failure of the unit power supply
2. The loss of continuity of the sensor element (catalytic bead)
3. The continuity of all conductors to the detector head (the sensor and transmitter)
4. Down-scale reading, below zero, equivalent to a concentration of more than 5 ppm

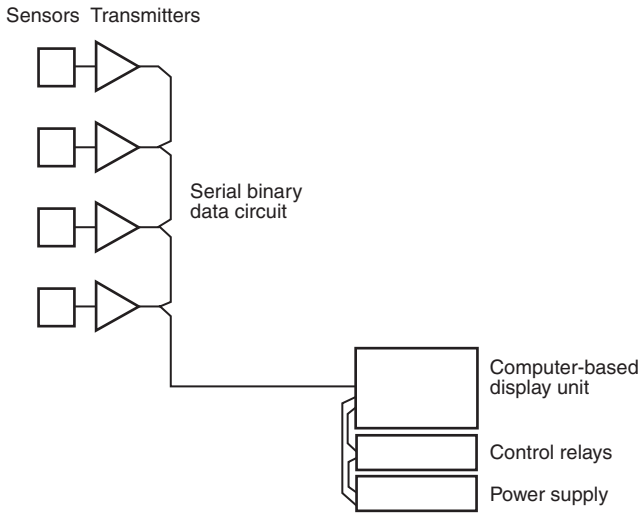

FIGURE 14.8.13 Wiring Architecture of the Addressable Flammable Gas Detection System

This is not entirely consistent with the supervisory requirements of *NFPA 72*. Furthermore, ANSI/ISA RP12.13 does not address supervision of any of the connections that are intended to initiate any type of automatic response to a gas concentration above threshold levels. This inconsistency is one of several system design issues that come into play when integrating or interconnecting flammable gas detection systems with fire protective systems. *NFPA 72* includes specific requirements for the power supplies, electrical supervision, isolation from ground, programming security, and supervision of output circuits that might not have been observed by the manufacturer of the gas detection system. The actuation of inerting, warning, and ventilation systems in response to high-level gas indication are all fire-protective actions that should be achieved with inherently reliable, supervised designs, as described in *NFPA 72*. Some authorities having jurisdiction (AHJ) might apply the requirements of *NFPA 72* to flammable gas detection systems when the flammable gas detection is integrated into the facility fire protection systems.

Toxic Gas Detection

The detection of many toxic gases is necessary in the same environments where flammable gases must be monitored. Most frequently, hydrogen sulfide gas is commonly encountered in petroleum exploration and production involving sour crude and/or sour gas. Consequently, many gas detection systems in place in the petroleum industries include both flammable gas and toxic gas detection for hydrogen sulfide, sulfur dioxide, and fluorine in the same system.

The architecture of most fixed gas detection systems lends itself to this reality. The systems are designed with transmitters and display units that can accommodate a number of interchangeable sensors, specifically designed for a particular gas. Combined flammable and toxic gas detection systems are commonly encountered.

The semiconductor and electrochemical sensors are most commonly used for the detection of toxic gases. The measurements are expressed in ppm and generally the threshold limit value (TLV) established by OSHA for the gas in question is placed in the upper half of the display range.

ANSI/ISA S12.15, PT I-90, *Performance Requirements for Hydrogen Sulfide Detection Instruments (10–100 ppm),*[3] requires that the toxic gas detection system supervise for the following:

1. The continuity of all conductors to the detector head (the sensor and transmitter)
2. The failure of the unit power supply
3. The loss of continuity of a circuit protection device
4. A down-scale reading, below zero, equivalent to a concentration of more than 5 ppm

This is not entirely consistent with the supervisory requirements of *NFPA 72,* which establishes requirements on the equipment design that are not normally assumed to be relevant when a manufacturer outside the fire protection community undertakes the design of a product. This becomes an important issue when integration of gas detection and fire alarm systems is contemplated.

Calibration and Maintenance

Both flammable and toxic gas detection systems require regular calibration and maintenance if reliable measurements are expected.[2,4] Each system has a specific set of calibration and maintenance criteria that is incorporated as part of the listing investigation by the nationally recognized testing laboratory. These procedures must be carefully and meticulously followed. In general, most systems using catalytic bead, semiconductor, and electrochemical sensors require calibration on a monthly schedule. The flame cell and flame ionization detectors usually require less frequent calibration.

The calibration of a gas detector, whether flammable or toxic, involves adjusting the electrical output of the transmitter to accurately reflect the atmosphere at the sensor. The first step is the zero adjustment. While the sensor is under normal ambient conditions with no gas present, the output of the transmitter is adjusted to 4.0 mA output to the display unit. The sensor is exposed to *test gas.* Test gas is a mixture of air and the gas to be detected, stored at elevated pressure in a specially designed cylinder with a sensor test fitting attached. The mixture is certified by the manufacturer as being accurate to within 1.0 percent LFL or 1.0 ppm, whichever is appropriate. Since there is an obvious hazard if the test gas concentration is at 100 percent LFL or 100 percent TLV, the test gas concentration is usually at 50 percent LFL or TLV, again whichever is appropriate. Exposure to the test gas is used to adjust the span output of the transmitter to the appropriate value for the test gas and sensor in question. In this way the electronics of the transmitter are used to correct for any nonlinearities and drift in the sensor. The display unit merely reads the current passing through the 4–20 mA circuit to the transmitter and displays it. Consequently, there is usually no calibration necessary at the display unit.

Eventually, the zero and span adjustments on the transmitter are insufficient to achieve both a zero and a correct span adjustment. This indicates that the sensor has aged to the point where it must be replaced. The rate of aging is very application specific and can occur without any apparent warning. Consequently, regular calibration is the only means to be confident that the gas detection system is operative and displaying an accurate measurement of the actual gas concentrations in the hazard areas.

Integration with Fire Alarm Systems

There are inconsistencies between the *NFPA 72* requirements for fire alarm signaling systems and the ISA standards for gas detection instruments. These inconsistencies become relevant when the conditions in the hazard area demand an integrated approach. Obviously, the presence of a flammable gas in an area sufficiently hazardous to warrant a fire alarm system represents an aspect of that hazard area that warrants immediate remedial action. Whether that remedial action consists of merely the activation of a notification appliance or whether it requires the activation of purge fans, process shutdown, deployment of an inerting agent, or some other response, these actions must be designed into the system in a manner that provides a high degree of intrinsic reliability and supervision if they are to represent a meaningful response. Typically, these responses are executed by a fire alarm system control unit that has been listed for releasing device service, and the flammable gas detection system serves as an initiating device in that system.

Since many gas detection systems use earth-ground as a circuit common, a practice that is forbidden in the context of fire alarm systems, there is often a fundamental power supply incompatibility between the gas detection control unit and the fire alarm system control unit. Consequently, the interface between the gas detection and the fire alarm system is often achieved through dry relay contacts. This is not the ideal means of signal transmission due to the relatively low reliability of dry relay contacts compared to solid-state devices. However, it is often what is found in the field. This circuit is shown in Figure 14.8.14.

It is important to understand that when flammable gas leaks occur it is not unusual for the cause of the leak to also lead to a heat source of ignition, making flammable gas detection an important fire prevention strategy. The commonly encountered flammable gases, such as natural gas, methane, ethane, and propane, are all dielectric materials. Being dielectrics they accumulate static electric charges when the velocity of the flow varies widely across the flow stream. Such velocity differentials regularly exist in the context of a leak of flammable gas from a high-pressure source. Consequently, the flow through the leak may generate large electrostatic potentials that are discharged as the gas escapes, creating electric sparks, which may be of sufficient energy and power to ignite the flammable gas/air mixture. This reality underscores the importance of detecting and expeditiously correcting flammable gas leaks.

PORTABLE GAS MONITORING INSTRUMENTS

Wherever there is the reasonable possibility of an accidental release of either flammable or toxic gas, there is the need to equip personnel with a portable instrument to warn them of such a hazard on entering. Both flammable and toxic gases are encountered in diverse locations throughout industry, for example, as a result of some form of accidental or opportunistic event, such as leakage from piping systems (both above and below ground) into the surrounding soil; from spillage or the decomposition of natural organic material in the soil; or sanitary landfills. Regardless of the source, the possibility and probability that a dangerous concentration of a flammable or toxic gas might exist in an area within a facility establish the need for portable gas monitors (Figure 14.8.15).

There are portable gas monitors designed for a wide range of performance objectives. It is important that the performance objectives for the gas monitoring instrument be fully understood before a unit is selected. Some applications require oxygen monitoring to ensure that there is sufficient oxygen for safe occupation of the space. Many applications require a monitor for only one specific gas, whereas other applications represent a number of concerns justifying the use of a multifunction monitor. Areas that contain concentrations of flammable gas above the LFL will necessitate an explosionproof or intrinsically safe

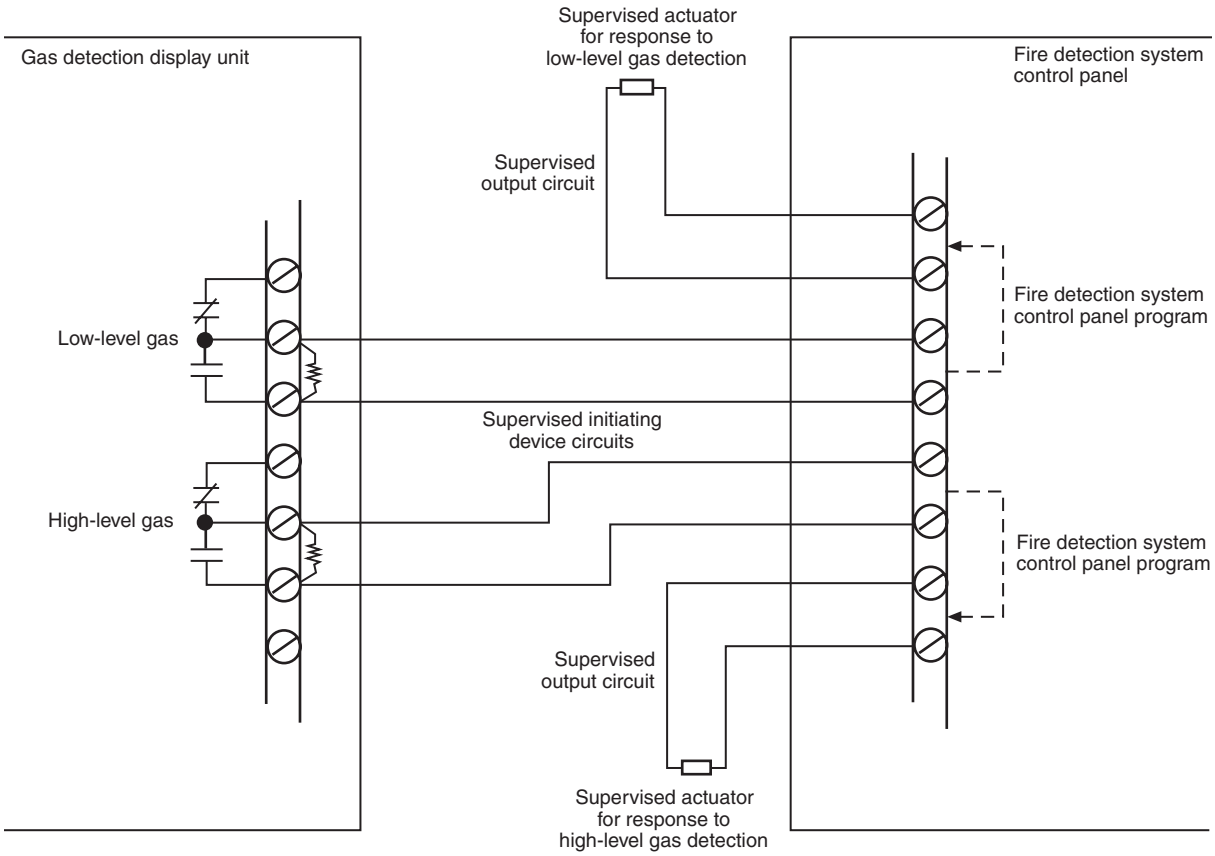

FIGURE 14.8.14 Commonly Encountered Interface Between the Gas Detection and the Fire Alarm System Used to Activate Automatic Responses to the Gas Detection Level Alarms

FIGURE 14.8.15 Portable Gas Monitor

instrument. Finally, some applications require that the unit operate continuously while the user is in the hazardous space, whereas others are intended to be used as a portable survey instrument operated on an intermittent basis. All of these intended use considerations have an important bearing on the selection of an instrument.

Portable gas monitoring instruments are available in a wide variety of forms. Some units depend on the diffusion of the air-gas mixture into the sensor. Others have provisions for a forced sampling means. Samples are drawn through a hose or tube, which is frequently equipped with a rigid extension or probe for ease in reaching inaccessible points. Suction is provided by a hand-operated rubber aspirator bulb or a battery-powered built-in motor-driven pump.

When using portable gas monitoring instruments the operator must keep in mind that all such instruments have a finite range of ambient conditions under which they can operate. Extremes in temperature, humidity, and barometric pressure (altitude) are likely to affect the accuracy and precision of the measurements they provide. Sampling steamy atmospheres is not recommended, since condensation of water within the instrument is likely to cause errors. Sampling from ovens or dryers operating at temperatures much higher than instrument ambient should also be avoided. Unless the solvents in question have flashpoints below instrument ambient temperature, vapors

might condense within the sampling tubing or measuring instrument, again causing errors.

Finally, if the portable gas monitoring instrument is to be used in areas where ignitible concentrations of flammable gas might exist, it should be designed and listed for use in hazardous locations as defined in Article 500 of NFPA 70. The manufacturer's label and instructions indicate the type of approval granted for the particular instrument.

Flammable (Combustible) Gas Monitoring Instruments

Flammable gas monitoring instruments generally use a catalytic bead or semiconductor sensor. The output from the sensor is directly displayed with a number of different techniques, ranging from an analog meter to digital readout. Most also include some form of audible alarm set at a level considered immediately hazardous. As a rule, flammable gas instruments must be set to read "zero" in uncontaminated air each time they are used. Like the fixed systems, the gas concentration is displayed in percent LFL. Generally, flammable gas monitoring instruments respond to all flammable gases or mixtures of flammable gases, irrespective of their chemical composition (Figure 14.8.16). This is usually desirable in a portable monitor, as it is unnecessary to know the exact identity of the flammable gas or gases prior to being able to assess the fire risk of the area being surveyed. Where it is necessary to selectively measure the concentration of some specific flammable gas, especially while in the presence of other combustibles, infrared absorption and gas chromatographic techniques on samples transported to a laboratory must be used.

Toxic Gas Monitoring Instruments

Similar to the flammable gas monitoring instruments, toxic gas monitoring instruments are often necessary in order to ensure personnel safety. Hydrogen sulfide monitors usually employ electrochemical sensors as do the sulfur dioxide, chlorine, and fluorine monitors. Carbon monoxide monitors are available using either the semiconductor sensor or the electrochemical sensor technologies (Figure 14.8.17). Other techniques that involve electrical detection of gas-specific chemical reactions are also employed. These include chemical stain, electro-conductance, and membrane permeability methods. These units generally display the concentration in ppm and include an audible signal when the concentration reaches a threshold value above which the threat to life and health is unacceptable.

Oxygen Concentration Monitoring Instruments

Oxygen concentration monitoring instruments are often critical life safety tools. Generally they utilize an electrochemical sensor. The partial pressure of the oxygen in the atmosphere controls the rate at which it diffuses through a porous membrane and into the electrochemical cell. Once in the cell, the oxygen enters into an electrochemical reaction, generating an electric current that is electronically scaled to display the oxygen concentration. The oxygen concentration is usually displayed as a simple "percent oxygen," usually on a scale graduated from 0 to 25 percent. Portable oxygen monitoring instruments usually include an audible alarm set for a level around 18 percent (Figure 14.8.18).

Except for setting the meter to read 20.8 percent while aspirating fresh air at the elevation (atmospheric pressure) where tests are to be made, no other calibration is necessary

FIGURE 14.8.16 Portable Multiple-Range Gas Monitoring Instrument (Source: Heath Consultants, Inc.)

FIGURE 14.8.17 Electrochemical Carbon Monoxide Monitoring Instrument That Includes an Indicator and Alarm (Source: MSA [Mine Safety Appliances Co.])

FIGURE 14.8.18 Individual Oxygen Indicator for Remote Sampling (Source: MSA [Mine Safety Appliances Co.])

for accurate reading in the range of oxygen concentrations in which it is permissible for people to work. (Current regulations require a minimum of 19.5 percent oxygen; otherwise, air must be supplied or self-contained breathing equipment must be used.) Enclosed spaces should also be tested to ensure sufficient oxygen is present to permit reliable gas measurements. Where readings are intended to be significant in the low range, that is, with inerting systems, the zero setting can be confirmed by sampling an oxygen-free gas, such as propane or nitrogen.

Calibration of Portable Gas Monitoring Instruments

Portable gas monitoring instruments require calibration on a regular basis if their measurements are to be relied on. The procedures for calibration vary from instrument to instrument. However, as with the fixed detection systems, most employ the use of a test gas. The "zero" of the unit is adjusted. Then it is subjected to test gas containing a known, certified concentration of the gas it is designed to measure. The span adjustment is then employed to achieve a measurement reading consistent with the known gas concentration.

The frequency at which units should be calibrated is determined by the authorities responsible for the life safety of the facility staff. Some authorities recommend calibration be verified daily, before use. Such a calibration check is accomplished by passing test gas through the instrument.

SUMMARY

This chapter is by no means a complete, authoritative presentation on gas detection. It is an introduction to this topic. The reader must be cautioned that the gas detection industry has developed over the years as part of the instrumentation industry, serving the needs of the chemical process and petroleum industries. Generally, the language is different from that used in the fire protection industry. Furthermore, the standards that have evolved over the years relating to gas detection do not address the concerns of the fire protection community in the customary manner. For example, consider that the 4–20 mA data transmission circuit is not recognized by *NFPA 72*.

As fire alarm systems become increasingly interactive with the facilities and production processes they protect, conflicts are expected to emerge in the requirements of various standards. These conflicts can only be resolved when fire protection professionals understand the basics of this technology and the objectives the standards were written to ensure. As fire alarm systems are more thoroughly interfaced with process control systems, questions of reliability, operability during impairment, and maintainability must be addressed in a manner that satisfies the needs of both fire protection and rigorous process control.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on gas and vapor detection systems and monitors discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 70, *National Electrical Code®*
NFPA 72®, National Fire Alarm Code®
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 720, *Standard for the Installation of Carbon Monoxide (CO) Warning Equipment in Dwelling Units*

Chapter 9

Carbon Monoxide Detection in Residential Occupancies

Art Black

Chapter Contents

Physical Properties and Sources of Carbon Monoxide
Carbon Monoxide Hazards
Development of Carbon Monoxide Detection Standards
Installation of Carbon Monoxide Detection Equipment
Carbon Monoxide Warning Equipment Alert Signals
Carbon Monoxide Detector Technologies
Response to Carbon Monoxide Alerts

Key Terms

biometric carbon monoxide detector, carbon monoxide, carbon monoxide detector, carboxyhemoglobin, electrochemical carbon monoxide detector, metal-oxide semiconductor carbon monoxide detector, temporal 3 signal, temporal 4 signal

Although the popularity of carbon monoxide (CO) detectors and requirements for CO detection installation have been growing in recent years, it cannot be assumed that everyone is familiar with the hazards of carbon monoxide, the symptoms of CO poisoning, the requirements for alarms and detectors, or the installation and mounting details for alarms and detectors. The fire service may value further guidance on best ways to respond to CO alarm and detector actuations.

For related topics, see Section 2, Chapter 6, "Fundamentals of Fire Detection"; Section 6, Chapter 2, "Combustion Products and Their Effects on Life Safety"; and Section 14, Chapter 3, "Notification Appliances."

PHYSICAL PROPERTIES AND SOURCES OF CARBON MONOXIDE

Physical Properties

Carbon monoxide is a colorless, odorless gas produced by incomplete combustion. Carbon monoxide is minimally denser than air under ordinary conditions. It burns in air with a characteristic blue flame. As a reducing agent, it removes oxygen from many compounds and is used in the reduction of metals from ores. When air containing carbon monoxide in any amount is inhaled, the oxygen in hemoglobin is replaced by carbon monoxide, resulting in oxygen starvation throughout the body.

Sources

Hazardous concentrations of CO can accumulate in any occupancy, whether a single-family dwelling unit, a hotel guest room, or a nonresidential occupancy. The vast majority of deaths due to CO poisoning, however, occur in one- and two-family dwellings.[1] Generally, the accumulation of CO is the result of improperly operating heating appliances; insufficient make-up air in the space; blocked, poorly designed, or poorly installed chimneys or vents; or a complete absence of needed vents. Other potential sources of CO, however, exist, including idling automobiles in attached garages and portable equipment, such as generators and barbecue grills.

In multiresidential occupancies such as hotels, apartment buildings, or condominium buildings, malfunctioning furnaces, boilers, or swimming pool heaters, or problems with the venting of such appliances, can cause potentially fatal build-ups of CO.

CARBON MONOXIDE HAZARDS

Solid, liquid, or gaseous fuels can produce CO gas in lethal concentrations. According to U.S. death certificate data, 200 to 300 unintentional-injury deaths a year are due to CO. With detection and early warning, the majority of these deaths could be readily prevented. It is also possible that a considerable number of additional CO deaths are not recognized as such, because the symptoms

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are not sufficiently unique as to prompt a routine postmortem examination. Every year, there are nearly a hundred additional deaths due to gas or vapor—principally CO—for which it is never determined whether the injury was intentional (e.g., suicide) or unintentional.

Exposure

The dangers of CO exposure depend largely on a number of variables, including the subject's health and activity level. Infants, pregnant women, and people with physical conditions that limit their body's ability to use oxygen (including people with emphysema, asthma, and heart disease) can be more severely affected by lower concentrations of CO than healthy adults. The subject's length of exposure and the initial carboxyhemoglobin (COHb) level, which could be elevated by smoking or exposure to operating motor vehicles in a confined space, are additional important variables. A person exposed to CO can be poisoned by a small amount of CO over a longer period of time or by a large amount of CO over a shorter period of time.

Symptoms of Carbon Monoxide Poisoning

The reactions to CO poisoning vary depending on several factors, including the age, general health, fitness, and general activity level of the victim immediately prior to the poisoning. The following equation can be used to determine the estimated percent of carboxyhemoglobin in the blood:[2]

$$\%COHb_t = \%COHb_0[e^{-(t/2398B)}] + 218[1 - e^{-(t/2398B)}] \times [0.0003 + (ppmCO/1316)]$$

where

$\%COHb_t$ = Percentage of COHb at time t

$\%COHb_0$ = Percentage of COHb in the blood at time 0

t = Time (min)

B = 0.0404 (work effort)

The concentration of CO, measured in parts per million (ppm), is a determining factor in the symptoms for an average healthy adult, as shown in Table 14.9.1.

TABLE 14.9.1 Carbon Monoxide Concentrations and Symptoms

Concentration (ppm CO)	*Symptoms*
50	No adverse effects with 8 hours of exposure
200	Mild headache after 2–3 hours of exposure
400	Headache and nausea after 1–2 hours of exposure
800	Headache, nausea, and dizziness after 45 minutes of exposure; collapse and unconsciousness after 2 hours of exposure
1000	Loss of consciousness after 1 hour of exposure
1600	Headache, nausea, and dizziness after 20 minutes of exposure
3200	Headache, nausea, and dizziness after 5–10 minutes of exposure; collapse and unconsciousness after 30 minutes of exposure
6400	Headache and dizziness after 1–2 minutes of exposure; unconsciousness and danger of death after 10–15 minutes of exposure
12,800 (1.28% by volume)	Immediate physiological effects; unconsciousness and danger of death after 1–3 minutes of exposure

CAUTION: The values in Table 14.9.1 are approximate values for healthy adults. Children, the elderly, and persons with pre-existing physical conditions might be more susceptible to the effects of carbon monoxide exposure. Continued exposure after unconsciousness can cause death.

Source: NFPA 720, *Standard for the Installation of Carbon Monoxide (CO) Warning Equipment in Dwelling Units,* Table B.1, 2005, p. 720-10.

DEVELOPMENT OF CARBON MONOXIDE DETECTION STANDARDS

After several well-publicized incidents in the early 1990s, the U.S. Consumer Product Safety Commission petitioned the National Fire Protection Association to create a standard for CO detection. The NFPA Standards Council acted on this request in 1993 by assigning development of a new document to the Technical Committee on Household Fire Warning Equipment. This committee was chosen because it had the necessary expertise in residential detection principles in its development of *NFPA 72®, National Fire Alarm Code®*.

In 1995 the Technical Committee on Household Fire Warning Equipment presented a "Recommended Practice on the Installation of CO Warning Equipment" to the NFPA membership at the annual meeting, where it was returned to the committee. In early 1996 the Standards Council reassigned the project to a new Technical Committee on CO and Fuel Gas Detection, which was given the task of developing two documents—one on detection of CO and the other on detection of fuel gas vapors.

The first NFPA document on CO detection, NFPA 720, *Recommended Practice for the Installation of Household Carbon Monoxide Warning Equipment,* was approved by the NFPA membership in 1997. NFPA 720 was a recommended practice, not a standard, so the installation details in the document were advisory only. Further, since the scope of the document was for family living units only, the document specifically excluded hotels, motels, and similar occupancies. NFPA 720 made recommendations for the selection, installation, operation, and maintenance of equipment that detects concentrations of CO that could pose a health hazard to occupants of a single-family living unit. Because of the multiple alarm thresholds involved, it was not intended to regulate CO detectors designed to detect hostile fire signatures.

The technical committee attempted a revision of NFPA 720 in 2000, which would have extended the recommendations

to all occupancies; however, that revision was returned to the committee at the NFPA fall meeting. The technical committee made some minor revisions to the 2003 edition of NFPA 720, including revisions pursuant to the changes in NFPA's Manual of Style. With the growing number of jurisdictions adopting requirements for installation of carbon monoxide warning equipment and the difficulty of a jurisdictional authority to reference a recommended practice, the Technical Committee converted the document into a standard in 2005. The Technical Committee is currently working on a modification to NFPA 720 to answer the growing need of jurisdictional authorities who are requiring carbon monoxide detection in other than single-family residences.

INSTALLATION OF CARBON MONOXIDE DETECTION EQUIPMENT

NFPA 720, now titled *Standard for the Installation of Carbon Monoxide (CO) Warning Equipmnt in Dwelling Units,* is the standard that provides guidelines for operation, installation, testing, and maintenance of carbon monoxide detectors in household occupancies (Figure 14.9.1). Currently there are no standards for carbon monoxide detection equipment in commercial occupancies (hotels, congregate residential buildings, and other commercial nonresidential buildings).

Household Dwelling Units

It is important to note that NFPA 720 is an installation standard and does not require the installation of carbon monoxide warning equipment. When required to be installed, or where protection is desired, CO detectors or alarms are to be located in any residential occupancy containing a fuel-burning appliance or fireplace or having an attached garage. A CO detector or alarm needs to be installed outside each separate sleeping area in the immediate vicinity of the bedrooms. Audibility of the warning signal is a determining factor when deciding how many detectors or alarms to install. Where bedrooms are separated and audibility could be impaired, more than one unit may be required.

FIGURE 14.9.1 Typical Household Carbon Monoxide Detector (Source: BRK Brands, Inc.)

CO is minimally denser than air, and concerns have been voiced about "plug-in" detector models that are mounted at the level of convenience receptacles located near the floor. Since the vapor density of CO is very close to that of air, however, it will readily mix with air given any air movement in the room, and detectors can thus be mounted either on the ceiling or on the wall. Underwriters Laboratories Standard 2034, *Standard for Single and Multiple Station CO Alarms,*[3] is the manufacturing standard for CO warning equipment. This standard requires that mounting specifications be part of the documentation required to be included with a CO detector or alarm. These manufacturer's directions need to be followed.

CO detection equipment is recommended in any family living unit containing a fuel-burning appliance or fireplace or any family-living unit having an attached garage. NFPA 720 parallels UL 2034 in the requirements for CO warning equipment as it relates to power supplies, equipment performance, and alarm signals.

NFPA 720 also contains provisions which require carbon monoxide warning equipment be interconnected to a household fire alarm control unit or a household combination fire/burglary alarm unit as a supervisory device. This information is of primary importance to the fire service, because on a fire alarm or combination fire/burglary alarm panel, an alarm signal would mean "fire." It is important to ensure that an incorrect alarm condition is not transmitted to a public fire service communications center.

Hotel and Congregate Residences

Because the scope of NFPA 720 is limited to single-family dwellings, there are no requirements in the document regarding CO detection equipment in hotels and congregate residences. However, where CO detection is required or desired in such occupancies, it is recommended that the CO warning equipment or detectors be installed in close proximity to fuel-burning equipment, such as furnace rooms and pool heater rooms. In addition, these devices should be connected to the premises fire alarm system as supervisory devices. This will allow for the on-site staff to be immediately notified of a CO problem.

Other Commercial Occupancies

As stated above, NFPA 720 applies solely to single-family dwellings. Where carbon monoxide detection is required or desired in commercial occupancies, sound engineering judgment is to be used in determining placement of carbon monoxide detection equipment and the necessary interconnection to building alarm systems.

CARBON MONOXIDE WARNING EQUIPMENT ALERT SIGNALS

The standard signal for a CO alarm is a single-tone "temporal 4" pattern, consisting of four cycles of 100 milliseconds "on"

and 100 milliseconds "off," followed by 5 seconds "off." The signal should continue until the alarm resets or the detector is manually reset. To conserve battery power, an exception allows the manufacturer to extend the 5 seconds "off" period to 60 seconds "off" after the first 4 minutes of alarm. The signal was selected as a unique alternative to existing smoke alarm signals or the temporal 3 pattern required for newer smoke alarms (Figure 14.9.2). Because many CO detectors and alarms resemble smoke detectors and alarms in appearance, developers saw the need to make the audible signal for CO detectors and alarms distinctively different. Another factor in the development of this signal was the need for the CO alarm to have enough power to continue operation for 12 hours, based on the premise that if the CO emissions began after the resident left for the day, the signal would need to last long enough for the resident to hear the signal on his or her return at the end of the day. Some CO detectors have a button to display the highest reading ever taken, so occupants can check for problems even after prolonged absences from the home.

CARBON MONOXIDE DETECTOR TECHNOLOGIES

Most commercially available carbon monoxide alarms use one of three detection technologies: biometric, metal-oxide semiconductor, or electrochemical.

Biometric

Biometric detectors are also called biomimetric, colorimetric, chem-optical technology, or gel-cell detectors. This sensor technology utilizes a material that mimics the response of human hemoglobin to carbon monoxide. In the presence of carbon monoxide, the amount of infrared light that will pass through the sensing material declines. The rate of change of the transmittance is used to calculate CO gas concentrations. Biometric sensors have demonstrated immunity to other gases that may be present and are not prone to false alarms.

Metal-Oxide Semiconductor

These detectors use tin dioxide (SnO_2) as a sensing element. The sensing material is heated by a heating element and CO gas is catalytically broken down at the surface. Electrons are released and reabsorbed by the tin dioxide. Electronics are utilized to measure the sensor resistance and from this to calculate the concentration of CO. These sensors have demonstrated excellent resistance to sensing other gases that may be present.

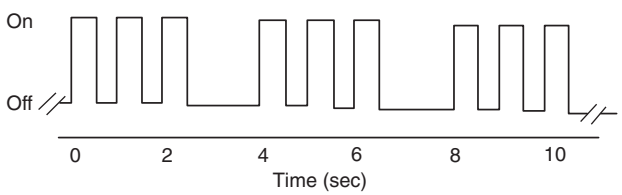

FIGURE 14.9.2 Temporal 3 Pattern Fire Alarm Evacuation Signal

Electrochemical

Electrochemical technology involves an acid electrolyte solution and platinum electrodes. The presence of carbon monoxide causes a chemical reaction that instigates a current flow through the circuit. This technology utilizes external circuitry to monitor the changes in potential and uses this information to calculate the concentration of CO. Electrochemical sensors are mechanically more complex than sensors using other technologies, but can provide much more accurate measurements of CO concentrations. These sensors have demonstrated good immunity to interfering gases.

RESPONSE TO CARBON MONOXIDE ALERTS

Occupant Response

The initial response by the occupant is to take "appropriate action" based on the knowledge that the CO detector has detected CO in the atmosphere. The recommended response includes the following:

- Opening windows to ventilate the area
- Assessing the medical condition of the occupants
- If necessary, calling the public fire service communications center (fire department)

In most cases, because of the low alarm threshold required by UL 2034, there is no need to call the fire department if the residence is immediately ventilated and appropriate service personnel are called to investigate the source of the CO. By the time service personnel (or the fire department responders) arrive, CO may no longer be present because the occupant took appropriate action by opening windows and doors. If any occupants are suffering from symptoms of CO poisoning and require medical attention, the emergency medical services system should be activated.

Emergency Service Response

Emergency response to CO alarms may be provided by first responders, primarily fire department and emergency medical personnel. The purpose of the first responders' action is to protect people, including themselves, from toxic levels of CO. In addition, utility company personnel or other "secondary responders" should respond to a CO alarm. The primary function of secondary responders is to service combustion equipment and appliances that are potential sources of CO.

SUMMARY

Hazardous concentrations of CO, a colorless, odorless gas produced by incomplete combustion, cause several hundred unintentional-injury deaths a year. The majority of these deaths occur in one- and two-family dwellings as the result of improp-

erly operating heating appliances, insufficient make-up air in the space; blocked, poorly designed, or poorly installed chimneys or vents; or a lack of vents. Additional sources of CO include idling vehicles in attached garages and portable equipment such as generators. For protection from toxic levels of CO, CO detection equipment is recommended in any family-living unit containing a fuel-burning appliance or fireplace or having an attached garage.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on carbon monoxide detection in residential occupancies discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 72®, National Fire Alarm Code®
NFPA 720, *Standard for the Installation of Carbon Monoxide (CO) Warning Equipment in Dwelling Units*

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Chapter 10

Security and Intrusion Detection Systems

Shane M. Clary

Chapter Contents

A Brief History of Security
Security Vulnerability Assessment
Overview of Physical Security
Considerations for a Site Survey
Vaults and Safes
Components and Issues in Electronic Security
Electronic Security and Intrusion Detection Systems
Electronic Security and Access Control
Video Surveillance

Key Terms

central station, electronic premises security system, enhanced call verification, intrusion detection, security, security vulnerability analysis (SVA), site survey

Fire protection and security are interrelated. The installation of an electronic security system within the premises is part of the built environment. How it operates with other systems within the same building is integral to the complete protection platform that may be installed. Such platforms protect occupants, contents, structures, business operations and first responders.

Security has been on the minds of many people since September 11, 2001. Security has many facets, from the protection of our borders, background checks of future employees, physical security, private security force deployment, cybersecurity, electronic security countermeasures, and intrusion detection systems, to name just a few. This chapter will provide a brief overview of premises security systems that are covered by two documents that were approved by the NFPA membership and subsequently by the NFPA Standards Council in 2005:

- NFPA 730, *Guide for Premises Security*
- NFPA 731, *Standard for the Installation of Electronic Premises Security Systems*

This chapter contains very limited text from NFPA 730; the practitioner needs to obtain a copy for a full understanding of the document.

The designer of a premises security system should be familiar with both NFPA 730 and NFPA 731, as well as many other publications available through the literature. Practitioners need to be as familiar with the concepts and principles of security as fire protection engineers are with their skill set. The consequences of a poor design can be just as devastating to the property or building owner, or the victim of a crime that occurs at or within a protected facility, as lack of adequate fire protection.

Also see Section 1, Chapter 6, "Premises Security"; and Section 14, Chapter 7, "Fire Protection Surveillance and Security Services."

A BRIEF HISTORY OF SECURITY

Security in one form or another has been around since at least ancient Egypt, in which the first documented use of locks is recorded.[1] The use of locks is mentioned in both the New and Old Testaments of the Bible.[2,3] One of the first—if not the first—security alarm systems was developed and used by the Romans.[4] Geese were used as both the detector and notification appliance.

Early Technology

Security up to around the 1800s primarily involved the use of private and public security forces. Security was one aspect of their duties; watching for and sounding the alarm for a fire was another. This early linkage of fire and security marked the beginnings of electronic security as we know it today.

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The first telegraph was patented in 1837 by Samuel Morse. It occurred to William F. Channing[5] of Boston, Massachusetts, that one should be able to use the technology of the telegraph to transmit the signal of a fire alarm. Up until this time, the transmission of the signal was done manually, generally by ringing bells to alert the fire companies. The use of electricity was new, however, and it was not until 1851 that the first system was approved for installation in Boston. By this time, Channing had teamed up with Moses G. Farmer, an electrical engineer who improved on the original design of the telegraph. This system was the first auxiliary municipal telegraph system, which used a series of 40 signal boxes, consisting of over 40 miles of wire installed throughout Boston and connected to a central station that would receive the signals. The system went operational on April 29, 1852.[6]

As word of this system spread, John N. Gamewell saw the potential of these systems in other cities. By 1859 he has secured most of the U.S. patents for this new technology. Unfortunately, the Civil War got in the way. Gamewell, being a native of South Carolina, was viewed by the United States government as being a supporter of the Confederacy. His patents were seized and sold. Gamewell was not able to return to his concepts and designs until after the end of the war.

While Gamewell continued to expand the fire alarm industry, Edwin Holmes was one of the first to see a need for electric burglar alarm protection. Holmes foresaw an industry that would be resistant to the financial swings of the time. He purchased the patent of Augustus R. Pope, who is thought to have patented the first burglar alarm system. Holmes set up his first shop in Boston, but the level of crime at that time was not sufficient to support an emerging industry. He therefore relocated to New York City. Even in the 1860s, intrusion detection systems were marketed as a deterrent to crime.[7]

The development of fire and burglar alarms continued on a parallel track. One of the most important innovations was the formation of the central station. A key contributor to this new technology was E. A. Calahan, who was also the inventor of the stock market ticker. In 1871, Calahan sold his central station patents to a syndicate of investors in New York City, who formed the American District Telegraph Company. By 1874, they had opened sixteen central stations in the New York City area, twelve being in Manhattan. A number of these central stations shared facilities with Western Union. Over time, American District Telegraph began to offer fire alarm systems in addition to burglar alarm systems. This did not go unnoticed by Gamewell, who in Boston, began to offer security systems.

A key development during this time was the invention of the McCulloh circuit. Up until this time, any break in the circuit would prevent signals from being received until the fault was cleared. Chauncey F. McCulloh designed a circuit that restores or reroutes a circuit around a single fault. This greatly improved the reliability of the signal transmission from the premises to the central station.

As this work was being done, Holmes was developing sensor technology that could be used to automatically detect an intrusion. Systems up until this time were still manual, in that the building occupants had to trip the system to transmit a signal to the central station. This was before the use of telephones and was, at that time, the fastest way to summon assistance. Holmes used a system of protective wiring, metallic foil, and brass contacts. He also developed a use for the galvanometer with directly connected systems so that each premises system could have a unique identifier.

Shift in Technology

Some of the technology that was developed during the 1800s was still in use in the 1990s. Although McCulloh circuits have been replaced, directly connected circuits are still in use. The brass contact has been replaced by the reed contact switch and foil has been replaced by audio discriminators or glass break detectors. Advances in this technology have transitioned from McCulloh and direct connect circuits to digital dialers, long-range radio, and, within the past several years, broadband. Detection technology, as described later in this chapter, has moved from protective wiring, foil, and contacts to space protection, sound and vibration detection, and contacts. The security practitioner needs to know the strengths and weaknesses of both the transmission methods and detection technologies.

SECURITY VULNERABILITY ASSESSMENT

The practitioner must take into consideration the entire property to be protected and the level of the threat against which one is trying to provide protection. Before any design work can be performed, a security vulnerability assessment (SVA) must be performed. According to NFPA 730, an SVA is "a systematic and methodical process for the following: (1) Examining ways an adversary might exploit an organization's security vulnerabilities to produce an undesired outcome [and] (2) developing countermeasures to address adversarial events." NFPA 730 further describes an SVA as "a technique for assessing the current status of an organization's threat exposures, security features and preparedness and can be used in developing and strengthening both security and safety layers of protection."[8]

Steps of an SVA

NFPA 730 outlines seven steps that should be taken as part of the SVA.

Formation of a Team. The team may be made up of both outside experts and key members of the facility to be protected. The goal is to receive as much relevant input as possible to design a system or program that will meet the needs of the end users.

Organization/Facility Characterization. This step involves the identification of assets; physical features and operations; laws, regulations and corporate polices; social and political environment; and internal activities.

Threat Assessment. Threat assessment includes the classification of critical assets, identification of potential targets, consequence analysis, and definition of potential threats.

Threat/Vulnerability Analysis. The threat/vulnerability analysis includes the identification of actual and potential threat scenarios and estimation of a relative security risk level.

Define the Specific Security Countermeasures. All the information obtained in the first four steps are analyzed to develop effective countermeasures to mitigate the defined threats and reduce the security risk.

Assess Risk Reduction. Take into account the countermeasures defined in Step 5 and reassess the relative security risk levels that were developed in Step 4 and consider additional security risk reduction measures that may be appropriate.

Document Findings and Track Implementation. Produce a written document of the findings and recommendations. The report would also track the implementation of the accepted recommendations.

With respect to Step 5 (Define the Specific Security Countermeasures), the practitioner should consider how to increase existing security layers for the premises. There should be a focus on the concentric circles of protection design methodology, as shown in Figure 14.10.1.

Primary Protection Elements

The SVA methodology considers four primary protection elements: deter, detect, delay, and respond.

- *Deter:* discouraging an adversary from attempting an assault by reducing the likelihood of a successful attack
- *Detect:* determining that an undesirable event has occurred or is occurring; includes sensing the event, communicating the alarm to an attended location, and assessing the alarm

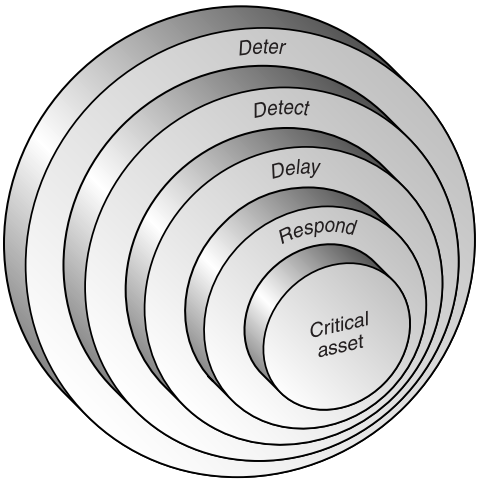

FIGURE 14.10.1 Concentric Circles of Protection (Source: NFPA 730, *Guide for Premises Security,* 2006, Figure A.5.2.5)

- *Delay:* impeding adversary penetration into a protected area
- *Respond:* counteracting adversary activity and interrupting the undesirable event

The threat level may be placed into three categories as shown in Table 14.10.1.

OVERVIEW OF PHYSICAL SECURITY

Security for the protection of a premises can be divided into two broad categories: physical security (environmental design) and electronic security.

TABLE 14.10.1 Threat Analysis Guidelines

Threat Level	*Nature of Threat*	*Required Capabilities*
Low	Stand off surveillance/espionage Minimum/occasional penetration Limited pilferage Minor demonstrations	Denial of surveillance and penetration Detection and deterrence of intruders Selective surveillance of critical areas Apprehension of pilferers
Medium	All of low threat intensified Sabotage Harassment Minor destruction and disablement Dissident demonstrations	Intensify response to low threat Earlier detection Immediate response (small groups) Increased mobility of response forces Identification and location of sabotage Capture of intruders
High	All of medium threat intensified Organized attack/armed conflict Major destruction Combat intelligence	Intensify response to medium threat Complete penetration denial Immediate response (large and small groups) Armed resistance, capture, destroy Sabotage detection and prevention Remote controlled and/or automated response capability Interface with allied forces

Crime Prevention Through Environmental Design (CPTED)

Generally, when one thinks of physical security, an image of fences, gates, and exterior lighting may come to mind. Although these are all forms of physical security, the practitioner must take into consideration the entire site, and if practicable the local environment as well. Crime prevention through environmental design (CPTED) is a holistic approach in which individual citizens and law enforcement come together to apply security concepts to entire neighborhoods or major urban districts, as well as urban subsystems such as a public venue.[9] CPTED is made up of four general principles:

- *Natural surveillance:* provides features that allow for intruders to be readily seen; this would include windows and doors that face streets and well-lit parking lots and sidewalks
- *Territorial reinforcement:* creates a sphere of influence; sets and defines the private property and spaces from public property and spaces
- *Natural access control:* creates a perception of risk; provides gateways that are clearly public and discourages access to private areas
- *Target hardening:* uses window locks, door locks, fencing

Although CPTED should be considered for new large-scale projects or in areas that over time have demonstrated a history of security-related issues, it may not be warranted or possible for a single site.

Role of the Site Survey

Before beginning any security-related project, the practitioner needs to conduct a site survey. Even if the project has yet to be constructed, the designer needs to review the local environment in which the facility will be located. This would include a review of crime statistics for the geographic area. If the facility already exists, the practitioner needs to perform an extensive review of the security features that are in place as well as the general construction of the facility.

CONSIDERATIONS FOR A SITE SURVEY

A site survey deals with the exterior of a premises. Several key components should be taken into consideration when performing an examination or specifying physical security:

- Physical barriers
- Lighting
- Locks
- Glazing
- Passive barriers

Physical Barriers

Physical barriers can be both natural and structural. Natural barriers include mountains, cliffs, canyons, rivers, or other terrain that is difficult to traverse. Structural barriers include fences, walls, bollards, floors, and roofs.

One of the most common types of fence used today is the chain-link. Chain-link fencing can be used almost anywhere there is a need to define the physical boundaries of a facility. To be most effective, a chain-link fence should be designed and installed to a nationally recognized standard. For chain-link fencing this standard is ASTM F567, *Standard Practice for the Installation of Chain-Link Fence*.

When possible, the fence line should be located no closer than 50 ft (15.2 m) to the buildings or outside storage areas, and 20 ft (6.1 m) to other areas. Chain-link fencing comes in a variety of heights; the most common for commercial and industrial use is 8 ft (2.4 m). Depending on the risk to the premises, greater heights can be specified. When an 8 ft (2.4 m) fence is specified, 7 ft (2.1 m) is for the fabric and the top foot is for a top guard. Posts are used to secure the fabric. For a fence with 7 ft (2.1 m) of fabric height, the posts should be set in concrete at a minimum depth of 36 in. (0.9 m). The line posts should be spaced equidistant at intervals not exceeding 10 ft (3 m). End posts, if used, should be set within 2 in. (50 mm) of building walls. A top tension wire should be provided as a support for the fence fabric. A top rail can also be used if appearance is critical but should be avoided as it provides a handhold for one that is attempting to climb over the fence. The fabric of a fence should be steel wire, No. 9 gauge or heavier. The fabric needs to be stretched taught and securely fastened to the posts. The bottom of the fabric should extend to within 2 in. (50 mm) of the hard ground or paving. For soft ground, the fabric should extend below the ground. The top of the fence should be provided with a top guard to deter attempts at climbing the fence. A top guard should be made up of three strands of No. 12 gauge barbed wire, at an angle of approximately 45°. For those facilities that require a higher level of protection, razor ribbon should be considered.

Lighting

The purpose of lighting is to provide and enhance visibility and deter intrusion. The use of protective lighting should be considered both along the fence line and the outside of the premises. Table 14.10.2 provides the recommended minimum illumination levels for fencing. Table 14.10.3 gives recommended minimum intensities for outdoor protective lighting for pedestrian and vehicle use areas among others. The practitioner should also

TABLE 14.10.2 Recommended Minimum Illumination Levels for Fencing

Location	*Footcandles (on horizontal plane at ground level)*
Perimeter of outer area	0.15
Perimeter of restricted area	0.4
Vehicular entrances	1.0
Pedestrian entrances	2.0
Entrances (inactive)	0.1

Source: NFPA 730, *Guide for Premises Security,* 2006, Table 6.4.6.1. Originally in U.S. Army Field Manual 19-30, 1979.

TABLE 14.10.3 Recommended Minimum Intensities for Outdoor Protective Lighting

Location	*Footcandles (on horizontal plane at ground level)*
Perimeter of outer area	0.15
Perimeter of restricted area	0.4
Vehicular entrances	1.0
Pedestrian entrances	2.0
Sensitive inner areas	0.15
Sensitive inner structures	1.0
Entrances (inactive)	0.1
Open yards	0.2
Docks/piers	1.0

Source: NFPA 730, *Guide for Premises Security,* 2006, Table 6.5.2.1. Originally in U.S. Army Field Manual 19-30, 1979.

consult the *Lighting Handbook*, 9th edition, published by the Illuminating Engineering Society of North America (IESNA).

There are a number of light sources that may be considered, based upon the application, including incandescent, fluorescent, and high-intensity discharge (HID). Types of HID lamps include mercury vapor, metal halide, and high-pressure sodium. In addition to the light source, the luminaire must also be considered. The luminaire is a complete lighting unit consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to a power source. The four general types of luminaires used for protective lighting are floodlights, streetlights, Fresnel lens units, and searchlights.

Locks

As mentioned above, locks in one form or another have been around since around 3000 B.C. Table 14.10.4 shows the categories and subcategories of locking systems that are in use today. The practitioner must take into account the level of protection required, the type of door or access portal in which the locking system is to be installed, and the type of key control system that is to be used. If tracking of personnel entering or leaving a secured area is required, the use of an access control system should be considered.

TABLE 14.10.4 Lock Types

Category	*Type*
Mechanical locks	Mortice Rim
Electrical locks	Electric solenoid bolts Electric strikes (fail secure, fail safe) Monitor strikes Motor lock
Electromagnetic locks	Direct hold Shearlock

Source: *NFPA Pocket Guide to Electronic Security System Installation,* 2005, Exhibit IV.33.

Locks are designed to provide various levels of deterrence or delay to entrance. Prior to laying out any locking and access control system, NFPA *101®*, *Life Safety Code®*, *NFPA 5000®*, *Building Construction and Safety Code®*, or the locally adopted building and fire codes should be consulted. It is vital that individuals within a premises are not trapped inside during an emergency event.

Although locking mechanisms that act to prevent access to buildings, floors, or specific rooms are permissible, these locks can in no way impede free egress from the space.

Glazing

Glazing or windows provide a means for natural light from the outside of a premises to be transmitted to the inside. Glazing can also be one of the weakest points of protection for a building. A common method of gaining unauthorized entry into a building is by the method of "smash-and-grab." Glazing can be decorative as well as resistant to attack and bullets. The types of glazing material that can be designed to be burglary-resistant include laminated glass, acrylic, and polycarbonate. When selecting the type of burglary-resistant glazing material to use, the practitioner should use UL 972, *Standard for Burglary Resistant Glazing Material*, 2002, and UL's *Burglary Protection Equipment Directory* as a guide. The directory may also be accessed via the Internet at http://database.ul.com/cgi-bin/XYV/template/LISEXT/1FRAME/index.htm.

In addition to the types of glazing material shown, these materials with the addition of composites may be used for bullet-resisting glazing material. Underwriters Laboratories (UL) has established eight ratings for bullet-resisting glazing material, Levels 1 through 8, based on penetration resistance from medium-, high-, and superpower small arms; high-powered hunting and sporting rifles; submachine guns; assault rifles; and shotguns.

Passive Barriers

Passive barriers, designed to blend into the background of a building or site as a design feature, are in place to deter or delay an attack—not only the smash-and-grab attack but also the crash-and-grab, in which a truck or other vehicle is driven into a building. This method of attack can be used not only for burglary but also by a hostile force attempting to place an explosive device in or near a building. The basic types of passive barriers are concrete planters, bollards, and Jersey barriers. See Figures 14.10.2 through 14.10.4 for examples of each.

VAULTS AND SAFES

Depending on the facility and its use, the practitioner may also have to consider using vaults and safes.

Vaults

The practitioner should be familiar with UL 608, *Burglary Resistant Vault Doors and Modular Panels.* There are four

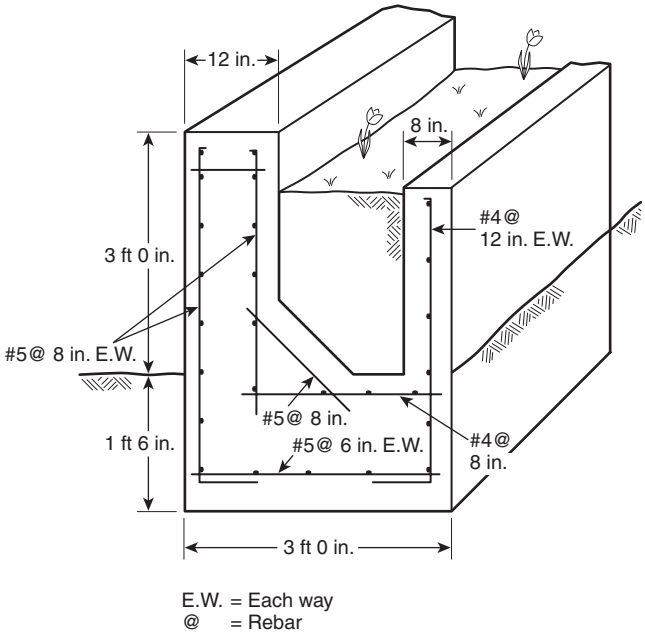

FIGURE 14.10.2 Concrete Planter (Source: NFPA 730, *Guide for Premises Security,* 2006, Figure 6.9.1.1)

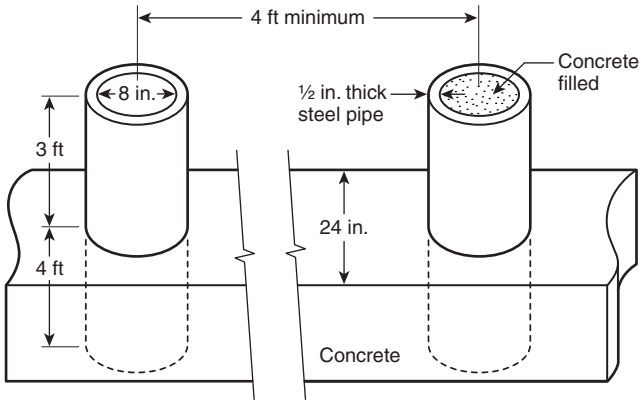

FIGURE 14.10.3 Concrete-Filled Bollard (Source: NFPA 730, *Guide for Premises Security,* 2006, Figure 6.9.2.1)

classifications for vault doors and walls, based on the time that the vault will resist the efforts of an attack:

- Class M ¼ hour
- Class 1 ½ hour
- Class 2 1 hour
- Class 3 2 hours

Alternate means of vault construction allows the use of reinforced concrete, steel lining, reinforced concrete blocks, or a combination of these materials. Table 14.10.5 shows the reinforced concrete equivalencies for the four types of UL-listed vault doors and modular panels.

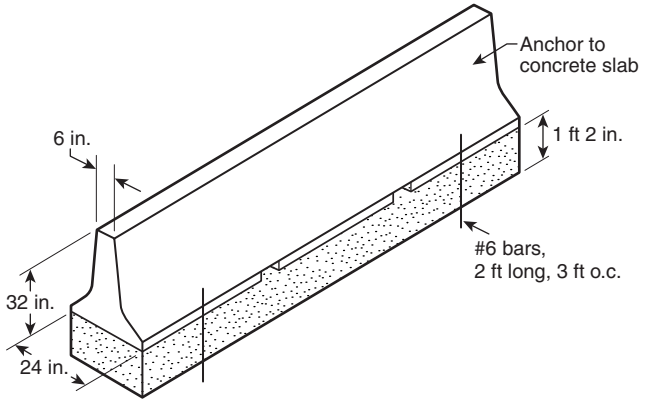

FIGURE 14.10.4 Jersey Barrier (Source: NFPA 730, *Guide for Premises Security,* 2006, Figure 6.9.3)

Safes

If the use of a safe is being considered, the practitioner should refer to UL 687, *Burglary Resistant Safes*. UL rates burglary-resistant safes according to the length of time a safe will resist attack. A UL label affixed to the door of the safe will identify that the safe has been listed by UL. UL-listed safes must also have a combination lock rated as Group 1 or 1R in accordance with UL 768, *Standard for Combination Locks*, and have a relocking device. The group rating signifies the ability of a mechanical lock to withstand expert manipulation. A Group 1 lock must be able to withstand 20 man-hours of expert manipulation. The Group 1R lock has this same specification, as well as being X-ray resistant. The UL-listed safe must also weigh a minimum of 750 lbs (340.2 kg) or be provided with a means of anchoring the safe to the premises. Table 14.10.6 shows UL-listed safe ratings.

COMPONENTS AND ISSUES IN ELECTRONIC SECURITY

Components of electronic security include central station monitoring, exterior and interior intrusion detection systems, access controls, and video surveillance. As mentioned previously, electric and now electronic security protection has been in place since the 1850s. Although the basic principles remain the same, the methods and technology have changed. The first advances from the technology of the 1800s occurred with the development of the ultrasonic detector by Sam Bagno[10] in 1948. This was the first form of volumetric protection using the Doppler effect to trigger the system.

Central Station Monitoring

The second great advance was the use of multiplex and the digital dialer. Prior to this innovation, signals were transmitted to the central station by either the McCulloh circuit or by means of a direct wire connection. These two means of signal transmission limited the distance that the central station could be from the protected premises. Central stations were generally located

TABLE 14.10.5 Reinforced Concrete Equivalencies to UL-Listed Vault Doors and Modular Panels

UL Classification	Thickness of Reinforced Concrete *in.*	*cm*	*Reinforcement Number of Rows of #5 Rebars*	*Reinforcement Number of Grids of Expanded Metal*
Class M	9	22.9	2	2
Class 1	12	30.5	3	2
Class 2	18	45.7	4	3
Class 3	27	68.6	5	4

Source: NFPA 730, *Guide for Premises Security,* 2006, Table 7.5.3.1.2.

near a telephone company's central office. During the 1960s the telephone companies began to notify the industry that copper or metallic circuits would in time no longer be available for use. These circuits were classified by the telephone industry as being Series 1000, which only carried direct current. The telephone industry now had Series 3000 circuits, which were of voice grade and carried alternating current. These circuits provided faster transmission rates and more data to be sent and received. Although there were attempts to digitize the McCulloh signal, by 1974 AT&T abandoned its efforts.

By the mid 1970s, a number of firms provided multiplex transmitters and receivers. Despite being more expensive than

TABLE 14.10.6 Safe Ratings

Rating	*Attack Tools*	*Body Construction*	*Area(s) of Attack*	*Entry Requirements*	*Attack Times*
TL-15	Common hand tools, picking tools, mechanical or portable electric tools, grinding points, carbide drills, and pressure applying devices and mechanisms	One-in. (25.4 mm) open hearth steel, or its equivalent, having a tensile strength of 50,000 psi (3,515,347 g/cm^2) or equivalent material	Door and front face	Opening the door or making a 6 in.^{2} (38.71 cm^2) opening	15 minutes
Record Safe	Same as TL-15 and including fishing and trapping devices and mechanisms			Same as TL-15 and including fishing and trapping	
TL-30	Same as TL-15 and including abrasive cutting wheels and power saws			Same as TL-15	30 minutes
TRTL-30	Same as TL-30 and including the oxyacetylene torch	Same as TL-15, with body encased in 3 in. (36.2 mm) of reinforced concrete or constructed of equivalent material	Door and front face	Opening the door or making a 2 in.^{2} (12.9 cm^2) opening	30 minutes
TL-15×6	Same as TL-30	Composite materials	Door and body	Same as TL-15	15 minutes
TL-30×6					30 minutes
TRTL-15×6	Same as TL-30 plus impact tools	Composite materials	Door and body	Same as TRTL-30	15 minutes
TRTL-30×6					30 minutes
TRTL-60×6					60 minutes
TXTL-60×6	Same as TRTL-15×6 plus explosives				

Notes: TL = Tool resistant.
TRTL = Torch and tool resistant.

Source: *NFPA Pocket Guide to Electronic Security System Installation,* 2005. Originally in UL 687, *Standard for Burglary Resistant Safes,* Underwriters Laboratories, Northbrook, IL, 2000.

McCulloh and direct wire, they did provide more information from the protected premises than the former technologies. The central station could now begin to receive zone annunciation from a single transmitter, allowing the central station to have a clearer picture of where the signal was coming from within the protected facility. As the multiplex system was constantly poling between the receiver and the transmitters, the central station could always be aware of the status of the phone line and the transmitter. With further advances in cryptographic transmission methods, multiplex transmissions are still used today for high-security assets.

But multiplex did not solve the larger problem of freeing the central station industry from its dependence on the Bell Operating Companies. Developed during the late 1970s and early 1980s, the digital dialer allowed the transmission of signals via Plain Old Telephone Service (POTS) lines. With the release and use of this technology, the central station was no longer required to be near the central office. A new industry of third-party central stations came into being, and the local alarm company no longer had to maintain their own central station. Today, although there are a number of firms that operate their own central stations, the majority of firms use a third-party central station. Although either type of firm can provide a high level of service, the practitioner should inquire into the location of the central station and whether it is operated by the security provider. In some cases, the central station may be located thousands of miles from the protected premises. The practitioner should always review the signal handling protocols of the central station and be aware of any restrictions that the local law enforcement provider might have placed on the response to alarms.

Issues in Electronic Security

Enhanced Call Verification. At the present time, a number of law enforcement agencies are requiring the use of Enhanced Call Verification, in which the protected premise and then a subscriber are contacted prior to making a service call. Although this has been successful in reducing the number of false alarms, it does insert a delay in the actual response. A number of agencies have promulgated ordinances that there is to be no response until the alarm is physically verified to ensure that an intrusion has occurred. This is a new concept. In bygone days, the police would respond prior to a third party verifying that an actual break-in had occurred.

Line Security. Digital dialers or communicators have one weakness that other transmission methods do not have, which is line security. When the phone line is cut from a premises that has a digital dialer, the central station will not be made aware of the loss. Other forms of signal transmission, including McCulloh, direct wire, multiplex, derived channel and long-range radio, provide the central station with an indication that a break has occurred. The practitioner needs to determine during the risk assessment phase if a backup communications path is required. The most common methods today are via cellular phone transmission or long-range radio. These methods may also be used as the primary path. If POTS is to serve as the primary means, the phone line should be supervised, either locally or by a second path. The supervision detects the voltage on the phone line. When the voltage is decreased or cannot be detected, the alarm control unit at the premises will activate a local trouble alarm or will transmit a supervisory signal over the second path to the central station. The practitioner should either review or specify the procedure that will be followed by the central station and the responsible party of the premises in the event of a lost phone line.

Broadband Communications. At the time that this chapter was written, broadband communications or the Internet was starting to be used for signal transmission. As with any new technology, there may be bends in the road before the final results are known. The practitioner should verify the operation of this method of signal transport if it is to be considered.

ELECTRONIC SECURITY AND INTRUSION DETECTION SYSTEMS

Intrusion detection systems can protect both the exterior and interior of a premises. The security practitioner should be familiar with NFPA 731, *Standard for the Installation of Electronic Premises Security Systems*, when laying out an intrusion detection system, closed-circuit television (CCTV) system, or access control system. One of the objectives of the risk assessment and site survey is to determine the level of protection to be provided. In addition to physical security as discussed previously, various forms of electronic security may also be seen as being appropriate.

UL Certification

Depending on the value of the property being protected, the practitioner may specify that the installed intrusion detection system be certificated by Underwriters Laboratories Inc. UL provides third party oversight and review of security systems that are installed in accordance with UL 681, *Standard for Installation and Classification of Burglar and Holdup Alarm Systems*. UL 681 provides a number of levels of protection or extents that the designer can specify. As the extent of protection increases, the level of detection within the premises increases. Table 14.10.7 provides an overview of the UL protection extents.

Exterior Detection

Exterior sensors must have a high probability of detection for all types of intrusions and a low unwanted-alarm rate for all expected environmental and site conditions.

The designer, in addition to the threat and risk assessment, needs to take into consideration the cost of the protection, both the equipment and its installation, as well as the cost of maintaining the equipment after the installation. For example, methods and equipment used for a power plant may not be required for a lumber storage yard.

Exterior devices include the following, several of which will be discussed in more detail:

- Audio
- Contacts
- Motion detection

TABLE 14.10.7 Extents of Intrusion Detection Protection for Premises and Stockrooms

Extent of Protection		External Openings				External Surfaces	
		Accessible	*Inaccessible*	*Movable Accessible*	*Movable Inaccessible*	*Walls, Floors, and Ceilings*	*Special Considerations*
4		Partial (2)					Contacts on at least two interior doors; or motion or sound detection on one or more selected areas; or one or more channels of radiation to limit movement within the premises.
3	Perimeter	Complete					
	Motion (4)			Partial (2,5)			Four-step (6) movement in each enclosed area with external openings.
	Sound			Partial (5)			Sound detectors in each enclosed area with external openings. Limited to buildings with good acoustical qualities.
	Channels			Partial (5)			Minimum length of beams equal to longest dimension of each enclosed area with external openings. Motion detectors can be used for channel protection.
2	Perimeter	Complete (3)			Partial (5)	Complete (7)	Exterior surfaces of monolithic concrete do not require protection.
	Motion			Partial (5)			Four-step (6) movement in each enclosed area with external openings.
	Sound			Partial (5)			Sound detectors in each enclosed area with external openings. Limited to buildings with good acoustical qualities.
	Channels	Complete (3)					Beams arranged to divide each enclosed area with external surfaces into at least three subdivisions. Maximum 1000 ft^2 for each subdivision.
1	Perimeter	Complete (3)	Complete (3)			Complete (7)	Protective wiring installed on all external surfaces.
	Sound or Vibration			Partial (5)	Partial (5)		Detectors adjusted to initiate an alarm if a manhole size opening is created in an opening, ceiling, floor, or wall.

Notes

1. Accessible means less than 18 ft (5.5 m) for grade or adjacent roofs; less than 14 ft (4.3 m) from horizontal openings; or less than 3 ft (0.91 m) from openings on same wall.
2. Doors only.
3. Complete protection of an opening means wiring or other recognized means applied to protect the opening (fixed or movable) plus contacts on movable openings.
4. Motion detection is provided by equipment such as ultrasonic, microwave, and passive infrared motion detectors. It is installed throughout each area.
5. Partial protection means a contact installed on a movable opening.
6. Four-step movement is a means of confirming volumetric radiation coverage by performing a series of walk tests through the enclosed area.
7. Complete protection of a surface means wiring or other recognized means to protect a wall, floor, or ceiling.

Source: *NFPA Pocket Guide to Security System Installation,* 2005, Exhibit III.42. Originally in Richard L. Sampson (Chairman), *A Practical Guide to Central Station Burglar Alarm Systems*, Central Station Alarm Association, Bethesda, MD, 1997, Table 4.

- Fence strain system
- Protective cabling
- Electric-field system
- Proximity
- Shock sensors
- Stress sensors
- Photo-electric cell
- Leaky coaxial

Motion Detection. The principal type of motion detection used for exterior protection is the microwave. Microwave detection sensors are categorized as bistatic or monostatic. Bistatic sensors use transmitting and receiving antennas located at opposite ends of the microwave link. Monostatic use the same antenna. Care should be taken when selecting a microwave detection system so that the field of detection does not extend beyond the area to be protected. Microwave energy can extend beyond the intended target area and cause false alarms from movement outside of the protected field.

When it has been determined that a fence is to be protected by a detection system, a paramount consideration in selecting the detection system is that the false or unwanted alarm rate is low. The fence itself must be in good condition and meet the minimum requirements of the detector's manufacture.

Fence-Strain System. The fence-strain system uses cables as transducers that are uniformly sensitive along their entire length. They generate an analog voltage when subject to mechanical distortions or stress resulting from fence motion.

Electric-Field System. An electric-field system consists of an alternating-current field generator, one or more field wires and one or more sensing wires, and a signal processor. The generator excites the field wires around which an electrostatic field pattern is created. The electrostatic field induces electrical signals in the sense wires, which are monitored by the signal processor.

Capacitance-Sensor System. A capacitance-sensor or proximity sensor measures the electrical capacitance between the ground and an array of sense wires. Any change in capacitance caused by an intruder approaching or touching one or more of the sense wires initiates an alarm.

Leaky Coaxial Cable System. Leaky coaxial cable (LCX) has been used for a number of years for perimeter protection. This method is also referred to as a ported cable system. The system involves lining the perimeter with two parallel LCX cables buried just below the surface of the ground. The depth is determined by the manufacture and coverage the designer wishes to obtain. These cables are generally buried in soil, but they can also be placed underneath asphalt and concrete. The LCX cable is slotted or ported so as to allow RF energy to be released. Two LCX cables are run parallel, one for transmission and the second for receiving. This generates a constant volume of EM field above the ground. Movement of objects with high capacitive properties above the cables will disturb the field, leading to detection when the coupled signal deviates from the stable reference signal.[11]

Interior Detection

Interior detection includes both perimeter and space detection. Perimeter protection is installed along the perimeter of the premises—doors, windows, walls, and roofs. Space protection provides detection within the interior of the premises.

Interior devices include the following, several of which are discussed further:

- Protective wiring
- Foil
- Traps
- Shock sensors
- Glass break sensors
- Sound detectors
- Motion detectors

Protective Wiring. Protective wiring is primarily found in older systems. The designer may find these methods useful for the protection of vents, skylights, and high windows. Protective wiring within mesh screens are still in common use for residential applications.

Shock Sensors. Shock sensors detect any vibration caused by attempted forced entry. The practitioner should take care in their application and avoid locations subject to high vibrations.

Glass Break Sensors. Glass break sensors are both audio (sound discriminators) and shock. They are activated by the frequency of breaking glass, or a combination of the frequency of breaking glass and the shock or vibration to the structure of the glass being broken. The use of glass break detectors has replaced the used of foil as the principal method of protecting glass. The practitioner should be aware that the placement of various films on the glazing material may dampen the effectiveness of the detector.

Sound Detectors. Sound or audio detectors can be used effectively to protect enclosed areas, vaults, warehouses, and similar enclosures. Microphone speaker sensors are installed on walls and ceilings of the protected area. The sensitivity of the system can be adjusted.

Motion Detectors. Motion detectors include microwave, passive infrared (PIR), two or more technologies (hybrid), and video motion. As discussed previously, the first form of motion detection was ultrasonic. Due to a high probability of false alarms, this method of space detection is rarely used today. The designer must use care in selecting and placing these detectors. Improper placement of these otherwise effective devices causes false and unwanted alarms.

Microwave. Microwave detectors used for interior detection are typically monostatic. The shape of the transmitted beam is a function of the antenna configuration. A variety of detection

patterns can be generated. Movement in the area will produce a Doppler frequency shift in the reflected signal and will produce an alarm if the signal satisfies the sensor's alarm criteria. Microwave detectors are best at detecting movement toward and away from the source. The practitioner should use care in selecting and placing this detection technology. Microwave energy can pass through glass doors and windows as well as lightweight walls or partitions constructed of plywood, plastic, or fiberboard. Microwave motion detectors are also susceptible to fluorescent lighting.

Passive Infrared. Passive infrared motion sensors detect a change in the thermal energy pattern caused by a moving intruder and initiate an alarm when the change in energy satisfies the detector's alarm criteria. The sensor's detection pattern is determined by the arrangement of lenses or reflectors. The pattern is not continuous but consists of a number of fingers, one for each mirror or lens segment. Numerous detection patterns are available, and the designer should select the one which meets the requirements of the protected space. PIR motion sensors are best at detecting movement across the field of view. PIR detectors should not be pointed toward a heat source or outside window that may catch the lights of traffic during the evening hours. Under no circumstances is a PIR motion detector that is listed for security to be used as part of an automatic fire detection system.

Video Motion. Video motion detection (VMD) combines space protection and closed-circuit TV (CCTV). A camera is mounted to cover the field of view. The active component for the VMD is not within the camera, but is a part of the processing equipment that is located at the receiving and viewing end of the system. During the programming of the system, active cells are selected within the field of view that is displayed by a camera to the monitor. When an object passes through an active field, the VMD will detect the movement and trigger an alarm. Detection is caused by the stable static view being disturbed by the motion through the active cells within the field of view.

ELECTRONIC SECURITY AND ACCESS CONTROL

Another form of electronic security is the access control system. Access control systems can control, restrict, and track the flow of personnel and visitors through a protected premises. The components of an access control system are controllers, readers, and tokens and credentials.

Controller

The controller is the front end of most access control systems. The controller may be a stand-alone unit or integrated with a computer. The controller contains information related to time schedules, access groups, and enrolled personnel. Before laying out any access control system, the practitioner should be familiar with the operating protocols of the premises. For larger systems the use of groups and access areas may come into play.

Readers and Credentials

Readers and credentials are closely related. The type of reader selected will dictate the type of credential to be used, and vice versa. Card readers may be of the following types:

- Hollerith
- Magnetic stripe
- Barium ferrite (BaFe)
- Radio frequency identification (RFID) (Proximity)
- Bar code
- Wiegand

Table 14.10.8 compares these systems according to various factors.

For enhanced security the practitioner may use biometric readers, which require a unique data set from the holder of a credential. Biometric credentials may be one of the following:

- Hand/finger geometry

TABLE 14.10.8 Comparison of Reader/Card Technologies

Card Type	*Technology*	*Durability*	*Resistance to Compromise*	*Reprogramming*	*Cost*
Magnetic Stripe	Magnetic media stripe	M	M	Y	L
BaFe	Magnetic pattern	H	M	Y	L
Wiegand	Magnetic pattern	H	H	N	M
Bar Code	Light/dark patterns	L	L	N	L
Hollerith	Hole patterns	L	L	N	L
Proximity	Electromagnetic	H	H	N	M

Notes:
L = Low
M = Medium
H = High
Y = Yes
N = No

Source: *NFPA Pocket Guide to Electronic Security System Installation,* 2005. Originally in Gerard Honey, *Electronic Access Control,* Newnes, Oxford, UK, 2000, Table 3.2.

- Fingerprints
- Handwriting
- Eye scan
- Voice recognition
- Face recognition

VIDEO SURVEILLANCE

Video surveillance systems, or CCTV, allow one to view and capture images from a protected location. The basic CCTV system is made up of a camera and monitor. If the image is to be captured for future viewing, then a recording device is required. CCTV systems can vary from a single camera with no recording device, perhaps located in a small mercantile shop for the manager to view the sales floor from the office, to systems that have over 1000 cameras with multiple monitors and recording devices, such as in a gaming establishment. Systems can monitor conditions both inside and outside the building.

The most important question that the practitioner must consider is "What is to be viewed?" Is the target to be the transactions that occur at a point-of-sale or activity along an exterior fence line? Does the system need to make out a car's license plate number or just the type of vehicle? The entire image recorded is the *field of view*; the focus of attention, such as a license plate, is the *critical viewing area.* For cameras placed to record images at a point of customer transactions, such as a teller window, the critical viewing area (face) should cover 15 percent of the camera's field of view under normal resolution. Action within the scene should cover at least 20 percent or more of the overall width of the field of view. The designer should always consider the appearance of the final image when making camera and lens selections.

CCTV cameras that are produced today for the majority of systems are charge-coupled device (CCD) units. Table 14.10.9 provides an overview of the various types of CCD cameras that are available at the time this chapter was written.

CCD cameras come in a variety of imager formats, the most common being the following:

- ¼ in.
- ⅓ in.
- ½ in.
- ⅔ in.
- 1 in.

The imager format is the usable part of the imager that is to be used. It is measured diagonally across the chip. The format of the camera will affect the view provided by the lens selected. The practitioner must look at both the camera format and the lens in order to make certain that the view selected is the view achieved.

Field of View

One can calculate the field of view by scene width as shown in Equation 1 or by scene height as shown in Equation 2.

TABLE 14.10.9 CCD (Charge-Coupled Device Cameras)

Camera Type	*Light Type*	*IR Sensitivity*	*Resolution*	*Lag Time*	*Retain Image*	*Auto-Iris Lens*	*Expected Life*
C-MOS/CCD	Full/fairly consistent 20–50 lx	Extreme high 1050–1300 nm average	Good/fair—Inside Fair/poor—Outside 300–400 TVL	None	None	Dependent on application	3–5 years dependent on conditions
Interline Transfer CCD	Low/full variable 3–5 lx	Extreme high 1050–1300 nm average	Very good to good 350 TVL & up average	None	None	Dependent on application	3–5 years dependent on conditions
Frame Transfer CCD	Low/full variable 0.1–5 lx	Excellent 800–850 nm	Excellent to very good 400 TVL & up	None	None	Dependent on application	3–5 years dependent on conditions
Hyper HAD CCD	Note 1 1–50 lx	None	Very good to good 375 TVL & up	None	None	Dependent on application	3–5 years dependent on conditions
Intensified CCD	Low/full variable .003 lx	None Visible light only	Good to fair 275 to 400 TVL	Note 2	Chip-None Note 3	Always	1–2 years dependent on conditions

Editor's Note: The CCD camera is the most popular CCTV camera in use at this time. They are entirely solid state.
Notes:
1. Due to design of chip, telephoto lenses will produce a sharper image.
2. The method of light amplification that is used will determine the amount of lag time in lower light conditions.
3. It is possible to burn an image into the 2nd generation intensifier that may be used in these cameras.

nm = nanometers
TVL = TV lines

Source: Exhibit V.9, *NFPA Pocket Guide to Electronic Security System Installation,* 2005. Originally in Charlie Pierce, *Application & Design of CCTV,* LeapFrog Training & Consulting, Davenport, IA, 2002, p. 28.

$$f = c\left(\frac{d}{w}\right) \quad (1)$$

where

c = Width of the charge-coupled device (CCD) chip

d = Distance from camera

w = Width of field of view

f = Focal length of camera lens

$$f = v\left(\frac{d}{h}\right) \quad (2)$$

where

v = Height of CCD chip

d = Distance from camera

h = Height of field of view

f = Focal length of camer lens

Another method takes into account the total critical viewing area as a percentage of the monitor. If the critical object takes up only a quarter of the total field of view within the monitor, then it would be 25 percent of the view. If the critical object took a third of the total field of view it would be 33.3 percent of the view and so forth (Table 14.10.10). Calculate the viewing area of the scene and also of the critical viewing area by multiplying the horizontal and vertical dimensions. Divide the critical viewing area by the total viewing area to obtain the critical viewing area in the monitor.

If the proportion of the critical viewing area is as expected, use the calculated focal length. If not, then change the focal length until the correct proportion is found, or change the distance of the camera until the correct proportion is found. In some cases, the solution will be in a new lens being selected.

Lenses

Lenses come in a number of formats. Table 14.10.11 lists common lens formats used with CCD cameras. The designer should use a field of view calculator to make the final determination. These calculators are available from most lens manufacturers. To select the proper lens for the format of the camera and the field of view, the designer should make an object distance calculation (Figure 14.10.5). When calculating the target view of the camera, the object distance must be considered. In addition to the actual distance of the camera from the target, the height of the camera must also be taken into consideration. The Pythagorean theorem is used in part to calculate the actual view distance. The square root of the number calculated is the object distance. Once the actual object distance is known, the designer can calculate the target size for a given, as seen in Table 14.10.12. CCTV cameras use a 4:3 aspect ratio. As such, the vertical view will always be 75 percent of the size of the horizontal view.

TABLE 14.10.10 Viewing Area as a Percentage of the Monitor

Camera Formats (in.)	*Horizontal (mm)*	*Vertical (mm)*
1/4	3.2	2.4
1/3	4.4	3.3
1/2	6.4	4.8
2/3	8.8	6.6

Source: NFPA 731, *Standard for the Installation of Electronic Premises Security Systems,* 2005, Table B.1(c).

TABLE 14.10.11 Lens Formats

Focal Length	*Lens*	*Range*
4 mm	Very wide angle	4–6 ft (1.2–1.8 m)
8 mm	Wide angle	12 ft (3.6 m)
16 mm	Standard	25 ft (7.6 m)
25 mm	Telephoto	45 ft (13.7 m)
50 mm	Long telephoto	50–60 ft (5.2–18.3 m)

Source: *NFPA Pocket Guide to Security System Installation,* 2005, Exhibit V.20.

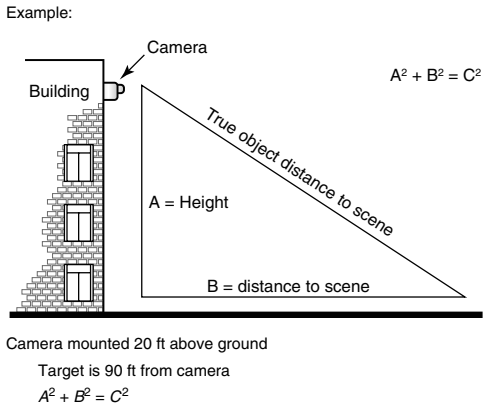

FIGURE 14.10.5 Object Distance Calculations (Source: *NFPA Pocket Guide to Security System Installation,* 2005, Exhibit V.21)

TABLE 14.10.12 Camera Formats

Camera format size	1/4 in.	1/3 in.	1/2 in.	2/3 in.	1 in.
Diagonal format	4 mm	5.5 mm	8 mm	11 mm	16 mm
Horizontal format	3.6 mm	4.8 mm	6.4 mm	8.8 mm	12.8 mm
Vertical format	2.7 mm	3.6 mm	4.8 mm	6.6 mm	9.6 mm

Source: *NFPA Pocket Guide to Security System Installation,* 2005, Exhibit V.22.

Depth of Field

Finally, when setting up an image to be viewed, lighting and depth of field must be considered. Depth of field is the region within the picture that will appear sharp in focus (Table 14.10.13). The format of the lens will affect the depth of field. The amount of available light will also affect the depth of field for a camera. In order to calculate the depth of field for an object that is not close to the camera, Equation 3 should be used.

Far Focus Limit

$$FF = (H \times D)/[H - (D - L)] \quad (3)$$

where

FF = Far focus limit (in mm)

H = Hyperfocal distance (in mm)

D = Lens focus distance (in mm)

L = Lens focal length

Example: 16 mm focal length, f-8 f-stop, ⅓ in. format, 150 ft focus distance (45.72 mm or 45,720 mm)

FF = (246,153 mm × 45,720 mm)/[246,153 mm – (45,720 mm – 16 mm)]

FF = 11,254,115,160 mm/246,153 mm – 45,704 mm

FF = 11,254,115,160 mm/200,449 mm

FF = 56,144 mm (56.144 m or 184 ft)

Editor's Note: In the example given, the object or target would be in focus. The hyperfocal distance is the plane on which everything within the view is at optimal focus.

To calculate the depth of field for an object that is close to the camera, Equation 4 should be used.

Near Focus Limit

$$NF = (H \times D)/[H + (D - L)] \quad (4)$$

where

NF = Near focus limit (in mm)

H = Hyperfocal distance (in mm)

D = Lens focus distance (in mm)

L = Lens focal length

Example: 16 mm focal length, f-8 f-stop, ⅓ in. format, 150 ft focus distance (45.72 mm or 45,720 mm)

NF = (246,153 mm × 45,720 mm)/[246,153 mm + (45,720 mm – 16 mm)]

NF = 11,254,115,160 mm/246,153 mm + 45,704 mm

NF = 11,254,115,160 mm/291,857 mm

NF = 38,560 mm (38.56 m or 126.5 ft)

To obtain the optimal image, in which the entire view would be in focus, Equation 5 would be used.

Hyperfocal Distance

$$H = (L \times L)/(f \times d) \quad (5)$$

where

H = Hyperfocal distance (in mm)

L = Lens focal length

f = Lens aperture f-stop

d = Diameter of circle of least confusion (in mm)

Example: 16 mm focal length, f-8 f-stop, ⅓ in. format

H = (16 mm × 16 mm)/(8 × 0.00013)

H = 256/0.00104

H = 246,153 mm

The circle of least confusion is the area that is out of focus before and after the hyperfocal distance. The circle is the area of greatest light concentration behind the lens but in front of the imager of the camera. See Table 14.10.14.

Recording

At the time that this chapter was written, the primary method of image storage was the digital video recorder (DVR). The number of images that can be stored on a single DVR is dependent on the size of the storage disk within the DVR, the image size, number of images per second, and quality.

SUMMARY

This chapter is only a snapshot of the knowledge base that the practitioner should understand prior to designing and specifying the security for a premises. The practitioner should also consult a number of the text references that are listed in the Bibliography.

TABLE 14.10.13 Depth of Field

Broad Depth of Field	*Narrow Depth of Field*
Wider angle of lens	More telephoto
More light	Less light

Source: *NFPA Pocket Guide to Security System Installation,* 2005, Exhibit V.29.

TABLE 14.10.14 Circle of Least Confusion

Format	*Circle of Least Confusion*
¼ in.	0.00019 mm
⅓ in.	0.00013 mm
½ in.	0.00009 mm
⅔ in.	0.00007 mm
1 in.	0.00005 mm

Source: *NFPA Pocket Guide to Security System Installation,* 2005, Exhibit V.31.

This chapter did not cover such topics as private security, data and information services security, pre-employment background checks, and a host of other subjects. Security can be both for the exterior and interior of the site. A site survey is an important step to be taken prior to any design or installation work being performed. A risk and vulnerability assessment should also be conducted. Present technology provides a vast variety of options that may be used in providing effective layers of protection and detection at a site. The objective of any security program is to deter, delay, detect and respond.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on security and intrusion systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA *101®*, *Life Safety Code®*
NFPA 730, *Guide for Premises Security*
NFPA 731, *Standard for the Installation of Electronic Premises Security Systems*
NFPA 5000®, *Building Construction and Safety Code®*

SECTION

15

Water Supplies for Fixed Fire Protection

David R. Hague

15.1 Fixed Water Storage Supplies for Fire Protection
15.2 Water Supply Requirements for Public Supply Systems
15.3 Hydraulics for Fire Protection
15.4 Water Supplies for Sprinkler Systems
15.5 Microbiologically Influenced Corrosion in Fire Sprinkler Systems
15.6 Water Distribution
15.7 Fire Pump Controllers and Power Supply Arrangements for Motor-Driven Fire Pumps

Section 15 of the *Fire Protection Handbook*® is the first of three sections concentrating on the myriad forms of fire suppression. Because water is the most prevalent fire suppression agent and water supply can determine the success or failure of fire suppression efforts, it is appropriate that the first of this handbook's suppression sections addresses water supplies for fixed fire suppression.

Chapter 1, "Fixed Water Storage Supplies for Fire Protection," contains information on the design, installation, and maintenance of constructed water storage supplies and the ways in which naturally occurring surface and groundwater supplies can be used for fire protection. Of particular interest are the provisions described for preventing water stored for fire protection supplies from freezing during cold weather and maintaining stability and functionality following a seismic event.

Chapter 2, "Water Supply Requirements for Public Supply Systems," gives information on planning for public water supply systems and outlines the methods used to evaluate public supplies for their adequacy and reliability. Hydraulic calculations and the Insurance Services Office (ISO) grading schedule are introduced.

Chapter 3, "Hydraulics for Fire Protection," provides a more in-depth review of material introduced in Chapter 2. Topics covered include relevant formulae, coefficient of flow, flow measurement, elastic wave theory, friction loss, K-factor, and use of a Moody diagram.

The next two chapters explore water and automatic sprinkler systems. Chapter 4, "Water Supplies for Sprinkler Systems," identifies the types of water supplies that are acceptable for fire sprinkler systems and the variables that must be considered in the system design. Chapter 5, "Microbiologically Influenced Corrosion in Fire Sprinkler Systems," addresses MIC and biological growth control, which have been extensively researched in allied engineering fields, but whose treatment in fire sprinkler systems is relatively new.

Chapters 6 and 7 turn to the important topic of fire pumps used in fixed fire protection. Chapter 6, "Water Distribution," covers types of pumps, their principles of operation, curves, head, horsepower, drives, and tests. Chapter 7, "Fire Pump Controllers and Power Supply Arrangements for Motor-Driven Fire Pumps," focuses on the electrical and control aspects of electric motor-driven fire pump installations and is specific to fire pump controllers, motors, and electrical power supply arrangements. Chapter 7 was expanded for this edition of the handbook to introduce variable speed motor-driven fire pumps, their applications, and field experience.

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Chapter 1

Fixed Water Storage Supplies for Fire Protection

Revised by
Bruce A. Edwards

Chapter Contents

Storage Tanks (Gravity and Suction)
Tank and Tower Foundations
Tank Towers
Tank Heating Equipment
Tank Equipment and Accessories
Embankment-Supported Coated Fabric Suction Tanks
Pressure Tanks
Natural and Constructed Suction Facilities

Key Terms

air lock, alternative water supply, fire pump, freezing prevention, static water supply, storage tank (elevated), storage tank (embankment-supported), storage tank (gravity), storage tank (ground-level), storage tank (suction), water supply

In a broad sense, fire protection water storage supplies include all bodies of water available as sources of supply, whether they are contained by constructed or natural barriers. Elevated, ground-level, or underground storage tanks of metal, wood, plastic, or rubberized fabric are examples of constructed storage facilities; rivers, ponds, and lakes, or other surface water sources are examples of natural storage facilities.

Open bodies of water, such as human-made reservoirs and freshwater pools created by the damming of streams, are sometimes used in private fire protection to supplement public water supplies or furnish the primary source of water for fire protection if public supplies are unavailable, insufficient in volume or pressure, or both or if they lack dependability. A common method of providing a fire protection water supply is to use elevated gravity tanks or ground-level suction tanks with fire pumps. Pressure tanks, with their limited capacity, may be used where storage requirements are relatively small or other means of storing water for fire protection are impractical.

This chapter contains information on the design, installation, and maintenance of constructed water storage supplies and the ways in which naturally occurring surface and groundwater supplies can be used for fire protection. Of particular interest are the provisions described for preventing water stored for fire protection supplies from freezing during cold weather and in seismic areas maintaining stability and functionality following a seismic event.

For related topics, see Section 13, Chapter 4, "Alternate Water Supplies"; Section 15, Chapter 4, "Water Supplies for Sprinkler Systems"; Section 15, Chapter 6, "Water Distribution"; and chapters in Section 16, "Water-Based Fire Suppression Equipment."

STORAGE TANKS (GRAVITY AND SUCTION)

The prevalence of the installation of hydraulically designed automatic fire sprinkler systems in new construction and renovations has reduced the reliance and use of elevated tanks for fire protection water supplies. The use of ground-level suction tanks, combined with fire pumps, has increased (Figure 15.1.1). Nevertheless, there are many elevated gravity tanks still in service used solely for fire protection water supplies, and they require high standards of maintenance to continue their reliability and functionality as sources for systems.

Tanks used for fire protection water supplies should not be used for any other purpose. In addition to negatively affecting the quantity of water and duration of flow available, tanks used for other purposes must usually be refilled frequently, and they become settling basins that collect large accumulations of sediment. When water is drawn from the tank, the sediment also is drawn into the yard or extinguishing system and may block the system.

If the tank is wood and is refilled frequently, the alternate drying and wetting of the lumber may appreciably shorten the life of the tank; with a steel tank, more frequent painting may be

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FIGURE 15.1.1 Suction Tank with Attached Pump House (Source: Columbian TecTank)

necessary, which means not only greater expense but also more time out of service.

Dual-purpose tanks will seldom be full, because domestic and industrial consumption constantly draws them down. In addition, the normal water level may continue to drop if the industry grows. If a fire occurs several years after the tank is installed, sufficient water at sufficient pressure might not be available. Should a dual-purpose tank be necessary, the outlet for the domestic and industrial supply should be set at a water level above the water dedicated for fire protection service.

Location

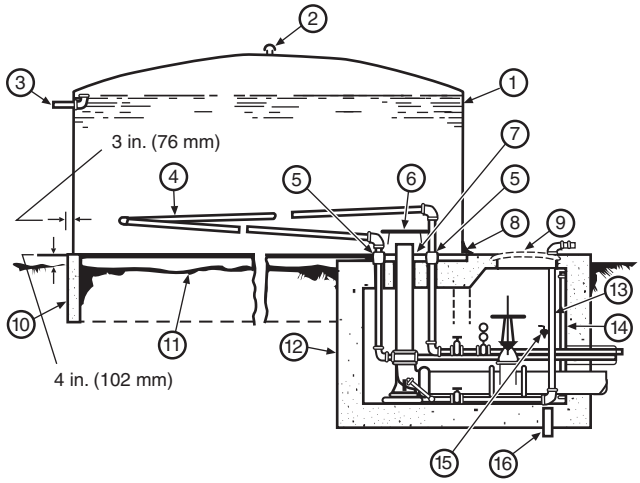
A gravity tank supported on an independent steel tower with foundations placed in the ground rather than on a building is the best arrangement. The tank should be built so that it will not be exposed to fire or physical damage. If lack of yard room makes this impossible, the exposed steelwork should be suitably protected by fire-resistant construction or coverings. The steel protection, when necessary, should include steelwork within 20 ft (6 m) of combustible buildings or openings from which fire might issue.

If the tank and supporting trestle are to be placed on the rooftop of a building, the building must be designed and constructed to carry the maximum load.

Suction tanks should be located so as to minimize yard piping. The pump house is generally placed close to the tanks to minimize suction piping. The tanks should not be located where they will be exposed to physical damage or fires from adjacent combustible construction or yard storage (Figure 15.1.2).

Design for Earthquake Resistance

Fire protection water storage tanks need to be designed to resist earth movement including earthquakes. In an earthquake, ground shaking sets up a rocking action and sloshing of water in the tank. These forces may produce stresses beyond those provided for in a design that allows only for ordinary dead, live, and wind loads. In areas where earthquakes are likely or possible, or where earthquake protection is required by local codes or authorities, fire protection water storage tanks should be designed to resist earthquakes. The primary goals are first to improve the reliability and likelihood that the fire protection system will remain in service after an earthquake and then to minimize potential water damage from a fire protection system



1. Pump suction tank
2. Screened vent
3. Stub overflow pipe
4. Steam coil for heating
5. Extra-heavy couplings welded to tank bottom
6. Vortex plate
7. Watertight lead slip joint
8. Flashing around tank
9. Manhole with cover
10. Concrete ring wall
11. Sand or concrete pad (depending on soil condition)
12. Valve pit
13. Drain pipe
14. Ladder
15. Drain cock
16. Valve pit drain

FIGURE 15.1.2 Ground-Level Suction Tank Showing the Discharge Pipe Connected to the Bottom of the Tank in a Valve Pit (Source: FM Global Property Loss Prevention Data Sheet 3-2, "Water Tanks for Fire Protection." © 2006 FM Global. Reprinted with permission. All rights reserved.)

leakage, with an understanding of the unpredictable nature of the size and severity of seismic events.

Water tanks and reservoirs fall into three categories—ground-level tanks, elevated tanks, and embankment-supported tanks.

Ground-Level Tanks. Ground-level tanks that either provide a suction supply for an adjacent fire pump or act as gravity tanks to provide sufficient water pressure for the fire protection system are the most common type in areas where seismic protection is required. For ground-level tanks, the four main seismic considerations are as follows:

1. Flexibility of pipe connections to tank. When the tank discharge pipe runs horizontally to a pump, two flexible couplings on the pipe should be provided between the tank and the pump. One should be as close to the tank wall as possible and the other within 24 in. (0.6 m) of the pump. When the tank discharge pipe feeds into an underground main, two flexible couplings must be provided between the tank and the ground entrance. One should be as close to the tank wall as possible; the other should be within 24 in. (0.6 m) of the ground entrance.
2. Anchorage of the tank and foundation to prevent horizontal and vertical displacement. Ground-level tanks should be anchored for seismic protection for the appropriate seismic ground motion. Additionally, the foundation design, which is often done separately from the tank design, should be coordinated with the tank design to ensure that the foundation is of sufficient size and mass to prevent rocking of the tank. Anchorage and foundation design details are best provided and/or reviewed by a qualified structural engineer. American Water Works Association standards D100, *Welded Steel Tanks for Water Storage,* and D103, *Factory-Coated Bolted Steel Tanks for Water Storage,* provide seismic design criteria for anchorage of tanks.
3. Clearance around pipe penetrations through pump house or other structural walls. At least 2 in. (50 mm) clearance should be provided on all sides of piping that passes through structural walls or other fixed structures.
4. Proper steel thickness near base of tank to avoid elephant footing. In areas with a high probability of strong ground motion, unanchored tanks may have significant vertical and horizontal displacements. Depending on the diameter of the tank and the height-to-diameter ratio, these expected displacements may vary. However, the main point is that unanchored tanks may create displacements that may not only damage the tank but also rupture the attached piping.

Elevated Tanks. Elevated tanks, where the tank body is mounted on legs or a pedestal, are less common in areas where seismic protection is required. Because of the complexity of any seismic analysis for this type of tank, a qualified structural engineer can best handle seismic analysis and design.

Embankment-Supported Tanks. Embankment-supported fabric tanks have an earthen embankment that supports a lined reservoir. Because of the complexity of any seismic analysis for this type of tank, seismic analysis and design are best handled by a qualified structural engineer.

Tank Capacities

Today it is usually uneconomical to install a gravity tank big enough and tall enough to be connected directly into the fire protection system and furnish an adequate supply for both hose streams from hydrants and water-based fire protection systems.

Years ago, because of limited capacity and pressure requirements, a gravity tank holding at least 30,000 gal (114 m^3) with its bottom at least 75 ft (22.9 m) above the ground could adequately supply both hose lines from hydrants and the extinguishing systems. Storage tank selection is still determined by the capacity and pressure required for both hose streams and areas' fire sprinklers for the possible duration of a fire; but because of the increased design density requirements of today, the suction tank and pump are often more economical than a gravity tank or gravity tank and booster pump.

Gravity and suction tanks are generally erected in standard sizes (Tables 15.1.1 and 15.1.2). The capacity required is determined by the intended use of the tank and is specified in the number of gallons (cubic meters) available from the tank (1 gal = 0.00379 m^3).

Steel gravity tanks are constructed on single pedestals or with suspended bottoms erected on towers with four columns for capacities from 50,000 to 200,000 gal (190 to 750 m^3) inclusive, six columns for capacities from 200,000 to 300,000 gal (750 to 1100 m^3) inclusive, and eight columns for tanks over 300,000 gal (over 1100 m^3).

Construction of Tanks

Existing gravity tanks are built of wood or steel and are supported by steel towers. Most new gravity tanks are built of steel

TABLE 15.1.1 Standard Sizes of Gravity Tanks

Steel Tanks		Wood Tanks		Standard Height	
gal	*m^3**	*gal*	*m^3**	*ft*	*m**
30,000	115	30,000	114	75	22.9
40,000	150	40,000	150	100	30.5
50,000	190	50,000	190	125	38.1
60,000	230	60,000	230	150	45.7
75,000	290	75,000	290	—	—
100,000	380	100,000	380	—	—
150,000	570	—	—	—	—
200,000	760	—	—	—	—
300,000	1100	—	—	—	—
400,000	1480	—	—	—	—
500,000	2000	—	—	—	—

*Figures rounded off as approximations from nominal customary American tank sizes.

TABLE 15.1.2 Common Sizes of Steel Pump Suction Tanks

gal	*m³**	*gal*	*m³**
50,000	190	250,000	950
75,000	290	300,000	1100
100,000	380	400,000	1500
125,000	475	500,000	2000
150,000	575	750,000	3000
200,000	750	1,000,000	4000

*Figures rounded off as approximations from nominal customary American tank sizes.

with some wood on pedestals. Reinforced concrete towers are sometimes used, and tanks can also be placed directly on top of the structures they supply. In a few cases, concrete has also been used for the tank shells themselves. Typical gravity tanks are shown in Figures 15.1.3 and 15.1.4. In Figure 15.1.4, note that the higher the tank, the greater the water pressure at the base of the tank.

Tanks should be designed and installed according to NFPA 22, *Standard for Water Tanks for Private Fire Protection,* which gives full requirements for construction materials, loads, unit stresses, details of design, foundations, accessories, and workmanship. Welding of towers should conform to code requirements for welding in building construction.[1]

Steel for tanks and towers should conform to the specifications in NFPA 22. Chief among these specifications are the American Water Works Association standards for steel tanks,[2,3] which give the thickness of steel plates and the welding and bolting practices that should be followed. Other standards referenced in NFPA 22 cover steel shapes, plate materials, bolts, anchor bolts and rods, forgings, castings, reinforcing steel, and filler material for welding.

Steel tanks and towers should be riveted, welded, or bolted (if factory coated). Unfinished bolts and nuts should be used only where not exposed to weather, water, or corrosive environments and in (1) field connections of nonadjustable tension

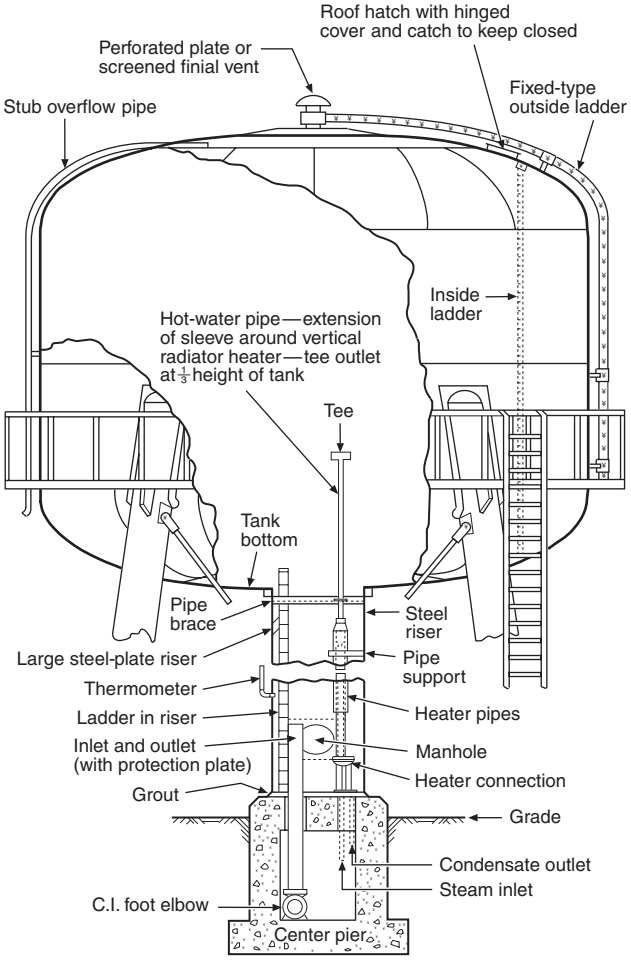


FIGURE 15.1.3 Typical Tower-Supported Double Ellipsoidal Tank

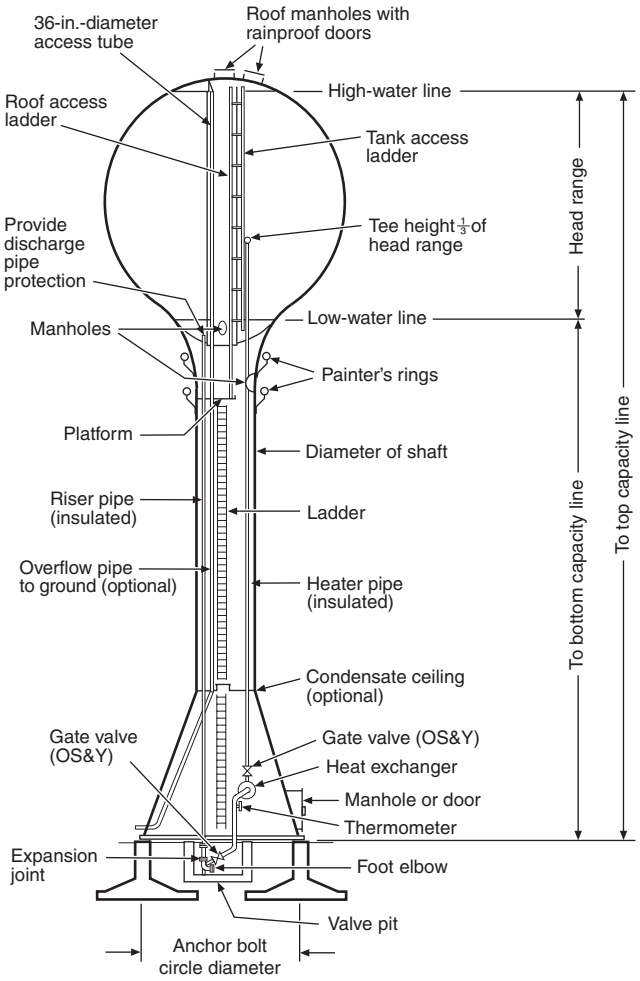


FIGURE 15.1.4 Typical Pedestal Tank

members carrying wind stress and (2) field connections of compression members and grillages in towers supporting tanks of 30,000 gal (114 m^3) or less capacity. Wood tanks and towers should conform to the specifications in NFPA 22, including types and dimensions of wood suitable for use, processes that should be used, and proper hoop materials and design, as well as unit loads and unit stresses for steel tanks and towers, and working stresses for timber for wood tanks.

During assembly and erection, plates should be bolted firmly together before riveting. Drift pins should not be used to bring parts together or to enlarge unfair holes.

No waste material, such as boards, roofing, paint cans, and so on, should be left in the tank or in the space at the top of the tank after its completion, because it may obstruct the piping.

Tanks should be put in service promptly after completion. Wood tanks may be damaged by shrinkage if left empty.

TANK AND TOWER FOUNDATIONS

The following are principles of good foundations for suction tanks and gravity tank towers.

Foundations in the Ground

Foundations should be designed to carry the maximum loads without excessive settlement. If wood piles are used above permanent low-groundwater level, they should be protected as specified by the American Wood Preservers Association.[4] Foundations should not be constructed over buried pipes or immediately adjacent to existing or former deep excavations unless the foundation bases go below the excavation.

Material. Foundations and footings should be built of concrete with a specified compressive strength not less than 3000 psi (20.69 MPa). The cement and aggregates, and the mixing and placing of the concrete, should conform to American Concrete Institute requirements for reinforced concrete.[5] Concrete work should conform to all requirements of ACI 301.[6]

Steel or wood pump suction tanks should be set on compacted crushed stone or granular base, or on concrete foundations. At least 3 in. (76.2 mm) of clean, dry sand, laid on compacted grade should be provided at the finished tank grade and should slope up toward the center of the tank at the rate of 1 in. in 10 ft (25.4 mm in 3 m). If the soil is good, at least 4 in. (100 mm) of crushed stone or sand is suggested. The material should then be laid on moistened and compacted gravel after removing unsuitable soil. Special consideration (outlined later) must be given if soil is poor.

A reinforced concrete ring wall at least 2½ ft (760 mm) deep below finished grade and 10 in. (250 mm) thick should surround the tank foundation. This ring normally projects 6 in. (152 mm) above the surrounding grade and should be reinforced against temperature and shrinkage and reinforced to resist the lateral pressure of the confined fill with its surcharge. If the ring wall is outside of the tank shell, asphalt flashing should be installed between the tank and the ring wall at ground level.

Where the soil does not provide direct support for the tank without excessive settlement, shallow foundation construction is not adequate, and a proper foundation needs to be designed by a structural engineer.

Form. The tops of foundations should be level and at least 6 in. (150 mm) above ground. The bottoms of foundation piers for towers should be located at a level that is below the frost line and, in the case of piers, at least 4 ft (1.2 m) below grade, resting on thoroughly tamped soil or rock.

Grouting and Flashing. Bearing or base plates should have complete bearing on the foundation or be laid on minimum 1 in. (25.4 mm) thickness cement grout to secure a complete bearing. The stressed portion of anchor bolts should not be exposed. If the stressed portions of anchor bolts must be exposed, they should be encased in cement mortar to protect against corrosion unless they are accessible for complete cleaning and painting. If structural shapes, plates, and bolts enter or are supported by masonry or concrete, the joint between the metal and masonry or concrete should be flashed with asphalt. (This does not refer to base plates under columns.)

Soil-Bearing Pressure. In order to find the proper depth of the foundation, the soil-bearing pressure must be determined by analyzing the subsurface and checking the foundations of other structures in the area. Test borings should be made by or under the supervision of an experienced soils engineer or soils testing laboratory. The borings should be made deep enough to determine the adequacy of the support (usually a minimum of 20 to 30 ft [6 to 9 m]). Evaluate the potential for subsidence, collapse, soil liquefaction, and settlement where the presence of limestone or other soluble rock types are present or suspected and include cavity investigation and competency of bedrock with the subsurface investigation.

Avoid constructing foundations over buried pipes or adjacent to existing or former deep excavations.

Piers

Pier foundations may be of any suitable shape and may be either plain or reinforced concrete. If they support a tower, their center of gravity should lie in the continued center of the gravity line of the tower column or else be designed for eccentricity. The height of piers should not be less than the mean width. The top surface should extend at least 3 in. (756 mm) beyond the bearing plates on all sides and be generally chamfered at the edges.

The tops of foundation piers should be level and at least 6 in. (152 mm) above grade, located at the correct elevations. The bottom of foundations should be located at a level that is the greater of either below the frost line or at least 4 ft (1.2 m) below grade.

Anchorage. The weight of piers should be sufficient to resist the maximum net uplift that occurs when the wind blows from any direction on the empty tank. The weight of dirt directly above the base of the pier may be included in the calculations.

Anchor bolts should be arranged to engage a weight at least equal to the net uplift with the tank empty and the wind blowing from any direction. Their lower ends should be hooked or fitted with anchor plates.

Anchor bolts should be accurately located with sufficient free length of thread to fully engage their nuts. Expansion bolts are not acceptable. The minimum size of anchor bolts should be 1½ in. (38 mm).

Center Pier. In addition to the weight of the water in a large plate riser, the weight of the column of water directly above the riser in the tank, and the weight of the steel plate, the center pier should be considered as supporting a hollow cylinder of water in the tank. If the hemispherical or ellipsoidal bottom is rigidly attached to the top of the large riser by a flat horizontal diaphragm plate, the radius of the hollow cylinder of water should be determined as specified under large risers discussed later in this chapter.

TANK TOWERS

Steel is generally used for the construction of tank towers (Figure 15.1.5). Details on the specific types of steel used in tanks can be found in NFPA 22.

Both dead loads and live loads should be considered when designing towers. The dead load is an estimate of the weight of all permanent construction and fittings. The live load is considered as the weight of the water when it overflows the top of the tank. Consideration should also be given to temporary loading, such as ice and snow.

The weight of the water located directly above any riser need not be considered when figuring loads unless the riser is suspended from the tank bottom. If the riser is used to support the tank bottom, the entire weight supported by the riser should be considered, including the weight of the water.

Additional factors to consider are wind, balcony, and earthquake loads. Wind loads are based on 30 lb/ft^2 (147 kg/m^3) for vertical plain surfaces and 18 lb/ft^2 (88 kg/m^3) over the total area of the vertical projection on cylindrical surfaces. These loads are applied to the center of gravity of the projected areas. A vertical load of 1000 lb (454 kg) should be applied to any 10 ft^2 (0.93 m^2) of area on a balcony floor and on each platform; 500 lb (227 kg) applied to any 10 ft^2 (0.93 m^2) of area on the tank roof; and 350 lb (159 kg) applied to each vertical section of the ladder. Snow loading is additional and considered in these loadings. Earthquake loading must be designed specifically for local conditions.

Ladders and Balconies

All tanks should have ladders on both the outside and inside, with convenient passage from one ladder to the other and through the roof hatch, arranged not to interfere with the opening of the hatch cover. Ladders are for inspection and maintenance of the tank's interior and exterior surfaces; they should be constructed of materials compatible to those of the tank and tower, and they should be easily accessible. Equipment exceeding 20 ft (6.1 m) should be equipped with a cage, a rigid notched rail, or another listed ladder safety device.

FIGURE 15.1.5 Elevated Wood Gravity Tank on Steel Tower (Source: Isseks Brothers)

Balconies and walkways constructed of wood or steel are recommended for towers over 25 ft (7.6 m) high. Balconies on tanks having a diameter in excess of 15.5 ft (4.7 m) should have a minimum width of 24 in. (607 mm) and, for smaller diameter tanks, a width of not less than 18 in. (457 mm). Railings should be at least 42 in. (1067 mm) high. Balconies and walkways should also be made of materials compatible with the tank and tower materials.

Tower Construction

During field erection, the columns of towers should be built on thin metal wedges driven to equal resistance so that all columns will be loaded equally after the structure is completed. The

spaces beneath the base plates and the anchor holes should be completely filled with cement mortar.

Sections of structural members for towers should be symmetrical and built of standard structural shapes or tubular sections. Structural shapes should be designed with open sections so that all surfaces exposed to air or moisture and subject to corrosion can be painted. Tubular sections of columns and struts should be airtight.

TANK HEATING EQUIPMENT

Fire protection water supplies in tanks subject to freezing must be heated. An ice plug in a riser pipe may make the tank water unavailable in case of fire and may break the pipe. Ice in or on tank structures has been the direct cause of collapse in several cases. The heating system must, therefore, be reliable and allow convenient and economical operation to 50°F (10°C). However, overheating can seriously damage wood tanks and the paint on steel tanks and, thus, it should be avoided.

Determination of Heater Capacity

To prevent freezing in any part of a tank during the coldest weather, the heating system must be of such capacity that the temperature of the coldest water in the tank or riser, or both, will be maintained at or above 42°F (5.6°C). The coldest weather temperature used to determine the need of heating should be based on the lowest mean temperature for one day, as shown on the isothermal map (Figure 15.1.6).

Tables 15.1.3 and 15.1.4 show the heat losses from tanks of common sizes exposed to various atmospheric temperatures. To determine, for example, what heater capacity would be needed for a 75,000 gal (284 m^3) steel tank in Duluth, Minnesota, one could interpolate from Figure 15.1.6 that the lowest mean temperature for one day in Duluth is –28°F (–33°C). According

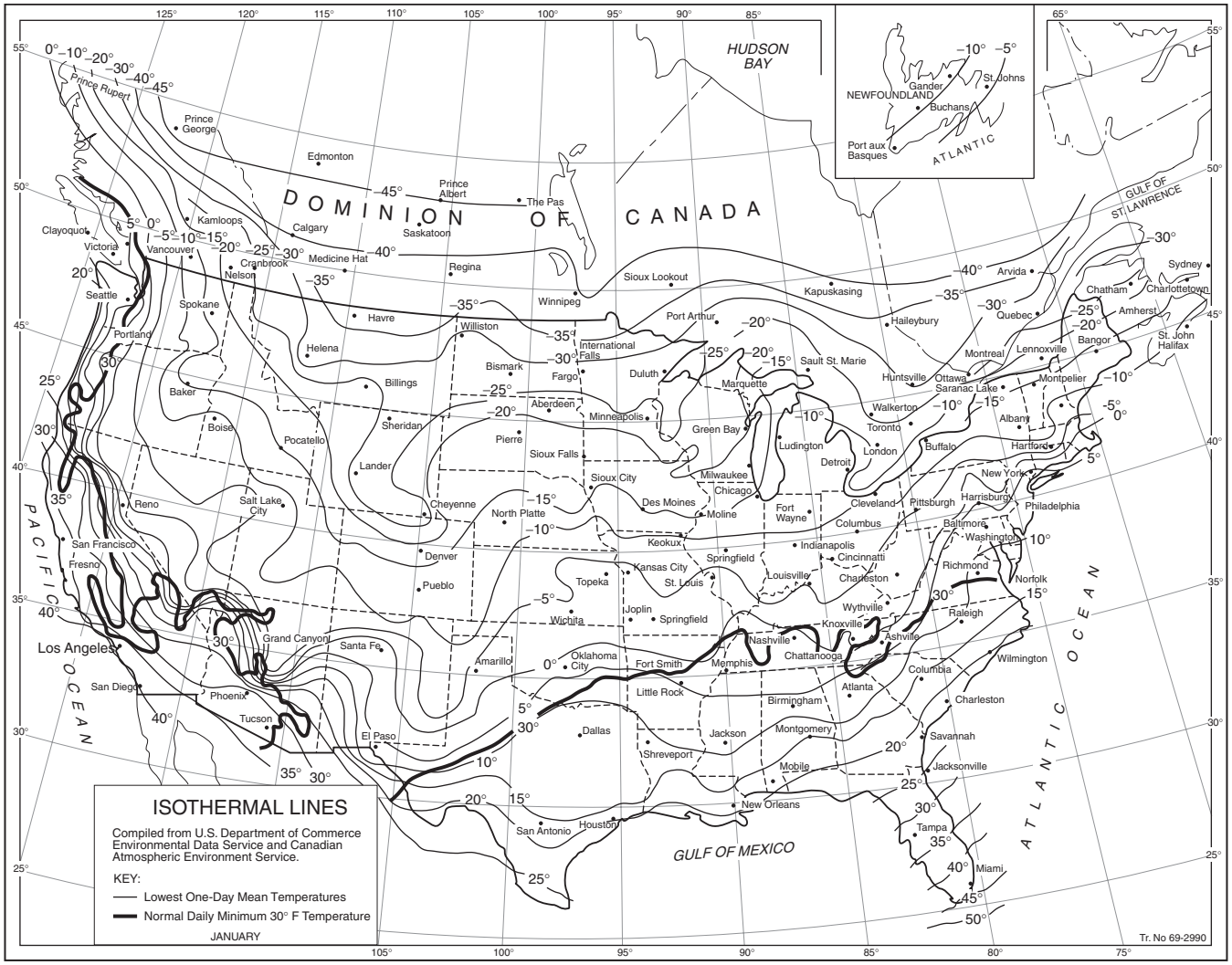


FIGURE 15.1.6 Isothermal Lines—Lowest One-Day Mean Temperature (for SI units, °C = (°F – 32) × 5/9)

TABLE 15.1.3 Heat Loss from Standpipes and Steel Suction Tanks

Thousands of British thermal units lost per hour when the temperature of the coldest water is 42°F (5.6°C). To determine capacity of heater needed, find the minimum mean atmospheric temperature for one day from the isothermal map, Figure 15.1.6, and note the following corresponding heat loss.

Temperature		Tank Capacities (thousands of gallons)															
		100,000 gal (378 m^3)		150,000 gal (567 m^3)		200,000 gal (757 m^3)		300,000 gal (1135 m^3)		400,000 gal (1514 m^3)		500,000 gal (1892 m^3)		750,000 gal (2838 m^3)		1,000,000 gal (3785 m^3)	
°F	*°C*	*Btu/hr*	*W*	*Btu/hr*	*W*	*Btu/hr*	*W*	*Btu/hr*	*W*	*Btu/hr*	*W*	*Btu/hr*	*W*	*Btu/hr*	*W*	*Btu/hr*	*W*
35	2	85	25	114	33	135	40	175	51	206	60	238	70	312	91	380	111
30	–1	121	35	162	47	193	57	248	73	294	86	340	100	445	130	542	159
25	–4	161	47	216	63	257	75	330	97	393	115	453	133	594	174	722	211
20	–7	202	59	271	79	323	95	414	121	493	144	568	166	745	218	907	266
15	–9	245	72	329	96	391	115	502	147	597	175	689	202	904	265	1099	322
10	–12	290	85	389	114	463	136	595	174	707	207	816	239	1071	314	1232	361
5	–15	337	99	452	132	539	158	691	202	822	241	949	278	1244	364	1514	443
0	–18	388	114	521	153	620	182	796	233	947	277	1093	320	1434	420	1744	511
–5	–21	441	129	592	173	705	207	905	265	1076	315	1241	364	1628	477	1987	582
–10	–23	498	146	669	196	797	234	1023	300	1216	356	1403	411	1841	539	2239	656
–15	–36	557	163	748	219	891	261	1143	335	1360	398	1569	460	2058	603	2503	733
–20	–29	619	181	830	243	989	290	1270	372	1510	442	1742	510	2286	670	2787	816
–25	–32	685	201	920	270	1096	321	1406	412	1673	490	1930	565	2532	742	3080	902
–30	–34	752	220	1010	296	1203	352	1545	453	1837	538	2119	621	2781	815	3383	991
–35	–37	825	242	1108	325	1320	387	1694	496	2015	590	2325	681	3050	894	3710	1087
–40	–40	898	263	1206	353	1437	421	1844	540	2193	643	2531	742	3320	973	4039	1183
–50	–46	1059	310	1422	417	1694	496	2175	637	2586	758	2984	874	3915	1147	4762	1395
–60	–51	1229	360	1651	484	1966	576	2524	740	3002	880	3463	1015	4544	1331	5528	1619

to Table 15.1.4, the heat loss at –28°F (–33°C) for a 75,000 gal (284 m^3) steel tank is approximately 659,000 Btu per hour (19,300 W). For a wood tank with these same specifications, Table 15.1.4 indicates a maximum heat loss of approximately 254,000 Btu per hour (74.4 kW).

Selection of Heating Method

The selection of a heating method depends primarily on the type of tank (height, construction, material, size, and shape) and its geographical location. The recommended methods of heating are covered in detail in NFPA 22.

There are three basic methods of heating tank water: (1) gravity circulation of hot water, (2) steam coils inside tanks, and (3) direct discharge of steam.

Gravity Circulation of Hot Water

Heating by gravity circulation is dependable and economical if correctly planned. Cold water received through a connection from the discharge pipe or from near the bottom of a suction tank or standpipe is heated and rises through a separate hot water pipe into the tank. Steam, coal burning, or oil heaters are ordinarily used; gas heaters or electric heaters are also satisfactory.

A steam heater ordinarily consists of a cast-iron or steel shell through which water circulates by gravity around steam tubes or coils of brass or copper. It should be located in a valve pit, in a heater house, or in a nearby building at or near the base of the tank. When the tank is over a building, the steam heater should be located in the top story.

Heater Thermometer. The convenience of a gravity system is that it permits discovery of the temperature of the coldest water in the system. A recording thermometer should be placed in the cold-water return pipe near the heater; it should be checked frequently to make sure that the temperature does not fall below 42°F (5.6°C). The temperature reading should be observed daily during subfreezing temperature conditions. (Water has its maximum density at 39.2°F [4°C]. When the temperature of the water falls below 39.2°F [4°C], there is an inversion, and the warmer water settles to the bottom of the tank while the colder water rises. Therefore, if the circulation heater is to be effective, sufficient heat must be provided so that the temperature of the coldest water will be above 42°F [5.6°C].)

Water Circulating Pipes. The size of pipe used for the circulation of heating water is given in Table 15.1.5. Pipe should be either copper water tubing or brass (85 percent copper) throughout. The hot water discharges into the tank through a tee fitting at the end of the hot-water pipe at a height about one-third up from the bottom of the tank. The return pipe connects into the discharge pipe at a point that guarantees circulation throughout

TABLE 15.1.4 Heat Loss from Elevated Tanks

Thousands of British thermal units lost per hour when the temperature of the coldest water is 42°F (5.6°C). To determine capacity of heater needed, find the minimum mean atmospheric temperature for one day from the isothermal map, Figure 15.1.6, and note the following corresponding heat loss.

Wood Tanks

Atmospheric Temperature		10,000 gal (38 m³)		15,000 gal (57 m³)		20,000 gal (76 m³)		25,000 gal (95 m³)		30,000 gal (114 m³)		40,000 gal (151 m³)		50,000 gal (189 m³)		75,000 gal (284 m³)		100,000 gal (378 m³)	
°F	°C	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W
35	–2	8	2	10	3	11	3	13	4	14	4	19	6	21	6	28	8	33	10
30	–1	11	3	14	4	16	5	19	6	21	6	27	8	31	9	40	12	49	14
25	–4	15	4	20	6	21	6	25	7	28	8	36	11	42	12	54	16	65	19
20	–7	19	6	25	7	27	8	32	9	35	10	46	13	54	16	69	20	83	24
15	–9	24	7	31	9	34	10	39	11	44	13	57	17	66	19	85	25	102	30
10	–12	28	8	36	11	40	12	46	13	51	15	68	20	78	23	100	29	121	35
5	–15	33	10	43	13	47	14	54	16	60	18	78	23	92	27	117	34	142	42
0	–18	38	11	49	14	53	16	62	18	69	20	90	26	106	31	135	40	164	48
–5	–21	43	13	56	16	61	18	71	21	79	23	103	30	120	35	154	45	187	55
–10	–23	49	14	63	18	69	20	80	23	89	26	116	34	136	40	174	51	211	62
–15	–26	54	16	71	21	77	23	89	26	100	29	130	36	153	45	195	57	236	69
–20	–29	61	18	79	23	86	25	99	29	111	33	145	42	169	50	217	64	262	77
–25	–32	68	20	87	25	95	28	110	32	123	36	160	47	188	55	240	70	291	85
–30	–34	74	22	96	28	104	30	121	35	135	40	176	52	206	60	264	77	319	93
–35	–37	81	24	105	31	115	34	133	39	148	43	193	57	226	66	289	85	350	103
–40	–40	88	26	114	33	125	37	144	42	162	47	210	62	246	72	317	93	382	112
–50	–46	104	30	135	40	147	43	170	50	190	56	246	72	290	85	372	109	450	132
–60	–51	122	36	157	46	171	50	197	58	222	65	266	78	307	90	407	119	490	144

Steel Tanks

Atmospheric Temperature		30,000 gal (114 m³)		40,000 gal (151 m³)		50,000 gal (189 m³)		75,000 gal (284 m³)		100,000 gal (378 m³)		150,000 gal (568 m³)		200,000 gal (757 m³)		250,000 gal (946 m³)		300,000 gal (1136 m³)	
°F	°C	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W	Btu/hr	W
35	17	43	13	51	15	59	17	77	23	92	27	120	35	145	42	168	49	69	20
30	12	62	18	72	21	83	24	110	32	132	39	171	50	207	61	242	71	192	56
25	7	82	24	96	28	111	33	146	43	175	51	228	67	275	81	323	96	340	100
20	2	103	30	120	35	139	41	183	54	220	64	287	84	346	101	405	119	506	148
15	–3	125	37	146	43	169	50	222	65	267	78	347	102	419	123	491	144	692	203
10	–8	147	43	172	50	200	59	263	77	316	93	411	120	496	145	582	171	893	262
5	–13	171	51	200	59	233	68	306	90	367	108	478	140	577	169	676	198	1092	320
0	–18	197	58	231	68	268	79	352	103	423	124	551	161	664	195	779	228	1309	384
–5	–23	224	66	262	77	304	89	400	117	480	141	626	183	755	221	884	259	1536	450
–10	–28	253	74	296	87	344	101	452	132	543	159	707	207	853	250	1000	293	1771	519
–15	–33	283	83	331	97	384	113	506	148	607	178	790	231	954	280	1118	328	2020	592
–20	–38	314	92	368	108	427	125	562	165	674	197	878	257	1059	310	1241	364	2291	671
–25	–43	348	102	407	119	473	139	622	182	747	219	972	285	1173	344	1375	403	2568	752
–30	–48	382	112	447	131	519	152	683	200	820	240	1068	313	1288	377	1510	442	2860	838
–35	–53	419	123	490	144	569	167	749	219	900	264	1171	343	1413	414	1656	485	3174	930
–40	–58	456	134	534	156	620	182	816	239	979	287	1275	374	1538	451	1803	528	3494	102
–50	–68	538	158	629	184	731	214	962	282	1154	338	1503	440	1814	532	2126	623	4186	122
–60	–78	624	183	730	214	848	248	1116	327	1340	393	1745	511	2105	617	2467	723	4936	144

Note: For each lineal foot of uninsulated riser 4 ft (1.2 m) in diameter, add the number of Btus or W in this column to the total heat loss at the different temperatures of the various tank capacities.

TABLE 15.1.5 Sizes of Circulating Pipes Required for Elevated Steel Tanks

Minimum One-Day Mean Temp.		Tank Capacity																	
		15,000 gal (57 m³)		20,000 gal (76 m³)		25,000 gal (95 m³)		30,000 gal (114 m³)		40,000 gal (151 m³)		50,000 gal (189 m³)		60,000 gal (227 m³)		75,000 gal (284 m³)		100,000 gal (378 m³)		150,000 gal (568 m³)	
°F	°C	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
10	–12	2	50	2	50	2	50	2	50	2	50	2	50	2	50	2	50	2	50	2½	65
5	–15	2	50	2	50	2	50	2	50	2	50	2	50	2	50	2	50	2	50	2½	65
0	–18	2	50	2	50	2	50	2	50	2	50	2	50	2	50	2	50	2½	65	2½	65
–5	–21	2	50	2	50	2	50	2	50	2	50	2	50	2	50	2	50	2½	65	2½	65
–10	–23	2	50	2	50	2	50	2	50	2	50	2	50	2	50	2½	65	2½	65	2½	65
–15	–26	2	50	2	50	2	50	2	50	2	50	2½	65	2½	65	2½	65	2½	65	3	80
–20	–29	2	50	2	50	2	50	2	50	2	50	2½	65	2½	65	2½	65	2½	65	3	80
–25	–32	2	50	2	50	2	50	2	50	2½	65	2½	65	2½	65	2½	65	3	80	3	80
–30	–34	2	50	2	50	2	50	2	50	2½	65	2½	65	2½	65	2½	65	3	80	3	80
–35	–37	2	50	2	50	2	50	2½	65	2½	65	2½	65	2½	65	3	80	3	80	3	80
–40	–40	2	50	2	50	2	50	2½	65	2½	65	2½	65	2½	65	3	80	3	80	3	80

the portion of the discharge pipe subject to freezing. A typical arrangement of a circulating heater and piping in a valve pit is shown in Figure 15.1.7.

Steam Coils Inside Tanks

Steam coils inside the tank do not permit convenient observation of water temperatures and have other faults that make them unsuited for heating elevated tanks except in areas of the South where only intermittent heating is necessary. This method may, however, be used for heating suction tanks and standpipes with flat bottoms supported near the ground level if coils are submerged continuously. The coil consists of at least 1¼ in. (32 mm) brass or copper pipe or 2 in. (50 mm) steel pipe, pitched to drain, supplied with steam at not less than 10 psi (0.7 bar) pressure through a pipe of sufficient size to furnish the needed quantity of steam from a reliable source. The coil should contain an area of heating surface to maintain the temperature of the coldest water at not less than 42°F (5.6°C). The surface water temperatures for elevated tanks, standpipes, and suction tanks should be determined by means of a listed temperature-detecting device.

Direct Discharge of Steam

Steam from a reliable supply is blown directly into the tank water through a pipe not less than 1 in. (25 mm) in diameter extending inside the frost-proof casing and through the bottom to a point above the maximum water level, then extending horizontally for a short distance and then downward to a point 3 or 4 ft (0.9 or 1.2 m) below the normal fire service water level. An air vent and check valve in the pipe above the surface of the water keeps the water from siphoning back down the steam line. This method is employed where the lowest mean temperature for one day is 5°F (–15°C) or above.

Solar Heating of Elevated Steel Tanks

With the increase in fossil fuel prices, work was done in Canada on the feasibility of solar heating of elevated steel tanks.[7] The basic technique is to insulate the entire tank, leaving a window on the south side through the insulation. The tank shell in the

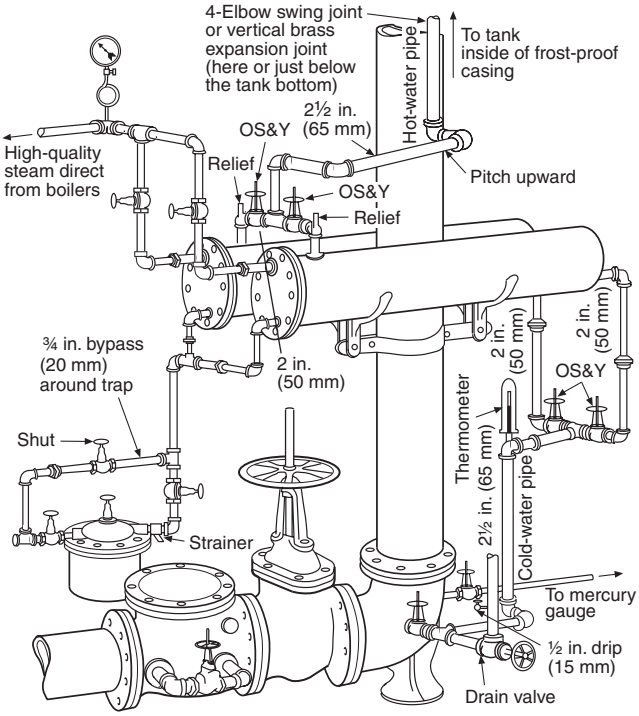


FIGURE 15.1.7 Piping Arrangement for a Multi-Unit, Steam-Heated Water Heater for a Gravity Circulation System

opening is painted flat black to absorb heat from the sun and the opening is double glazed.

Retrofit installations of solar heating systems on existing tanks involve special precautions in the attachment of components to the tank, such as the use of adhesives. The costs would be relatively high and the payback period long.

For new tanks, low-cost welding techniques can be used for attachment of collector components to the tank. With substantially all energy being supplied by the sun, a backup heating system can be a low-cost electrical system. Compared to a conventional tank with a fossil fuel–fired boiler heating system, a solar-heated tank with an electrical backup heating system is likely to have a lower capital cost. A solar-heated tank should have a backup heating system.

TANK EQUIPMENT AND ACCESSORIES

A complete installation of a gravity or suction tank includes the necessary pipe connections, valve enclosures, and, where appropriate for the particular tank, such features as a frost-proof casing for the riser.

Valve Pits

A valve pit should be of sufficient size to provide at least 12 in. (305 mm) to 18 in. (457 mm) around all necessary and contained equipment. Details of the construction of the pit and its arrangement, including clearance around equipment, waterproofing, manhole and ladder, and drainage, should conform to the recommendations given for valve pits (Figure 15.1.8).

Valve Enclosures

The tank heater and other fittings are sometimes installed in an enclosure above grade. In such a case, the indicating valve and the check valve are generally placed in the horizontal pipe below the frost line in a small pit heated sufficiently to maintain a temperature of at least 40°F (4.4°C) during the most severe weather. Ground fault interruption should be provided on all electrical circuits.

The enclosure may be of concrete, brick, cement plaster on metal lath, or any other noncombustible material with suitable heat-insulating properties. The roof should be strong enough to support the frost-proof casing and other loads without excessive deflection.

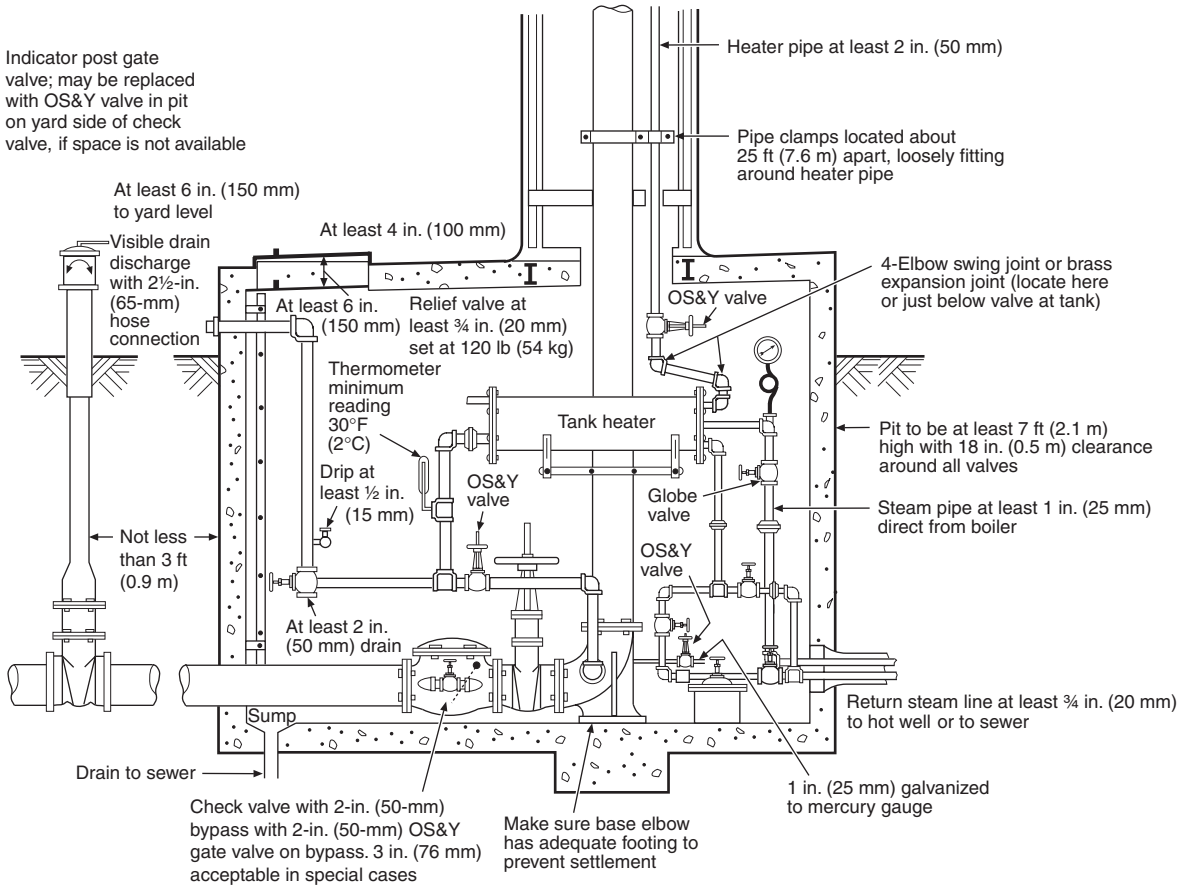


FIGURE 15.1.8 Valve Pit and Tank Connections at Base of Riser

Frost-Proof Casings

Except in the case of a large steel riser, a frost-proof casing around all exposed tank piping is necessary in localities where the lowest mean atmospheric temperature for one day as shown by the isothermal map (see Figure 15.1.6) is 20°F (–6.7°C) or lower. Tank piping subjected to temperatures below freezing within unheated buildings or dry risers of elevated tanks must also be adequately protected. Noncombustible frost-proof casings should be used where there is danger of serious fire exposure.

Large Risers

Large steel-plate riser pipes 3 ft (0.9 m) or more in diameter, without frost-proof casings, are often desirable and acceptable where properly heated. The fire hazard and upkeep of the frost casing are thereby avoided, the expansion joint in the discharge pipe is eliminated, and it is not necessary to have a walkway to reach the valves. When the tank is on an independent tower, a concrete valve pit at the base of the discharge pipe and the pier are usually built as a single unit to support the riser (see Figure 15.1.3). On the other hand, the larger valve pit at the base of the riser makes the initial cost higher than it is for equipment with small risers.

Water-Level Indicators

A water-level gauge of suitable design must be provided and located to prevent it from freezing. Careful installation, adjustment, and proper maintenance of the gauge are necessary. Where an altitude gauge is used, it should be a minimum 6 in. (152 mm) in diameter and of noncorrosive construction.

Mercury gauges are no longer permitted for new installations. Where existing mercury gauges are used/installed, they should be maintained in accordance with NFPA 22.

Overflow Pipes

The inlet of the overflow pipe should be located at the top capacity or high-water line of the tank. The pipe below the roof support structure and below any unwelded seams should be of adequate capacity for the operating conditions, but should not be less than 3 in. (80 mm) in diameter. Overflow pipes should be brought to grade. However, if dripping water or a small accumulation of ice is not objectionable, the overflow may pass through the side of the tank near the top and extend not more than 4 ft (1.2 m), with a slight downward pitch to discharge beyond the balcony and away from the ladders.

When a stub pipe is undesirable, the overflow pipe can be extended down through the tank bottom and inside the frost-proof casing or steel-plate riser, discharging through the casing near the ground or roof level. The section of the pipe inside the tank should be brass, flanged cast iron, or steel.

Painting Tanks, Seams, and Margins

All interior surfaces of steel tanks exposed to water immersion of the vapor phase zone above the high water level, inside dry surfaces, and exterior surfaces shall be cleaned, primed, and painted. After construction, all weld seams, unprimed margins, and any areas where the primer has been damaged shall be cleaned, primed, and painted. Only lead-free paints and primers should be used. Wax coating systems are no longer permitted.

EMBANKMENT-SUPPORTED COATED FABRIC SUCTION TANKS

Embankment-supported coated fabric (ESCF) tanks can be used as suction tanks for fire protection. NFPA 22 contains details on construction, installation, and maintenance of ESCF tanks.

The tank is usually composed of a reservoir liner with an integral flexible roof and is designed to be supported by earth underneath and on all four sides. The material of some ESCF tanks is a nylon fabric coated with an elastomer compounded to provide resistance to abrasion and weather. Support is provided by a specifically prepared excavation and earthen berm.

Preparation of the installation site is critical to the reliability of an ESCF tank. The embankment should be designed for stability and drainage. Usually, a shallow excavation the size of the bottom of the tank is made where local soil and groundwater conditions permit. The excavated earth is then graded to form a stable embankment for the upper sides of the tank. The exterior of the berm should be graded to allow for rain and snow drainage and pipe connections, and the interior graded to match the contour of the tank, including rounded corners. ESCF tanks may be placed underground with the top of the tank at grade level, or they may be placed above ground where the earthen berm provides the entire support.

When the excavation meets the shape requirements of the tank and all sharp rocks and debris have been carefully removed from the floor of the tank excavation, a 6 in. (150 mm) layer of fine sand or clean soil is spread over a 3 in. (75 mm) underlayment of selected pea gravel, which provides a firm smooth bed with good drainage. The tank is then placed in the foundation, and all connections are made. Installation of the tank in the prepared embankment shall be accomplished with the assistance of the tank manufacturer's field technician. The tank should be shipped to the site packaged in a material that is designed for ease of handling by a crane and winch and that facilitates efficient placement in the enclosure. The fittings shall be installed on site. At the time of installation, the tank should be filled and final adjustments on the tank made to ensure that it rests uniformly against the embankment on all four sides. The tank must be tested for leakage after installation. After the tank is filled, a coating is applied to the exposed surface to protect it from the atmosphere. See Figure 15.1.9 for a typical ESCF installation.

As with other types of storage tanks, water temperature in ESCF tanks should be maintained at not less than 42°F (5.6°C). An acceptable method of providing heat is a water recirculation system with a heat exchanger (Figure 15.1.10). When the ambient water temperature drops below 42°F (5.6°C), a thermostat activates a pump that draws water from the tank through an inlet-outlet fitting and pumps the heated water back into the tank through a recirculation fitting located in the bottom of the tank diagonally opposite the inlet-outlet fitting. Heat losses in ESCF tanks are given in Table 15.1.6.

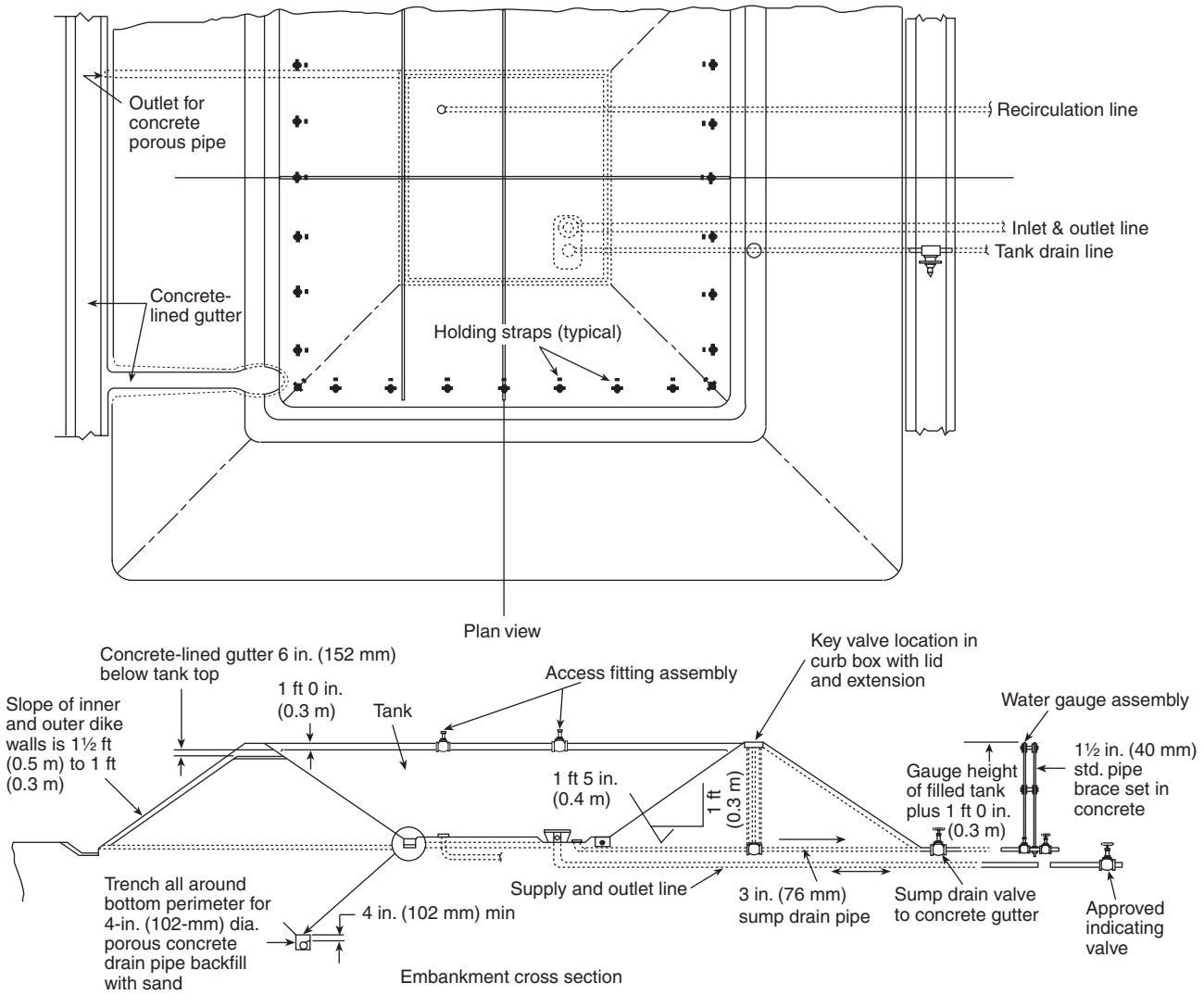
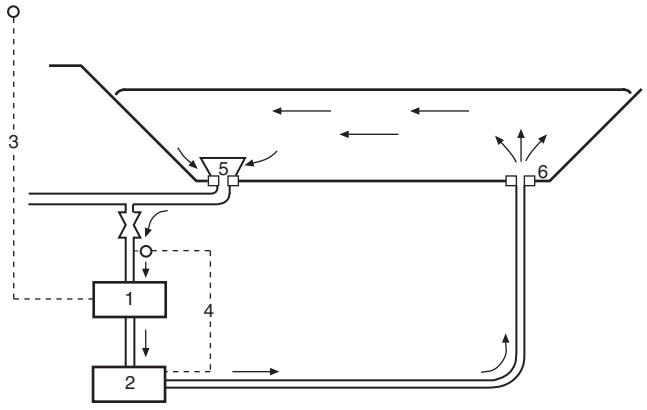


FIGURE 15.1.9 Installation Details of a Typical Embankment-Supported Fabric (ESF) Tank, Including Fittings



1. Recirculation pump
2. Heat exchanger
3. Unit sensing atmosphere temperature starts pump and water recirculation enabling heat stored in ground to transfer into water at higher rate.
4. Unit sensing water temperature starts heat exchanger when required.
5. Inlet-outlet fitting
6. Recirculation fitting

FIGURE 15.1.10 Recirculation and Heating System for an ESF Tank

PRESSURE TANKS

Pressure tanks are used for limited private fire protection services, such as sprinkler systems, standpipe and hose systems, and water spray fixed systems. A typical pressure tank installation is shown in Figure 15.1.11.

Tank capacity should be approved by the authority having jurisdiction (AHJ) and is considered to be the total contents, both air and water in the cylinder. Pressure tanks are sized by the supply of water needed to meet the demand of the fire protection system as calculated in Chapter 14 of NFPA 13, *Standard for the Installation of Sprinkler Systems*. The pressure shall be sufficient to push all of the water out of the tank while maintaining the necessary residual pressure required by NFPA 13 at the top of the sprinkler system.

Most pressure tanks are located above the top level of the sprinklers. Tanks exposed to combustible contents within the room or enclosure, or within rooms or enclosures of combustible construction, should be protected by automatic sprinklers.

Subject to the approval of the AHJ, tanks may be located in the basement or elsewhere. When the AHJ permits the tank to be buried, the requirements of NFPA 22 must be followed. Tanks for this service generally are not over 15,000 gal (34 m^3)

TABLE 15.1.6 Heat Loss from Embankment-Supported, Rubberized Fabric Suction Tanks

Thousands of British thermal units lost per hour when the temperature of the coldest water is 42°F (5.6°C). To determine capacity of heater needed, find the minimum mean atmospheric temperature for one day from the isothermal map, Figure 15.1.6, and note the following corresponding heat loss.

Exposed Tank Surface				Tank Capacities													
Atmospheric Temperature		Heat Loss Tank Radiating Surface		100,000 gal (378 m^3) 2,746 ft^2 (255 m^2)		200,000 gal (757 m^3) 4,409 ft^2 (410 m^2)		300,000 gal (1,136 m^3) 6,037 ft^2 (561 m^2)		400,000 gal (1,514 m^3) 7,604 ft^2 (706 m^2)		500,000 gal (1,893 m^3) 9,139 ft^2 (849 m^2)		600,000 gal (2,274 m^3) 10,630 ft^2 (988 m^2)		800,000 gal (3,407 m^3) 13,572 ft^2 (1,261 m^2)		1,000,000 gal (3,785 m^3) 16,435 ft^2 (1,527 m^2)	
°F	*°C*	*Btu*	*k/m²*	*Btu*	*W*	*Btu*	*W*	*Btu*	*W*	*Btu*	*W*	*Btu*	*W*	*Btu*	*W*	*Btu*	*W*	*Btu*	*W*
35	–2	22	252	61	693	98	1113	134	1522	168	1,908	202	2,294	235	2,669	300	3,407	363	4,122
30	–1	29	324	78	886	126	1431	173	1965	217	2,464	261	2,964	304	3,452	389	4,417	470	5,337
25	–4	35	399	96	1090	155	1760	212	2407	266	3,021	320	3,634	372	4,224	476	5,405	576	6,541
20	–7	42	472	114	1295	183	2078	251	2850	315	3,577	379	4,304	441	5,008	564	6,405	682	7,745
15	–9	48	545	132	1499	212	2407	290	3293	364	4,134	438	4,974	510	5,792	652	7,404	789	8,960
10	–12	55	619	149	1692	241	2737	329	3736	413	4,690	497	5,644	579	6,675	740	8,403	896	10,175
5	–15	61	693	167	1896	269	3055	369	4190	463	5,258	557	6,325	648	7,359	828	9,403	1003	11,390
0	–18	68	767	185	2101	298	3384	408	4633	512	5,814	616	6,995	717	8,142	916	10,402	1109	12,594
–5	–21	74	839	203	2305	326	3702	447	5076	561	6,371	675	7,665	786	8,926	1004	11,401	1216	13,809
–10	–23	80	913	220	2498	355	4031	486	5519	610	6,927	734	8,335	855	9,709	1092	12,401	1322	15,013
–15	–26	87	986	238	2703	384	4361	525	5962	659	7,484	793	9,005	924	10,493	1180	13,400	1429	16,228
–20	–29	93	1060	256	2907	412	4679	564	6405	708	8,040	852	9,675	992	11,265	1268	14,399	1536	17,443
–25	–32	100	1134	273	3100	441	5008	604	6859	758	8,508	912	10,357	1061	12,049	1356	15,399	1642	18,647
–30	–34	106	1206	291	3205	469	5326	643	7302	807	9,164	971	11,027	1130	12,832	1444	16,398	1749	19,862
–40	–40	119	1355	327	3713	526	5973	721	8188	905	10,277	1089	12,367	1268	14,399	1620	18,397	1962	22,809
–50	–46	132	1498	362	4111	584	6632	799	9073	1003	11,390	1207	13,707	1406	15,967	1796	20,395	2175	24,699
–60	–51	145	1648	397	4508	641	7279	878	9971	1102	12,514	1326	15,058	1544	17,534	1972	22,394	2389	27,129

Note: Heat loss for a given capacity with a different radiating surface than shown above is obtained by multiplying the radiating surface by the tabulated heat loss per ft^2 (m^2) for the atmospheric temperature involved. The minimum radiation surface area is the wetted surface exposed to atmosphere. No heat loss is figured for tank bottoms resting on grade.

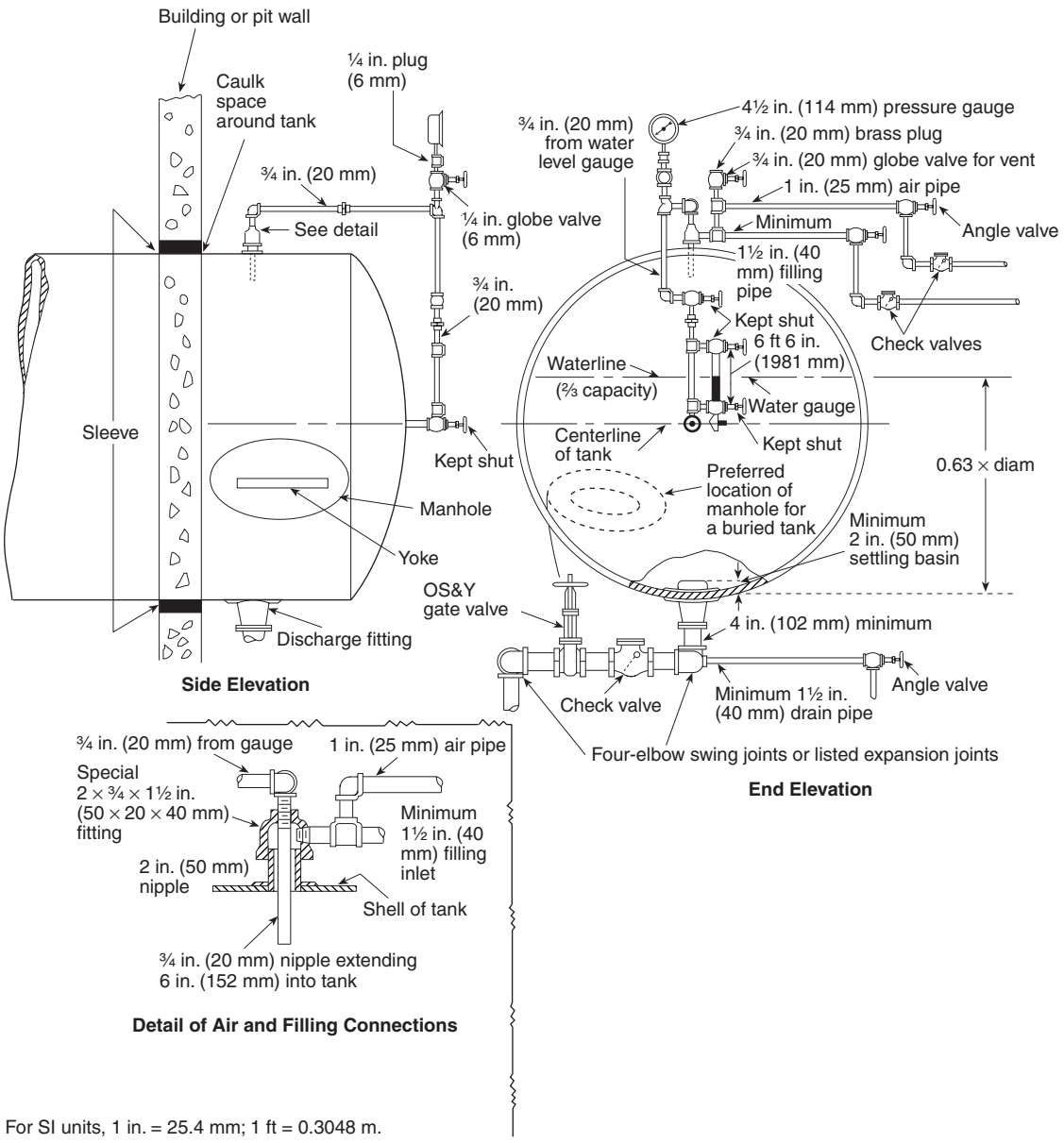


FIGURE 15.1.11 Typical Pressure Tank Installation (Source: Adapted from NFPA 22, *Standard for Water Tanks for Private Fire Protection*, Figure B.1(a), 2003, pp. 22–65)

capacity. For larger supplies, more than one tank would be employed (Table 15.1.7).

The tank is normally kept two-thirds full of water (a water-level gauge provided and the tank plate marked "2/3 capacity line") and a gauge pressure of at least 75 psig (517 kPa) is maintained. A listed air pressure gauge with a maximum range equivalent to twice the normal working pressure should be installed. As the last of the water leaves the pressure tank, the residual pressure shown on the gauge should not be less than zero and should give at least 15 psi (103 kPa) pressure at the highest automatic discharge device under the main roof of the building.

Air for pressure tanks should be supplied by compressors capable of delivering not less than 16 ft^3/min (0.045 m^3/min) of free air for tanks of 7500 gal (28.4 m^3) total capacity and not less than 20 ft^3/min (0.057 m^3/min) for larger sizes.

Relationship of Air Pressure and Volume in Tanks

The volume of air in the tank at any time varies inversely with the pressure:

$$\frac{P_1}{P_2} = \frac{V_2}{V_1}$$

Pressures are absolute pressures, not gauge pressures, as used in the preceding general formula. Let us apply this

TABLE 15.1.7 Typical Dimensions of Horizontal Pressure Tanks of Standard Sizes

Approx. Gross Capacity		Approx. Net Cap. ⅔ Full		Inside Diam.		Inside Length		Approx. Wt. of Water ⅔ Full	
gal	*L*	*gal*	*L*	*in.*	*m*	*ft*	*m*	*lbs*	*kg*
3000	11,355	2000	7,570	60	1.5	20.2	6.2	16,670	7,568
3000	11,355	2000	7,570	66	1.7	17.0	5.2	16,670	7,568
3000	11,355	2000	7,570	72	1.8	14.2	4.3	16,670	7,568
4500	17,033	3000	11,355	66	1.7	25.4	7.7	25,000	11,350
4500	17,033	3000	11,355	72	1.8	21.3	6.5	25,000	11,350
4500	17,033	3000	11,355	78	2.0	18.2	5.5	25,000	11,350
6000	22,710	4000	15,140	72	1.8	28.2	8.6	33,340	15,136
6000	22,710	4000	15,140	78	2.0	24.2	7.4	33,340	15,136
6000	22,710	4000	15,140	84	2.1	21.0	6.4	33,340	15,136
7500	28,388	5000	18,925	78	2.0	30.3	9.2	41,670	18,918
7500	28,388	5000	18,925	84	2.1	26.2	8.0	41,670	18,918
7500	28,388	5000	18,925	90	2.3	22.7	6.9	41,670	18,918
9000	34,065	6000	22,710	84	2.1	31.4	9.6	50,000	22,700
9000	34,065	6000	22,710	90	2.3	27.3	8.3	50,000	22,700
9000	34,065	6000	22,710	96	2.4	24.0	7.3	50,000	22,700

Note: 4500 gal (17 m^3) gross capacity is the minimum ordinarily accepted for pressure tanks for automatic sprinkler systems.

formula to the special condition that exists in a tank used to supply water for sprinklers. Except where there is danger of air lock, it is desirable to have a gauge pressure of 15 psi (103 kPa) remaining in the tank when the last water leaves. Thus,

P_2 = Residual pressure required + atmospheric pressure

= 15 psi + 15 psi

= 30 psi

Since at this condition the tank is full of air,

$$V_2 = 1$$

If the tank is at or above the top line of sprinklers, the tank will be normally kept two-thirds full of water, so,

$$V_1 = \frac{1}{3}$$

Therefore,

$$P_1 = P_2 \times \frac{V_2}{V_1} = 30 \times \frac{1}{1/3} = 30 \times 3 = 90 \text{ psi}$$

The corresponding gauge pressure would be 90 psi (710 kPa), minus the atmospheric pressure, 15 psi (103 kPa), or 75 psi (517 kPa).

If the tank is below the top line of sprinklers, the required residual pressure would be increased 0.434 psi for every foot (0.912 kPa/m) of elevation represented in the distance between the base of the tank and the highest sprinkler. If we call this value *H,* we have

$$P_1 = P_2 \times \frac{V_2}{V_1} = (30 + 0.434H)\frac{V_2}{V_1}$$

Gauge pressure to be carried in the tank would be $P_1 - 15$, or

$$(30 + 0.434H)\frac{V_2}{V_1} - 15$$

For a tank ⅓ full of air $\frac{V_2}{V_1} = 3$, and gauge pressure would be

$$3(30 + 0.434H) - 15 = 75 + 1.30H$$

For a tank ½ full of air $\frac{V_2}{V_1} = 2$, and gauge pressure would be

$$2(30 + 0.434H) - 15 = 45 + 0.87H$$

Air Lock

A condition known as air lock can occur when a pressure tank and a gravity tank are connected into the sprinkler system through a common riser. Air lock occurs when the gravity water pressure at the gravity tank check valve is less than the air pressure trapped in the pressure tank and the common riser by a column of water in the sprinkler system, after water has been drained from the pressure tank. For example, if the pressure tank is kept two-thirds full of water with an air pressure of 75 psi (5.2 bar), and a sprinkler opens 35 ft (10.7 m) or more above the point the common tank riser connects to the sprinkler system, the pressure tank drains, leaving an air pressure of 15 psi (1.0 bar) balanced by a column of water of equal pressure (35 ft [10.7 m] of head) in the sprinkler system. The gravity tank check valve is held closed unless the water pressure from the gravity tank is more than 15 psi (1 bar) (35 ft [10.5 m] head).

Air lock can be prevented by increasing the volume of water and decreasing the air pressure in the pressure tank so that little or no air pressure remains after water has been exhausted. For example, if the pressure tank is kept four-fifths full of water, with an air pressure of 60 psi (4.1 bar), the air pressure remaining in the tank after water has been drained is zero, and the gravity tank check valve opens as soon as the pressure at that point from the pressure tank drops below the static head from the gravity tank.

Under normal conditions, air lock can be conveniently avoided in new equipment by connecting the gravity tank and pressure tank discharge pipes together 45 ft (13.7 m) or more below the bottom of the gravity tank (Figure 15.1.12) and by placing the gravity tank check valve at the level of the connection.

Construction of Pressure Tanks

Pressure tanks are constructed in accordance with *ASME Boiler and Pressure Vessel Code,*[8] with modifications given in NFPA 22. Important modifications are a minimum hydrostatic test at 150 psi (10 bar) and a test for tightness.

Where subject to freezing, tanks should be located in substantial noncombustible housings. Tank rooms should be large enough to provide free access to all connections, fittings, and manholes, at least 18 in. (457 mm) around the rest of the tank. The distance between the floor and any part of a tank should be at least 3 ft (0.9 m).

The interiors of pressure tanks are inspected at three-year intervals to determine whether corrosion is taking place and whether repainting or repairing is needed. When necessary, tanks should be scraped, wire brushed, and repainted with an approved metal-protective paint. Relief valves should be tested at least once each month.

Provisions should be made to drain each tank independently of all other tanks and the sprinkler system by means of a pipe not less than 1½ in. (40 mm) in diameter.

The filling supply or pump should be reliable and capable of replenishing the water to be maintained in the tank against the normal tank pressure in not more than 4 hours.

Plastic Tanks

Plastic tanks are increasingly being used for fire protection water supplies, however, not without limitations mainly related to capacity. Polyethylene tanks used in aboveground applications as gravity tanks have maximum capacities of 12,000 to 15,000 gallons. Fiber reinforced plastic (FRP) tanks used in underground applications as suction tanks have a maximum capacity of 50,000 gallons. Advantages of plastic tanks are that they do not rust or corrode, are lighter in weight, and do not require assembly. Disadvantages of plastic tanks include their limited capacity and combustibility (requiring sprinkler protection where installed in buildings).

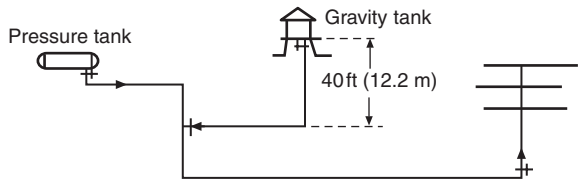


FIGURE 15.1.12 Gravity Tank and Pressure Tank Showing How Risers Are Connected to Avoid Air Lock

NATURAL AND CONSTRUCTED SUCTION FACILITIES

The advantages of piped systems make them the first choice for a water supply for fire protection, but sometimes other water may be more convenient or less expensive. Examples are rural areas and resorts without a piped water system for fire protection. In many of these, however, water is available for fire protection in the ocean, lakes, ponds, rivers, and streams. Cisterns or tanks can be used at locations distant from natural water sources. Small ponds in parks and swimming pools are not particularly good sources of emergency water because this competes with their regular purposes.

For water sources such as those mentioned, the general term *suction supplies* is used to distinguish these supplies from the conventional public water systems for fire protection. Static suction supplies must, in general, be used where they are found and require drafting to lift the water and pumping to move the water to the point of use by fire protection systems. Although there have been instances where water in suburbs, farms, and forests was used to provide effective fire streams at very long distances, laying hose lines more than 750 to 1000 ft (225 to 300 m) seldom makes it possible to provide good protection because of the time required to lay the long lines and the greater difficulty in operating them. Before using naturally occurring water supply sources such as rivers, streams, ponds, lakes, and wells, their reliability, accessibility, and ability to meet required fire protection system demands must be verified. Seasonal fluctuations due to other usage, drought, and freezing must be considered and evaluated. Water supplies from rivers, streams, ponds, lakes, and wells need to be managed to avoid the introduction of mud, sediment, and vegetation. In addition, these water supplies should pass through removable screens and strainers that are installed and maintained to ensure an unobstructed water supply.

Ground Tanks and Cisterns

If no hydrant on a water system is available, one way to ensure the amount of water required for fire fighting is to store it in underground tanks or cisterns at locations where hydrants would normally be installed. The fire department pumper can then get water from a connection on the tank or by dropping a suction hose into the tank. Such tanks and cisterns are filled from domestic water sources too small for fire fighting. The water does not have to be changed so frequently that it presents difficulties.

Static water supplies are of obvious value in rural, farm, and remote areas, but they are equally important for emergency conditions in more urban areas. Before the present

public water systems were developed, some cities provided underground reservoirs or cisterns for fire protection. When water was needed for fire fighting, a pumper suction hose was simply dropped through a manhole. Some of these cisterns are still used in San Francisco and Chicago. Even though San Francisco has a regular water system and a separate system of high-pressure mains, it has been considered prudent, because of the threat of earthquake, to keep over 100 cisterns in service, most of which hold 75,000 gal (284 m^3). Some of the oldest cisterns have brick walls. Newer ones are reinforced concrete.

Rivers and Ponds

Rivers and ponds are important auxiliary water sources, but merely because the water can be seen does not mean that it can be used for fire fighting. These sources of water must have suitable approaches so that fire apparatus can get near the water without becoming mired. A cleared space and some fill in many cases will provide access. These sources must be studied to determine that the water is available all year round and to select the best possible approach. They should also be recorded and mapped and given periodic attention in much the same manner that hydrants are maintained.

At such locations, it is usually necessary to provide a wet pit, basin, or cistern into which water can flow and the pumper suction strainer can be placed. There should be a screen or weir so that large objects will not interfere with the suction strainer. In some places, a permanent suction pipe and strainer can be installed. The details of such an arrangement are the same as those for a fire pump operating under a lift. NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection,* contains guidelines for proper arrangement of wet pits for supplying vertical shaft fire pumps taking suction under a lift. The suction pipe should be laid with enough cover so that it will not freeze. It can be connected at the top to a hydrant with one or more pumper suction connections.

Small Streams and Brooks

Where water supply comes from a brook or stream, it is usually best to drain the water into a sump rather than attempt to use it straight from the flowing stream. If there is a marshy bank or shore, it may be best to go out into the pond or stream to a point where water can be collected in a sump. From the sump in the pond or stream, a pipe should be laid for draining to another sump, the latter located near where the fire apparatus will stand.

In some sumps, and particularly in open water that freezes over in winter, covers may not be feasible at the point where the sump is provided for pumper suction. At such locations, an anchored plug of wood can be floated where the pumper suction should be taken. Such a plug should have a minimum diameter larger than the pumper suction hose and be tapered so that, when frozen in ice, it can be driven down and out of position with a sledgehammer.

In some parts of the country, streams do not flow continuously. A covered cistern of generous capacity may be filled when water flows. Thus, the water may be stored for a longer period than it would keep in an open reservoir.

Water from streams and ponds is more important in areas without public water systems. There are areas where even a brook, if dammed and with a proper pumper approach and a suction basin, can provide good protection at little cost.

For projects in which a stream will be dammed to form static water, experienced civil engineers should be consulted. Details of the dam construction and decisions about the amount of water to be impounded depend on many factors and may require a comprehensive engineering survey. The dam's effect on users of the stream and flood conditions also has to be considered.

Harbors and Rivers

The principal problem with using harbors and rivers as suction supplies is that their water levels change. In harbors, ocean tide levels vary continuously throughout any given 24 hour period. River water levels are seasonal, but the problem is generally the same.

Where there is little fluctuation in the level of a natural water source, a simple pier or platform may be all that is needed to make the water available. If a pumper can be driven onto a sturdy pier, it can go to work when its suction line is dropped over the side. But where the water level varies, special arrangements are needed. If the water is always deep enough for drafting, a hinged ramp leading down to a large float is feasible. But more common is a sloping beach down which the water recedes too far to be accessible at all times. Reservoirs that can be filled at high tide are one solution to this problem.

Where a bridge passes over tidewater, water can be obtained by permanently installing a deep-well pump with a discharge pipe to a point convenient for fire department pumper use. The most practical way to use tidewater supplies is to provide pumps on boats, supplementary to any fireboats in service. Relatively large quantities of water for fire fighting can be obtained from river and harbor sources because large-capacity pumps are normally provided on fireboats, and where there are no fireboats, large pumps can be installed on a boat or barge and pressed into use to supply water for fire protection. To use the water on land, it is necessary to provide a place at which a fireboat or a barge with pumps can tie up and discharge into tanks or a special pipe system with hydrants from which land-based pumping equipment can take the water.

Wells

Wells have become increasingly popular for both domestic use and fire supply for industrial sites, and in more rural areas, located beyond the reach of a piped water supply. Before a well is constructed, a thorough examination of the groundwater must be made. This examination generally includes an aquifer performance analysis and a review of the history of nearby wells. The water in the ground must be of sufficient capacity and dependability and of reasonably good quality. A vertical-shaft turbine pump is used to draw the water from wells into the fire system or into a storage tank.

SUMMARY

Water storage facilities and pump suction supplies are a crucial element for fire protection systems. To ensure an adequate and usable water supply for fire protection, it is necessary to properly design and engineer these supplies to (1) ensure an adequate capacity and duration for the fire protection system being supplied; (2) make sure that the structural design includes all necessary features for resistance to earthquakes and other external exposures (including fire); and (3) ensure that an adequate heating system is provided to prevent freezing of the stored water supply. The discussion within this chapter is intended to make that process easier. For best results, it would be prudent to employ the services of experienced designers and suppliers to meet those goals.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fixed water storage facilities discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 22, *Standard for Water Tanks for Private Fire Protection*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*

Chapter 2

Water Supply Requirements for Public Supply Systems

Lawrence J. Wenzel

Chapter Contents

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Factors Affecting Water Requirements
History of Water Supply Systems
Number of Hose Streams
Engineering: Distribution Network, Hydrant Spacing, Storage
The Insurance Grading Schedule

Key Terms

American Water Works Association (AWWA), hydraulic calculations, Insurance Services Office (ISO) grading schedule, needed fire flow (NFF), water pressure, water supply (domestic service), water supply (fire protection), water supply (public)

The amount of water needed and the economics of supplying it are basic questions underlying the planning of water supply systems for fire suppression.

This chapter gives information on planning for public water supply systems and outlines the methods used to evaluate public supplies for their adequacy and reliability. The chapter does not cover the specifics of water supply requirements for automatic suppression systems within individual properties.

Specifics are covered in the following chapters of Section 16: Chapter 3, "Automatic Sprinkler Systems"; Chapter 6, "Residential Sprinkler Systems"; Chapter 8, "Water Mist Fire Suppression Systems"; Chapter 9, "Water Spray Protection"; and Chapter 10, "Standpipe and Hose Systems."

FACTORS AFFECTING PUBLIC WATER SUPPLY DESIGN

Most public water supply systems serving a substantial number of customers are, and should be, designed for a dual purpose: (1) to supply water for normal domestic demands, such as drinking and sanitary purposes, as well as for processing and industrial uses, and (2) to provide water for emergency purposes. The latter purpose would include the supply for fire department use, such as through hydrants, and for fixed automatic suppression systems, such as automatic sprinklers and standpipe systems.

The variety of hazards encountered in most communities and the need to plan for future growth must be considered when evaluating these objectives. In some cities, there may be a heavy industrial demand. At the same time, demands for industrial use and lawn sprinkling may affect the required capacity of the system. The adequacy of a public water system for fire protection cannot be taken for granted, and the other demands must be determined to estimate their effects on the capacity of the system.

Public water systems must also be reliable. Because the occurrence of a fire should not affect domestic demands, the water system must be designed to meet the simultaneous demand rates for both purposes. In addition, portions of the pumping or distribution system may be out of service due to breakdown or scheduled maintenance, so the consequences of these interruptions must be examined for acceptability when evaluating system reliability.

When assessing reliability, another factor to take into account is the system's ability to supply increased amounts of water in peak periods that may last only a relatively short time. For example, oceanfront communities in northern climates, such as areas on Cape Cod, Massachusetts, will have a much higher seasonal demand that will begin Memorial Day and end around Labor Day each year. The increase in demand due to the influx of people has a definite effect on the system's ability to supply water at the time of an emergency. The system's ability to provide fire flow during peak usage seasons must be considered in any evaluation. Thus, testing to evaluate a system's reliability must consider the time that the system will be subjected to its highest flows.

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WATER REQUIREMENTS

Demands for Domestic Purposes

To determine the domestic demands on a public water supply, it is necessary to focus on variations in water consumption with respect to the time of year, the day of the week, and even the hour of the day. Obviously, as more water is used in a given system for normal consumption, less remains for fire protection. Normal consumption demands are usually expressed in the following terms:

- Average daily demand, or the average of the total amount of water used each day during a 1 year period.
- Maximum daily demand, or the maximum total amount of water used during any 24 hour period in a 3 year period. Unusual situations that might have caused an excessive use of water, such as refilling a reservoir after cleaning, should not be considered when determining this figure.
- Peak hourly demand, or the maximum amount of water used in any given hour of a day.

A joint report of committees from the American Society of Civil Engineers, the American Water Works Association (AWWA), and others suggested that the maximum general service demand on a waterworks system be taken as the peak hourly demand during a test year.[1] The report noted that this figure was the only figure that could be fairly compared with the maximum fire flow requirement.

The maximum daily demand can be estimated as 1.5 times the average daily consumption if the actual maximum is not known. The peak hourly rate usually varies from two to four times the normal hourly rate. The effect these varying consumption rates have on the ability of the system to deliver required fire flows varies with the system design. Both maximum daily consumption and peak hourly consumption should be considered to ensure that water supplies and pressures do not reach dangerously low levels during these periods and that adequate water will be available if there is a fire. But keep in mind that these are only estimates and there may be other issues to consider. For example, a water supply for an area that has a high concentration of carpet or textile mills as its primary industrial base may have periods that can severely skew these estimates. If all of the carpet mills open their "dye beks" at the same time on a given day, and conduct a heavy amount of dyeing operations for an extended period of time, there can be a severe spike in the daily consumption. For the period that their operations are being conducted, the water supply in the area may be dangerously low. These types of industrial periods must be considered.

Water Requirements for Fire Fighting

The water requirements for fire fighting include the rate of flow, the residual pressure required at that flow, and the total quantity required. The American Water Works Association defines the required fire flow as "the rate of water flow, at a residual pressure of 20 psi and for a specified duration that is necessary to control a major fire in a specific structure."[2] The fire protection community has informally adopted the figure of 20 psi as the lowest pressure to which fire protection systems will be designed. These include sprinkler systems and fire pumps using the municipal supply as a suction or supply source.

CALCULATING FIRE FLOW RATES

The required flow rate for properties protected by automatic sprinklers is based either on the sprinkler system design as required by NFPA 13, *Standard for the Installation of Sprinkler Systems* (hereinafter referred to as NFPA 13), or on the exact details of the hydraulic sprinkler system design for the systems installed in the structure. (Also see NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height,* and NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes.*) The flow required is that of the sprinkler system plus the anticipated hose stream or manual fire-fighting requirements. It also may be necessary to consider additional water supply needs for buildings with neighboring structures that present an exposure to the structure being considered.

Several methods are currently used to calculate required waterflow rates for *nonsprinklered* properties. These include the following:

- The Insurance Services Office (ISO) method
- The Iowa State University (ISU) method
- The Illinois Institute of Technology Research Institute method

Insurance Services Office (ISO) Method

Probably the most comprehensive and widely recommended methods for estimating fire flow requirements are found in the Insurance Services Office's *Fire Suppression Rating Schedule.*[3] It provides guidance for estimating fire flow requirements for specific structures and was designed for insurance rating purposes. The flows determined by this method are generally considered a good estimate, and, as a result, the ISO method has received widespread use. The ISO method considers building construction, occupancy, adjacent exposed buildings, and fire communication paths between buildings.

The basic formula in the schedule is

$$NFF_i = (C_i)(O_i)(X + P)_i$$

where

NFF_i = Needed fire flow (*NFF*) in gal per min (L/min)

C_i = A construction factor that depends on the construction of the structure under consideration

O_i = An occupancy factor that depends on the combustibility of the occupancy

$(X + P)_i$ = An exposure factor that depends on the extent of exposure from and to adjacent structures

The subscripts in the formula indicate that, where portions of a building have differing characteristics, a factor can be calculated for each section and multiplied by the percentage it represents of the effective area to obtain a weighted factor. The

weighted C_i factor should not be less than the individual factor required for any individual section.

Construction Factor. The construction factor, C_i, is calculated from the following formula:

$$C_i = 18f\sqrt{A_i}$$

where

F = Coefficient related to the class of construction
= 1.5 for construction class 1 (frame)
= 1.0 for construction class 2 (joisted masonry)
= 0.8 for construction class 3 (noncombustible) or construction class 4 (masonry, noncombustible)
= 0.6 for construction class 5 (modified fire resistant) or construction class 6 (fire resistive)

A_i = Effective building area

The effective building area is the total square foot (m^2) area of the largest floor plus one of the following:

- For construction classes 1 through 4, 50 percent of all other floors
- For construction classes 5 and 6, 25 percent of the area not exceeding the two other largest floors when all of the vertical openings have at least 1½-hour-rated protection, or 50 percent of the area not exceeding eight other floors when vertical openings are unprotected or have less than 1½ hour protection

The value of C_i should never be less than 500 gpm (1893 L/min) for any construction class, nor greater than 8000 gpm (30,280 L/min) for construction classes 1 and 2, and 6000 gpm (22,710 L/min) for construction classes 3, 4, 5, and 6, or any single, one-story building, regardless of construction.

Occupancy Factor. The occupancy factor, O_i, reflects the combustibility of the occupancy on the needed fire flow and is determined from the occupancy combustibility class. Occupancy factors can be found in Table 15.2.1. Typical occupancies and their classification can be found in Table 15.2.2. For more detailed occupancy classification information, see NFPA *101*®, *Life Safety Code*®.

Exposure and Communication [$(X = P)_i$] Factors. The exposure and communication factors are determined as

$$(X + P)_i = 1 + \sum_{i=g}^{n} X_i + P_i$$

where

n = Number of sides of subject building
$(X + P)_i$ = A maximum value of 1.75

The exposure factor, X_i, reflects the need for additional water to reduce the exposure to adjacent buildings. It depends on the separation distance, the construction of the exposed building wall, and a length-height value—that is, the length of the exposed wall in feet (m) multiplied by the height in stories. Values can be obtained from Table 15.2.3.

TABLE 15.2.1 Occupancy Factors

Occupancy Combustibility Class	*Occupancy Factor (O_i)*
C-1 (Noncombustible)	0.75
C-2 (Limited combustible)	0.85
C-3 (Combustible)	1.00
C-4 (Free burning)	1.15
C-5 (Rapid burning)	1.25

The fire communication factor, P_i, reflects the potential fire spread through open or enclosed communicating passageways between buildings and is taken from Table 15.2.4. Where there is more than one connection, only the one with the largest factor is used. Where there are no openings, $P_i = 0$.

Needed Fire Flow. The needed fire flow (*NFF*) is calculated from the formula given previously and from the foregoing factors. The *NFF* calculated from the formula should be rounded to the nearest 250 gpm (946 L/min) for flows under 2500 gpm (9463 L/min) and to the nearest 500 gpm (1893 L/min) for larger flows and then adjusted by the following:

- For buildings with a wood roof, add 500 gpm (1893 L/min).
- The needed flow should not exceed 12,000 gpm (45,420 L/min) nor be less than 500 gpm (1893 L/min). The practical reason for these figures is that manual fire-fighting methods using hose streams and heavy stream appliances are not likely to need a larger supply, considering the general arrangement of buildings and the availability of hydrants.
- For habitational buildings, use the calculated *NFF* up to 3500 gpm (13,248 L/min) maximum.
- For groupings of one-family and small two-family dwellings not more than two stories high, the required fire flow given in Table 15.2.5 may be used.

Iowa State University (ISU) Method

The Iowa State University method[4] is another common method used to determine waterflow rates for fire fighting. It uses a more theoretical approach and is based on the amount of water needed to deplete the oxygen in a confined area when the water is vaporized into steam by the heat of the fire. Tests conducted by the university indicate that a fire is best controlled if the amount of water necessary to deplete the oxygen is applied within 30 seconds.

The required flow in gpm is given as

$$\text{Required flow} = \frac{V}{100}$$

where V is the enclosed volume (length of the structure multiplied by its width and height) in cubic feet. (For SI units: 1 gpm = 3.785 L/min; 1 ft^3 = 0.0283 m^3.)

This method is unique in that it does not consider the occupancy hazard, only the volume of the building to be filled with steam. It is essentially a formula that is used in determining the

TABLE 15.2.2 Occupancy Classification

C-1 (Noncombustible)	C-4 (Fire burning)
Steel or concrete products storage, unpackaged	Aircraft hangers, with or without servicing/repair
	Apparel manufacturing
C-2 (Limited combustible)	Auditoriums
Apartments	Breweries
Ceramics manufacturing	Building material sales and storage
Churches	Cotton gins
Concrete products manufacturing	Food processing
Courthouses	Freight depots, terminals
Dormitories	Furniture—new or secondhand
Hospitals	Metal coating or finishing
Hotels	Paper and paper product sales and storage
Metal products fabrication	Paper products manufacturing
Metals industries (primary)	Printing shops and allied industries
Motels	Rubber products manufacturing
Offices	Theaters, other than motion picture
Parking garages	Warehouses
Schools	Wood product sales and storage
	Woodworking industries
C-3 (Combustible)	
Amusement park buildings, including arcades and game rooms	C-5 (Rapid burning)
Automobile sales and services	Cereal or flour mills
Baking and confectionery	Chemical manufacturing
Dairy processing	Chemical sales and storage
Department stores	Cleaning and dyeing material sales and storage
Discount stores	Distilleries
Food and beverage—sales, service, or storage	Meat or poultry processing
General merchandise—sales or storage	Paint sales and storage
Hardware, including electrical fixtures and supplies	Plastic or plastic product sales and storage
Leather processing	Plastic products manufacturing
Motion picture theaters	Rag sales and storage
Pharmaceutical retail sales and storage	Textile manufacturing
Repair or service shops	Textile products fabrication, except clothes
Soft drink bottling	Upholstering shops
Supermarkets	Waste and reclaimed materials sales and storage
Tobacco processing	
Vacant buildings	

amount of water required to begin to reduce the size of a compartment fire.

Due to inefficiencies in applying water, some experts feel that the rate should be 2 to 4 gal per 100 ft^3 (7.6 to 15.0 L/2.8 m^3) of building volume rather than the 1 gal per 100 ft^3 (3.785 L/2.8 m^3) in the formula. Other variations include changing the value in the denominator based on the occupancy hazard. Obviously, high-hazard occupancies require more water to absorb the heat release of the burning occupancy.

This formula has been used for approximately 50 years and is extremely simple to apply. For most buildings, the entire volume of the structure should be used, including the volume of basements, attics, crawl spaces, and other concealed spaces. For groups of buildings, the largest calculated flow rate should be used.

Illinois Institute of Technology Research Institute Method

The Illinois Institute of Technology method was based on a survey of 134 fires in the Chicago area. The results of the survey were used with regression analysis to develop fire flow formulas based on building area. The fire flow rate is based on one of the following formulas:

$$\text{Flow for residential occupancies} = 9 \times 10^{-2}A^2 + 50 \times 10^{-2}A$$

$$\text{Flow for other occupancies} = -1.3 \times 10^{-5}A^2 + 42 \times 10^{-2}A$$

where A is the area of the fire in square feet. (For SI units: 1 ft^2 = 0.0929 m^2.)

TABLE 15.2.3 Factors for Exposure, X_i

Construction of Facing Wall of Subject Building	*Distance (ft) to the Exposed Building*	*Length-Height of Facing Wall of Exposed Building*	Construction of Facing Wall of Exposed Building Classes			
				2, 4, 5, and 6		
			1, 3	*Unprotected Openings*	*Semiprotected Openings (Wired Glass or Outside Open Sprinklers)*	*Blank Wall*
Frame, metal, or masonry with openings	0–10	1–100	0.22	0.21	0.16	0
		101–200	0.23	0.22	0.17	0
		201–300	0.24	0.23	0.18	0
		301–400	0.25	0.24	0.19	0
		Over 400	0.25	0.25	0.20	0
	11–30	1–100	0.17	0.15	0.11	0
		101–200	0.18	0.16	0.12	0
		201–300	0.19	0.18	0.14	0
		301–400	0.20	0.19	0.15	0
		Over 400	0.20	0.19	0.15	0
	31–60	1–100	0.12	0.10	0.07	0
		101–200	0.13	0.11	0.08	0
		201–300	0.14	0.13	0.10	0
		301–400	0.15	0.14	0.11	0
		Over 400	0.15	0.15	0.12	0
	61–100	1–100	0.08	0.06	0.04	0
		101–200	0.08	0.07	0.05	0
		201–300	0.09	0.08	0.06	0
		301–400	0.10	0.09	0.07	0
		Over 400	0.10	0.10	0.08	0
Blank masonry wall	Facing wall of the exposed building is higher than subject building. Use the above table, except use only the length-height of facing wall of the exposed building above the height of the facing wall of the subject building. Buildings five stories or over in height consider as five stories. When the height of the facing wall of the exposed building is the same or lower than the height of the facing wall of the subject building, $X_i = 0$.					

For SI units: 1 ft = 0.305 m.

Source: Insurance Services Office © 1980.

OTHER FLOW CONSIDERATIONS

Regardless of the method used to determine the flow rate, the required fire flow should be available simultaneously with consumption at the maximum daily rate.

When evaluating the flow required for general public protection, both the AWWA and the ISO suggest that 3500 gpm (13,248 L/min) is the upper limit to be provided and that large facilities or those with severe hazards that need flow rates up to 12,000 gpm (45,420 L/min) be individually analyzed to determine the required flow rate.

There are fires in which quantities of water in excess of the required fire flow are used. Water supplies of 50,000 gpm (189,250 L/min) or greater have been used in fire suppression, but designing systems capable of delivering flows of that magnitude is not cost-effective nor practical. Expecting the municipal system to deliver these large flow rates is not reasonable; thus, private supplies are often developed to become the primary supply for large-flow industrial sites, or to augment the municipal supply. This development is a site-by-site determination, based on the available municipal flow rates and supplies.

Fire Flow Duration

The number of hours during which the required fire flow should be available varies from 2 to 10 hours, as indicated in Table 15.2.6. It should be noted that many water authorities place an upper limit of 2 to 4 hours on fire water supply duration due to economics.

Evaluating System Capacity

The capacity of a water system is determined by the total amount of water it must furnish. This amount is the sum of water required for domestic or industrial uses and water required for the fire service. In small towns the requirements for fire protection almost always exceed other requirements.

The AWWA recommends that the rate used be either the peak hourly rate or the maximum daily rate plus fire flow,

TABLE 15.2.4 Factors for Communications, P_i

	Fire-Resistive, Noncombustible, or Slow-Burning Communications				Communications with Combustible Construction					
	Open	Enclosed			Open			Enclosed		
Description of Protection of Passageway Openings	*Any Length*	*10 ft or Less*	*11 ft to 20 ft*	*21 ft to 50 ft*[a]	*10 ft or Less*	*11 ft to 20 ft*	*21 ft to 50 ft*[a]	*10 ft or Less*	*11 ft to 20 ft*	*21 ft to 50 ft*[a]
Unprotected	0	[b]	0.30	0.20	0.30	0.20	0.10	[b]	[b]	0.30
Single Class A fire door at one end of passageway	0	0.20	0.10	0.00	0.20	0.15	0.00	0.30	0.20	0.10
Single Class B fire door at one end of passageway	0	0.30	0.20	0.10	0.25	0.20	0.10	0.35	0.25	0.15
Single Class A fire door at each end or double Class A fire doors at one end of passageway	0	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Single Class B fire door at each end or double Class B fire doors at one end of passageway	0	0.10	0.05	0.00	0.00	0.00	0.00	0.15	0.10	0.00

For SI units: 1 ft = 0.305 m.
Note: When a party wall has communicating openings protected by a single automatic or self-closing Class B fire door, it qualifies as a division wall (defined in greater detail in the ISO *Commercial Fire Rating Schedule*) for reduction of area.
Note: Where communications are protected by a recognized water curtain, the value of P_i is 0.
[a]For over 50 ft, $P_i = 0$.
[b]For unprotected passageways of this length, consider the two buildings as a single fire division.

TABLE 15.2.5 Fire Flows for Groups of Dwellings

Exposure Distances		Suggested Required Fire Flow	
ft	*m*	*gpm*	*L/min*
Over 100	30.5	500	1893
31–100	9.5–30.5	750–1000	2839–3785
11–30	3.4–9.2	1000	3785
10 or less	3.1 or less	1500	5678

whichever is larger. In most large cities, the peak hourly rate exceeds the maximum daily consumption rate plus fire flow and is, therefore, the controlling factor in the supply system design. In smaller communities, however, the reverse is true and the maximum daily consumption rate plus fire flow is the controlling factor. For many years, water consumption has been increasing in most municipalities, resulting in increased peak hourly rates. Consequently, there has been an increase in the number of municipalities in which the peak hourly rate controls designs of the supply system. However, there is no guarantee that a fire will not occur at the peak hour, and some recommend that the capacity of the system be sufficient to meet the peak hourly rate plus the fire flow rate.

Fire flows are a very important consideration in all areas served by the distribution system and, in many instances, they govern the size of pipe used in these locations. In all systems, the supply should be sufficient to provide for automatic sprinklers and other automatic water-based fire suppression systems, in addition to the other demand rates imposed on the system. For example, many smaller cities and large towns restrict lawn watering in summer months to specified periods, depending on local conditions. The demand rates imposed by lawn watering are excessive in many water supply systems, possibly depleting storage facilities and reducing pressure throughout the system for many hours. In such situations, there would be little or no water available for fire suppression systems, particularly at higher elevations.

PRESSURE CHARACTERISTICS OF SYSTEMS

The pressures for which systems are normally designed are the result of practical attempts to provide adequate pressures both for domestic consumption and for fire protection. If either demands special ranges of pressure, materials and design methods are available that will allow almost any desired range.

For example, San Francisco has a separate system, designated the "high-pressure system," that is under the control of the fire department. All system pipe is heavy cast iron, tar coated, and lined, and it is tested on installation and repair to 450 psi (3103 kPa). Two steam-operated pump stations can pump water from San Francisco Bay into the system, and 20,000 gpm (75,700 L/min) at 250 psi (1724 kPa) can be delivered to most of the principal mercantile district. San Francisco provided this

TABLE 15.2.6 Duration of Required Fire Flow

Required Fire Flow		*Million Gallons per Day*	*Million Liters per Day*	*Duration Hours*	Required Fire Flow		*Million Gallons per Day*	*Million Liters per Day*	*Duration Hours*
gpm	*L/min*				*gpm*	*L/min*			
1000	3,785	1.44	5.45	2	4,500	17,033	6.48	24.53	4
1250	4,731	1.80	6.81	2	5,000	18,925	7.20	27.25	5
1500	5,678	2.16	8.18	2	5,500	20,818	7.92	29.99	5
1750	6,624	2.52	9.54	2	6,000	22,710	8.64	32.71	6
2000	7,570	2.88	10.90	2	7,000	26,495	10.08	38.16	7
2250	8,516	3.24	12.26	2	8,000	30,280	11.52	43.61	8
2500	9,463	3.60	13.63	2	9,000	34,065	12.96	49.06	9
3000	11,355	4.32	16.35	3	10,000	37,850	14.40	54.51	10
3500	13,248	5.04	19.08	3	11,000	41,635	15.84	59.96	10
4000	15,140	5.76	21.80	4	12,000	45,420	17.28	65.41	10

system primarily because an earthquake might put the regular public water system out of service. A few other cities have similar high-pressure systems.

Modern fire department pumpers make heavy streams and high pressures available from ordinary water systems where adequate volume is provided. Cities that formerly had separate fire main systems operating at so-called high pressures now generally keep them at normal public water pressures. The second system still provides an advantage, though, even if it is not at high pressure, because it is still available and becomes a valuable source of "volume."

Public water systems reflect a compromise on the question of pressures. Pressures in the range of 65 to 80 psi (448 to 552 kPa) are common. This range, which is adequate for ordinary consumption in buildings up to about 10 stories, will provide a good supply of water for automatic sprinkler systems in buildings of about four stories, in which occupancies are classified as "ordinary" or "light." Where pressures of this order are provided, it is reasonably easy to compensate for local fluctuations.

Because of the increased cost of energy, closer scrutiny is being given to the water pressure that systems should provide. A reduction in water pressure will substantially reduce pumping costs. Before a general reduction is made, however, a study should be conducted as to the effects it could have on sprinklers and other fixed fire suppression systems. If a reduction in pressure is planned, it is imperative that the system remain capable of meeting anticipated demand rates, or steps must be taken to lower the demand rates to a point where they will be within the capability of the system. In many cases, the reduction of pressure will have an adverse effect on private industrial and commercial-building fire protection systems using pumps, as the municipal supply is the suction source for many private systems.

A minimum residual pressure of at least 20 psi (138 kPa) should be maintained at hydrants delivering the required fire flow. Pumpers will operate where hydrant pressures are less. Where hydrants are well distributed and of the proper size and type so that friction losses in the municipal system will not be excessive, it may be possible to set 10 psi (69 kPa) as the minimum operating pressure. Sufficient hydrant pressure should be maintained to prevent a negative pressure from developing in the street mains, which might cause damage to the municipal system. In some older systems, back siphonage of polluted water from some interconnected source may still be a problem. But, in most areas and municipal systems, better backflow prevention has eliminated this problem. Many state health departments prohibit the use of residential pressures of less than 20 psi (138 kPa). However, in a severe fire situation in many locations, a pressure lower than 20 psi (138 kPa) may have to be used to develop necessary fire flows and the movement of water volume from one area to another. Proper emergency planning on the part of the public fire officials can generally eliminate this situation.

Pressures in a public water system may be considered excessive as they approach 150 psi (1034 kPa). As pressures increase, they tend to cause leaks in domestic plumbing, and special attention is required to restrain pipelines in the ground. Pipe and fittings used in ordinary public water systems are designed for maximum working pressures of 150 psi (1034 kPa), but it is not good practice to operate with pressures that high. Pressure-reducing valves can be used in sections of a system where variations in topography result in excessive pressures. Individual water services to buildings may require pressure-reducing valves to keep the pressure on domestic piping at safe levels.

SYSTEMS FOR HIGHER ELEVATIONS

When water must be supplied to high elevations, a separate water distribution system is usually provided for the elevated section so that reasonable pressures are maintained. In such cases, the elevated area should be provided with its own water storage facility, and pumps may be provided to boost the water from other parts of the system.

Likewise, the upper stories of a high-rise building are sometimes provided with dedicated risers (express risers) to deliver water to these upper floors. High-rise structures are normally divided into a number of pressure zones, and zones of more

than 12 stories can be outside the normal pressure ranges. In any case, each pressure zone must be provided with water in the amounts needed for sprinkler system and hose stream use, and each system is usually supplied by a series of pumps and, sometimes, tanks arranged so that each zone is fed from the zone below. Care should be taken to ensure that pumps would be able to operate even during power failures.

For information and guidance concerning water supplies for high-rise structures, see NFPA 13; NFPA 14, *Standard for the Installation of Standpipe and Hose Systems;* and NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection.*

ADEQUACY AND RELIABILITY OF SUPPLY

The adequacy of any given water supply system can be determined by engineering estimates. The source (e.g., storage facilities and distribution system) must be sufficient to furnish all the water that combined fire and domestic needs may call for at any one time. The arrangement of the supply and pumping facilities may render the supply inadequate or affect its reliability.

Pumping systems commonly are arranged so that one set of pumps takes suction from wells or from a river, lake, or other body of water. If the water does not have to be filtered, the pumps may discharge directly into the distribution system. Where filtration or other treatment is necessary, pumps take suction from the primary or raw water source and discharge to sedimentation basins or other facilities and then to filter beds. After the water is processed, it flows to clear-water reservoirs from which a second set of pumps takes suction and discharges the water directly into the supply system. Unfortunately, failure of any part of the equipment may affect the entire system.

There are still communities that use direct-pumping methods and have no stored water capacity. These types of systems rely on pumps operating in stages, based on the demand. These "pump-only" systems require constant attention to the mechanics of the equipment, as each piece of pumping equipment is that much more important. Without storage capacity, which can buy maintenance time for repairs and parts replacement, additional thought has to be put into keeping critical equipment maintained and backed up.

When assessing the reliability of the supply works, one should evaluate the following:

- Minimum yield
- Frequency and duration of droughts
- Condition of intakes
- Possibility of earthquakes, floods, and forest fires
- Ice formations
- Silting up or shifting of river channels
- Security of installations to prevent physical damage
- Availability of replacement equipment and parts
- Ability to divert flow within the system to avoid local outages and reduced pressure

Reservoirs out of service for cleaning and the interdependence of parts of waterworks also affect reliability. The condition, arrangement, and dependability of individual units of plant equipment, such as pumps, engines, generators, electric motors, fuel supply, electric transmission facilities, and similar items, are also factors. Pumping stations of combustible construction may be destroyed by fire unless they are protected by automatic sprinkler systems.

Duplication of pumping units and storage facilities, and arrangement of mains and other distribution piping so that water may be supplied to any area from more than one direction, are measures that can ensure continuous operation. The importance of duplicate facilities is shown by the frequency of their use. Many utilities design their systems so that the peak hourly rate and required fire flow rate can be supplied when any pump or section of the distribution system is out of service.

The amount of water needed to control and extinguish a fire in a given property currently cannot be established in precise terms. Better fire experience databases should make it possible to tailor fire flows more specifically to conditions that might be expected at the time of a fire. Better analysis may indicate a need to increase fire flow beyond what is presently required, or it may result in a water system design based on a balance between the risk involved and the economics of maintaining the water system.

A detailed discussion of all the factors to be considered in designing a water supply system is beyond the scope of this handbook. An overview of the subject can be found in AWWA M24, *Dual Water Systems,* and AWWA M31, *Distribution System Requirements for Fire Protection.*

FACTORS AFFECTING WATER REQUIREMENTS

Codes and Ordinances

Fire prevention codes can effectively limit hazards and ignition sources within buildings, which, in turn, may limit the number and size of fires by controlling combustibles in a fire area. A good building code further reduces the chance for a serious fire by requiring construction materials and building assemblies that will contain a developing fire to a given area. Codes alone can reduce considerably the amount of water needed for fire fighting. Zoning ordinances that establish distances between properties can be effective in controlling exposure situations.

Fire Detection and Extinguishing Systems

The increased use of automatic suppression systems, whether they use water or some other agent, will affect the quantities of water required. As more widespread use is made of early warning systems and automatic suppression systems, it will be possible to equate the effect of these systems with required fire flow, and there may well be a reduction to the amount of water needed to suppress a fire. Water supply requirements are just one factor in a system that determines what the potential for a fire is, how extensive that fire will be, and what measures will be needed to suppress it. Research continues to measure all these factors, and experience adds valuable information, allowing the establishment of fire flows on the basis of thoroughly researched and documented principles.

HISTORY OF WATER SUPPLY SYSTEMS

Historically, water supply systems for cities and towns were developed primarily to provide drinking water and water for sanitary purposes rather than for fire protection. However, it was found that large cities that required substantial amounts of water for domestic purposes usually had enough water to provide a useful supply for fire-fighting purposes.

This supply issue led to inquiries in the late nineteenth century into the additional cost of waterworks that could provide water for fire fighting, as well as other uses. A number of distinguished engineers associated with individual waterworks examined the problem and presented their findings in technical papers at engineering society meetings. Papers by J. Herbert Shedd,[5] J. T. Fanning,[6] and Emil Kuichling[7] give the details of discussions in which standards for American and Canadian waterworks were first developed (Table 15.2.7). Keep in mind that at the turn of the century, when these engineers practiced, the advent of automatic sprinkler protection was just arriving. Thus, most of their research and findings dealt with the effectiveness of hose streams. It continues to be a cornerstone in determining the validity of hose stream use by today's fire service, in a very general nature.

NUMBER OF HOSE STREAMS

In these discussions, the starting point for computing the cost of water for fire protection was to estimate the number of hose streams that a fire department might need for fire fighting. This was usually estimated using as a basis the central portion of a city where the largest buildings were located and where there was the greatest building congestion. The number of streams was found to be related, in a very rough way, to the population. Shedd's proposal,[5] which was the first, used hose streams discharging 200 gpm (757 L/min). He suggested that a community of 5000 would need about 5 such streams and that the needs of other cities could be graduated up to 30 streams in a city of 180,000. Fanning[6] proposed streams requiring about 54 psi (372 kPa) pressure. His figures were similar to Shedd's,[5] beginning at 7 streams for a community of 4000 and going up to 25 streams for a city of 150,000.

Kuichling[7] suggested a formula in which the number of streams required would be the square root of the population in thousands multiplied by 2.8. There were arithmetical differences as to how these estimates worked out for individual cities, but they were all of the same general order (see Table 15.2.7). Most important, they provided a basis from which waterworks designers could estimate costs.

The most important paper produced during this time was John R. Freeman's "The Arrangement of Hydrants and Water Pipes for the Protection of a City Against Fire," published in 1892.[8] Freeman had done the fundamental work on waterflow through hose and nozzles, so he was able to pin down the definition of a standard fire stream to one with a discharge of 250 gpm (946 L/min) at 40 to 50 psi (276 to 345 kPa) pressure. He said that the relationships suggested by Shedd[5] and Fanning[6] between population and the number of streams required were of the right order, but he did not think the needs of individual cities could be quite so definitely ascertained. He suggested two to three streams as a minimum for a population of 1000, graduated up to 30 to 50 streams at 200,000 (see Table 15.2.7). Most significantly, he warned, "Ten streams, or as large a proportion thereof as the financial consideration will permit, may be recommended for a compact group of large, valuable buildings, irrespective of a small population."[8]

ENGINEERING: DISTRIBUTION NETWORK, HYDRANT SPACING, STORAGE

Freeman[8] noted a fundamental difference between systems designed to supply ordinary water needs and those for fire

TABLE 15.2.7 Estimates of Fire Flow

	Number of Fire Streams Required Simultaneously				
Population in Thousands	*Shedd 1889*	*Fanning 1892*	*Freeman 1892*	*Kuichling 1897*	*NBFU 1911*
1	—	—	2–3	3	4
4	—	7	—	6	8
5	5	—	4–8	6	9
10	7	10	6–12	9	12
20	10	—	8–15	12	17
40	14	—	12–18	18	24
50	—	14	—	20	26
60	17	—	15–22	22	28
100	22	18	20–30	28	36
150	—	25	—	34	44
180	30	—	—	38	48
200	—	—	30–50	40	48

Sources: Shedd,[5] Fanning,[6] Kuichling,[7] Freeman,[8] and Metcalf, Kuichling, and Hawley.[9]

protection: fire draft required concentration of the water, whereas domestic draft was a matter of distribution.

Freeman[8] asserted that, if a water system were to supply fire protection needs, the distribution system should be designed to concentrate the needed amounts of water. Small pipes were sufficient for distribution, but larger ones were needed to concentrate supply to fire streams. He suggested 6-in. (152-mm) diameter pipe as the minimum for residential districts and noted that 8 in. (203 mm) pipe was adequate only if it formed part of a network of distribution pipes whose intersections were not far apart.

Another important point Freeman[8] made was that hydrants should be placed where they could concentrate streams at specific blocks or groups of buildings rather than be placed arbitrarily a certain number of feet (m) apart on the street mains. His work on hose streams showed how long hose lines reduced the water that can be delivered promptly to a fire. Therefore, he suggested a working rule for hydrant spacing of 250 ft (76 m) between hydrants in compact mercantile and manufacturing districts and 400 ft (122 m) to 500 ft (153 m) in residential districts. These working rules are still used as guides for good design.

Freeman[8] further insisted that fire supply should be in addition to maximum domestic consumption, and he laid the foundation for the eventual recognition of this principle. He also calculated how much water should be stored in standpipes, elevated tanks, or elevated reservoirs. He figured that flow for all of the hose streams required should be supplied from a reliable source, such as an elevated storage reservoir, for at least 6 hours when the system was also furnishing maximum demands for domestic and other uses. He also calculated that to supply the combined fire and domestic needs in a system provided with reliable pump capacity a 1 hour supply in a standpipe, elevated tank, or elevated reservoir would be acceptable.

THE INSURANCE GRADING SCHEDULE

As early as 1889, the National Board of Fire Underwriters (NBFU) began to make fire protection surveys of municipalities. This work was intensified in 1904 after a conflagration in Baltimore, Maryland. Today the ISO surveys communities in all but a few states. The ISO survey, called the *Fire Suppression Rating Schedule,*[3] was discussed in detail earlier in this chapter.

The current ISO procedure for establishing fire flows is different from the original NBFU formula, which was commonly used for many years as a guide to determine the fire flow required in downtown business districts of municipalities (see Table 15.2.7). The formula gave the fire flow, G, in gpm as a function of the population, P, in thousands. (For SI units: 1 gpm = 3.785 L/min.)

$$G = 1020\sqrt{P}\,(1 - 0.01\sqrt{P})$$

In making fire protection surveys, engineers from NBFU and insurance bureaus estimated the fire flow requirements in sections of municipalities outside the downtown business district. As cities became more decentralized, the formula based on population became less reliable as a guide for the fire flow needed downtown. In addition, it became apparent that a guide to engineering judgment was needed for the other sections of the cities. In 1948, a paper by A. C. Hutson,[10] assistant chief engineer at NBFU, provided some specific suggestions for estimating fire flow requirements in these sections, based on the type of construction and the area of a building. This eventually led to the current ISO rating system.

SUMMARY

The time to worry about the requirements of a fire protection water supply is not when the fire has broken out but rather long before the incident occurs. Fire protection water is almost always a shared entity with the domestic users, and fire protection supplies are needed only when there is an emergency. However, the total supply available to an area has to consider both normal and emergency uses.

The fire service has a number of methods available to help determine the adequacy and reliability of the water supply in the event of a fire. The amount of water needed will always be a function of the occupancy and the construction of the building in question, and in many cases, the outside exposures to the structure. There are quick ways to develop fire flow needs that encompass all of these parameters, and the fire service uses these routinely.

Adequacy and reliability of the water supply system when needed are not to be taken for granted. Careful planning as to what is needed and then careful analysis of availability are key to planning before an incident occurs.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on water supply requirements for public supply systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*
NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*

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Chapter 3

Hydraulics for Fire Protection

Kenneth W. Linder

Chapter Contents

Hydraulic Properties of Water
Bernoulli's Theorem
Flow of Water Through Orifices
Coefficients of Flow
Flow Measurement
Flow of Water in Pipes
Water Hammer
Elastic Wave Theory

Key Terms

Chezy formula, coefficient of flow, Darcy-Weisbach formula, elastic wave theory, friction loss, Hazen-Williams formula, hydraulic calculations, hydraulically designed system, K-factor, Moody diagram, velocity head, velocity pressure, water hammer

Hydraulics is a subset of fluid mechanics that deals with the flow of water. As applied to fire protection, it involves the flow of water through pipes, valves, fittings, and orifices such as hydrant outlets, nozzles, and sprinklers. This chapter describes the physical properties of water that are pertinent to hydraulic calculations and the basic formulas used to calculate flow and pressure loss in fire protection systems. It does not include details on the specific rules required to design hydraulically calculated sprinkler systems in accordance with NFPA 13, *Standard for the Installation of Sprinkler Systems,* or the algorithms used to determine how the flow splits in looped systems or more complex gridded piping systems.

For related topics see Section 17, Chapter 3, "Characteristics and Hazards of Water and Water Additives for Fire Suppression."

HYDRAULIC PROPERTIES OF WATER

As used in this handbook, water refers to fresh water unless otherwise specified. All calculations are made in U.S. gallons (gal), unless otherwise indicated. One U.S. gal equals 3.78 L. An Imperial gal equals 1.20 U.S. gal (4.54 L).

Material Properties

Density. Density, ρ, is defined as mass per unit volume:

$$\rho = \left(\frac{\text{mass}}{\text{volume}}\right)$$

The density of water, as with many other liquids, varies with temperature. The maximum density of water occurs at 39.2°F (4.0°C) and is 62.43 lbm (pound mass) per ft^3 (1000 kg/m^3 [kilograms per m^3]) in vacuum or 62.35 lbm per ft^3 (998.7 kg/m^3) in air. For most hydraulic calculations, an approximate value of 62.4 lbm per ft^3 (1000 kg/m^3) is usually used. Average seawater has a density of 64.1 lbm per ft^3 (1030 kg/m^3) at 39.2°F (4.0°C).

Specific Weight. The specific weight of a material, *w,* is defined as $w = \rho g$ where g is the acceleration due to gravity. The specific weight is usually measured in lbf (pound force) per ft^3 in U.S. customary units and kgf (kilogram force)/m^3 in SI units and is

$$w = \rho g = 62.4 \frac{\text{lbm}}{\text{ft}^3} \times 32.2 \frac{\text{ft}}{\text{sec}^2} \times 1 \frac{\text{lbf} \cdot \text{sec}^2}{32.2\ \text{lbm} \cdot \text{ft}} = 62.4 \frac{\text{lbf}}{\text{ft}^3} = 1000\ \text{kgf per m}^3$$

A common, though incorrect, practice is to use the terms *pound mass* (lbm) and *pound force* (lbf) interchangeably, since one lbm has a weight of one lbf under standard gravity. (A similar situation exists in SI units with kg (kilogram) and kgf [kilogram force].) In this chapter, pound (lb)

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means pound force (lbf) and kilogram (kg) means kilogram force (kgf), as is common in engineering practice.

One ft^3 (0.028 m^3) equals 7.48 U.S. gal. Assuming the specific weight of water is 62.4 lb per ft^3 (1000 kg/m^3), 1 gal of water, therefore, weighs 62.4 lb per ft^3 ÷ 7.48 gal per ft^3, or 8.34 lb (3.78 kg).

Viscosity. Viscosity is a measurement of a fluid's resistance to flow and is usually measured in pound sec per $foot^2$ ($lb\ sec/ft^2$) in U.S. customary units or newton sec per $meter^2$ ($N{\cdot}sec/m^2$) in SI units. Viscosity, like density, varies with temperature. At 32°F (0.0°C), water has an absolute viscosity, μ of 3.746×10^{-5} lb sec/ft^2 (1.793×10^{-5} $N{\cdot}sec/m^2$). In hydraulic problems, viscosity is often divided by density. This relative viscosity, called kinematic viscosity, υ, is defined as

$$\upsilon = \frac{\mu}{\rho}$$

Although viscosity is an important factor in fluid flows, most fire protection hydraulics applications assume water at ambient conditions, and the empirical formulas normally used to calculate losses do not take into account changes in viscosity.

An exception are hydraulic calculations involving foam concentrate solutions in foam-water sprinkler systems or large antifreeze solutions in blast freezers or other very cold areas where the solution is significantly more viscous than water at ambient conditions.

Pressure

Pressure, *p,* is the unit that measures the force, caused by compression, per unit area in a fluid. In fire protection hydraulics, pressure is normally measured in pounds per square inch (psi) or in kilopascals (kPa), as indicated by a pressure gauge, or as head, *h,* in feet (ft) or meters (m) of water. Pressure is also commonly measured as a head of mercury, atmosphere, bar, or newtons per square meter (N/m^2).

For waterflow in pipes, the total pressure, p_t, is the sum of normal pressure, p_n and velocity pressure, p_υ:

$$p_t = p_n + p_\upsilon$$

Normal Pressure. Net or normal pressure is the pressure exerted against the side of a pipe or container by the liquid in the pipe or container with or without flow. Without flow, this pressure is called "static pressure" or "static head." With flow, this pressure is called "residual" pressure.

The pressure exerted by a column of water is related to its specific weight. Expressed slightly differently, the specific weight is

$$\frac{62.4\ \text{lb}}{\text{ft}^3} = \frac{62.4\ \text{lb}}{\text{ft}^2\ \text{ft}} \times \frac{1\ \text{ft}^2}{144\ \text{in}^2} = 0.433\ \text{psi per ft}$$

It follows that pressure and static head are related by the following formulas:

$$p = wh = 0.433h$$

$$h = \frac{p}{w} = \frac{p}{0.433} = 2.31p$$

For SI units, the weight of a 1 m column of water equals a force of 9.81 kPa or

$$p = 9.81h$$

$$h = \frac{p}{9.81} = 0.102p$$

A 1 in. (25.4 mm) head of mercury generates a pressure of 0.491 psi (3.39 kPa) and is equivalent to a 1.135 ft (0.3456 m) head of water.

Normal atmospheric pressure is taken as 14.7 psi (101.4 kPa), equivalent to a head of water of 33.95 ft (10.35 m) and a head of mercury of 29.9 in. (760 mm).

Velocity Head or Velocity Pressure. The velocity, υ, produced in a mass of water by pressure acting upon it is the same as if the mass were to fall freely, starting from rest, through a distance equivalent to the pressure head in feet. This relationship is represented by Torricelli's equation:

$$\upsilon = 2\sqrt{gh}$$

where υ = the velocity produced in ft/sec (m/sec), g = the acceleration due to gravity or 32.2 ft/sec^2 (9.81 m/sec^2), and h = the head in ft (m) producing the velocity.

Just as a static head can be converted into a velocity head, velocity head can be converted to an equivalent static pressure head. This relation is

$$h_\upsilon\ (\text{velocity head}) = \frac{\upsilon^2}{2g}\ (\text{ft})$$

Because

$$p_\upsilon = 0.433h_\upsilon$$

the velocity pressure can be expressed as

$$p_\upsilon = 0.433\ \frac{\upsilon^2}{2g}\ (\text{psi})$$

In SI units

$$p_{\upsilon m}\ (\text{kPa}) = 9.81\ \frac{\upsilon^2}{2g}$$

for υ in m/s.

Values of velocity pressure for different rates of flow in various pipe sizes are shown in Figure 15.3.1. (For SI units see Figure 15.3.2.) Velocity head or velocity pressure may be calculated by formulas involving velocity and pipe diameter:

$$h_\upsilon = \frac{\upsilon^2}{64.4}\ \text{ or }\ p_\upsilon = \frac{0.433\upsilon^2}{64.4} = \frac{\upsilon^2}{149}$$

In SI units

$$h_{\upsilon m} = 0.0151\upsilon^2\ \text{ and }\ p_{\upsilon m} = 0.5\upsilon^2$$

A convenient equation for calculating velocity in feet per second (fps) from the rate of flow can be developed from the principle of conservation of mass. For a steady-state one-dimensional flow with average velocity υ, this principle can be stated as

$$Q = a\upsilon$$

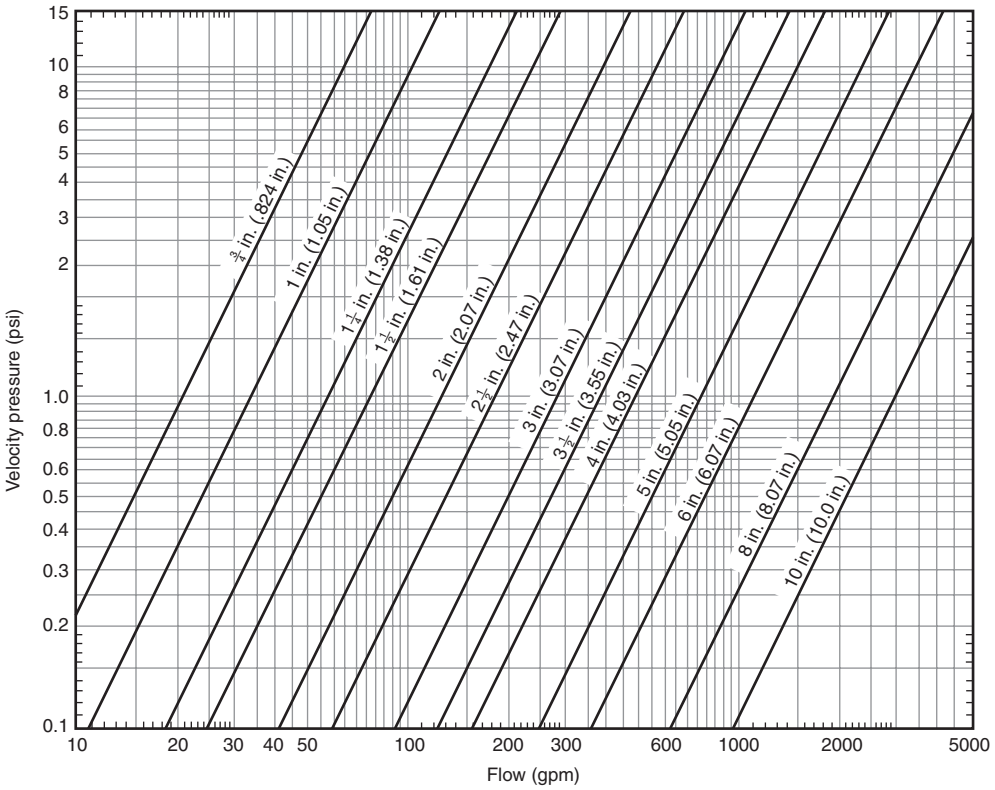


FIGURE 15.3.1 Graph for the Determination of Velocity Pressure (English Units)

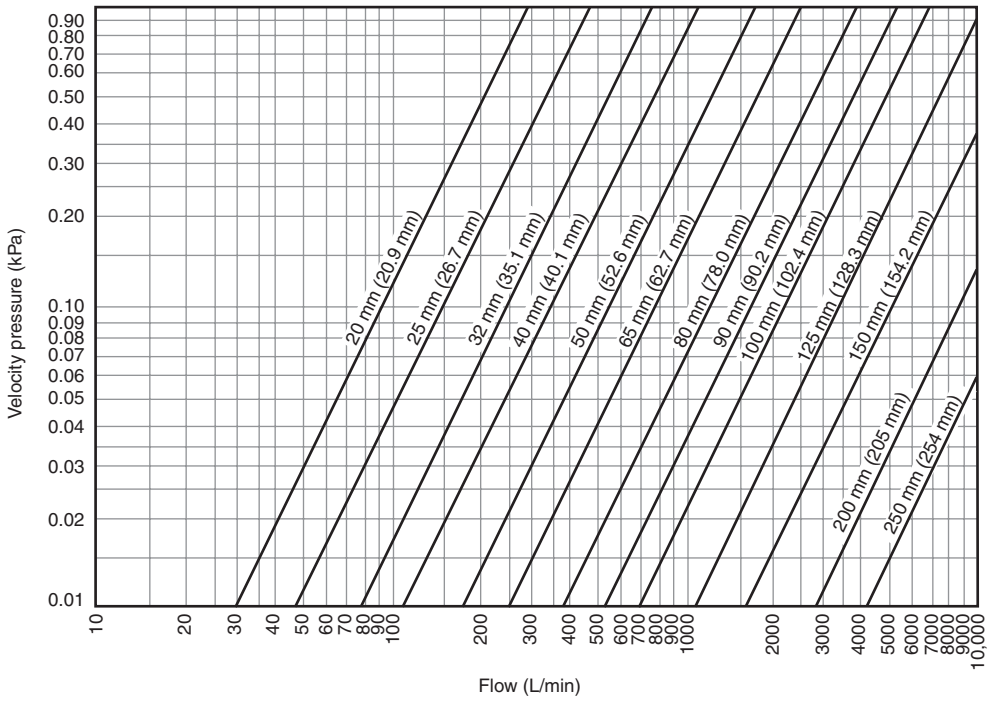


FIGURE 15.3.2 Graph for the Determination of Velocity Pressure (SI Units)

It follows that

$$\upsilon = \frac{Q}{a}$$

where υ = the average velocity in ft/sec, Q = the flow in ft^3/sec, and a = the cross-sectional area of the pipe in ft^2.

For a pipe with flow in gpm and diameter in in., the velocity is

$$\upsilon(\text{fps}) = \frac{Q(\text{gal/min})}{60 \text{ sec/min} \times 7.48 \text{ gal/ft}^3} + \frac{\pi d^2 \text{ (in.)}^2}{4 \times 144 \text{ in.}^2/\text{ft}^2}$$

$$= \frac{Q \times 4 \times 144}{60 \times 7.48 \times \pi d^2} = \frac{0.4085 \times Q}{d^2}$$

It follows that h_υ and p_υ are

$$h_\upsilon = \frac{\upsilon^2}{2g} = \frac{(0.4085Q)^2}{(d^2)^2} \div 64.4 = \frac{Q^2}{d^4}\frac{(0.4085)^2}{64.4} = \frac{Q^2}{386d^4}$$

$$p_\upsilon = \frac{Q^2}{d^4} \times \frac{0.433}{386} = \frac{Q^2}{891(d)^4}$$

In SI units, the formula for velocity pressure is expressed as

$$p_{\upsilon m} = 225\frac{Q_m^2}{d_m^4}$$

where

$p_{\upsilon m}$ = Velocity pressure (kPa)
Q_m = Flow (L/min)
d_m = Inside diameter (mm)

EXAMPLE 1: Find the velocity pressure in 1-in. Schedule 40 pipe with 36 gpm flowing. The actual diameter of the pipe is 1.049 in.

SOLUTION: $p_\upsilon = \frac{Q^2}{891(d)^4} = \frac{36^2}{891(1.049)^4} = 1.20$ psi

EXAMPLE 2: Find the velocity pressure in a 25-mm (actual diameter) pipe with 100 L/m flowing.

SOLUTION: $P_{\upsilon m} = 225\frac{Q_m^2}{(d_m)^4} = \frac{225 \times (100)^2}{(25)^4} = 5.8$ kPa

Total Head. At any point within a piping system that contains water in motion, there is a pressure head, h_p (normal pressure head), acting perpendicular to the pipe wall independent of velocity, and a velocity head, h_υ acting parallel to the wall but exerting no pressure against the wall. Therefore, the total head, $H = h_p + h_\upsilon$, expressed as pressure (psi) instead of feet is

$$p_t = 0.433h_p + 0.433\frac{\upsilon^2}{2g}$$

In SI units, total head expressed in kPa is

$$p_{tm} = 9.81h_{pm} + 9.81\frac{\upsilon_m^2}{2g}$$

where

p_{tm} = Total pressure (kPa)
h_{pm} = Head (m)
υ_M = Velocity (m/sec)

Pressure Sources

The sources of pressure head commonly found in fire protection hydraulic systems include the following.

Gravity (Elevated Tanks, Reservoirs, Standpipes). Head is the elevation of the water supply surface above the point under consideration, measured directly in ft (m) or converted from a pressure gauge reading.

Pumping. Head is the combination of pump discharge pressure and any difference in elevation between the pump discharge gauge and the point under consideration.

Pneumatic (Pressure Tanks). Head is the tank air pressure combined with any difference in elevation in tank water surface and the point under consideration.

Combination. Any combination of the above pressure sources.

BERNOULLI'S THEOREM

Bernoulli's theorem expresses the physical law of conservation of energy applied to problems of incompressible fluid flow. The theorem can be defined as follows: "In steady flow without friction, the sum of the velocity head, pressure head, and elevation head is constant for any incompressible fluid particle throughout its course." In other words, the total pressure (head) is the same at all locations within the system.

(Note that, in Bernoulli's theorem, all of the individual head terms, i.e., velocity head, pressure head, and elevation head are expressed in ft [m]. When using velocities in fps [m/sec] and gauge pressure in psi [kPa], they must be converted to ft [m], or all of the terms expressed as pressures.)

Bernoulli's Theorem Expressed Mathematically

Real systems are not frictionless, however, and in practice, losses due to pipe friction and other factors are accounted for. Expressed mathematically, Bernoulli's theorem, when applied to locations A and B, is

$$\frac{\upsilon_A^2}{2g} + \frac{p_A}{w} + z_A = \frac{\upsilon_B^2}{2g} + \frac{p_B}{w} + z_B + h_{AB}$$

where

υ (υ_m) = Velocity in fps (m/sec)
g (g_m) = Acceleration of gravity (32.2 fps [9.81 m/sec^2])
p (p_m) = Pressure (lb/ft^2 [kPa])
z (z_m) = Elevation head (distance above assumed datum, in ft [m])
w (w_m) = Specific weight of the fluid in lb/ft^3 (64.4 pcf or 9.81 kN/m^3 for water)

$\frac{\upsilon^2}{2g}\left(\frac{\upsilon_m^2}{2g}\right)$ = Velocity head in ft (m)

$\frac{p}{\omega}\left(\frac{p_m}{\omega_m}\right)$ = Pressure head in ft (m)

$h_{ab}(h_{abm})$ = Lost head between location A and location B in ft (m)

Application of Bernoulli's Theorem

Consider a reservoir and a pipeline discharging water to atmosphere at *B* (Figure 15.3.3). Assuming datum through B, Bernoulli's theorem applied from the water surface at A to the outlet at B is

$$\frac{v_A^2}{2g} + \frac{p_A}{w} + z_A = \frac{v_B^2}{2g} + \frac{p_B}{w} + z_B + h_{AB}$$

The velocity at A is practically zero because the tank is very large, and the gauge pressure is zero because only atmospheric pressure works on the water surface. At A, the elevation is z_A measured in ft (m) above the datum.

At B, the elevation above the datum is zero; the gauge pressure is zero, since the water is discharging to atmosphere; and only velocity pressure is available as the water leaves the outlet. (A gauge at a right angle to the emerging stream would register zero pressure.)

Therefore,

$$0 + 0 + z_A = \frac{v_B^2}{2g} + 0 + 0 + h_{AB}$$

or

$$\frac{v_B^2}{2g} = z_A - h_{AB}$$

Lost head, h_{AB}, is the sum of (1) hydraulic losses at the reservoir where water enters the pipeline, at the valve, and at the discharge outlet, plus (2) the friction loss in the pipeline. The values of the components producing lost head can be estimated, as discussed later in the chapter.

As another example, calculate the head loss across 1000 ft of 8 in. pipe with 750 gpm flowing from a 2½ in. hydrant outlet at B and a residual pressure at hydrant A of 40 psi. With no flow, hydrant A has a 60 psi static pressure, and hydrant B has an 80 psi static pressure. Assume a datum through hydrant B. Again, Bernoulli's theorem applied from point A to point B applies:

$$\frac{v_A^2}{2g} + \frac{p_A}{w} + z_A = \frac{v_B^2}{2g} + \frac{p_B}{w} + z_B + h_{AB}$$

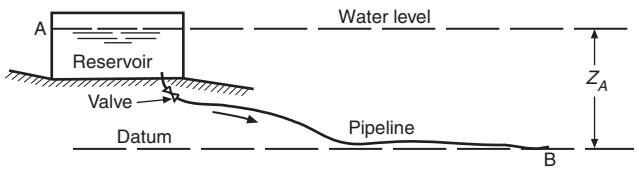


FIGURE 15.3.3 Graphic Representation of the Application of Bernoulli's Theorem to a Reservoir and Pipelines

Because we are interested in finding the head loss from A to B (h_{AB}), we rearrange Bernoulli's equation to solve for this term:

$$h_{AB} = \frac{v_A^2}{2g} + \frac{p_A}{w} + z_A - \frac{v_B^2}{2g} - \frac{p_B}{w} - z_B$$

The next step is to use the information provided to calculate each of the terms on the right side of the equation, starting with the velocity head at A:

$$v_A = \frac{Q}{a} = \frac{Q}{\frac{\pi d^2}{4 \times 144}}$$

$$= \frac{750 \text{ gpm}}{\frac{7.48 \text{ gal/ft}^3 \times 60 \text{ sec/min}}{\frac{3.1416 \times (8 \text{ in.})^2}{4 \times 144 \text{ in.}^2/\text{ft}^2}}} = 4.79 \text{ fps}$$

$$\frac{v_A^2}{2g} = \frac{(4.79 \text{ fps})^2}{64.4 \text{ fps/sec}} = 0.36 \text{ ft} \approx 0.4 \text{ ft}$$

Next we calculate the pressure head at A:

$$\frac{p_A}{w} = \frac{40 \text{ psi} \times \frac{144 \text{ in.}^2}{\text{ft}^2}}{62.4 \text{ pcf}} = 93.2 \text{ ft}$$

$$z_A = (80 \text{ psi} - 60 \text{ psi}) \times 2.31 \text{ ft/psi} = 46.2 \text{ ft}$$

Because we are using point B as our datum or zero-elevation reference, z_A is the elevation difference between points A and B. We can use Bernoulli's equation with no flow to determine this difference. Because there is no flow, the velocity head terms are zero. Also, because there is no flow, there is no friction or head loss. We know that because the static pressure at B is greater than the static pressure at A, the elevation of A is positive. Solving for the elevation difference we get

$$z_A - z_B = \frac{p_B}{w} - \frac{p_A}{w}$$

We know the pressure head at B is 80 psi and that head at A is 60 psi. Because the elevation at B is zero, substituting and converting the units we get

$$z_A = (80 \text{ psi} - 60 \text{ psi}) \times 2.31 \text{ ft/psi} = 46.2 \text{ ft}$$

The velocity at B is calculated in the same manner as at A:

$$v_B = \frac{Q}{a} = \frac{750 \text{ gpm}}{\frac{7.48 \text{ gal/ft}^3 \times 60 \text{ sec/min}}{\frac{3.1416 \times (2.5 \text{ in.})^2}{4 \times 144 \text{ in.}^2/\text{ft}^2}}} = 49.02 \text{ fps}$$

$$\frac{v_B^2}{2g} = \frac{(49.02 \text{ fps})^2}{64.4 \text{ fps}} = 37.3 \text{ ft}$$

There is no normal pressure, as the flow discharges to atmosphere.

$$\frac{p_B}{w} = 0$$

$z_B = 0$ since the datum goes through hydrant B. Thus

$$h_{AB} = 0.4 + 92.3 + 46.2 - 37.3 - 0 - 0 = 101.6 \text{ ft}$$

One further problem is expressed in SI units. Water is pumped via a pipeline, up a 5.0 m incline from A to B. The pipeline at A has an inside diameter of 80 mm and a static pressure of 300 kPa. If the pipeline has changed in diameter to 70 mm at B and there is frictional head loss over the length of the pipe (h_{AB}) of 12 m, determine the residual pressure at B for a flow rate of 4200 L/min.

The solution is expressed as

$$\frac{\upsilon_A^2}{2g} + \frac{p_A}{w} + z_A = \frac{\upsilon_B^2}{2g} + \frac{p_B}{w} + z_B + h_{AB}$$

Rearranging for the pressure head at B,

$$\frac{p_B}{w} = \frac{\upsilon_A^2}{2g} + \frac{p_A}{w} + z_A - \frac{\upsilon_B^2}{2g} - z_B - h_{AB}$$

Substituting,

$$\upsilon_a = \frac{Q}{a_a} = \frac{4200 \text{ L/min}}{\dfrac{60 \text{ sec/min} \times 1000 \text{ L/m}^3}{\pi (80 \text{ mm})^2 / 4 \times 10^6 \text{ mm}^2/\text{m}^2}}$$

$$\frac{\upsilon_A^2}{2g} = \frac{(13.9 \text{ m/sec})^2}{2 \times 9.81 \text{ m/sec}^2} = 9.8 \text{ m}$$

$$\frac{p_A}{w} = \frac{300 \text{ kPa}}{9.81 \text{ kPa/m}} = 30.6 \text{ m}$$

$$z_A = 0 \text{ (datum through A)}$$

$$\upsilon_B = \frac{Q}{a_B} = \frac{4200 \text{ L/min}}{\dfrac{60 \text{ sec/min} \times 1000 \text{ L/m}^3}{\pi (70 \text{ mm})^2 / 4 \times 10^6 \text{ mm}^2/\text{m}^2}} = 18.2 \text{ m/sec}$$

$$\frac{\upsilon_B^2}{2g} = \frac{(18.2 \text{ m/sec})^2}{2 \times 9.81 \text{ m/sec}^2} = 16.9 \text{ m}$$

$$z_B = 5.0 \text{ m}$$

$$h_{AB} = 12 \text{ m (friction loss)}$$

Then

$$\frac{p_B}{w} = 9.81 + 30.6 + 0 - 16.9 - 5 - 12 = 6.5 \text{ m}$$

In pressure terms

$$6.5 \text{ m} \times 9.81 \frac{\text{kPa}}{\text{m}} = 64 \text{ kPa}$$

that is, the residual pressure at B is 64 kPa.

FLOW OF WATER THROUGH ORIFICES

As a liquid leaves a pipe, conduit, or container through an orifice and discharges to atmosphere, the normal pressure is converted to velocity pressure. The rate of flow though an orifice can be expressed in terms of velocity and cross-sectional area of the stream, the basic relations being $Q = a\upsilon$, where Q = rate of flow in ft^3/sec (m^3/sec); a = area of cross section in ft^2 (m^2); and υ = velocity at the cross section in ft/sec (m/sec) (Table 15.3.1). From the previous discussion in this chapter on velocity head, it is known that

$$Q = a\sqrt{2gh}$$

and h (ft) = 2.307p (psi). It follows that, with the orifice diameter in inches, Q in gal/min, and h in psi,

$$Q = 60 \times 7.4805 \times \frac{\pi d^2}{4 \times 144} \times \sqrt{64.4 \times 2.3077 p_\upsilon}$$

$$Q = 29.84 d^2 \sqrt{p_\upsilon}$$

In SI units, the flow formula is expressed as

$$Q_m = 0.0666 d_m^2 \sqrt{p_{\upsilon m}}$$

where

Q_m = Flow rate (L/m)

d_m = Inside diameter (mm)

$p_{\upsilon m}$ = Velocity pressure (kPa)

The above equations (and tables derived therefrom) assume that (1) the jet is a solid stream the full size of the discharge orifice, and (2) 100 percent of the available total head is converted to velocity head, which is uniform over the cross section. This is a theoretical situation only, however, as these two conditions are not totally attainable, as the following discussion will show.

COEFFICIENTS OF FLOW

In actual flow from nozzles or orifices, the velocity, considered to be average velocity across the entire cross section of the stream, is somewhat less than the velocity calculated from the head. The reduction is due to friction of the water against the nozzle or orifice and turbulence within the nozzle and is accounted for by a coefficient of velocity, designated c_υ. Values of c_υ are determined by laboratory tests. With well-designed nozzles, the coefficient of velocity is nearly constant and is approximately equal to 0.98.

Some nozzles are designed so that the actual cross-sectional area of the stream is somewhat less than the cross-sectional area of the orifice. This difference is accounted for by the coefficient of contraction, designated c_c. Coefficients of contraction vary greatly with the design and quality of the orifice or nozzle. For a sharp-edged orifice, the value of c_c is about 0.62.

The coefficients of velocity and contraction are usually combined as a single coefficient of discharge, designated c_d:

$$c_d = c_\upsilon \times c_c$$

The basic flow equation can now be written as

$$Q = 29.84 c_d^4 d^2 \sqrt{p_\upsilon}$$

In SI units the formula is

$$Q = 0.0666 c_d d_m^2 \sqrt{p_{\upsilon m}}$$

TABLE 15.3.1 Theoretical Flow Through Circular Orifices—gpm (L/min)

This table may be computed from the formula $Q = 29.84cd^2\sqrt{p}$ ($Q = 0.0666cd_m^2\sqrt{p_m}$) with $c = 1.00$. The theoretical discharge from seawater, as from fireboat nozzles, may be found by subtracting 1 percent from the figures in the following table or from the value computed using the formulas.

When pressures are read with a Pitot gage at a nozzle, the nozzle discharge in most cases will correspond to the values in the table within a range of 1 to 3 percent for nozzles up to 1⅜ in. (35 mm) in diameter. For larger diameter nozzles, the principles discussed in "Nozzle Method of Measuring Flow" in this chapter of the handbook apply. Appropriate coefficients should be applied where it is read from a hydrant outlet. Where more accurate results are required, a coefficient appropriate to the particular nozzle must be selected and applied to the figures of the table.

The discharge from circular openings of sizes other than those in the table may readily be computed by applying the principles that quantity discharged under a given head varies as the square of the diameter of the opening.

		Orifice Diameter in. (mm)																						
Pressure psi (kPa)	*Velocity ft/sec (m/sec)*	*0.375 (9.53)*	*0.5 (12.7)*	*0.625 (15.9)*	*0.75 (19.1)*	*0.875 (22.2)*	*1 (25.4)*	*1.125 (28.6)*	*1.25 (31.8)*	*1.5 (38.1)*	*1.75 (44.5)*	*2 (50.8)*	*2.25 (57.2)*	*2.375 (60.3)*	*2.5 (63.5)*	*2.625 (66.7)*	*2.75 (69.9)*	*3 (76.2)*	*3.25 (82.6)*	*3.5 (88.9)*	*3.75 (95.25)*	*4 (102)*	*4.5 (114)*
1	12.2	4.20	7.46	11.7	16.8	22.8	29.8	37.8	46.6	67.1	91.4	119	151	168	187	206	226	269	315	366	420	477	604
(6.89)	(3.71)	(15.9)	(28.2)	(44.1)	(63.4)	(86.4)	(113)	(143)	(176)	(254)	(345)	(451)	(571)	(636)	(705)	(777)	(853)	(1020)	(1190)	(1380)	(1590)	(1800)	(2280)
2	17.2	5.93	10.6	16	23.7	32.3	42.2	53.4	65.9	95.0	129	169	214	238	264	291	319	380	446	517	593	675	855
(13.8)	(5.25)	(22.4)	(39.9)	(62.4)	(89.8)	(122)	(160)	(202)	(249)	(359)	(489)	(638)	(808)	(900)	(998)	(1100)	(1210)	(1440)	(1690)	(1960)	(2240)	(2550)	(3230)
3	21.1	7.27	12.9	20.2	29.1	39.6	51.7	65.4	80.8	116	158	207	262	292	323	356	391	465	546	633	727	827	1050
(20.7)	(6.43)	(27.5)	(48.9)	(76.4)	(110)	(150)	(195)	(247)	(305)	(440)	(599)	(782)	(990)	(1100)	(1220)	(1350)	(1480)	(1760)	(2060)	(2390)	(2750)	(3130)	(3960)
4	24.4	8.39	14.9	23.3	33.6	45.7	59.7	75.5	93.3	134	183	239	302	337	373	411	451	537	630	731	839	955	1210
(27.6)	(7.43)	(31.7)	(56.4)	(88.2)	(127)	(173)	(226)	(286)	(353)	(508)	(691)	(903)	(1140)	(1270)	(1410)	(1560)	(1710)	(2030)	(2380)	(2770)	(3170)	(3610)	(4570)
5	27.3	9.38	16.7	26.1	37.5	51.1	66.7	84.4	104	150	204	267	338	376	417	460	505	601	705	817	938	1070	1350
(34.5)	(8.31)	(35.5)	(63.1)	(98.6)	(142)	(193)	(252)	(319)	(394)	(568)	(773)	(1010)	(1280)	(1420)	(1580)	(1740)	(1910)	(2270)	(2670)	(3090)	(3550)	(4040)	(5110)
6	29.9	10.3	18.3	28.6	41.1	56.0	73.1	92.5	114	164	224	292	370	412	457	504	553	658	772	895	1030	1170	1480
(41.4)	(9.10)	(38.9)	(69.1)	(108)	(156)	(212)	(276)	(350)	(432)	(622)	(847)	(1110)	(1400)	(1560)	(1730)	(1910)	(2090)	(2490)	(2920)	(3390)	(3890)	(4420)	(5600)
7	32.3	11.1	19.7	30.8	44.4	60.4	78.9	100	123	178	242	316	400	445	493	544	597	711	834	967	1110	1260	1600
(48.3)	(9.83)	(42.0)	(74.7)	(117)	(168)	(229)	(299)	(378)	(467)	(672)	(915)	(1190)	(1510)	(1680)	(1870)	(2060)	(2260)	(2690)	(3150)	(3660)	(4200)	(4780)	(6050)
8	34.5	11.9	21.1	33.0	47.5	64.6	84.4	107	132	190	258	338	427	476	528	582	638	760	891	1030	1190	1350	1710
(55.2)	(10.5)	(44.9)	(79.8)	(125)	(180)	(244)	(319)	(404)	(499)	(718)	(978)	(1280)	(1620)	(1800)	(2000)	(2200)	(2410)	(2870)	(3370)	(3910)	(4490)	(5110)	(6460)
9	36.6	12.6	22.4	35.0	50.4	68.5	89.5	113	140	201	274	358	453	505	560	617	677	806	946	1100	1260	1430	1810
(62.0)	(11.1)	(47.6)	(84.6)	(132)	(190)	(259)	(338)	(428)	(529)	(761)	(1040)	(1350)	(1710)	(1910)	(2110)	(2330)	(2560)	(3040)	(3570)	(4140)	(4760)	(5410)	(6850)
10	38.6	13.3	23.6	36.9	53.1	72.2	94.4	119	147	212	289	377	478	532	590	650	714	849	997	1160	1330	1510	1910
(68.9)	(11.7)	(50.2)	(89.2)	(139)	(201)	(273)	(357)	(451)	(557)	(802)	(1090)	(1430)	(1810)	(2010)	(2230)	(2460)	(2700)	(3210)	(3770)	(4370)	(5020)	(5710)	(7220)
11	40.4	13.9	24.7	38.7	55.7	75.8	99.0	125	155	223	303	396	501	558	619	682	748	891	1050	1210	1390	1580	2000
(75.8)	(12.3)	(52.6)	(93.5)	(146)	(210)	(286)	(374)	(473)	(585)	(842)	(1150)	(1500)	(1809)	(2110)	(2340)	(2580)	(2830)	(3370)	(3950)	(4580)	(5260)	(5990)	(7580)
12	42.2	14.5	25.8	40.4	58.1	79.1	103	131	162	233	317	413	523	583	646	712	782	930	1090	1270	1450	1650	2090
(82.7)	(12.9)	(54.9)	(97.7)	(153)	(220)	(299)	(391)	(495)	(611)	(879)	(1200)	(1560)	(1980)	(2200)	(2440)	(2690)	(2960)	(3520)	(4130)	(4790)	(5490)	(6250)	(7910)
13	44.0	15.1	26.9	42.0	60.5	82.4	108	136	168	242	329	430	545	607	672	741	814	968	1140	1320	1510	1720	2180
(89.6)	(13.4)	(57.2)	(102)	(159)	(229)	(311)	(407)	(515)	(636)	(915)	(1250)	(1630)	(2060)	(2290)	(2540)	(2800)	(3080)	(3660)	(4300)	(4980)	(5720)	(6510)	(8240)
14	45.6	15.7	27.9	43.6	62.8	85.5	112	141	174	251	342	447	565	630	698	769	844	1000	1180	1370	1570	1790	2260
(96.5)	(13.9)	(59.4)	(106)	(165)	(237)	(323)	(422)	(534)	(660)	(950)	(1290)	(1690)	(2140)	(2380)	(2640)	(2910)	(3190)	(3800)	(4460)	(5170)	(5940)	(6750)	(8550)
15	47.2	16.3	28.9	45.1	65.0	88.5	116	146	181	260	354	462	585	652	722	796	874	1040	1220	1420	1630	1850	2340
(103)	(14.4)	(61.3)	(109)	(170)	(245)	(334)	(436)	(552)	(681)	(981)	(1340)	(1740)	(2210)	(2460)	(2730)	(3000)	(3300)	(3920)	(4610)	(5340)	(6130)	(6980)	(8830)
16	48.8	16.8	29.8	46.6	67.1	91.4	119	151	187	269	366	477	604	673	746	822	903	1070	1260	1460	1680	1910	2420
(110)	(14.8)	(63.4)	(113)	(176)	(253)	(345)	(451)	(570)	(704)	(1010)	(1380)	(1800)	(2280)	(2540)	(2820)	(3110)	(3410)	(4060)	(4760)	(5520)	(6340)	(7210)	(9130)
17	50.3	17.3	30.8	48.1	69.2	94.2	123	156	192	277	377	492	623	694	769	848	930	1110	1300	1510	1730	1970	2490
(117)	(15.3)	(65.4)	(116)	(182)	(261)	(356)	(465)	(588)	(726)	(1050)	(1420)	(1860)	(2350)	(2620)	(2900)	(3200)	(3510)	(4180)	(4910)	(5690)	(6540)	(7440)	(9410)

(continued)

TABLE 15.3.1 Continued

Pressure *psi* *(kPa)*	*Velocity* *ft/sec* *(m/sec)*	*0.375* *(9.53)*	*0.5* *(12.7)*	*0.625* *(15.9)*	*0.75* *(19.1)*	*0.875* *(22.2)*	*1* *(25.4)*	*1.125* *(28.6)*	*1.25* *(31.8)*	*1.5* *(38.1)*	*1.75* *(44.5)*	*2* *(50.8)*	*2.25* *(57.2)*	*2.375* *(60.3)*	*2.5* *(63.5)*	*2.625* *(66.7)*	*2.75* *(69.9)*	*3* *(76.2)*	*3.25* *(82.6)*	*3.5* *(88.9)*	*3.75* *(95.25)*	*4* *(102)*	*4.5* *(114)*
18	51.7	17.8	31.7	49.5	71.2	96.9	127	160	198	285	388	506	641	714	791	872	957	1140	1340	1550	1780	2,030	2,560
(124)	(15.7)	(67.3)	(120)	(187)	(269)	(366)	(478)	(606)	(748)	(1080)	(1470)	(1910)	(2420)	(2700)	(2990)	(3300)	(3620)	(4310)	(5050)	(5860)	(6730)	(7,660)	(9,690)
19	53.1	18.3	32.5	50.8	73.2	100	130	165	203	293	398	520	658	734	813	896	984	1170	1370	1590	1830	2,080	2,630
(131)	(16.2)	(69.2)	(123)	(192)	(277)	(377)	(492)	(622)	(768)	(1110)	(1510)	(1970)	(2490)	(2770)	(3070)	(3390)	(3720)	(4430)	(5190)	(6020)	(6920)	(7,870)	(9,960)
20	54.5	18.8	33.4	52.1	75.1	102	133	169	209	300	409	534	676	753	834	920	1010	1200	1410	1630	1880	2,140	2,700
(138)	(16.6)	(71.0)	(126)	(197)	(284)	(386)	(505)	(639)	(789)	(1140)	(1550)	(2020)	(2560)	(2850)	(3150)	(3480)	(3820)	(4540)	(5330)	(6180)	(7100)	(8,080)	(10,200)
21	55.9	19.2	34.2	53.4	76.9	105	137	173	214	308	419	547	692	771	855	942	1030	1230	1440	1680	1920	2,190	2,770
(145)	(17.0)	(72.8)	(129)	(202)	(291)	(396)	(517)	(655)	(808)	(1160)	(1580)	(2070)	(2620)	(2920)	(3230)	(3570)	(3910)	(4660)	(5470)	(6340)	(7280)	(8,280)	(10,500)
22	57.2	19.7	35.0	54.7	78.7	107	140	177	219	315	429	560	709	789	875	964	1060	1260	1480	1710	1970	2,240	2,830
(152)	(17.4)	(74.5)	(132)	(207)	(298)	(406)	(530)	(670)	(828)	(1190)	(1620)	(2120)	(2680)	(2990)	(3310)	(3650)	(4010)	(4770)	(5600)	(6490)	(7450)	(8,480)	(10,700)
23	58.5	20.1	35.8	55.9	80.5	110	143	181	224	322	438	572	724	807	894	986	1080	1290	1510	1750	2010	2,290	2,900
(159)	(17.8)	(76.2)	(135)	(212)	(305)	(415)	(542)	(686)	(847)	(1220)	(1660)	(2170)	(2740)	(3060)	(3390)	(3730)	(4100)	(4880)	(5720)	(6640)	(7620)	(8,670)	(11,000)
24	59.7	20.6	36.5	57.1	82.2	112	146	185	228	329	448	585	740	825	914	1010	1110	1320	1540	1790	2060	2,340	2,960
(165)	(18.2)	(77.6)	(138)	(216)	(310)	(423)	(552)	(699)	(862)	(1240)	(1690)	(2210)	(2790)	(3110)	(3450)	(3800)	(4170)	(4970)	(5830)	(6760)	(7760)	(8,830)	(11,200)
25	61.0	21.0	37.3	58.3	83.9	114	149	189	233	336	457	597	755	842	933	1030	1130	1340	1580	1830	2100	2,390	3,020
(172)	(18.5)	(79.2)	(141)	(220)	(317)	(431)	(564)	(713)	(880)	(1270)	(1730)	(2250)	(2850)	(3180)	(3520)	(3880)	(4260)	(5070)	(5950)	(6900)	(7920)	(9,020)	(11,400)
26	62.2	21.4	38.0	59.4	85.6	116	152	193	238	342	466	609	770	858	951	1050	1150	1370	1610	1860	2140	2,430	3,080
(179)	(18.9)	(80.8)	(144)	(225)	(323)	(440)	(575)	(728)	(898)	(1290)	(1761)	(2299)	(2910)	(3240)	(3590)	(3960)	(4350)	(5170)	(6070)	(7040)	(8080)	(9,200)	(11,600)
27	63.3	21.8	38.8	60.6	87.2	119	155	196	242	349	475	620	785	875	969	1070	1170	1400	1640	1900	2180	2,480	3,140
(186)	(19.3)	(82.4)	(147)	(229)	(330)	(449)	(586)	(742)	(916)	(1320)	(1795)	(2344)	(2970)	(3310)	(3660)	(4040)	(4430)	(5270)	(6190)	(7180)	(8240)	(9,380)	(11,900)
28	64.5	22.2	39.5	61.7	88.8	121	158	200	247	355	484	632	799	891	987	1090	1190	1420	1670	1930	2220	2,530	3,200
(193)	(19.6)	(83.9)	(149)	(233)	(336)	(457)	(597)	(755)	(933)	(1340)	(1830)	(2390)	(3020)	(3370)	(3730)	(4110)	(4510)	(5370)	(6310)	(7310)	(8390)	(9,550)	(12,100)
29	65.7	22.6	40.2	62.8	90.4	123	161	203	251	362	492	643	814	906	1004	1110	1220	1450	1700	1970	2260	2,570	3,250
(200)	(20.0)	(85.5)	(152)	(237)	(342)	(465)	(608)	(769)	(949)	(1370)	(1860)	(2430)	(3080)	(3430)	(3800)	(4190)	(4600)	(5470)	(6420)	(7440)	(8550)	(9,720)	(12,300)
30	66.8	23.0	40.9	63.8	91.9	125	163	207	255	368	501	654	827	922	1020	1130	1240	1470	1730	2000	2300	2,620	3,310
(207)	(20.3)	(86.9)	(155)	(241)	(348)	(473)	(618)	(782)	(966)	(1390)	(1890)	(2470)	(3130)	(3490)	(3860)	(4260)	(4680)	(5560)	(6530)	(7570)	(8690)	(9,890)	(12,500)
31	67.9	23.4	41.5	64.9	93.5	127	166	210	260	374	509	665	841	937	1040	1140	1260	1500	1750	2040	2340	2,660	3,360
(214)	(20.7)	(88.4)	(157)	(246)	(354)	(481)	(629)	(796)	(982)	(1410)	(1920)	(2510)	(3180)	(3550)	(3930)	(4330)	(4750)	(5660)	(6640)	(7700)	(8840)	(10,100)	(12,700)
32	69.0	23.7	42.2	65.9	95.0	129	169	214	264	380	517	675	855	952	1060	1160	1280	1520	1780	2070	2370	2,700	3,420
(221)	(21.0)	(89.8)	(160)	(250)	(359)	(489)	(639)	(808)	(998)	(1440)	(1960)	(2560)	(3230)	(3600)	(3990)	(4400)	(4830)	(5750)	(6750)	(7820)	(8980)	(10,200)	(12,900)
33	70.0	24.1	42.9	67.0	96.4	131	171	217	268	386	525	686	868	967	1070	1180	1300	1540	1810	2100	2410	2,740	3,470
(228)	(21.4)	(91.2)	(162)	(253)	(365)	(497)	(649)	(821)	(1014)	(1460)	(1990)	(2600)	(3280)	(3660)	(4050)	(4470)	(4910)	(5840)	(6850)	(7950)	(9120)	(10,400)	(13,100)
34	71.1	24.5	43.5	68.0	97.9	133	174	220	272	391	533	696	881	981	1090	1200	1320	1570	1840	2130	2450	2,780	3,520
(234)	(21.6)	(92.4)	(164)	(257)	(370)	(503)	(657)	(832)	(1030)	(1480)	(2010)	(2630)	(3330)	(3710)	(4110)	(4530)	(4970)	(5920)	(6940)	(8050)	(9240)	(10,500)	(13,300)
35	72.1	24.8	44.1	69.0	99.3	135	177	223	276	397	541	706	894	996	1100	1220	1340	1590	1860	2160	2480	2,820	3,570
(241)	(22.0)	(93.8)	(167)	(261)	(375)	(511)	(667)	(844)	(1040)	(1500)	(2040)	(2670)	(3380)	(3760)	(4170)	(4600)	(5040)	(6000)	(7050)	(8170)	(9380)	(10,700)	(13,500)
36	73.1	25.2	44.8	69.9	101	137	179	227	280	403	548	716	906	1010	1120	1230	1350	1610	1890	2190	2520	2,860	3,630
(248)	(22.3)	(95.2)	(169)	(264)	(381)	(518)	(677)	(856)	(1060)	(1520)	(2070)	(2710)	(3430)	(3820)	(4230)	(4660)	(5120)	(6090)	(7150)	(8290)	(9520)	(10,800)	(13,700)
37	74.2	25.5	45.4	70.9	102	139	182	230	284	408	556	726	919	1020	1130	1250	1370	1630	1920	2220	2550	2,900	3,680
(255)	(22.6)	(96.5)	(172)	(268)	(386)	(525)	(686)	(868)	(1070)	(1540)	(2100)	(2740)	(3470)	(3870)	(4290)	(4730)	(5190)	(6180)	(7250)	(8410)	(9650)	(11,000)	(13,900)
38	75.2	25.9	46.0	71.9	103	141	184	233	287	414	563	736	931	1040	1150	1270	1390	1660	1940	2250	2590	2,940	3,720
(262)	(22.9)	(97.8)	(174)	(272)	(391)	(532)	(695)	(880)	(1090)	(1560)	(2130)	(2780)	(3520)	(3920)	(4350)	(4790)	(5260)	(6260)	(7350)	(8520)	(9780)	(11,100)	(14,100)
39	76.1	26.2	46.6	72.8	105	143	186	236	291	419	571	745	943	1050	1160	1280	1410	1680	1970	2280	2620	2,980	3,770
(269)	(23.2)	(99.1)	(176)	(275)	(396)	(540)	(705)	(892)	(1100)	(1590)	(2160)	(2820)	(3570)	(3980)	(4400)	(4860)	(5330)	(6340)	(7440)	(8630)	(9910)	(11,300)	(14,300)

40	77.1	26.5	47.2	73.7	106	144	189	239	295	425	578	755	955	1060	1180	1300	1430	1700	1,990	2,310	2,650	3,020	3,820
(276)	(23.5)	(100)	(178)	(279)	(402)	(547)	(714)	(903)	(1120)	(1610)	(2190)	(2860)	(3610)	(4030)	(4460)	(4920)	(5400)	(6420)	(7,540)	(8,740)	(10,000)	(11,400)	(14,500)
41	78.1	26.9	47.8	74.6	107	146	191	242	299	430	585	764	967	1080	1190	1320	1440	1720	2,020	2,340	2,690	3,060	3,870
(283)	(23.8)	(102)	(181)	(282)	(407)	(553)	(723)	(915)	(1130)	(1630)	(2210)	(2890)	(3660)	(4080)	(4520)	(4980)	(5470)	(6510)	(7,630)	(8,850)	(10,200)	(11,600)	(14,600)
42	79.0	27.2	48.3	75.5	109	148	193	245	302	435	592	774	979	1090	1210	1330	1460	1740	2,040	2,370	2,720	3,090	3,920
(290)	(24.1)	(103)	(183)	(286)	(412)	(560)	(732)	(926)	(1140)	(1650)	(2240)	(2930)	(3700)	(4130)	(4570)	(5040)	(5530)	(6590)	(7,730)	(8,960)	(10,300)	(11,700)	(14,800)
43	79.9	27.5	48.9	76.4	110	150	196	248	306	440	599	783	991	1100	1220	1350	1480	1760	2,070	2,400	2,750	3,130	3,960
(297)	(24.4)	(104)	(185)	(289)	(417)	(567)	(740)	(937)	(1160)	(1670)	(2270)	(2960)	(3750)	(4180)	(4630)	(5100)	(5600)	(6660)	(7,820)	(9,070)	(10,400)	(11,800)	(15,000)
44	80.9	27.8	49.5	77.3	111	152	198	251	309	445	606	792	1000	1120	1240	1360	1500	1780	2,090	2,420	2,780	3,170	4,010
(303)	(24.6)	(105)	(187)	(292)	(421)	(573)	(748)	(947)	(1170)	(1680)	(2290)	(2990)	(3790)	(4220)	(4670)	(5150)	(5660)	(6730)	(7,900)	(9,160)	(10,500)	(12,000)	(15,100)
45	81.8	28.1	50.0	78.2	113	153	200	253	313	450	613	801	1010	1130	1250	1380	1510	1800	2,110	2,450	2,810	3,200	4,050
(310)	(24.9)	(106)	(189)	(296)	(426)	(579)	(757)	(957)	(1180)	(1700)	(2320)	(3030)	(3830)	(4270)	(4730)	(5210)	(5720)	(6810)	(7,990)	(9,270)	(10,600)	(12,100)	(15,300)
46	82.7	28.5	50.6	79.1	114	155	202	256	316	455	620	810	1020	1140	1260	1390	1530	1820	2,140	2,480	2,850	3,240	4,100
(317)	(25.2)	(108)	(191)	(299)	(430)	(586)	(765)	(968)	(1200)	(1720)	(2340)	(3060)	(3870)	(4320)	(4780)	(5270)	(5790)	(6890)	(8,080)	(9,370)	(10,800)	(12,200)	(15,500)
47	83.6	28.8	51.1	79.9	115	157	205	259	320	460	627	818	1040	1150	1280	1410	1550	1840	2,160	2,510	2,880	3,270	4,140
(324)	(25.5)	(109)	(193)	(302)	(435)	(592)	(773)	(979)	(1210)	(1740)	(2370)	(3090)	(3920)	(4360)	(4830)	(5330)	(5850)	(6960)	(8,170)	(9,470)	(10,900)	(12,400)	(15,700)
48	84.5	29.1	51.7	80.8	116	158	207	262	323	465	633	827	1050	1170	1290	1420	1560	1860	2,180	2,530	2,910	3,310	4,190
(331)	(25.7)	(110)	(195)	(305)	(440)	(599)	(782)	(989)	(1220)	(1760)	(2390)	(3130)	(3960)	(4410)	(4890)	(5390)	(5910)	(7040)	(8,260)	(9,580)	(11,000)	(12,500)	(15,800)
49	85.3	29.4	52.2	81.6	117	160	209	264	326	470	640	836	1060	1180	1310	1440	1580	1880	2,210	2,560	2,940	3,340	4,230
(338)	(26.0)	(111)	(197)	(309)	(444)	(605)	(790)	(1000)	(1230)	(1780)	(2420)	(3160)	(4000)	(4460)	(4940)	(5440)	(5970)	(7110)	(8,340)	(9,680)	(11,100)	(12,600)	(16,000)
50	86.2	29.7	52.8	82.4	119	162	211	267	330	475	646	844	1070	1190	1320	1450	1600	1900	2,230	2,580	2,970	3,380	4,270
(345)	(26.3)	(112)	(200)	(312)	(449)	(611)	(798)	(1010)	(1250)	(1800)	(2440)	(3190)	(4040)	(4500)	(4990)	(5500)	(6040)	(7180)	(8,430)	(9,780)	(11,200)	(12,800)	(16,200)
52	87.9	30.3	53.8	84.1	121	165	215	272	336	484	659	861	1090	1210	1340	1480	1630	1940	2,270	2,640	3,030	3,440	4,360
(358)	(26.8)	(114)	(203)	(318)	(457)	(622)	(813)	(1030)	(1270)	(1830)	(2490)	(3250)	(4120)	(4590)	(5080)	(5600)	(6150)	(7320)	(8,590)	(9,960)	(11,400)	(13,000)	(16,500)
54	89.6	30.8	54.8	85.7	123	168	219	278	343	493	672	877	1110	1240	1370	1510	1660	1970	2,320	2,690	3,080	3,510	4,440
(372)	(27.3)	(117)	(207)	(324)	(466)	(634)	(829)	(1050)	(1290)	(1860)	(2540)	(3310)	(4200)	(4670)	(5180)	(5710)	(6270)	(7460)	(8,750)	(10,200)	(11,700)	(13,300)	(16,800)
56	91.2	31.4	55.8	87.2	126	171	223	283	349	502	684	893	1130	1260	1400	1540	1690	2010	2,360	2,740	3,140	3,570	4,520
(386)	(27.8)	(119)	(211)	(330)	(475)	(646)	(844)	(1070)	(1320)	(1900)	(2590)	(3380)	(4270)	(4760)	(5280)	(5820)	(6380)	(7600)	(8,920)	(10,300)	(11,900)	(13,500)	(17,100)
58	92.8	32.0	56.8	88.8	128	174	227	288	355	511	696	909	1150	1280	1420	1570	1720	2050	2,400	2,780	3,200	3,640	4,600
(400)	(28.3)	(121)	(215)	(336)	(483)	(658)	(859)	(1090)	(1340)	(1930)	(2630)	(3440)	(4350)	(4850)	(5370)	(5920)	(6500)	(7730)	(9,080)	(10,500)	(12,100)	(13,700)	(17,400)
60	94.4	32.5	57.8	90.3	130	177	231	293	361	520	708	925	1170	1300	1440	1590	1750	2080	2,440	2,830	3,250	3,700	4,680
(414)	(28.8)	(123)	(219)	(342)	(492)	(669)	(874)	(1110)	(1370)	(1970)	(2680)	(3500)	(4430)	(4930)	(5460)	(6020)	(6610)	(7870)	(9,230)	(10,700)	(12,300)	(14,000)	(17,700)
62	96.0	33.0	58.7	91.8	132	180	235	297	367	528	719	940	1190	1330	1470	1620	1780	2110	2,480	2,880	3,300	3,760	4,760
(427)	(29.2)	(125)	(222)	(347)	(499)	(680)	(888)	(1120)	(1390)	(2000)	(2720)	(3550)	(4490)	(5010)	(5550)	(6120)	(6710)	(7990)	(9,380)	(10,900)	(12,500)	(14,200)	(18,000)
64	97.5	33.6	59.7	93.3	134	183	239	302	373	537	731	955	1210	1350	1490	1640	1810	2150	2,520	2,920	3,360	3,820	4,830
(441)	(29.7)	(127)	(226)	(352)	(508)	(691)	(902)	(1140)	(1410)	(2030)	(2760)	(3610)	(4570)	(5090)	(5640)	(6220)	(6820)	(8120)	(9,530)	(11,100)	(12,700)	(14,400)	(18,300)
66	99.0	34.1	60.6	94.7	136	186	242	307	379	545	742	970	1230	1370	1520	1670	1830	2180	2,560	2,970	3,410	3,880	4,910
(455)	(30.2)	(129)	(229)	(358)	(516)	(702)	(917)	(1160)	(1430)	(2060)	(2810)	(3670)	(4640)	(5170)	(5730)	(6320)	(6930)	(8250)	(9,680)	(11,200)	(12,900)	(14,700)	(18,600)
68	101	34.6	61.5	96.1	138	188	246	311	384	554	754	984	1250	1390	1540	1700	1860	2210	2,600	3,010	3,460	3,940	4,980
(469)	(30.6)	(131)	(233)	(363)	(523)	(712)	(931)	(1180)	(1450)	(2090)	(2850)	(3720)	(4710)	(5250)	(5820)	(6410)	(7040)	(8370)	(9,830)	(11,400)	(13,100)	(14,900)	(18,800)
70	102	35.1	62.4	97.5	140	191	250	316	390	562	765	999	1260	1410	1560	1720	1890	2250	2,640	3,060	3,510	3,990	5,060
(483)	(31.1)	(133)	(236)	(369)	(531)	(723)	(944)	(1200)	(1480)	(2120)	(2890)	(3780)	(4780)	(5330)	(5900)	(6510)	(7140)	(8500)	(9,970)	(11,600)	(13,300)	(15,100)	(19,100)
72	103	35.6	63.3	98.9	142	194	253	320	396	570	775	1010	1280	1430	1580	1740	1910	2280	2,670	3,100	3,560	4,050	5,130
(496)	(31.5)	(135)	(239)	(374)	(538)	(733)	(957)	(1210)	(1500)	(2150)	(2930)	(3830)	(4840)	(5400)	(5980)	(6590)	(7240)	(8610)	(10,100)	(11,700)	(13,500)	(15,300)	(19,400)
74	105	36.1	64.2	100	144	197	257	325	401	578	786	1030	1300	1450	1600	1770	1940	2310	2,710	3,140	3,610	4,110	5,200
(510)	(31.9)	(136)	(243)	(379)	(546)	(743)	(970)	(1230)	(1520)	(2180)	(2970)	(3880)	(4910)	(4570)	(6060)	(6690)	(7340)	(8730)	(10,200)	(11,900)	(13,600)	(15,500)	(19,600)
76	106	36.6	65.0	102	146	199	260	329	406	585	797	1040	1320	1470	1630	1790	1970	2340	2,750	3,190	3,660	4,160	5,270
(524)	(32.4)	(138)	(246)	(384)	(553)	(753)	(984)	(1240)	(1540)	(2210)	(3010)	(3930)	(4980)	(5550)	(6150)	(6780)	(7440)	(8850)	(10,400)	(12,000)	(13,800)	(15,700)	(19,900)
78	108	37.1	65.9	103	148	202	264	334	412	593	807	1050	1330	1490	1650	1820	1990	2370	2,780	3,230	3,710	4,220	5,340
(538)	(32.8)	(140)	(249)	(389)	(561)	(763)	(997)	(1260)	(1560)	(2240)	(3050)	(3990)	(5050)	(5620)	(6230)	(6870)	(7540)	(8970)	(10,500)	(12,200)	(14,000)	(15,900)	(20,200)

(continued)

TABLE 15.3.1 Continued

Pressure *psi* *(kPa)*	*Velocity* *ft/sec* *(m/sec)*	*0.375* *(9.53)*	*0.5* *(12.7)*	*0.625* *(15.9)*	*0.75* *(19.1)*	*0.875* *(22.2)*	*1* *(25.4)*	*1.125* *(28.6)*	*1.25* *(31.8)*	*1.5* *(38.1)*	*1.75* *(44.5)*	*2* *(50.8)*	*2.25* *(57.2)*	*2.375* *(60.3)*	*2.5* *(63.5)*	*2.625* *(66.7)*	*2.75* *(69.9)*	*3* *(76.2)*	*3.25* *(82.6)*	*3.5* *(88.9)*	*3.75* *(95.25)*	*4* *(102)*	*4.5* *(114)*
80	109	37.5	66.7	104	150	204	267	338	417	601	817	1070	1350	1510	1670	1840	2,020	2,400	2,820	3,270	3,750	4,270	5,400
(552)	(33.2)	(142)	(252)	(394)	(568)	(773)	(1010)	(1280)	(1580)	(2270)	(3090)	(4040)	(5110)	(5690)	(6310)	(6960)	(7,630)	(9,090)	(10,700)	(12,400)	(14,200)	(16,200)	(20,400)
82	110	38.0	67.6	106	152	207	270	342	422	608	828	1080	1370	1520	1690	1860	2,040	2,430	2,850	3,310	3,800	4,320	5,470
(565)	(33.6)	(144)	(255)	(399)	(574)	(782)	(1020)	(1290)	(1600)	(2300)	(3130)	(4090)	(5170)	(5760)	(6380)	(7040)	(7,720)	(9,190)	(10,800)	(12,500)	(14,400)	(16,300)	(20,700)
84	112	38.5	68.4	107	154	209	273	346	427	615	838	1090	1380	1540	1710	1880	2,070	2,460	2,890	3,350	3,850	4,380	5,540
(579)	(34.0)	(145)	(258)	(404)	(582)	(792)	(1030)	(1310)	(1620)	(2330)	(3170)	(4140)	(5230)	(5830)	(6460)	(7120)	(7,820)	(9,310)	(10,900)	(12,700)	(14,500)	(16,500)	(20,900)
86	113	38.9	69.2	108	156	212	277	350	432	623	847	1110	1400	1560	1730	1910	2,090	2,490	2,920	3,390	3,890	4,430	5,600
(593)	(34.4)	(147)	(262)	(409)	(589)	(801)	(1050)	(1320)	(1630)	(2350)	(3200)	(4190)	(5300)	(5900)	(6540)	(7210)	(7,910)	(9,420)	(11,100)	(12,800)	(14,700)	(16,700)	(21,200)
88	114	39.4	70.0	109	157	214	280	354	437	630	857	1120	1420	1580	1750	1930	2,120	2,520	2,960	3,430	3,940	4,480	5,670
(607)	(34.8)	(149)	(265)	(414)	(595)	(810)	(1060)	(1340)	(1650)	(2380)	(3240)	(4230)	(5360)	(5970)	(6620)	(7290)	(8,010)	(9,530)	(11,200)	(13,000)	(14,900)	(16,900)	(21,400)
90	116	39.8	70.8	111	159	217	283	358	442	637	867	1130	1430	1600	1770	1950	2,140	2,550	2,990	3,470	3,980	4,530	5,730
(620)	(35.2)	(150)	(267)	(418)	(602)	(819)	(1070)	(1350)	(1670)	(2410)	(3280)	(4280)	(5420)	(6030)	(6690)	(7370)	(8,090)	(9,630)	(11,300)	(13,100)	(15,000)	(17,100)	(21,700)
92	117	40.2	71.6	112	161	219	286	362	447	644	877	1140	1450	1610	1790	1970	2,160	2,580	3,020	3,510	4,020	4,580	5,800
(634)	(35.6)	(152)	(270)	(423)	(609)	(828)	(1080)	(1370)	(1690)	(2430)	(3310)	(4330)	(5480)	(6100)	(6760)	(7450)	(8,180)	(9,740)	(11,400)	(13,300)	(15,200)	(17,300)	(21,900)
94	118	40.7	72.3	113	163	222	289	366	452	651	886	1160	1460	1630	1810	1990	2,190	2,600	3,060	3,540	4,070	4,630	5,860
(648)	(36.0)	(154)	(273)	(427)	(615)	(837)	(1090)	(1380)	(1710)	(2460)	(3350)	(4380)	(5540)	(6170)	(6840)	(7540)	(8,270)	(9,840)	(11,600)	(13,400)	(15,400)	(17,500)	(22,100)
96	119	41.1	73.1	114	164	224	292	370	457	658	895	1170	1480	1650	1830	2010	2,210	2,630	3,090	3,580	4,110	4,680	5,920
(662)	(36.4)	(155)	(276)	(432)	(622)	(846)	(1110)	(1400)	(1730)	(2490)	(3390)	(4420)	(5600)	(6240)	(6910)	(7620)	(8,360)	(9,950)	(11,700)	(13,500)	(15,500)	(17,700)	(22,400)
98	121	41.5	73.9	115	166	226	295	374	462	665	905	1180	1500	1670	1850	2040	2,230	2,660	3,120	3,620	4,150	4,730	5,980
(676)	(36.8)	(157)	(279)	(436)	(628)	(855)	(1120)	(1410)	(1750)	(2510)	(3420)	(4470)	(5660)	(6300)	(6980)	(7700)	(8,450)	(10,100)	(11,800)	(13,700)	(15,700)	(17,900)	(22,600)
100	122	42.0	74.6	117	168	228	298	378	466	671	914	1190	1510	1680	1870	2060	2,260	2,690	3,150	3,660	4,200	4,770	6,040
(689)	(37.1)	(159)	(282)	(441)	(634)	(864)	(1130)	(1430)	(1760)	(2540)	(3450)	(4510)	(5710)	(6360)	(7050)	(7770)	(8,530)	(10,200)	(11,900)	(13,800)	(15,900)	(18,000)	(22,800)
105	125	43.0	76.4	119	172	234	306	387	478	688	936	1220	1550	1720	1910	2110	2,310	2,750	3,230	3,750	4,300	3,890	6,190
(724)	(38.1)	(163)	(289)	(452)	(650)	(885)	(1160)	(1460)	(1810)	(2600)	(3540)	(4620)	(5850)	(6520)	(7230)	(7970)	(8,740)	(10,400)	(12,200)	(14,200)	(16,300)	(18,500)	(23,400)
110	128	44.0	78.2	122	176	240	313	396	489	704	958	1250	1580	1770	1960	2160	2,370	2,820	3,310	3,830	4,400	5,010	6,340
(758)	(38.9)	(166)	(296)	(462)	(666)	(906)	(1180)	(1500)	(1850)	(2660)	(3620)	(4730)	(5990)	(6670)	(7400)	(8150)	(8,950)	(10,600)	(12,500)	(14,500)	(16,600)	(18,900)	(24,000)
115	131	45.0	80.0	125	180	245	320	405	500	720	980	1280	1620	1800	2000	2200	2,420	2,880	3,380	3,920	4,500	5,120	6,480
(793)	(39.8)	(170)	(302)	(473)	(681)	(926)	(1210)	(1530)	(1890)	(2720)	(3710)	(4840)	(6130)	(6820)	(7560)	(8340)	(9,150)	(10,900)	(12,800)	(14,800)	(17,000)	(19,400)	(24,500)
120	134	46.0	81.7	128	184	250	327	414	511	735	1000	1310	1650	1840	2040	2250	2,470	2,940	3,450	4,000	4,600	5,230	6,620
(827)	(40.7)	(174)	(309)	(483)	(695)	(946)	(1240)	(1560)	(1930)	(2780)	(3790)	(4940)	(6260)	(6970)	(7720)	(8520)	(9,350)	(11,100)	(13,100)	(15,100)	(17,400)	(19,800)	(25,000)
125	136	46.9	83.4	130	188	255	334	422	521	751	1020	1330	1690	1880	2090	2300	2,520	3,000	3,520	4,090	4,690	5,340	6,760
(862)	(41.5)	(177)	(315)	(493)	(710)	(966)	(1260)	(1600)	(1970)	(2840)	(3860)	(5050)	(6390)	(7120)	(7880)	(8690)	(9,540)	(11,400)	(13,300)	(15,500)	(17,700)	(20,200)	(25,500)
130	139	47.8	85.1	133	191	260	340	431	532	766	1040	1360	1720	1920	2130	2340	2,570	3,060	3,590	4,170	4,780	5,440	6,890
(896)	(42.3)	(181)	(322)	(502)	(724)	(985)	(1290)	(1630)	(2010)	(2890)	(3940)	(5150)	(6510)	(7260)	(8040)	(8860)	(9,730)	(11,600)	(13,600)	(15,800)	(18,100)	(20,600)	(26,000)
135	142	48.8	86.7	135	195	265	347	439	542	780	1060	1390	1760	1960	2170	2390	2,620	3,120	3,660	4,250	4,880	5,550	7,020
(931)	(43.1)	(184)	(328)	(512)	(737)	(1000)	(1310)	(1660)	(2050)	(2950)	(4010)	(5240)	(6640)	(7390)	(8190)	(9030)	(9,910)	(11,800)	(13,800)	(16,100)	(18,400)	(21,000)	(26,500)
140	144	49.7	88.3	138	199	270	353	447	552	794	1080	1410	1790	1990	2210	2430	2,670	3,180	3,730	4,330	4,970	5,650	7,150
(965)	(43.9)	(188)	(334)	(521)	(751)	(1020)	(1330)	(1690)	(2090)	(3000)	(4090)	(5340)	(6760)	(7530)	(8340)	(9200)	(10,100)	(12,000)	(14,100)	(16,400)	(18,800)	(21,400)	(27,000)
145	147	50.5	89.8	140	202	275	359	455	561	808	1100	1440	1820	2030	2250	2480	2,720	3,230	3,800	4,400	5,050	5,750	7,280
(1000)	(44.7)	(191)	(340)	(531)	(764)	(1040)	(1360)	(1720)	(2120)	(3060)	(4160)	(5430)	(6880)	(7660)	(8490)	(9360)	(10,300)	(12,200)	(14,300)	(16,600)	(19,100)	(21,700)	(27,500)
150	149	51.4	91.4	143	206	280	365	463	571	822	1120	1460	1850	2060	2280	2520	2,760	3,290	3,860	4,480	5,140	5,850	7,400
(1030)	(45.4)	(194)	(345)	(539)	(776)	(1060)	(1380)	(1750)	(2150)	(3100)	(4220)	(5520)	(6980)	(7780)	(8620)	(9500)	(10,400)	(12,400)	(14,600)	(16,900)	(19,400)	(22,100)	(27,900)

The coefficient of discharge, c_d, is defined as the ratio of the actual discharge to the theoretical discharge. For any specific orifice or nozzle, values of c_d are determined by standard test procedures using this definition. The actual rate of flow is measured by calibrated meters, or "weigh tanks." The theoretical flow is calculated using $c_d = 1.0$, the carefully measured orifice or nozzle diameter, and the measured velocity pressure in the flow equation.

Standard Orifice

An orifice with a sharp entrance edge, shown as form (1) in Figure 15.3.4, is known as a standard orifice and is commonly used to measure waterflow. If the shape of the orifice is changed so as to decrease the contraction, its capacity will be increased. Form 1 in the illustration is a standard orifice having a sharp edge on the approach side. Form 2, when in a thin plate, gives the same stream characteristics as Form 1. Form 3 is the reverse of 1. In Form 4, the edge is rounded to conform to the shape of the stream. The coefficients of discharge of 3 and 4 are greater than those of the standard orifices, approaching a value of 1.0 in the case of 4. As water leaves the orifice, it contracts to form a jet whose cross-sectional area is less than that of the orifice. The contraction is complete at the plane a', which is located a distance from the plane of the orifice equal to approximately half the diameter of the jet (Figure 15.3.5).

The quantity flowing is obviously the same at the orifice a as at the contracted section a', so the quantity flowing could be obtained by measuring the velocity and area at either of these planes. Expressed in a formula, where Q is ft^3/sec (m^3/sec), υ is velocity in ft/sec (m/sec), and a is the area in ft^2 (m^2),

$$Q = \upsilon a = \upsilon' a'$$

The coefficient of discharge for a standard orifice is the product of the coefficient of velocity and the coefficient of contraction, or $c = 0.98 \times 0.62 = 0.61$.

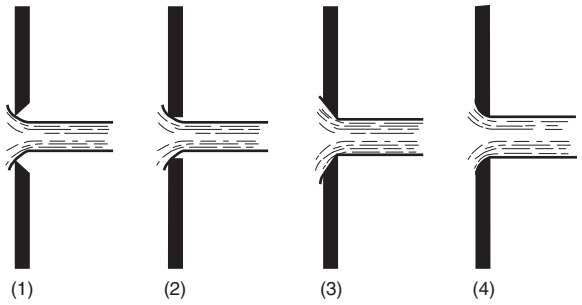


FIGURE 15.3.4 Orifices of Various Shapes

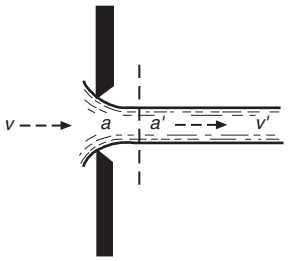


FIGURE 15.3.5 Flow Through a Standard Orifice

Other Orifices

The hydraulic characteristics of good solid-stream nozzles are consistent within a wide range of flow conditions. The velocity at the surface of the stream of most such nozzles is reduced slightly by friction against the orifice or nozzle. A coefficient of velocity of 0.97 is usually applied to nozzles of fire stream sizes to account for this friction.

Coefficients of discharge are available for the flow through hydrants, hose nozzles, automatic sprinklers, and other common fire protection discharge outlets. Representative values for the coefficients of discharge are given in Table 15.3.2. Again, these coefficients only apply when there is flow through the full orifice or nozzle opening with a reasonably uniform velocity profile. Three general types of hydrant outlets and their coefficients of discharge are shown in Figure 15.3.6.

TABLE 15.3.2 Typical Discharge Coefficients of Solid-Stream Nozzle

Spray sprinkler, average (nominal ½-in. dia.)	0.75
Spray sprinkler, average (nominal 17/32-in. dia.)	0.95
Large-drop sprinkler (0.64 in. dia.)	0.90
Standard orifice (sharp edge)	0.62
Smooth-bore nozzles, general	0.96–0.98
Underwriter playpipes or equal	0.97
Deluge or monitor nozzles	0.997
Open pipe, burred opening	0.80
Open pipe, smooth, well rounded	0.90
Hydrant butt, smooth and well-rounded outlet, flowing full*	0.90
Hydrant butt, square and sharp at hydrant barrel*	0.82
Hydrant butt, outlet square, projecting into barrel*	0.70

*See Figure 15.3.6.

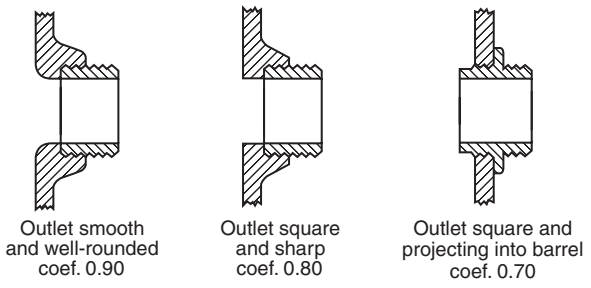


FIGURE 15.3.6 Three Types of Hydrant Outlets and Coefficients of Discharge

Flow in Short Tubes

A tube attached to an orifice is known as a standard short tube if it is 2½ to 3 times longer than the diameter of the orifice, and its diameter is the same as the orifice. A shorter tube will not flow full, and friction losses in a longer tube will affect results when used as a measuring device, hence the specified length limit.

The characteristics of a standard short tube and a short conical converging tube are shown in Figures 15.3.7 and 15.3.8, respectively. The principles of flow in orifices apply, but with different coefficients. With the conical tube, the coefficients c_v and c_c vary with the angle β. When β is 0 degrees, the converging tube becomes a cylindrical tube, with $c_c = 1$ and $c_v = 0.82$; c_d is then 0.82. As the angle β increases, the coefficient of contraction (c_c), develops, and the coefficient of velocity (c_v) increases, approaching the 0.98 value for a sharp-edge orifice. Relations are such that the coefficient of discharge attains a maximum value of 0.94, with a β angle of about 13 degrees.

FLOW MEASUREMENT

Pitot Tube Method of Measuring Flow

The most commonly used method of measuring flow in an open stream discharging from an orifice, nozzle, or open pipe is by direct measurement of the velocity head that produces the flow. This measurement process makes use of the well-known Pitot tube and pressure gauge combination.

When the small opening (usually not over 1/16 in. [1.6 mm] in diameter) is inserted into the center of a stream at the point of maximum contraction, with the opening directly in the line of flow, the gauge will indicate the total head at that location. With the stream open to the atmosphere, there will be no pressure head, so the indicated reading will be velocity head alone, and thus the velocity of the stream can be calculated directly. As a result, velocity pressure is sometimes referred to as Pitot pressure.

If the area of the cross section of the stream at the location of the velocity measurement location is known, the quantity flowing can be determined from the relation, $Q = av = 29.84 c_d d^2 \sqrt{p}$ or in SI units, $Q_m = 0.0666 c_d d_m^2 \sqrt{p_{vm}}$, previously derived. In practice, discharge tables are usually used to determine the flow from hydrants and nozzles (see Table 15.3.1).

A typical Pitot tube as used in the measuring of the flow from a fire stream nozzle is shown in Figure 15.3.9. For the usual forms of orifices and nozzles, the coefficient of discharge (c_d) is accurately known, so that $a = c_d \times$ actual discharge opening. For example, with a sharp-edge orifice the area of the stream may be determined from the actual diameter of the orifice opening and the use of the 0.62 coefficient of discharge, as outlined in the previous section on flow-through orifices.

When measuring flow from a straight-stream fire nozzle, the use of the Pitot tube method only holds with reasonable accuracy for tip sizes up to 1⅜ in. (35 mm) supplied from 2½-in. (64-mm) hose. Above that, the error rate increases beyond acceptable limits, as the assumptions of uniform velocity and full flow become less valid. An exception is the Underwriters playpipe that maintains a uniform coefficient over a wide range of flows and pressures for tip sizes of 1⅛ or 1¾ in. (29 or 45 mm).

The Pitot tube method is also commonly used to measure the flow discharging from the outlets of fire hydrants to determine the water supply available for fire protection. Unlike the flow entering a nozzle on the end of a pipe or hose line, the flow through large hydrant outlets, or through smaller hydrant outlets at high velocities, has neither a uniform velocity profile nor full flow, since the additional turbulence generated by the flow passing through the hydrant has not dissipated.

In cases such as these, the flow conditions must be changed so that the assumptions needed for the Pitot tube method are valid, or an alternative method, such as the one described next under "Nozzle Method of Measuring Flow," should be used. If

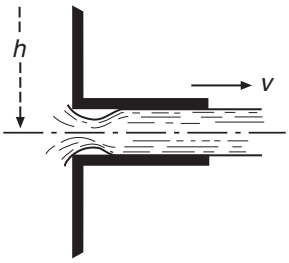


FIGURE 15.3.7 Flow in Cylindrical Short Tube

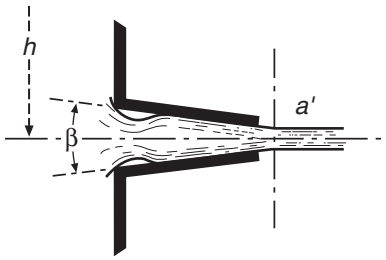


FIGURE 15.3.8 Flow in Short Conical Converging Tube

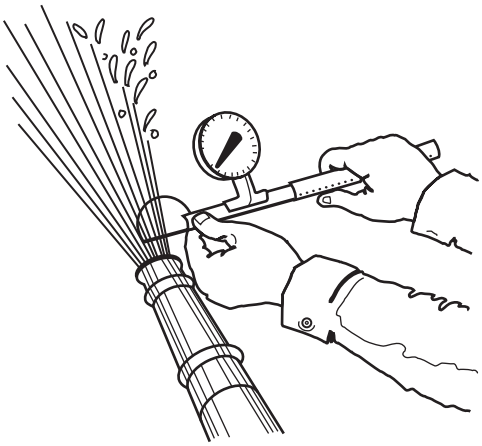


FIGURE 15.3.9 Taking Nozzle Pressure with a Pitot Tube

flow is from an open hydrant outlet, hoses and nozzles, a reducer, or a short tube can often be connected to the outlet to improve the flow characteristics.

Nozzle Method of Measuring Flow

The rate of discharge can also be calculated from the gauge pressure at the base of the nozzle. The flow formula for using base pressure is

$$Q = \frac{29.84cd^2\sqrt{p_1}}{\sqrt{1 - c^2\left(\frac{d}{D}\right)^4}}$$

where

Q = Flow in gallons per minute

c = Coefficient of discharge

d = Diameter of outlet (in.)

p_1 = Gauge pressure at base of nozzle (psi)

D = Inside diameter of fitting to which gauge is attached (in.)

For SI units, the formula is expressed as

$$Q = \frac{0.0666cd_m^2\sqrt{p_{1m}}}{\sqrt{1 - c^2\left(\frac{d_m}{D_m}\right)^4}}$$

where

Q_m = Flow (L/min)

c = Coefficient of discharge

d_m = Diameter of outlet (mm)

p_{1_m} = Gauge pressure at base of nozzle (kPa)

D_m = Inside diameter of fitting to which gauge is attached (mm)

This is the same formula that is used for discharge from an orifice, except that (1) gauge pressure at the base of the nozzle is substituted for Pitot pressure, and (2) a factor is added that represents the ratio between gauge pressure (normal) and total pressure at the nozzle base. (Total pressure is gauge plus velocity pressure.)

When base pressure is to be used, the gauge is attached to a fitting close to the nozzle with a straight piece of approach pipe or hose to eliminate turbulence or unstable flow conditions. To obtain greater accuracy than provided by a simple fitting, a piezometer fitting may be used. With this device, the gauge is connected to an annular tube or channel having a number of small holes drilled into the waterway around the circumference. The mean or resultant static pressure indicated by the gauge is p_1 in the formula above.

Although accurate and convenient for fixed test arrangements, the measurement of pressure at the base of a nozzle is not practical for usual hose stream operations. However, because a Pitot gauge is useless with spray-type nozzles, or other devices producing special types of discharge, the base pressure method is necessary.

Discharge Calculations

The most common method of estimating nozzle or orifice discharge is to use Table 15.3.1. The flow from the table, corresponding to the measured Pitot pressure and orifice diameter, is multiplied by the discharge coefficient (see Table 15.3.2).

EXAMPLE 1: A Pitot reading of 20 psi was measured on an open 2½-in. smooth and well-rounded hydrant butt. From Table 15.3.2, the discharge coefficient is 0.90. From Table 15.3.1, theoretical flow for a 20-psi velocity head is 834 gpm. The discharge is $Q = 834 \times 0.90 = 751$ gpm. (Or subtract 10 percent from 834 and get 751 gpm.)

EXAMPLE 2: A Pitot reading was 200 kPa at a 38.1-mm pipe with a square sharp opening (discharge coefficient = 0.80). From Table 15.3.1, 200 kPa gives a theoretical flow of 1370 L/min. The actual flow would be $0.8 \times 1370 = 1100$ L/min

Discharge curves, such as those shown in Figure 15.3.10, are available for many nozzles and are sufficiently accurate for most fire flow calculations. These usually incorporate the specific discharge coefficients for the nozzle involved, but occasionally plot theoretical flow. Nozzle discharge can also be determined by the standard formulas previously discussed. (See "Flow of Water Through Orifices" and "Nozzle Method of Measuring Flow" in this chapter).

EXAMPLE 3: Calculate the rate of discharge from a 2 in. (51 mm) nozzle with a pressure measured by a 2½ in. (64 mm)

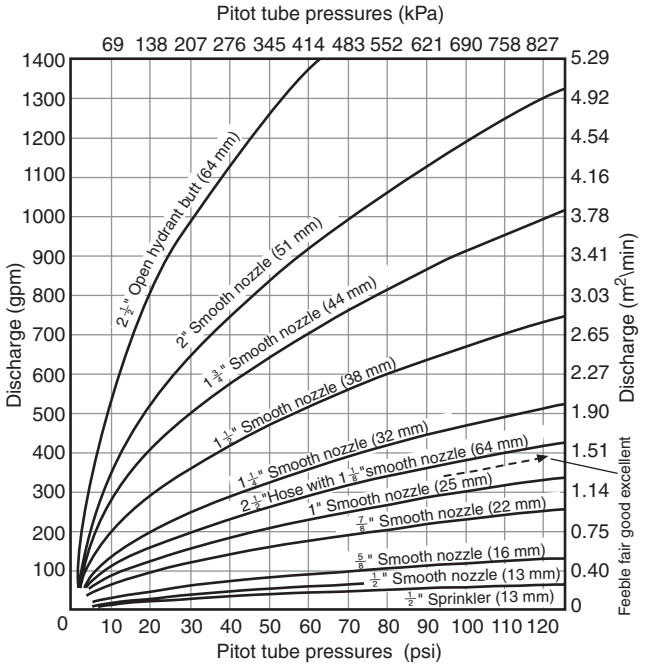


FIGURE 15.3.10 Relative Discharge Curves

piezometer ring and gauge of 80 psi (552 kPa) at the base of the nozzle. The nozzle has a coefficient of discharge of 0.99.

Using the formula for the nozzle method of measuring flow,

$$Q = \frac{29.84cd^2\sqrt{p_1}}{\sqrt{1 - c^2\left(\frac{d}{D}\right)^4}}$$

$$Q = \frac{29.84 \times 0.99 \times (2)^2\sqrt{80}}{\sqrt{1 - (0.99)^2\left(\frac{2}{2.5}\right)^4}}$$

$$Q = 1366 \text{ gpm } (5171 \text{ L/min})$$

To simplify calculations for a specific orifice or nozzle, the constants in the flow formula can be combined, reducing the formula to

$$Q = K\sqrt{p}$$

where K combines the constants 29.84 (0.0666 in SI units), c_d, and d^2. Table 15.3.3 lists K-factors of some common discharge orifices used for fire protection. For SI units, use the K_m values.

Because

$$K = \frac{Q}{\sqrt{p}}$$

the K values of spray nozzles can be calculated from data in testing laboratory listings of nozzles. For some nozzles, the flow rate at 25 and 125 psi (170 and 162 kPa) pressure is given, from which the K-factor can be calculated.

EXAMPLE 4: A certain fire service spray nozzle is rated for 83 gpm at 50 psi. What is the discharge at a pressure of 25 psi? Since we know the flow at a known pressure, we can calculate the K-factor. The K-factor is

$$K = \frac{83}{\sqrt{50}} = \frac{83}{7.07} = 11.7$$

At 25 psi pressure, the discharge would be

$$11.7\sqrt{25} = 11.7 \times 5 = 58.5 \text{ gpm}$$

Because the K-factor is constant, we can also calculate the new flow directly. Since $Q = K\sqrt{p}$, it follows that $K = \frac{Q}{\sqrt{p}}$ and that $\frac{Q_1}{\sqrt{p_1}} = \frac{Q_2}{\sqrt{p_2}}$.

Therefore, $\frac{83}{\sqrt{50}} = \frac{Q_2}{\sqrt{25}}$ and $Q_2 = \frac{83 \times \sqrt{25}}{\sqrt{50}} = 58.5$.

EXAMPLE 5: Determine the discharge from a 51 mm hydrant butt ($c_d = 90$) at a pressure of 350 kPa.

$$K_m = 0.0666cd_m^2 = 0.0666 \times 0.90 \times 51^2 = 156$$

Thus,

$$Q_m = K_m\sqrt{p_m} = 156\sqrt{350} = 2918 \text{ L/min}$$

Alternatively, from Table 15.3.3, $K_m = 154.7$. Thus,

$$Q_m = K_m\sqrt{p_m} = 154.7\sqrt{350} = 2894 \text{ L/min}$$

TABLE 15.3.3 Values of K for Various Discharge Orifices

Type of Orifice	Nominal Diameter *(in.)*	Nominal Diameter *(mm)*	K-Factor *gpm/p$^{1/2}$*	K-Factor *lpm and P$_m^2$*
Sprinkler	1/4	7	1.3–1.5	1.9–2.2
Sprinkler	5/16	8	1.8–2.0	2.6–2.9
Sprinkler	3/8	10	2.6–2.9	3.7–4.2
Sprinkler	7/16	11	4.0–4.4	5.8–6.3
Sprinkler	1/2	13	5.3–5.8	7.6–8.4
Sprinkler	17/32	14	7.4–8.2	10.6–11.8
Sprinkler	5/8	16	11.0–11.5	15.9–16.6
Sprinkler	3/4	19	13.5–14.5	19.5–20.1
Sprinkler	25/32	19.8	16.0–17.6	23.1–25.4
Sprinkler	15/16	23.6	23.9–26.5	38.9–43.0
Nozzle	1/2	13	7.2	10.3
Nozzle	7/8	22	22.2	32.0
Nozzle	1	25	29.1	41.9
Nozzle	1 1/16	27	32.8	47.2
Nozzle	1 1/8	29	36.8	53.0
Nozzle	1 3/16	30	41.0	59.0
Nozzle	1 1/4	32	45.4	65.4
Nozzle	1 5/16	33	50.1	72.1
Nozzle	1 3/8	35	54.9	79.1
Nozzle (c = 0.97 for all nozzles)	1 7/16	37	60.0	86.4
Nozzle	1 1/2	38	65.4	94.2
Nozzle	1 9/16	40	70.9	102.0
Nozzle	1 5/8	41	76.8	110.6
Nozzle	1 11/16	43	82.8	119.2
Nozzle	1 3/4	44	89.0	128.2
Nozzle	1 13/16	46	95.5	137.5
Nozzle	1 7/8	48	102.0	146.9
Nozzle	1 15/16	49	109.0	157.0
Nozzle	2	51	116.0	167.0
Hydrant butt (c = 0.90)	2	51	107.4	154.7
Hydrant butt (c = 0.90)	2 1/4	57	135.9	195.7
Hydrant butt (c = 0.90)	2 1/2	64	167.8	241.6

Note that in this example the answers from the two methods are close but do not exactly match. Care needs to be taken that the results do not imply a higher degree of accuracy than actually exists. Given the nature of the flow from a hydrant butt, assuming a flow of about 2900 L/min would be appropriate in this case.

Flow Meters

When it is not convenient to discharge water to the atmosphere, meters are used to determine flow.

Venturi Tube. The Venturi principle has a number of applications in fire protection. The Venturi tube is essentially a tapered

constriction in a pipe. In the constricted part, the velocity must be greater than in the straight tube, and the pressure is correspondingly less, in accordance with Bernoulli's theorem. If the increase in velocity through the restricted portion is sufficient, the pressure at that point will be less than atmospheric, and a suction will be created at any opening into the side of the tube. The Venturi tube is illustrated in Figure 15.3.11. The diverging portion of a Venturi tube serves only to restore the system pressure with a minimum of friction loss.

Venturi Meter. The Venturi principle as applied in the Venturi meter for the measurement of flow in closed pipelines under pressure is as follows.

With no elevation difference along the line of flow, Bernoulli's theorem becomes

$$\frac{\upsilon_1^2}{2g} + \frac{p_1}{w} + 0 = \frac{\upsilon_2^2}{2g} + \frac{p_2}{w} + 0$$

In Figure 15.3.11,

$$\frac{p_1}{w}$$

is represented by h_1, and

$$\frac{p_2}{w}$$

by h_2, which are used in the following equations.

The quantity of liquid passing through all portions of the Venturi meter must be the same. Therefore,

$$Q = a_1\upsilon_1 = a_2\upsilon_2 \text{ or } \upsilon_1 = \frac{Q}{a_1} \text{ or } \upsilon_2 = \frac{Q}{a_2}$$

Substituting in Bernoulli's theorem,

$$\frac{\left(\frac{Q}{a_1}\right)^2}{2g} + h_1 = \frac{\left(\frac{Q}{a_2}\right)^2}{2g} + h_2$$

$$\frac{\left(\frac{Q}{a_2}\right)^2}{2g} - \frac{\left(\frac{Q}{a_1}\right)^2}{2g} = h_1 - h_2$$

$$Q^2\left(\frac{1}{a_2^2} - \frac{1}{a_1^2}\right) = 2g(h_1 - h_2)$$

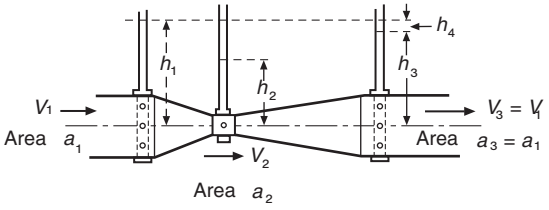


FIGURE 15.3.11 The Venturi Tube

$$Q^2\left(\frac{a_1^2 - a_2^2}{a_1^2 a_2^2}\right) = 2g(h_1 - h_2)$$

$$Q = \frac{a_1 a_2}{\sqrt{a_1^2 - a_2^2}}\sqrt{2g(h_1 - h_2)}$$

For any specific Venturi meter, a_1 and a_2 are known constant values. There is also a friction loss coefficient, which is usually determined by test and which does not remain constant with very low velocities. Combining the known constant values, the Venturi meter formula is generally expressed as

$$Q = \mathrm{K}\sqrt{(h_1 - h_2)}, \text{ or } Q = \mathrm{K}\sqrt{\frac{p_1}{w} - \frac{p_2}{w}}$$

By test, a value of k for any specific meter can be established with reasonable accuracy, thus allowing the measurement of flow to be calculated from the pressure differential across the meter.

When used as a device for inducing gas or liquid into the stream, as is made possible by the reduced pressure, in the throat section, the hydraulic performance will not be in strict accordance with the above theoretical calculations because energy is expended on the induced substance.

Orifice Meters. When water flows through a thin sharp-edged orifice (such as the standard orifice discussed earlier) within a pipe, the flow diameter contracts the same way it does when the flow discharges to atmosphere and then increases back to the full pipeline diameter. The pressure at the pipe wall is reduced due to this change in flow and is related to the flow rate (Figure 15.3.12).

Bernoulli's equation can be applied to an orifice meter in the same way as it is applied to the Venturi meter. The resultant K-factor or discharge coefficient depends on several factors, including the ratio of orifice/pipe diameter and the location of the pressure taps upstream and downstream of the orifice.

ASME Flow Nozzle. Flow can also be measured by an ASME flow nozzle, as shown in Figure 15.3.13. The pressure taps for this device are normally one pipe diameter upstream of the nozzle and one-half pipe diameter downstream from the nozzle inlet. Combining known constant values, the Venturi meter formula is generally expressed as

$$Q = \mathrm{K}\sqrt{(h_1 - h_2)}, \text{ or } Q = \mathrm{K}\sqrt{\frac{p_1}{w} - \frac{p_2}{w}}$$

FLOW OF WATER IN PIPES

The theory of liquid flow in pipes involves the same continuity principles used in the previous discussions. These include continuity of energy (Bernoulli's theorem with friction) and continuity of flow.

When water flows through a pipe, there is always a drop in pressure. Theoretically, the lost head between two points is caused by (1) friction between the moving water and the pipe wall and (2) friction between water particles, including that produced by turbulence when flow changes direction or when

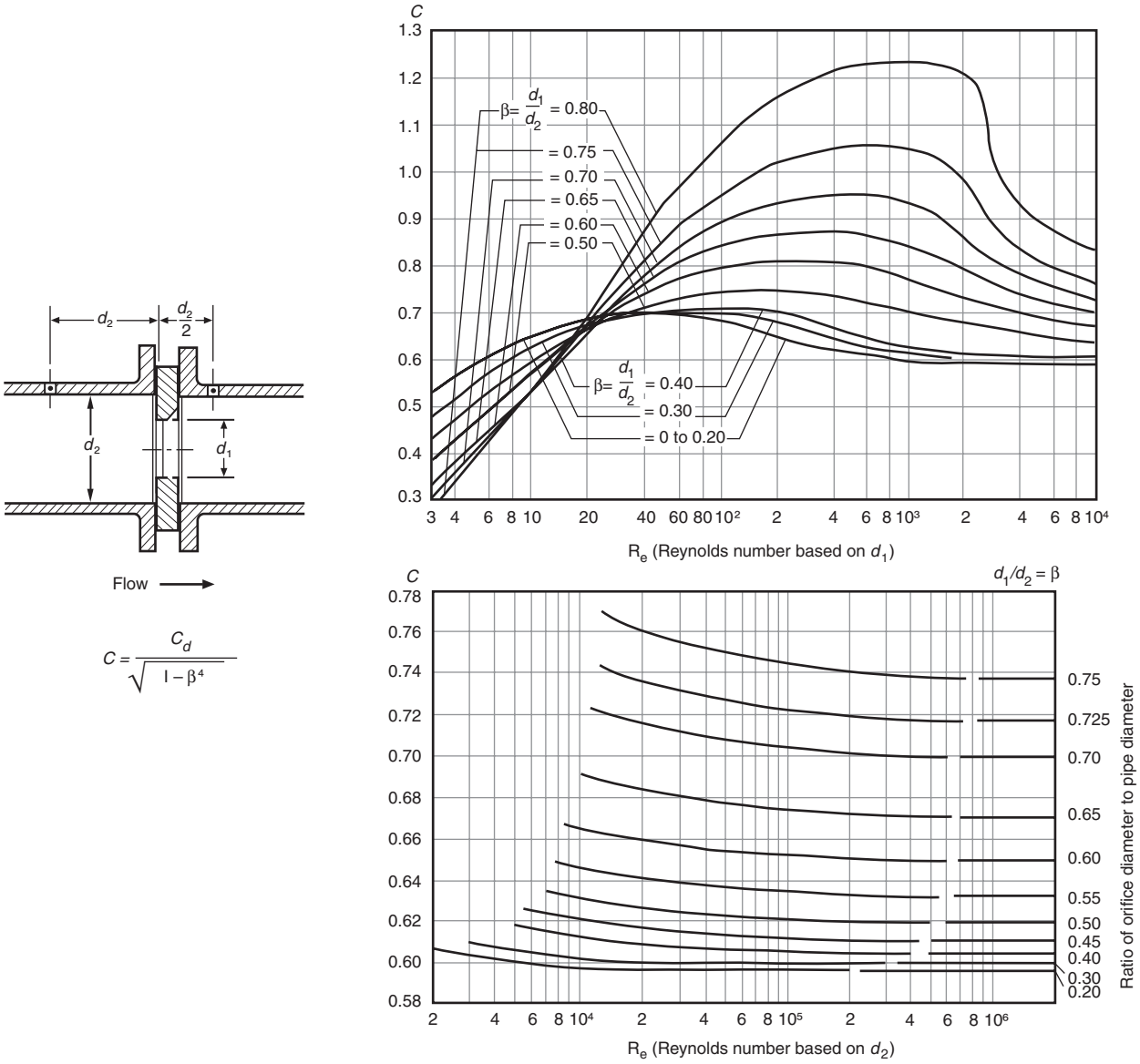


FIGURE 15.3.12 Flow Coefficient *C* for Square-Edged Orifice Meters

a rapid increase or decrease in velocity takes place, such as at abrupt changes in pipe diameter. A change in velocity results in some conversion of velocity head to pressure head, or vice versa.

At low velocity in a smooth pipe, very little turbulence is produced, and the flow is called "laminar" or "streamline" flow. With this condition, all particles of water move along the pipe in definite paths, which are essentially straight lines in concentric layers. Friction loss occurs due to shear stress, mainly in a thin boundary layer at the pipe wall, and also between adjacent stream layers. The friction loss is small compared to that of turbulent flow.

The flow within either a smooth or a rough pipe remains laminar until the velocity reaches what is called critical velocity. At this point, there is a range of unstable flow that is neither laminar nor completely turbulent, which is called the transition zone.

As the flow continues to increase, it becomes turbulent. In turbulent flow the fluid moves in an eddying mass, and, at any point, the individual water particles move rapidly in a random manner rather than in a straight line.

Reynolds demonstrated that for any fluid the critical point at which the flow changes from laminar to turbulent could be predicted. In circular pipes, the critical point occurs when the dimensionless parameter $d\nu\rho/\mu$ (called the Reynolds number) is approximately 2000. The transition to complete turbulence is complete for Reynolds numbers exceeding 4000.

Most fire protection systems and water distribution mains function under turbulent flow conditions, and friction losses within the pipe itself account for most of the lost head. Other

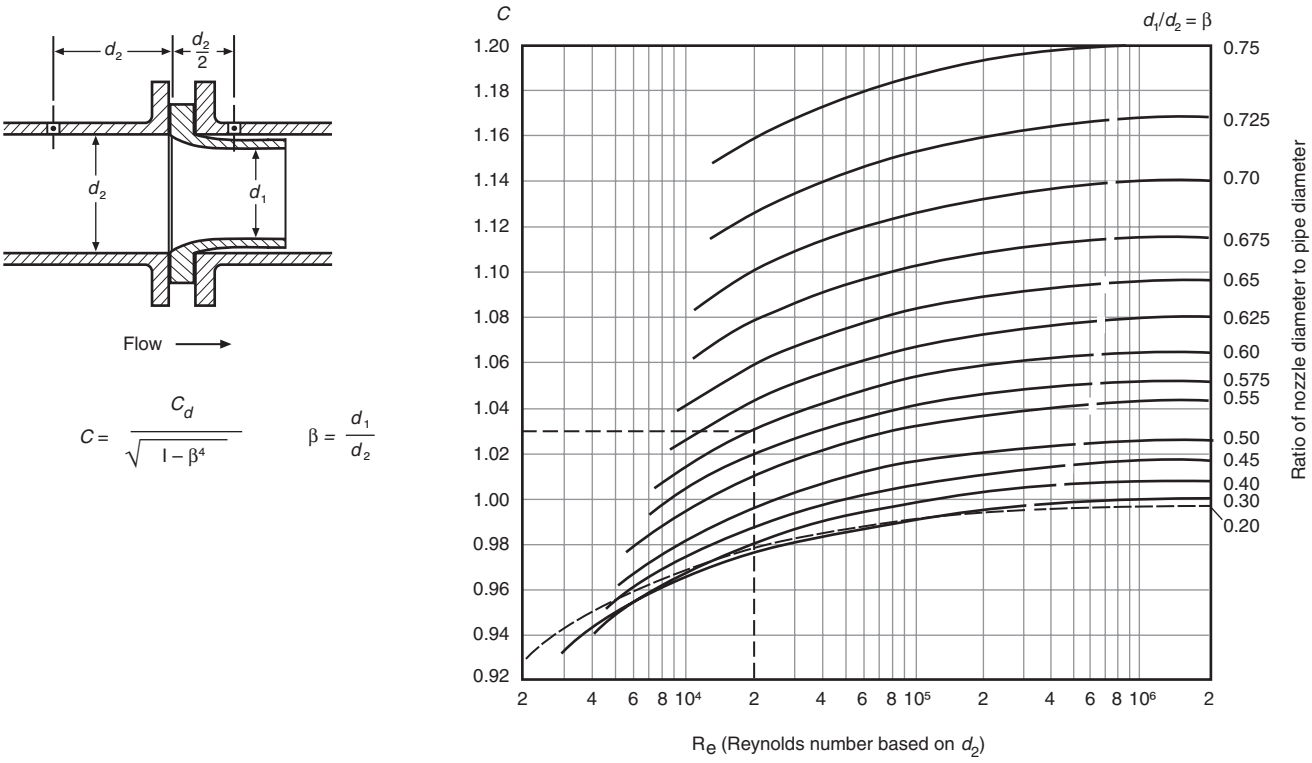


FIGURE 15.3.13 Flow Coefficient *C* for ASME Flow Nozzles

losses are usually considered together and are called "minor losses" or "losses in fittings."

Friction (Head) Loss Flow Formulas

Experimental data have established that frictional resistance in a pipe shall be as follows:

1. Independent of pressure in the pipe
2. Proportional to the amount and character of the flow
3. Variable with the velocity of the flow (nearly proportional to the second power of the velocity for velocities above the critical; if velocity is below critical, resistance varies with the first power)

The Chezy Formula. One of the best-known and oldest expressions relating velocity to friction loss in piping is known as the Chezy formula:

$$v = c\sqrt{rs}$$

where

c = A factor that is dependent on the kind and roughness of the pipe

r (the hydraulic radius) = Area/circumference = $d/4$ where d = diameter of the pipe in ft (m)

s = The hydraulic slope = h/l = slope of hydraulic gradient in which h is the head loss in length of pipe l in ft (m). (See Section 15, Chapter 1, "Fixed Water Storage Supplies for Fire Protection," for a discussion of hydraulic gradients.)

Therefore,

$$v = c\sqrt{d/4 \times h/l} \text{ or } h = \frac{4lv^2}{c^2 d}$$

The Darcy-Weisbach Formula. Another classic formula for friction loss, applicable to long, straight pipes of uniform diameter and roughness, is ascribed to Darcy, Manning, Fanning, and others. In modern textbooks, the formula is derived by analysis of forces acting on a flowing particle of water in a pipe. Often called the Darcy-Weisbach formula, it is a variation of Chezy's formula, with a friction factor f replacing c, and expressed as follows:

$$h = f\frac{l}{d}\frac{v^2}{2g}$$

where

h = Friction head

f = Friction factor

l = Length of pipe

d = Diameter of pipe

v = Velocity

g = Acceleration of gravity

The Darcy-Weisbach formula is suitable for all Newtonian fluids. (A Newtonian fluid is one where the viscosity is constant at a specific temperature, regardless of pressure and the rate of

shear.) The friction factor f is dimensionless and variable and depends on the pipe roughness and the Reynolds number.

The value of f can be computed by the Colebrook-White equation, which is neither a completely empirical nor rigidly theoretical formula. This equation is usually written as

$$\frac{1}{\sqrt{f}} = -2 \log_{10}\left[\frac{\varepsilon}{3.7D} + \frac{2.51}{R\sqrt{f}}\right]$$

where

ε = Linear measure of roughness

f = Darcy-Weisbach friction factor

D = Pipe diameter (ft)

R = Reynolds number

(For SI units: 1 ft = 0.305 m.)

Computing f by the formula can be avoided by using tables and charts known as "Moody" diagrams.

Figure 15.3.14 is a Moody diagram (© Hydraulic Institute, 1954) from which f can be read directly off the chart. Values for friction factor are on the vertical scale, at left. The dimensionless parameter, ε/D is sometimes difficult to obtain, and it may be necessary to assume a value for ε/D based on experience and judgment. The roughness factor of new pipe usually can be provided by the manufacturer.

The Hazen-Williams Formula. The friction-flow formulas commonly used in fire protection hydraulics have been developed by experiment and experience. These formulas (which are variations of the Chezy formula) are usually exponential in the form $v = Cr^x s^y$, where v is velocity, c the coefficient of friction, r the hydraulic radius (area divided by circumference), and s the hydraulic slope (loss of head divided by length). The most popular exponential formula is the Hazen-Williams, its basic form being $v = 1.31Cr^{0.63}s^{0.54}$. The friction coefficients in formulas of this type are constant for a specific roughness of pipe and are independent of velocity, and thus the accuracy of these formulas is variable. However, the fixed values generally assumed for viscosity and density are considered adequate for most fire protection hydraulic work.

The basic form of the Hazen-Williams formula ($v = 1.31cr^{0.63}s^{0.54}$ is not practical for ordinary fire protection flow calculations. The form normally used is expressed in terms of pressure loss in psi rather than velocity, in terms of actual diameter rather than the hydraulic radius, and in terms of flow in gpm.

Because the hydraulic radius is the area divided by the circumference, it can be expressed as

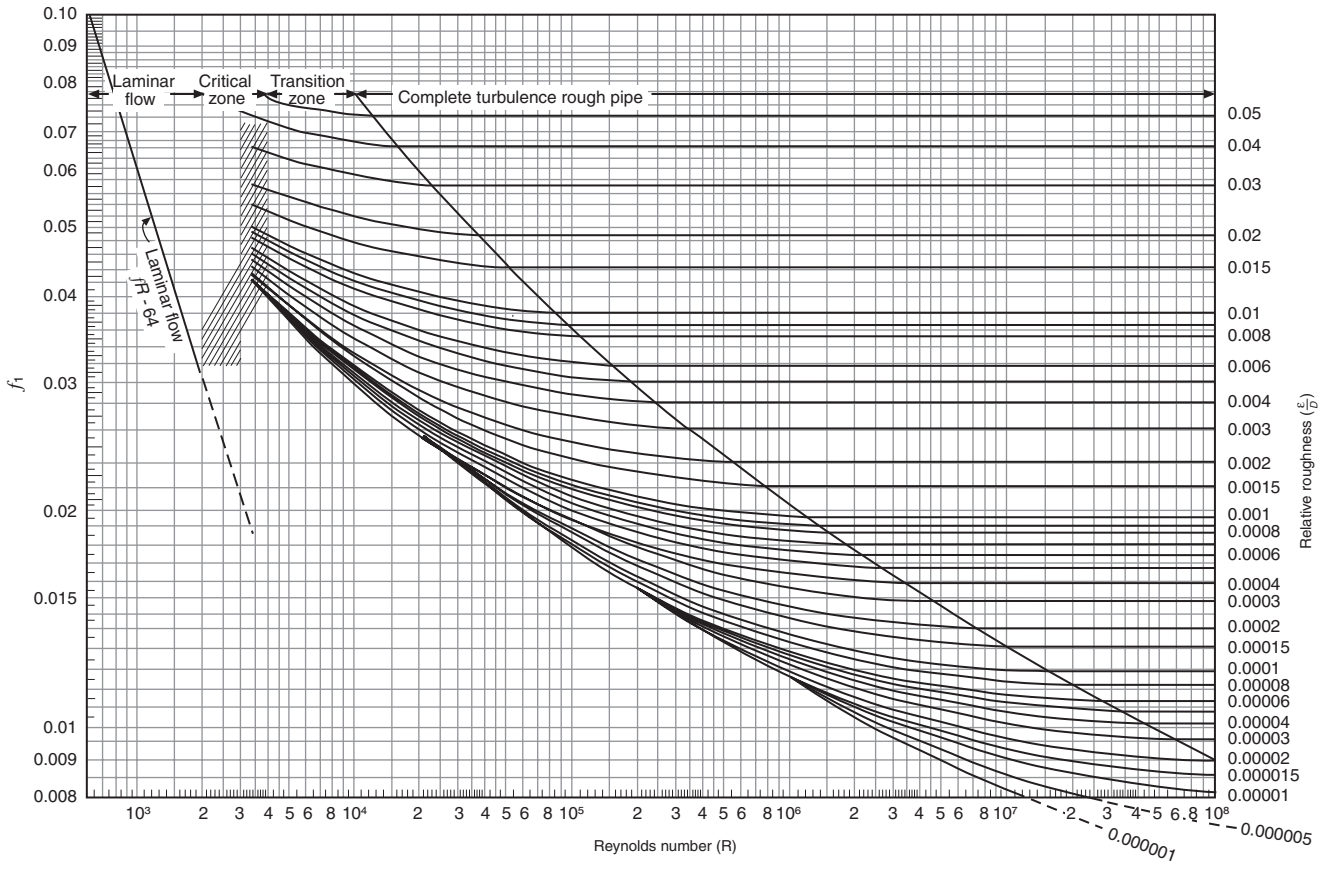


FIGURE 15.3.14 Moody Diagram for Friction in Pipe

$$r = \frac{\text{Area}}{\text{Circumference}} = \frac{\pi d^2/4}{\pi d} = \frac{d}{4}$$

where the diameter is in terms of feet or

$$r = \frac{d}{4} \times \frac{1 \text{ ft}}{12 \text{ in.}} = \frac{d}{48}$$

where the diameter is expressed in inches.

The hydraulic slope (s) is simply the pressure loss divided by the length. The Hazen-Williams formula is usually used to determine the pressure loss per ft of pipe, so the length is 1 and can be replaced by the pressure loss (p), again in ft.

Because we want to use flow rather than velocity, we know from the discussion on velocity pressure that

$$v = \frac{Q}{a} = \frac{0.4085Q}{d^2}$$

where Q is expressed in gallons per minute and d is expressed in inches. Substituting,

$$\frac{0.4085Q}{d^2} = 1.31C\left(\frac{d}{48}\right)^{0.63}(2.31p)^{.54}$$

Solving for p we get

$$(2.31p)^{.54} = \frac{0.4085Q/d^2}{1.31C(d/48)^{0.63}} = \frac{0.3118Q}{Cd^2(d/48)^{0.63}}$$

$$2.31p = \frac{0.3118^{1/0.54}Q^{1/0.54}}{C^{1/0.54}d^{2/0.54}(d/48)^{0.63/0.54}}$$

$$= \frac{0.3118^{1.85}Q^{1.85}}{C^{1.85}d^{3.7}(d/48)^{1.17}} = \frac{0.11579Q^{1.85}}{C^{1.85}d^{4.87}48)^{1.17}}$$

$$p = \frac{4.64Q^{1.85}}{C^{1.85}d^{4.87}} \cong \frac{4.52Q^{1.85}}{C^{1.85}d^{4.87}}$$

which is the formula normally used for fire protection purposes. The derived constant 4.64 is slightly different than the normally accepted constant of 4.52 due to rounding errors in the derivation and the constants in the original formula. The remainder of this discussion will use the generally accepted formula with a constant of 4.52.

In SI units the formula is

$$p_m = 6.06 \times \frac{Q_m^{1.85}}{C^{1.85}d_m^{4.87}} \times 10^2$$

where

p_m = Pressure loss (kPa) per m of pipe

Q_m = Rate of flow (L/min)

d_m = Inside diameter (mm)

Friction Loss Calculations. The solutions of many fire protection problems involving pipe flow and friction do not require direct calculation using formulas, since tables and charts are readily available. However, in using the simplifying charts and tables, great care must be taken to identify the C value (coefficient of friction) on which the chart or table is based. Where the type or condition of a pipe necessitates the use of a different C value, the friction loss from the table must be multiplied by a conversion factor to obtain the correct results for the desired C value.

By way of illustration, Table 15.3.4 gives values of p when C = 100 for standard pipe sizes from ½ in. to 30 in. in diameter. For values of C other than 100, the tabular value losses are multiplied by the corresponding factor in Table 15.3.5. Where a different type of pipe is used, the friction loss from the table can be corrected using the formula

$$\Delta p_a = \Delta p_{40}\left(\frac{d_{40}}{d_a}\right)^{4.87}$$

where

Δp_a = Actual friction loss

Δp_{40} = Friction loss in Schedule 40 pipe

d_{40} = Internal diameter of Schedule 40 pipe

d_a = Internal diameter of actual pipe

EXAMPLE: Determine the friction loss with 700 gpm, flowing in 700 ft of 8-in. cast-iron pipe having a C value of 80.

SOLUTION: From Table 15.3.4, the loss for 700 gpm per 100 ft of 8 in. pipe with C = 100 is 0.662 psi. From Table 15.3.5, the conversion factor for C = 80 is 1.51. Because friction loss is directly proportional to the length of pipe, multiply 0.662 × 7 × 1.51 = 6.95 psi (answer). Since other than Schedule 40 steel pipe is used, this value must be adjusted using the previously discussed formula:

$$\Delta p_a = \Delta p_{40}\left(\frac{d_{40}}{d_a}\right)^{4.87}$$

$$= 6.95\left(\frac{8.071}{8.23}\right)^{4.87}$$

$$= 6.32 \text{ psi}$$

The Hazen-Williams Diagram. Figure 15.3.15 is a graphical representation of Table 15.3.4, except that it is based on a Hazen-Williams coefficient of C = 120 rather than C = 100, as used in the table. For other C values use: Value of C: 80 100 120 130 140 150; multiplying factor: 2.12 1.40 1.00 0.86 0.75 0.66. It is limited in scope to pipes not over 10 in. in diameter, and due to the reduced scale is less accurate than the table.

Figure 15.3.16 gives data in SI units for pipes up to 10 in. (254 mm) in diameter, again based on C = 120. For other C values use: Value of C: 80 100 120 130 140 150; multiplying factor: 2.12 1.40 1.00 0.86 0.75 0.66.

EXAMPLE 1: What is the friction loss in 300 ft (90 m) of 8-in. cement-lined cast-iron pipe, flowing 1500 gpm (5678 L/min)?

SOLUTION: From the intersection of the 1500 gpm vertical line with the sloping 8 in. pipe diameter line in Figure 15.3.15, read

TABLE 15.3.4 Friction Loss[a] in Pipe

Flow	Pipe Size[b]										Flow
Gpm	*½*	*¾*	*1*	*1¼*	*1½*	*2*	*2½*	*3*	*3½*	*4*	*Gpm*
5	17.9	4.55	1.40	0.369	0.174	0.052	—	—	—	—	5
10	64.5	16.4	5.06	1.33	0.629	0.186	0.078	0.030	—	—	10
15	***5***	34.7	10.7	2.82	1.33	0.394	0.166	0.064	0.028	—	15
20	—	59.1	18.2	4.89	2.27	0.671	0.282	0.109	0.048	0.027	20
30	0.019	***6***	38.6	10.2	4.80	1.42	0.598	0.231	0.102	0.057	30
40	0.033	—	65.8	17.3	8.17	2.42	1.02	0.393	0.174	0.097	40
50	0.050	.020	***8***	26.2	12.3	3.66	1.54	0.593	0.263	0.147	50
60	0.069	.029	—	36.6	17.3	5.12	2.16	0.831	0.369	0.206	60
70	0.092	.038	—	48.7	23.0	6.81	2.87	1.11	0.490	0.274	70
80	0.118	.049	—	62.4	29.4	8.72	3.67	1.41	0.628	0.350	80
90	0.147	.060	—	77.6	36.6	10.8	4.56	1.76	0.781	0.435	90
100	0.178	.074	—	***10***	44.5	13.1	5.55	2.14	0.949	0.529	100
120	0.250	.103	—	—	62.3	18.5	7.77	3.00	1.33	0.741	120
140	0.333	.137	0.034	—	82.9	24.6	10.3	3.98	1.77	0.986	140
160	0.426	.175	0.043	—	106.0	31.4	13.2	5.10	2.26	1.26	160
180	0.529	.218	0.054	0.018	***12***	39.1	16.5	6.34	2.81	1.57	180
200	0.643	.265	0.065	0.022	—	47.5	20.0	7.71	3.42	1.91	200
220	0.768	.316	0.078	0.026	—	56.7	23.9	9.19	4.08	2.28	220
240	0.902	.371	0.091	0.031	0.013	***14***	28.0	10.8	4.79	2.67	240
260	1.05	.430	0.106	0.036	0.015	—	32.5	12.5	5.56	3.10	260
280	1.20	.493	0.122	0.041	0.017	—	37.3	14.4	6.37	3.55	280
300	1.36	.562	0.138	0.047	0.019	—	42.3	16.3	7.24	4.04	300
350	1.81	.746	0.184	0.062	0.026	0.012	***16***	21.7	9.63	5.37	350
400	2.32	.955	0.235	0.079	0.033	0.015	—	27.8	12.3	6.88	400
450	2.88	1.19	0.292	0.099	0.041	0.019	—	34.6	15.3	8.55	450
500	3.51	1.44	0.353	0.120	0.049	0.023	0.012	42.0	18.6	10.4	500
550	4.18	1.72	0.424	0.143	0.059	0.028	0.015	50.1	22.2	12.4	550
600	4.91	2.02	0.498	0.168	0.069	0.033	0.017	58.8	26.1	14.6	600
650	5.70	2.34	0.577	0.195	0.080	0.038	0.020	68.2	30.3	16.9	650
700	6.53	2.69	0.662	0.223	0.092	0.043	0.023	***18***	34.7	19.4	700
750	7.42	3.05	0.752	0.254	0.104	0.049	0.026	—	39.4	22.0	750
800	8.36	3.44	0.848	0.286	0.118	0.056	0.029	—	44.5	24.8	800
850	9.35	3.85	0.948	0.320	0.132	0.062	0.032	—	49.7	27.7	850
900	10.4	4.28	1.05	0.356	0.146	0.069	0.036	—	***20***	30.8	900
950	11.5	4.73	1.17	0.393	0.162	0.076	0.040	—	—	34.1	950
1000	12.6	5.20	1.28	0.432	0.178	0.084	0.044	—	—	37.5	1000
1250	19.1	7.85	1.94	0.653	0.269	0.127	0.066	—	—	***24***	1250
1500	***30***	11.0	2.71 (18.7)	0.914	0.376	0.178	0.093	—	—	—	1500
1750	—	—	3.61	1.22	0.501	0.236	0.123	—	—	—	1750
2000	.007	—	4.62	1.56	0.641	0.303	0.158	0.089	0.053	0.022	2000
2250	.009	—	—	1.94	0.797	0.376	0.196	0.111	0.066	0.027	2250
2500	.011	—	—	2.35	0.969	0.457	0.239	0.134	0.081	0.033	2500
2750	.013	—	—	2.81	1.16	0.545	0.285	0.160	0.096	0.040	2750
3000	.016	—	—	3.30	1.36	0.641	0.334	0.188	0.113	0.046	3000
4000	.027	—	—	—	2.31	1.09	0.569	0.321	0.192	0.079	4000
5000	.040	—	—	—	3.49	1.65	0.860	0.485	0.290	0.119	5000

For SI units: 1 psi = 6.895 kPa; 1 gpm = 0.378 L/min; 1 in. = 25.4 mm.

Note: Actual inside diameter for sizes ½ in. through 3½ in. is given for greater accuracy as these sizes include sprinkler branch lines and the smaller sizes of cross mains. For sizes 4 in. and greater, the nominal diameters were used as a fairly safe average for the diameters of various types of underground pipes as follows: cast-iron unlined and Enameline, greater than nominal; cast iron cement lines and Class 200 asbestos cement, less than nominal; Class 150 asbestos-cement sizes 6 and 8 in. less than nominal, and other sizes even nominal. (A 0.10 variation is true for Class 150 cement lined only—see ASHD FT-9 through 45 for actual IDs.)

This table will be useful in approximating friction loss in flow through existing underground piping where the type, inside diameter, and condition are frequently unknown. However, in such cases, a flow test is recommended.

When the type, inside diameter, and condition are known, and in designing new systems for all sizes and types of pipes, the friction loss tables should be used. Friction tables based on Hazen-Williams formula are published in *Automatic Sprinkler Hydraulic Data* by "Automatic" Sprinkler Corporation of America, and tables based on the Darcy-Weisbach formula are published in *Standards of the Hydraulic Institute.*

[a]Friction loss in lb/in.^{2} per 100 ft of pipe and are based on a Hazen-Williams *C* of 100. To convert friction loss to other values of *C,* see Table 15.3.5.

[b]Calculations are based on the internal pipe diameter of Schedule 40 steel pipe for pipe sizes ½ to 3½ in. and the nominal pipe diameter for pipe sizes 4 to 30 in.

TABLE 15.3.5 Conversion Factors for Friction Loss in Pipe for Values of Coefficient Other Than 100

C	*Factor*	*C*	*Factor*	*C*	*Factor*
150	0.472	110	0.838	70	1.93
145	0.503	105	0.914	65	2.22
140	0.537	100	1.00	60	2.57
135	0.574	95	1.10	55	3.02
130	0.615	90	1.22	50	3.61
125	0.662	85	1.35	45	4.38
120	0.714	80	1.51	40	5.48
115	0.772	75	1.70	35	6.97

left horizontally for a loss of head value, which is found to be 0.019 psi per foot. For 300 ft, the loss would be 300 × 0.019 psi or 5.7 psi. The probable *C* value of cement-lined pipe is 140 (Table 15.3.6), and the conversion factor is 0.75 (Figure 15.3.15). Therefore, the friction loss is 5.7 × 0.75 = 4.3 psi. Since other than Schedule 40 steel pipe is used, this value must be adjusted using the previously discussed formula.

$$\Delta p_a = \Delta p_{40}\left(\frac{d_{40}}{d_a}\right)^{4.87}$$

$$= 4.3\left(\frac{8.071}{7.98}\right)^{4.87}$$

$$= 4.54 \text{ psi}$$

EXAMPLE 2: What is the friction loss in 400 m of 150 mm 30-year-old unlined cast-iron pipe (*C* = 80) for a flow of 10,000 L/min?

SOLUTION: From the intersection of the 10,000 L/min vertical line with the sloping 150 mm pipe diameter line in Figure 15.3.16, read left horizontally for a loss of head value, which is 480 kPa per 100 m. For 400 m, the loss would be 4 × 480 kPa or 1920 kPa, based on *C* = 120. For cast-iron pipe, *C* = 80 and the conversion factor is 2.12 (see Figure 15.3.16). Therefore, the friction loss is 1920 × 2.12 = 4070 kPa.

Equivalent Pipes. Problems involving piped water supplies and fire protection systems occasionally require substitution of one pipe for another. The term "equivalent pipe" usually means a pipe having the same friction loss as the pipe for which it is

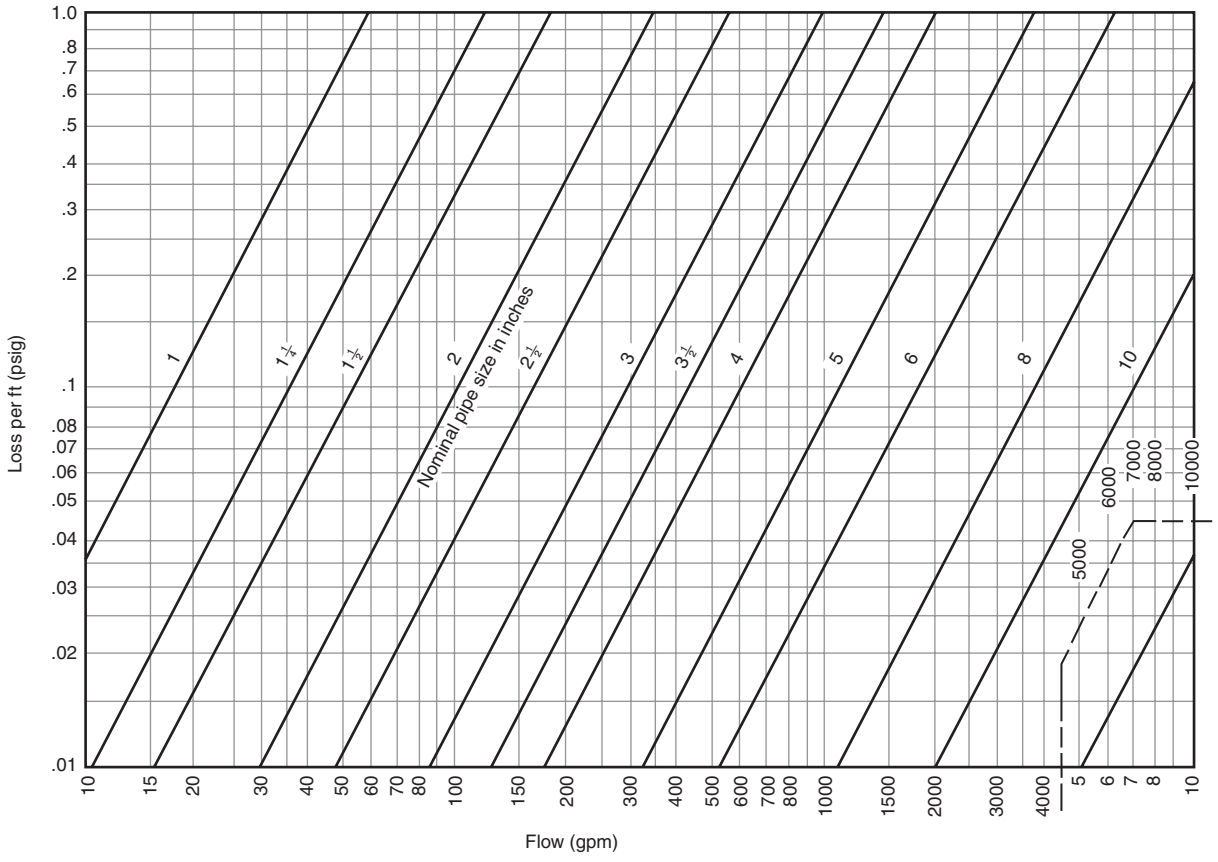


FIGURE 15.3.15 Friction Loss in Schedule 40 Steel Pipe, Hazen-Williams *C* = 120

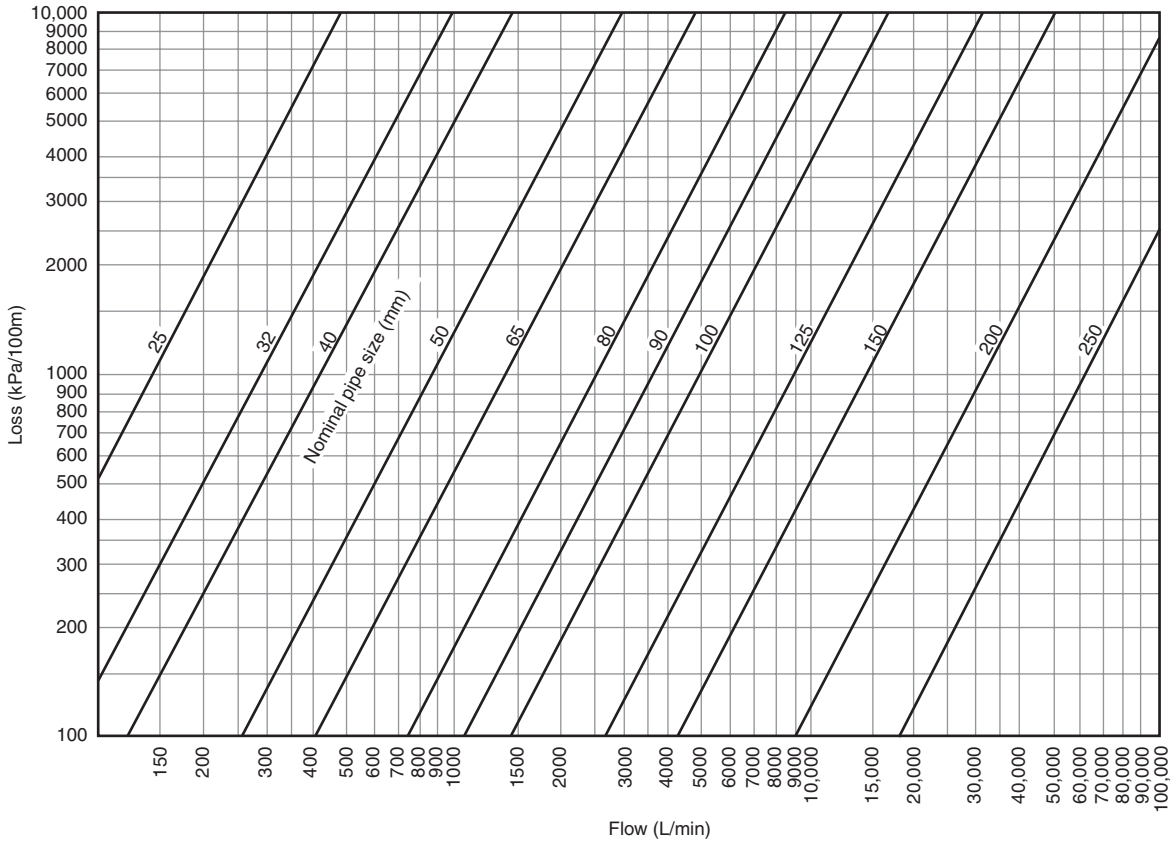


FIGURE 15.3.16 Friction Loss (SI units) in Schedule 40 Steel Pipe, Hazen-Williams $C = 120$

TABLE 15.3.6 Guide for Estimating Hazen-Williams *C*

Kind of Pipe	Value of *C* 1[a]	2[b]	3[c]
Cast iron, unlined			
10 years old	110	90	75
15 years old	100	75	65
20 years old	90	65	55
30 years old	80	55	45
50 years old	70	50	40
Cast iron, unlined, new		120	
Cast iron, cement-lined		140	
Cast iron, bitumastic enamel-lined		140	
Average steel, new		140	
Riveted steel, new		110	
Asbestos-cement		140	
Reinforced concrete		140	
Plastic		150	

Note: *C* values chosen for design of piping systems should be based on applicable NFPA standard or the authority having jurisdiction.
[a]Water mildly corrosive. Use same values for fire-protection mains having no mill-use or domestic draft.
[b]Water moderately corrosive.
[c]Water severly corrosive.

being substituted. The formula for using the friction loss table is applicable here.

EXAMPLE: What length of 8 in. pipe ($C = 110$) is equivalent to 700 ft of 6 in. pipe ($C = 85$)?

SOLUTION: $N_1 \times \frac{L_1}{100} \times T_1 = N_2 \times \frac{L_2}{100} \times T_2$

where

$N = C$ factor conversion for each pipe

$L =$ Length of each pipe

$T =$ Friction loss from Table 15.3.4

Assume a rate of flow (say, 1000 gpm) and substitute known values:

$$1.35 \times \frac{700}{100} \times 5.20 = 0.838 \times \frac{L_2}{100} \times 1.28$$

Solving for L_2,

$$\frac{1.35 \times 700 \times 5.20}{0.838 \times 1.28} = 4581 \text{ ft}$$

which can be rounded off to 4600 ft.

Minor Losses

Although the friction loss within the pipe normally accounts for most of the lost head, head losses also occur when the flow in a pipe changes direction, the pipe size changes, or a valve or other fitting is encountered. These losses are typically referred to as minor losses even though they can be significant for some fittings, such as swing check valves or backflow preventers, that are commonly found in fire protection systems.

The amount of minor losses from fittings can be found in many references and is often expressed in various forms. The most common are as an equivalent length (l/d), a resistance coefficient (k), or a flow coefficient (C_v).

Equivalent Length. For most fire protection calculations, friction loss is obtained by using the equivalent length method from a table such as Table 15.3.7, which expresses the friction loss of the fitting as an "equivalent pipe length" having the same friction loss as the fitting. This length is then added to the length of the pipe to which the fittings are connected to obtain the total friction loss of pipe and fittings.

EXAMPLE: Calculate total friction loss for 600 L/min flow through 200 m of nominal 2 in. (50 mm) pipe ($C = 120$) that incorporates three 90 degree elbows, one tee junction (90-degree turn), and two butterfly valves.

SOLUTION: Using Table 15.3.7 for equivalent lengths of fittings ($C = 120$),

Fittings or Pipe	*Number*	*Equivalent Length per Fittings (m)*	*Total Equivalent Length (m)*
Std. elbow	3	1.5	4.5
T-junction	1	3.1	3.1
Butterfly	2	1.8	3.6
Pipe	1	200.0	200.0
		Total equivalent pipe length =	211.2

From Figure 15.3.15, the total friction loss of 600 L/min flow in 50 mm (2 in. nominal) pipe is 500 kPa per 100 m of

TABLE 15.3.7 Equivalent Pipe Length Chart

	Fittings and Valves Expressed in Equivalent ft (m) of Pipe						
	¾ in. (20 mm)	*1 in. (25 mm)*	*1¼ in. (32 mm)*	*1½ in. (40 mm)*	*2 in. (50 mm)*	*2½ in. (50 mm)*	*3 in. (80 mm)*
45° Elbow	1 (0.3)	1 (0.3)	1 (0.3)	2 (0.6)	2 (0.6)	3 (0.9)	3 (0.9)
90° Standard elbow	2 (0.6)	2 (0.6)	3 (0.9)	4 (1.2)	5 (1.5)	6 (1.8)	7 (2.1)
90° Long-turn elbow	1 (0.3)	2 (0.6)	2 (0.6)	2 (0.6)	3 (0.9)	4 (1.2)	5 (1.5)
Tee or cross (flow turned 90°)	4 (1.2)	5 (1.5)	6 (1.8)	8 (2.4)	10 (3.1)	12 (3.7)	15 (4.6)
Gate valve	—	—	—	—	1 (0.3)	1 (0.3)	1 (0.3)
Butterfly valve	—	—	—	—	6 (1.8)	7 (2.1)	10 (3.1)
Swing check*	4 (1.2)	5 (1.5)	7 (2.1)	9 (2.7)	11 (3.4)	14 (4.3)	16 (4.9)

	Fittings and Valves Expressed in Equivalent ft (m) of Pipe						
	3½ in. (90 mm)	*4 in. (100 mm)*	*5 in. (125 mm)*	*6 in. (150 mm)*	*8 in. (200 mm)*	*10 in. (250 mm)*	*12 in. (300 mm)*
45° Elbow	3 (0.9)	4 (1.2)	5 (1.5)	7 (2.1)	9 (2.7)	11 (3.4)	13 (4.0)
90° Standard elbow	8 (2.4)	10 (3.1)	12 (3.7)	14 (4.3)	18 (5.5)	22 (6.7)	27 (8.2)
90° Long-turn elbow	5 (1.5)	6 (1.8)	8 (2.4)	9 (2.7)	13 (4.0)	16 (4.9)	18 (5.5)
Tee or cross (flow turned 90°)	17 (5.2)	20 (6.1)	25 (7.6)	30 (9.2)	35 (10.7)	50 (15.3)	60 (18.3)
Gate valve	1 (0.3)	2 (0.6)	2 (0.6)	3 (0.9)	4 (1.2)	5 (1.5)	6 (1.8)
Butterfly valve	—	12 (3.7)	9 (2.7)	10 (3.1)	12 (3.7)	19 (5.8)	21 (6.4)
Swing check*	19 (5.8)	22 (6.7)	27 (8.2)	32 (9.8)	45 (13.7)	55 (16.8)	65 (19.8)

Use with Hazen-Williams $C = 120$ only. For other values of C, the figures in this table should be multiplied by the factors below.

Value of C	80	100	120	130	140	150
Multiplying factor	0.472	0.713	1.00	1.16	1.32	1.51

(This is based on the friction loss through the fitting being independent of the C factor applicable to the piping.)
Specific friction loss values or equivalent pipe lengths for alarm valves, dry pipe valves, deluge valves, strainers, and other devices or fittings should be made available to the authority having jurisdiction.
Note: Use the equivalent ft (m) value for the "standard elbow" on any abrupt 90 degree turn, such as the screw-type pattern. Use the equivalent ft (m) value for the "long-turn elbow" on any sweeping 90 degree turn, such as a flanged, welded, or mechanical joint elbow type.
*Due to the variations in design of swing check valves, the pipe equivalents shown in this table should be considered average.

pipe. Because friction loss is directly proportional to length of pipe, total loss is given by

$$\frac{211.2}{100} \times 500 = 1056 \text{ kPa}$$

The loss due to fittings is given by

$$\frac{11.2}{100} \times 500 = 56 \text{ kPa}$$

or 5.3 percent of the total friction loss.

Resistance Coefficients. Resistance coefficients are sometimes used to express the head loss in a fitting as a function of velocity according to the relationship:

$$h_f = k\frac{v^2}{2g}$$

The equivalent length and the resistance coefficient methods are related. Using the basic Darcy-Weisbach formula,

$$h = f\frac{l}{d}\frac{v^2}{2g} = k\frac{v^2}{2g}$$

or

$$k = f\frac{l}{d}$$

Most entrance losses are calculated using resistance coefficients. Figure 15.3.17 provides resistance coefficients for some common entrance conditions and fittings.

Flow Coefficients. Where the loss in a fitting is defined by a flow coefficient C_v, the coefficient is defined as the flow of water that will produce a known friction loss (usually 1 psi) through the fitting. The relationship is usually shown as

$$Q = C_v\sqrt{h}$$

We know from our discussion on pressure that pressure (expressed in terms of psi) and head (expressed in terms of ft) are related by the formula

$$h = \frac{p}{w} = \frac{p}{.433}$$

Substituting, we get

$$Q = C_v\sqrt{\frac{p}{4.33}} \quad \text{or} \quad \sqrt{\frac{p}{4.33}} = \frac{Q}{C_v}$$

Squaring both sides and solving for p we get

$$p = 0.433\frac{Q^2}{C_v^2}$$

The flow coefficient can be shown to be related to the resistance coefficient. Because

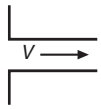
$$h = k\frac{v^2}{2g} \quad \text{and} \quad h = \frac{Q^2}{C_v^2} \quad \text{then} \quad k\frac{v^2}{2g} = \frac{Q^2}{C_v^2}$$

Rearranging we get

$$C_v^2 = \frac{2gQ^2}{kv^2}$$

FRICTION LOSS COEFFICIENTS

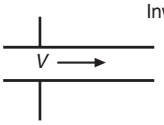
Head loss = $h = k\frac{v^2}{2g}$



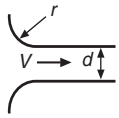
Sharp-edged inlet

$k = 0.5$

Inward projecting pipe



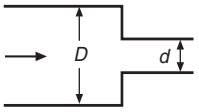
$k = 0.8 - 1.0$



Rounded inlet

r/d	0.05	0.1	0.2	0.3	0.4
k	0.20–0.25	0.09–0.17	0.08	0.05	0.04

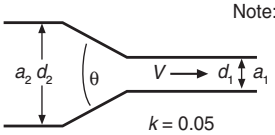
SUDDEN CONTRACTION



D/d	1.1	1.5	2.0	3.0	10
k	.15	0.28–0.30	0.36–0.40	0.42–0.50	0.50

GRADUAL CONTRACTION

Note: Use k with V of small pipe section



NOTE: Use k with V from large pipe

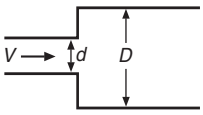
$k = 0.05$

2 $\beta = \frac{d_1}{d_2}$

IF $\theta \le 45$ degrees $k = \frac{0.8 \sin\frac{\theta}{2}(1-\beta^2)}{\beta^4}$

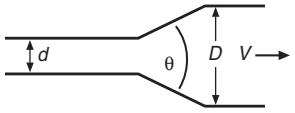
$\theta > 45$ degrees $k = \frac{0.5(1-\beta^2)\sqrt{\sin\frac{\theta}{2}}}{\beta^4}$

SUDDEN ENLARGEMENT



d/D	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
k	0.98	0.92	0.83	0.71	0.56	0.41	0.28	0.13	0.04

GRADUAL ENLARGEMENT



NOTE: Use k with V in large pipe

$\beta = d/D$

If $\theta \le 45$ degrees $k = \frac{2.6 \sin\frac{\theta}{2}(1-\beta^2)}{\beta^4}$

If $\theta > 45$ degrees $k = \frac{(1-\beta^2)^2}{\beta^4}$

FIGURE 15.3.17 Friction Loss Coefficients

Because $Q = av$ and $a = \pi d^2/4$ we get

$$C_v^2 = \frac{2g(\pi d^2 v/4)^2}{kv} = \frac{2gd^4\pi^2 v^2}{16kv^2} = \frac{gd^4\pi^2}{8k}$$

Solving for C_v we get

$$C_v = \frac{\sqrt{g}d^2\pi}{\sqrt{8k}} = \pi d^2\sqrt{\frac{g}{8k}}$$

For d in inches, and C_v in gpm/$\sqrt{\text{psi}}$, the formula is normally expressed as

$$C_v = \frac{29.9d^2}{\sqrt{k}}$$

EXAMPLE 1: Water at a flow rate of 1500 gpm is flowing into an 8 in. pipe with a sharp entrance where it attaches to the side of a tank. What is the friction loss in psi due to the losses caused by the sharp entrance?

SOLUTION: From Figure 15.3.17, a sharp entrance has a resistance coefficient (k) of 0.5. We know that $h = k\frac{v^2}{2g}$, and from the earlier discussion on velocity that $v = \frac{0.4085 \times Q}{d^2} = \frac{0.4085 \times 1500}{8^2} = 9.37$ ft/sec. We want the pressure loss in terms of psi, and not feet, so

$$p = 0.433h = 0.433 \times 0.5 \times \frac{9.37^2}{2g} = 0.30 \text{ psi}$$

EXAMPLE 2: Given the same tank and pipe, what flow would result in an entrance loss of 1 psi?

SOLUTION: We could use the same equations as in the first example and solve for the velocity that creates a loss of 1 psi. An alternative solution is to calculate the flow coefficient, which is defined as the flow that generates a 1 psi loss. We know that for d in inches and C_v in gpm/$\sqrt{\text{psi}}$ that

$$C_v = \frac{29.9d^2}{\sqrt{k}}$$

In this case $d = 8$ and the resistance coefficient k is 0.5, so

$$C_v = \frac{29.9 \times 8^2}{\sqrt{0.5}} = 2706 \text{ gpm}$$

WATER HAMMER

Water hammer is an effect of the pressure rise (surge) that accompanies a sudden change in the velocity of water flowing in a pipe. When deceleration of velocity is rapid or completely stopped, the kinetic energy of the moving water column is absorbed temporarily by elastic deformation of the pipe and by the compressibility of water. A pressure wave is then formed that is reflected back and forth within the pipe.

Pressure surges may be initiated by the closing of a valve, stopping of a pump, or by the sudden development of abnormal water demand when a water main breaks. Occasionally, the operation of automatic control valves in sprinkler systems may result in the reversal of flow and a buildup of high pressure in the fire protection system.

Consideration of water hammer and transient pressure surges is traditionally based on the elastic wave theories of Joukowski and Allievi. Chapter 4-2 of the *SFPE Handbook of Fire Protection Engineering* provides an alternative discussion based on the elastic wave theories of Zhukovsky.

The force of water hammer is sometimes sufficient to rupture pipes, fittings, or hose lines. Theoretically, the resultant forces could be infinite if the system were totally inelastic.

The elasticity of hose tends to reduce the danger from water hammer, but the sudden closing of shutoff nozzles on long hose lines may cause a pressure rise sufficient to rupture the hose. Tests on water hammer were conducted by Robert Fitzgerald of the New York City Fire Department and published in that department's *WNYF Magazine* in July 1949. Tests with low-pressure hydrants indicated that pressure surges from the closing of nozzles became acute in long hose lines and that shock waves developed that traveled from the nozzle to the hydrant and back toward the nozzle, developing pressure surges approximately twice the hydrant pressure. These tests point to the advantage of operating nozzle valves slowly.

Discharge lines from pumps are subject to water hammer caused by water column separation. This may occur when a pump suddenly stops (due to power failure, manual shutdown, etc.) or if the discharge valve is closed too quickly with the pump operating. Separation takes place somewhere downstream, especially at a summit, or where the downward slope of the pipe increases sharply. When forward movement becomes exhausted, the flow reverses direction and closes the gap.

When a pump is located at an elevation above the system outlet, a vacuum breaker in the line may provide effective control. When there is static head on a pump at discharge, it is practically impossible to completely eliminate a water column reversal. Surge suppressors or special-type vacuum breakers designed to bypass a portion of the reverse flow water column around the check valve or control valve may be effective.

The restarting of a fire pump too quickly after a tripout may cause excessive surging, and installations subject to intermittent operation should be protected by time-delay relays. Simple relief valves are considered useless, because their operation is too slow to counteract the speed of the pressure rise. In fire protection systems, a jockey pump is used to maintain a high pressure on the system and reduce the water hammer causing surge when the fire pump starts. If the jockey pump pressures are set too low, the starting of a fire pump can cause a significant surge of water into the fire protection system and result in water hammer. To avoid this surge the jockey pump should be set to maintain a pressure just above the churn pressure of the pump, so that when the pump starts, there is minimal waterflow and pressure increase on the piping system.

The principal factors contributing to water column separation are (1) rate of flow stoppage, either by rapid closing of a valve, or the fast deceleration of a pump; (2) length of pipe system (this factor determines the time that pressure continues to fall before positive-pressure waves returning from the far end of the line counteract the initial pressure drop); (3) the normal operating pressure at critical points, such as the crests of hills;

and (4) the velocity of the water just before pump stoppage or valve closure occurs; the greater the velocity, the larger the size of the void, reverse flow velocity, and the final pressure rise.

ELASTIC WAVE THEORY

The basic concepts of elastic wave theory (EWT) are as follows:

1. The magnitude of the pressure rise is proportional to the fluid velocity destroyed and to the velocity of the pressure wave.
2. The pressure rise is independent of the length and profile of the pipe.
3. The velocity of the pressure wave is the same as the velocity of sound through water.

The theoretical pressure rise when flow is stopped instantly may be calculated by the formula

$$\Delta p = \frac{0.433av}{g}$$

where

Δ_p = Pressure rise (psi)

a = Velocity of the pressure wave (ft/sec)

v = Waterflow velocity (fps)

g = Acceleration of gravity (ft/sec^2)

In SI units, the formula is

$$\Delta p_m = \frac{9.81a_m v_m}{g_m}$$

where

Δp_m = Pressure rise (kPa)

a_m = Velocity of the pressure wave (m/sec)

v_m = Waterflow velocity (m/sec)

g_m = Acceleration of gravity (m/sec^2)

In practice, the calculated Δp may be reduced, allowing for valve closure characteristics and friction loss in the pipe. Usually, this is a matter of judgment and experience. For the pipe sizes used in fire protection systems, an allowance of 100 to 125 psi (690 to 860 kPa) is suggested.

The pressure rise, Δp, is at maximum when the flow is stopped in a time equal to or less than the critical time of the pipe, which is the time required for the pressure wave to travel from the point of closure to the end of the pipe and return. The formula for critical time is

$$T = \frac{2L}{a}$$

where L = length of pipe.

The wave velocity, a, is

$$a = \frac{12}{\sqrt{\frac{w}{g} \times \left(\frac{1}{k} + \frac{d}{E \times e}\right)}}$$

where

w = Weight of water (lb/ft^3)

g = Acceleration of (ft/sec^2)

k = Bulk modulus of compressibility of water (psi)

E = Young's modulus of elasticity of pipe wall material (psi)

e = Thickness of the pipe wall (in.)

d = Inside diameter of the pipe (in.)

To avoid calculating a, use the chart in Figure 15.3.18. The figures on the curves represent values of E in millions of pounds per inch^2 (bulk modulus of elasticity).

The calculated pressure rise in a 6-in. cast-iron pipe is about 60 psi per foot (1357 kPa/m) of arrested velocity.

The water hammer potential of distribution systems, especially those with automatic pumps, should be examined and practical steps taken to reduce the probability of destructive pressure surges. It should be noted, however, that because of the conditions under which dedicated fire protection distribution systems are designed (automatic operation of pumps with check valves in their discharge lines), the potential for water hammer cannot be completely eliminated.

To prevent water hammer, valves and hydrants should be maintained in good condition and operated carefully to prevent an abrupt reduction in flow; remote-controlled power-operated valves should be carefully timed to prevent them from closing too fast (never less than 5 sec).

SUMMARY

Water is the most universally used agent for fire protection. It can be applied manually using hydrants, standpipes, and hose lines or automatically via sprinkler, water spray, or other water-based

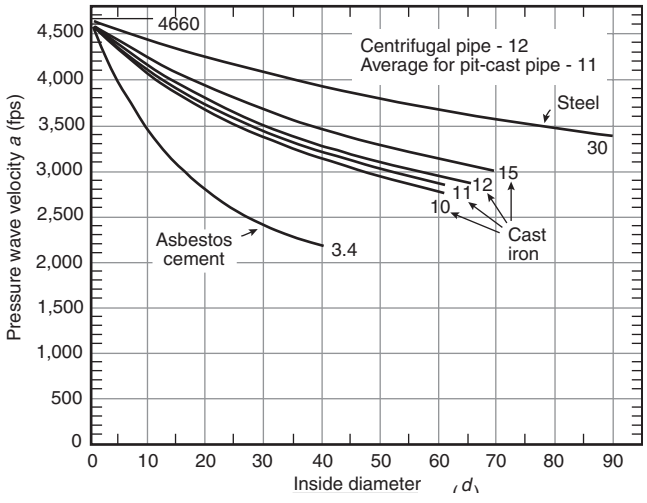


FIGURE 15.3.18 Surge Wave Velocity Chart for Water

systems. It is commonly available through public or private piping systems and storage tanks on the protected property.

The fundamentals of hydraulics presented in this chapter are applied in the design of these systems. The chapter covered the basic properties of water; the concepts of pressure, velocity, and velocity head were combined with Bernoulli's theorem on the conservation of energy for noncompressible fluids to derive the basic equations for the flow of water through orifices and ways to measure that flow. Energy losses occur in real systems, and several methods can be used to calculate those losses. The empirical relationship developed by Hazen and Williams is the most widely used and accepted of these methods to determine the friction loss of water in pipes of fire protection systems. Finally, methods were provided to deal with losses to fittings that are found in piping systems and a glimpse into the problem of water hammer in closed piping systems. The methods provided can be used to make most of the common fire protection water calculations and are the basis for calculating more complex piping arrangements, including those involving looped or gridded piping systems and those with multiple sources of water supply.

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Chapter 4

Water Supplies for Sprinkler Systems

Wayne M. Martin

Chapter Contents

Types of Supplies
Influence of Various Factors on Water Supply Need
Water Supply Requirements for Sprinkler Systems
Occupancy Classifications
Water Supply Requirements for Hose Stream Protection
Hydraulically Designed Sprinkler Systems

Key Terms

automatic sprinkler system, fire department connection, fire pump, hydraulically designed system, hydraulic calculations, K-factor, microbiologically influenced corrosion (MIC), pipe schedule method, private water supply, public water supply, reduced pressure zone, velocity pressure

Every automatic sprinkler system must have at least one automatic water supply of adequate pressure, capacity, and reliability. An "automatic" supply is one that is not dependent on any human intervention to manually operate valves, start pumps, or make connections to supply water at the time of a fire. Both the rate of flow and the duration of that flow must be considered.

This chapter identifies the types of water supplies that are acceptable for fire sprinkler systems and the variables that must be considered in the system design. The following factors are to be considered: occupancy hazard classification, supplementary hose stream demand, adequate pressure demands, the fundamentals of a hydraulically designed sprinkler system, and sprinkler system piping sizes matched with the available water supply.

Chapters in Section 15 of this handbook covering water supplies for fixed fire suppression focus on understanding the complexities of providing adequate water supplies for sprinkler systems. Of particular interest are the following chapters in Section 15: Chapter 1, "Fixed Water Storage Supplies for Fire Protection"; Chapter 2, "Water Supply Requirements for Public Supply Systems"; Chapter 6, "Water Distribution"; and Chapter 3, "Hydraulics for Fire Protection," which discusses the fundamentals of waterflow through pipes and orifices. Also relevant is Section 16, Chapter 9, "Water Spray Protection," which is of value because there is no definitive line between sprinkler systems and water spray systems, and many of the water supply requirements that pertain to sprinkler systems apply equally to water spray systems.

TYPES OF SUPPLIES

Automatic fire sprinkler systems can be supplied from a single source or a combination of sources such as a municipal water supply, elevated gravity tanks, at-grade tanks or reservoirs, pressure tanks, rivers, lakes, and ground well water.

In theory, a single water supply would seem to be all that is necessary for satisfactory protection. However, a single supply may be temporarily out of service, it may be disabled at the time of a fire or before a fire is completely extinguished, or its pressure or capacity may be below normal during an emergency. Therefore, a secondary supply is recommended depending on the strength and reliability of the primary supply; the value and importance of the property; the area, height, and construction of the building; the use or occupancy; and the outside exposures.

Connections to Public Waterworks Systems

A connection from a reliable public waterworks system of adequate capacity and pressure is the preferred single or primary supply for automatic sprinkler systems. In determining its adequacy, one must consider not only the normal capacity and pressure of the system but also the minimum

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pressures and flows available at unfavorable times, such as the summer months; periods of heavy demand on the system, such as those created by large industrial areas; or periods of impairment caused by flood or by ice conditions in winter. These conditions are typically referred to as seasonal lows.

Daily demands will fluctuate as well. Consider the early morning hours when the population is preparing for work or school. Demands created by domestic plumbing system use will be greater than at other times of the day.

The size and arrangement of street mains and feeders from public water supplies are also important. Connections from large mains fed two ways or from two mains on a grid system may provide an excellent supply. Street mains less than 6 in. (152 mm) in diameter are usually considered inadequate and unreliable. Feeds from dead-end mains are also undesirable. Water meters, if required, should be of types listed for the fire service. Flow and pressure tests under varying conditions of demand are generally necessary to determine the amount of public water available for fire protection.

Cross Connections Between Public and Private Supplies

Where a secondary supply is needed to supplement the public water supply, public and private fire service mains can be connected to feed into a single fire protection system. When the private fire service main is from a nonpotable source and it is connected to the public main, the systems are said to be cross connected. In some localities, cross connections may be prohibited or closely regulated by health authorities.

Federal regulations approved in 1986 require states to provide quality water when it is intended for public consumption. States and municipal governments have taken various steps beyond the federal mandate to protect the potable water supply. Double check valves and reduced pressure zone (RPZ) backflow prevention devices may be required when the sprinkler system will be supplied by a potable water source.

These devices, which are intended to protect the public water supply from potential contamination, are oftentimes costly and have a negative impact on the available water supply and pressures to the sprinkler system. Although no documentation exists of any actual problems with respect to sprinkler systems and potable water, many state health and environmental agencies have been successful in mandating such devices to protect the public from some perceived or potential threat.

Gravity Tanks

Gravity tanks of adequate capacity and elevation make a good primary supply and may be acceptable as a single supply. Details of the construction, heating, and maintenance of gravity tanks are given in NFPA 22, *Standard for Water Tanks for Private Fire Protection.* In determining tank size and elevation, the following information should be considered: sprinkler system design area; density or rate of water application; duration of operation; water allowances for inside hose, outside hydrants, water curtain, and exposure sprinklers; and arrangement of the underground supply piping and fire department connections.

Suction Tanks

With the advent of hydraulically designed sprinkler systems, suction tanks have become an acceptable means of design. Suction tanks are typically constructed of steel, concrete, or embankment-supported coated fabric. NFPA 22 should be consulted for details.

Fire Pumps

A fire pump with a reliable source of power and a reliable suction water supply is a desirable piece of equipment. Fire pumps are used to a great extent because of the hydraulic advantages of having a water supply available at high pressure. With ample water, a fire pump can maintain a high pressure over a long period of time and may be a necessary part of some installations requiring greater water pressure than would be available otherwise. For details of power sources, pump construction, installation, and methods of control and operation, consult NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*.

Most fire pumps today are started automatically. Automatic control of fire pumps is needed where an immediate water demand is necessary, as with a sprinkler or standpipe system. Automatic fire pumps must have their suction under a positive pressure to avoid the delays and uncertainties of priming.

Most fire pumps are powered by electric motors or diesel engines. Where a reliable source of power is available at all times, an electrically driven installation may be the most desirable. Where the power supply is questionable, a diesel-driven fire pump would be preferred. In some critical installations, such as hospitals and high-rise buildings, a diesel-driven emergency power generator may be used to supply secondary power to the electric motor. The use of a diesel-driven fire pump in a critical installation would eliminate the need for much of the capacity of the emergency generator.

The automatic control of electrically driven centrifugal pumps must be arranged to prevent frequent, repeated starting of the motor, either by initiating continuous running until stopped manually or by using a timing device that stops the motor automatically only after a predetermined period of operation. The frequent repeated starting and stopping of a fire pump can be alleviated by the installation of a pressure maintenance pump or jockey pump.

Pressure Tanks

Pressure tanks have several possible uses in automatic sprinkler protection. An important limitation is the small volume of water that can be stored in such tanks.

In situations where an adequate volume of water can be supplied by a public or private source but where the pressure is not sufficient to serve a sprinkler system directly, the pressure tank gives a good starting pressure for the first sprinklers that operate. In tall buildings where the public water pressure is too low for effective water distribution to the highest sprinklers, pressure tanks may be used to supply such sprinklers during the time required for an automatically operated fire pump to begin supplying water.

Each proposed use of pressure tanks calls for special consideration and analysis of water capacity, location, and arrangement of the connection to the sprinkler system. Each installation must usually have specific approval. Details on the construction and installation of pressure tanks are given in NFPA 22.

Fire Department Connections

Under fire conditions that cause a considerable number of sprinklers to operate, public water or tank supplies may not provide water at sufficient pressure for effective sprinkler discharge and distribution. In addition, the pressure in many public water supplies to sprinkler systems may be reduced materially by hose streams from hydrants. In such cases, a connection through which the fire department can pump water into the sprinkler system provides an important secondary supply. A fire department connection is a standard part of a fire sprinkler system installation and would be omitted only if the building were inaccessible to the fire department or the sprinkler system exceeded the pumping capacity of the fire department, such as a deluge system. A fire department connection may also be omitted from a single-story building that does not exceed 2000 ft^2 (186 m^2) in size.

Fire department connections must be located and arranged so that hose lines can be readily and conveniently attached without interference from nearby objects. Each fire department connection must be properly identified with a sign, for example, autosprinkler or standpipe. Each connection must be fitted with a check valve, but not with a gate valve, so that the connection will not be shut off inadvertently. There should be a proper drain, as well as a drip device between the check valve and the outside hose coupling. Figures 15.4.1 and 15.4.2 show the main features of a fire department connection. In Figure 15.4.1, a check valve allows the use of a single hose line. Other details of installation and pipe size are given in NFPA 13, *Standard for the Installation of Sprinkler Systems.*

Where a wet pipe sprinkler system has a single riser, the fire department connection should be attached to the system side of the controlling valve, as shown in Figure 15.4.3. For a dry pipe system, the fire department connection should be between the

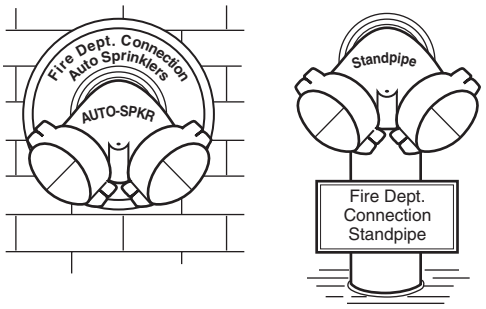


FIGURE 15.4.1 Typical Siamese Connections for Sprinkler Systems and Standpipes

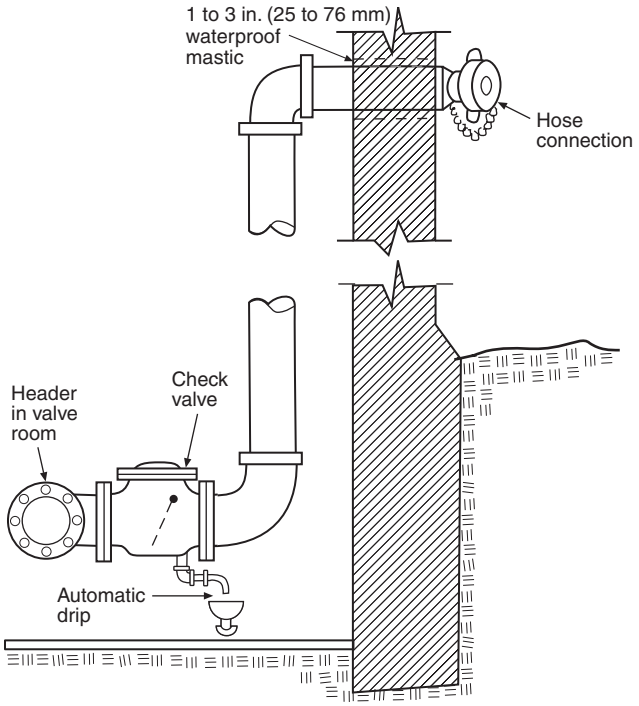


FIGURE 15.4.2 Typical Fire Department Connection

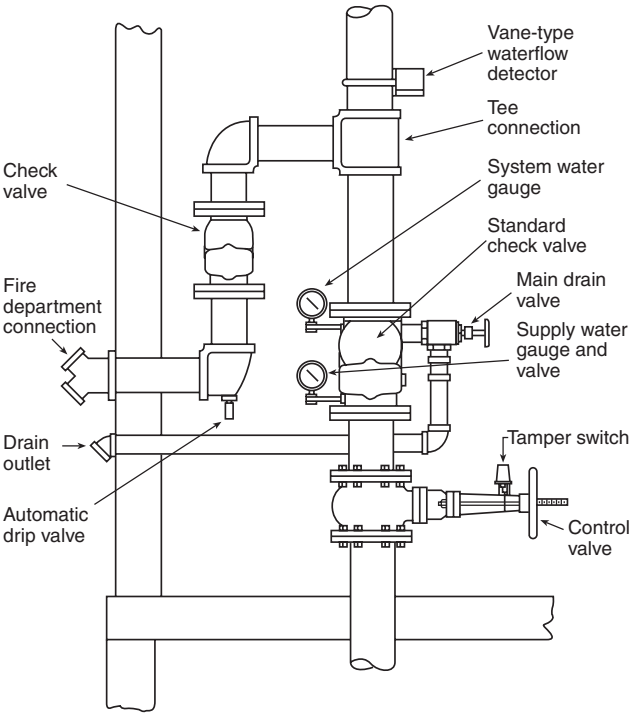


FIGURE 15.4.3 Straight Pipe Riser (Source: *Automatic Sprinkler Systems Handbook,* 1999, Exhibit 5.26)

system control valve and the dry pipe valve. This makes it possible to pump water into the system even if the valve is closed. If there are two or more sprinkler system risers, each with its own separate connection to a public main, each system must have its own fire department connection. If more than one riser is connected to a yard system, the fire department connection should feed into the yard system on the supply side of all riser shutoff valves, and there must be a check valve in all other water supply connections into the yard system to prevent backflow and loss of water supplied through the fire department connection. If one riser is shut off, the fire department connection can still supply all other risers. If two or more sprinkler system risers are fed by one sprinkler connection, one fire department connection can supply both risers.

In an emergency, a fire department can pump water from public hydrants or other sources of water into a sprinkler system through hose connected to a yard hydrant or other hose connection using a double female hose coupling, if other supply connections have a check valve or a gate valve that can be closed.

INFLUENCE OF VARIOUS FACTORS ON WATER SUPPLY NEED

Determining the water supply requirement for most sprinkler systems is not always easy because of the many variables involved. If a water source that can supply all the sprinklers is available, there is no problem, but such a water supply is seldom practical except in the case of small systems. The water supply requirement for any sprinkler system is directly related to the number of sprinklers expected to operate, which is determined by the hazard classification and the anticipated use of outside and inside hose stream demands.

Records kept by NFPA before 1970 show that 20 or fewer sprinklers opened in 93 percent of all anecdotally reported fires in sprinklered buildings. Older data are almost certainly skewed to bigger fires and more severe outcomes. Given this history, it is not surprising that water supply adequacy is not usually difficult to assure and inadequacy is rarely the cited reason for unsatisfactory sprinkler performance. Thus, water supply is a significant concern, particularly with large sprinkler systems and with systems protecting greater-than-ordinary hazards.

Establishing the water supply requirement for a sprinkler system requires the system designer to consider factors relating to sprinkler control and sprinkler system extinguishment. Where the cooling effect from the water discharged by sprinklers is greater than the heat liberated by the fire, the sprinklers can gain control. When the reverse occurs, as when a water supply is overtaxed or system design is inadequate, the sprinklers cannot control the fire and the sprinkler system may ultimately fail. Where all conditions are favorable, the fire should be controlled by the operation of only a small number of sprinklers. Because conditions vary with different classes of occupancy, areas, and types of buildings, the number of sprinklers expected to operate to control a fire may range up to the total number in the design area, and the water supply should be provided accordingly.

The following factors affect the number of sprinklers that might open in a fire and must therefore be considered in determining the water supply requirement.

Hazard of Occupancy (Including Flash Fire Hazard and Potential Rate of Heat Release)

This is the most important factor and one requiring experienced judgment to evaluate. Where a flash fire hazard is present, it is usually necessary to provide enough water to operate all of the sprinklers in any individual fire area.

Initial Water Pressure

When fire sprinklers are submitted to testing laboratories for listing, they are subjected to water distribution and fire tests. These tests are conducted at a minimum flow of 15 gpm (57 L/min) per sprinkler. The pressure required to produce this flow through a standard ½ in. orifice (12.7 mm) sprinkler with a nominal K-factor of 5.6 is approximately 7 psi (0.5 bar). The minimum operating pressure of any sprinkler is 7 psi (0.5 bar) according to NFPA 13. The designer must verify the listing for a specific sprinkler. The listing may require minimum operating pressure greater than 7 psi (0.5 bar).

At higher initial water pressures, the discharge is correspondingly greater. For example, at a pressure of 15 psi (1.03 bar), a sprinkler (K = 5.6) will discharge 22 gpm (83 L/min) or an average of approximately 0.17 gal/ft^2/min (6.8 L/min/m^2) for one sprinkler with an area of coverage of 130 ft^2 (12 m^2). At 30 psi (2.07 bar), the discharge is 31 gpm (117 L/min), and at 50 psi (3.45 bar), it is 40 gpm (151 L/min). With a greater discharge, there is a better chance of fire control from a small number of sprinklers and less need for large volumes of water to supply a large number of sprinklers.

Obstructions to Distribution of Water from Sprinklers

Nonstructural building elements such as high piled stocks, pallets, racks, and shelving must be considered, especially in extra hazard and various types of storage occupancies. Obstructions create a greater chance that a larger number of sprinklers needing larger water supplies will open and a lesser likelihood that the fire will be controlled in its initial stages.

High Ceilings and Air Current Conditions

With ceilings of unusual height, there is a greater chance that natural air movement will carry heat away from the sprinklers immediately over a fire, resulting not only in a delay in the application of water, but also resulting in the opening of sprinklers remote from the area of fire origin. More water or a larger sprinkler density is usually needed under such conditions. The same situation exists wherever there are drafts, such as in areas open on the sides to the outside where winds can divert heat from sprinklers over the fire.

Unprotected Vertical Openings

Sprinkler systems in multistory buildings are usually designed on the assumption that fire will be controlled on the floor of origin. Where there are unprotected openings up through which heat and fire may spread, it may be expected that more sprinklers will

open, particularly in the case of a fire originating near the vertical opening. In the case of high combustibility, the interconnected floors may need to be considered as one fire area. This means more water and larger pipe sizes in risers and supply lines.

Wet Pipe versus Dry Pipe Systems

Because of the delay due to exhausting air from dry pipe systems, more sprinklers are expected to open on dry pipe systems than on wet pipe systems. This may call for greater water supplies. Design areas are increased by 30 percent to account for this delay.

Obstructions to Sprinkler Discharge

Sprinkler discharge patterns may be significantly affected by an obstruction. Historically building structural members and other building elements such as ducts were considered. Recently other types of smaller building elements such as piping and light fixtures were considered as obstructions to water distribution. Columns, beams, girders, bar joists, light fixtures, soffits, and HVAC ductwork can obstruct water distribution to the point where additional sprinklers may be necessary to account for the obstruction, the result being more sprinklers in the design area. Floor-mounted obstructions, such as privacy curtains, freestanding interior partitions, and room dividers, require similar special treatment. NFPA 13 addresses the areas of concern with regard to obstructions. Each type of sprinkler—that is, standard spray, sidewall, large drop, extended coverage, and early suppression fast response (ESFR)—is treated separately with its own obstruction requirements.

Extent of Coverage and Exposures

Any fire in an unsprinklered space extending to an area with automatic sprinklers places an abnormal demand on the sprinkler system and requires increased water supplies so that the system may function effectively.

Regardless of the size of the building, NFPA 13 requires a specific design area that relates to the occupancy fire hazard rather than the size of the building. The idea behind this concept is to provide a water supply that is adequate to cover this design area for a given period. The sprinklers in the most remote portion (hydraulically remote areas) of this area are used as the basis of design. The capability of supplying sprinklers in this area automatically means that sprinklers that are physically closer to the water supply source can be supplied as well.

WATER SUPPLY REQUIREMENTS FOR SPRINKLER SYSTEMS

Notwithstanding the general problems involved in arriving at water supply requirements, the fire hazard represented by different building occupancies has made it possible to establish requirements for water supplies for sprinkler systems. The occupancy classification is the primary consideration, with latitude allowed for other contributing factors.

Selection of the appropriate water supply guide table in NFPA 13 is based on the design approach for sprinkler piping. The pipe schedule approach is the oldest version and first appeared in the standard in 1896. The concept of hydraulically designed systems was advanced in 1969 and is the predominate design approach method used today. Minimum water supply requirements for the pipe schedule design method, as shown in Table 15.4.1, are based on occupancy classification (light or ordinary hazard).

The total water supply required is determined from Table 15.4.1, and the water for hose streams is included. If stored water is used, the total waterflow required would have to be multiplied by the duration of flow to determine whether the capacity of the stored supply is adequate, a factor that would not be pertinent for a reliable municipal water source.

The pipe schedule method that is the basis of Table 15.4.1 has certain limitations and should be used only with experienced judgment. The pipe schedule method is permitted only for new installations of 5000 ft^2 (465 m^2) or less at a minimum residual of 15 psi (1.03 bar) at the base of the riser, or if the area exceeds 5000 ft^2 (465 m^2) the minimum residual must be 50 psi (3.4 bar) at the elevation of the sprinkler. The pipe schedule design method is also permitted for modifications to existing pipe schedule systems. The effectiveness of a pipe schedule system is limited to the use of ½ in (12.7 mm) orifice sprinklers. Extra hazard occupancies and storage occupancies involve complex factors requiring special consideration and the use of the hydraulic calculation design method.

Where fire pumps contribute to the sprinkler system water supply, pumps of standard size used with adequate rates of discharge are required. The water supply for a pump must be adequate and reliable to provide for continuous pump operation.

Where pressure tanks furnish the water supply, the tank installation should comply with the appropriate provisions of NFPA 22. Where a combination of different water supplies is provided in the interest of reliability, it is good practice to have the rate of supply from each source at least equal to the minimum requirement for the system.

OCCUPANCY CLASSIFICATIONS

Light-Hazard Occupancies

The quantity or combustibility of contents is low and fires with relatively low rates of heat release are expected. Examples of

TABLE 15.4.1 Water Supply Requirements for Pipe Schedule Sprinkler Systems

Occupancy Classification	*Minimum Residual Pressure Required (psi)*	*Acceptable Flow at Base of Riser (Including Hose Stream Allowance) (gpm)*	*Duration (min)*
Light hazard	15	500–750	30–60
Ordinary hazard	20	850–1500	60–90

For SI units: 1 gpm = 3.785 L/min; 1 psi = 0.0689 bar.

light-hazard occupancies are residential buildings, dormitories, office buildings, the seating areas of restaurants, and hospitals. In these occupancies, the potential rate of heat release is low, areas are usually subdivided, and a small number of sprinklers normally should control any fire. For hydraulically designed systems, 150 gpm (568 L/min) for sprinkler operation and an additional 100 gpm (378 L/min) for hose stream demand (Table 15.4.2) will generally make a good starting point for system demand. A total of 500 to 750 gpm (1893 to 2839 L/min) for pipe schedule systems may be necessary for the same hazard, thereby making this a less desirable design approach.

Ordinary-Hazard Occupancies

Ordinary-hazard occupancies are divided into two groups: Group 1 and Group 2.

Group 1. This ordinary-hazard classification includes occupancies, such as parking garages, bakeries, laundries, and canneries, in which the combustibility of contents is moderate, stockpiles of combustibles do not exceed 8 ft (2.4 m), and the rate of heat release for a fire is greater than that for the light-hazard classification. Ordinary-hazard Group 1 occupancies will require a minimum of 225 gpm (851 L/min) for sprinkler operation and an additional 250 gpm (946 L/min) to support inside and outside hose streams. If a pipe schedule approach is selected, a minimum flow of 850 gpm (3217 L/min) is necessary.

Group 2. This ordinary-hazard classification includes occupancies such as clothing factories, mercantile, pharmaceutical manufacturing, certain woodworking occupancies, and repair garages. With this group, the combustibility of contents, storage heights, and obstruction features are moderate to high, stockpiles do not exceed 12 ft (3.7 m), and the rate of heat release is greater than Group 1. Ordinary-hazard Group 2 occupancies will require a minimum flow of 300 gpm (1125 L/min) for sprinkler operation, plus an additional 250 gpm (946 L/min) to operate the inside and outside hose streams. If design is based on the pipe schedule method, a minimum total flow of 850 gpm (3217 L/min) is necessary.

Extra Hazard Occupancies

Extra hazard occupancies consist of properties where quantity and combustibility of contents is very high. Flammable and combustible liquids, dust, lint, or other materials may be present, introducing the probability of rapidly developing fires with high rates of heat release. Closely spaced sprinklers and larger pipe sizes are expected. Extra hazard occupancies are divided into two groups: Group 1 and Group 2.

Group 1. Extra hazard occupancies (Group 1) include those that may produce severe fires where little or no flammable or combustible liquids are present. These include such occupancies as die casting, plywood and particleboard manufacturing, printing (using inks with below 100°F [37.8°C] flashpoints), rubber manufacturing operations, sawmills, textile operations, and upholstering with plastic foam operations.

Group 2. Extra hazard occupancies (Group 2) include those that may produce severe fires where moderate to substantial amounts of flammable or combustible liquids are present, or where shielding of combustibles is extensive. These include such occupancy hazards as asphalt saturating, flammable liquids spraying, flow coating, open oil quenching, solvent cleaning, and varnish and paint dipping.

In any treatment of hazards by general groups of occupancy, it must be noted that individual properties differ markedly and that buildings of the same nominal occupancy classification may show widely different individual hazards that should be considered in any determination of water supply.

WATER SUPPLY REQUIREMENTS FOR HOSE STREAM PROTECTION

The values given in Table 15.4.1 include hose stream requirements. In considering water requirements for hose streams, one should realize that if sprinklers perform effectively, little hose stream assistance is required. Although this is generally the case, a realistic view must be taken of possible contingencies and of the amount of water that might be needed for hose stream protection under adverse conditions. Hose streams may also be necessary to accomplish final extinguishment of the fire. However, it should be noted that current sprinkler system technology is intended to control a fire, not necessarily to extinguish it.

In evaluating hose stream requirements, one should consider several possibilities, such as the amount of water necessary for final extinguishment and cleanup operations, or the steps that may have to be taken in the event that sprinklers are retarding fire spread but are not fully effective in gaining control of the fire and extinguishing it.

HYDRAULICALLY DESIGNED SPRINKLER SYSTEMS

Planning new water supplies or evaluating existing supplies for sprinkler systems requires information about the hydraulic behavior of sprinkler piping systems.

A hydraulically designed sprinkler system is one in which pipe sizes are selected on a pressure loss basis to provide a prescribed density in gallons per minute per square foot ([L/min]/m^2), or a prescribed minimum discharge pressure or flow per sprinkler, distributed with a reasonable degree of uniformity over a specified area. This system permits the selection of pipe sizes in accordance with the characteristics of the water supply available. The stipulated design density and area of application will vary with occupancy hazard. This language is the verbatim definition of a hydraulically designed system, taken from NFPA 13. This definition sets the basic premise for the preferred method of sprinkler system design.

Table 15.4.2 and Figure 15.4.4 are used to determine density, area of sprinkler operation, and water supply requirements for hydraulically designed sprinkler systems. Systems must be calculated to satisfy a single point on the appropriate design curve, and interior piping must be based on this design point. It

TABLE 15.4.2 Hose Stream Demand and Water Supply Duration Requirements for Hydraulically Calculated Systems

Hazard Classification	*Inside Hose (gpm)*	*Total Combined Inside and Outside Hose (gpm)*	*Duration (min)*
Light	0, 50, or 100	100	30
Ordinary	0, 50, or 100	250	60–90
Extra hazard	0, 50, or 100	500	90–120

For SI units: 1 gpm = 3.785 L/min.

is not necessary to meet all points on the selected curve. In some cases where a large water supply is available, it might be advantageous, because of the elimination of a fire pump, to design the system using the top portion of the curve. In other cases, it might be better to design with smaller areas of application and higher densities, because these tend to limit fire size, even though a fire pump is required.

When selecting a point on the curve in Figure 15.4.4, it should be noted that more total water is necessary in terms of flow and capacity as one moves up the curve. As an example, for a light-hazard system, a 1500-ft^2 (139-m^2) area requires a density of 0.10 gpm/ft^2 (4.1 [L/min]/m^2), or a flow of 150 gpm (568 L/min). If a 2500-ft^2 (232-m^2) area is selected, the density is only 0.08 gpm/ft^2 (3.2 [L/min]/m^2), but the total flow is increased to 200 gpm (757 L/min).

The same hazard occupancy classifications that apply to pipe schedule sprinkler systems apply to hydraulically designed sprinkler systems. However, the recommended water supply figures are somewhat lower due to the greater efficiency of a calculated system.

The water allowances for inside and outside hose streams may be combined and added to the system requirement at the system connection to the underground main. The total water requirement must be calculated through the underground main to the point of supply.

For deluge and water spray systems with open orifices, calculations are essential. Automatic sprinkler systems protecting high-piled storage require a specific water density for fire control. Because the hydraulic design approach results in superior design, it always should be selected as the preferred method.

Hydraulic Calculation Programs

Since NFPA 13 first permitted the use of hydraulic calculations, several computer programs have been developed that can assist the designer with this particular task. These programs are not required to be listed nor are they governed by NFPA 13. They must, as a minimum, be capable of providing the information required for any hydraulic calculation procedure. This information includes, but is not limited to, the hydraulic reference points, the flow and pressure at specific points, the pipe diameter, and, for a grid system, a printout showing the flow direction and quantities.

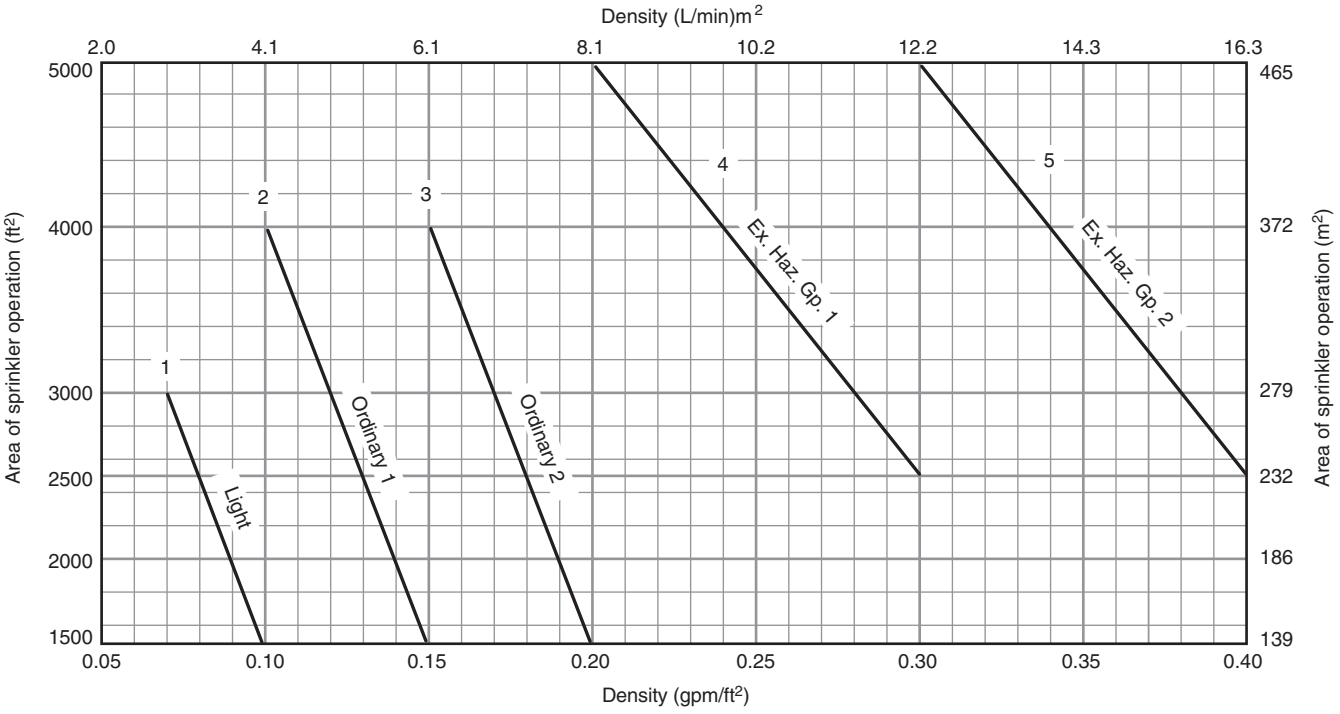


FIGURE 15.4.4 Design Curves for Hydraulically Calculated Sprinkler System

The capabilities and limitations of computer programs are as wide ranging as the cost differences among them. Before buying one of these programs, the user should investigate and compare the various hydraulic software programs, including the support the programs offer.

Flow Calculation Method

A method of making flow calculations for sprinkler systems is given in NFPA 13.

The design area for flow calculations should be chosen as the most hydraulically demanding area for the sprinkler system. The area should have a dimension parallel to the branch line of 1.2 times the square root of the area of anticipated sprinkler operation. The 1.2 times the square root of the area is added to ensure that the long side of the rectangle is along the branch line. In grid systems, the hydraulically most demanding area must be verified using at least two additional sets of calculations. This technique is referred to as "peaking," and it is merely a check to prove that the most demanding area has been calculated.

Each sprinkler in the design area must discharge at a flow rate at least equal to the stipulated minimum water application rate or density. Begin calculations at the sprinkler hydraulically farthest from the supply connection. In common system configurations, this will be the end sprinkler on the end branch line. The minimum operating pressure for any sprinkler must not be less than 7 psi (48 kPa) or the pressure necessary to deliver the design density at the hydraulically most remote sprinkler or a higher minimum pressure as specified in the laboratory listing. Special sprinklers, such as extended-coverage, ESFR, in-rack, and large drop, will require operating pressures well in excess of this 7 psi (48 kPa) minimum.

Most Remote Sprinkler

Assuming a minimum pressure of 10 psi (69 kPa) at the most remote sprinkler and a discharge coefficient of 0.75 for a standard ½ in. (12.7 mm) orifice sprinkler, there is a discharge of 17.7 gpm (67 L/min) calculated from the formula

$$Q = 29.83cd^2\sqrt{p}$$

used in calculating flows through orifices and short tubes. For a given sprinkler, the product of these numbers in the equation—$29.83cd^2$—becomes a constant and is denoted as the sprinkler K-factor. In the case of a ½ in. (12.7 mm) orifice sprinkler, the constant is 5.6 and is derived by multiplying the following numbers: $29.83 \times 0.75 \times (½)^2 = 5.6$. A simplified equation may now be used to describe flow through the sprinkler orifice. The new equation is

$$Q = K\sqrt{p}$$

Velocity pressure is not a factor at the most remote sprinkler, but it may be considered at all the other sprinklers in the example that follows. Some organizations ignore velocity pressure in their calculations. The omission of velocity pressure is conservative and on the safe side.

Example for Second Sprinkler from the End

The following example considers the effects of velocity pressure. Some computer programs consider velocity pressure and others do not. The hydraulic calculation example presented in the Annex of NFPA 13, Figure A.14.3.2(a) through Figure A.14.3.2(d), does not consider velocity pressure and is an example of hydraulic calculations by the old-fashioned method, by hand, not computer generated.

Assuming sprinklers 10 ft (3.05 m) apart on branch lines, with the end section of pipe 1 in. (25.4 mm) nominal diameter, the friction loss at 17.7 gpm (67 L/min) flow with a Hazen-Williams formula coefficient of 120 (value for black steel pipe) will be 1.0 psi (7 kPa).

The total pressure at the second sprinkler will be 10.0 + 1.0 psi (69 +7 kPa) = 11.0 psi (76 kPa). Velocity pressure, if used in the procedure, is calculated from the formula

$$P_v = 0.001123\frac{Q^2}{D^2}$$

where

P_v = Velocity pressure (psi)

Q = Flow (gpm)

D = Inside pipe diameter (in.)

The velocity pressure relates to the system design by

$$P_n = P_t - P_v$$

where

P_n = Normal pressure

P_t = Total pressure

P_v = Velocity pressure

Of this, velocity pressure based on a flow of 17.7 gpm (67 L/min) will be 0.3 psi (2 kPa). The normal pressure (pressure acting perpendicular to the pipe wall) acting on the second sprinkler is the total pressure of 11.0 psi (76 kPa), less the velocity pressure of 0.3 psi (2 kPa), which equals 10.7 psi (74 kPa). On all sprinklers except the end sprinkler, only normal pressure is considered as acting on the sprinklers. The discharge from the second sprinkler, at a pressure of 10.7 psi (74 kPa), will be 18.3 gpm (69 L/min).

The pipe between the second and third sprinkler, also 1 in. (25.4 mm) in diameter, 10 ft (3.05 m) long, and with a flow of 17.7 gpm (67 L/min) + 18.3 gpm (69 L/min) = 36.0 gpm (136 L/min), will have a friction loss of 3.8 psi (26 kPa) and a velocity pressure of 1.2 psi (8 kPa). Normal pressure at the third sprinkler is 10.7 psi (74 kPa) + 3.8 psi (26 kPa) – 1.2 psi (8 kPa), or 13.3 psi (92 kPa).

Other Sprinklers on a Branch Line

Figure 15.4.5 can be used to establish the velocity pressure correction needed for various pipe sizes and flows. This figure may be used for any pipe type, but it is based on the use of Schedule

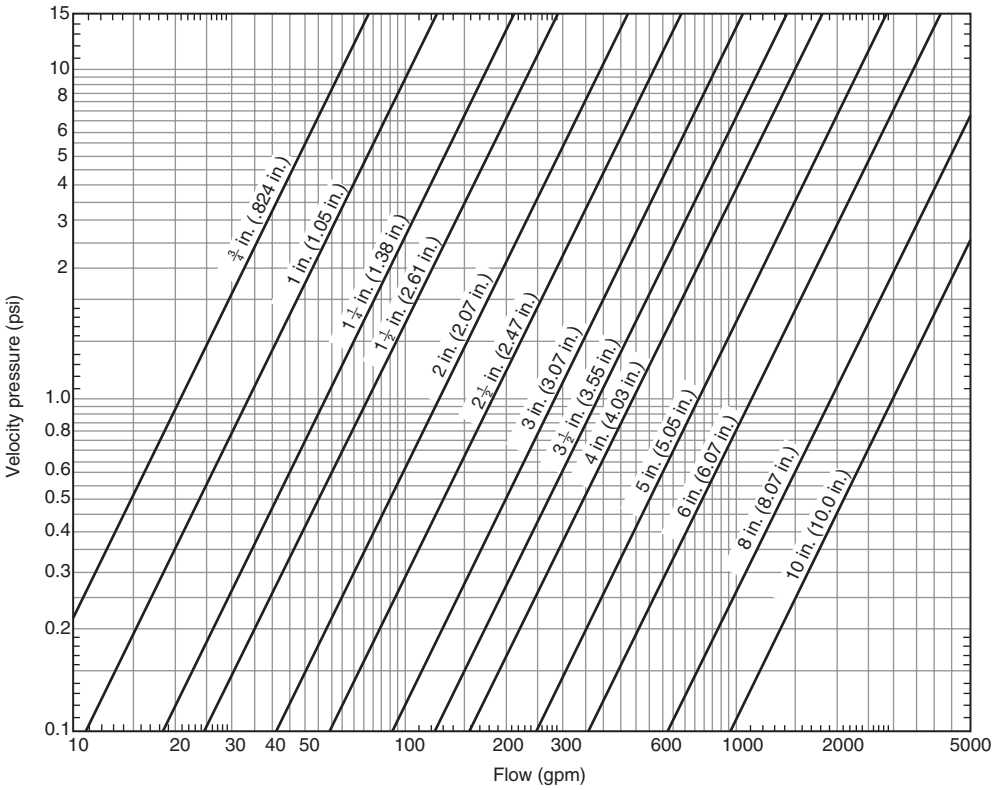
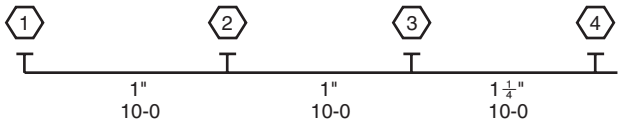


FIGURE 15.4.5 Graph for the Determination of Velocity Pressure

40 pipe. The difference in velocity pressure is minuscule as it relates to schedule of pipe.

Figure 15.4.6 is an example of the velocity pressure component, determined as follows: The flow between the last sprinkler and the next to last sprinkler on the branch line was determined to be 17.7 gpm (67 L/min) and the pipe size is 1 in. (25.4 mm). The graph in Figure 15.4.5 is now used to locate a flow of 17.7 gpm (67 L/min) on the *x*-axis, going vertically from this point until the 1 in. (25.4 mm) line is intercepted. The corresponding pressure is taken from the *y*-axis and is determined to be 0.3 psi (2.1 kPa). This procedure can now be repeated for each combination of pipe sizes and flows.



Summary

	Flow (gpm)	Friction loss (psi)	Velocity pressure (psi)	Normal pressure (psi)
1 2	17.7	1	0.3	11
2 3	36	3.8	1.2	13.3
3 4	57.5	3.9	1.0	15.0

FIGURE 15.4.6 Example of Velocity Pressure

Up to this point, velocity pressure has been based on flow downstream from the sprinkler being considered; this has been confirmed by tests. It has also been shown by those tests that beyond the second sprinkler, velocity pressure should be figured from the flow on the upstream side of the sprinkler being considered. This figuring is done by trial and error, assuming a flow from the sprinkler, calculating the velocity pressure from the total flow, determining a normal pressure, and calculating a flow from the normal pressure. If the calculated flow is not reasonably close to the assumed flow, assume a different flow and repeat the procedure until the two are close.

For example, assume a flow from the third sprinkler of 19.0 gpm (72 L/min) and assume that the pipe between the third and fourth sprinkler is 1¼ in. (32 mm). Total flow is 36.0 gpm (136 L/min) + 19.0 gpm (72 L/min) = 55.0 gpm (208 L/min). Velocity pressure is 0.9 psi (6 kPa), and normal pressure at the third sprinkler is therefore 15.7 psi (108 kPa) – 0.9 psi (6 kPa), or 14.8 psi (102 kPa). Corrected flow then becomes 21.6 gpm (82 L/min), which is not close enough to the 19.0 gpm (72 L/min) assumed. Try an assumed flow of 21.4 gpm (81 L/min). Velocity pressure at 57.4 gpm (217 L/min) is 1.0 psi (7 kPa); normal pressure is 14.7 psi (101 kPa), and the new corrected flow is 21.5 gpm (81 L/min). Total flow at the third sprinkler then becomes 36.0 gpm (136 L/min) + 21.5 gpm (81.4 L/min) = 7.5 gpm (217.6 L/min). The calculating procedure for the other

sprinklers on the branch line is the same as it is for the third sprinkler. If this set of conditions is compared to pipe schedule design, it will be seen that the 15 psi (103 kPa) minimum riser pressure has been exceeded, unless, as is quite probable, the pressure with 57.5 gpm (217.6 L/min) flow is substantially higher than that with a 500 gpm (1893 L/min) flow. Whether the pressure with 57.5 gpm (217.6 L/min) flow is higher than 15 psi (103 kPa) depends on the characteristics of the water supply. In any case, it appears that with not many more sprinklers open, the pressure at the most remote sprinkler will be less than the 10 psi (69 kPa) selected in this example.

Branch Lines, Cross Mains, Risers, and Fittings

Cross-Main Pressure at the Branch Line Connection. This pressure is the normal pressure at the nearest open sprinkler increased by the friction loss and the velocity pressure in the intervening pipe. If the branch line is fed through a tee and nipple, additional friction loss allowances must be made, although the friction loss in nipples less than 6 in. (152 mm) long is customarily neglected.

Two Branches in One Line of Sprinklers. These may have the same or different numbers of sprinklers. The pressure at the entrance to the two branches will always be the same. The computations starting at the end sprinklers will be duplicated for the number of open sprinklers. After the discharge from any number of sprinklers on a branch line has been computed and the pressure needed to produce the flow has been determined, the entire branch line can be considered to have the discharge characteristics of a single orifice, and the discharge constant K in the formula $Q = K\sqrt{p}$ can be determined, P being the net pressure where flows are taken from tees in the cross main.

Branches on Opposite Sides of a Cross Main. These branches may have different numbers of sprinklers open, in which case the cross-main pressure must be the higher of the two computed values. This situation increases the discharge from the branch giving the lower computed pressure, and the actual discharge must be calculated for the higher pressure using the equation

$$\frac{Q_1}{Q_2} = \sqrt{\frac{P_1}{P_2}}$$

where P_2 is taken as the higher pressure, Q_2 the corresponding increased discharge to be determined, and P_1 and Q_1 the pressure and corresponding discharge from the branch requiring only the lower pressure. This proportion and its associated concept is important in that only one pressure can be present at a particular junction point.

After the appropriate increased discharge has been determined, the two rates of flow can be combined and K calculated for the combined branches.

When sprinklers on the second branch line are assumed to have opened, starting at the cross-main sprinkler, the opened sprinkler most remote from the cross main is considered as the end sprinkler in the branch line computation, the next opened is the second, and so on, regardless of nonoperating sprinklers on the outer end of the branch.

Cross-Main Pressures. Cross-main pressures are calculated with the same procedure used for sprinklers on a single branch line, except that it is not necessary to use the trial-and-error procedure for the third and additional branch lines because the effect of change in velocity pressure with flows passing through tees in the cross main is usually negligible. The net pressure producing the flow in successive branch lines is taken as the normal pressure at the end branch line, increased by the friction loss in the pipe between the branches.

Riser Pressure. Riser pressure is taken as the normal pressure at the nearest flowing branch, increased by the total friction loss between this branch and the riser and by the velocity pressure in the cross main at the riser connection.

Friction Loss in Fittings. This friction loss is generally included in calculations only when the fitting involves a change in the direction of flow. An exception to this is the fitting immediately preceding the sprinkler. Friction loss in control, gate, and check valves and in strainers, meters, backflow devices, and similar devices is always included. The friction loss in piping between the source of supply and the opened sprinklers obviously must be included in all calculations.

Differences in elevation must be allowed for on the basis that each foot (meter) of height represents 0.433 psi (9.82 kPa/m). In multistory buildings, this may be a substantial factor. Feed mains, cross mains, and branch lines within the same system may be looped or gridded to divide the total water flowing to the design area.

Grid Systems. Many grid systems are currently being installed. The use of grid systems means that every sprinkler is fed from several directions, with a resulting reduction in pipe sizing. The hydraulic calculations required for a grid system are complex and almost impossible without the use of computers.

Water Supply Treatment

Microbiologically influenced corrosion (MIC) is now addressed in NFPA 13. In areas with water supplies known to have contributed to MIC, water supplies shall be tested and appropriately treated prior to filling or testing the metallic piping systems.

MIC is corrosion occurring on the interior of copper tubing and all types of steel piping that is accelerated by microorganisms. The overall effect is the formation of deposits or colonies and the pitting of metallic system piping in relatively short periods of time. Aside from the pinhole leaks that MIC creates, obstructions caused by tubercles can change the friction factor and the cross sectional area of the pipe.

Corrosion experts have known about MIC for decades, but the presence of MIC in fire protection systems is a relatively new phenomenon.

SUMMARY

Perhaps the most important item of an automatic fire sprinkler system is the water supply. The sprinkler system discharge criteria must be satisfied by the water supply in terms of adequacy and reliability. Adequacy refers to the pressure, rate of flow, du-

ration, and in general the amount of water present. Reliability is more subjective and dependent on the availability of the water from the source or combination of sources.

Many variables are involved in determining the water supply requirements for most sprinkler systems. System design, occupancy classifications, obstructions to discharge, and hose stream allowances are a few of the variables to be considered.

An adequate water supply is the crucial factor when a fire occurs in a fire sprinkler protected property. Sufficient water must be available to control or suppress the fire when sprinklers actuate.

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Reference to the following NFPA codes, standards, and recommended practices will provide further information on water supplies for sprinkler systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code*™
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*
NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 22, *Standard for Water Tanks for Private Fire Protection*
NFPA 291, *Recommended Practice for Fire Flow Testing and Marking of Hydrants*

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Chapter 5

Microbiologically Influenced Corrosion in Fire Sprinkler Systems

Bruce H. Clarke ■ Anthony M. Aguilera

Chapter Contents

Defining Corrosion
The Corrosion Problem
Defining MIC
Sources of MIC Infection
MIC Corrosion Process
Prevention and Treatment

Key Terms

automatic sprinkler system, corrosion (general), C-factor, Hazen-Williams formula, microbiologically influenced corrosion (MIC)

Beginning in the early 1990s, concerns began to increase about microbiologically influenced corrosion (MIC) affecting fire sprinkler systems due to multiple cases involving the abnormally rapid development of pinhole-sized leaks and highly obstructive interior biological pipe growths. Most of these occurred in systems well before the end of the system's life expectancy, after 5 to 20 years of service. However, some systems began to show signs of critical obstruction and began developing leaks in less than one year. Research into the cause of these leaks, which have greatly increased in the last two decades, has led to a growing awareness of the problem. In the past 20 years MIC has grown from a relatively unknown topic of regional discussions to one now generating widespread concern throughout several countries. MIC in fire protection systems also has become the subject of a wide array of speculation, debate, and, in some cases, gross inaccuracies.

At the time this chapter is being written, there are still few well documented time-proven solutions that are also universally accepted "best practices" throughout the fire protection industry. Although MIC and biological growth control have been extensively researched in many allied engineering fields for decades, treatment in fire sprinkler systems is relatively new. And although there are several detection and treatment systems that appear to be effective, long-term data to support overall effectiveness claims are still limited. This chapter will provide an overview of the issues related to microbiologically influenced corrosion in the fire protection industry.

For related topics, see the following chapters in Section 16: Chapter 1, "Principles of Automatic Sprinkler System Performance"; Chapter 2, "Automatic Sprinklers"; Chapter 3, "Automatic Sprinkler Systems"; and Chapter 11, "Care and Maintenance of Water-Based Extinguishing Systems."

DEFINING CORROSION

General Corrosion

Generating a universal "working definition" for MIC in fire protection is complex. And to understand the relationship of MIC and sprinkler components, general corrosion and its various causes must first be understood. One edition of *Webster's* defines corrosion as "the wearing away of materials by chemical action(s)." Another edition simply defines it as "the wearing away of material gradually." The online encyclopedia Encarta describes corrosion as "specifically being related to the gradual action of natural agents such as air or salt water on metals." All these definitions are generally true but are also very confusing to those in the fire protection industry who are looking for answers. Even definitions presented by the corrosion engineering communities, though more detailed, can at times appear somewhat contradictory and very confusing.

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Corrosion can occur from many biophysical reactions and be described from a multitude of scientific viewpoints. *General corrosion* typically refers to uniform corrosion that occurs on most unprotected metallic systems. This corrosion can be associated with the uniform rust layer seen on many steel structures. Besides rust from oxidation, several other types of general corrosion include stray current, uniform biological, galvanic, molten salt, dealloying, chemical, high temperature, and general carburization. And some specific nonbiological corrosion processes having adverse effects on fire protection sprinkler systems that must always be considered with MIC include oxygen, acid, and oxygen-acid corrosion.[1]

Microbiologically Influenced Corrosion

In contrast to general, or uniform, corrosion, MIC is a form of localized corrosion. Material is lost at discrete points instead of universally across an entire surface. There are several types of localized corrosion, including pitting, crevice, cratering, and filiform (Figure 15.5.1).

As with the various other types of corrosion, MIC can take many forms and affect different systems in unique ways. But, for the fire protection profession, an industry-specific definition can be developed. This definition captures both the causes and effects of this problem with several continuous generalities to avoid some of the current inaccuracies. Thus, microbiologically influenced corrosion in fire protection systems can be described as "an electrochemical corrosion process that is concentrated and accelerated by the activity of specific bacteria within a fire sprinkler system resulting in the premature failure of metallic system components."[2]

THE CORROSION PROBLEM

Concentrated and Accelerated Corrosion

All metallic systems normally begin to corrode to various degrees from the instant moisture contacts metal, which typically appears as general corrosion. By definition, in comparison, the MIC process is both concentrated and accelerated. With general corrosion, when moisture is introduced into a system, a thin layer of oxidation occurs relatively evenly throughout the pipe wall surface. This type of corrosion is typically not a significant concern in fire sprinkler systems and does not require treatment because it does not change a pipe's interior surface roughness (i.e., C-factor) unevenly. The rate of decay is also typically slow. A typical corrosion rate in sprinkler pipe is highly dependent on water quality, but with MIC, this relatively slow corrosion rate is abnormally accelerated and not evenly dispersed. The result changes a relatively smooth pipe to one with pits and valleys.

$$p = 4.52Q^{1.85}/(c^{1.85}d^{4.87})$$

where

p = Frictional resistance in psi/ft

Q = Flow in gpm

c = Frictional loss coefficient

d = Internal diameter of pipe

Although there has not been a detailed study on exactly what amount of pipe change (or changes in pipe wall roughness) are

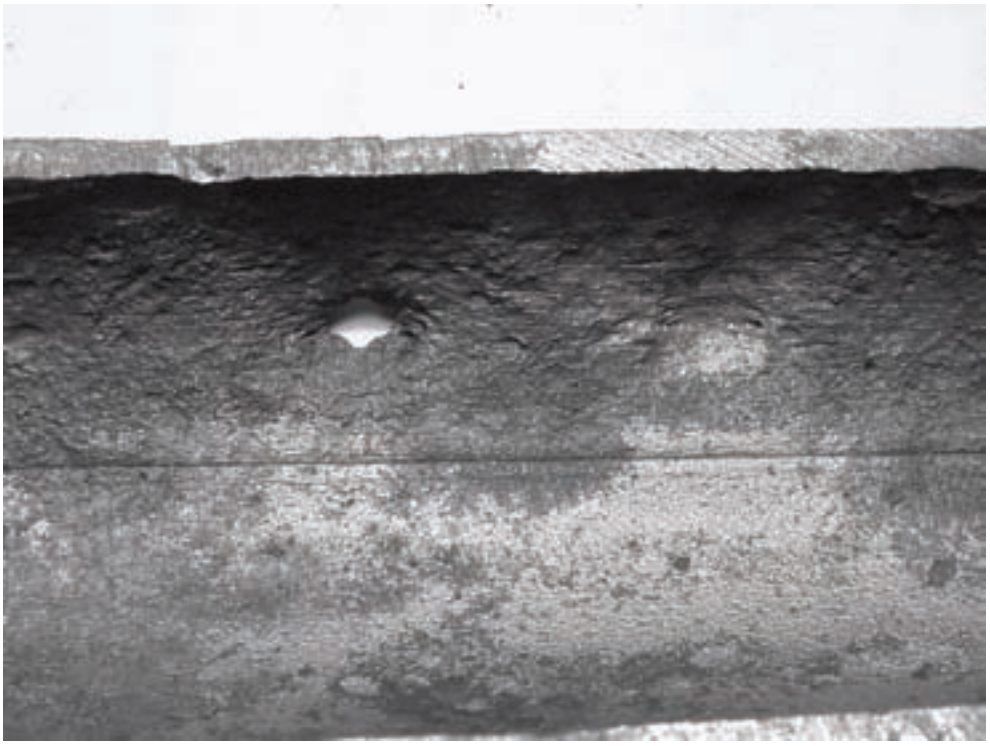

FIGURE 15.5.1 Interior Pinhole Leak

unacceptable, the Hazen-Williams formula makes several points clear:

1. Pipe surface texture is critical in sprinkler system effectiveness. With *c* based on pipe wall smoothness, any increase in roughness decreases the value of *c* and thereby increases the pressure loss in each linear foot of sprinkler pipe. Even a small amount of internal corrosion, especially in smaller main feed areas, could potentially make a system less effective in fire control.
2. Pipe diameter is a significant contributor to friction loss. Thus the smaller the pipe, the more dramatically corrosion affects friction loss and overall performance.

Although this formula is not intended to be used for nonuniform pipe surfaces, it is clear that random pockets of biological growth have the potential to affect performance. This result is especially likely if a sprinkler system has a minimum design buffer, which is regularly the case (Figure 15.5.2 and Figure 15.5.3).

MIC is the result of specific bacteria (see section on defining MIC). A multitude of bacteria is always omnipresent in all ecosystems, including the interior of sprinkler systems. Just as only a small number of bacteria on earth have the potential to cause human sickness, only a relatively small number of bacteria have the potential to cause the rapid system destruction currently linked to MIC. Thus, as defined, only a few specific bacteria concentrate and accelerate the general or uniform corrosion process.

Premature Failure

The ultimate effect of MIC in fire protection systems is the premature failure of metallic components.

Premature Failure Defined. It is clear that MIC and other related forms of corrosion cause sprinkler systems to fail prematurely. What constitutes "premature" with regard to the integrity of specific system components has not officially been defined in the industry. Long-term warranties are not typical with system components; however, with proper maintenance a sprinkler system is typically expected by the industry to last over 50 years before major repairs are required. In most cases of MIC, it has appeared that after treatment of the affected areas healthy systems can be expected to exceed this normal life expectancy.

However, as discussed, failure is a function of both integrity and function. And a system without leaks is never considered acceptable if it fails functionally (i.e., in fire control). Any time a system is in service and fails to operate as designed, it has experienced an unacceptable premature failure.

FIGURE 15.5.2 Exterior View of Pipe with No Signs of Internal Corrosion

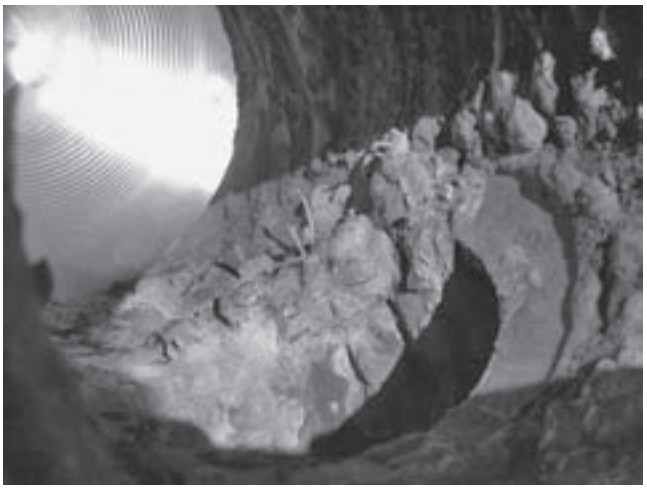

FIGURE 15.5.3 Interior View of Pipe Shown in Figure 15.5.2 with Approximately 65% Obstruction to 6 in. Tee Connection

Forms of Premature Failure. Premature failure can take two forms, both requiring individual consideration. First is the failure of a system to hold water, in other words, pinhole leaks that require component replacement (Figure 15.5.4). Leaks can cause significant damage and require immediate action. Leaks can also lead to excessive direct and indirect costs, as well as inherent risks from repeated system impairments.

In one known case, MIC-related leaks resulted in the shutdown of an aerospace manufacturer's global computing center.[3] A pinhole leak developed in a wet pipe sprinkler branch line located over the mainframe equipment of the computing center. Water from the leak not only damaged computing equipment but also resulted in over 5000 hours of lost operations time. Property damage from similar leaks at other sites has also been documented in the millions of dollars.[3,4]

The second and more concerning effect is the failure of a system to operate as designed to achieve fire control. This failure not only affects property loss but also could threaten lives. Several systems with MIC have been found with obstructed sprinkler drops, the result of debris generated as a by-product of microbial activity (called biofilm or biosludge). Many in the industry have found systems with feed mains over 60 percent obstructed from biological growth.[4,5] An analysis of corrosion

FIGURE 15.5.4 Exterior Pinhole

buildup indicates that thousands of pounds of debris can accumulate in medium-sized piping.[6] This buildup of debris presents an obvious hydraulic concern as many affected sprinkler systems today will not provide fire control as the required discharge criteria, in terms of flow and pressure, are not available due to obstruction and associated frictional pressure loss.

Extent of MIC in the Sprinkler Industry

Currently only a limited number of credible national studies on the extent of the MIC problem in the fire protection industry exist. Most data are primarily anecdotal. No detailed comparative engineering-based study on effectiveness of the various treatment options currently being marketed has been completed. Complicating this lack of data, reported MIC cases rarely have secondary analysis to differentiate MIC as a primary contributing cause over other types of corrosion involving similar symptoms. Equally important, follow-up engineering data on treatment are rarely published.

The results of MIC in other industries are well documented. The Energy and Power Research Institute has estimated that corrosion in the U.S. electric power industry costs $5 billion to $10 billion each year. Corrosion is said to be the culprit in half the forced outages each year in steam generating plants.[7] And data collected from before the 2001 U.S. power shortage showed corrosion to be the primary factor in more than 10 percent of U.S. power generation costs.[7] In the gas and nuclear industries, MIC is specifically said to account for 15 to 30 percent of corrosion-related failures.[8] And reports indicate that to prevent such problems, North American companies spend in excess of $1.5 billion per year (over $7 billion globally) on treatment chemicals to prevent microbial corrosion and fouling. Similar information, as mentioned, is not available for the fire protection industry. Although several industry groups have been attempting to compile data on this problem for several years, only two national studies have been published for the fire protection industry.[9,10] Thus, the true extent and cost of the problem are still not fully known.

In 1996, the National Fire Sprinkler Association sent out a questionnaire in its quarterly membership magazine requesting member information on sprinkler system failures that have been experienced. Results yielded approximately 40 responses from across the United States and Canada, which appeared to indicate that MIC was a "widespread problem." However, due to the reasons previously stated, the quality of analytical techniques used by respondents to confirm MIC as a cause and the lack of investigation after detection and treatment bring the results of this study into question.

The only other related studies and data compilations completed have been conducted by FM Global. In its studies, in losses involving sprinkler systems, corrosion is the fifth leading cause of system failures. This conclusion is based on a review of data from 1988 to 1997. In another study by the FM Metallurgical Laboratory between 1994 and 2000 reviewing 155 cases of sprinkler system leaks, MIC was found to be present in approximately 40 percent of cases. Details on whether the presence of MIC directly caused leaks were not indicated in all these cases.[10] In another FM study of piping field samples between 1991 and 2002, over 60 percent of these failures are attributed to MIC.[11]

Pinning the Blame

Part of the problem in obtaining detailed conclusive evidence is the complexity and cost of such investigations. This problem is also a major point of frustration with owners experiencing these types of problems. Due to the nature of electrochemical corrosion, most corrosion engineers agree that the degree to which

MIC specifically increases or contributes to general corrosion can never be conclusively determined. In fact, the complex biological interactions between bacteria and host materials are still not fully understood in many cases. There are simply too many variables and uncertainties that affect all corrosion reactions, especially those involving bacterial interactions. Thus, a percentage of blame or rate of corrosion from MIC likely cannot be numerically defined in any study. Any database generated at this point will likely list only reported cases, not confirmed cases. Thus, the best that can be achieved in the future is a regularly updated database indicating where reported cases are occurring, method of failure detection, interior condition of pipe, methods of testing, and treatment with future corrosion monitoring.

Materials Affected by MIC

Although steel sprinkler pipe is the typically observed first point of failure, sprinkler orifice caps, control valves, fittings, and supply tanks may also be subject to damage from MIC. Numerous cases of obstructive growth and pinhole leaks associated with MIC have been found within 20 feet of the discharge side of site fire pumps—an interesting phenomenon due to the velocity of waterflow at this point in the system piping. Although evidence suggests that only metallic components are susceptible to MIC, it is clear that some grades and alloys of steel are definitely more susceptible than others. As an example, certain grades of stainless steel are more susceptible than regular steel pipe, whereas others appear to show signs of resistivity. And although plastic components, such as underground water mains, are not subject to direct MIC, they are subject to the effects of biofouling or bacterial debris blockage from upstream corrosion activity.

DEFINING MIC

Oxygen Tolerance

MIC-related bacteria are classified primarily by oxygen tolerance; that is, they are aerobic or anaerobic. Aerobic bacteria require oxygen to flourish and reproduce. Anaerobic bacteria do not require oxygen to flourish and reproduce.[9] The most damaging MIC appears to take place within a highly complex community with multiple species of bacteria. This community includes not only aerobic and anaerobic bacteria but also facultative bacteria, those MIC bacteria that function in both aerobic and anaerobic environments. All three types of bacteria can play a role in the somewhat random interactions that can occur in microbiologically influenced corrosion.[12]

Metabolism

In defining MIC bacteria further, classification is not absolute and can become confusing. The most commonly used method of categorizing bacteria associated with MIC is by metabolism. These categories are basically definitions of what each bacteria type eats (or metabolizes) and excretes as a by-product. As these terms imply, where plants use photosynthesis (i.e., light) to develop energy, bacteria use chemosynthesis (i.e., eating/breathing various chemicals or minerals) to sustain life. Metabolic classifications are not universally replicated among scientists and can be somewhat confusing. A single bacteria type may fall under more than one metabolic definition. Some of the commonly referenced categories include sulfur-reducing bacteria, metal-reducing bacteria, acid-producing bacteria, iron-depositing bacteria, low-nutrient bacteria, iron-related bacteria, iron-reducing bacteria, iron-oxidizing bacteria, sulfate-oxidizing bacteria, slime-forming bacteria, and iron bacteria.[9,12–14]

Scientific Nomenclature

Finally, all bacteria (i.e., all plants and animals) can be classified by their scientific name under phylum, class, order, family, genus, and species. For example, one type of sulfate-reducing bacteria is anaerobic and metabolizes sulfate to sulfide. The sulfate-reducing bacteria group includes the genera *Desulfovibrio, Desulfobacter,* and *Desulformaculum.*[2] All are of the phylum Thiopneutes, which interestingly translates from Greek to "sulfur-breathers."

SOURCES OF MIC INFECTION

Although there are no conclusive relational studies in the fire protection industry, as noted there are growing beliefs that a sprinkler system's water supply is not the only (and possibly primary) source of bacterial infection. Bacteria capable of causing MIC are potentially present in soil, air, and cutting oils as well as water. Thus, the manufacture, shipping, storage, and flushing of system materials should be addressed in all MIC investigations. MIC does not occur only in water-filled systems. Dry pipe systems are also susceptible. Dry systems may even be more susceptible to damage than are wet systems, due to the humidified atmosphere that is created after trip testing. A trip test and subsequent drain can create the right atmospheric moisture content for some bacterial colonies to thrive. Complete drainage and the subsequent use of truly dried air or nitrogen gas appear to mitigate this problem. With regard to tubercle growth alone, dissolved oxygen content, not bacteria, may be the only considerable factor in prevention.

MIC CORROSION PROCESS

As with other forms of corrosion, MIC removes material through a series of electrochemical interactions. As such, both an electrical component and a chemical component occur with MIC. The electrical component occurs through electron transfer. Electron transfer removes pipe wall material one electron at a time. With MIC, this exact interaction is highly dependent on the specific bacteria involved. Within a sprinkler system, metallic parts become anodic in relation to the cathodic corrosion cell and surrounding water. Basic cathodic depolarization occurs as electrons are stripped away through various forms of oxidation and are pulled to an atom with another electrical potential. Although many of the complex cellular interactions of bacteria are still unclear and can vary by system, there appear to

be several somewhat universal steps in the MIC process. They are as follows:[2]

1. Bacteria enter the system, attach to metallic components, and begin to rapidly colonize and reproduce.
2. Aerobic colonies metabolize nutrients from the water and/or the metal surfaces they are attached to and, subsequently, excrete a polymer film by-product that bonds together to form crustaceous nodules called tubercles.
3. Tubercles and associated biofilms create microenvironments on the metallic material surface (under the tubercles). Tubercles are hard protective shells formed by biological activity. Tubercles typically have an open interior fluid cavity over the corrosion floor area with an approximate 3–4 pH (Figure 15.5.5).
4. The underdeposit area (i.e., under the tubercles) becomes oxygen depleted (i.e., anaerobic and anodic) in relation to the surrounding system's water or air, which remains aerobic and cathodic. Thus, electrons in the anodic metal flow to the cathode through a reduction reaction.
5. Underdeposit anaerobic bacteria metabolize pipe wall materials and excrete acids (such as acetic acid) as by-products, which are very aggressive to the carbon steels used in sprinkler piping. Relative acidity and alkalinity levels within the tubercle shells are reduced to an approximate pH of 2–4, which chemically attack the metallic component surface. On painted sprinkler piping, it is common to observe blisters where through-wall penetration has occurred. Testing of the fluid within these blisters has shown a pH of less than 3.

The described corrosion process can continue indefinitely until the aerobic and anaerobic bacteria in the system are killed. The tubercles created from bacterial colonization must also be broken down to destroy the underdeposit microenvironment. Even without bacteria in the underdeposit of a corrosion cell, the process can continue indefinitely, as the corrosion chain in its final phases is no longer reliant on their activity.

PREVENTION AND TREATMENT

References from Allied Fields

Currently, the fire protection industry has a very limited number of directly usable references supported by scientific data. However, there is excellent information on data from other industries. The National Association of Corrosion Engineers (NACE) has published multiple studies about MIC detection and treatment for many years. The American Society for Testing and Materials (ASTM) offers several publications on proper bacterial testing practices. Also the American Water Works Association (AWWA) offers standards describing the proper management of the somewhat hazardous chemicals typically used in injection devices attached to sprinkler systems for microbial control.

Fire Protection Codes and Standards

The National Fire Protection Association (NFPA) also addresses MIC. NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems,* discusses MIC treatment, inspection, and detection in some detail. NFPA 13,

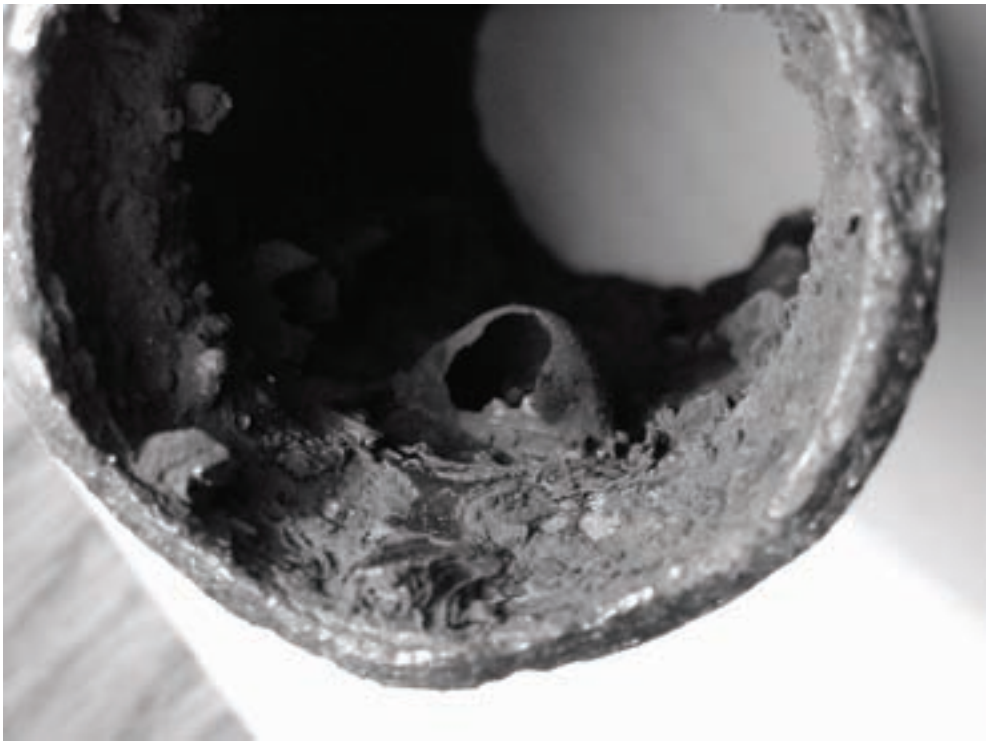

FIGURE 15.5.5 Interior Tubercle

Standard for the Installation of Sprinkler Systems, contains a requirement that provides more guidance. In covering water supply treatment, NFPA 13 states:

> Water supplies and environmental conditions shall be evaluated for the existence of microbes and conditions that contribute to microbiologically influenced corrosion (MIC). Where conditions are found that contribute to MIC, the owner(s) shall notify the sprinkler system installer and a plan shall be developed to treat the system. . . .

Although this requirement has generated curiosity, the resulting questions about effective treatment remain. NPFA 13 indicates that water supplies "shall be evaluated for the existence of microbes and conditions that contribute to microbiologically influenced corrosion (MIC)" . . . and if present or suspected . . . "a plan shall be developed to treat the system." The who, how, and when are still in debate by those addressing this issue. Who is best qualified to make the determination of when a failure is the result of MIC and if a biocidal treatment program will prevent all future failures? And how is a system best tested (i.e., with the most technical accuracy and cost-effectiveness) to confirm MIC? Almost anything requiring laboratory work can be overtested. And undertesting can lead to a false sense of security. Answers to these questions are still evolving.

Operational Considerations

As the industry continues to develop methods to treat and prevent MIC, building owners are faced with the challenge of managing associated risks to their assets and business operations. At-risk businesses should review the interdependence of various operations to identify critical locations.

Proper Diagnosis

The analysis required to properly select a course of action to address MIC is typically outside the scope of most sprinkler contractors and engineers. Thus, until treatment methods become universally proven and standardized, the most critical step in proper mitigation begins with the selection of a qualified corrosion control consultant.

With the wrong choice, a large amount of money can be spent on a problem that may not be correctable. A poor treatment choice could actually accelerate the corrosion rate and increase the affected area beyond that experienced before treatment. The company chosen to determine treatment must have detailed knowledge not only of microbial corrosion control but also of metallurgy and sprinkler system dynamics. Fire sprinkler systems have flow characteristics and concerns that are much different from other industrial processes and systems where MIC is typically addressed.

Specific Considerations for Fire Sprinkler Systems

Other industries deal with MIC in systems containing fluids that are either always static or always flowing, such as in cooling towers. Unlike sprinkler systems, dynamic systems have flow rates that are relatively constant, requiring that prescribed chemical dose rates be constant. A constant flow rate does not occur in sprinkler systems. Variable differences are seen with system drains and refills, inspector testing, and main drain tests. The dose rate for each of these flows must be considered to ensure that the chemical injection rate is always effective. Other industrial systems also have multiple points where biocidal chemicals can be injected. In contrast, sprinkler system water can realistically only be treated at system risers, backflow apparatus, or suction tanks.

Finally, it must again be stated that it is critical to understand that premature system failure can be a function of both bacterial infection and water quality that is incompatible with components. In the majority of premature system failure cases, water chemistry or poor design may be the only likely factors requiring consideration. A high bacterial count does not always indicate that MIC will occur, and conversely, a low bacterial count does not discount that MIC has occurred in the past, in a given system, and will not occur again in the near future.

Detection in Existing Systems

In existing systems suspected of being infected, the first step is to have all possible water supply sources (tank, city mains, ponds, rivers, etc.) and the interior of each system tested for bacterial levels and activity. Although current technology makes this detection easy, analysis of the results is somewhat complex. And, as previously stated, in determining treatment, bacterial detection is worthless without factoring in water quality. The laboratory used for analysis should be capable of giving conclusive details of water supply mineral and chemical levels, pipe wall deposit compositions, and type-specific bacterial counts. Multiple tests are used in these analyses from simple bacterial incubation with visual inspection to sulfur print or DNA testing. Obviously, not all tests are required or are necessarily needed. Current preferred analysis methods run the spectrum, depending on the consultant chosen. Costs for such testing can also vary widely.

Mitigation in Affected Systems

When MIC is confirmed in operational systems, the building owner is first faced with a fundamental question. Can the system be salvaged (i.e., cleaned) or does it have to be replaced? Currently, this cost/benefit decision requires further study and is not supported one way or the other by documented best practices in the fire protection industry.

Pipe cleaning is typically an option when corrosion (i.e., pitting) is not excessive. However, *excessive* is a relative term. The after-cleaning quality of the pipe must be considered, both for future longevity and system hydraulics. The resulting frictional loss from numerous pits after cleaning could affect system performance. This result, of course, is typically outside the scope of work of most corrosion control consultants. When replacement materials are chosen that are different than those of the original system, they must also be accounted for in hydraulic analysis of the posttreated system. Case studies suggest that

pipe cleaning may remove corrosion by-products that are, in effect, stopping the flow of water through existing pipe penetrations, subsequently resulting in leaks.[12] Prudence dictates that complete mitigation must include some form of treatment once pipes are cleaned.

Prevention in New Systems

In new systems, it is critical that susceptibility be determined before any systems are filled or tested with any water. If water tests are positive for MIC-related bacteria, a chemical injection system must be installed and used from the first fill. This includes hydrostatic testing and preliminary fills. The treatment methodology must also consider that water delivery of treatment chemicals might not effectively treat high spots, remote areas, or areas that trap air within the system.

If MIC is anticipated, one form of risk reduction may be to specify thicker piping in the design. Although this option only tends to buy time, it may serve as a prudent measure until universally accepted treatment methods are developed. Thicker walls buy time, not because they are less susceptible to MIC—a point on which evidence to date is inconclusive—but simply because a thicker wall has more material to corrode before a through-wall leak develops.

Another possibility in design is to remove the risk of leaks before MIC treatment is even evaluated. Areas such as those occupied by critical energized equipment can often be addressed by removing overhead sprinkler piping and limiting leak exposure through use of sidewall sprinkler coverage. Where it is not feasible to relocate large feed mains, piping can be sleeved so as not to permit potential leaks to contact energized equipment. Although these efforts provide some measure of immediate relief, they do not address the root cause or present a long-term solution to the problem.

Finally, the frequency of sprinkler and waterflow device testing must be addressed. Most agree that repeated draining and refilling of sprinkler systems can increase both biological and nonbiological forms of corrosion. Draining and refilling provide nutrients and oxygen to bacterial colonies and oxygen for general tuberculation. Some facilities have noted substantial reductions in the frequency of leaks by reducing the frequency of drain and alarm testing.

It is critical to note that once a system is filled with infected water, treatment can become exponentially more complex because any future treatment from a chemical injection system must now be effective in remote and stagnant system legs. In bacteria-positive areas, several additional water quality tests should be completed throughout the first year of service to ensure that contamination has not occurred from any other sources.

Chemical Injection

Once system components have been cleaned and sterilized or replaced, a chemical injection system must be installed to prevent recurrence. Once installed, this system will be required to be operational continuously. As with any other mechanical system, this system will require continuous preventive maintenance.

Several commercially available chemical injection systems have been specifically designed for installation on fire protection systems. Some simply use existing hardware and chemicals modified from MIC treatment in other utilities, such as cooling towers. At the time of this writing, none of the systems currently available were believed to be specifically listed or approved for use as a sprinkler system component. Although most systems appear to be effective when properly installed and maintained, reliability and effectiveness have not been time-proven when compared with other industrial system benchmarks. Past references should always be investigated with any choice.

Most injection systems currently available are designed to work with specific chemicals. These selected chemicals and dose rates are critical. Some bacteria can develop chemical resistance over time if doses are not strong enough and bacteria are not quickly killed. A small number of bacteria believed to be related to MIC (such as the genera *Bacillus* and *Clostridium*) are known to have the ability to convert to a spore state when they encounter adverse conditions that are not lethal.[2,15] Spores are impervious to penetration by most chemicals and can thus survive biocide treatments indefinitely. Although subsequent treatments may slow or stop their activity, spores will reappear if and when treatments are stopped and resume colonization. With a weak chemical attack, bacteria may also become resistant to the chemicals chosen.

As with other factors involved in treatment, the choice of chemical depends on the consultant. These chemicals generally include penetrants and biodispersants to break up the tubercles that protect underdeposit colonies, a biocide to kill the bacteria in the colonies, and a corrosion inhibitor to protect the interior surfaces of the system.

When such a system is chosen, the applicable authority having jurisdiction (AHJ) should be consulted. In addition to frictional loss concerns mentioned from changes in pipe surface roughness, increased backflow prevention hardware may be required. This could mean a pressure drop of 10 psi (0.7 bar) or more to sprinkler systems in addition to that created by pitting if cleaning is chosen. In new system designs, added alarm system contacts should also be planned to monitor injection system chemical levels, operational status, and trouble conditions such as loss of power. Many pre-engineered systems provide contact points for these signals. As with fire detection, the perceived "best choice" is at the discretion of the person choosing, and opinions on this subject are highly variable.

Unlike other industrial systems treated for MIC, several unique interactions must be considered. First, sprinkler systems are typically located directly over people. The chemicals used must therefore be nontoxic in contemplation of accidental discharge or exposure to fire fighters under fire conditions. The effect of chosen chemicals on fire fighting (i.e., heat absorption) and chemical reaction with fire (i.e., heat) also needs consideration. Second, system designs typically place water discharge (such as from an inspector's test ports) into foliage or biologically sensitive drains and dry wells. Most municipal wastewater treatment plants (to which typical drains ultimately flow) require bacterial activity to decompose waste. Too large a quantity of biocides in municipal drains could be a problem.

In conclusion, a complete toxicity review with the highest possible biocidal chemical concentration must be completed. As much as possible, these chemicals should be noncombustible, colorless, odorless, and nontoxic. These chemicals must also be nondeteriorating to rubbers and polymers such as those used on pipe couplings, sprinkler O-rings, and valves. Chemical storage should also be reviewed, as several chemicals currently in use degrade rapidly with heat and may create relatively toxic vapors.

Opinions of which chemicals are believed to be "most effective" in control vary. Choices are available from those currently used for treatment in cooling towers and boilers to specifically patented compounds for fire protection systems. Some of the more common chemicals currently in use specifically for microbial control in sprinkler systems include quaternary ammonium compounds, organosulfur compounds, bromines, carbamates, isothiazalone, phosphates, and chlorines. Sodium silicate is effectively used in bulk quantities by several municipalities as an inhibitor, but this use should be avoided for individual systems due to the potential for sprinkler plugging that overdosing can cause. At the writing of this article, no chemical can conclusively be said to be proven as the most effective. The chemical choice may greatly depend on the bacteria present and system water quality.

SUMMARY

Current testing and treatment options can be confusing. Treatment is slowly evolving and research is continuing. Several industry groups, allied groups, and insurance companies are looking at the problem and applicable solutions. Many universities, governments, and private industry groups also continue to research microbial control in general industry, as they have for the past several decades. These efforts will continue to provide improved treatment options in our industry.

As the need to address this problem draws on the industry's creativity for resolution, prudent thinking requires us to evaluate each solution's impact on overall sprinkler system integrity and performance. In light of this problem, the overwhelming value of sprinkler systems should not be regarded as tarnished or tainted. Although some with repeated MIC problems may view sprinklers as a risk to property, the reduction of risk to life and property from fire these systems provide should never be overshadowed.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on microbiologically induced corrosion in fire sprinkler systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*

Chapter 6

Water Distribution

John D. Jensen

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Key Terms

affinity law, cavitation, discharge specific speed (N_d), fire pump (centrifugal), fire pump controller, fire pump (positive displacement), impeller, net positive suction head (available), net positive suction head (pump), total head (H), water hammer

This chapter covers the operating principles of stationary pumps used for fire protection, the methods of driving them, and the testing and maintenance procedures that should be followed to keep them in top operating condition.

Fire pumps are used to increase the water supply pressure available from public mains, gravity tanks, reservoirs, or other sources. The first modern fire pumps were the wheel-and-crank reciprocating-type, belt-driven pumps from mill machinery. If plant operations were stopped during a fire, the pump could not operate. At best, these pumps were inadequate.

Better water supplies became necessary as automatic sprinkler systems became more common, and mill pumps were replaced by rotary, or displacement, pumps driven by friction drive from horizontal waterwheels supplying power to the plant. As steam supplanted waterpower, the reciprocating steam pump was adopted for fire protection. For many years the Underwriter duplex, double-acting, direct-steam-driven unit was universally accepted as the "standard" fire pump.

Today, the stationary centrifugal and positive displacement fire pump is standard (Figures 15.6.1 and 15.6.2). Its compactness, reliability, easy maintenance and hydraulic characteristics, and the variety of available drivers—electric motors, steam turbines, and diesel engines—have made the Underwriter pump obsolete, although not entirely extinct.

Although the centrifugal fire pump is most widely used and is the basis for this chapter, the positive displacement fire pump is briefly defined and described.

The NFPA standard on fire pumps is NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection* (hereinafter referred to NFPA 20). Other NFPA documents that contain information on fire pumps include NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam;* NFPA 13, *Standard for the Installation of Sprinkler Systems;* NFPA 14, *Standard for the Installation of Standpipe and Hose Systems;* NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection;* NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems;* NFPA 22, *Standard for Water Tanks for Private Fire Protection;* NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems* (hereinafter referred to as NFPA 25); and NFPA 750, *Standard on Water Mist Fire Protection Systems.*

For related topics, see Section 15, Chapter 7, "Fire Pump Controllers and Power Supply Arrangments for Motor-Driven Fire Pumps."

CENTRIFUGAL FIRE PUMP

An outstanding feature of a horizontal or vertical centrifugal pump is the relation of discharge to pressure at constant speed; that is, when the pressure head is increased, the discharge is reduced. With positive displacement pumps, the rated capacity can be maintained against any head if the power is adequate to operate the pump at the rated speed and if the pump, fittings, and piping can withstand the pressure.

Listed horizontal and vertical fire pumps are available with rated capacities from 25 to 5000 gpm (95 to 18 925 L/min). Pressure ratings range from 40 to 394 psi (276 to 2758 kPa) for horizontal pumps and 26 to 510 psi (517 to 3448 kPa) for vertical turbine pumps. Listed centrifugal fire pump designs include horizontal-end-suction, vertical in-line, split-case (horizontal and vertical shaft),

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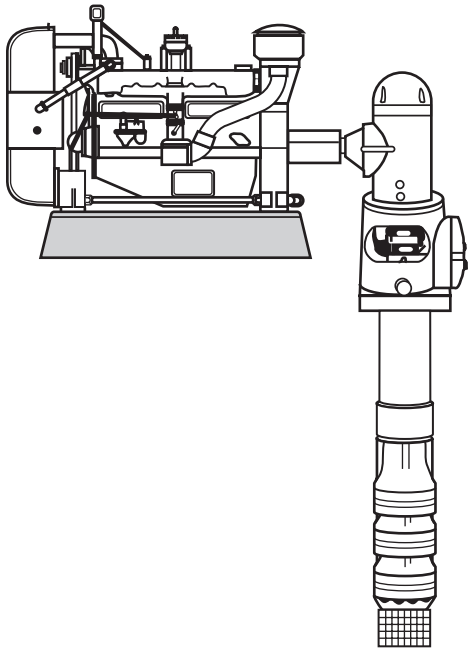


FIGURE 15.6.1 Vertical Turbine Fire Pump with a Right-Angle Gear and Engine Drive

and vertical-turbine types. Vertical turbine pumps are centrifugal pumps with one or more impellers discharging into one or more bowls and a vertical educator or column pipe that connects the bowls to the discharge head on which the pump driver may be mounted. It is anticipated that larger-capacity fire pumps will be listed in the future (Table 15.6.1).

The "size" of a horizontal centrifugal pump is generally the diameter of the discharge outlet. However, it is sometimes indicated by both suction and discharge pipe flange diameters. The size of a vertical turbine pump is the diameter of the pump bowl (see Figure 15.6.1).

POSITIVE DISPLACEMENT FIRE PUMP

Positive displacement fire pumps have been used in fire protection for many years. In fact, they were the first pump type to be used for mobile fire truck applications. Positive displacement pumps by nature are capable of high discharge pressures, something the fire service requires for many types of fire fighting.

Positive displacement, as defined by the Hydraulic Institute, essentially means that the same volume of liquid is displaced per revolution of the pumping element or rotor. Many different styles of positive displacement pumps exist; however, this short synopsis is not meant to define the wide variety of positive displacement pumps. Rather, it is intended to advise the fire protection professional that positive displacement pumps are vastly different from the more familiar centrifugal pumps.

Positive displacement pumps in general operate at lower revolutions per minute than centrifugal pumps do, can generate very high discharge pressures, and are capable of pumping a wide variety of fluids, both thin and thick.

Starting in the 1960s, gear pumps have been used to pump foam concentrate agents both on fire truck and fixed foam systems for stationary uses such as aircraft hangars, flammable liquid storage tank fire protection, and refinery process units.

Centrifugal pumps are not well suited to pumping foam concentrates because centrifugal pumps do not offer the necessary slower operating speeds, low foam agitation and shear, self-priming vapor locking, and other critical features that positive displacement pumps offer.

NFPA 20 recognizes that positive displacement pumps are suited for foam concentrate and the low-flow/high-pressure requirements of water mist systems. The 1999 edition of NFPA 20 was expanded to include an entire chapter on positive displacement pumps. Adding that chapter was necessary because of the increasing application of these types of pumps in the fire protection industry and their suitability for foam and water mist systems. The chapter has specific language that guides users and design engineers on selecting and applying a positive displacement pump for both foam and water service.

A key part of this chapter in NFPA 20 is the requirement for the positive displacement pump to be listed or approved for the intended service, meaning that the positive displacement pump must have a third-party listing and verification of performance standards whether the pump is used for foam or water service.

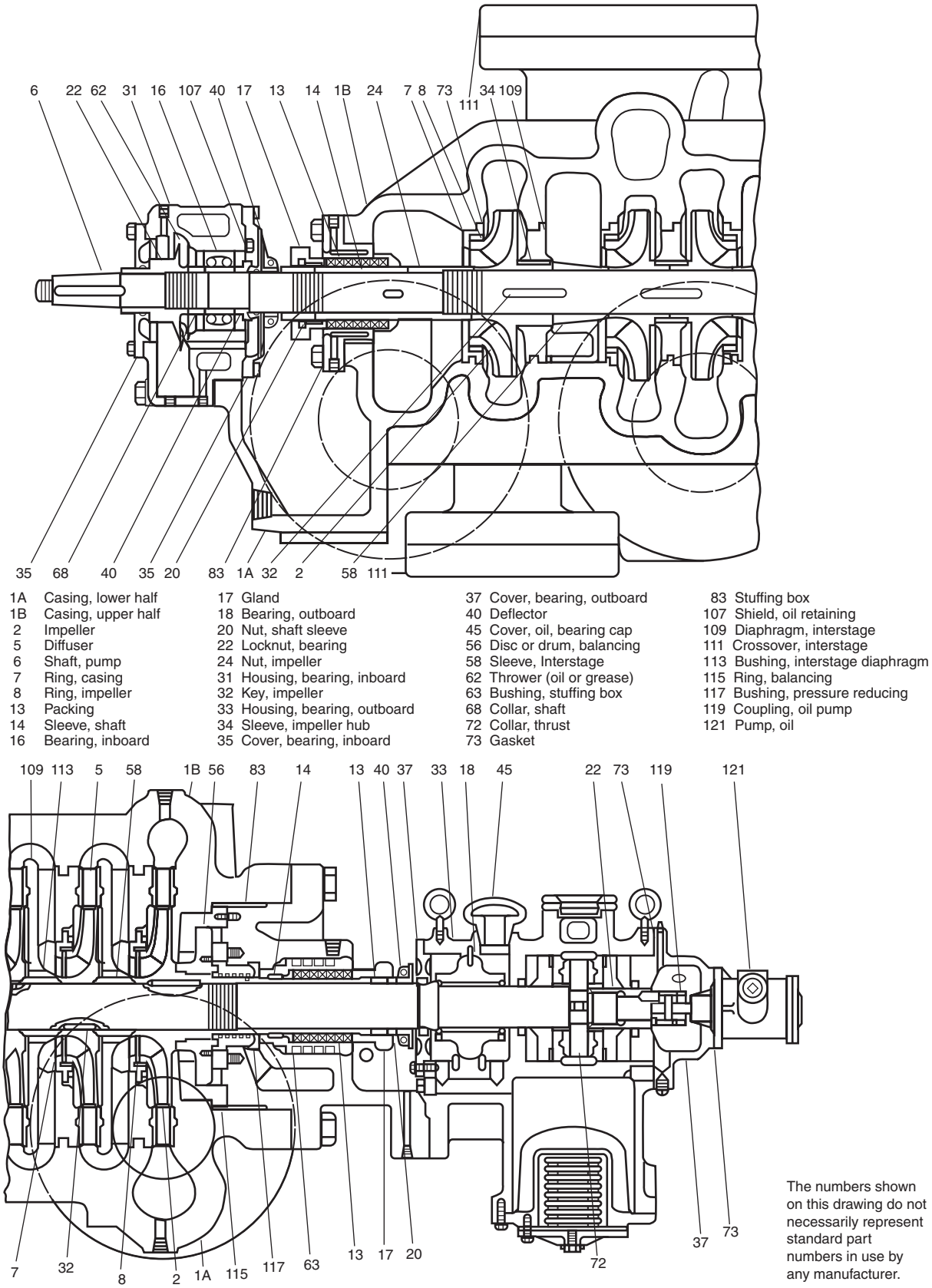
PRINCIPLES OF OPERATION

The two major components of a centrifugal pump are a disc, called the impeller, and the casing in which it rotates (Figure 15.6.3). It operates by converting kinetic energy to velocity and pressure energy. Power from the driver, which is an electric motor, a diesel engine, or a steam turbine, is transmitted to the pump through the shaft, rotating the impeller at high speed. The way that energy is converted varies with the type of pump. The major classes are known as radial flow and mixed flow. These pumps are identified by the direction of flow through the impeller, with reference to the axis of rotation (Figure 15.6.4).

The horizontal-shaft, single-stage, double-suction volute pump is the type most commonly applied to fire protection service and to commercial use (Figure 15.6.5). In these pumps, waterflow from the suction inlet in the casing divides and enters the impeller from each side through an opening called the "eye." Rotation of the impeller drives the water by centrifugal force from the eye to the rim and through the casing volute to the pump discharge outlet. The kinetic energy acquired by the water in its passage through the impeller is converted to pressure energy by gradual reduction of velocity in the volute.

Multistage Pumps

In order to give high pressure, two or more impellers and casings can be assembled on one shaft as a single unit, forming a multistage pump (see Figure 15.6.2). The discharge from the first stage enters the suction of the second stage, discharge from the second stage enters the suction of the third, and so on. The pump capacity is the rating in gal per min (L/min) of one stage; the pressure rating is the sum of the pressure ratings of the individual stages, minus a small head loss.



1A Casing, lower half
1B Casing, upper half
2 Impeller
5 Diffuser
6 Shaft, pump
7 Ring, casing
8 Ring, impeller
13 Packing
14 Sleeve, shaft
16 Bearing, inboard
17 Gland
18 Bearing, outboard
20 Nut, shaft sleeve
22 Locknut, bearing
24 Nut, impeller
31 Housing, bearing, inboard
32 Key, impeller
33 Housing, bearing, outboard
34 Sleeve, impeller hub
35 Cover, bearing, inboard
37 Cover, bearing, outboard
40 Deflector
45 Cover, oil, bearing cap
56 Disc or drum, balancing
58 Sleeve, Interstage
62 Thrower (oil or grease)
63 Bushing, stuffing box
68 Collar, shaft
72 Collar, thrust
73 Gasket
83 Stuffing box
107 Shield, oil retaining
109 Diaphragm, interstage
111 Crossover, interstage
113 Bushing, interstage diaphragm
115 Ring, balancing
117 Bushing, pressure reducing
119 Coupling, oil pump
121 Pump, oil

The numbers shown on this drawing do not necessarily represent standard part numbers in use by any manufacturer.

FIGURE 15.6.2 Cross Section of a Typical Multistage Centrifugal Pump (Source: Hydraulic Institute, http://www.pumps.org)

TABLE 15.6.1 Pump Types and Their Pressure and Capacity Ranges

	Pressure Range		Capacity Range	
Pump Type	*psi*	*kPa*	*gpm*	*L/sec*
Horizontal-end-suction	40–186	276–1282	25–750	1.6–31.5
Suction in-line	40–186	276–1282	25–750	1.6–31.5
Split case (horizontal and vertical)	40–294	276–2027	150–5000	9.5–315.4
Vertical turbine	25–510	179–3516	250–5000	15.8–315.4

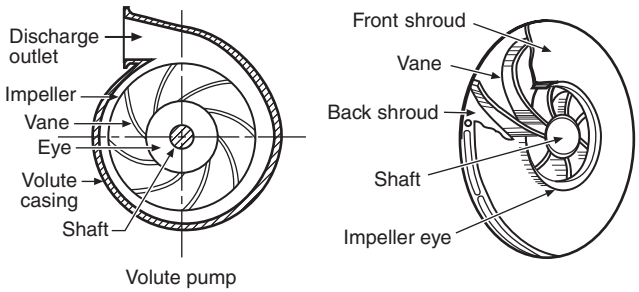


FIGURE 15.6.3 Volute Casing and Impeller

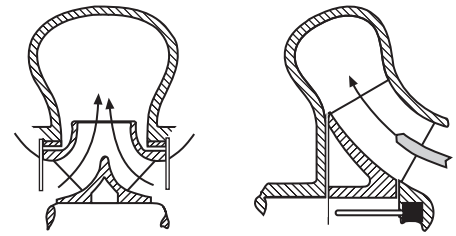


FIGURE 15.6.4 Two Major Types of Fire Pumps

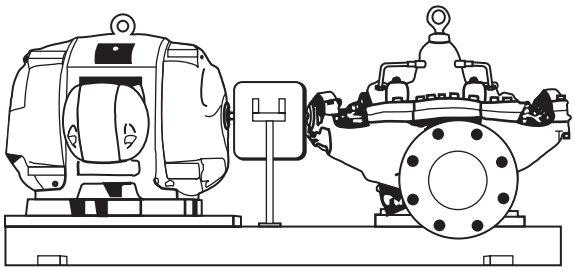


FIGURE 15.6.5 Horizontal Shaft, Single-Stage Centrifugal Pump, with Cutaway View of the Pump

High-Pressure Service Pumps

Single-stage pumps can be designed for high-pressure service by increasing the impeller diameter or the rated speed. In addition, single-stage pumps can also be installed in series to achieve the necessary pressure. In some high-rise buildings, vertical turbine pumps are installed in a subbasement and take suction from a sump pit. As shown in Table 15.6.1, these pumps are capable of developing pressures in excess of 500 psi (3448 kPa).

CHARACTERISTIC PUMP CURVES

The characteristic curves (Figure 15.6.6) of a horizontal-, centrifugal-, or vertical-turbine-type pump are as follows:

1. Total head versus discharge (ft of head or psi of pressure versus gpm)
2. Brake horsepower versus discharge
3. Efficiency versus discharge (water hp/input hp versus gpm)

Illustrated curves in Figure 15.6.6 are for a 500-gpm, 100-psi, 2000-rpm, diesel-engine-drive pump with a 14 in. impeller. Note that the shutoff point (churn pressure) is 110 psi; the maximum brake horsepower is 55; and the maximum efficiency is 75 percent at the overload point (150 percent of rated capacity). Head is 90 psi at the 65 percent minimum required at overload.

These curves assume that the pump is operated at a constant speed equal to its rated rpm (revolutions per minute). In

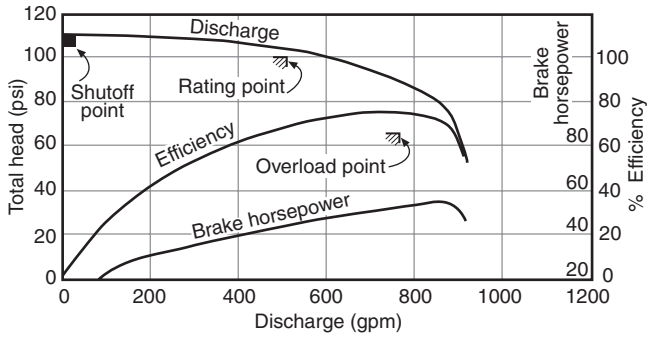


FIGURE 15.6.6 Typical Centrifugal Fire Pump Characteristic Curves

actual service, the speed of the driver varies with changes in the flow capacity.

Curves for positive displacement–type pumps are shown in Figure 15.6.7.

The flow and pressure ratings of commercial pumps are usually established on the basis of maximum efficiency and desired speed. Impellers can be designed for flat, medium, or steep head-discharge characteristics, as required for various uses. Figure 15.6.8 illustrates how the head-discharge curve is affected by the diameter of the eye, the width of the impeller, the number of vanes, and the shape or angle of the vanes.

TOTAL HEAD

The total head of a pump is the energy imparted to the liquid as it passes through the pump. It may be expressed in various units of pressure, but for fire protection it is generally given in pounds per square inch (psi) or kilopascals (kPa), or in feet (ft) or meters (m) of liquid measured vertically. The total head is calculated by subtracting the energy in the incoming liquid from the energy in the discharging liquid. The total head (H) of a pump is calculated by the formula

$$H = h_d + h_{Vd} - h_s - h_{Vs}$$

where

H = Total head (ft [m])

h_d = Discharge head (ft [m])

$h_{Vd} = \frac{Vd^2}{2g}$ = discharge velocity head (ft [m])

h_s = Total suction head (ft [m])

$h_{Vs} = \frac{Vv^2}{2g}$ = suction velocity head (ft [m])

V = Average velocity (ft/sec [m/sec])

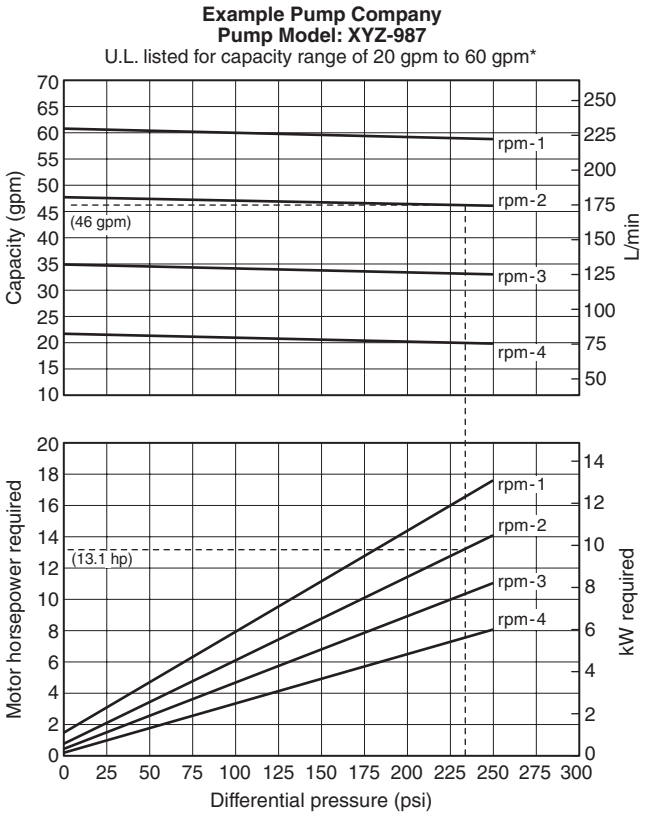
g = Acceleration due to gravity (32.2 ft/sec^2 [9.81 m/sec^2])

For a horizontal split-case pump, the individual heads (h_V) are measured at the pump discharge nozzle flange and at the suction flange (Figure 15.6.9). The heads are read from pressure gauges attached to the pump flanges. The velocity head must be calculated for the volume of liquid passing through the flanges. One expression of this relationship is

$$h_v = \frac{V^2}{2g}$$

If the flanges have the same diameters, there will be no difference between the incoming and outgoing velocity, and the calculation can be omitted.

For a vertical turbine pump, the discharge head is theoretically read at the discharge flange of the pump. Since this flange usually is inaccessible for gauge readings, a gauge is used at the discharge fitting at the top of the pump column pipe (Figure 15.6.10). The discharge pressure at the pump discharge flange therefore equals the pressure at the gauge above, plus the pressure effect of the vertical distance between



*Conforms to requirements of Chapter 8 of NFPA 20 on positive displacement foam concentrate and additive pumps.

FIGURE 15.6.7 Typical Positive Displacement Pump Characteristics Curve

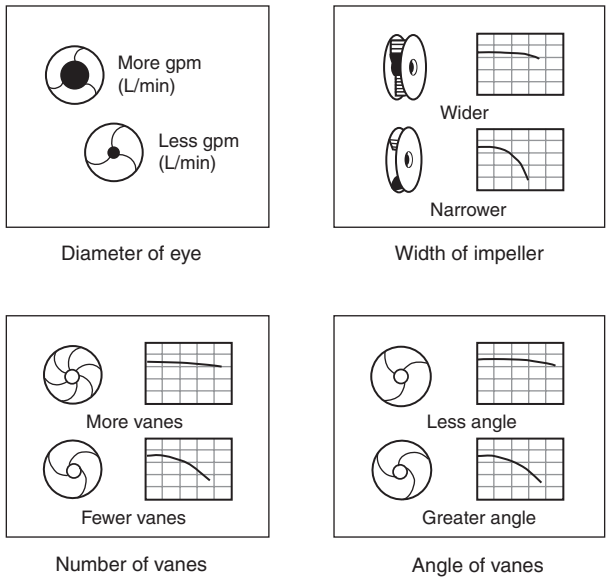
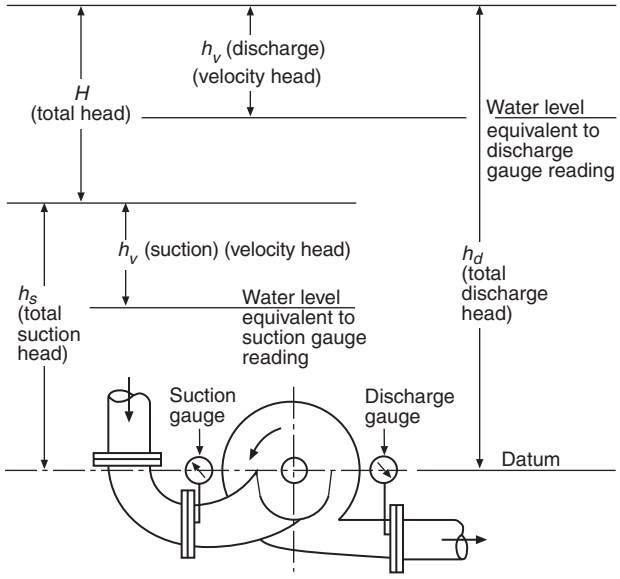


FIGURE 15.6.8 Effect of Impeller Design on Head-Discharge Curves for Fire Pumps



Installation with suction head above atmospheric pressure shown.

FIGURE 15.6.9 Typical Head of Horizontal Shaft Centrifugal Fire Pumps

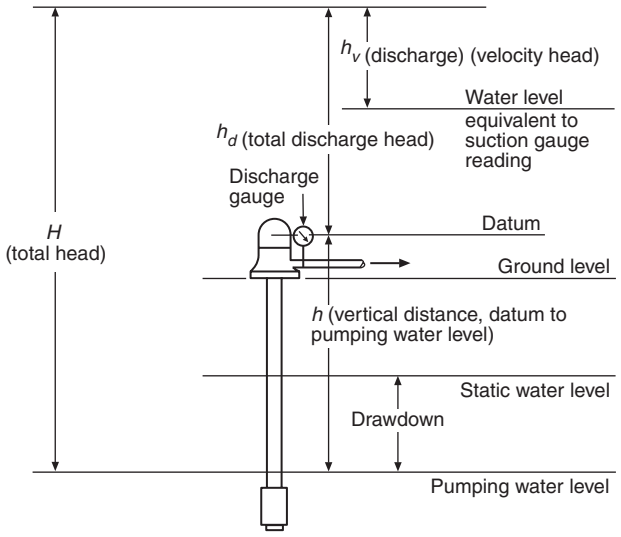


FIGURE 15.6.10 Total Head of Vertical-Turbine-Type Fire Pumps

the two points, plus the friction loss between the two points. In most cases, the friction loss is so small that it may be disregarded.

The suction head is the vertical distance from water level to the pump discharge flange. The velocity head of the incoming liquid is assumed to be zero. Hence, the formula would now take the following form:

$$H = h_d + h_{Vd} - h_s = (h_{gd} + L) + h_{Vd} - h_s$$

where

h_{gd} = Discharge gauge reading (ft [m])

L = Gauge pump flange (ft [m])

h_s = Water level when pumping to pump flange [ft (m)]

However, $L - h_s = h$, the vertical distance between the discharge gauge and water level. Therefore the formula becomes

$$H = h_{gd} + h_{Vd} + h$$

Hydraulic and power losses within the pump due to turbulence, disc friction, and shock are represented by the efficiency rating.

Total head at rated capacity is used to establish the rated head of a pump. Actually, the rated head is the amount of energy given to the water.

The total head of a vertical-turbine-type pump may also be defined as the vertical water-to-water dimension of the system in which the pump operates. However, there is a difference in the method of measuring total head. As shown in Figure 15.6.10, it is the sum of the vertical distance between water level in the well or pit, the discharge head indicated by the gauge on the pump outlet, and the velocity head at the gauge connection.

DISCHARGE SPECIFIC SPEED (N_d)

Discharge specific speed is a number relating the head, capacity, and speed of a centrifugal pump for design purposes. Actually, discharge specific speed is the revolutions per minute (rpm) of a geometrically similar impeller that will discharge 1 gpm (3.8 L/min) at 1 ft (0.3 m) total head. The formula for calculating discharge specific speed of a centrifugal pump is

$$N_d = \frac{\text{rpm} \times \text{gpm}^{1/2}}{H^{3/4}}$$

where

N_d = Specific speed number

H = Head (ft [m])

When values of head, speed, and capacity in the formula correspond to pump performance at optimum efficiency, the specific speed may be used as one measure of pump performance. Impellers designed for high heads usually have low specific speeds, and impellers designed for low heads have high specific speeds.

A pump of low specific speed will operate satisfactorily with greater suction lift than a pump of the same head and capacity with a higher specific speed. Experience shows that specific speed is a useful guide for determining maximum suction lift or minimum suction head.

Fire pumps are not allowed to take suction under lift. However, some existing installations may be encountered when a centrifugal pump is subject to lift conditions exceeding 15 ft (4.5 m), and it may be necessary to provide a larger pump at less speed. With low lift or positive head on the suction, a smaller pump operating at greater speed may be used. Abnormally high

suction lifts may seriously reduce pump capacity and efficiency or cause excessive vibration and cavitation.

NET POSITIVE SUCTION HEAD

Net positive suction head (NPSH) is the pressure head that causes liquid to flow through the suction pipe and fittings into the eye of a pump impeller. The pump itself has no ability to "lift," and the suction pressure depends on the nature of the supply.

Although not permitted, a horizontal pump being supplied from a pond, stream, open well, or uncovered reservoir, where the water level is below the pump, would have a suction head equal to atmospheric pressure minus the lift. If the water level is above the pump, as from a water main or aboveground tank, the suction head is atmospheric pressure plus static pressure.

Pressure readings at the inlet flange of a pump operating under lift are negative with respect to the gauge but positive when referred to absolute pressure—hence, the expression "net positive suction head." Absolute pressure is gauge pressure plus barometric pressure.

There are two kinds of NPSH to consider. Pump NPSH is a function of the pump design and varies with the capacity and speed of any one pump and with the designs of different pumps. Available NPSH is a function of the system in which the pump operates and can be calculated readily. Curves of NPSH versus gallons per minute usually can be obtained from pump manufacturers.

Figure 15.6.11 shows an NPSH curve for a typical fire pump. Note that the required NPSH is 10 ft at 2000 gpm and 18 ft at 3000 gpm. The shutoff point equals the churn pressure at zero flow; the overload point equals 150 percent of rated flow at 65 percent of the rated pressure.

When the water source is above the pump, available NPSH = atmospheric pressure (ft or m) + static head on suction (ft or m) – friction and fitting losses in suction piping (ft or m) – vapor pressure of liquid (ft or m). Note that the vapor pressure of water at 90°F (32°C) is 1.6 ft (0.48 m).

For any pump installation, the available system NPSH must be equal to or greater than the pump NPSH at the desired operating conditions.

CAVITATION

Cavitation is a complex phenomenon that can take place in pumps or other hydraulic equipment. As water flows through the suction pipe of a centrifugal pump and enters the eye of the impeller, the velocity increases and pressure decreases. If the pressure falls below the vapor pressure corresponding to the temperature of the water, pockets of vapor will form. When the vapor pockets in the flowing water reach a region of higher pressure, they collapse with a hammer effect, causing noise and vibration. Tests have shown that the extremely high instantaneous pressures that may be developed in this manner may pit various parts of the pump casing and impeller. Conditions may be mild or severe, and mild cavitation may occur without much noise. Severe cavitation can cause reduced efficiency and, ultimately, failure of the pump if it is not corrected.

PUMP AFFINITY LAWS

The mathematical relationships among head, capacity, brake horsepower, and impeller diameter are called the pump affinity laws. Law 1 assumes constant impeller diameter with change of speed. Law 2 assumes constant speed with change in diameter of the impeller. These laws are expressed by proportion, as follows:

Law 1

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}, \quad \frac{H_1}{H_2} = \frac{N_1^2}{N_2^2}, \quad \frac{\text{bhp}_1}{\text{bhp}_2} = \frac{N_1^3}{N_2^3}$$

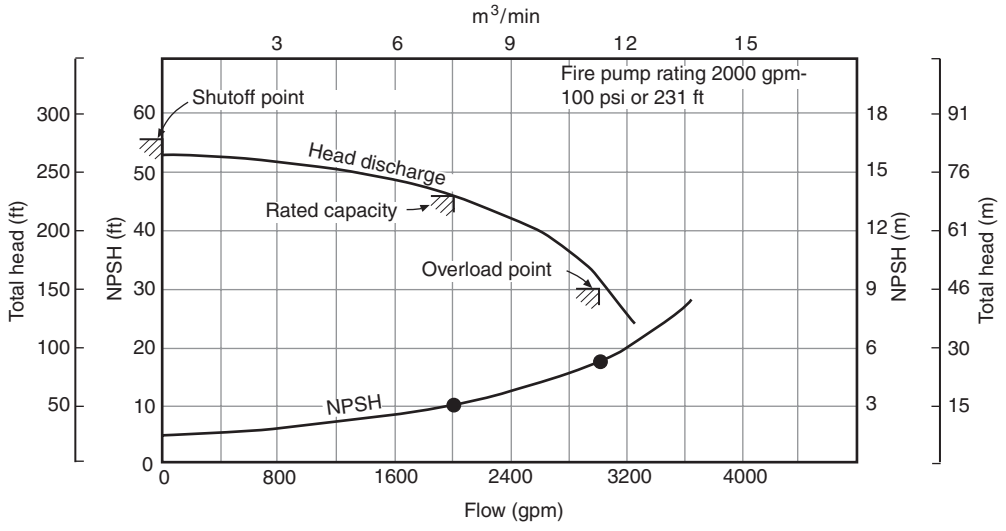


FIGURE 15.6.11 NPSH Curve of a Typical Fire Pump

Law 2

$$\frac{Q_1}{Q_2} = \frac{D_1}{D_2}, \quad \frac{H_1}{H_2} = \frac{D_1^2}{D_2^2}, \quad \frac{\text{bhp}_1}{\text{bhp}_2} = \frac{D_1^3}{D_2^3}$$

The nomenclature for the relationship is

Q = Capacity

H = Head, N = Speed

D = Impeller diameter

bhp = Brake horsepower

Thus,

Q_1 = gpm (L/min) at N_1 or D_1

Q_2 = gpm (L/min) at N_2 or D_2

H_1 = Head in ft (m) at N_1 or D_1

H_2 = Head in ft (m) at N_2 or D_2

bhp_1 = Brake horsepower (kW) at N_1 or D_1

bhp_2 = Brake horsepower (kW) at N_2 or D_2

Law 1 applies to common types of pumps, including horizontal centrifugal pumps and vertical turbine pumps. Law 2 applies to centrifugal pumps with reasonably close agreement between calculated and tested performance. Generally, pumps with low specific speeds show closer agreement than do pumps with high specific speeds.

The pump affinity laws should be applied when proposed changes in a fire pump installation would increase the speed or significantly raise the pressure of the suction supply. Greater speed would increase the power demand, and high discharge pressure might be undesirable. In some instances, it is possible to trim the impeller. This should not be done without the approval of the pump manufacturer. Likewise, when a variable pump driver is used, the pump affinity laws will apply when the rotational speed of the pump is changed to control the output head in feet (m) available.

STANDARD HEAD DISCHARGE CURVES

The shape of the standard head discharge curve of a fire pump is determined by three limiting points: the shutoff, the rating, and the overload.

Shutoff

With the pump operating at rated speed and no flow, the total head of a horizontal centrifugal pump, vertical turbine pump, or an end-suction pump at shutoff must be between 100 and 140 percent of the rated head pressure at the 100 percent flow capacity.

The shutoff point represents the maximum allowable total head pressure. Otherwise, the pump would have a rising or convex characteristic curve. Such pumps are not listed. With a convex curve, there could be two flow points for one pressure.

Rating

The curve should pass through or above the point of rated capacity and head (Figure 15.6.12).

Overload

At 150 percent of rated flow capacity, the total head pressure should not be less than 65 percent of the rated total head. The curve should pass through or above the overload point. Most fire pumps have curves with a small margin above the theoretical overload, and some models have a cavitation or "break" point in the curve just beyond overload.

HORIZONTAL-SHAFT CENTRIFUGAL FIRE PUMPS

Horizontal-shaft centrifugal fire pumps are required to be installed to operate under positive suction head. If the water supply is such that suction lift cannot be avoided, vertical turbine fire pumps should be installed. NFPA 20 does not allow the use of horizontal-centrifugal fire pumps taking suction under lift for new installations.

Types of Pump

Horizontal centrifugal fire pumps are of the split-case, vertical in-line, or end-suction type (Figures 15.6.5 and 15.6.13). The end-suction type is manufactured to ANSI specifications[1] for centrifugal pumps. In general, there are no limits on the capacities of split-case fire pumps, but the maximum rated capacity of any listed fire pump is currently 5000 gpm (18 925 L/min).

Suction Supplies from Public Mains

When streams, ponds, and other open bodies of water are used, properly screened intakes should be provided to prevent fish,

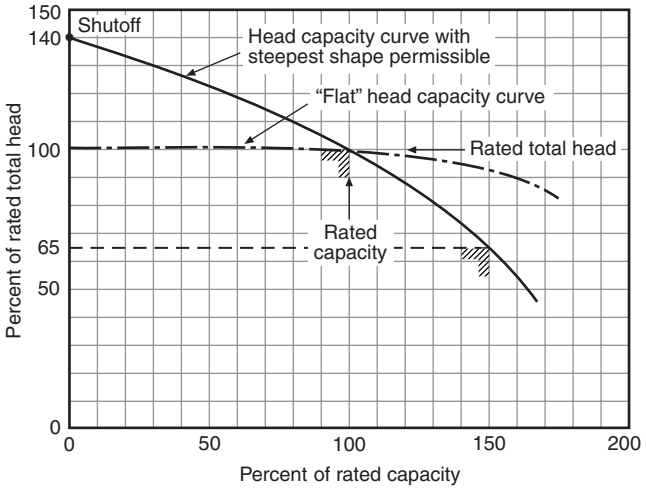
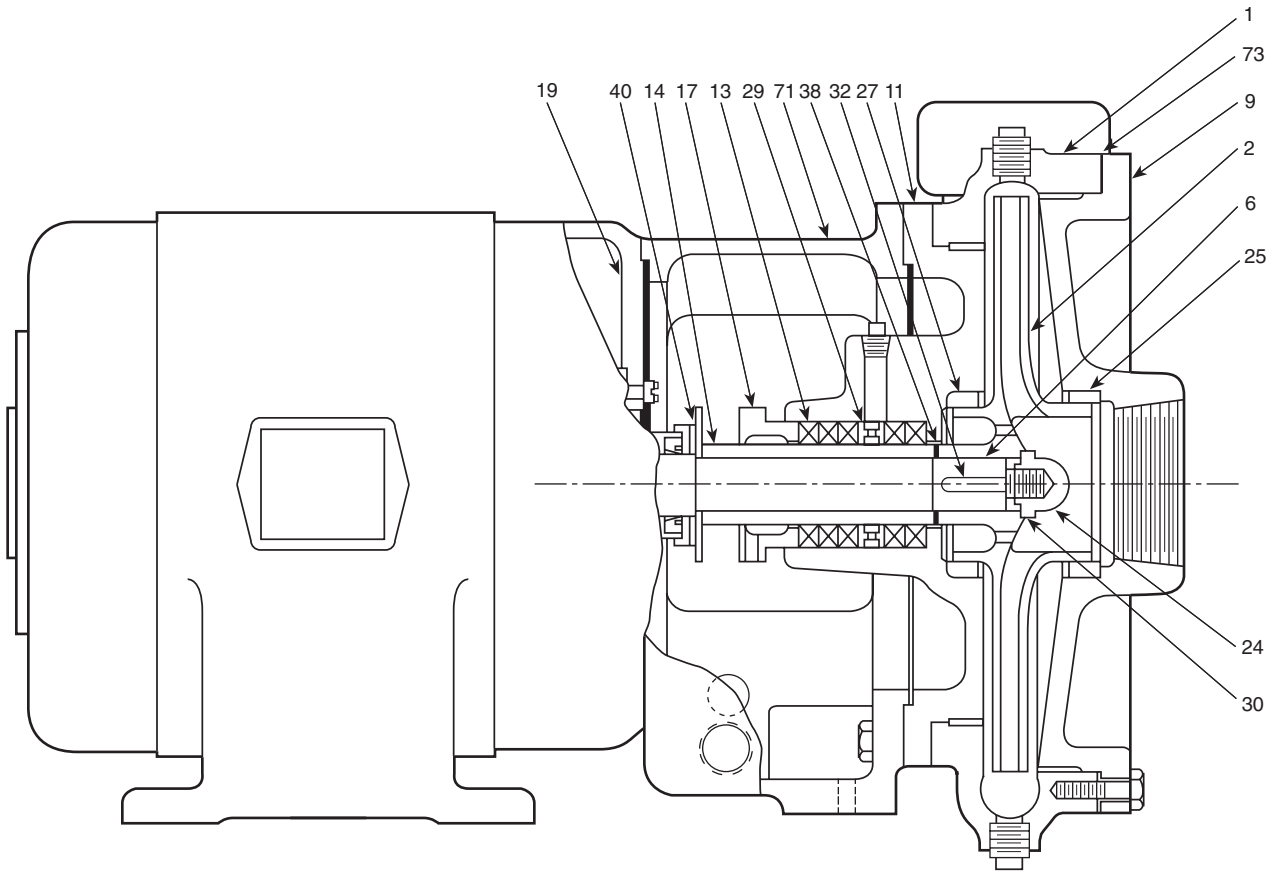


FIGURE 15.6.12 Pump Characteristic Curves



1 Casing
2 Impeller
6 Shaft
9 Cover, suction
11 Cover, stuffing box
13 Packing
14 Sleeve, shaft
17 Gland
19 Frame
24 Nut, impeller
25 Ring, suction cover
27 Ring, stuffing box cover
29 Ring, lantern
30 Gasket, impeller nut
32 Key, impeller
38 Gasket, shaft sleeve
40 Deflector
71 Adapter
73 Gasket

NOTE: The numbers used in this figure do not necessarily represent standard part numbers used by any manufacturer.

FIGURE 15.6.13 An Overhung Impeller, Close-Coupled, Single-Stage, In-Line, Vertical Fire Pump (Source: Hydraulic Institute, http://www.pumps.org)

eels, and foreign material from entering the pump and the fire protection system. Some older pumps may have a foot valve such as the one shown in Figure 15.6.14. However, pumps taking suction under lift are not allowed for new installations as per NFPA 20.

Use of nonpotable water should be avoided when fire pumps discharge into a system that is also connected to public mains or to other potable supplies. Otherwise, there will be cross connections, which are restricted in some locations by federal clean water act regulations or health or water utility authorities. In those cases where cross connections cannot be avoided, listed or approved backflow prevention devices acceptable to health and water authorities are required to prevent contamination of potable water supplies. Such devices should be installed on the discharge side of the pump. Where a backflow preventer is required to be installed in the suction piping, it must be at least

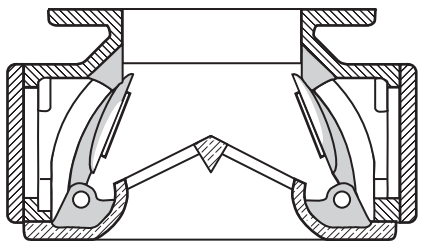


FIGURE 15.6.14 A Typical Foot Valve of Good Design Shown in the Open Position

10 pipe diameters from the suction flange of the fire pump. It is preferred, however, to locate the backflow preventer at least 50 ft (16 m) from the pump suction flange. When a diesel engine pump driver is used and the source of cooling water is connected to the pump discharge, a reduced pressure backflow preventor is required to be installed in the cooling water piping as shown in the annex to NFPA 20.

Suction Water Storage Tanks

The volume of suction storage should be sufficient to supply the pump or pumps at 150 percent of the pump's rated capacity for the required duration of the water demand. This is normally 1 to 4 hours. Aboveground, underground, or fire well tanks filled with potable water are recommended for supplying fire pumps.

Break Tanks

At locations where a direct connection between a public water supply and a private fire protection system is prohibited, either for public health or hydraulic reasons, a break tank installation may be desirable. A break tank is an automatically filled tank that provides a suction supply for a fire pump without a direct connection to a public supply (Figure 15.6.15). This is done by an actual physical break or gap between the public supply and a private protection system. Water from the public supply enters the break tank from a height above the tank's overflow outlet and falls freely to the surface of the water in the tank. A fire pump is needed to take suction from the tank, as the water is no longer under pressure from the public supply. The fire pump may be a vertical turbine, horizontal, or positive displacement type.

A separate tank may be provided for each fire pump in an installation. The flow into the tank from the public supply is controlled by an automatic fill mechanism, and since the water in the tank is considered potable, the top of the tank should be closed.

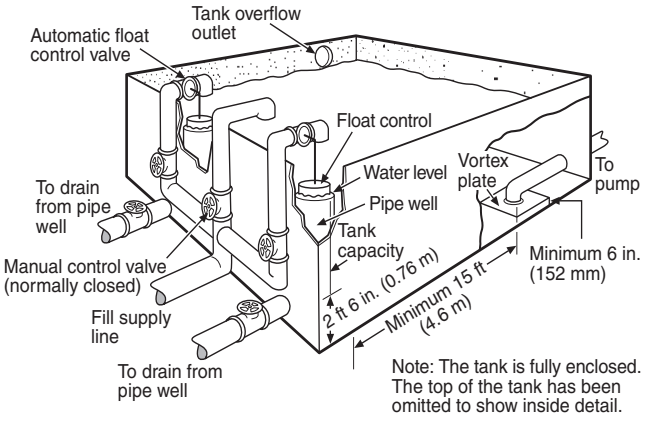


FIGURE 15.6.15 A Break Tank Used in Connection with a Fire Pump When a Direct Connection Between a Public Water Supply and a Private Fire Protection System Is Prohibited

Break tanks are less reliable than good, full-sized suction tanks, as the automatic fill mechanisms could fail. There is no NFPA standard for the design and installation of break tanks, but to the extent possible, the requirements of NFPA 22 and NFPA 20 should be used.

Booster Pumps

These are fire pumps taking suction from public water mains or industrial water systems. (In a mechanical sense, all pumps are booster pumps.) As a prelude to purchasing and installation, the available fire waterflow is obtained by conducting flow tests. The pump is sized by first conducting a flow test of the water supply and plotting the test on a water-supply graph having pressure versus volume (gpm), semi-log $N^{1.85}$ paper (SI units: 1 gpm = 3.785 L/min). The required water demand is then plotted to determine what pressure is required. The manufacturer's characteristic curves are researched to find one that adds the required pressure at a volume range of 90 percent of rated capacity to 130 percent of the rated pump capacity. The pump should be sized so that, when pumping is at 150 percent of rated (overload) capacity, the pump does not lower the water supply pressure to a gauge pressure less than 10 psi (69 kPa), or a safe point that may be determined by the local health authorities. Full overload capacity of the pump, plus the probable flow drawn from area hydrants by the fire department, are calculated, and they should not drop the gauge pressure in the water mains below 10 psi (69 kPa) or that allowed by the public health authorities. Head rating of the pump should be sufficient to meet all pipe friction in the connection plus pressure demand.

Pump Accessories

Auxiliary devices have an important bearing on the complete functioning of a pump as a fire protection water supply, and their provision or omission should never be decided solely on the basis of cost. NFPA 20 gives detailed information concerning their installation. The following items are worthy of special consideration.

Relief Valves. These are required on the pump discharge line when the operation of the pump can result in excess pressure that would exceed the pressure rating of the fire protection system. The design of this device is very critical to the proper operation of the fire protection water supply. If the pump is oversized for flow and pressure, the main relief valve should not be used to limit the pressure and discharge excess quantities of water during the normal weekly run test and annual flow test. This is of particular importance in climates where there is freezing weather for a portion of the year. In these situations the designer should look further at other pump choices and optional drivers for the pump that will limit the discharge head. A good example is a variable-speed diesel engine or electric motor listed system.

Hose Valves. Approved 2½-in. (64-mm) hose valves can be used in testing pumps and for hose stream(s) fire protection. The valves are attached to a header or manifold outside the pump room, or otherwise located to avoid water damage to the pump,

driver, and controller. The number of valves needed depends on the pump capacity. The number of 2½ in. (64 mm) outlets provided is based on a 250 gpm (946 L/min) flow per outlet. Design consideration should be made to use a fixed, listed flowmeter with water discharging back to the water source to conserve water and improve the accuracy of flow test results. When the water supply is tested, the hose valves, fire hose, and nozzles should be used for the test.

Automatic Air Release Valves. These are installed on the top of the pump casing(s) and arranged for automatic or remote-control operation. The purpose is to release trapped air in the casing and to minimize pump cavitation. An automatic air release is desirable on any pump with a casing that is normally full of water.

Circulation Relief Valves. These are installed on pumps that start automatically or by remote control. Their function is to open at slightly above rated pressure, when there is little or no discharge, so that sufficient water is discharged to prevent the water in the pump from overheating. These valves are not required on diesel-engine-driven pumps where cooling water is taken from the pump discharge.

Vertical Turbine Fire Pumps

Vertical turbine pumps were originally designed to pump water from wells. As fire pumps, they are recommended in instances where a fire well is used as the water source or the horizontal pumps would operate with suction lift. An outstanding feature of vertical pumps is their ability to operate without priming. Vertical pumps may be used to pump from streams, ponds, wet pits, wells, underground water storage tanks, cisterns, and break tanks.

Suction from wells is acceptable if the adequacy and reliability of the well has been established and the entire installation is built in conformance with NFPA 20. There is no maximum pump depth. The water level in the well is required to cover the pumping bowls to a depth required by the pump manufacturer's recommendations. If the yield from a well is too small to supply a fire pump, low-capacity, commercial well pumps can be used to fill conventional ground-level tanks or reservoirs for the fire pump supply.

A vertical fire pump assembly consists of a discharge head or right-angle gear drive, a pump column pipe and discharge fitting, an open or enclosed drive shaft, a bowl assembly containing the impellers, and a suction strainer (Figures 15.6.16 and 15.6.17). The principle of operation is comparable to that of a multistage horizontal centrifugal pump. Except for shutoff pressure, the characteristic curve is the same as it is for horizontal pumps (see Figure 15.6.12).

Vertical Turbine Barrel or Can Pump

Sometimes vertical-type multistage pumps are installed in a casing called a "barrel" or "can" for high-pressure installations (Figure 15.6.18).

Vertical pumps have the same standard capacity ratings that horizontal fire pumps have. Pressure ratings are standardized and vary by the number of bowls and diameter of the bowls.

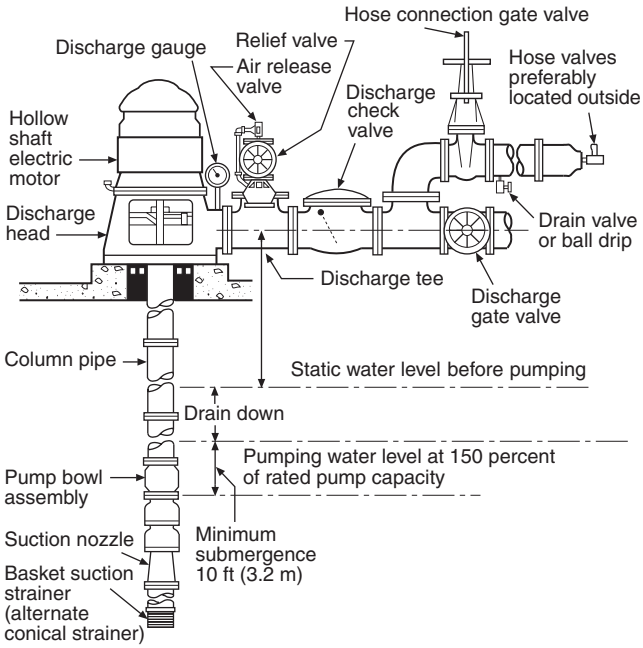


FIGURE 15.6.16 Vertical-Shaft-Turbine-Type Pump Installation in a Pit. Note: The distance between the bottom of the strainer and the bottom of the wet pit should be one-half of the pump bowl diameter but less than 12 in. (305 mm).

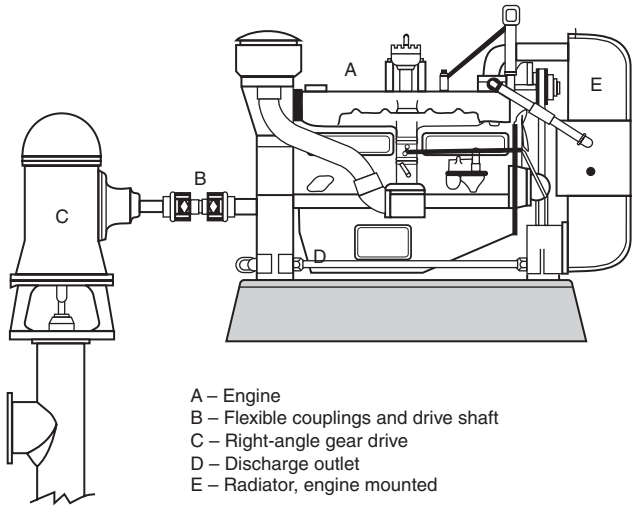


FIGURE 15.6.17 Engine-Driven Vertical Fire Pump

By changing the number of stages, or the impeller diameters, or both, the pump manufacturer can provide a specific total head at rated speed. Pressures are available up to 520 psi (3585 kPa). Vertical or horizontal mounted electric motors can be used, as well as hollow shaft motors. Diesel engines (mounted vertically or horizontally) or steam turbines can be used by means of right-angle gear heads.

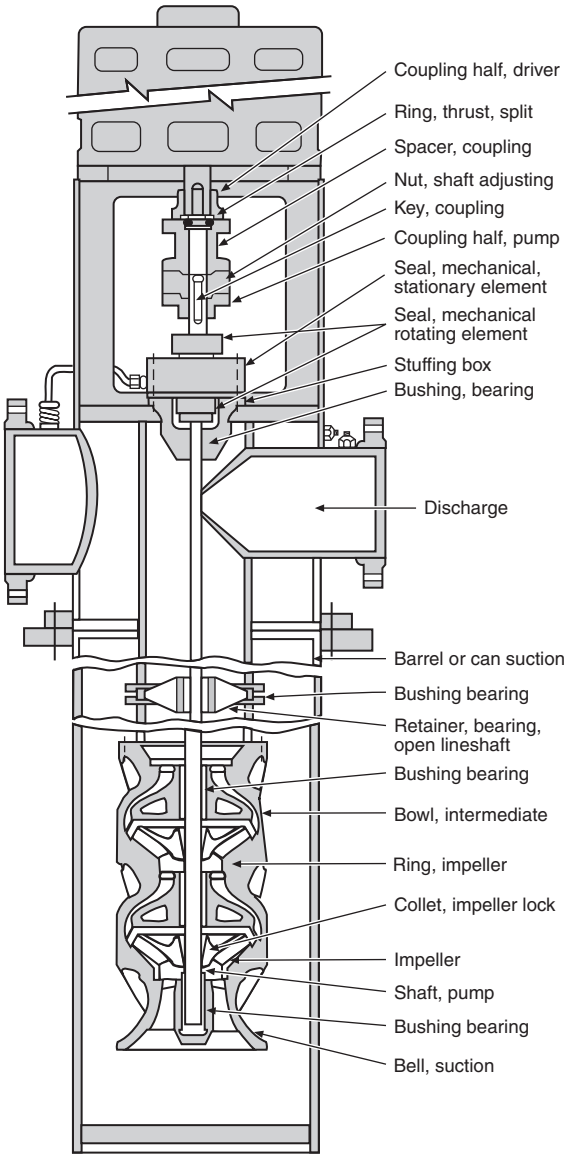


FIGURE 15.6.18 A Turbine-Type, Vertical, Multistage, Barrel or Can Pump

FIRE PUMP CAPACITY AND HEAD RATING

The capacity and pressure ratings of fire pumps must be adequate to meet flow and pressure demands consistent with water supply requirements for the property in question. Fire pumps are designed to provide their rated capacity with a safety factor built in (150 percent of rated capacity at 65 percent of rated pressure) to provide some protection in case of greater-than-expected demand at the time of a fire. The following examples show one method of how rated capacity and pressure can be determined by using the standard fire pump curve for a typical manufacturer's pump characteristic curve (see Figure 15.6.12).

EXAMPLE 1: HORIZONTAL CENTRIFUGAL PUMP The estimated water demand for sprinklers and hose streams is 1400 gpm at 90 psi. The suction supply is a ground-level storage tank, and the minimum inlet gauge pressure is 0 psi at maximum flow.

PROBLEM: Determine the required rated capacity and pressure of the pump.

SOLUTION: Solution is determined by the following steps:

1. Meet the demand of 1400 gpm with the capacity of the pump, which is 150 percent of rated capacity.
2. Thus, 1400 ÷ 150 percent = 933 gpm. The nearest standard pump rating is approximately 1000 gpm.
3. Therefore, 1400 gpm demand would be 140 percent of capacity.
4. From the manufacturer's pump characteristic curve, it is determined that, at 140 percent capacity, the total pressure is 72 percent of rated pressure.
5. Under conditions of operation, the total pressure equals the discharge pressure (90 psi) plus suction pressure (0 psi).
6. Therefore, net pressure at 1400 gpm equals 90 + 0 = 90 psi, and rated pressure at 1000 gpm = 90 ÷ 72 percent = 125 psi.

ANSWER: Pump rating should be not less than 1000 gpm at 125 psi.

EXAMPLE 2: HORIZONTAL CENTRIFUGAL PUMP (SI UNITS) The estimated water demand for a sprinkler system is 2000 L/min at a pump discharge pressure of 400 kPa. The suction supply is a well with a lift of 5 m from water surface to the pump.

PROBLEM: Determine the required rated capacity and pressure of the pump.

SOLUTION: Solution is determined by the following steps:

1. Meet the demand of 2000 L/min with the overload capacity of the pump which is 150 percent of rated capacity.
2. Thus, 2000 ÷ 150 percent = 1330 L/min. The nearest standard pump rating is approximately 1500 L/min.
3. Therefore, 2000 L/min demand would be 2000/1500 × 100 percent = 133 percent of rated capacity.
4. From the manufacturer's pump characteristic curve, it is determined that, at 133 percent capacity, the total pressure is 78 percent of rated pressure.
5. Under conditions of operation, the net pressure equals the discharge pressure (400 kPa) minus suction pressure (5 m head = 5 ÷ 9.81 kPa = 50 kPa).
6. Therefore, net pressure at 2000 L/min equals 400 + 50 = 450 kPa, and rated pressure at 1500 L/min = 450 ÷ 78 percent = 580 kPa.

ANSWER: Pump rating should be not less than 1500 L/min at 580 kPa.

EXAMPLE 3: VERTICAL TURBINE PUMP IN A WELL The estimated water demand at ground level is 1100 gpm at 100 psi.

Tests and weather records show that the aquifer, or underground water source, is reliable and adequate at all seasons. The static level is 45 ft below the surface. The draw down, or vertical distance, between the static and pumping water levels is 40 ft at 1100 gpm pumping rate.

PROBLEM: Determine the rated capacity and pressure of the pump.

SOLUTION: Solution is determined by the following steps:

1. Meet the demand of 1100 gpm with the rated capacity of the pump, which is 100 percent of rated capacity.
2. Thus, 1100 ÷ 100 percent = 1100 gpm. The nearest standard pump rating is approximately 1100 gpm.
3. Therefore, the 1100 gpm demand would be 110 percent capacity.
4. From the manufacturer's pump characteristic curve, it is determined that, at 110 percent capacity, the total pressure is 70 percent of the rated pressure.
5. At 1100 gpm, pressure demand at the surface = 100 psi.
6. Static level (ft) + drawdown level (ft) = Pumping level (ft). In the example 45 ft static water level + 40 ft drawdown level = 85 ft pumping level. Now converting ft of water to psi, 85 ft × 0.434 psi/ft = 37 psi. Determine the pumping pressure required for the example: 100 psi + 37 psi = 137 psi, and 100 psi/137 psi = 0.73 (%), and finally, 137 psi/0.73 = 188 psi.

ANSWER: The pump rating should be not less than 1000 gpm at 188 psi.

EXAMPLE 4: BOOSTER PUMP ON PUBLIC WATER CONNECTION A sprinklered building in a city has an estimated sprinkler demand of 750 gpm at 60 psi. Based on fire flow tests from nearby street hydrants, 750 gpm at 27 psi is available for sprinklers at the inlet flange of the pump. Allowance has already been made for hose streams.

PROBLEM: Determine the rated capacity and pressure of the pump.

SOLUTION: Solution is determined by the following steps:

1. Meet the demand of 750 gpm with the rated capacity of the pump, which is 100 percent of rated capacity.
2. Thus, 750 ÷ 100 percent = 750 gpm, a standard pump rating.
3. The total pressure at 100 percent capacity is 100 percent rated net pressure.
4. With positive head suction supply, the net pressure equals discharge pressure minus suction pressure; thus, at 750 gpm flow, net pressure equals 60 – 27 = 33 psi.
5. Therefore, 33 ÷100 percent = 33 psi.

ANSWER: The pump rating should be 750 gpm at 33 psi.

NFPA 20 recommends that the pump not be used at over 140 percent capacity. This leaves a small reserve as pump curves drop off sharply after 150 percent. Generally, a one size larger pump is recommended than the calculations indicate. When the pump is used above its rated capacity, the available pressure is reduced.

HORSEPOWER OF FIRE PUMPS

Before matching a driver to a pump, it is necessary to know the maximum brake horsepower demand of the pump at rated speed. This demand can be determined directly from the horsepower curve provided by the pump manufacturer. Typical fire pumps reach maximum brake horsepower between 140 and 170 percent of rated capacity.

Engine Horsepower

Engines specifically designed for use with fire pumps are rated by measuring the horsepower developed with all accessories in operation and then making some allowance for wear and tear. When equipped for fire pump driver service, an allowance of not less than 10 percent greater than the maximum brake horsepower is required by the pump under any conditions of pump load. Typical bare engines and usable horsepower curves are shown in Figure 15.6.19.

The engine manufacturer's test curves are based on barometric pressure of 29.61 in. (752 mm) Hg, which approximates 300 ft (90 m) above sea level and 77°F (25°C). The usable horsepower of a fire pump engine should be reduced for each 1000 ft (300 m) rise in altitude above 300 ft (90 m) by 3 percent for a diesel engine and 1 percent for each 10°F (5.6°C) rise above 77°F (25°C).

If the curves are not available, horsepower can be calculated by the formula (in U.S. customary units)

$$\text{bhp} = \frac{5.83QP}{10{,}000 \times E} \quad \text{or} \quad \text{bhp} = \frac{QP}{1710 \times E}$$

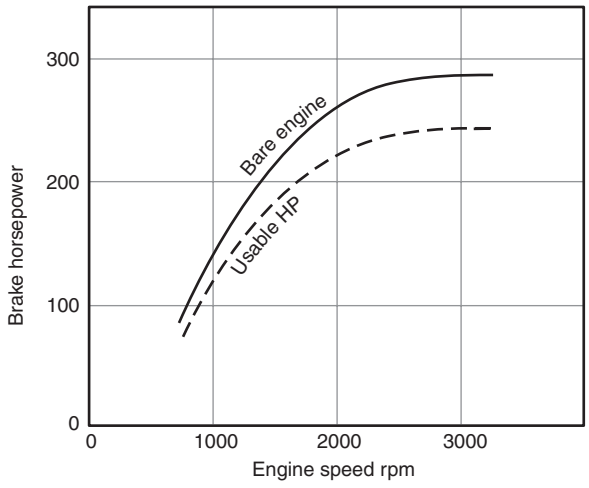


FIGURE 15.6.19 Typical Engine Horsepower Curves

where

bhp = Brake horsepower

Q = Gallons per minute

P = Total head (psi)

$$E = \text{Efficiency} = \frac{\text{Water horsepower}}{\text{Input horsepower}}$$

The efficiency at maximum brake horsepower is usually 60 to 75 percent.

PROBLEM: Find by formula the minimum horsepower needed to drive a 1000 gpm, 100 psi, 1760 rpm horizontal centrifugal fire pump.

SOLUTION: Solution is determined by the following steps:

1. Assume 65 percent efficiency at 160 percent capacity.
2. From a standard pump curve, the pressure is 55 percent at 160 percent capacity or 55 psi at 1600 gpm.
3. By formula,

$$\text{bhp} = \frac{5.83 \times 1600 \times 55}{10{,}000 \times 0.65} = 79$$

ANSWER: Not less than 79 usable brake horsepower.

IN SI UNITS.

$$\text{Output power} = \frac{0.167 Q_m P_m}{10{,}000E}$$

where

kw = Power output (kilowatts)

Q_m = Liters per minute

P_m = Total head (kPa) or net pressure

$$E = \text{Efficiency} = \frac{\text{Water power output}}{\text{Input power}}$$

PROBLEM: Find by formula the minimum power output needed to drive a 4000 L/min, 700 kPa, 1760 rpm horizontal centrifugal fire pump.

SOLUTION: Solution is determined by the following steps:

1. Assume 65 percent efficiency at 160 percent capacity.
2. From a standard pump curve, the pressure is 55 percent at 160 percent capacity or 385 kPa at 6400 L/min.
3. By formula,

$$\text{Power output} = \frac{0.167 \times 6400 \times 385}{10{,}000 \times 0.65} = 63 \text{ kW}$$

ANSWER: Not less than 63 kW output.

FIRE PUMP DRIVERS

Power for driving fire pumps is selected on the basis of reliability, adequacy, safety, and economy. The reliability of utility electric power may be judged by the record of outages and by review of the power sources and distribution layout of the system in question.

Some public utilities in metropolitan areas operate steam distribution systems. When high-pressure steam is available, it is practical to use steam turbine-driven fire pumps. Some remote industrial plants generate their own electricity using steam or hydro power, or both. Utility electric power is also used.

Diesel engines have the advantage of not being dependent on outside sources of power.

Electric Motors

Electric motors for driving fire pumps must be listed for fire pump service. These motors are designed in accordance with specifications of National Electrical Manufacturers Association (NEMA) or Electrical Manufacturers Association of Canada (EMAC). All electrical equipment and wiring in a fire pump installation is required to comply with NFPA 70, *National Electrical Code*®, Article 675.

Section 15, Chapter 7, "Fire Pump Controllers and Power Supply Arrangements for Motor-Driven Fire Pumps," provides a detailed discussion on electric motor design considerations.

Electric Motor Controllers

The fire pump controller used for an electric-driven pump is a critical component to ensure the successful operation of the pump. Such controllers are equipped with a variety of internal components to achieve this level of reliability. These components may include elements such as circuit breakers, disconnecting means, timers, and similar devices. Recently, an electric motor controller that uses a variable-speed system has been listed for use in fire pump applications. This controller is an additional tool that can be used by the designer to control the discharge head developed by a fire pump. This type of system is of particular value where the pump takes suction from a variable pressure source such as a city water supply that has a higher pressure in some seasons of the year and a very low pressure in other times of the year. It is also of value for some of the new sprinklers that require a high operating pressure to maintain a water application rate to control a fire in warehouses and high-hazard occupancies.

Section 15, Chapter 7, "Fire Pump Controllers and Power Supply Arrangements for Motor-Driven Fire Pumps," describes details for the design and selection of electric motor controllers.

Engine Controllers

Controllers are used for automatic operation of engine-driven fire pumps. The specifications for construction, location, and methods of actuation of engine controllers are the same as for electric motor controllers. Automatic controllers are equipped with manual starting and stopping switches. Diesel engine controllers are available as electric or air starting types. Unlike electric motor controllers that are available in a limited service type for less than 30 hp, all diesel engines, large or small, require the same operational features. Details on the design of the electric operated diesel engine controller are found in Section 15,

Chapter 7, "Fire Pump Controllers and Power Supply Arrangements for Motor-Driven Fire Pumps." Air-operated diesel engine controllers are required to have the same operational features as the electric controller.

Audible supervisory devices are provided to indicate low oil pressure in the lubrication systems, high engine-jacket water temperature, failure of the engine to start automatically, and shutdown from overspeed.

Steam Turbine

When adequate and reliable steam supplies are available, turbine-driven fire pumps are acceptable. Only well-built machines of good design with industrial records of proven reliability are used. Special arrangements are needed for automatic operation. Speed rating should not exceed 3600 rpm, because this is the maximum speed of listed fire pumps. Detailed requirements for steam supply, speed governors, and controls are contained in NFPA 20.

Diesel Engines

Engines that are powered by diesel fuel are used for fire pump service. Engines powered by gasoline, natural gas, or LP-gas are not recognized by NFPA 20.

In addition to NFPA 20, reference should be made to NFPA 31, *Standard for the Installation of Oil-Burning Equipment,* and NFPA 37, *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines.* Installations should be made in conformance to local codes.

The development of unsatisfactory conditions, such as pump running, failure to start, high cooling water temperature, and low oil pressure, should be indicated by supervisory signals, not by shutting down the engine. The intent is to keep the pump operating just as long as possible. The importance of constant supervision for automatic pumps is obvious. Recently, a new operating system has been developed to control the discharge head (or pressure) from a diesel engine driven fire pump. This system operates as part of the diesel engine and not the controller like the electric motor driven fire pump. Both have the same advantage of being able to accurately control the pump discharge pressure when the suction pressure is variable or the pressure needs of a fire sprinkler system in a warehouse or high-hazard occupancy need to be maintained at a constant pressure to control a fire in the occupancy.

Cooling Systems. An adequate cooling system is vital to the reliable operation of a diesel engine. A closed pipe system with a heat exchanger and a thermally insulated manifold is the preferred cooling arrangement for a diesel engine recognized in NFPA 20. Only clean or potable water should be circulated through the engine block. Raw water is piped from the fire pump and discharged through the heat exchanger tubes to free discharge in a visible location, such as the cone of the building drain or building exterior. On some engines, the manifolds, oil coolers, and other parts are equipped with water jackets, as recommended by the engine manufacturer. Most engines require a raw waterflow of 15 to 30 gpm (57 to 114 L/min).

In cooling water systems connected to potable water systems and where an antifreeze with inhibitors is used inside of the engine block, federal clean water act regulations and local water suppliers are requiring that reduced-pressure backflow preventors be installed in the cooling water piping upstream of the heat exchanger in both the main cooling waterline and the bypass line. Details of the acceptable arrangement are found in the annex to NFPA 20.

Figure 15.6.20 shows the raw water from the fire pump entering the system through the strainer (1), which prevents sediment from entering the system, and the pressure regulator (2), which protects the heat exchanger from excessive pressure. The solenoid valve (3) is required with automatic control of the engine. The valve (4), normally closed, may be used to bypass the regulator and solenoid valve. The exhaust manifold (5) may be cooled by the clean water circulating system.

Another method of providing cooling to the diesel engine is a closed loop radiator. The radiator can be remotely installed outside of the pump room or on the engine platform. When the radiator is mounted on the engine skid, it should be arranged to pull the air across the engine and out through the radiator. The radiator is sized, according to engine manufacturer's recommendations, to remove the engine-radiated heat and to provide the internal engine cooling requirements.

Fuel Tanks. The storage tank for the diesel engine fuel is sized to contain at least an 8 hour supply. A larger capacity can be provided if facilities for prompt refilling are not available. Tank capacity is estimated by allowing 1 gal/hp. (For SI units: 1 pt = 0.473 L, and 1 gal = 3.785 L.) (See diagrams of typical fuel systems in NFPA 20.)

The fuel storage tank is required to be installed inside the fire pump room, because all listed diesel engines require fuel to be available by gravity, thereby eliminating the fuel pump on the engine. The bottom of the tank is at or above the level of the fuel injectors. This location also allows for easy inspection and maintenance of the tank.

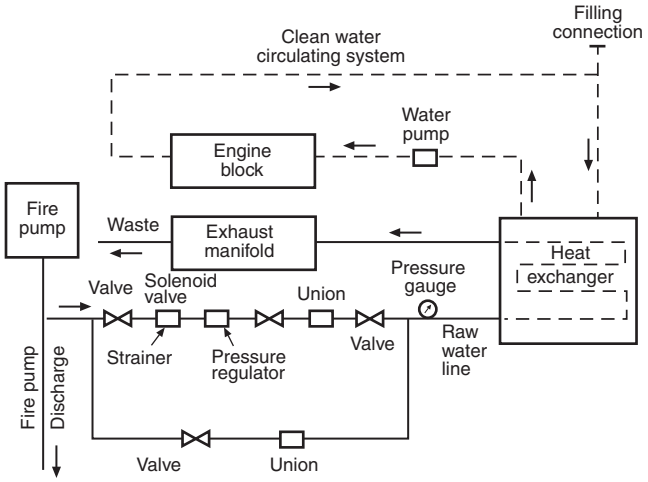


FIGURE 15.6.20 A Typical Heat-Exchanger Cooling System for an Automatically Controlled Engine-Driven Fire Pump That Does Not Require Backflow Protection

Battery Chargers. The energy source needed for automatic starting of a diesel-driven fire pump depends on a sufficient capacity from the battery system. The charges used to satisfy this requirement are specifically listed for fire pump service, and consist of rectifiers, transformers, and relays.

Batteries are provided in two banks with alternate starting cycles to increase the system reliability.

Automatic Pump Control

Most fire pump installations are arranged for automatic operation, preferably with automatic start and manual shutdown. The choice between manual and automatic shutdown depends on the specific conditions involved in a pump's installation and use. Horizontal centrifugal pumps under automatic control must always operate under a head to avoid the need for priming.

Each engine controller is equipped with a separate pressure switch and sensing line that actuate the pump unit when pressure in the water system piping drops to a preset level. Unless the normal water supply static pressure is higher than the pump starting pressure, an automatic jockey (pressure maintenance) pump must be provided to maintain pressure in the system at the higher level.

Actuation of a pump by waterflow instead of by pressure drop is desirable for certain installations, such as those in which: the opening of a moderate number of sprinklers would not drop the system pressure enough to move the pressure switch; high-hazard occupancies in which a fire would demand fire pump service without delay; combined fire protection and plant service systems where a pressure maintenance pump would be impractical; and occupancies in which pressure fluctuates so much that a stable cut-in pressure could not be obtained.

The wiring system of a pump controller includes terminals for connection of a relay to an external supervisory circuit from a sprinkler, deluge, or special fire protection system. To secure reliable pump actuation, external circuits should be installed in conformance with the following NFPA standards, depending on the nature of the signaling system:

NFPA 70, *National Electrical Code®*, Article 695
NFPA 72®, *National Fire Alarm Code®*

Circuits for remote automatic starting of fire pumps should be powered from the controller power.

FIELD ACCEPTANCE TESTS

After a new fire pump has been installed, it is required to make a performance test. Defects and faults are discovered and steps are taken to remedy them. These tests enable the purchaser to determine that the contract has been properly concluded. They also demonstrate the need for future maintenance tests.

Details of the acceptance tests are given in NFPA 20. The test demonstrates the adequacy of the pump and the ability of the pump to deliver water in accordance with its head-capacity curve. The prime mover is operated under various conditions and its performance recorded. There are provisions for electric motors, steam turbines, and diesel engines. Repeated operation of the controlling equipment is required to ensure that full operation of the unit will result from either manual or automatic operation of the controller.

Flow tests are conducted to develop the pressure-discharge characteristic curve of the pump. The procedure followed is to run the pump at three to four different flows, including shutoff (no water flowing). The rate in gallons per minute (L/min) is determined with a Pitot tube and gauge at the nozzles (preferably standard 30-in. [762-mm] long Underwriter playpipes) attached to hose lines from an outside hose-valve header. The discharge is varied by changing the number of lines, the size of nozzle tips, or both; or by using an installed waterflow meter with flow to an open source. Flow is varied by opening or closing the valve on the meter line.

The nozzles may be attached directly to outdoor headers, without hose lines, if water damage can be avoided. Disposal of test water is often a problem, and the length of hose lines depends on the drainage facilities available and the exposure to property and people.

For every flow, pressure readings are taken at the suction gauge and the discharge gauge. The revolutions per minute are also measured using a revolution counter or a tachometer, if available.

The net pressures are calculated from the pump gauge readings, and the flows in gallons per minute corresponding to the Pitot readings are obtained from discharge tables. The flow required for coolant purposes for diesel engine-driven pumps can be added to the measured flow. However, it is usually difficult to accurately measure this flow, so an estimate based on the manufacturer's recommendations may have to be used. In many cases, this flow is small enough to be considered negligible.

With the growing problems of waste water disposal, many pump installations are equipped with waterflow meters for the acceptance test and the periodic service tests. The meters should be installed in conformance with NFPA 20, in order to function properly and not interfere with the operation of the pump.

Vertical turbine fire pumps are tested in the same manner as horizontal pumps, except that there is no suction gauge. The pumping water level should be recorded at each test point.

Figure 15.6.21 presents data obtained by a typical field acceptance test of a horizontal 1500 gpm, 100 psi, 1760 rpm (5678 L/min, 689 kPa, 1760 rpm) diesel-engine-driven centrifugal pump. The net pressure and total flows are calculated from the observed data and plotted (Figure 15.6.22). The curve best

Acceptance Test for a 1500-gpm, 100-psi, 1760-rpm Fire Pump

			Hose	Streams			Corrected to 1760 rpm			
rpm	Discharge (psi)	Suction (psi)	Net (psi)*	No.	Size (in.)	Pitot Pressure (psi)	gpm*	Total*	gpm*	Net (psi)*
1700	125	+16	109	0	–	–	–	0	0	118
1695	120	+18	102	1	1¾	70	742	742	772	110
1690	110	+16	94	2	1¾	60, 60	687, 687	1374	1420	101
1686	95	+17	79	3	1¾	55, 55, 55	657, 657 657	1971	2060	85
1675	85	+16	69	4	1¾	35, 37, 48, 48	525, 540 614, 614	2293	2410	76

* Calculated from observed data.

FIGURE 15.6.21 Example of a Log for a Fire Pump Acceptance Test

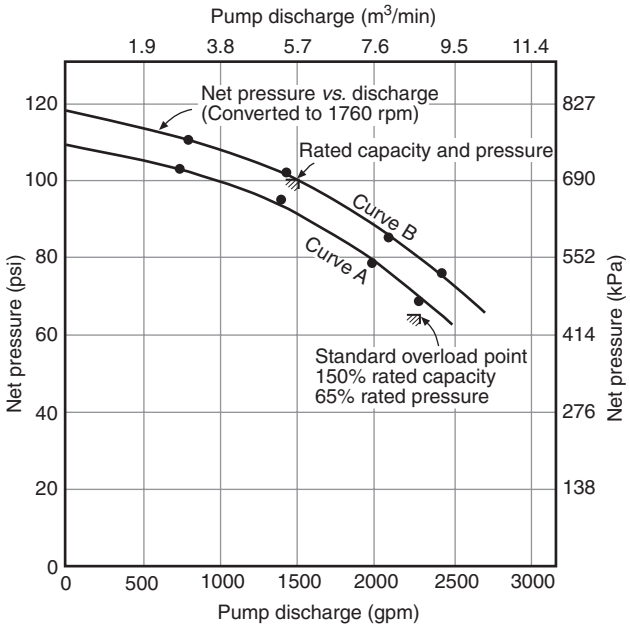


FIGURE 15.6.22 Head Capacity Curves Plotted from Data Compiled in a Fire Pump Acceptance Test

fitting the plotted points is then drawn (Curve A). In this installation, the engine governor appeared to be out of adjustment, restricting the average speed to 1689 rpm, whereas the rated speed was 1760 rpm.

Since the pump was tested at less than rated speed, the observed net pressures and flows were converted to what they would have been at the rated speed of 1760 rpm. Curve B is the characteristic curve at rated conditions. Although the rating point was barely reached, the overload point exceeded the minimum by a good margin. With the engine adjusted to operate at full speed, the pump performance would be acceptable. The following is the conversion calculation procedure that was followed.

Flow is directly proportional to rpm; net pressure is proportional to rpm.[2] For example, test flow, 1971 gpm at 1686 rpm:

$$\text{Flow at 1760 rpm} = 1971\left(\frac{1760}{1686}\right) = 2060 \text{ gpm}$$

Net pressure for 1971 gpm at 1686 rpm is 78 psi. Net pressure for 2060 gpm at 1760 rpm is

$$78\left(\frac{1760}{1686}\right)^2 = 85 \text{ psi}$$

Similar calculations can be carried out in SI units using the affinity laws mentioned previously in this chapter.

LOCATION AND HOUSING OF CENTRIFUGAL PUMPS

Fire pumps are preferably housed in buildings of fire-resistant or noncombustible construction. Even when the climate is so mild that there is no danger of freezing, sufficient enclosure is needed to protect against dirt, corrosion, and tampering. Structural separation of the pump room from other parts of a property is a requirement.

Pump rooms and power facilities should be as free as possible from exposure to fire, explosion, flood, earthquake, and windstorm damage.

Light, heat, ventilation, and floor drainage should be provided for pump rooms. A dry location above-grade is preferred. Pump rooms should be large enough to facilitate easy access to all equipment and devices for inspection, testing, and maintenance.

Fire pumps are located as close as possible to those areas where protection is most important. In some large properties, it may be necessary to have water supplies at more than one point to obtain the most favorable distribution system.

PUMP TESTS

A fire pump must be flow tested annually to ensure that the pump, driver, suction, and power supply function properly and to correct faults that may be found. The hydraulic performance of the pump is measured by a flow test, using a flow meter or hose and nozzles connected to the pump header or yard hydrants. Three points on the standard curve are checked: (1) shutoff, (2) overload (150 percent of rated capacity), and (3) at capacity rating.

Automatic operation is tested by lowering the system pressure, giving due consideration to the layout of the fire protection system, that is, pressure drop or waterflow actuation, jockey pump, and so on.

The water level of wells, ponds, and reservoirs and the condition of suction screens and intakes, above- and below-ground tanks, and so on should be carefully inspected. The history of power outages, low water, and failure of any kind that involves pump, driver, or associated equipment also should be investigated and gauge records from engine controllers recorded for future evaluation.

PUMP OPERATION AND MAINTENANCE

A fire pump can be depended on to work in an emergency only if it is properly operated and maintained. (See NFPA 25 for requirements for inspection, testing, and maintenance of these systems.) It is required that an inspection and testing program that includes written instructions and recordkeeping be implemented. It is further required to have someone at the property at all times who is designated and instructed to operate the pump and its driver. A short (30-min diesel engine; 10-min electric motor) test is required to be made each week by discharging water from some convenient outlet or recirculating through a flow meter.

Fire Alarm Interface

When a supervisory signal indicates an automatic fire pump is operating, the person responsible for the fire pump should proceed to its location immediately. The pump should be allowed to run until the emergency is over, when it may be shut

down manually. During this and every other operating period, the equipment should be checked carefully to see that it is performing properly.

To minimize too-frequent starting and stopping, an electric motor controller has a timer that keeps the motor running for at least 1 minute for each 10-hp motor rating; not less than 10 minutes is required. With electric motors, it is necessary to allow the electrical windings to cool down after starting, to minimize damage to the windings.

It is preferable with all pump drivers to permit the unit to run until it is shut down manually.

When there is more than one automatic fire pump, the controllers are arranged to operate the pumps in a predetermined sequence. The diesel engine is usually first, followed by the electric motor or second diesel engine. Control of the pump from one or more remote pushbuttons, which will start but not stop the pump, may be provided, if desired. If there is deluge valve control of an open discharge device system, the pump may be started by a drop-out relay in a closed circuit. The cooling and lubrication of a centrifugal fire pump is so dependent on water that the pump must never be run unless the pump casing is full of water. Close attention should be given to the bearings and stuffing boxes during the first few minutes of running to see that they do not heat up and need no adjustment. When water reaches the water seal, a small leak at the stuffing box glands is desirable. The suction inlet and discharge outlet pressure gauges should be read weekly to see that the inlet is not obstructed by a choked screen or partially closed valve.

With a vertical-shaft-turbine-type fire pump, the water level can be observed if suction is from a visible supply. If the pump takes suction from a well, water level testing equipment must be used. The groundwater level at the pump should be checked at the weekly test interval during the year and the drawdown should be determined during the annual 150 percent capacity test. These tests should indicate any important change in the groundwater supply.

The direction of rotation of the pump and the speed of operation should be checked each week.

Power Supply Maintenance

The source of electric power for the pump should be checked weekly. With an electric motor drive this means current supply for the motor and its auxiliary equipment. For steam turbine drive, it means the steam supply up to the control valve and the absence of condensate from supply, turbine, and exhaust. If the pump is driven by a diesel engine, there must be adequate fuel for 8 hours of operation. The batteries must be fully charged.

The starting equipment must be test-operated and its functioning carefully checked. Any evidence of a drop in voltage greater than –15 percent (nominal voltage less 15 percent) to an electric motor or a drop in steam pressure to a turbine must be investigated.

With a diesel engine drive, the crankcase oil must be replenished or renewed as needed, the oil filter and air cleaner given the necessary attention, the automatic battery charging equipment checked, and the specific gravity of battery electrolyte determined at least once a month.

RECIPROCATING STEAM FIRE PUMPS

Although no new reciprocating steam fire pumps have been installed in recent years, a few may still be in service. These fire pumps are commonly referred to as Underwriter steam fire pumps. The general features of a direct-acting duplex steam pump are shown in Figure 15.6.23. The size of the steam and exhaust ports of this type of pump is larger than it is in the general-purpose steam pump, thus permitting higher speeds. The steam supply pipe should be an independent line run from boiler to pump in such a way that it will not be damaged by fire or other hazards.

Automatic control can be provided by a pressure governor to regulate steam supply to the pump in accordance with the water pressure on the pump discharge. For successful operation, it is nearly always necessary to provide a small, automatically controlled jockey pump to maintain system pressure, control supply leakage, and avoid continuous operation of the large pump.

FIRE PUMP APPROVAL AND LISTING

NFPA standards for design and installation of various fire protection systems require the use of approved equipment, or listed equipment, or both, including fire pumps, for installations requiring them. Under the testing and listing approval system, the manufacturer is responsible for providing a listed or approved pump that will perform satisfactorily when installed in conformance with NFPA 20. Contractors or others are responsible for installing the driver-pump combination in accordance with the provisions of NFPA 20, whereas it is the customer's obligation to provide adequate data about the pump driver, power supply, water supply, location, and so on.

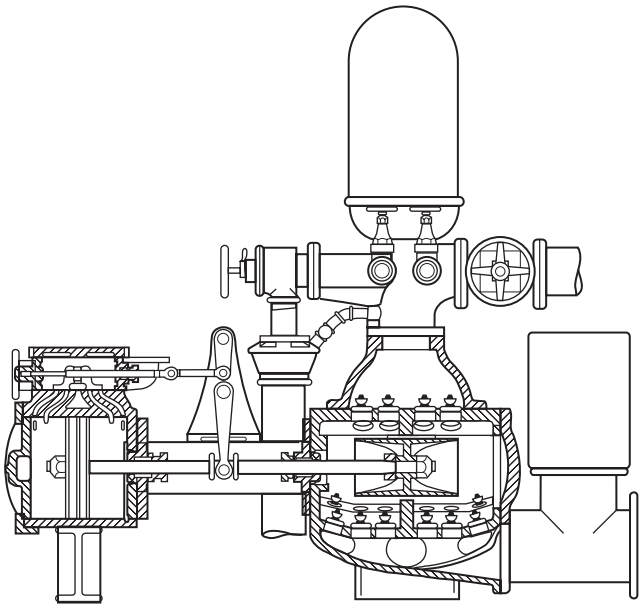


FIGURE 15.6.23 Sectional View of an Approved Duplex Steam Pump

Fire pumps are designed to provide maximum reliability and specific net head-discharge characteristics. Except for periodic inspections and tests, fire pumps are idle most of the time. Pumps for commercial use, on the other hand, are chosen for maximum efficiency and economy.

To obtain a listing of a new pump, the manufacturer submits plans and specifications to a testing agency for review and comment. After any revisions or corrections have been agreed to, arrangements are made for representatives of the testing agency involved to witness the required approval tests at the manufacturer's plant.

If the results are satisfactory, the new pumps are listed in the usual manner or with any restrictions considered desirable. It is the duty of the manufacturer to shop-test every unit sold and to furnish certified curves of head, efficiency, and brake horsepower versus discharge. The NPSH curve of the pump should be provided on request.

Many of the listed fire pumps used today are top-quality commercial units. These pumps are upgraded when necessary, trimmed, and fitted to meet all the approval requirements for fire protection.

SUMMARY

Fire pumps provide the water supply pressure, or they enhance the existing water supply pressure, for powering fire protection systems such as automatic sprinklers. This chapter described different types of fire pumps, that is, centrifugal pumps and positive displacement pumps. The chapter further discussed the principles of fire protection operation, including a discussion of the power sources that drive fire pump systems. The chapter concluded with a description of field acceptance tests and pump operation and maintenance procedures.

BIBLIOGRAPHY

References Cited

1. ANSI B73.1, *Specification for Horizontal End-Suction Centrifugal Pumps for Chemical Process,* American National Standards Institute, New York, 2001.
2. *Hydraulic Institute Standards,* 16th ed., 2005.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on water distribution discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*
NFPA 13E, *Recommended Practice for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems*
NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 22, *Standard for Water Tanks for Private Fire Protection*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 31, *Standard for the Installation of Oil-Burning Equipment*
NFPA 37, *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines*
NFPA 54, *National Fuel Gas Code*
NFPA 70, *National Electrical Code®*
NFPA 72®, *National Fire Alarm Code®*
NFPA 110, *Standard for Emergency and Standby Power Systems.*

Chapter 7

Fire Pump Controllers and Power Supply Arrangements for Motor-Driven Fire Pumps

Revised by
James S. Nasby ❑ John R. Kovacik

Chapter Contents

Worldwide Standards for Fire Pump Controllers
Electric Power Supply Arrangements for Motor-Driven Fire Pumps
Electric Drive Controllers
Limited-Service Controllers
Full-Service Controllers
Variable Speed Electric Motor–Driven Fire Pumps
Controller Parameters
Standard Controller Components
Standard Controller Features
Nonmandatory Controller Features
Transfer Switches

Key Terms

combination controller, fire pump controller, fire pump (diesel-engine driven), fire pump (electric-motor driven), fire pump (steam-turbine driven), fire pump (variable speed), power transfer switch

Where determined to be necessary through hydraulic analysis, a fire pump is a critical component of the overall water-based fire protection system. A successful outcome to a fire incident depends on the proper operation of the fire pump or pumps because the pump generates the necessary waterflow and pressure for fire control or extinguishment. In this regard, it is not just the fire pump that is of concern. All components that enable the pump to operate must be considered and be properly designed, installed, and maintained. This chapter focuses on the electrical and control aspects of electric motor–driven fire pump installations and is specific to fire pump controllers, motors, and electrical power supply arrangements.

Specific requirements concerning the design, construction, and performance of fire pump components are covered in NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection.* NFPA 70, *National Electrical Code®*, addresses how the electrical equipment—including the wiring of the power supply, fire pump controller, fire pump motor, and ancillary circuits—are to be installed. NFPA 20 covers the commissioning (acceptance testing) of fire pump equipment, whereas NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems,* addresses the routine servicing of fire pump equipment after it has been commissioned.

This chapter is intended to assist those involved with fire pump installations with making better decisions that will lead to more reliable and successful fire protection. This chapter provides added detail and establishes a perspective for the requirements spelled out in NFPA 20, NFPA 25, and NFPA 70 as they pertain to the electrical and control aspects of fire pump installations. In the end, the fire pump installation needs to be reliable and adequate for the life of the building. If determined not to be, corrective actions need to be immediately identified and executed in order to maintain the reliability of the fire protection of the building and maintain the expected degree of property and life-safety protection.

This chapter first appeared as new Section 10, Chapter 8, in the 19th edition of the *Fire Protection Handbook.* The revision in this edition primarily incorporates the extensive changes to the power supply text and requirements of the 2007 edition of NFPA 20. This revision also recognizes the introduction of variable speed motor-driven fire pumps, their applications, and field experience.

For related topics see, Section 15, Chapter 4, "Water Supplies for Sprinkler Systems"; and Section 15, Chapter 6, "Water Distribution."

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WORLDWIDE STANDARDS FOR FIRE PUMP CONTROLLERS

Fire pumps and fire pump controllers are widely used throughout the world wherever the need for water exceeds the ability of water supply systems to provide it. The style or type of fire pumps, drivers, and controllers used in North America are the type governed by NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection.* In much of the rest of the world, this type of equipment is known as either the NFPA type of fire pump installation or the North American style of fire pump installation. Although many countries have adopted other NFPA standards, such as NFPA 70, *National Electrical Code®*, only a few countries outside of the United States and Canada (e.g., Brazil, Panama, Malaysia, Korea, Indonesia, and Australia) have also adopted NFPA 20 for fire pumps. In other countries, "NFPA-style" equipment is used when North American insurance, financing, or ownership is involved. The other U.S.-based fire pump controller standards are UL 218, *Approval Standard for Fire Pump Controllers,* by Underwriters Laboratories Inc. and FM 1321/1323, *Approval Standard for Fire Pump Controllers for Electric Motor Driven and Diesel Engine Driven Fire Pumps,* by Factory Mutual (FM Global).

Outside of the United States, fire pump controllers and drivers are very different from the NFPA-style equipment. Specifically, most of Europe uses LPC-style equipment. LPC stands for the Loss Prevention Council, which is headquartered in England. The LPC's Loss Prevention Certification Board publishes a list of approved LPC equipment. The Loss Prevention Certification Board is in the process of establishing standards for diesel engines and electric motor–driven fire pump controllers, namely, LPS1236 and LPS1237, respectively. In addition, the British Standards Institute (BSI) offers standard BS 5306: Part 2, a fire pump standard in which the equipment described is similar to that in LPC-type installations. Further, a new European norm, EN 12845, on automatic sprinkler systems is now being used in certain countries. Table 15.7.1 summarizes the key salient features of these two types of fire pump equipment.

ELECTRIC POWER SUPPLY ARRANGEMENTS FOR MOTOR-DRIVEN FIRE PUMPS

The major components of a motor-driven fire pump installation include the pump, the electric motor, and the controller. Another less obvious but equally important component is the electric power supply. Because electric motors require an electric power supply to operate, the arrangement and type of electric power supply used is critical. Loss of electrical power during a fire incident would totally disable the fire protection system, which could then result in potential loss of the building. Therefore, the electric power supply is as critical as any other component of the fire pump installation.

When a fire pump operates, it must do so as intended for the length of time necessary for fire protection operations. Therefore, the electrical power supply must also remain available for this time period. Sufficient electrical capacity to start the fire pump motor and to maintain proper operating speeds once started must also be available. Additionally, the electrical supply must be of sufficient capacity for the locked rotor condition.

A locked rotor condition occurs when a rock or other object gets lodged in the fire pump between the fire pump casing and the impeller or if the pump shaft is seized (frozen) due to long periods of neglect. If the pump shaft cannot rotate freely, it will cause the motor to draw high currents, usually during the starting sequence, as the motor attempts to turn the pump shaft. This prolonged high current can cause significant damage to the electrical equipment and the motor, impairing the entire fire protection system. A prolonged locked rotor condition is not considered a normal condition.

The intent of NFPA 20 is to set higher limits on the overcurrent protection devices than what is normally allowed or required by NFPA 70 to increase the likelihood that the fire pump motor can dislodge an obstruction or free a frozen pump and allow pumping to commence or continue. For some motor starting methods, especially for emergency mechanical starting, the current required for starting the motor can reach a locked rotor condition. Various methods are employed so that the short-term high-inrush starting currents do not open the disconnecting means in the fire pump controller during pump starting.

Overall, electrical safety and preservation of electrical equipment are considered secondary objectives in NFPA 20. This philosophy is contrary to the general requirements of NFPA 70, in which requirements are written to minimize electrical hazard to buildings and occupants, reduce the likelihood of damage to electrical equipment, and decrease the possibility of ignition from overloaded electrical circuits. In this regard, NFPA 70 specifies certain safety devices to protect people and equipment from hazardous voltages and electrical currents. NFPA 20, however, which essentially pertains to the effective and continued operation of the fire pump once a fire has occurred, overrides the general safety provisions of NFPA 70. NFPA 20 considers the fire pump equipment to be sacrificial so as to provide continued water delivery for fire-fighting operations for as long as possible. The potential for damaging the motor or other equipment because of high electrical currents is not considered an appropriate reason for shutting down the fire pump and the water-based fire protection system.

The 2007 edition of NFPA 20 included significant revisions to the power supply requirements in Chapter 9. Sections 9.1, 9.2, and 9.3 were rewritten to clear up the following concerns with the existing text:

1. The portion of the power supply that must be dedicated to the fire pump installation
2. Questions on whether the normal supply arrangement is allowed to change based on provisions for backup power
3. Clarification of the requirements for using the "campus-style" arrangement
4. Questions on whether more than one backup source of power is permitted
5. Increased guidance for services over 600 volts (privately owned transformers)

In the 2007 edition, NFPA 20, Section 9.1, "General," is essentially the same as in the 2003 edition, except that a new Sec-

TABLE 15.7.1 Comparison of Fire Pump Controller Characteristics

Parameter or Attribute	*LPC*	*NFPA*
All Controllers (Both Diesel and Electric Motor Driven)		
Manual stop required (no automatic stop)	All fire pumps	All sole-source pumps
Enclosure type (protection)	IP65 (dust tight, spray resistant)	NEMA 2 (drip proof)
Usual location of pressure switch	Separate from controller	Within controller
Pressure recorder required	No	Yes
Electric Motor Drive Controllers (Low-Voltage Full-Service Controllers)		
Power for electric motor driver	Separate building circuit	Separate service or feeder
Maximum load on electric motor driver	90.9%[a]	115%
Separate isolating switch required	No	Yes
Overcurrent protection	Fuses	Circuit breaker
Overcurrent protection	200%, for 5 hr minimum	300% or less, no trip
Motor locked rotor protection timing	75% of motor burn-out time	8 to 20 sec
Emergency run manual operator required	No	Yes
Overload relays allowed	No	No
Diesel Engine Drive Controllers		
Maximum load on diesel engine driver	90.9%[a]	90.9%[a]
Overspeed shutdown	Prohibited	Mandatory
Low oil and high-temperature shutdown	Prohibited	During test only
Cranking batteries	Two	Two
Battery capacity	6 cranks each	12 cranks each
Cranking cycle times (sec)	15 sec cranking, 10 sec resting	15 sec cranking and resting
Cranking cycles	Six on one battery	Six, alternating
Emergency manual cranking	Both batteries in parallel	Either or both[b]
Test start light after a pump demand run	Required	Not required
Automatic weekly test circuit	Not required	Required
Battery charger size (for lead acid batteries)	3.5 to 7% of 10-hr capacity	Total capacity recharge of both batteries in 24 hr or less
Typical charger size for 100 amp-hour batteries	3.5 to 7 amperes	10 amperes[c]
Typical charger size for 200 amp-hour batteries	7 to 14 amperes	10 amperes[c]
Location of tachometer and speed switch	In controller	On engine

[a]Driver must be 110% of maximum pump load.
[b]Varies with the controller design (manufacturer); some have one start button, others two.
[c]Either two 10 ampere chargers or a single divided 20 ampere charger is typical.

tion 9.1.4 was added as a relocation of an existing requirement that all power supplies are to be located and arranged to protect against damage by fire from within the premises and exposing hazards. This requirement previously applied where power was supplied by a service. It now applies to all power sources. Section 9.2 was retitled "Normal Power," and Section 9.2.2 was rewritten to identify the types of power supplies that may serve as the normal source of power to the electric motor–driven fire pump. The requirements for the one allowable disconnecting means and associated overcurrent protection installed in the power supply to the fire pump controller are now covered in Section 9.2.3. Section 9.3 was retitled "Alternate Power," and Section 9.3.1 was rewritten to relocate an existing requirement that at least one alternate source of power is to be provided when the height of the structure is beyond the pumping capacity of the fire department apparatus. Since it applies to the need for alternate power, its new location is more appropriate. The types of power supplies that may serve as the alternate source of power to the electric motor–driven fire pump where reliable power cannot be obtained from a service connection or on-site power production facility are identified in Section 9.3.2.

Sources of Electric Power Supplies

The following electrical power supplies are acceptable for fire pump installations under specific conditions. As will be

described, only a reliable utility service or private power station can be used as a stand-alone individual power supply.

Utility Service. *Service* is the conductors and equipment for delivering energy from the electricity supply system to the wiring system of the premises served. Generally stated, the service is the equipment provided by the public utility used to deliver electrical power to the facility for all normal operations. Specifically, the service begins where the utility wiring stops (service point), and the service ends at the customer side of the service disconnecting means (usually the main switch or main circuit breaker). Ideally for fire pump installations, electrical power should be provided through a direct dedicated circuit to the fire pump controller from the service point as indicated in Figure 15.7.1. The connection is made from either a dedicated service or as a tap ahead of the service disconnect supplying the premises' electrical equipment. For either of these arrangements, the fire pump controller serves as the service disconnecting means. If this direct connection is not possible, other options exist and are discussed in the following section on dedicated connection of supply conductors. In general, the service equipment needs to be located and arranged to minimize the possibility of damage by fire and other hazards from both within the premises and external exposures.

On-Site Electrical Power Production Facility. On-site generation encompasses one or more prime movers and generators located on the premises that serve as the normal electric power source for the premises. In other words, the on-site generation supplies all electrical loads on the facility. This power supply is also referred to as a private power station. A prime mover is described as a mechanical device such as a turbine used to drive a generator. As with the utility service described previously, electrical power should ideally be provided via a direct dedicated circuit to the fire pump controller from the private power station, and the power generation facility needs to be located and protected to minimize the possibility of damage by fire and other hazards from within the premises and from external exposures. This equipment must be located in a separate building or in a structure cut off from the remainder of the premises. An on-site standby or emergency generator as described next cannot be considered on-site generation because its purpose is to supply emergency electrical loads only.

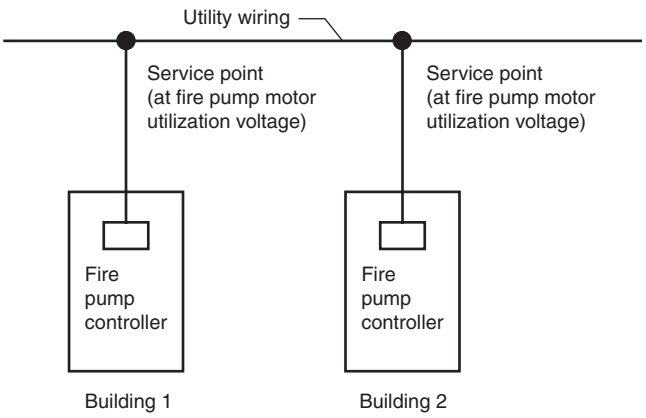


FIGURE 15.7.1 Direct Connection to Utility Service

On-Site Standby (or Emergency) Generator. Generators are considered an emergency or backup electrical power supply. Generators are not intended to serve as the normal source of power for the facility and are, therefore, not considered a private power production facility. Generators do not need to be dedicated solely to fire pump operations but must be of sufficient capacity to allow normal starting and running of the fire pump motors while supplying all other simultaneously operated loads such as elevators and emergency lighting. NFPA 110, *Standard for Emergency and Standby Power Systems,* addresses the installation of these generators.

Feeder Sources. Feeders constitute a power supply arrangement in which power is delivered from a single service point to fire pump equipment in more than one building through a nondedicated circuit. Unlike the arrangement for a utility service or private power station that requires a dedicated circuit from the service point to the fire pump equipment, feeders employ conductors from the service point to deliver power to multiple buildings. Figure 15.7.2 illustrates two feeder arrangements, one supplied from a utility service and the other supplied from a private power station.

Feeder sources are limited to multibuilding campus-style arrangements with fire pumps located at one or more buildings, where the utility service or private power station arrangement is not practicable and where the feeder arrangement is acceptable to the authority having jurisdiction (AHJ). A campus-style facility generally encompasses a considerable contiguous area. Under these circumstances, two feeder sources or a single feeder source in combination with another power supply can be considered a reliable source of electrical power. (See the section on individual sources of power supplies for additional information.)

Other Sources. Diesel engines and steam turbines can also serve as power supplies for fire pumps, although not for the electric motors. Diesel engines and steam turbines are stand-alone power supplies not requiring a backup or emergency source of power. Where diesel engines or steam turbines are used in combination with electric motor drives, they serve as an entirely redundant fire pump arrangement to the electric motor–driven fire pump. Although NFPA 20 does not require this type of arrangement, insurance companies may do so depending on the risk in question. The installation of diesel engines and steam turbines is addressed in Section 15, Chapter 6, "Water Distribution."

Individual Sources of Electric Power Supplies

The basic rule for power supply is that electrical power is to be supplied to the motor-driven fire pump by an individual stand-alone reliable source or by two or more (multiple) independent sources. Therefore, if the utility service or private power station is considered reliable, only one source is needed. If a single power supply is unreliable, then additional sources of electrical power must be provided. Additionally, regardless of the reliability of a proposed single power supply, where the height of the

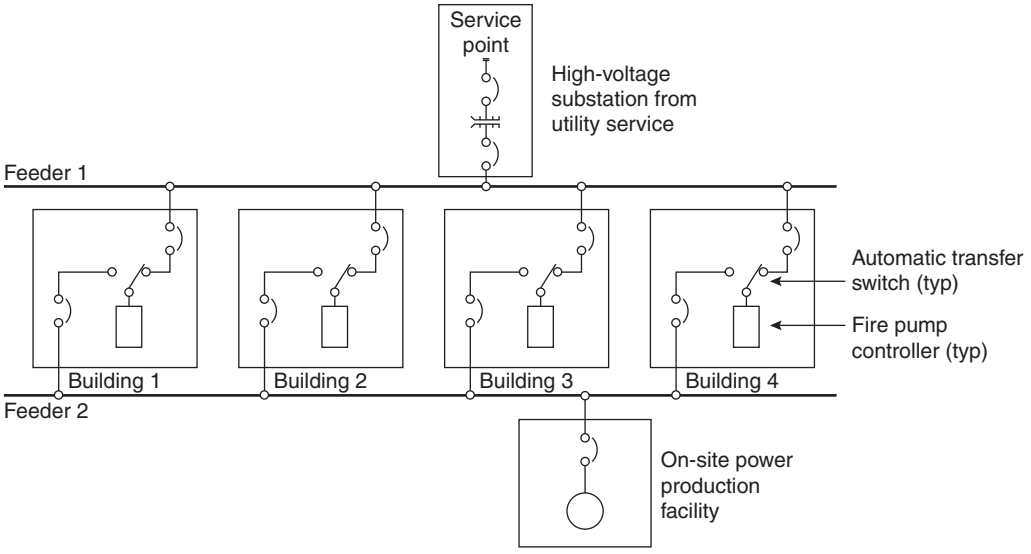


FIGURE 15.7.2 Feeder Arrangement from Two Independent Sources

building is beyond the pumping capacity of the fire department, a second source of power needs to be provided. This provision addresses the situation of the electrical power supply being inadvertently lost or intentionally disconnected during a fire, and the fire department not being able to deliver the necessary water pressure and flow to fight the fire.

Local regulations often override the requirements of NFPA 20 and usually specify additional conditions under which more than one power supply is required even if a single source is considered reliable. For example, the building code in one state requires that all fire pumps serving high-rise buildings, assembly and educational facilities with more than 300 occupants, buildings classified as hazardous occupancies, and institutional facilities in which surgical or treatment operations are conducted be provided with emergency power.

Reliability of Electrical Power Supply

Reliability of the power supply generally pertains to the availability of the power supply and how it is arranged and connected to the fire pump controller. NFPA 20 suggests that a reliable electrical power supply is one that experiences only infrequent power disruptions from environmental conditions or human interaction. This statement implies that a reliable power source can tolerate some limited interruptions and supports the notion that zero risk is unattainable. Responsibility for determining reliability of the power source in terms of its availability and whether it meets the intent of NFPA 20 rests with the AHJ.

The service owned by the public utility and a private on-site electrical power production facility are the only two electric power sources that NFPA 20 would consider to be reliable. However, local regulations and other conditions usually specify additional restrictions in this regard. In some instances, the AHJ might not consider the public utility or private power station as a reliable electrical power source for the fire pump(s) due to frequent power interruptions. For example, under the rolling power blackout conditions in California during 2000 and 2001, the single power source, the public utility, was not considered reliable and corrective action was needed for emergency power. As described previously, it is important to recognize that a private on-site power generation facility or private power station is not the same as an on-site generator.

There have always been questions as to what defines a reliable power supply. The 2003 edition of NFPA 20 first introduced annex material that provided guidance on the selection of such a power supply. The 2007 edition revised that annex material to provide more specific criteria. The Fire Pump Committee included the following guidance for determining the reliability of the power supply:

1. The source power plant has not experienced any shutdowns of longer than 4 continuous hours in the year prior to plan submittal.
2. No power outages have been experienced in the area of the protected facility that were caused by failures in the power grid that were not due to natural disasters or electric grid management failure.
3. The normal source of power is not supplied by overhead conductors outside the protected facility.
4. Only the disconnect switches and overcurrent protection devices permitted by Section 9.2.3 are installed in the normal source of power. The committee did add two requirements to the body of the standard to specify certain levels of performance that, to a certain degree, define the capability (and reliability) of the power supply. The standard now states that all power supplies shall (a) have the capacity to run the fire pump on a continuous basis and (b) comply with the voltage drop requirements of Section 9.4. These are key elements of pump performance.

The use of phase converters as part of the power supply to the fire pump motor has raised concerns regarding the reliability of such a supply. The 2007 edition of NFPA 20 added annex mate-

rial stating that "Phase converters that take single-phase power and convert it to three-phase power for the use of fire pump motors are not recommended because of the imbalance in the voltage between the phases when there is no load on the equipment. If the power utility installs phase converters in their own power transmission lines, such phase converters are outside the scope of this standard and need to be evaluated by the AHJ to determine the reliability of the electric supply." Although there are no requirements prohibiting their use, phase converters are not considered a reliable source of power and are not recommended for fire pump service.

Multiple Sources of Power

Where multiple electric power sources are provided, NFPA 20 requires that they be arranged and located so that a fire, structural failure, or operational accident that interrupts one source will not cause an interruption of the other source. Additionally, on-site standby generators must be protected to minimize the possibility of damage by fire and other hazards from within and external to the premises.

When reliable electrical power cannot be obtained from either the utility service or a private power station, a redundant or backup source of power by one of the following arrangements is required:

- Combination of two or more sources of either utility service or private power station
- Combination of on-site standby generator and either utility service or private power station
- Combination of feeders from two separate sources
- Combination of feeder source and on-site standby generator
- Diesel engine–driven or steam turbine–driven fire pump

Combination of Two or More Sources of Either Utility Service or Private Power Station. Under this arrangement, a combination of two independent utility sources, two separate private power stations, or a utility source and private power station would suffice. It is important to recognize that where two utility sources are considered, they must be independent of one another. An arrangement consisting of two separate service points from the same utility equipment would not be considered an acceptable combination of power sources.

Combination of On-Site Standby Generator and Either Utility Service or Private Power Station. In this case either the utility service or the private power station would provide power for normal operations and the standby generator would provide backup power. In the event that normal power is lost and a fire occurs, the standby generator would be available to start and operate the fire pump motor. This arrangement should not be interpreted to mean that only the standby generator should be arranged to start and operate the pump. The normal electrical power supply also needs to be sized and arranged to execute this function.

Combination of Feeders from Two Separate Sources. This arrangement is depicted in Figure 15.7.2. Feeder 1 delivers power from the utility service, and feeder 2 delivers power from the private power station. Under this arrangement, both feeder conductors constitute an independent power source because they are delivering power from two separate sources. The intent is that failure of one source will not or should not affect or cause the failure of the other source. If feeder sources were arranged such that two separate feeder conductors supplied power to a building from two separate service points from the same utility service, the feeder source would only be considered as a single unreliable power source. As previously indicated, the feeder source can only be used for multibuilding campus-style complexes where a direct connection to the utility service or a private power station is not practicable and where such an arrangement is acceptable to the AHJ.

Combination of Feeder Source and On-Site Standby Generator. This arrangement is depicted in Figure 15.7.3. The feeder connects the utility service power source to multiple buildings and each building contains a standby generator. As indicated in the previous section, the feeder source can only be used for multibuilding campus-style complexes where a direct connection to the utility service or a private power station is not practicable and where such an arrangement is acceptable to the AHJ.

Diesel Engine–Driven or Steam Turbine–Driven Fire Pump. The diesel engine or steam turbine would be redundant to the electric motor–driven pump, which in turn is supplied by the utility service or a private power station. The diesel engine or steam turbine cannot be redundant to an electric motor fire pump powered exclusively by a feeder source or an on-site generator. However, as previously discussed, where a diesel engine or steam turbine fire pump arrangement is provided, NFPA 20 permits the diesel engine or steam turbine to serve as a standalone driver not requiring any backup power supplies.

Dedicated Connection of Supply Conductors

To minimize the possibility of accidentally disconnecting the power supply to the fire pump, the power supply to the fire pump must not be disconnected when the power for the facility is disconnected. For this reason, a reliable power supply is one that contains a separate dedicated connection to the service point or a connection to the supply side of the service disconnecting means. The only exception to this general rule pertains to feeder sources in which the disconnection of power to the fire pumps is permitted under circumstances that automatically ensure the continued availability of the alternate power supply. Because feeders use a single circuit to supply several buildings, disconnecting power to the feeder at any one of a number of points would potentially cut off power to all buildings served by the feeder and, thus, their fire pumps as well. It is also strongly advised that the power circuit for any fire pump not be routed through any other building to minimize the chance of a fire in one building knocking out the fire protection in any other building(s).

The most preferred power supply arrangement is a direct connection, as illustrated in Figure 15.7.4. In this arrangement, the power supply conductors directly connect the service point

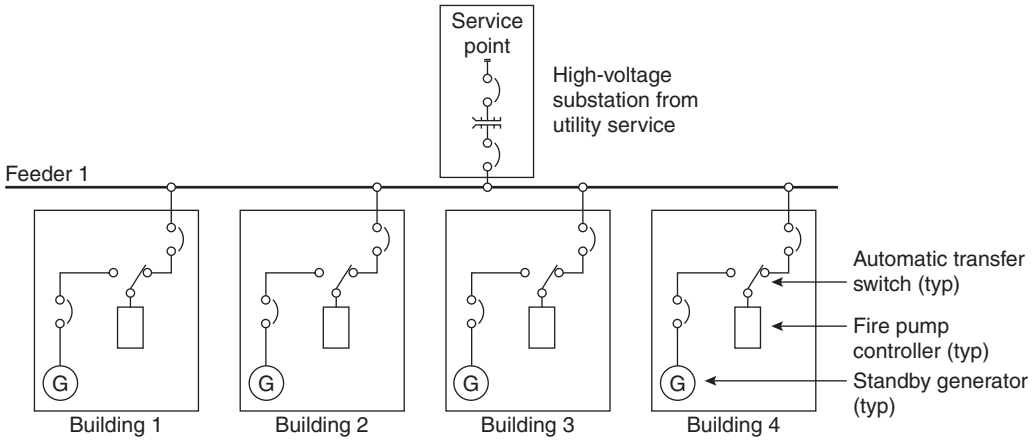


FIGURE 15.7.3 Feeder Source in Combination with an On-Site Standby Generator

or private power station to the fire pump controller or a combination fire pump controller power transfer switch, where more than one power supply is used. Under this arrangement, there is no disconnecting means or overcurrent protection device(s) other than that provided by the fire pump controller. In essence, the fire pump controller becomes the service disconnecting means and overcurrent protection device and is listed as such. Arranging the power supply in this manner minimizes the possibility that the fire department will inadvertently cut off power to the fire pump when the facility's power supply is disconnected.

NFPA 20 recommends that where anticipated risks are large and interruption for fire pump service would seriously affect protection, at least two separate circuits from the power supply to the pump room be provided. The circuits should be run by separate routes or in such a manner that failure of more than one at the same time would be only a remote possibility.

Supervised Connection of Supply Conductors

Where a utility service or private power station serves as the power supply but a direct connection from these sources is not practicable, NFPA 20 allows for two other power supply arrangements. These include a supervised connection and a connection incorporating a transformer. Note that connections for feeder sources are addressed separately later. For both arrangements, the circuits that supply electric motor–driven fire pumps must be supervised against inadvertent disconnection. The first arrangement, referred to as a supervised connection, allows for a single disconnecting means and overcurrent protective device(s) to be installed ahead of the fire pump controller, as illustrated in Figure 15.7.5. A supervised connection is allowed under specific conditions only, pertaining to selection of the overcurrent protective device, means of disconnecting power, marking of the disconnecting means and the controller, and supervision of the disconnecting means as described in the following sections.

Overcurrent Protective Device Selection. Overcurrent is any current in excess of the rated current of equipment such as the fire pump motor, or the ampacity of a conductor, and can result from overload, short circuit, or ground fault. An overload condition for an electric motor includes locked rotor in which the motor is loaded so heavily that the motor shaft cannot turn. Locked rotor can be caused when a stone or other obstruction prevents the fire pump impeller from freely rotating. The overcurrent protective device, normally a circuit breaker for fire pump applications, serves to protect the motor from destroying itself under specific overload conditions. It senses when the amount of current flowing through the supply conductors exceeds a certain value and opens the circuit.

For a supervised connection, the overcurrent protective device on the supply conductors serving the fire pump equipment must be selected or set to carry indefinitely the sum of

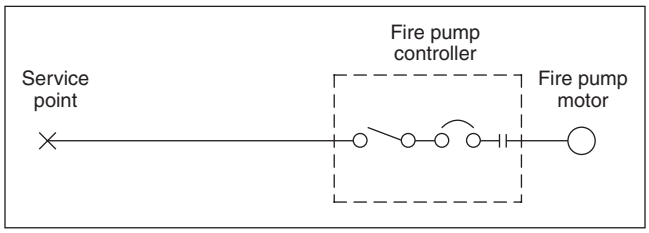


FIGURE 15.7.4 Direct Connection Between Service Point and Fire Pump Motor

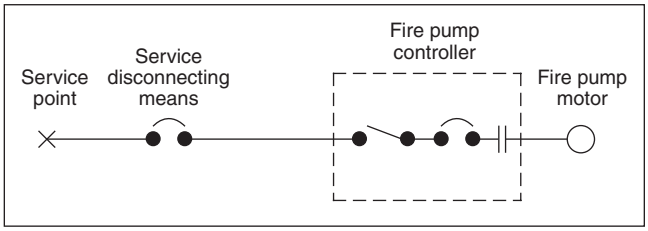


FIGURE 15.7.5 Installation of a Disconnecting Means

the locked rotor current of the fire pump motor(s), the pressure maintenance pump motor(s), and the full-load current of the associated fire pump accessory equipment when connected to this power supply. This value of overcurrent protection is set higher than that typically required for NFPA 70 for nonfire pump equipment. In other words, more current is allowed to pass through the conductors and motor, increasing the potential for equipment failure and the possibility of an additional ignition source. The reason for allowing more current to pass is to permit operation of the fire pump equipment for as long as possible during a fire. As previously indicated, the fire pump equipment is considered sacrificial and preservation of fire pump equipment is not an acceptable reason for disconnecting power to the pump equipment during a fire.

Although the overcurrent protective device is required to carry the locked rotor current indefinitely, in actuality this time period is normally limited by the disconnecting means located in the controller. When a motor is started, a large inrush current occurs and, in many cases, especially for manual (emergency mechanical) starting, is as high as that experienced during a locked rotor condition. For this reason, the overcurrent protective device must have a sufficiently high ampere rating to avoid opening the circuit on the occurrence of large but temporary inrush currents required for motor starting. In this regard, the locked rotor protection in the fire pump controller will allow for the motor to be started without disrupting the circuit. The upstream overcurrent protective device is required to hold the motor locked rotor current indefinitely to allow the fire pump controller to govern when or if the circuit is to be interrupted.

Disconnecting Means. The disconnecting means is a manually or automatically operated device that removes electrical circuits from their power supply. The disconnecting means can consist of circuit breakers for most controllers or fused switches in medium-voltage controllers. The supplemental disconnecting means permitted through a supervised connection is supplemental to the manual and automatic disconnecting means located in the fire pump controller and is intended for only periodic use. The supplemental disconnecting means must possess the following characteristics:

- Identified as suitable for use as service equipment
- Lockable in the closed position
- Located at a sufficiently remote location from other building or other fire pump source disconnecting means that inadvertent operation at the same time would be unlikely

Service equipment is the necessary equipment that connects the lead end of service conductors to the electrical circuits of a building or other structure. Service equipment usually consists of a circuit breaker(s) or fused switch(es) and their accessories and is intended to constitute the main control and cutoff of the electrical supply. Service equipment is intended to disconnect all ungrounded conductors in a building from the service-entrance conductors. The disconnecting means at any one location should not consist of more than six circuit breakers or six switches and is required to be readily accessible either outside the building or inside nearest the point of entrance of the service-entrance conductors.

Disconnect Marking. The disconnecting means must be permanently marked "Fire Pump Disconnecting Means" to make clear the purpose of the disconnecting means. The letters are to be marked at least 1 in. (25.4 mm) in height and they are to be visible without opening enclosure doors or covers.

Controller Marking. A placard must be placed adjacent to the fire pump controller stating the location of the additional disconnecting means and the location of the key if the disconnecting means is locked.

Supervision. The disconnecting means must be supervised in the closed position by one of the following methods:

- Central station, proprietary, or remote station signal device
- Local signaling service that will cause the sounding of an audible signal at a constantly attended location
- Locking of the disconnecting means in the closed position
- Sealing of the disconnecting means and approved weekly recorded inspections where the disconnecting means are located within fenced enclosures or in buildings under the control of the owner. The intent of monitoring is to ensure that if the power supply is inadvertently disconnected, corrective action can be immediately taken.

Power Supply Connection Incorporating a Transformer

Where the supply voltage differs from the utilization voltage of the fire pump motor, that is, the loaded voltage and the rated motor voltage, a transformer meeting the requirements of NFPA 70 along with a disconnecting means and overcurrent protection can be installed between the fire pump controller and the service point, as illustrated in Figure 15.7.6. Where this arrangement is employed, specific conditions pertaining to the selection of the overcurrent protective device, the means of disconnecting power, the marking of the disconnecting means and the controller, and supervision of the disconnecting means as described for a supervised connection apply. It is important to note that secondary side overcurrent protection on the transformer is not permitted.

The transformer must be dedicated to fire pump equipment unless it supplies a feeder source as described in the section on feeder arrangement. The transformer must be rated at mini-

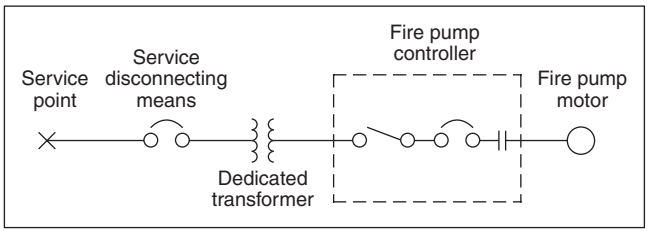


FIGURE 15.7.6 Installation of a Disconnecting Means and a Transformer

mum of 125 percent of the sum of the fire pump motor(s) and pressure maintenance pump motor loads and 100 percent of the associated fire pump accessory equipment supplied by the transformer. Note, however, that this rating is a thermal rating and that 125 percent will almost never be large enough to meet the voltage drop requirements.

The most critical limiting conditions for both the supervised connection and the transformer connection are the location of the disconnecting means that are to be remote from the other service disconnecting means and the overcurrent protection setting that is to be set to carry indefinitely the sum of the locked rotor current of the fire pump motors and the pressure maintenance pump motors, plus the full-load current of the connected fire pump accessory equipment.

Feeder Arrangement

Where feeder sources are used, the 2007 edition of NFPA 20 indicates that the overcurrent protection and the disconnecting means are to be arranged as indicated in NFPA 70 rather than that specified for a supervised connection as indicated previously. However, the 2008 edition of NFPA 70 provides no latitude in this regard and requires that the overcurrent protection and disconnecting means be arranged like that for a supervised connection. In other words, the circuit breaker on the feeder conductor needs to be set to carry indefinitely the sum of the locked rotor current of the fire pump, jockey pump, and other accessory equipment; and the disconnecting means must be suitable as service equipment, lockable in the closed position, and located at a sufficiently remote location from other building or fire pump source disconnecting means. Additionally, where more than one disconnecting means is supplied by a single feeder, the overcurrent protective device in each disconnecting means must be coordinated with all other supply side overcurrent protective devices. This requirement is to ensure that only the breaker nearest the fault or short circuit trips open.

The transformer on the feeder conductor may serve loads other than those dedicated to the fire pump. The transformer must be rated at a minimum of 125 percent of the sum of the fire pump motor(s) and pressure maintenance pump(s) motor loads and 100 percent of the remaining load supplied by the transformer, that is, all other loads served by the feeder. As described in the section on connection incorporating a transformer, the transformer will normally need to be larger to meet the voltage drop criteria.

Connection to a Power Transfer Switch

Perhaps the most complex arrangement is that of multiple power sources serving a fire pump motor. Transfer of power to the fire pump controller between the normal supply and the alternate supply, including an on-site generator, is to take place within the pump room. Figure 15.7.7 illustrates two acceptable arrangements for two power sources feeding a single fire pump motor. The combination fire pump controller/power transfer switch shown in arrangement I of Figure 15.7.7 must be listed for such fire pump service. Arrangement II of Figure 15.7.7 shows where a separately mounted power transfer switch is used. As in the case of the combination fire pump controller/power transfer switch, the separately mounted power transfer switch must be listed for fire pump service. Unless the emergency power source is an on-site generator, the disconnecting means and overcurrent protective devices shown must meet the requirements for a supervised connection as specified previously.

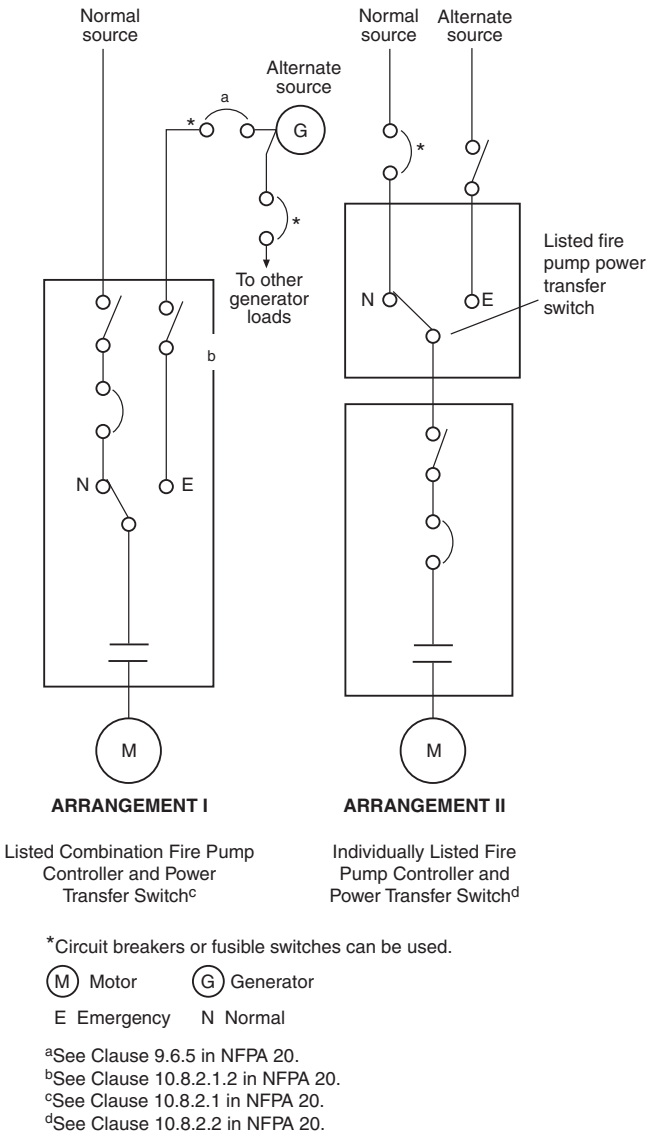


FIGURE 15.7.7 Two Acceptable Arrangements for Two Power Sources Feeding a Single Fire Pump Motor (Source: NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection,* Figure A.10.8, 2007, p. 20-75)

Physical Protection of Supply Conductors

In general, conductors feeding fire pumps and their accessories must be protected to resist possible damage by fire, structural failure, or operational accident.

Supply Conductors. These are physically routed outside buildings and installed as service-entrance conductors in accordance

with NFPA 70. If supply conductors cannot be physically routed outside buildings, they can be routed through buildings if installed under not less than 2 in. (50 mm) of concrete beneath the building, or if installed within a building in a raceway that is encased in concrete or brick not less than 2 in. (50 mm) thick. For a feeder arrangement, the requirement for protecting service conductors applies to all supply conductors on the load side of the service disconnecting means that constitute the normal source of supply to that fire pump. However, where there are multiple sources of supply with means for automatic connection from one source to the other, the requirement only applies to those conductors on the load side of the point of automatic connection between sources.

Circuit Conductors. These are on the load side of the final disconnecting means and overcurrent protective devices permitted for a supervised connection and must be kept entirely independent of all other wiring. The conductors are to supply only loads that are directly associated with the fire pump system, and they are to be protected to resist potential damage by fire, structural failure, or operational accident. They are permitted to be routed through buildings if encased in 2 in. (50 mm) of concrete, or within enclosed construction dedicated to the fire pump circuit(s) and having a minimum 2 hour fire resistance rating, or be listed electrical circuit protective systems with a minimum of 2 hour fire resistance. The 2008 *NEC* increased the fire resistance ratings from 1 to 2 hours to be consistent with *NFPA 72®, National Fire Alarm Code®,* which requires 2 hour survivability of the notification circuits and the interconnecting wiring of the fire command center.

Wiring. The installation must comply with any restriction provided in the listing of the electrical circuit protective systems used. The supply conductors located in the electrical equipment room where they originate and in the fire pump room are not required to have the minimum 2 hour fire separation or fire resistance rating, unless otherwise required by NFPA 70.

All wiring from the controllers to the pump motors needs to be rigid metal conduit, intermediate metal conduit, liquidtight flexible metal conduit, or liquid-tight flexible nonmetallic conduit Type LFNC-B or Type MI cable. Where wire connectors are used in the fire pump circuit, the connectors must also be listed. All wiring from engine controllers and batteries must be protected against mechanical injury and must be installed in accordance with the controller and engine manufacturer's instructions. See the section on motor wiring in *Pumps for Fire Protection* for more information in this regard.

The 2007 edition of NFPA 20 added a requirement addressing the use of single conductors entering the fire pump controller enclosure. The requirements addressed two concerns. Single conductors entering the fire pump controller enclosure separately could produce significant heating of the metallic enclosure due to magnetic forces. Also, certain electrical circuit protective systems could produce flammable gases that must be prevented from entering the fire pump controller enclosure. The new requirement states: "Where single conductors are used, they shall be terminated in a separate junction box" (not the fire pump controller). This permits splicing to a different wiring method that allows for all phase conductors to enter the controller through the same raceway. It also allows for the sealing of cables outside of the fire pump controller enclosure to keep flammable gases at a safe distance from the controller enclosure.

Fire Pump and Fire Pump Controller Power Transfer Switch. Although not directly pertaining to the protection of conductors, the fire pump controller and fire pump power transfer switch are not to be used as a junction box to supply other electrical equipment, including the pressure maintenance pump. Additionally, the fire pump controller and fire pump power transfer switch cannot serve any loads other than the fire pump for which it is intended. In this regard, a fire pump controller cannot serve more than one fire pump.

Buried Installation. A completely underground circuit from the service point or the private power station to the pump room is strongly recommended and should be arranged where practicable. This guideline also pertains to feeder conductors. Where such buried installation is not possible, that portion of the overhead circuit adjacent to the property served by the fire pump or to exposing properties or structures should be installed with consideration to potential damage in case of fire or other hazard. Where the pump room is part of, or in close proximity to, the property or structures that the pump is intended to protect, the conductors should be underground for some distance from the pump room.

The physical protection of the supply conductors provides a means of minimizing the impact from external exposures as well as minimizing the spread of fire as a result of overcurrent within the conductors themselves. During fire conditions, conductors from the service point or private power station are susceptible to direct impact and failure from collapsing buildings and other structural members on the facility as well as failure from direct impact by the fire. Where ignition is a result of overcurrent in the fire pump power supply conductors, the general construction arrangement described previously also serves to minimize the spread of fire.

Junction Boxes. The 2007 edition of NFPA 20 added requirements addressing the use of junction boxes for routing conductors to or from a fire pump controller. As previously mentioned, where single conductors are used to provide power to a fire pump controller, they must be terminated in a separate junction box. In addition, junction boxes are often used to terminate cables and change to some other form of wiring to the fire pump controller. The new requirements state that:

1. The mounting and installing of a junction box shall not violate the enclosure Type (NEMA) rating of the fire pump controller(s).
2. The mounting and installing of a junction box shall not violate the integrity of the fire pump controller(s) and shall not affect the Short Circuit Rating of the controller(s).
3. At a minimum, a (NEMA) Type 2, dripproof enclosure (junction box) shall be used and the enclosure shall be listed to match the fire pump controller enclosure Type rating.
4. Terminals, junction blocks, splices, and the like, when used, shall be listed.

Voltage Drop and Conductor Sizing

The voltage at the controller line terminal must not drop more than 15 percent below normal (controller-rated voltage) under motor-starting conditions. The voltage at the motor terminal must not drop more than 5 percent below the voltage rating of the motor when the motor is operating at 115 percent of the full-load current rating of the motor. (See the section on controllers for discussion of starting of motors.) This limitation does not apply for emergency-run mechanical starting, which may experience larger inrush currents.

Conductors supplying a fire pump motor(s), pressure maintenance pumps, and associated fire pump accessory equipment will have a minimum rating of 125 percent of the sum of the fire pump motor(s) and pressure maintenance motor(s) full-load currents and 100 percent of the associated fire pump accessory equipment. Conductors supplying only a fire pump motor(s) will have a minimum rating of 125 percent of the fire pump motor(s) full-load current(s).

Arrangements for an On-Site Standby Generator

An on-site generator used to supply backup power to fire pump motors needs to be of sufficient capacity to allow normal starting and running of the motor(s) driving the fire pump(s) while supplying all other simultaneously operated load(s). Generally, the generator does not need to be sized for locked rotor current if locked rotor current is not required for normal starting, such as for part winding and autotransformer starting. Where protective devices are installed in the on-site power source circuits at the generator, such devices need to be set to allow instantaneous pickup of the full pump room load. Additionally, a tap ahead of the on-site generator disconnecting means is not required as is for the connection of other power sources.

On-site standby generators are to comply with the voltage drop requirements previously discussed and are to meet the requirements of Level 1, Type 10, Class X systems of NFPA 110. The fuel capacity is to be sufficient to provide 8 hours of fire pump operation at 100 percent of the rated pump capacity in addition to the supply required for other demands. Where the generator is installed to supply power to loads in addition to one or more fire pump drivers, the fuel supply should be sized to provide adequate fuel for all connected loads for the desired duration. These connected loads can include such loads as emergency lighting, exit signage, and elevators.

Where more than one fire pump and motor are used, such as for high-rise buildings, automatic sequencing of the starting of the fire pumps is both permitted and required, as described in the following section on controllers. Starting all pumps simultaneously is not desirable from a pump performance standpoint. Additionally, this would create tremendous inrush currents and a higher voltage drop as more than one motor attempts to start.

ELECTRIC DRIVE CONTROLLERS

Controllers are devices that govern, in some predetermined manner, the starting and stopping of the fire pump driver as well as the monitoring and signaling of the starters and the condition of the fire pump unit (Figure 15.7.8). This section describes attributes of the different types of electric drive controllers and provides a broad perspective on the use of various types of controllers.

Fire Pump Controller Characteristics

Because of their intended function, fire pump controllers possess unique characteristics when compared to controllers for other types of applications. The most obvious is the limited protection of the fire pump motor and the motor circuit and components. The power path components of the controller, like the fire pump motor and power wiring circuits, are considered sacrificial. (Note that fire pump equipment is considered sacrificial because safeguards associated with other building equipment to preserve equipment do not apply. Fire-fighting operations must continue until the fire is extinguished even if the fire-fighting equipment is eventually damaged.) Controllers do not include motor overload relays and the only overload, overcurrent, or short circuit protection for the controller, motor, and wiring is provided by the fire pump controller circuit breaker. Note that the requirements differ for limited-service fire pump controllers, which use a different type of circuit breaker, and for medium-voltage controllers, which use special fuses and overcurrent sensing. Nonetheless, these controllers also sacrifice the fire pump motor and wiring similar to all other fire pump controllers.

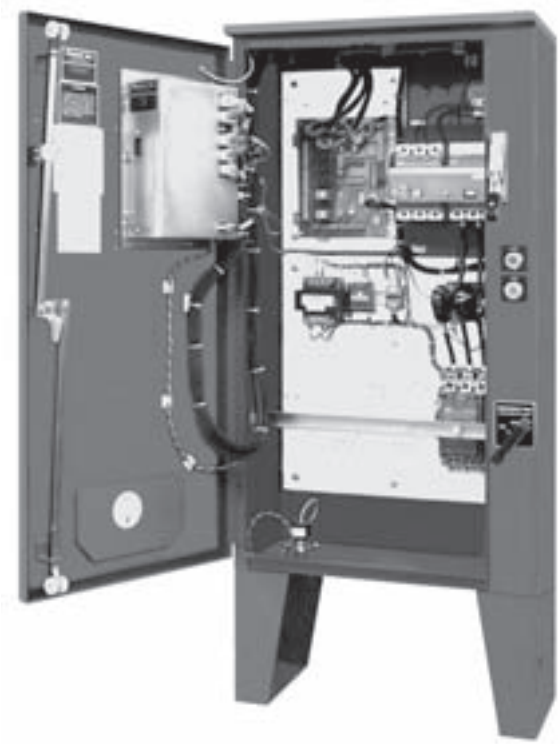


FIGURE 15.7.8 Electric Fire Pump Controller (Source: ASCO Power Technologies, Firetrol Brand Products)

Motor Overheating. The fire pump circuit breaker is not allowed to trip on currents less than 300 percent of FLA (full-load amperes), which is seven times the motor-rated heating compared with that at rated FLA. Running the motor at these high currents will overheat the motor's windings, which will damage or destroy the motor, the controller, and/or the power wiring in a fairly short time. Although not a desirable condition, operating the motor at these high currents is permissible so that fire-fighting operations can continue. This is the reason the motor, controller, and wiring are considered to be sacrificial. Nonetheless, this equipment must be protected from needless damage, stress, or destruction. It is, therefore, recommended that the motor current be monitored for overload (overcurrent) conditions. All listed controllers are available with an optional motor overcurrent alarm circuit.

Ground Fault Monitoring. Another unique characteristic is that ground fault protection is prohibited. However, ground fault monitoring is allowed. The same applies for low voltage, phase loss, phase reversal, underfrequency, and so on. Monitoring is allowed or mandated for some of these conditions, but the controller must keep the fire pump motor running under any of these conditions. The only exception is allowing the controller to protect the motor from attempting to start under a single-phase condition that would destroy the motor. In this condition it is better to protect the motor, as there is no opportunity to start a three-phase motor at rest when supplied with a single-phase power source.

Critical Path Control Circuitry. Another peculiarity of fire pump controllers is the sacrificial nature of the critical path control circuitry. The critical path or critical starting path encompasses every component and connection needed for successful starting of a fire pump. NFPA 20 mandates that the control circuitry within the controller not be protected by fuses or circuit breakers other than the controller's main motor circuit breaker.

Critical Electrical Parameters

Among other things, three electrical parameters are absolutely crucial to the successful starting and running of any fire pump motor: (1) the starting (locked rotor) voltage drop at the controller (15% maximum drop allowed), (2) the service factor (115% maximum) load current voltage drop at the motor (5% maximum allowed), and (3) the ability to start the motor without any false tripping of the fire pump breaker (in the fire pump controller) or any upstream overcurrent protection (fuses or circuit breaker). The voltage drop considerations are covered in more detail in the section on power supplies.

LIMITED-SERVICE CONTROLLERS

Fire pumps and their associated fire pump controllers come in two service types: full service and limited service. Limited-service fire pumps and controllers were introduced in the late 1940s in response to a major insurance organization request for simpler, less expensive controllers for use on smaller risks. One way of helping to assure that these units would be restricted to use on smaller risks was to impose the 30 horsepower (22 kW) maximum size limitation. The controllers are allowed to use the common "inverse time" nonadjustable circuit breaker rather than the special characteristic fire pump circuit breaker as required in full-service controllers. Typical listed limited-service controllers use thermal-magnetic-type circuit breakers. A further cost savings is accomplished by not requiring the separate isolating switch as is required in full-service controllers. In accordance with NFPA 20, these controllers are allowed only where such use is acceptable to the AHJ. Each such installation must be so approved.

Limited-service controllers must meet all of the requirements of full-service controllers with the two exceptions noted previously. By not requiring a full-service fire pump controller, the following characteristics of overcurrent protection are *not* required and are not normally found in these units: (1) they need not hold 300 percent continuously, (2) they need not meet the trip time requirements of 8 to 20 seconds at locked rotor current, and (3) they need not be adjustable. Moreover, the inverse time circuit breaker is required to be between 150 percent and 250 percent of the motor full-load current. This provides a wide range of motor locked rotor trip times. Based on commercially available and commonly used circuit breakers, the trip times can be far less than the minimum 8 second trip time and well over the 20 second maximum time required of full-service controllers. This is due to the difference in circuit breaker trip curves among different ratings, types, and manufactures of thermal-type circuit breakers and due to the motor rated full load current versus the breaker rated current.

Single-Phase Limited-Service Controllers

NFPA 20 states that limited-service controllers can be used for across-the-line starting of squirrel-cage motors of 30 horsepower or less. In some cases the motor horsepower is small enough to allow the use of single-phase motors and controllers when the use of same is approved by the AHJ. Listed controllers are available for those cases where a single-phase pump motor is adequate and where the source of supply will tolerate the starting and running currents while still meeting the voltage drop requirements of 15 percent maximum while starting and 5 percent maximum while running at 115 percent of motor full-load amperes (FLA).

Three-Phase Limited-Service Controllers

Most limited-service controllers and motors are three-phase types. The advantage of three-phase units is lower line currents for any given horsepower at a given voltage. More importantly, three-phase squirrel-cage motors are inherently more reliable than single-phase versions. This is because a single-phase motor contains a start winding in addition to the run winding and also contains a start winding cutout switch or relay to accelerate the motor. These extra components serve to reduce reliability over the simpler three-phase motors that contain none of these extra items.

Means of Starting Limited-Service Controllers

All limited-service controllers are required to be across-the-line, full-voltage, starting types only. This requirement further limits their complexity and, thus, costs. The maximum allowed horsepower limitation of 30 hp (22 kW) also limits the size of the power path components. The circuit breaker is either of the so-called E frame or F frame size. The contactors are similarly limited in size.

FULL-SERVICE CONTROLLERS

All fire pump controllers, with the exception of limited-service controllers, are known as full-service controllers solely to differentiate them from the limited-service types. All full-service controllers must be three phase since regular fire pump motors must be three-phase motors. There are no listed single-phase full-service fire pump controllers.

Low Voltage (600 Vac Maximum)

The majority of fire pump motors and controllers are of the so-called low-voltage type, in electrical power utility terminology, meaning that they are used on power sources of 600 Vac or less. Typical low-voltage power source voltages range from 120 Vac at 60 Hz or 220 Vac at 50 Hz, single phase, and up to 600 Vac, three phase.

Medium Voltage (Up to 7200 Vac)

Some installations use medium-voltage motors and controllers for convenience because the facility already has this voltage available, for example, in large mills and process plants. Another example is multibuilding campus-style sites where the power distribution is at medium voltage. Medium-voltage controllers are also used to avoid the step-down transformer, which would otherwise be needed to reduce the voltage to the range of low-voltage (600 Vac or less) controllers and motors. This transformer also requires upstream disconnect and overcurrent protection. Lastly, medium-voltage controllers are being used more often because the "service" from the power utility is increasingly at medium voltage rather than at low voltage, as was nearly universal not too many years ago.

Medium-voltage fire pump controllers differ from low-voltage controllers by one significant item: the customary fire pump circuit breaker is replaced by three special "R"-rated, medium-voltage, current-limiting motor circuit fuses and a contactor tripping circuit. The tripping circuit has the same characteristics as the circuit breaker in low-voltage controllers, namely, the 300 percent no-trip and the 8- to 20-second trip time at locked rotor (600%). The motor contactor is used to break overload currents whereas the fuses break the higher short circuit currents. Matching the controller and motor horsepower or FLA is vital to prevent false tripping of the fuses, which take considerable time to replace. Note that the NFPA 20 standard does not require the controller to be equipped with spare fuses. It only requires that the controller have a "compartment or rack" within it for the fuses and that a "spare set of fuses be kept readily available" therein by someone.

Low-Voltage, Full-Service Controller Starting

The fire pump is generally required to be connected directly to the incoming service to minimize the chance of unintentional disconnection of the fire pump power supply during a fire. However, this often results in one of two opposite conditions. The first is that the service is of very high capacity and across-the-line starting can safely be used, particularly if emergency power or alternate standby power will not be needed for the pump. In these cases, the short circuit ratings are of utmost importance. The second case is where a dedicated step-down transformer is used for the fire pump. In this case, the size of the dedicated transformer can be reduced somewhat (but not all the way down to the thermal rating) by the use of reduced inrush starting.

Where emergency power is needed and supplied by an on-site generator, the fire pump(s) is often the largest load on the genset. In these cases, the extra cost of the reduced inrush starting fire pump controller, and sometimes of the special motor, is often justified by the savings in the size and cost of the genset. Nonetheless, all fire pumps, whether or not reduced inrush starting, must be capable of starting by the use of the emergency mechanical operator. This mechanical operator is the reason that the genset must be large enough to start the pump or pumps in the ATL (across-the-line) full-voltage starting mode while supplying all other simultaneously operated load(s). This can result in an increase in the size of the genset even though the 15 percent maximum starting current voltage drop under motor-starting conditions is waived for this method of starting. Table 15.7.2 summarizes the various types of starting methods.

Across-the-Line (ATL or Direct-on-Line) Starting

Across-the-line starting mode is the simplest and most common form of fire pump motor starting. ATL starting is also the least expensive, making it the logical choice where the electrical supply or supplies are adequate for the high- inrush (600%) currents that are incurred by this method. This method also produces the highest starting torque, namely, the motor's full-rated starting torque, ignoring any voltage drop. Both NFPA 20 and the *NEC* require that the voltage drop during starting must not exceed 15 percent of the controller's rated voltage at the controller inlet (line) terminals. It is important to note that this requirement applies to any and all sources feeding the controller. With combination transfer switch fire pump controller units, this requirement applies to both of the two input source line terminals and requires a fairly "stiff" power source. Long power wiring runs will cause additional voltage drop, requiring less voltage drop from the source, and must be taken into account to ensure that the voltage drop during pump starting does not exceed the 15 percent limit. This also applies to a genset or to a transformer used to supply a fire pump.

The reason for the maximum drop of 15 percent during starting is based on the fire pump controller contactor and control circuit operating voltages. These components typically have a specified operating voltage of 85 percent of rated nominal voltage. An unloaded power line will usually be at or above the rated voltage. However, as soon as the motor contactor closes, the

TABLE 15.7.2 Fire Pump Starting Type Characteristics for Electric Fire Pump Motors and Controllers

Starting Type	*Motor Type Note*	*Starting Steps Note*[a]	*Closed Transition*	*Starting Amps and KVA % LRA*	*Starting Amps and KVA % FLA*	*Starting Power Factor*	*Starting Power % ATL*	*Starting Torque % ATL*	*Accelerate Full Load to Full Speed*
Across-the-line[b]	Any	1	N/A	100	600	40	240	100	Yes
Part winding[c]	Special[d]	2	Yes	65	390	40	156	48	Usually
Primary resistor[e]	Any	2	Yes	65	390	80	314	42	Yes
Primary reactor[e]	Any	2	Yes	65	390	30	111	42	Yes
Neutral reactor[e]	6/12 Lead	2	Yes	65	390	30	111	42	Yes
Wye-delta open[f]	6/12 Lead	3	No	33/100	200/600	40	80/240	33	No
Wye-delta closed[f,g]	6/12 Lead	4	Yes	33/100	200/600	40	80/240	33	No
Soft start/stop[h]	Any	2	Yes	40/67	240/400	Varies	Ramps	16/44	Yes
Autotransformer[e,i]	Any	3	Yes	46	276	40	110	42	Yes

Note: Refer to section on reduced voltage starting for details.
[a]The three- and four-step methods are basically two steps (accelerate and run) with the third and fourth steps being transition steps.
[b]Also called ATL or *direct-on-line.* Motor power factor taken as 40%. Other values shown are due to the effects of the controller.
[c]Part-winding parameters vary with the motor. Starting amps and KVA vary from around 60% to 70%; starting torque from around 45% to 50%. The motor can start a fully loaded pump if it has no large torque dip or cusp. See the text discussion on part-winding starting for details.
[d]Part-winding motors must be wound specifically for this service. Some motors may not accelerate to full speed in the starting mode. See Note (c).
[e]Figures are for tap set at 65%, which yields a motor voltage of 65% of line (main) voltage.
[f]The dual figures are for starting and transition. The transition values are to finish accelerating a fully loaded pump. Examples include deluge or open systems, restarting a fully loaded pump after a power failure or interruption, and failure of another pump feeding the same system.
[g]Ignores the momentary transition resistor loads.
[h]Varies with pump load and particular soft starter used. Values shown are for a fully loaded pump and are typical only.
[i]The 46% starting amps and KVA figures include the autotransformer exciting current.

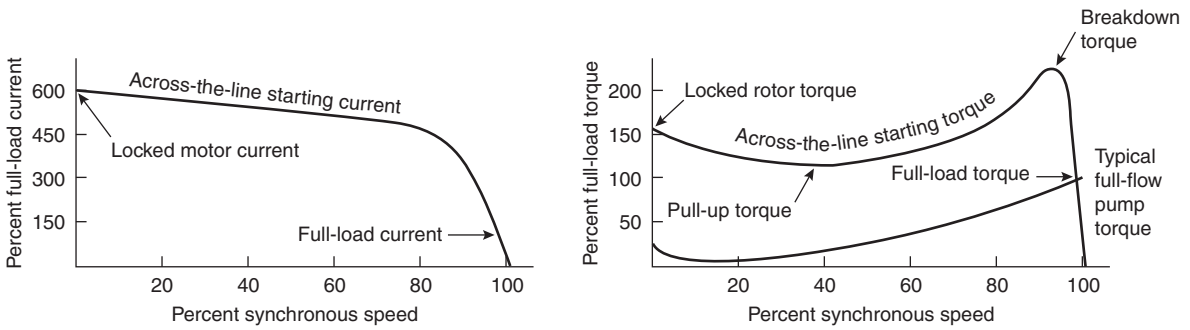
motor locked rotor impedance is applied to the power source, which will always cause some amount of voltage drop. If this voltage drop exceeds the maximum allowed 15 percent value, the motor contactor or other control components may not have enough voltage to remain closed and may cause disconnection of the motor, which will cause highly destructive rapid cycling (chattering) of the motor contactor and will cause the controller breaker to trip and/or damage or destroy the contactor(s) and/or the motor or pump coupling.

Given adequate voltage, the ATL motor torque will be more than adequate to start a fully loaded fire pump under any conditions of ultimate pressure and flow that comply with NFPA 20. NFPA 20 requires that the motor current in any phase not exceed 115 percent of FLA under *any* condition of pump load or voltage imbalance. This requirement determines the minimum size motor (horsepower) needed for a given pump. When this motor size requirement is met and given that the line voltage is 85 percent or more of rated voltage during starting (no more than a 15% drop), the motor torque will easily be able to accelerate the pump to full rated speed, regardless of the pump hydraulic load. Figure 15.7.9 illustrates the voltage curve for ATL starting versus the pump curve.

The first torque shown on the curve in Figure 15.7.9 is the locked rotor torque, also known as the motor's stall torque. This is the amount of torque that the motor will deliver to "break away" a frozen, stiff, or stuck pump. The second torque shown is the so-called pull-up torque. This is the minimum motor torque in the acceleration (starting) region. The torque curve from this point increases, as does the pump torque requirements. The motor torque, however, is always greater than the required pump torque by a wide margin, about twice what is needed. The third torque shown is the so-called breakdown torque, which is the border between the motor's starting torque region and its running torque region. The final torque shown is the full-flow pump torque, which must be less than the motor's rated full-load (plus service factor) torque. When this condition is not met, the motor current will likely exceed the maximum allowed 115 percent FLA current and the motor will likely overheat. Finally, it is important to note that the motor's starting torque (i.e., all three previously named torques) is proportional to the square of the voltage applied to the motor during starting.

Reduced Voltage Starting

All reduced inrush starting types are of the reduced voltage type, the reduced current type, or both. However, the reduced voltage types also reduce the motor's starting current, since in the starting region, the motor's current draw is proportional to the voltage applied to it. This relationship is the opposite of the case



(a) Starting current vs. motor speed for ATL starting

(b) Motor starting torque and pump torque curves for ATL starting

FIGURE 15.7.9 ATL Motor Starting Characteristics for a Typical 75 hp, 4 pole, Nema B, Code G Motor: (a) Starting Current vs. Motor Speed for ATL Starting, and (b) Motor Starting Torque and Pump Torque Curves

in the motor's running region, where the motor draws more current when given less voltage in order to draw enough electrical power to produce the required mechanical power.

The comments regarding voltage drop are just as important for reduced controllers as they are for across-the-line controllers, if not more so. All reduced voltage controllers have more contactors and control components than do ATL controllers, so they are more prone to the relay dropout and contactor chattering problems. An additional, and more likely, mode of failure exists, whereby the accelerate timer may not time out or operate, which then leaves the controller and motor in the accelerate mode indefinitely. This will cause motor overheating, depending on the motor (pump) load, which will ultimately lead to motor burnout followed by tripping of the controller circuit breaker, usually after the motor has been damaged or destroyed. The controller will likely also suffer varying degrees of damage, depending on its type and other factors.

The usual purpose of reduced inrush type of controllers is to reduce the starting current, which makes it easier to meet the 15 percent maximum allowed starting current voltage drop. Another reason that they are often used is to reduce the required size of an alternate (backup) source genset needed to meet the voltage drop requirements. Reduced inrush controllers are sometimes also used, especially soft start type controllers, to reduce the hydraulic surge on pump starting and/or to reduce the water hammer that can occur on pump shutdown when the pump check valve closes. Even so, these systems must still be able to start the motor in the full-voltage ATL mode, using the emergency mechanical operator, which is required of *every* fire pump controller type, without causing any blown fuses (where used) or any tripped circuit breakers, either upstream of the controller (if used) or the controller's circuit breaker. In either case, the sizing requirement for upstream circuit protection, where used, remains the same, namely, that any upstream protection must meet the NFPA 20 (and *NEC*) requirements for holding (carrying), indefinitely, the sum of the fire pump(s) locked rotor current(s) plus all other connected loads, except for the alternate (emergency) source side, if used.

Part Winding Starting. This method of starting requires motors to have two windings operating in parallel for running *and* to be manufactured and labeled as suitable for part winding. As a result, the applications for this starting type are somewhat limited, especially at the higher voltages, which often need the motor windings connected in series rather than in parallel for running.

Part winding starting is a reduced current type of starting because only half of the motor's windings are energized during starting, which nearly doubles the motor load impedance and nearly halves the motor current. Due to magnetic effects, the actual starting current is about 65 percent of the rated locked rotor current, which yields a starting current of around 390 percent of FLA. The stall torque is close to 50 percent of nominal because full voltage is delivered to one-half of the motor's windings. However, there does exist a "cusp," or torque dip, during acceleration, usually at one-half of the rated speed of the motor.

At the end of the acceleration period, which is limited to 10 seconds, the second motor contactor closes to energize the second set of motor windings, which then supplies the motor with its full running power, making this starting type a "two-step" starting means. It is also of the closed transition type because power is never interrupted or disconnected from the motor starting windings. This starting method has the same power factor as the motor itself during acceleration of around 40 percent (0.40 power factor) as it does not add to or change the motor's impedance other than using only half of the motor windings. Thus, this method is usable for starting from a genset for dual-source installations, but it is not the best method. Other methods have lower starting power (kilowatt) demands.

Primary Resistor Starting. Primary resistor starting has long been used to reduce the starting (inrush) current of fire pump controllers. It is a reduced voltage starting method because three resistors, or sets of resistors, are inserted in series with the motor during the starting (accelerating) period. The usual value used is 65 percent, which is the voltage supplied to the motor (at stall). The other 35 percent of the voltage is dropped vectorially across the three resistors, which are in each of the incoming lines. The motor torque follows the square of the voltage law, yielding a stall torque around 42 percent of rated stall torque. Meanwhile, the starting current is reduced to 65 percent of locked rotor amperes (LRA) or around 390 percent of FLA. At the end of the

acceleration period, the main motor contactor bypasses the resistors to apply full-line voltage to the motor, which makes this starting type a two-step starting means. It is also of the closed transition type because power is never interrupted or disconnected from the motor. This starting method can be used with any fire pump motor, including three-lead motors. This starting method changes the starting power factor to a higher value than the motor's own power factor because the resistors represent a unity (100%) power factor load. All other starting methods have a lower starting power (kilowatt) demand.

For economic reasons, the resistors need to provide only a 5 second acceleration period. As a result, this is the only reduced starting type limited to less than the otherwise maximum allowed 10 second acceleration period. Normal controller construction includes venting the cabinet that houses the resistors due to the large amount of heat generated during starting (around 130 kW for a 100 horsepower motor).

Primary Reactor Starting. Primary reactor starting has also long been used to reduce the starting (inrush) current of fire pump controllers. It is a reduced voltage starting method because a saturable reactor is inserted in series with the motor during the starting (accelerating) period. The reactors have multiple voltage taps, but the usual value used is 65 percent, which is the voltage supplied to the motor (at stall) with the other 35 percent of the voltage being vectorially dropped across the reactor coils. The result is a stall torque around 42 percent of rated stall torque. Meanwhile, the starting current is reduced to 65 percent of LRA or around 390 percent of FLA. On the 65 percent tap with 42 percent of the motor torque available for starting, the motor will normally accelerate a pump even if it is fully loaded. This is particularly true because the accelerate timer can be set for the full allowed maximum time of 10 seconds, as the reactors must be capable of 15 seconds of accelerate time, which also makes this method a very robust reduced inrush starting method.

At the end of the acceleration period, the main motor contactor bypasses the starting reactor coils to apply full-line voltage to the motor making this starting type a two-step starting means. It is also of the closed transition type because power is never interrupted or disconnected from the motor. This starting method can be used with any motor, including three-lead motors.

The reactor has a very low power factor (less than 5%) and, therefore, has very little heat dissipation. As a result, no venting is required for these controllers, and so any cabinet construction type can be had. This low power factor leads to a combined value lower than the motor's own power factor. As a result, the size (horsepower and kilowatts) of the genset can be basically the same for either reactor or autotransformer starting.

Wye-Delta (Star-Delta)—Open Transition Starting. Like part winding starting, wye-delta (also known as star-delta) starting changes the motor windings to affect the reduced inrush starting. A detailed description of the characteristics of these motors appears in the book *Pumps for Fire Protection Systems.* These motors must be of the so-called delta run type, meaning that the windings are meant to be connected in delta (end to end) while running. Both ends of each winding coil must be brought out to the motor junction box for external connection to allow the windings to be connected in the wye (star) configuration for starting.

Although wye-delta starting gives the largest current reduction, it also produces the least starting torque. The starting torque follows the square law for the coils, which have only 58 percent of their rated current, and so the motor delivers only 33 percent of rated starting torque. Although useful for unloaded motors, such as unloaded chiller compressors, or loads that are small compared to the motor horsepower, this starting method will *not* accelerate a loaded centrifugal pump up to speed if the pump horsepower demand is anywhere close to the motor's rated horsepower. It often will not have enough torque to accelerate a pump at shutoff (churn), especially with high-speed pumps, which typically have a higher churn horsepower load. If the motor is not up to speed during the acceleration period, the motor will have to finish accelerating the load (pump) after the acceleration period when it is in the full-voltage (delta) configuration. Unfortunately, this situation will also result in normal starting currents of near locked rotor (LRA) until the pump (motor) is up to speed. The resulting characteristic is sometimes called delayed across-the-line starting.

As the voltage applied to the windings is less than normal rated voltage, the wye-delta method of starting is of the reduced voltage type, although the voltage reduction takes place entirely within the motor. In operation, the controller uses three motor contactors, typically designated as M1, M2, and Y. Initially contactors M1 and Y close to connect the motor coils in the wye configuration for acceleration. At the end of the acceleration period the controller opens the wye contactor. As one end of each winding is now open, the motor is deenergized at this point and loses some of its speed. After some delay, the second main motor contactor (M2) connects these open ends of the motor windings to the respective incoming lines. This is the full-voltage, delta-configuration running mode. This delay is anywhere from a few milliseconds up to a full second, depending on the controller design. Any delay longer than the minimum of a few milliseconds will result in motor deceleration and high starting (accelerating) currents when the motor is reenergized at full voltage in the delta running configuration.

This method, therefore, is a three-step starting method. Because the motor windings are deenergized for at least some period of time, this is also known as an open transition starting means, referring to the conditions of the windings (open circuited) prior to the instant of reconnection to full-line voltage.

In addition to possibly incurring full ATL starting currents, there may also be a brief, but very high, current spike at the instant of transition to full voltage due to the open transition method of switching the motor windings. This spike occurs when the motor magnetic vector phase angle differs from that of the line (mains) voltage when the M2 contactor closes. The greater the phase angle difference, the greater will be the current spike, which can be up to 18 times FLA (1800%). The magnitude of the transient will be higher on larger or stiffer power sources. This spike can cause undesired tripping of the circuit breaker when it occurs. This current spike is worse if the motor does reach full speed during the acceleration period,

because the back electromotive force (EMF) (generated voltage) is a function of the motor speed—hence, the conundrum. If the motor does not reach full speed, it will draw ATL starting currents, after the transition, for as long as it takes the motor to reach full speed. In the opposite case where the motor does reach full speed, the motor's back EMF can cause large transition spikes and cause unintended circuit breaker tripping sooner or later.

Three methods have been used to mitigate this current spike condition. The first is to turn down the accelerate timer to a short interval (a few seconds or less) so that the motor does not have time to come up to full speed. The second method is to add a delay to the transition period to allow the motor magnetic field and, hence, its back EMF to decay. Although these measures will reduce the spike, they will also allow the motor to lose much of its speed. The results are full ATL starting currents and no benefit from reduced inrush starting. Either of these methods amounts to a delayed ATL starting of the motor.

The third method is to make the transition rapidly and also control the direction of the winding vector angle change. The idea is to have the vector angle fall back rather than jump ahead and, thus, serve to cancel the effect of the motor slowdown phase angle shift. This requires the use of a controller with a built-in leading phase monitor and means for changing the closing (transition) phase angle from lagging to leading.

Like ATL and part winding starting, this method has the same power factor as does the motor during acceleration, that is, around 40 percent (0.40 power factor) because it only changes the voltage applied to the motor windings. This method is of only limited use for starting from a genset for dual-source installations because the motor will not likely be up to speed during the acceleration period. As a result, the genset will necessarily have to attempt to produce across-the-line starting currents for at least some amount of time.

Wye-Delta (Star-Delta)—Closed Transition Starting. Closed transition wye-delta (star-delta) starting has the same starting characteristics as the open transition wye-delta starting method. The main difference between closed transition and open transition wye-delta starting is the reduction of the transition transient (spike) current. The starting current is the same, and the starting torque is the same (33%) for either open or closed transition wye-delta starting. This, again, is not enough torque to fully accelerate most loaded pumps.

During acceleration, this method is the same as the open transition starting method and is, therefore, also of the reduced voltage type. In operation, the controller uses four rather than three motor contactors. Initially, the motor windings are connected together in wye as with the open transition starting. At the end of the acceleration period, a transition (S) contactor closes to connect one end of each of three transition resistors to the line power, which briefly puts the three resistors in wye in parallel with the motor windings. A short time later, the Y contactor opens, which places the motor windings in series with the resistors. The resistors allow the line voltage to pull the motor magnetic vector to that of the line voltage phase angle or close to it. At the end of this time, the second main motor contactor (M2) short circuits the resistors and, thus, connects the ends of the motor windings to the respective incoming lines, which is the full-voltage, delta running mode.

As a result, this method is four-step starting. The motor windings are never deenergized at any time, making a closed transition starting means. As with the open transition starting, if the motor has not reached full speed during the acceleration period, the motor will finish accelerating in the across-the-line (full-voltage) mode with resulting ATL starting currents for the duration of the acceleration period. It also has the same starting power factor as the open transition starting; that is, around 40 percent (0.40 power factor) or the same as the motor itself.

This method also has the same limitations as open delta when used with a genset for dual source installations. As the motor may not be up to speed, the genset will have to attempt to produce ATL starting currents for some period of time. If the genset is not sized to produce these starting currents, the resulting voltage drop may cause contactor chattering and ultimately controller and/or motor damage or destruction.

Soft Start (SCR) Starting. Soft start starting is a newer method of motor starting. Basically, it varies the voltage fed to the motor over the acceleration period and, thus, affects the starting current and, therefore, the starting torque. The usual case is to start with a lower voltage and increase (ramp up) the voltage to the full-line voltage during the acceleration period. Because the acceleration period is limited by code to a maximum of 10 seconds, this period is usually selected for the voltage ramp-up time and, thus, the motor acceleration period. In addition to soft start starting, all listed fire pump controllers using this scheme also offer the so-called soft stop deceleration when the pump is no longer needed. Because the voltage to the motor is being controlled, this method of starting is the reduced voltage type.

Soft start starters are specified and used for one of two reasons, if not both: (1) for reduced inrush starting and (2) for hydraulic reasons, mainly to reduce pressure and/or flow surges during start-up, and/or to reduce the water hammer or hydraulic shock that can occur during pump shutdown when the pump check valve closes (slams shut).

The soft starter operates in a manner similar to a large variable transformer. The motor is usually started with around 30 to 40 percent of the rated voltage (the so-called ramp start voltage) and yields an initial starting torque of 9 to 16 percent, which assures no sudden acceleration. The voltage then ramps up, usually in a linear fashion. The motor torque still follows the square of the voltage law and, therefore, the motor torque builds up as the square of the applied voltage. After the voltage has reached 100 percent (or within 10 seconds), the main motor contactor closes to bypass the soft starter. This operation reduces the heat buildup in the controller that would occur if the soft starter continued to supply the motor running current. This starting method is a two-step starting type; however, the distinction is minor because the motor should already be at full voltage by the time the main motor contactor closes. Since the motor is at no time deenergized during or after the starting (accelerate) cycle, this starting method is of the closed transition starting type. This main motor contactor also provides for the required emergency mechanical starting of the fire pump motor. Some designs also employ an isolating (start) contactor to shield the

soft start starter from line voltage transients while in the standby mode. Some also employ a mode switch to allow the unit to work in an across-the-line mode for start-up (commissioning) or emergency automatic fire protection.

Because the voltage varies over time in a continuous fashion, both the motor torque and starting current draw also vary over time. One estimate gives an accelerate time of around 7 seconds for a fully loaded (full-flow) pump with a peak starting current of around 400 percent and an estimate of around 3 seconds and peak current of around 300 percent for an unloaded (no-flow) pump.

The soft stop shutdown cycle is basically the reverse of the starting cycle. To stop the pump, the controller first opens (deenergizes) the main motor contactor (M) with the soft starter SCRs set to 100 percent (full voltage). The soft starter then ramps the voltage down. Some designs incorporate a delay or pedestal dwell time as part of the stopping sequence. Designs employing an isolating (start) contactor open (deenergize) same at the end of the ramp-down time to isolate the soft starter from line transients.

Because the motor voltage is both nonlinear and time variant, the circuit power factor is not constant. It remains inductive because the motor itself is inductive. The power factor is the same as that of the motor when the SCRs are fully on (full voltage to the motor), around 40 percent (0.40 power factor). The motor will "appear" more inductive at lower voltages due to the delayed conduction angle. When these starters are used with gensets, the gensets must be sized conservatively as the starting current cannot be easily determined without analyzing the motor, starter, and pump dynamics during starting under full pump load. In any case, the worst case size needed would be that needed for across-the-line starting.

Autotransformer Starting. Autotransformer starting has also long been used for reduced (inrush) starting of fire pump controllers. It too is a reduced voltage starting method. The transformer is of the autotransformer type, which is about half the size of a normal isolated winding-type transformer. The autotransformer has multiple voltage taps, but the usual value used is the 65 percent tap, which is the voltage supplied to the motor (at stall) and gives a stall torque of around 42 percent of the rated stall torque. Meanwhile, the starting current is reduced to around 46 percent of LRA or around 270 percent of FLA when the autotransformer exciting (saturation) current is accounted for.

During acceleration, a Y contactor connects the autotransformer low side terminals together, and a start contactor(s) connects the top of the autotransformer windings to line power. The motor connects directly to the autotransformer's voltage reduction taps. At the end of the acceleration period, the controller disconnects (opens) the autotransformer wye connection, which is the second step. During this brief step, the autotransformer acts as a saturable reactor (series impedance) similar to the primary reactor starting method. Finally, after a fraction of a second, the main motor contactor (M) short circuits the top of the transformer windings to apply full voltage to the motor, which makes this method a three-step starting means. This method is also of the closed transition type since power is never interrupted or disconnected from the motor. This starting method can be used with any motor including three-lead motors.

Like the saturable reactor, the autotransformer is actually overdesigned because it too must be designed for 15 second acceleration periods to meet NFPA 20 requirements. As the maximum allowed acceleration period is only 10 seconds, this method is also a very robust reduced starting method and results in very low stress and temperature rise of components.

The autotransformer preserves the motor's 40 percent starting power factor during acceleration as it does not add to or change the motor's impedance but merely increases its magnitude to reduce the starting current. This characteristic makes it advantageous for starting from a genset for dual-source installations as it is least demanding of genset power and, therefore, size. Therefore, it is on a par with primary reactor starting on a power (kilowatt) size basis; however, it reduces the current further. This current reduction is an advantage when long power lines separate the genset from the fire pump or in remote areas or other areas where current reduction is as important or more important than starting power reduction. Like primary reactor starting, this method also has very little heat dissipation during starting. As a result, no venting is required for these controllers. Thus, one can have any cabinet construction type. Also, like the reactor case, multiple starting rarely causes the autotransformer to be more than slightly warm.

Medium- (High-) Voltage Full-Service Controller Starting

Across-the-Line (ATL or Direct-on-Line) Starting. This starting method is electrically the same as the low-voltage ATL starting method. The difference in controller construction relates to the fact that all currently listed medium-voltage fire pump controllers use vacuum contactors for the main motor contactor. Also, Class R motor circuit fuses are used in place of the fire pump circuit breaker used in low-voltage controllers. The motor locked rotor protection is provided by deenergizing the motor contactor instead of tripping the circuit breaker in low-voltage units. Further, additional safety interlocking is used due to the dangerous amount of electrical energy available. Some controllers use triple safety interlocking. First, the isolating switch is interlocked with the main contactor (M) in a two-way fashion so that the isolating switch may neither be opened nor closed while the contactor is closed. Second, the high-voltage door is interlocked with the isolating switch so that it cannot be opened if the isolating switch is closed. Third, the isolating switch cannot be closed if the high-voltage door is open. Some designs also interlock access to the incoming wiring (bus bar) compartment to the high-voltage door and also electrically interlock the control transformer(s) to allow for low-voltage testing of control circuitry. Another difference with medium-voltage controllers is that the interrupting and short circuit ratings are given in MVA (megavolt-amperes) rather than in symmetrical amperes.

Primary Reactor Starting. The primary reactor starting method has the same motor starting characteristics as the low-voltage counterpart. The controller construction differs slightly

in the way the two motor contactors are connected. The run contactor and the reactor are connected to the output of the main contactor to allow the full safety interlocking of the main contactor to provide full safety for the second (run) contactor, the reactor, and all other medium-voltage components and wiring. Because there are two contactors used to run the motor at full voltage, there are also two emergency mechanical manual operator handles, providing the added benefit of reduced inrush starting even when the manual operators are used. The main contactor operator is actuated first, and when the motor is up to speed or within 10 seconds, the second run contactor operator is actuated.

Neutral Reactor Starting. This method is a variation of the primary reactor starting method, except that the reactor is moved from the line (primary) side of the motor to the wye point (neutral) of the motor, which must be of the six-lead wye-wound type. The operation and characteristics are otherwise identical to those in the primary reactor starting method. The advantage of this method is that the reactor is not subjected to full-line voltage. This method is used for controllers rated above 5000 V.

Autotransformer. This starting method is also electrically comparable with its low-voltage counterpart. All electrical characteristics and type descriptions are the same as for the low-voltage equivalent with the previously stated differences for medium-voltage controllers.

VARIABLE SPEED ELECTRIC MOTOR–DRIVEN FIRE PUMPS

This section summarizes a significant change occurring in fire pump technology by outlining the availability, application, and installation of variable speed fire pumps (Figures 15.7.10 and 15.7.11) and controllers. More specifically, this section covers (1) the relevant changes to the fire pump standard, (2) the state of the art, including a brief history, (3) example installations, (4) the equipment involved including controller features and functions, (5) application needs, and (6) hydraulic considerations, particularly system time constants. This type of fire pump operation is new and requires both additional and innovative design and application considerations. As a result, certain sections are both detailed and exhaustive where needed to avoid incomplete information.

The section also describes how the 2007 edition of NFPA 20 affects variable speed fire pumps.

Update on NFPA 20

Although variable speed pumps have been used for a number of years in pumping applications such as process pumps and domestic booster pumps, the 2003 edition of NFPA 20 contains the first mention of variable speed fire pumps. That edition added both diesel engine–driven and electric motor–driven variable speed fire pumps. With the exception of wound rotor manually controlled fire pumps in New York City, variable speed fire pumps have not heretofore been used in stationary fire pump applications.

FIGURE 15.7.10 Closed Door View of Model ECV-250-46, 250 hp, Single-Source, Variable Speed Source Fire Pump Controller in NEMA 12 Enclosure with Air-to-Air Heat Exchanger (Source: Master Control Systems, Inc.)

Prior to the 2003 edition of NFPA 20, fire pumps were considered to be constant speed units. Although designed to run at a fixed speed under normal conditions, traditional diesel-driven fire pumps have always been considered variable speed drivers since the engine speed can exceed normal rated running speed should certain failures occur. The only pressure control allowed was the required pressure relief valves to prevent an overspeed occurrence from damaging the sprinkler system due to excessive pressure. As such, from a sprinkler design standpoint, diesel-driven pumps are considered to be constant speed systems.

The initial considerations of variable speed systems to *actively* control system pressures were incorporated into the 2003 edition of NFPA 20 and constituted the first recognition of variable speed fire pump systems, both diesel engine–driven and electric motor–driven fire pump systems. Another significant change in the 2003 edition of NFPA 20 in this regard is the prohibition of the use of main relief valves for "normal" system pressure control. They are only allowed for the purpose of preventing system damage during *abnormal* conditions. Both variable speed diesel drivers and electric motor drive variable speed controllers use active feedback control to regulate the pump discharge pressure. Active feedback control makes use of mechanical or electrical (electronic) means to compare the pump output pressure against a preset desired (set point) pressure and adjust the speed of the driver up or down as needed in order to

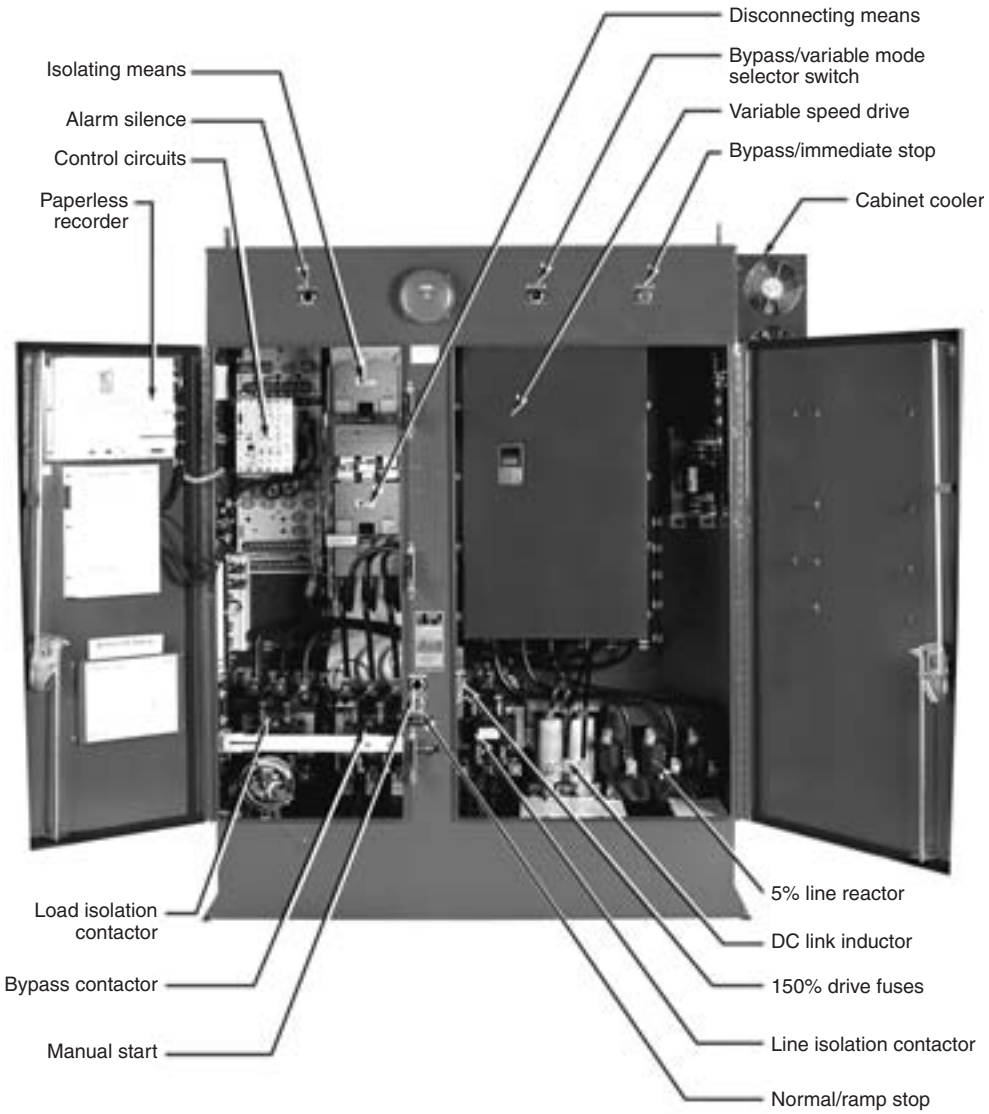


FIGURE 15.7.11 Open Door Flagged View of Model ECV-250-46, 250 hp Single-Source, Variable Speed Source Fire Pump Controller (Source: Master Control Systems, Inc.)

match the pump output pressure to the desired set point value. In operation, a difference value between the actual output pressure and the set point pressure is created and amplified and used to control the speed of the driver to minimize the magnitude of said error signal. Accordingly, they are able to limit system pressures to safe values or provide a source of closely regulated pressure or both. The feedback control scheme tends to maintain the pump output pressure close to the desired set point value and, thus, compensate for suction pressure variations, suction side friction losses, and pump curve variations over the full range of output flow (gpm) rates.

Finally, the 2007 edition of NFPA 20 established a significant body of requirements for variable speed motor drive fire pump controllers that is delineated next. Much of this work was done by two task groups, namely, an NFPA 20 Variable Speed task group and a NEMA Variable Speed Controller task group. The 2007 edition also establishes requirements for break tanks, which are another means of dealing with pressure variations in the suction supply.

State of the Art, Variable Speed Electric Motor–Driven Fire Pump Controllers

The first UL-listed variable speed electric drive fire pump controller was available in 2003. The balance of this section presents an overview description of the unit, a brief history of its application, and application examples.

Controller Overview. All compliant variable speed controllers consist of both a full-service fire pump controller and a separate variable speed controller section. There are two main operating modes for these controllers, namely, the variable speed mode

and the bypass mode. In the bypass mode, the unit operates as a fixed full-speed, full-service fire pump controller. These controllers may be either the single power source type or the dual power source combination transfer switch and fire pump controller type. The normal operating mode for these units is the variable speed mode. In this mode, the controller compares the system pressure to a previously set desired value, that is, the pressure set point, and adjusts the speed of the pump to produce the desired system pressure. Typical pressure regulation accuracy is better than one-tenth of 1 psi. For example, with a system set to 140 psi (9.6 bar), the variable speed controller will produce a pump output pressure within 0.1 psi of the desired 140 psi (9.6 bar) set point pressure over the full range of rated pump flow. The same is true whether the set point is 70 psi (4.8 bar), 175 psi (12 bar), or any pressure within the capability of the pump involved.

The bypass path is used for full-speed pump testing, commissioning, and servicing. It is also used on failure of the variable speed portion of the controller. The bypass mode can be manually selected by a manual mode switch, although the controller will automatically revert to the full-speed bypass mode should the variable speed portion either fail to operate or fail to meet system pressure requirements. The starting means in the bypass mode may be either full voltage or reduced voltage starting types. These are used to reduce the size of the genset required where emergency power is utilized. Reduced inrush starting controllers installed to date are either of the primary reactor or the soft start types. Since the bypass path constitutes a complete full-service fire pump controller, it includes an emergency mechanical operator. Since this feature connects the pump motor directly to the power source, its use always causes the pump to run at full speed.

In the variable speed mode, the controller makes use of a variable frequency drive (VFD) to control the voltage and frequency fed to the fire pump motor. In this way, the unit controls both the speed and torque of the motor. All units currently in service also incorporate both soft starting (ramp-up) and soft stopping (ramp-down) operation. In this mode of operation, the controller ramps up the motor (pump) speed to a preset idle speed, typically two-thirds of rated speed. At this speed, the pump pressure produced is around 44 percent of rated pressure boost since the pump pressure gain is related to the square of the pump rpm (revolutions per minute). At this low-boost pressure the pump normally does not produce any flow if the system is pressurized. If the system pressure is below the controller set point pressure, the controller will continue to accelerate the pump to the speed required to meet the set point pressure. If need be, the controller will accelerate the pump all the way up to full speed in order to cause the pump to produce the desired pressure. If and when the pump does achieve the desired set point pressure, the controller maintains the pump at that speed. If necessary, the controller will adjust the motor speed up or down in order to maintain the pressure at the desired set point value.

A main relief valve is required if the fire pump can exceed the system rated pressure when operating at full speed, at churn (shut off), and with the maximum anticipated suction pressure. This requirement is important since the pump will operate at full speed in the bypass mode, including the emergency mechanical operator mode of operation.

Application History. Designing fire sprinkler systems has become a challenge for a number of reasons, including the following:

1. Higher pressure demand at the top of high-rise buildings, typically 100 psi (6.9 bar) at the roof hydrants
2. Varying suction pressures, especially when dual water supplies are required (municipal and tank)
3. Need to limit maximum pressures to 175 psi (12 bar) component ratings to avoid the cost of higher pressure components
4. Need to limit pressure at certain types of sprinklers, such as large drop sprinklers, to avoid exceeding their operating ratings or degrading their performance
5. Requirement for backflow preventers in most systems
6. Various pressure drops that occur with large orifice sprinklers and increasing waterflow, including pump curve, suction piping friction loss, and discharge piping friction loss
7. Dual water supply requirements (tank and municipal) that are required in some jurisdictions

In the past, because of these design constraints, some designers and installers have made use of active pressure control means by the use of a so-called "main relief valve." However, these were prohibited with the 2003 edition of NFPA 20. The other hydraulic means sometimes used to control pressure are main or riser pressure regulating or pressure reducing valves (PRVs). The latter are different from those used to control the pressure of fire water on a given floor of a high-rise building, where allowed by local code. However, variable speed fire pumps or break tanks are now being used for the purpose of pressure control.

The first variable speed fire pumps were motor-driven units commissioned in spring 2004. They have since been used in numerous fire sprinkler systems and also in dual-use systems. Some examples of dedicated fire sprinkler system applications include (1) airport parking garages, (2) college housing midrise buildings that have been retrofitted with full sprinkler coverage, (3) a 1.8 million ft^2 (167,200 m^2) distribution center, (4) a municipal courthouse, (5) high-rise condominium buildings, and (6) a three-zone, high-rise commercial office building, among others. These particular units are all booster pumps taking suction from city water mains.

Dual-purpose applications in service include (1) combination domestic (potable) water and fire water pumps (four booster pumps) for a very large shopping center, (2) dual-purpose process water and fire water for a multibuilding commercial and residential complex where the process water is used for heat pumps for both cooling and heating, and (3) triple-purpose domestic water, fire water, and water tower fill pump with three distinct operating modes for a multibuilding medical housing complex.

Most of these units are combination transfer switch units, which are also reduced voltage starting in the bypass mode (Figure 15.7.12) since emergency power is from an on-site genset. A few units are single-source type but receive emergency power as part of the site power distribution. Units in service vary in size

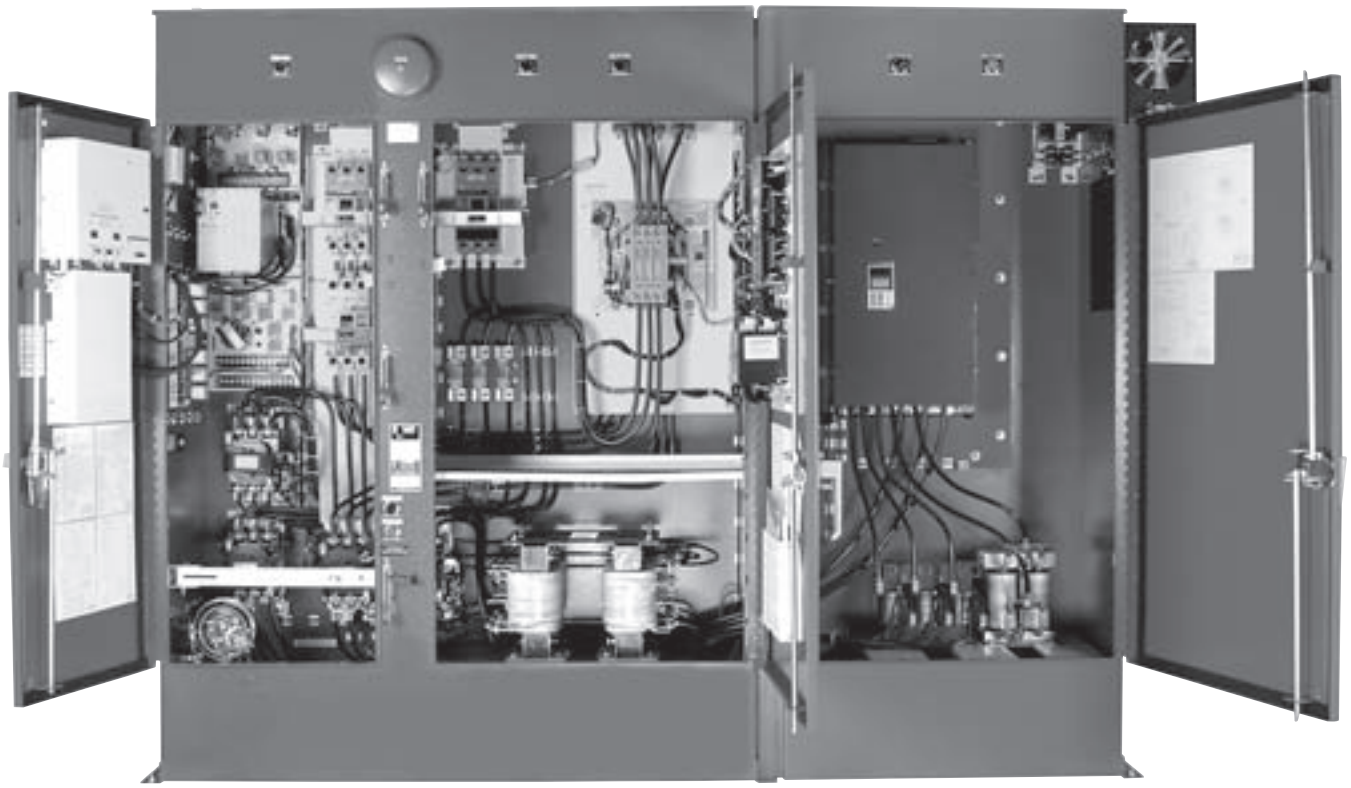


FIGURE 15.7.12 Open Door View of Model ECVRT-125-46, 125 hp, Dual-Source, Variable Speed Fire Pump Controller with Reduced Inrush (Primary Reactor) Starting in Bypass Mode (Source: Master Control Systems, Inc.)

from 30 hp to 300 hp. As to pump types currently in operation, one unit is a vertical pump taking suction from a below-the-floor reservoir. Several are vertical in-line pumps; two are vertical deep well pumps; and the remainder are horizontal split-case pumps. One of the deep well pumps is of the water-lubricated type since the water is potable. Water-lubricated vertical pumps require special considerations to assure adequate lubrication water is supplied in time and also maintained under worst-case conditions.

Application Example—The Triple-Purpose Pump. The previously mentioned triple-purpose pump is a vertical deep well pump that uses the water tower for backup domestic and fire water. For filling the tower, the controller is started remotely by the site building management system, which also controls the speed of this pump in this mode. The speed is controlled to less than full-pump output flow to provide for optimum water treatment (chlorination, etc.). The pump can also be started remotely by the complex fire alarm system, in which case the controller accelerates the pump to full speed. If the controller pressure switch trips, which is the third operating mode, the controller accelerates the pump to full speed unless it detects that the tower is full. In this system the pressure cannot exceed 80 psi (5.5 bar) on a continual basis since that is the pressure that will overflow the tower.

Application Example—The Dual-Purpose Pump. The dual-purpose process water and fire water system is also a vertical deep well pump. In this system, a second well pump provides a backup source of water. It also shares the duty of providing the water since this system operates on a 24 hour, seven day basis. The two pumps alternate duty on a weekly basis and also operate in a so-called duplex mode of operation. In this mode, if the running pump controller (lead pump) ramps its pump to near full speed (97% of full speed), it will call for the reserve pump (lag pump) to start and ramp up to its idle speed. If the reserve pump needs to accelerate above its preset idle speed to meet the pressure demand, it signals the lead pump to lock to full speed so that the lag pump can take over the job of regulating system pressure. In this way only one controller is regulating the system pressure rather than having two competing for the job. If and when the reserve pump drops back down to idle speed, it unlocks the primary (lead) pump controller so that it can resume the job of regulating system pressure. If the reserve (lag) pump remains at idle for a predetermined length of time, it ramps the pump down to around one-third rated speed and then stops it.

Since the controllers operate independently, either will accelerate to full speed if the system pressure cannot be satisfied in the normal manner. This way, failure of one controller does not inhibit the operation of the other. No central pressure control is involved since both pumps and controllers operate independently other than causing the other pump to start or to lock the other pump to full speed. This system operates at around 140 psi (9.6 bar). Since both wells are within 20 ft (6.1 m) of a major river, there is no chance of depleting either. The two wells are

separated from one another by some distance in order to keep them independent of one another.

Application Example—A Four-Pump System. The four pumps at the major shopping center mentioned earlier operate in a triplex mode where one, two, or three pumps operate as system flow demands. In this system, two 30 hp (22 kW) pumps serve as the lead and second pump to supply domestic water demands and also fire water if the demand is not too great. The third pump is a 60 hp (45 kW) unit and is capable of supplying needed fire water. The fourth pump is also 60 hp (45 kW) and serves as a backup for the third pump. It takes over the duty of the third pump if that pump or its motor or controller fails. The triplex operation is similar to the duplex operation described previously. The lead pump starts upon pressure drop sufficient to trip its pressure switch or via a remote start input signal from the site fire alarm system. It regulates the system pressure needs (around 95 psi [6.6 bar]) unless the system demand causes it to ramp up to near full speed. In that event, it signals the second 30 hp (22 kW) pump to start and accelerate to its idle speed. If pump 2 needs to accelerate above its idle speed, it locks the lead pump to full speed and takes over regulating the system. If the second pump accelerates to near full speed, it signals the third pump (60 hp [45 kW]) to start and accelerate to its idle speed. Similarly, if pump 3 accelerates above idle speed, it locks pump 2 to full speed and takes over the job of pressure regulation. If pump 3 fails, pump 4 takes over and shuts down pump 3 to keep from overloading the genset if the system is running under emergency power.

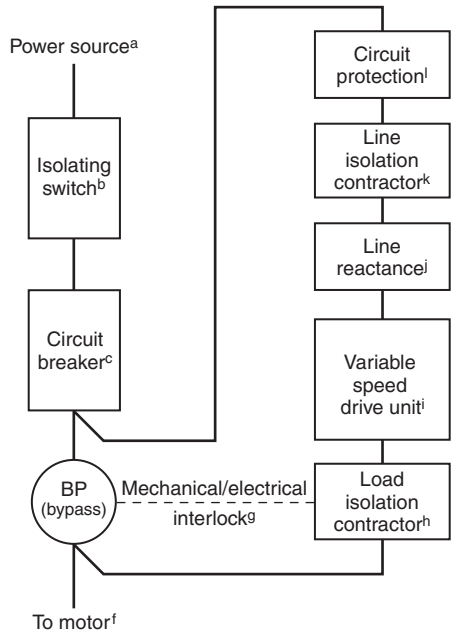
If and when the system flow demand diminishes sufficiently, the pump controllers reverse the described operation as follows. If the lag pump (pump 3) decelerates down to idle speed, it unlocks pump 2 so that pump 2 can take over pressure regulation. If pump 3 remains at idle for the automatic stop interval, or if the minimum run time has elapsed and if the idle stop delay has also elapsed, controller 3 shuts down pump 3. If the system demand drops down enough for pump 2 to reduce to its idle speed, it unlocks pump 1 (lead pump) to take over the system pressure regulation. If and when all timers are satisfied, controller 2 will shut down pump 2. Since there is no central control, failure of one controller will not affect the operation of the others. Like the duplex system, these units are equipped with sequential starting as required by NFPA 20 to prevent all three pumps from starting simultaneously. Although this situation will not normally occur when the controllers are in the variable speed mode, it would happen if they are in the bypass mode if not equipped with the required sequential starting feature. This system also has a commercial domestic pumping system, but in the event of a power failure, the variable speed fire pumps will take over the job of providing the shopping center with domestic water as well as fire water if needed. These multipurpose units already have tens of thousands of hours of accumulated variable speed operating (running) time.

Equipment Description

The equipment and functions described hereinafter are those required by the 2007 edition of NFPA 20. The primary emphasis in NFPA 20 is that the variable speed path and the bypass path are both reliable and robust and also are as independent of one another as possible. This philosophy is to protect the integrity and independence of the bypass path to the fullest extent practical. In this way, variable speed controllers can be more reliable than a traditional fire pump controller if, as required, two conditions are met: (1) the design and construction of the bypass path is not diminished in any way from that of any other full-service fire pump controller, and (2) the variable speed path does nothing to diminish or potentially damage the controller bypass path. These two conditions being met yields a full-service fire pump controller with a redundant variable speed path. It is also desirable for said variable speed path (Figure 15.7.13) to also be reliable and robust as is expected from any fire pump controller to provide a reliable source of fire water at the expected controlled pressure.

Controller Equipment Features

In order for active pressure control to be achieved in a reliable and robust manner, certain unique functions are also required of the controller. The major functions are delineated next.



[a]See Section 9.2 in NFPA 20.
[b]See Clause 10.4.2 in NFPA 20.
[c]See Clauses 10.4.3 and 10.4.4 in NFPA 20.
[d]See Clause 10.4.5 in NFPA 20.
[e]See Clause 10.5.3.2 in NFPA 20.
[f]See Clause 9.5.1.3 in NFPA 20.
[g]See Clause10.10.3.3 in NFPA 20.
[h]See Clause 10.10.4 in NFPA 20.
[i]See Clause 10.10.1.1 in NFPA 20.
[j]See Clauses 10.10.6.1 and 10.10.6.2 in NFPA 20.
[k]See Clause 10.10.4 in NFPA 20.
[l]See Clause 10.10.5 in NFPA 20.

FIGURE 15.7.13 Variable Speed, Pressure-Limiting Control (Source: NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection,* Figure A.10.10, 2007, p. 20-75)

Control and Alarm Elements. The major control and alarm elements of controller equipment include the following:

- Separate pressure switch for controller start and stop control and for use by the pressure bypass timer
- A low-pressure timer to automatically switch the controller into the bypass mode if the controller pressure switch remains tripped too long
- Separate and independent pressure sensing for the VFD (also known as a VSD, variable speed drive) or ASD (adjustable speed drive) speed control
- A manual mode control switch to allow operation in the full-speed bypass mode or the normal variable speed mode
- Alarm light and remote contacts to indicate drive (VFD) failure detected
- Drive failure timer to automatically switch the controller into the bypass mode on detection of a failure of the VFD
- Alarm light and remote contacts to indicate controller in bypass mode

Power, Isolation, and Circuit Protection. The major power, isolation, and circuit protection elements of controller equipment include the following:

- Full horsepower rated isolating contactor to keep the VFD powered down until needed. The purpose of this contactor is to prolong the life of the VFD and also to avoid VFD capacitor overvoltage shutdown due to power line surges, spikes, or overvoltage when the controller and pump are on standby (not running).
- Full horsepower rated VFD output motor (load) contactor to isolate the VFD from the bypass path.
- Full horsepower rated bypass contactor as part of the controller bypass path. This contactor is also operated by the emergency mechanical operator (see Figures 15.7.11 and 15.7.13). These last two contactors are both electrically and mechanically interlocked to prevent backfeeding line power to the VFD when the controller is operating in the bypass mode. Backfeeding would damage the VFD and probably cause the fire pump circuit breaker to trip and would disable the bypass path, leaving the fire pump inoperable.
- Circuit protection (fuses or circuit breaker) to isolate the VFD power path on circuit or component failure. This protection is set to trip at a value and time that will avoid tripping the controller fire pump circuit breaker, and thus leave the controller bypass path intact.
- A 5 percent or better line reactor to reduce harmonic currents within and upstream of the controller. This reactor also reduces harmonic currents within the VFD and protects the VFD rectifiers and capacitors from line voltage spikes and transients. Most importantly, it reduces the likelihood of VFD overvoltage shutdown due to these same spikes and transients.

System-Related Elements. The major system-related elements of controller equipment include the following:

- Alarm light and remote contacts to indicate that the system pressure is exceeding the VFD set point. This can be caused by a failure within the controller or by other pumps pressurizing the system.
- The means to control the system pressure in view of the multiple hydraulic, electrical, and mechanical time constants involved. This control is needed for successful and stable controller operations and requires the use of a full 3 term PID (proportional-integral-derivative) process controller or, at least a 2 term PI controller with suitable means to adjust and adapt to the conditions and requirements of the installation. This degree of control is needed to yield both stable operation and timely adjustment of the pump speed to give prompt response to changes in the system demand (flow) or suction pressure variations or both. Time constants are discussed later in this section.
  - The settings required for all of the preceding elements must both be lockable and also be marked and visible for service personnel.
  - For multiple variable speed pump installations, no common pressure control is allowed. Each controller must sense and control pressure independently to avoid a single point of failure in multiple-pump installations.

Additional Considerations. The controller equipment must be designed with the following requirements in mind:

- The controller must be able to deal with the heat given off by the VFD unit, which is typically 2 to 3 percent of the motor horsepower rating and is similar to the amount of heat given off by the motor itself. Better controllers do this without pulling air through the controller. This method requires an isolated means of cooling and keeps the inside of both the controller and the sensitive control portions of the VFD unit free from dirt, dust, and moisture that would otherwise occur in vented units.
- The VFD must be rated for the type of pump involved. Positive displacement pumps require a VFD unit with a higher current rating than that needed for centrifugal pumps for a given horsepower. Centrifugal pumps present a variable torque load to the pump motor, which reduces the power needed from the VFD as compared to positive displacement pumps because these present a load whose torque is relatively constant over speed.
- The controller must be designed to take care to avoid causing excessive currents when switching modes, particularly from variable speed mode to the bypass mode. This can be done with a motor restart delay of a few seconds to allow any motor magnetic flux and resultant back EMF (voltage) to decay to safe values before connecting said motor to the power source, especially if the bypass mode incorporated full-voltage (across-the-line) starting.
- There are a number of additional design considerations (Figure 15.7.14 and 15.7.15) that, if properly accounted for and manufactured, can further enhance the ability of these units to deal with various field conditions in a forgiving and robust manner.

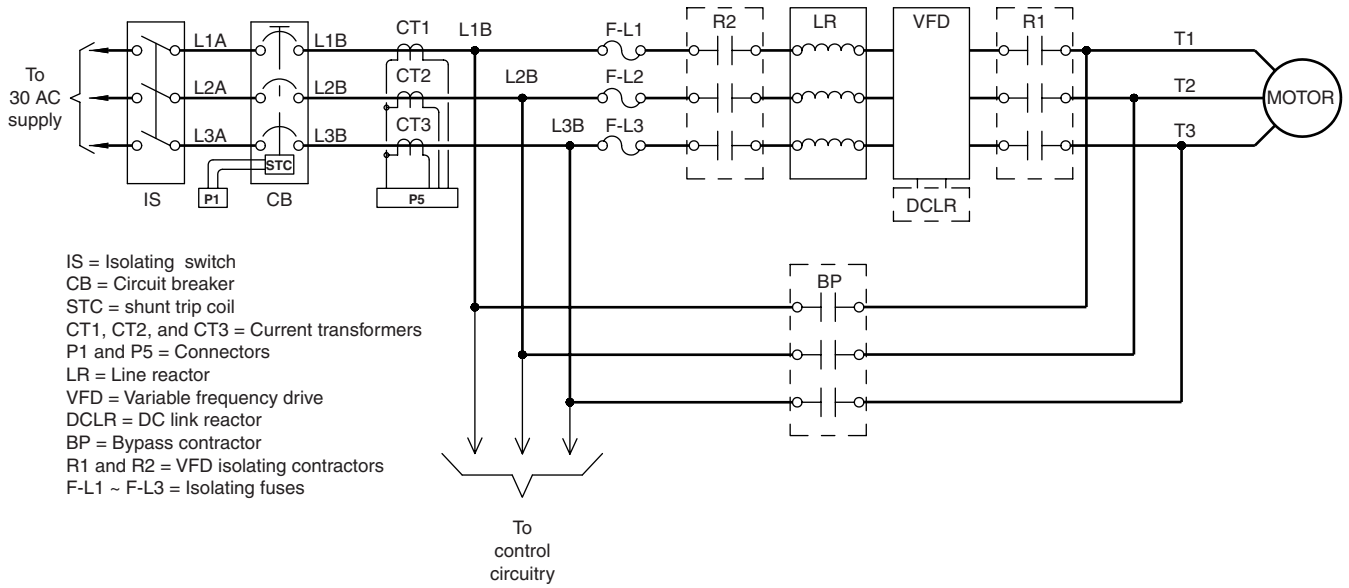


FIGURE 15.7.14 Single-Source, Variable Speed Fire Pump Controller with Full-Voltage (ATL) Starting in Bypass Mode (Source: Master Control Systems, Inc.)

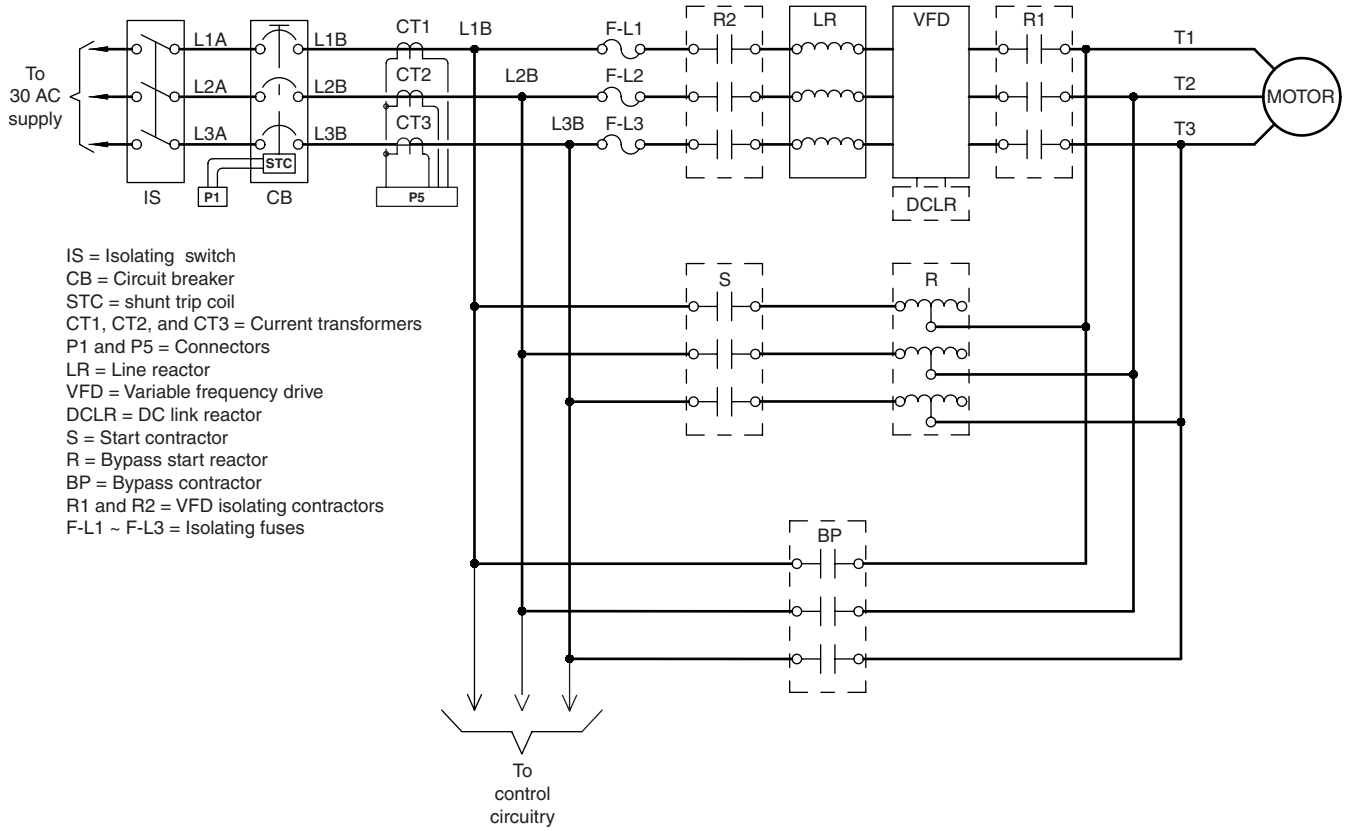


FIGURE 15.7.15 Variable Speed Fire Pump Controller with Reduced Inrush Starting in Bypass Mode (Source: Master Control Systems, Inc.)

Special Application-Related Controller Requirements. The controller equipment must be designed to meet the following application-related requirements:

- Where motor wiring distance exceeds manufacturer's ratings, a motor dV/dT (spike) filter or a load reactor must be incorporated into the controller to reduce motor voltage spikes to a safe and tolerable level.
- Skip frequencies may be required to be programmed into the VFD for vertical pumps. Application requirements are discussed later.
- Special enclosures such as NEMA 12 (UL Type 12) or better. Special enclosures will likely require upgrading the VFD cooling means or equipment.
- Additional door interlocking is needed where multiple bay controllers are involved for safety.

Functions

Certain new functions are required of these controllers, either by code (NFPA 20) or otherwise for successful operation. These include:

1. *Bypass mode lock-on.* When either the drive failure or the low-pressure timers time out to switch the controller automatically to the bypass mode of operation, the controller must lock onto that mode until manually shut down. Although the controller may be equipped with an automatic stop feature, that feature is not allowed to stop a pump running in the bypass mode. This lock-on also prevents the controller from switching modes back and forth between variable and full-speed bypass operation. Once in bypass, the controller must both stay in that mode and also not cause the pump to stop. The requirement is necessary as the bypass mode of operation represents a fallback either due to a failure or due to the manual mode switch being manually set to bypass. The controller must not interfere with this mode of operation since it is presumed that the variable speed mode has experienced a failure.

2. *Two stop push buttons.* These provide both normal ramp-down stopping and emergency instant pump stopping. The emergency stop push button is also the method of stopping the pump if it is running in the bypass mode.

3. *Coordination of start and stop pressures of the controller pressure switch with the VFD set point pressure for proper operation of the controller.* This coordination is needed whether the controller is set for manual stop or for automatic stop operation.

4. *Automatic stop based on VFD operating frequency.* The controller must not stop itself automatically if there is a requirement for water (fire water still being delivered). This means that the system pressure must both be at or above the pressure set point and that the pump running is no longer needed.

Operating Sequence

The description that follows briefly outlines normal controller and pump operation for a single fire pump. For proper operation, the VFD pressure set point is set to a value above the controller pressure switch reset (stop) set point.

Normal Operation—Variable Speed Mode—Automatic Pressure Loss Start. The following steps outline normal controller and pump operation:

1. Controller pressure switch trips (contacts close) to signal a pressure loss (pressure drop) pump demand.
2. The two VFD contactors (line side and load side) close to energize the VFD and to connect it to the motor.
3. The drive failure timer (DFT) begins timing.
4. The low-pressure timer (LPT) also begins timing.
5. If the VFD is healthy, it sends a "Drive Ready" signal that stops the DFT timer.
6. The VFD accelerates the motor to its set idle speed and continues to ramp up the motor speed sufficiently to cause the pump to raise the system pressure high enough to reset the controller pressure switch, which stops the LPT timer.
7. The VFD controls the motor in a closed loop mode (feedback) using the PID or PI process controller to maintain and regulate the system pressure at the programmed VFD pressure set point.
8. The VFD promptly responds to changes in water demand to adjust the motor and pump speed without excessive pressure overshoot or excessive delay to prevent excessive pressure drop.
9. Likewise, the VFD responds suitably to changes in pump supply (suction) pressure changes.
10. The VFD adjusts the pump speed to bring the pressure to within 1 psi (0.07 bar) of the desired pressure set point under stable demand (flow) conditions.
11. If and when the system demand drops to either low or no-flow conditions, the VFD throttles back the pump speed to that needed to just maintain the desired pressure. This is typically around two-thirds of pump rated speed resulting in a pressure boost of around 44 percent of rated boost, which will be too low to flow any water under normal conditions.

12a. The pump remains at this speed if the controller is set for manual stop, or

12b. The VFD signals the automatic stop timer that no water is being delivered. If the minimum run time has already occurred, the controller stops the pump. If not, it keeps the pump at idle speed until the minimum run timer is satisfied (times out), and then it stops the pump.

13. This leaves the controller and pump in the normal standby mode.

Normal Operation—Variable Speed Mode—Remote Deluge Valve Start Demand or Remote Momentary (Remote Start Push-Button) Demand. The following steps outline normal controller and pump operation:

1. The controller starts the motor as previously.
2. If there is no demand for water, the pump remains at the pressure maintenance speed.
   a. If started from a remote momentary (push-button) demand, the controller continues to run the pump at the low pressure maintenance speed until manually shut down.
   b. If started from a remote deluge (static) demand and depending on the controller type, the unit will remain run-

ning at low speed or stop after the minimum run timer times out if arranged for automatic stop.

3. If a demand for water occurs during the time that the pump is running, the VFD will accelerate the pump as needed. The controller will not shut the pump down even if or when the automatic stop time occurs in units set for automatic stop.

Normal Operation—Variable Speed Mode (Local Start Push-Button Demand). The following steps outline normal controller and pump operation:

1. The controller starts the motor as previously.
2. If there is no demand for water, the pump remains at the pressure maintenance speed.
3. The unit will remain running at low speed, or if a demand for water occurs, the VFD will accelerate the pump as needed. The controller will not stop the pump since it was started locally (manually).

Manually Set Bypass Mode (Mode Switch Set to Bypass). In this mode, the fire pump controller acts as a nonvariable speed (full-speed) full-service fire pump controller except as follows:

1. On a pressure loss demand (controller pressure switch trip), the controller starts the pump motor and runs it at full-line voltage and frequency to cause the motor to run at full rated speed. The controller continues to run until manually stopped regardless of whether it is equipped for automatic stop and regardless of whether the controller pressure switch is reset.
2. On a remote deluge start pump demand signal, the controller starts and runs the pump until manually stopped as in the preceding exception.
3. On a remote momentary demand (remote push button), the controller starts and runs the pump until manually stopped as in the first exception.

Abnormal Operation. The following steps outline abnormal controller and pump operation:

1. If the drive fault timer (DFT) times out, the controller begins its switch to bypass sequence. It will:
   a. Deenergize both VFD contactors to isolate both the VFD and the pump motor.
   b. Pause for the motor restart time (a few seconds) to allow motor flux to decay to reduce the motor back EMF (voltage) to a safe level.
   c. Restart the pump motor in the bypass full-speed mode.
   d. Continue running the pump at full speed until stopped manually.
2. If the low-pressure timer (LPT) timer times out, the controller will begin the switch to bypass sequence as above.
3. If the controller pressure switch recloses any time during variable speed running operation:
   a. The controller ramps the pump motor up to full speed, if not already there.
   b. The low-pressure timer (LPT) begins timing.
   c. If the pressure climbs high enough to reset the pressure switch, the LPT timer resets and the drive continues normal variable speed operation.
   d. If the LPT times out, the controller begins the switch to bypass sequence as above.
4. Should a fault in the motor occur during variable speed running, the VFD will normally shut down the motor since the output current from the VFD is limited to safe values.
5. If a fault occurs in the VFD input circuitry or if the VFD otherwise begins to draw excessive current, one of the following events occurs:
   a. The VFD branch (path) circuit protection (fuses or circuit breaker) trips to prevent the main fire pump circuit breaker from tripping.
   b. The drive fault timer begins timing and causes the controller to initiate the switch to bypass sequence.
   c. Since the motor is stopped, the pressure will likely drop enough to trip the controller pressure switch, which will start the low-pressure timer and subsequently cause the controller to initiate the switch to bypass sequence.
6. If the line voltage has spikes, transients, or voltage surges of sufficient magnitude, it will cause the VFD, if running, to go into its "overvoltage" shutdown mode. Better-quality VFD units, including all variable speed fire pump controllers installed as of this writing, will tolerate up to 800 Vdc on the capacitors before shutting down the VFD. This is 18 percent higher than the nominal 680 Vdc (480 × 1.414) on a 480 Vac system. In the event that the VFD goes into its overvoltage shutdown mode:
   a. The VFD will stop the motor and clear the drive ready signal.
   b. When the drive fault timer (DFT) times out, the controller begins its switch to bypass sequence as above.
   c. In the process, the VFD is disconnected from the power source and will reset the overvoltage shutdown mode. If not damaged by the overvoltage condition, it will be available for service on the next pump demand.
   d. The unit switches to bypass until manually shut down.

Application Considerations

For a variable speed fire pump installation to be successful (reliable and robust), certain unique requirements of the installation are needed. At a minimum, they include the following:

1. Adequate ventilation is required. The controller mounting must be per the manufacturer's instructions so as to not block controller ventilation requirements.
2. The pump room or pump house must be adequately cooled or ventilated to prevent heat from both the controller and the motor from exceeding the maximum allowed controller-rated ambient temperature.
3. The motor wiring length must not exceed the manufacturer's rating to avoid excessive motor voltage spikes that can damage the motor insulation.
4. As with other fire pumps, the motor must be a NEMA Design B, Starting Code G.

5. The motor must be suitable for and labeled for use with a variable speed drive (e.g., it must be marked as an inverter duty motor).
6. The motor-rated horsepower may not be exceeded. It is not allowed to use the motor into its service factor. The maximum allowed motor running current is 1.0 times the motor nameplate full-load current (FLA), not 1.15 times.
7. The pump and motor must be rigidly coupled to prevent motor torque oscillations.
8. For horizontal pumps, the pump and motor must be properly grouted for the same reason.
9. A relief valve is required for emergency and manual full-speed operation if the pump can exceed the system pressure rating when running at full speed and at churn.
10. For vertical turbine pumps, all resonant frequencies (or speeds) up to full speed must be known and programmed into the controller. These are skip frequency(s).
11. For water-lubricated pumps specify minimum speed and maximum allowed acceleration time to said speed, if applicable. Also specify the minimum idle speed needed to keep the top bearing wet at the lowest anticipated well-water level.

Basic Hydraulic System Considerations

Feedback Control Theory. With the availability of variable speed fire pumps, the system designer can now design for the worst-case low suction pressure and maximum pump demand factors and not have to worry about how high the pressure rises during low-flow or no-flow conditions, such as occur during pump testing. Note that actively controlling pressure implies the use of a feedback control system, which is the case with either diesel engine or electric motor–driven systems. This operation is always the case whether these systems are referred to as pressure limiting or not. The control of pump discharge pressure occurs by way of sensing the pressure at the pump discharge, comparing it to a set reference value, the "set point pressure," and using the difference, either positive or negative, to increase or decrease the speed of the pump driver in order to bring the pump pressure up to or down to the desired set point value as other system parameters vary, such as system flow and suction pressure.

Feedback System Control Gain. The gain of the system determines how close the controlled variable comes to the desired set point value. In the case of variable speed electric motor–driven controllers, the gain should always be high enough to allow controlling pump discharge pressure to within 0.1 psi (6.9 mbar) of the desired set point value. However, if the gain is too high, the system may not converge on the desired final value (set point value) in a smooth manner. Too much gain can lead to either overshoot or oscillation and unstable operation. These problems will not occur with properly set and operating PID or PI feedback controller.

System Time Constants. Every feedback control system has one or more time constants—the time that it takes for such a system to settle to within 37 percent of its ultimate value. A hydraulic system, such as a fire sprinkler system, may be either an open system or a closed system.

Open Systems. An open system is one that is open to the atmosphere somewhere. Typical are sprinkler systems fed from elevated tanks or towers. System pressure is determined by gravity and the height of the water in the tower or tank. These can have long time constants. Several seconds is not unusual. The longest time constants on one multibuilding medical housing campus measured 20 to 24 seconds along with several shorter ones.

Closed Systems. Most building fire sprinkler systems are closed, meaning that system pressure is maintained by means other than gravity. In hydraulic systems, the system time constant is dependent on a number of variables, but the two primary variables are the size of the system and the amount of air in the system. Pressure in these systems is maintained by a pressure maintenance pump, also called "Jockey Pump" or "make-up pump," whose start and stop pressures are coordinated with the churn pressure of the fire pump. The size of the system determines how many tons of water are entrained within the system. The amount of air trapped in the system determines both the amount of stored energy in the system and the overall system time constant. Specifically, with very little trapped air, the system time constant can be very short, even less than 1 second. This case can occur in high-rise buildings when the air has been bled out of the branch piping. On the other hand, large factory or warehouse buildings often have a large amount of trapped air in the system and, therefore, have long time constants.

Multiple Time Constants. Sprinkler systems may have numerous branches, each of which will have varying amounts of trapped air. These several branches will, therefore, have varying time constants. Most important is the time constant of the system as viewed from the variable speed fire pump. In systems with multiple buildings and multiple underground loops, there can be several time constants due to varying sizes of subsystems (buildings) and varying amounts of trapped air (Figure 15.7.16).

Hydraulic Versus Electrical Time Constants. A second source of multiple time constants is the variable speed pump itself. When the pump is off, the system will have a main (fundamental) time constant or resonant point. When the pump is turned on or is accelerating, it can cause a different, usually shorter, time constant, since it is acting as a forcing function in feedback theory terms. Also, the motor and controller times are under the control of both the VFD set parameters as well as the PID set parameters. These time constants are important only while the system check valve is open, meaning when the pump is delivering water.

Other Applications. Time constant considerations will be different for other systems but must still be considered for stable and responsive system operation. Examples of these other systems are agent pumps (foam agent, etc.) and water mist systems. Some of these employ positive displacement pumps that also require the use of unloader valves during motor starting.

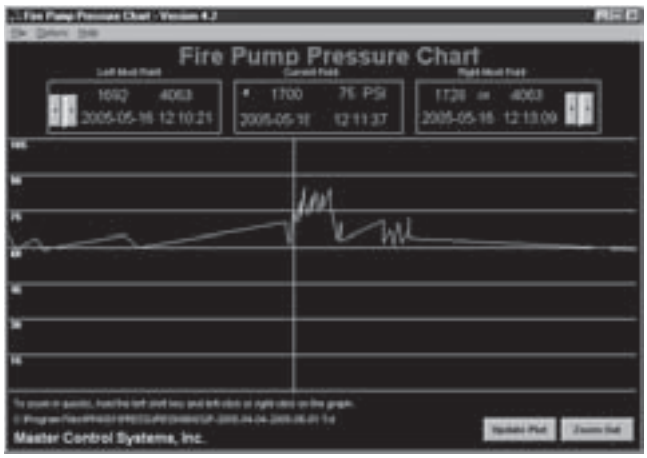


FIGURE 15.7.16 Screen Shot of Pressure Plot Showing Several Different System Time Constants (Source: Master Control Systems, Inc.)

CONTROLLER PARAMETERS

It is paramount that the fire pump installation and the fire pump package (pump, motor, and controller) be coordinated. Any mismatch can result in a nonfunctional package that will have to be corrected or replaced. Worse yet, the mismatch can result in an installation that appears to work but is unreliable. This situation may not be discovered until the pump is needed for fire suppression. Finally, since substantial fault currents and voltages exist, miscoordination can and does result in unsafe installations.

Nameplate Parameters

Voltage. The controller's parameters must match the incoming power and the motor that it will be controlling. The line voltage must be the same as the controller-rated voltage and the motor-rated voltage. Special care must be taken for part winding and wye-delta (star-delta) starting controllers to determine that the intended motor is rated for the respective type of starting at the intended voltage. This is especially true of dual-voltage (series/parallel) motors.

Frequency. The controller-rated frequency must match that of the incoming power (mains). To be specific, 60 Hz controllers will not be reliable when used at 50 Hz and vice versa, unless the controller is designed, rated, marked, and listed for such dual-frequency service. Most controller components that operate at the line frequency are affected by the applied frequency in one of two ways. First, 60 Hz components used at 50 Hz at the same voltage will draw more current due to the reduced inductive impedance (reactance) at the lower frequency and will thus run hotter and possibly overheat. The second, and often the more important, effect occurs with AC-powered relays, contactors, timers, and so forth. When used at a higher frequency than intended, such as with a 50 Hz coil used at 60 Hz, the coil will have a lower inrush (pickup or pull-in) current. Such use will result in lower pull-in force, which may not be adequate under normal or low-line voltage conditions. Note that some devices are rated, and labeled, for such dual-frequency use because they have been designed, tested, and listed under both frequencies.

Horsepower or Motor Kilowatt Rating. The controller components are sized for a specific maximum motor FLA and service factor. Applying a larger-than-rated motor voids the controller listings, invalidates the design, and usually voids the controller warranty. It is also dangerous and unreliable, especially when the unit is needed to deliver water at full flow for any length of time. The use of a smaller-than-rated motor must be approved by the controller manufacturer to assure proper coordination because the sizing of the circuit breaker shunt trip unit (for the motor locked rotor protection) covers only limited ranges of motor FLA.

Short Circuit Rating

Every fire pump controller has a labeled short circuit current rating in accordance with NFPA 20. The current is given in either symmetrical amperes (A) or in symmetrical kiloamperes (kA) where 1 kA is 1000 A. As detailed in NFPA 20, these ratings are established by the listing agencies Underwriter's Laboratories (UL) and Factory Mutual (FM) by way of testing, which is often destructive. The testing affirms that the equipment can both withstand the rated short circuit current and that the equipment can safely interrupt said short circuit currents. In order to pass the test, the equipment may not become a shock hazard or a fire hazard. NFPA 20 also makes it clear that to determine the suitability of the controller, the short circuit current availability of the power source supplying the controller must be determined. This determination requires a short circuit study. A controller rated at 30,000 A is an entirely unknown variable if connected to a power source capable of delivering more than 30,000 A. If the controller short circuit rating is exceeded, the equipment may become a fire or shock hazard during or after a short circuit event. It is important to note that the interrupting capacity rating of the circuit breaker (and/or isolating switch) inside of the controller is not the rating of the controller. These two different ratings should never be confused or used interchangeably.

With dual-power sources, two short circuit ratings are involved and must be coordinated with the alternate (emergency) power source (genset, other utility, etc.), namely, the interrupt capacity rating and maximum allowed ampere size upstream circuit breaker. See the section on power transfer switches for details.

STANDARD CONTROLLER COMPONENTS

Certain elements are common to all or most fire pump controllers.

Nameplate

A listed electric motor–driven fire pump controller must bear a ratings nameplate that gives the important electrical parameters, including operating voltage, motor horsepower or ampere

rating, or both, the minimum operating temperature, and the enclosure type, among other parameters. The ratings also include the required short circuit rating. UL listing and FM approval marks are also required.

Isolating Switch

An isolating switch is required and is present on all controllers except on limited-service controllers. These are sized to have an ampere rating at least 115 percent of the full-load current rating of the motor and/or be horsepower rated at not less than the motor horsepower. An isolating switch is not necessarily a load break rated switch. If the isolating switch is not mechanically interlocked with the controller circuit breaker, a warning label must also be present to warn of operating (opening or closing) the isolating switch if the circuit breaker is closed. This is because the isolating switch is not required to be rated or tested for closing on to or interrupting faults.

Circuit Breaker (Disconnecting Means)

The fire pump circuit breaker serves several purposes. It is an important and integral part of the controller short circuit design and rating. It must safely interrupt fault currents up to the rated short circuit rating of the controller. In many, if not most, modern designs, both the isolating switch and the circuit breaker are of the molded case construction and share the task of clearing high fault (heavy short circuit) currents between the two devices. The circuit breaker is required to be rated at 115 percent or more of the motor FLA. The circuit breaker will have an interrupt capacity rating. However, this rating is not the same as the controller short circuit rating. It may be either higher or lower than the circuit breaker's interrupt capacity rating. Note that medium-voltage fire pump controllers use current-limiting, R-rated motor circuit fuses instead of a circuit breaker for this fault-clearing function.

Motor Locked Rotor Overcurrent Protection

Modern controllers use a separate current sensing trip unit in conjunction with a shunt trip solenoid, which is part of the circuit breaker. The circuit breaker itself is usually a molded case switch with a shunt trip solenoid. The trip unit senses the motor current flowing and compares it with the desired tripping curve characteristics. The two points that define the breaker trip characteristic curve are the 300 percent no-trip value and the 8 to 20 second trip time at 600 percent of the motor FLA. These trip units have setting switches to select a range of motor FLA values for the motor being used. Using a trip setting higher than the motor FLA value is more likely to result in a motor that will burn out before the trip unit can open the circuit breaker. If the trip unit setting is lower than the motor FLA, the circuit breaker is more likely to trip prematurely. Trip units with smaller ranges (more settings) are able to provide more precise motor protection.

Limited-service controllers are allowed to have a wider range of motor protection by allowing the use of thermal circuit breakers. Medium-voltage controllers use the trip unit to deenergize the motor contactor to take the motor off-line under overload conditions up to and including locked rotor. The contactors are tested for this duty to UL 347 on high-voltage industrial control equipment.

Motor Contactor(s)

The main motor contactor(s) takes the place of a motor starter in conventional combination motor controllers. There is no motor overload relay. Motor tripping is accomplished by opening the circuit breaker. The number and purpose of contactors vary with the controller starting type, as illustrated in Table 15.7.3.

Pressure Switch

An automatic controller of the pressure-actuated type will be equipped with a pressure-actuated switch. The pressure switch is required to have independent high and low set point adjustable settings. This pressure switch has traditionally been a Bourdon tube type pressure switch, although pressure transducers, along with amplifier circuitry, are used in some designs instead, especially in those jurisdictions where products incorporating mercury are prohibited. This switch has been a hermetically sealed mercury "tilt bottle" type of pressure switch, which protects the contacts from atmospheric and environmental conditions.

The pressure switch settings are normally determined by the hydraulic design of the installation and by the AHJ over the installation. The setting of the start and stop pressure of every fire and jockey pump in a system is of vital importance. The settings need to be correct for the fire protection system (the fire sprinkler system) to function correctly and deliver the required amount of water or agent. Moreover, incorrect settings can damage the system by either overpressure or excessive water surging, either of which can damage an underground piping system (loop).

Start and Stop Push Buttons

Every controller has a manual "Start" push button known as the manual electric control at controller. Operation of the "Start" push button locks the controller into a running condition. If the controller is of the reduced inrush starting type, the starting will be in the reduced inrush starting mode. In most controller de-

TABLE 15.7.3 Summary of Number of Motor Contactors Versus Starting Type for Fixed and Variable Speed

Starting Type	*Number of Contactors*
ATL	1
Part winding	2
Primary resistance	2
Primary reactor	2
Wye-delta open transition	3
Wye-delta closed transition	4
Soft start	2[a]
Auto transformer	3
Variable speed	At least 3[b]

[a]Three for soft start if an isolating (start) contactor is provided.
[b]Depending on which bypass starting method is used.

signs, the "Stop" push button will stop the pump regardless of whether or not a demand still exists. If there is still a demand, the pump will restart when the "Stop" button is released.

Emergency-Run Mechanical Control at Controller

The emergency mechanical operator will start the pump motor by physically closing the main motor contactor M or both of the two main motor contactors (typically M1 and M2). As a result, the motor is started at full voltage. Most low-voltage controllers have an electrical assist mechanism to avoid undue contact erosion due to arcing or welding of the contacts because of slow opening or slow closing of the contactor.

Emergency Stopping

With low-voltage, single-source (nontransfer switch) controllers, emergency stopping of the pump can always be accomplished by opening the controller circuit breaker. This operation allows stopping of the motor in case there are one or more welded contacts in the motor contactor(s). This method of stopping will still work if a dual-source (transfer switch) controller is running on the normal source. Some dual-source controllers (the so-called dual-utility controllers) have two circuit breakers, allowing emergency stopping of the motor regardless of which source it is connected to.

In medium-voltage controllers, it is the motor contactor that must always break the motor circuit. The only exception is when a controller is equipped with a suitably rated disconnect switch in lieu of the usual isolating switch. As noted earlier, the motor circuit fuses interrupt the motor current only during a high-current short circuit. These fuses are coordinated with the motor size and the other power path components. Therefore, the "Stop" push button serves as both the normal and the emergency stopping means.

Surge Arrester

The surge arrester offers mixed benefits. The purpose of the surge arrester is to protect the fire pump controller from line surges, mainly lightning surges, although no secondary equipment (nonutility equipment) will survive a direct lightning hit on its incoming lines. The surges in question are induced surges caused by capacitive or inductive coupling from a nearby lightning strike rather than a direct strike. When a surge does occur, it will find the path of least resistance. This will be equipment or wiring devices having the weakest dielectric strength (voltage withstand). The purpose of surge arresters is to absorb this surge energy before it can cause damage to equipment or wiring devices. Equipment having the highest voltage withstand will not conduct the surge energy since other equipment and/or equipment having arresters will do that job instead. Equipment having a high enough voltage withstand will thus be unaffected by such surges.

For lightning arresters to be effective, they need to be sized in accordance with the energy available versus their ability to absorb said energy. Basically, they should be sized in accordance with the upstream impedance, which limits the energy. Arresters are rated on how large of a current surge they can absorb and how often they can absorb the same. When an arrester absorbs more than this rated energy, its leakage current (follow-on current) can be high enough to destroy it, even if a first surge or a repeated surge does not. This can be immediate or may be delayed due to a condition known as thermal runaway. This condition occurs when the self-heating caused by leakage current leads to internal heating faster than the heat can be dissipated. Suitably rated and well-designed arrester equipment is available. However, the cost and size prevent their widespread use inside fire pump controllers as standard equipment. They are sometimes installed in parallel with fire pump controllers. Because of this hazard, some designs mount the arresters "out of sight" for personnel safety. Some designs also provide fuses to protect the equipment from damage due to blown arresters.

STANDARD CONTROLLER FEATURES

The description of certain standard features of electric drive fire pump controllers follows. The list is not exhaustive. For a complete list, see NFPA 20.

Devices and Controls

Locks. Most or all listed controllers have, or should have, a lockable cabinet. The means may be by way of padlock hasps, a lockable door handle(s), key-lockable handle(s), or separate key lock(s). If the pressure switch is a Mercoid Bourdon tube type, its setting knobs are lockable or can be sealed with a seal wire. Most or all controllers have isolating switch or circuit breaker operator handles that can be locked on or off. The "On" position is used to lock the unit in the standby fire protection mode, whereas the "Off" position is used as a lockout for servicing.

Interlocks. Most listed controllers have an interlock between the cabinet door(s) and the isolating switch operator mechanism or handle. This interlock prevents opening of the door while the isolating switch is in the "On" position (unit energized). The interlock also prevents closing of the isolating switch while the door is still open. These interlocks are important because the controllers operate at lethal voltages. They are also very important for controllers that are connected to high-fault power supplies. These controllers are very unforgiving of accidental short circuits. It is also most important to be sure that the door is closed before energizing the unit, especially when closing the circuit breaker. Should a pump demand exist and a short circuit exist, there will be venting of ionized gases in one or more of the power devices. This can cause explosive pressures within the controller. If the controller door(s) is not closed and latched, serious injury can occur. This is also the reason for greater emphasis on short circuit availability and controller short circuit rating coordination. Medium-voltage controllers have additional interlocking between the motor contactor and the isolating switch and the high-voltage door.

External Operators. All listed electric fire pump controllers have an emergency mechanical operator. Low-voltage controllers also have a circuit breaker operator. Medium-voltage

controllers have an isolating switch operator in lieu of the circuit breaker operator. Full-service low-voltage controllers have either two operators or one combined operator for the isolating switch and the circuit breaker. The required external operators are shown in Table 15.7.4.

Manual Electrical Control. All listed controllers have, as a minimum, the required "Start" and "Stop" push buttons. Controllers have circuitry that keeps the pump running if started from the local "Start" push button independent of an automatic stop (minimum run timer) circuit. The same applies for a remote lockout or remote shutdown circuit. Because the pump was started manually and locally, it should not be stopped automatically or remotely.

Pressure Loss Starting. Controllers used for pressurized systems also have the pressure switch described previously.

Remote Starting. When controllers are used for an unpressurized system, a deluge system, or a monitor nozzle system, the controller must be equipped with a remote start option circuit. The controller might not be equipped with a pressure switch. These units are actuated by the opening of a remote (external) contact, such as from a deluge valve contact, a fire or smoke alarm relay contact, or a remote or central station push-button contact, among others, to signal the controller to start. Some systems are a combination of both pressurized and deluge type sprinklers. For these systems, the controller has both a pressure switch and a remote start option circuit.

Accelerate Time. Reduced inrush (reduced current) type of controllers have one or more means to set the accelerate time. Most, but not all, are adjustable. In addition, primary resistor, primary reactor, and autotransformer controllers have two or more taps for setting the motor starting voltage. Similarly, soft start controllers have various adjustments for setting the voltage and time parameters.

Input Signals

All electric fire pump controllers have power inlet terminals for the motor power circuit. Dual-source controllers have two such inputs. A second (or third) power source is sometimes also supplied to a controller equipped with certain options. This additional source is the so-called supervisory power supply, usually a 115 Vac (at 60 Hz) or 220 Vac (at 50 Hz) branch circuit. It is used for a supervisory power loss start circuit option for a so-called built-in alarm set circuit option.

TABLE 15.7.4 External Operators

Controller Type	Controller Voltage	
	Low Voltage	*Medium Voltage*
Limited service	Circuit breaker operator only	(not applicable)
Full service	Circuit breaker operator and isolating switch operator	Isolating switch operator only

All automatic controllers have at least one pump demand input to signal the controller to start the fire pump. The most common is a pressure sense line fitting that connects to the controller's internal pressure switch. Other inputs include the aforementioned remote start circuit. Some controllers have separate remote start inputs, either as standard equipment or as optional equipment, one specifically for deluge or fire alarm contacts and the other specifically for remote start push-button contacts. Some designs use circuitry to keep the automatic stop circuitry from canceling the latter demand as it is initiated manually.

A controller may also have an input for a remote stop or lockout signal, either as standard equipment or as optional equipment. This input signal is sometimes used to keep a second pump from starting unless a first pump has failed to start.

Controllers can also have other inputs, usually for alarm, monitoring, or supervising purposes. Some of these are described in the section on alarms and indications.

Output Signals

The main output from an electric fire pump controller is the motor power, which comes from the main motor contactor(s) as described previously. Controllers may also be equipped (as standard or optional equipment) with auxiliary control power output at the same voltage levels as those described for supervisory power input. This power is often used as one of the power inputs to a remote alarm set (alarm panel). In jurisdictions that allow or mandate low-suction shutdown, this auxiliary power may be used as one source of power for a low-suction shutdown panel. This source of power is usually limited to a current of 1 A or less and is normally protected by a fuse or circuit breaker to prevent damage to the controller's control power transformer because this is often in the critical starting path of the controller.

Controllers used in multiple-zone installations (the so-called high-zone and low-zone installations) have an output signal from the high-zone controller(s) to signal the lower-zone pumps to start in order to supply water to the higher-zone pump suction inlets. The low-zone controller(s) have inputs, such as remote start, to accept the start signals from the high-zone controller(s). See the section on high-zone delay for pumps in series.

All controllers must be equipped with a minimum of three output alarm contacts, for motor (or pump) running, power available (or power failure or phase loss), and phase sequence reversed (or phase reversal). Dual-source (transfer switch) controllers must also supply two additional output alarm contacts: one to indicate when the transfer switch is in the emergency (alternate) source position and the other to indicate when the emergency isolating switch is opened. Various controller options supply additional contacts for alarm, monitoring, or supervisory purposes. Some of these are described next.

Alarms and Indications

All electric fire pump controllers must have at least two indicator pilot lights (visible indicators). One is used to indicate

that power is available in all phases at the line terminals of the contactor(s). The other is used to indicate a phase reversal of the power source to which the line terminals of the motor contactor are connected. Controllers may also have an optional motor (pump) running signal light, among others.

When the pump room is not constantly attended, alarms must be provided "at a point of constant attendance." In the absence of such an attendant, the mandatory three (or five for dual-source controllers) alarm contacts should be connected to either an on-site alarm set installed at a point of constant attendance (switchboard, security post, etc.) or an off-site monitoring location such as a central watch or alarm service. Not monitoring the alarm contacts results in degraded fire protection because pump failure conditions go unheeded and uncorrected for some period of time. Similarly, a pump running condition should always cause someone to be in attendance at the pump to watch for problems. More importantly, a pump running alarm might be due to the pump responding to an actual fire condition. Such a condition should always initiate a course of action that includes immediate attendance at the fire pump to monitor its operation and possibly allow for intervention in the event of trouble with the pump, motor, or controller.

All electric controllers must also signal an alarm condition if a single-phase condition occurs, whether or not the motor is running. This condition may be either annunciated as separate light and alarm contacts or it may be combined with the power available/phase loss alarm light and contacts.

Strictly speaking, only the loss of phase open or closed contact is required. However, all listed controllers provide both open and closed contacts. Since these contacts operate in opposition, they can signal power failure (phase loss) and power available conditions.

Dual-source controllers (combination transfer switch fire pump controllers) require additional alarms related to the transfer switch itself. These are a pilot light and contacts to indicate when the transfer switch is in the normal source position and when it is in the emergency (alternate) source position. The same is required to indicate when the emergency source side isolating switch is open as well as a local audible alarm for this indication. These units also require contacts to initiate genset starting when the alternate source is a standby generator set. The required alarms for electric fire pump controllers are given in Table 15.7.5.

TABLE 15.7.5 Required Alarms for Single- and Dual-Source (Transfer Switch) Controllers

Alarm	*Contacts*	*Visible*	*Audible*
All Fire Pump Controllers			
Power available	Yes	Yes	Optional
Motor (pump) running	Yes	Optional	Optional
Phase sequence reversed	Yes	Yes	Optional
All Variable Speed Controllers			
Drive failure (variable speed drive failed)	Optional	Yes	Optional
Bypass mode (full speed running)	Optional	Yes	Optional
Overpressure (115% of set pressure)	Optional	Yes	Optional
Dual-Source Controllers or Power Transfer Switches			
Transfer switch in normal position	Optional	Yes	Optional
Transfer switch in emergency position	Yes	Yes	Optional*
Emergency isolating switch open	Yes	Yes	Yes

*Some controllers provide this audible alarm as standard in addition to the emergency isolating switch open audible alarm.

High-Zone Delay for Pumps in Series

In high-rise buildings, a lower-zone pump is often used to supply suction pressure to the next or higher-zone pump. This arrangement is usually done when more than one pump is needed to supply the required head (psi pressure). When the suction of one pump is supplied directly from the discharge of another pump, the pumps are considered to be in series.

Each pump supplying pressure to another pump must be arranged to start before the pump it supplies. The starting requirement prevents the higher-zone pump from running dry or cavitating. When only two zones are involved, a demand for the high-zone pump causes the high-zone controller to send a demand signal to the lower-zone pump before energizing the high-zone pump motor. The delay is required to be between 5 and 10 seconds, which allows the lower-zone pump to come up to speed and supply water to the high-zone pump. In practice, the high-zone controller merely delays the actuation of the motor contactor(s) for a fixed delay time (5 to 10 seconds), while sending the demand (start) signal to the low-zone controller. The high-zone controller should impose this start delay for every demand source to avoid cavitation or dry running. This delay interval is usually known as the high-zone delay.

In case of more than two zones, all the higher-zone pumps must delay starting their motors while sending a start signal to the lower-zone pump controller. In the case of three zones, when the highest-zone controller receives a demand signal, it sends the demand signal to the middle-zone pump remote start input while delaying the start of the high-zone motor by 10 to 20 seconds. The middle-zone controller likewise sends a demand signal to the low-zone pump controller. The low-zone controller starts its pump motor immediately and supplies suction pressure to the middle-zone pump. In 5 to 10 seconds, the middle-zone controller starts its pump motor and supplies suction pressure to the high-zone pump. In 10 to 20 seconds the third- (highest-) zone pump starts to provide discharge (system) pressure.

Failure of a leading motor to start must not prevent subsequent pumps from starting. This requirement is accomplished with the aforementioned delay scheme because the high- or higher-zone pumps will start unconditionally after their set time delay, regardless of the state of other pumps. This scheme is followed with the intent that the high(er)-zone pumps will still

have enough suction pressure to provide at least some pressure and flow.

Sequence Starting for Pumps in Parallel

When pumps feed a common system or manifold, they are considered to be pumps in parallel. This scheme is usually implemented when more than one pump is needed to supply the required flow or when the added reliability of having more than one pump is desired. Although electric motor–driven pumps are used in parallel, many applications for parallel pumps for increased flow capacity (gal/min) use diesel drives.

Controllers for each unit of multiple-pump units must incorporate a sequential timing device to prevent any one motor from starting simultaneously with any other motor. There are two main reasons for this requirement. One is to prevent excessive load on the electrical systems from simultaneous starting of pumps. The other is to reduce the stress on the associated piping system. In these installations, the controllers are equipped with a sequence start timer, which inhibits pump starting during the delay period. The delays are set in the required 5 to 10 second intervals, although the first unit need not have any delay in most applications. At the end of the time interval, the controller in question will start the pump regardless of whether previous pumps have started or not. The only exception is controllers that reset if the demand signal ceases during the timing interval.

Control of Pumps in Series and Parallel

Some installations use two fire pumps in each zone in order to provide a backup pump in case the primary pump fails. In a three-zone installation, there is a total of six pumps. Where emergency (alternate) power is required, the controllers are sometimes interlocked to prevent both motors in any zone from starting to avoid overloading the alternate power source genset. One scheme uses a combination of failure to start, motor overload, or power failure signals from the primary pump to lock it out and pass the demand signal to the low-zone pump. When motor current exceeds a fixed percentage (e.g., 15%) a motor running signal is sent to the backup pump to lock it out. The backup pump is equipped with sequence start delay in order to allow the primary pump to start.

High-Pressure Wet Parts (Plumbing, Pressure Switch, and Recorder)

Most listed controllers are rated at 275 to 300 psi (19 to 21 bar) working pressure and use 300 psi (21 bar) full-scale pressure-sensing elements (pressure switches or pressure transducers and pressure recorders, where used). Pressure switches suitable for higher-pressure applications are available for use with these systems. The pressure switch and pressure recorder are the most delicate devices with regard to overpressure.

Stainless Steel Wet Parts (Plumbing, Pressure Switch, and Pressure Recorder)

Although more common with diesel drive fire pump controllers, this feature is needed when the pump takes suction from seawater or other brackish or corrosive water sources. The book *Pumps for Fire Protection Systems* provides additional detail in this regard.

NONMANDATORY CONTROLLER FEATURES

Listed electric fire pump controllers are available with a great number of options, features, and modifications. Some of these affect controller or pump operation and/or functionality. Some provide additional information (indications or readings) or additional protection for the equipment or the installation. Others modify the construction of the controller itself. The following paragraphs describe some of the options that affect pump operation and/or reliability of operation.

Motor Burnout Protection

Motor Overload Alarm. A motor overload alarm is one of the best ways to provide increased fire pump reliability, if properly used and monitored. This feature is available as an option with most listed controllers. Because the code prohibits the usual overload relay in the interest of keeping the flow of water running during a fire, the motor is subject to damage or destruction by any number of overload or overcurrent conditions. Although no overload relay or protection is allowed by code, other than that provided by the controller circuit breaker, an overload alarm feature is allowed. This alarm will warn of an overloaded motor due to pump problems, a low line voltage condition, a controller stuck in the accelerate mode for any reason, a single-phase condition, or a damaged or degraded motor.

Single-Phase Start Protection. All electric fire pump motors and controllers are three phase except for a small number of limited-service controllers and pumps. Attempting to start a three-phase pump with only single-phase power will cause the motor to draw starting currents until it is destroyed, until the fire pump circuit breaker trips, or often both. Fortunately, all electric fire pump controllers inherently protect the motor from starting during a single-phase condition on two of the incoming lines, namely, the lines that are used to supply control power to the motor contactor(s). Some designs also complete the protection by providing single-phase motor start protection on the third phase as well. This difference is seen during wide-area single-phase events. Note that the fire pumps will attempt to start after the jockey pump or pumps trip off-line due to the same single-phase condition.

Motor Restart Delay. If a running motor is briefly taken off-line and then reconnected (restarted), a very high transient can occur, depending on the phase angle difference between the motor's back EMF voltage and the line voltage to which it is reconnected. This phenomenon is the same as that described in the preceding section on wye-delta controllers, but it can be worse as the motor will have full-line voltage rather than the smaller 57 percent wye-mode voltage. This can cause a false trip of the circuit breaker, which takes the pump off-line until someone manually resets the fire pump circuit breaker or possibly the

upstream (service) breaker or replaces the fuses. To prevent this situation, some controllers are equipped with a restart delay as standard equipment, which operates by sensing when the motor contactors drop out (deenergize). The circuit then inhibits the contactors from reenergizing for a few seconds, which is enough time to allow the motor magnetic flux, and the resultant motor back EMF voltage, to decay to a safe value. After the delay period, the restart delay circuit allows the controller to restart the motor and also resets itself to be ready for the next motor interruption.

Exterior Measurement Means. The exterior measurement means facilitates reading controller (motor) voltages and currents from outside the controller. This means addresses personnel safety since both lethal voltages are always present and very high and dangerous short circuit fault currents are available. The best personnel protection against this danger is for the controller door to be securely closed and latched. This measurement means also provides an easy way to monitor the health of the installation and its power source if adequate records are kept of the motor running voltage and current readings during the weekly test running.

Alarms and Other Signals

As previously mentioned, additional alarm inputs and/or outputs are available as optional equipment in these controllers. Some of the more commonly used additional signals and alarms follow. The terms *pump room* and *pump house* are used interchangeably.

Sensor (Input) Signals. Some of the commonly used sensor (input) signals include the following:

- Low pump room temperature (freeze alert)
- Low reservoir temperature (freeze alert)
- Low suction pressure
- Low reservoir level
- Reservoir empty
- Relief valve open
- Flow meter on

Output Signals. Some of the commonly used output signals include the following:

- Motor overload (amperes exceed 115% of FLA) alarm
- Failure to start (within time limit) alarm
- AC volts low alarm (precise detector)
- Load shed signal (transfer switch units)
- Communications options, including telephone dialer to a remote location or pocket pager or cell phone, network reporting, Internet access, or wide area access

Other Selected Options

Automatic Weekly Test Start. Although required in all diesel fire pump controllers, this option is seldom specified in electric drive controllers. NFPA 25 now requires weekly rather than monthly test starting of these pumps. This feature can aid in meeting this requirement, although NFPA 25 does require the weekly test to be attended by qualified operating personnel. Note that electric drive pumps must be equipped with circulation relief valves in order to provide enough waterflow to keep the pump from overheating due to running at churn (shutoff).

Failure to Start. This alarm is a complement to the pump running alarm as it indicates that the pump should be running but is not. This alarm is of utmost importance during a fire.

Built-In Alarm Set. This option provides an audible alarm (bell, horn, etc.) for the standard alarms listed in the section on alarms. It uses a separate source of power—supervisory power—for this function. This option also includes a means of silencing the audible alarm.

Control Power Loss Start. In some high-risk applications, this option starts the pump in the event of internal control power loss. This feature overcomes the inaction that would ensue when a pump demand occurs.

Supervisory Power Loss Start. Supervisory power loss start is an older method of annunciating loss of supervisory power by way of the motor running alarm. Better methods provide two sources of power or battery backup or dial-up communications to monitor and alarm a loss of supervisory power.

Built-In Recording and/or Telemetry. Most controllers are available with built-in pressure recorders of the paper chart, strip chart, or paperless variety. Some units also record alarms and/or other parameters. Some units allow local or remote data access because they can transmit said data on command or on occurrence via various network communications media.

Environmental, Construction, and Other Treatment Options and Modifications

Controller Enclosure (Cabinet) Space Heaters (Strip Heaters). High moisture, especially condensation, is ruinous to electrical and electronic equipment. This condition occurs when the equipment is subjected to either damp atmospheres or varying temperatures (hot in daytime and cool at night). Cabinet heaters help avoid this condensation or excessive moisture. Some designs use heaters that are operated at one-half of their rated voltage, which reduces the temperature of the heater and increases its life. Also, some designs control the heater by use of a humidistat rather than a thermostat, which is more efficient because the purpose of the heaters is to control humidity. Designs that leave the heaters on continuously are outmoded and wasteful of energy.

Motor Heaters. Controllers may be equipped with pilot contacts to enable the motor heater or, depending on the wattage, the slave contactor for the motor heater. This contact will be closed except during motor running.

Controller Enclosure (Cabinet) Construction. NFPA 20 requires a minimum enclosure construction of NEMA Type 2 (UL Type 2), which is rated as and suitable for indoor use only and

is dripproof only. Note that this is the minimum requirement. NFPA 20 also requires that the "fire pump, driver, and controller" be protected against possible interruption of service through damage caused by "any adverse conditions." A NEMA 2 enclosure rating only "provides a degree of protection against limited amounts of falling water and dirt." They are tested for water dripping from the downward vertical direction only. They do not necessarily provide any degree of splash, spray, or water impingement from any of the numerous possible sources of pressurized water within the pump room, especially when the pump room is equipped with fire sprinklers. Also, NEMA 2 enclosures are not necessarily dustproof. The enclosure types described in Table 15.7.6 provide better protection than the standard NEMA 2 rating.

Another enclosure that is also available is the so-called NEMA 3R rated enclosure. It is rated for outdoor use for rain protection. This construction is typically the kind used for outdoor disconnect switches, such as on air conditioning units and outdoor advertising signs. It is basically a variation of NEMA 1 construction and it specifically allows water to enter the enclosure and accumulate within it, although the water is not allowed to wet electrical parts or accumulate to the level of the lowest electrical live part. This construction offers only limited protection of the controller since moisture can enter and accumulate therein. In some cases, the manufacturer builds a NEMA 3R enclosure similar to a NEMA 4 enclosure instead.

TABLE 15.7.6 Enclosure Types

Enclosure Type[a]	*Location*	*Protection*
NEMA 12	Indoor	Dripping water and dust (was splash and oil resistant)
NEMA 13	Indoor	Spraying water (and oil) and dust
NEMA 3	Outdoor	Rain, dust, and ice
NEMA 4	Outdoor	Rain, dust, ice, splashing, and hose-directed water (hose-tight)
NEMA 4XA	Outdoor	Same as NEMA 4, but corrosion resistant (special paint finish)
NEMA 4XB	Outdoor	Same as NEMA 4, but also corrosion resistant of type 304 stainless steel[b]
NEMA 4XC	Outdoor	Same as NEMA 4, but also corrosion resistant of type 316 stainless steel
NEMA 4XCL	Outdoor	Same as NEMA 4XC, but type 316 low-carbon stainless steel

[a]Differences exist between exact definitions and testing methods. The NEMA 4XA, 4XB, 4XC, and 4XCL designations are unofficial and are for reference only. These enclosures are considered as 4X.

[b]The 400 series of stainless steels (such as type 403) is magnetic and does not offer nearly the level of corrosion protection that the nonmagnetic 300 series of stainless steels offers.

The current requirements for raceway terminations for fire pump controllers address the problem of the fire pump controller Type rating being compromised by (1) the use of improperly rated conduit hubs and fittings and (2) field modifications made to the controller enclosure not endorsed by the controller manufacturer.

Current requirements for raceway terminations state the following:

1. Listed conduit hubs shall be used to terminate raceway (conduit) to the fire pump controller.
2. The (NEMA) Type rating of the conduit hub(s) shall be at least equal to that of the fire pump controller.
3. The installation instructions of the manufacturer of the fire pump controller shall be followed.
4. No alterations to the fire pump controller other than conduit entry per the *NEC* shall be allowed.

Other Approvals. To comply with NFPA 20, these controllers are all listed for fire service. Although other possibilities exist, they are all UL listed and almost all are also FM Global approved. Some equipment is available with "CE" (compliance with European norms) compliance certification. Note that these European norms (compliance requirements standards) are widely adopted equipment safety standards within and throughout the European Economic Community.

Electromagnetic Compatibility (EMC). Microprocessor-controlled equipment can and does radiate a certain amount of high-frequency noise. It is also susceptible to disruption by nearby portable radio equipment. Another approval available from some manufacturers is UL EMC certification of compliance (conformance) to standards covering electromagnetic radiation and other electrical disturbances such as transients, surges, and dropouts. The EMC standard used to access conformance (conformity) requires a two-way evaluation, meaning that the equipment is both tested for immunity (susceptibility) from these influences as well as tested and evaluated for emissions (radiation) of deleterious energy. Both radiated and line (power mains) conducted energy are evaluated.

TRANSFER SWITCHES

Where more than one source of electric power supply is needed, a power transfer switch is required to connect the power supplies to the controller. Some combinations use more than one such switch. The following section discusses other considerations and requirements regarding these switches.

There are two different methods of incorporating a power transfer switch. The first includes a listed combination fire pump controller and power transfer switch. The second includes an individually listed fire pump controller and power transfer switch. It is specifically required that both types of transfer switches be listed for electric motor–driven fire pump service. An ordinary listed transfer switch is neither adequate nor permitted. Fire pump transfer switches are also examined and tested to the requirements of UL 1008.

Combination Transfer Switch Fire Pump Controllers

Combination controller-transfer switch units are more common and provide for control of the pump motor and for the switching of the electric power supplies. These units are commonly called dual-source controllers (Figure 15.7.7).

Limited-Service Combination Units. As with single-source controllers (nontransfer switch controllers), these units are also available as listed and approved complete units. Most listed units can be used as service-entrance equipment. These units feature the same controller functions described in the section on limited-service controllers. They also provide all the required features of the power transfer switch as are required of full-service units. These units are subject to the same 30 hp (22 kW) limitation as their single-source counterparts.

Full-Service Combination Units. Full-service dual-source units are available as listed equipment in roughly the same variety as listed single-source controllers. They are available in the same starting types (ATL and reduced inrush starting) and in the same low-voltage ranges and horsepower ranges. Note that listed medium-voltage combination units are not available as of this writing. The listing criteria for these units examines their coordination, identification, location, interwiring, and interlocking requirements. Specifically, these units are examined against UL standards UL 1008 (transfer switches), UL 508 (industrial control equipment), UL 218 (fire pump controllers), and FM Standard FM-1321/1323 (fire pump controllers). The following discussion centers on those items that are not found in single-source controllers or that were not previously covered.

Short Circuit Ratings. The nameplate parameters of voltage, frequency, horsepower (or motor kilowatt) rating, and service factor are covered in the section on controllers. Short circuit ratings require additional concern with these transfer switch units as two sources of power are involved, which require two separate short circuit ratings. Also note that the controller normal side short circuit rating is the same as was discussed in the section on controllers. The emergency (alternate) source side will normally have both a short circuit rating and a maximum allowed size rating for the upstream circuit breaker.

When the alternate source of power is provided by a second utility power source, NFPA 20 requires an emergency side circuit breaker meeting the same requirements as the normal side (or single-source) fire pump circuit breaker. The emergency side nameplate short circuit ratings will give the required maximum short circuit rating of this (alternate utility side) power source in the same manner as the required normal side rating.

The more common case of a second power source is a standby generator. An emergency side circuit breaker is not required for smaller gensets. In the absence of this emergency side circuit breaker, the controller must show both the emergency side short circuit rating and maximum size (ampere) rating or rating of the upstream circuit breaker. This maximum upstream fuse or breaker size rating (restriction) is based on the tested and listed short circuit ratings of the transfer switch, which are based on the upstream device that limits and finally interrupts the fault current. Like the controller itself, the transfer switch short circuit ratings are also established by testing. This testing uses a maximum size breaker (or fuses) to limit the fault current that the transfer switch will be subject to and is capable of handling. Larger-frame-size circuit breakers (or fuses) will allow more fault current to pass compared to a comparable but smaller-frame-size breaker or fuse. This is why the use of a larger than rated breaker violates the transfer switch short circuit ratings. On the other hand, if the circuit breaker or fuses are too small, they may trip or blow prematurely, disabling emergency power to the fire pump. The result of either condition is an installation that is unreliable and unsafe to both personnel and property. Note that although upstream fuses are allowed and used, circuit breakers eliminate the need to search for replacement fuses, and also they avoid the problem of incorrect replacement fuses being used.

In general, standard controllers have emergency side short circuit ratings that are lower than the normal side ratings on any particular unit. They also vary with horsepower because the size of the internal transfer switch varies with horsepower. Larger switches have higher short circuit ratings and abilities. Some units use so-called self-protecting switches for the emergency side isolating switch, and, as a result, rate both sides with the same short circuit ratings. This is possible as they have been examined and/or tested to meet the short circuit and interrupting requirements in order to be so rated. For the same reason, the upstream breaker size restriction may no longer apply.

Additional Parameters. The following issues should be considered:

- *Normal side voltage sensors.* The transfer switch is required to transfer to the alternate source if the voltage in any phase falls below 85 percent of the motor's rated voltage. All listed controllers have a means to adjust the transfer voltage(s).
- *Phase reversal.* When a phase reversal of the normal source occurs, the transfer switch must initiate a transfer to emergency (by simulating a normal source power failure). Some designs use the controller's usual phase reversal circuitry on the load side of the transfer switch, whereas others use two separate sensors for the purpose.
- *Emergency side voltage and frequency.* The transfer switch is inhibited from transferring unless and until the genset output voltage has reached suitable voltage and frequency levels. This is usually monitored in only one phase of the emergency source to reduce costs.
- *Second utility (emergency side) three-phase voltage sensors.* If the unit is designed for dual utility application, the single-phase voltage/frequency sensor is replaced by three-phase sensing like that used on the normal source side.
- *Genset start signal (transfer) delay.* An adjustable delay is usually set for a few seconds to prevent nuisance starting of the genset on short duration power glitches (dropouts).
- *Retransfer delay.* Another adjustable delay is used to delay retransfer from the alternate power source to the normal source

until the normal source is stabilized (see NFPA 20). This is typically set to 30 minutes or so to avoid transferring back to the normal source while it is still experiencing outages, dropouts, or single-phase events, as is typical during a lightning storm. Retransfer delay also prevents problems caused when the genset runs for a short period of time.

Standard Components. The following issues should be considered:

- *Barriered or separate compartment.* It is important that faults occurring in the normal source compartment not be allowed to propagate into the emergency compartment and vice versa. This consideration is more critical at voltages above 240 Vac because the resulting arcs are more difficult to extinguish and more ionized gases are created. Besides being highly destructive, these ionized gases are highly conductive and are a means of fault propagation.
- *Emergency source isolating switch.* In these controllers, the other isolating switch is known as the normal source isolating switch. This emergency side isolating switch must be equipped with means to prevent starting of the emergency source generator from this controller if this isolating switch is open. This means, however, does not prevent starting of the genset from other means. This isolating switch must also be supervised both locally and remotely, which is usually done with multiple pilot switch or limit switch contacts actuated by the isolating switch or its mechanism.
- *Manual (mechanical) transfer.* A means for safe manual (nonelectrical) operation of the power transfer switch must be provided. This manual means need not be externally operable. At present, no listed units are externally operable. Thus, the controller door(s) must be opened to manually transfer the switch. As most standard transfer switches are not rated for manual switching under load, it is important that they be deenergized by opening both isolating switches before attempting a manual transfer. Both the normal and the emergency isolating switches must be opened to completely deenergize the power sources before attempting a manual mechanical transfer. Not following the prescribed procedure is a distinct safety hazard, especially if a short circuit is involved.
- *Push buttons.* Transfer switch controllers have a test push button to simulate a loss of normal source power. Although not specifically required, most or all listed controllers also have a bypass push button to retransfer the transfer switch back to the normal position. Note, however, that this retransfer is predicated on having suitable normal source power present. This bypass push button bypasses the retransfer delay timer, which is often set for around 30 minutes.
- *Other items.* The required controls (push buttons), lights, alarms, and remote alarm contacts are covered in the section on controllers.

Standard Features. The primary standard features have been discussed in the sections on standard equipment or important and other parameters. These include voltage and frequency sensors, phase reversal sensing, transfer and retransfer delays, and the genset start signal. Also required is a means to prevent higher-than-normal inrush currents when transferring the fire pump motor from one source to the other. These are the same high transient (spike) currents that can occur if a spinning motor is transferred to a source whose phase angle differs significantly from that of the motor's back EMF voltage. This is the same phenomenon described in the section on controllers (under restart delay and wye-delta open transition starting). The usual method to prevent such transient currents is for the transfer switch to signal the controller to shut down the motor for a few seconds while inhibiting transfer of the transfer switch. This is to allow enough time for the motor magnetic flux to decay to a safe level.

Another means that can be used is the so-called program neutral type of transfer switch. Rather than switching immediately from one source to another, the transfer switch has an in-between (neutral) open position in which the load is not connected to either source. In operation, the switch first moves to this in-between (neutral) position and dwells there for a few seconds. At the end of this delay, the switch completes its travel to the other power source.

A third method is sometimes specified for these controllers for this same purpose. It is the so-called in-phase monitor circuit available from transfer switch suppliers. This scheme is highly variable in fire pump installations. It should not be used without one of the other schemes for controlling transient currents. The variables are due to several factors. The first one is the low-inertia nature of centrifugal pumps, which causes very rapid spin down when power is interrupted. The second variable is the fact that there can be a permanent difference of phase angle between the two sources such as with a dual utility, even though the phase sequence (rotational sense) can still be correct. For example, one source can be described as having phases A-B-C whereas the other might be B-C-A or C-A-B. These last two phases are 120° apart from the first and from each other. The third factor is that the transfer may be due to a phase reversal.

Other Features of Combination Controllers. Another standard feature can include an emergency source circuit breaker. As stated earlier, where the alternate (emergency) source is another utility source (i.e., a second utility), the controller must have a second circuit breaker and locked rotor overcurrent protection the same as the normal source side of the controller. Its emergency isolating switch must meet all the requirements of the normal source isolating switch. In certain installations, the alternate source is on-site generation from large gensets such as those used with "emergency bus" type installations. Moreover, the emergency bus may be normally fed by more than one source through one or more transfer switches, is usually normally "hot" (energized), and usually fed by a utility source in the normal or standby condition. This is another reason for having an emergency side (second) circuit breaker in the controller in these installations, because this utility source may be capable of high-fault currents. In any case, the controller emergency side short circuit rating must be suitable for the sources to which it is or to which it can be connected, particularly when a combination of upstream transfer switches may ultimately connect to a utility source of power.

Nonmandatory Features. Some transfer switch controller combinations have a mechanical interlock between the normal source isolating switch and the emergency source isolating switch. This interlocking prevents the emergency source side switch from closing if the normal source side switch is still open. This prevents false or inadvertent starting of the genset due to lack of power on the normal source side circuitry. Similarly, the normal side switch cannot be opened until the emergency switch is also opened. The transfer switch and genset can still be tested in these designs by opening the normal side circuit breaker.

The following issues should be considered:

- *Engine "overrun" (cooldown) timer.* All listed controllers have either an optional or a standard engine overrun timer. This timer keeps the start signal to the genset asserted after the transfer switch has retransferred back to the normal source. The purpose is to allow the engine to cool down with no load applied to its generator, which, therefore, allows the engine to run unloaded. This timer is typically set for 10 to 30 minutes.
- *Load shed contacts.* Load shed contacts are used to signal another load to disconnect from the genset in order to provide enough power and current to start the fire pump. These contacts are usually maintained for the entire time that the fire pump runs. In other cases, the contacts are momentary to unload the genset enough to start the fire pump but then allow some loads to reconnect to the genset. This scheme may also include delaying the start of the fire pump for up to 10 seconds to allow time for the shed loads to disconnect.
- *Higher short circuit ratings.* All listed controllers are available in higher short circuit ratings on the emergency source side as well as on the normal source side.
- *Emergency side circuit breaker.* Even when not mandatory, this option provides better protection for the fire pump motor. It may also be used in conjunction with higher short circuit ratings on the emergency source side, particularly when used with higher-capacity gensets or on high-capacity emergency bus systems.
- *Other options and modifications.* Other optional equipment or features are available from the various listed controller manufacturers. Oversized transfer switches are sometimes requested for higher reliability and/or higher short circuit ratings. Sometimes transfer switches from a specific manufacturer are specified and supplied to coordinate with other transfer switches used in a facility or building. Also, some transfer switches are supplied with communication ports to allow communication of status information with so-called building automation systems, telemetry systems, or remote monitoring and alarm recording systems. Additional or other nonstandard alarm and signal contacts and/or alarm lights are also available.

Individual Power Transfer Switch and Fire Pump Controllers

Individual power transfer switch and fire pump controller units consist of a listed single-source (nontransfer switch) fire pump controller and a listed fire pump power transfer switch (see Figure 15.7.7). As previously stated, both the transfer switch and fire pump controller must be listed for fire protection service. It should be noted that not all UL-listed transfer switches are listed for fire service.

Much of the section on combination controllers also applies to these separate transfer switches. This section will detail different and/or additional requirements for installations using separate transfer switches. These are also known as upstream transfer switch installations.

Location. The transfer of power to the fire pump controller between the normal supply and the alternate supply must take place within the pump room. Hence, the fire pump transfer switch must be installed in the same pump room or pump house as the fire pump controller to which it is connected.

Number of Switches Required. If alternate power is required for one or more fire pumps, each fire pump controller requires its own dedicated transfer switch. More than one fire pump (controller) cannot be fed from a single transfer switch.

Coordination of Short Circuit Current Ratings. The same considerations regarding short circuit ratings for the combination controller transfer switch also apply to the separate transfer switch. Here, however, neither the manufacturers of the controller nor the transfer switch provide the coordination.

NFPA 20 requires an isolating switch, or service disconnect, where required, ahead of the normal input terminals of the transfer switch. This requirement will be the case for any transfer switch unless the service device, usually a circuit breaker, is supplied as part of the transfer switch and the transfer switch is rated, listed, and labeled as service entrance equipment. If this circuit breaker is not provided, an upstream device must be supplied. It must meet, among other things, the 600 percent rule that requires that any such overcurrent protective device be selected or set to carry indefinitely the sum of the locked rotor current of the fire pump motor plus any additional connected loads. This requirement is a very important limitation to the transfer switch short circuit rating since its size must not exceed the maximum upstream device size qualification of the transfer switch short circuit rating.

With separate transfer switches, this rating will apply to both incoming sides, normal and emergency, unless circuit breakers are supplied as part of the transfer switch. As a result, the coordination may be missing or incorrect. A dangerous and unreliable situation then ensues. For specifics, see NFPA 20 and NFPA 70.

The transfer switch must be sized at 115 percent of the motor FLA current. However, the transfer switch will most likely have to be larger in order to meet the maximum size rating of the upstream circuit breaker (or fuse).

The matter is further complicated by the listed transfer switch manufacturers typically having two or three different short circuit device rating charts. Typical is (1) the any breaker or the any molded case breaker rating, (2) the specific breaker or coordinated breaker ratings, and (3) the fuse category, which is usually of a particular type (class) of fuse.

Coordination of Phase Reversal Switching. The transfer switch is required to switch to emergency power on reversal of

the normal source power. This phase reversal sensing circuitry should be included as part of the transfer switch. Either two such circuits are needed, or else one such circuit should be on the load side of the transfer switch.

Coordination of Alternate Source Isolating Switch. When the alternate power source is a second utility, another upstream service and overcurrent device like the one described previously is required and must also meet the 600 percent sizing rules. Otherwise, for the more typical genset alternate power source installations, an emergency side isolating switch is required. Again, due to cost, such a switch is not standard equipment on all listed fire pump transfer switches. It must either be ordered as an option with the switch or purchased and installed separately. In any case, the switch must meet the following requirements:

- It must be lockable in the "On" position. Note, incidentally, that all listed enclosed isolating or safety switches can be locked in the "Off" position, but not all of them are capable of being locked in the "On" position.
- A placard with large (1.0 in. [25.4 mm]) lettering must be affixed to the outside of this switch reading "Fire Pump Isolating Switch."
- Another placard must be mounted in the pump room "adjacent to the fire pump controller," stating the location of this switch and the location of the key for unlocking it.
- The isolating switch must be supervised to indicate when it is not closed. Four methods are allowed and listed in the standard.
- The supervision must operate an audible and visual (alarm light) on the transfer switch and also at a remote point where required.
- Contacts to interlock with the transfer switch engine start contacts are required to prevent signaling the genset to start if this isolating switch is open.

Alarm Circuits. The transfer switch will usually have at least one set of position-indicating remote alarm contacts as standard. It may or may not have the position-indicating lights as standard. It will not likely have the isolating switch alarm light and contacts unless it is ordered with an isolating switch as part of the transfer switch.

Generator Start Circuit Override. The transfer switch will normally have the engine start contacts as standard equipment. However, it will not normally have the engine start override (lockout) means, unless it is ordered with an isolating switch option. These contacts are needed to prevent undesired and/or unexpected starting of the genset by this transfer switch when the isolating switch (wherever it is located) is opened. Note, however, that other transfer switches can and will start the genset.

Higher-Than-Normal Inrush Currents. A means must be provided to prevent higher-than-normal inrush currents when transferring the fire pump motor from one source to the other. As discussed in the section on combination units, there are currently three methods used for this purpose. The momentary motor shutdown method requires signaling circuitry (contacts) wired from the transfer switch to the fire pump controller, properly equipped, to momentarily shut down the fire pump motor.

Checklist. All the following should be verified for each installation. The following is usually supplied:

- NEMA 2 enclosure as a minimum
- The manual (mechanical) transfer means
- The three normal side voltage sensors
- The alternate side single-phase voltage and frequency sensor (for genset applications)
- The manual (mechanical) transfer means
- The two position indicator lights
- The engine start delay timer and the retransfer delay timer
- The engine start contacts
- The test (transfer) switch (push button)

The following may not be supplied as standard equipment:

- Three-phase voltage sensing on the alternate source side for dual (second) utility jobs
- The normal side service disconnect and overcurrent protection fuses or breaker
- A second service-entrance device for dual-utility jobs
- The emergency side isolating switch
- The ability to lock the emergency side, isolating switch in the "on" position
- An external fire pump isolating switch placard
- A placard next to the controller giving the location of this isolating switch
- Supervision of the isolating switch by one of the four means given
- Contacts to interlock with the engine start contacts
- Audible and visible alarm to indicate isolating switch open
- Isolating switch contacts for remote alarm
- Means to prevent higher-than-normal motor inrush currents
- Phase reversal sensing and transfer circuitry

Finally, the coordination of both the normal source side and the alternate source side short circuit ratings must be performed by someone. This coordination must include (1) any upstream protective device(s), (2) the transfer switch, (3) the fire pump controller, and (4) the available short circuit current. Unfortunately, miscoordination may not be discovered until it is uncovered during an inspection; worse yet, miscoordination may not be discovered even then. Installations that are not coordinated for proper short circuit protection are more likely to be unreliable and unsafe from a personnel and fire hazard standpoint.

SUMMARY

Fire pumps are critical to fire protection systems because they generate the necessary waterflow and pressure needed for fire control and extinguishment. It is especially true where more than one pump must be relied on for proper system operation. Therefore, the components that go into fire pumps are equally important and must be properly designed, installed, and main-

tained. This chapter presented information on fire pump components, specifically on the electric power supply and control aspects of motor-driven fire pump installations.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the fire pump controllers and power supply arrangements for motor-driven fire pumps discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*
NFPA 13E, *Recommended Practice for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems*
NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 22, *Standard for Water Tanks for Private Fire Protection*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 31, *Standard for the Installation of Oil-Burning Equipment*
NFPA 37, *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines*
NFPA 70, *National Electrical Code®*
NFPA 72®, National Fire Alarm Code®
NFPA 110, *Standard for Emergency and Standby Power Systems*

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SECTION 16

Water-Based Fire Suppression Equipment

Christian Dubay

16.1 Principles of Automatic Sprinkler System Performance
16.2 Automatic Sprinklers
16.3 Automatic Sprinkler Systems
16.4 Hanging and Bracing of Water-Based Systems
16.5 Sprinkler Systems for Storage Facilities
16.6 Residential Sprinkler Systems
16.7 Ultra-High-Speed Water Spray Systems
16.8 Water Mist Fire Suppression Systems
16.9 Water Spray Protection
16.10 Standpipe and Hose Systems
16.11 Care and Maintenance of Water-Based Extinguishing Systems

The eleven chapters in Section 16 of the *Fire Protection Handbook*® review water-based fire suppression equipment. Water-based fire suppression was perhaps the first fire protection technology and has evolved to become a widely used mainstay of fire protection.

Chapter 1, "Principles of Automatic Sprinkler System Performance," describes the thermal response, water distribution, and spray cooling characteristics of sprinklers and distinguishes between fire control and fire suppression by sprinklers.

Chapter 2, "Automatic Sprinklers," presents the operating principles, temperature ratings, and water discharge characteristics of automatic sprinklers and describes types of sprinklers. In a similar vein, Chapter 3, "Automatic Sprinkler Systems," covers topics such as system components and materials, installation requirements, and design considerations, as well as plans, calculations, and system acceptance.

Chapter 4, "Hanging and Bracing of Water-Based Systems," considers hangers, hanger installation, earthquake bracing, and joint restraint of underground piping.

Chapter 5, "Sprinkler Systems for Storage Facilities," begins with a discussion of commodity classification and storage arrangement, height, and clearance. It then discusses sprinkler systems and associated design factors unique to storage operations.

Automatic sprinkler systems were first developed for and are still predominantly used in nonresidential occupancies. By contrast, Chapter 6, "Residential Sprinkler Systems," describes specialized technology for residential sprinkler systems, residential sprinkler standards, residential sprinkler experience, and incentives for more widespread use of residential sprinklers.

The section next turns to two highly specialized types of systems. Chapter 7, "Ultra-High-Speed Water Spray Systems," introduces types of systems that are available for explosion protection, including squib-actuated systems, pilot-actuated systems, and portable systems. The use of water mist fire suppression, discussed in Chapter 8, "Water Mist Fire Suppression Systems," came about as a result of requirements for sprinklers on passenger ships and the search for alternatives to ozone-depleting halocarbons. The chapter provides details on the components, types of systems, calculation methods for single and twin fluid systems, pump selection and application of positive displacement pumps, and maintenance issues.

Chapter 9, "Water Spray Protection," covers the uses and applications of water spray systems for fire suppression, control, and extinguishment and describes the components of spray systems and the specialized uses of the systems. The primary distinction between a water spray and a sprinkler system is that of specific coverage versus general area coverage. Water spray systems have typically been provided to protect a specific piece of equipment with surface coverage.

Chapter 10, "Standpipe and Hose Systems," describes design and installation considerations, commissioning, and fire department operations using standpipe systems. Outside hose systems are also reviewed.

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The section concludes with treatment of system inspection and maintenance. Chapter 11, "Care and Maintenance of Water-Based Extinguishing Systems," covers the activities that are central to system reliability. Among other topics, the chapter covers sources of obstruction in sprinkler system pipes and methods for flushing and cleaning them, as well as sprinkler leakage and water damage.

Chapter 1

Principles of Automatic Sprinkler System Performance

Russell P. Fleming

Chapter Contents

Thermal Response of Sprinklers
Water Distribution and Spray Cooling Characteristics of Sprinklers
Interaction of Sprinkler Distribution and Burning Fuel
Fire Control by Sprinklers
Fire Suppression by Sprinklers
Recent Developments

Key Terms

actual delivered density (ADD), automatic sprinkler system, convective heat flow, density/area curve, heat release rate, required delivered density (RDD), spray pattern, sprinkler sensitivity, thermal response, water distribution

Most fire sprinkler systems are designed so that each individual sprinkler can react to heat from a fire, operating to distribute water over the source of that heat. The complex nature of the interaction of fire and sprinklers historically has prevented an analytical approach to sprinkler system design, but today there is a growing appreciation for measuring the performance characteristics of sprinklers and for using those characteristics in new combinations to achieve specific fire protection goals. The characteristics include thermal response, water distribution, and fire suppression and control capability.

This chapter discusses the response, distribution, and fire-extinguishing characteristics of automatic sprinkler systems and the mechanisms by which it is believed that those characteristics work together for successful sprinkler system performance.

See also Section 2, Chapter 7, "Theory of Fire Extinguishment," and other chapters in Section 16, particularly Chapter 2, "Automatic Sprinklers"; and Chapter 6, "Residential Sprinkler Systems."

THERMAL RESPONSE OF SPRINKLERS

Although it is possible to equip sprinkler systems with elaborate detection systems intended to recognize other fire products or signatures, it is heat detection that serves as the basis of sprinkler system response. Therefore, a basic understanding of heat production and movement in a fire is an important first step in an analysis of the way fire sprinkler systems work.

Convective Heat Flow in Fires

Since combustion is an exothermic process, burning fuels produce heat. Even smoldering fires produce heat, although the level of heat can be so low as to be ineffective in actuating thermal detectors. However, smoldering fires generally develop to a flaming stage before producing untenable room conditions. Once the fire reaches the flaming stage, the heat release rate of the fire will grow in a manner related to the nature of the fuel and its arrangement, the ventilation conditions, and other factors.

Heat is released from a fire in several forms: radiation, conduction, and convection. It has been determined that convective heat transfer is most important in activating sprinklers.[1] Convective heat transfer involves heat transfer through a circulating medium, which, in the case of fire sprinklers, is the room air. The air heated by the fire rises in a plume, entraining other room air as it rises. When the plume hits the ceiling, it generally splits to produce a ceiling gas jet (Figure 16.1.1). The thickness of this ceiling jet flow is approximately 5 to 12 percent of the height of the ceiling above the fire source, with the maximum temperature and velocity occurring 1 percent of the distance from

Russell P. Fleming, P.E., is executive vice-president for the National Fire Sprinkler Association, Inc., in Patterson, New York. He has served on more than a dozen different NFPA technical committees, including the Technical Correlating Committee on Automatic Sprinklers.

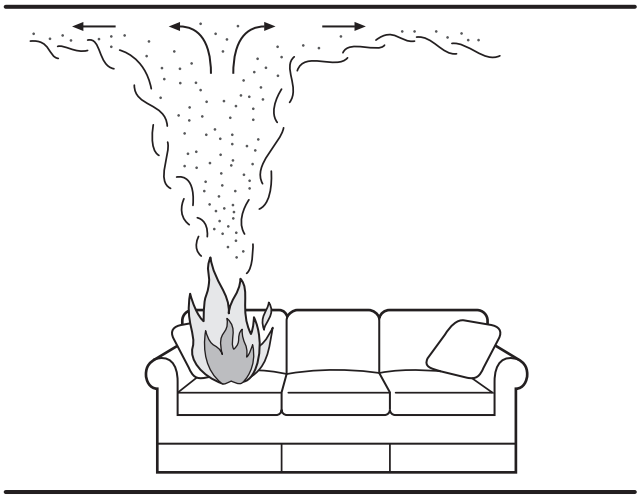


FIGURE 16.1.1 Plume-Ceiling Interaction

the ceiling to the fire source.[2] The heat-sensing elements of sprinklers within this ceiling jet are then heated by conduction of the heat from the air.

Quantifying Sprinkler Sensitivity

Tremendous effort has been made in recent years to quantify the thermal sensitivity of sprinklers and other heat-actuated detectors. This effort is aimed at making it possible to use analytical methods to predict the time of sprinkler response.

Several terms have come into use as part of this process. One is the time constant τ (tau), which is a measure of the thermal sensitivity of a body and is defined as:

$$\tau = \frac{mc}{h_c a}$$

where

m = Mass of the body

c = Specific heat of the body

h_c = Convective heat transfer coefficient

a = Area of the body exposed to gas flow

The time constant has units of seconds but cannot be determined readily for any specific body due to difficulties in estimating the convective heat transfer coefficient. This term varies with the velocity of the gases that pass by the body. As a result, the time constant is measured using a plunge test apparatus, first developed for use with sprinklers in 1976.[3] This apparatus generally consists of a circulating air oven with a known air temperature and velocity (Figure 16.1.2). The air temperature is set well above the nominal operating temperature of the sprinkler. At time $t = 0$, a sprinkler is "plunged" into the heated air. The amount of time it takes for the sprinkler to operate is recorded and is presumed to be the time necessary for the sprinkler operating mechanism to move from room temperature to the nominal operating temperature.

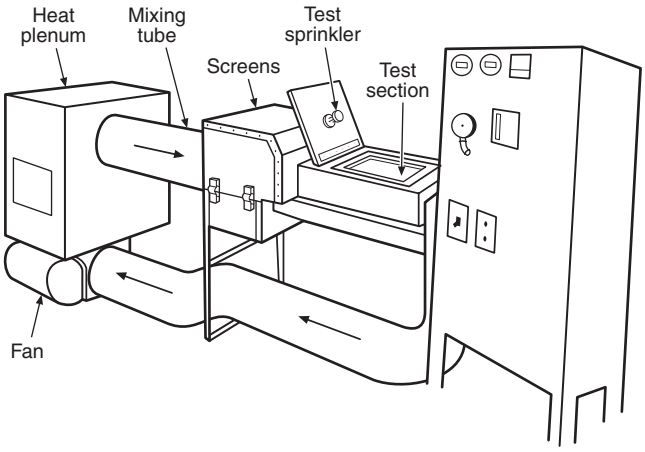


FIGURE 16.1.2 Sprinkler Plunge Test Apparatus

The use of the plunge test permits determination of the time constant, because it provides two data points with regard to the sensitivity of a sprinkler. It is known that the sprinkler was at ambient room temperature, T_a, at $t = 0$, and it is known that the sprinkler reached its nominal operating temperature, T_L, at time $t = t_{act}$, the time of sprinkler activation. Based on the known shape of the curve by which a body takes on or loses heat to its environment, the time constant can be determined. Under plunge test conditions, involving a constant environmental temperature, the time constant is effectively the amount of time that would be needed for the body to move 62.8 percent of the way to the temperature of its heated environment (Figure 16.1.3). In an environment in which the temperature is constantly increasing, the time constant is the amount of time by which the body lags behind its environment after some initial period of time equal to approximately four times the time constant (Figure 16.1.4).

Due to the fact that the time constant varies with the velocity at which it is measured, it is not a particularly useful term. Researchers at Factory Mutual Research Coporation (now FM Global) therefore developed a new term, "response time index" (RTI), as a measure of sprinkler sensitivity independent of velocity.[4] The researchers observed that the convective heat transfer coefficient of blunt bodies in cross-flows was roughly

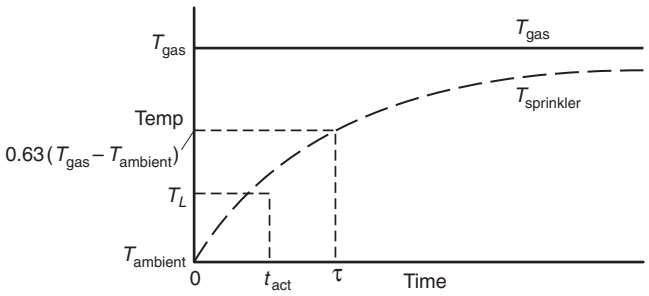


FIGURE 16.1.3 Representation of Time Constant τ for Constant Temperature Condition

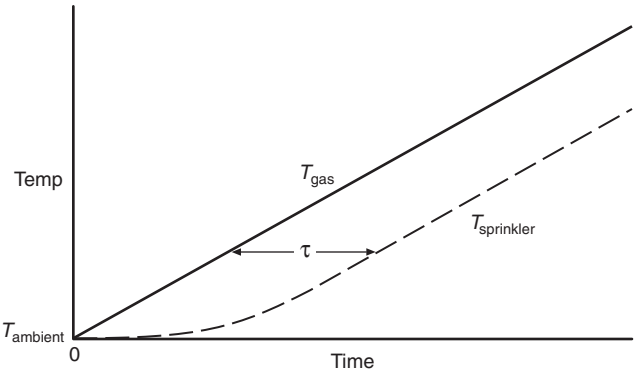


FIGURE 16.1.4 Representation of Time Constant τ for Constantly Increasing Temperature Condition

proportional to the square root of the velocity of those flows. This meant that the time constant is roughly proportional to the inverse of the square root of flow velocity. By multiplying the time constant by the square root of its corresponding velocity, they could eliminate the effects of the convective heat transfer coefficient's dependence on flow velocity:

$$\text{RTI} = \tau u^{1/2} = \text{A constant}$$

It should be noted that, depending on the units of velocity used, the actual units of RTI are either $m^{1/2}sec^{1/2}$ or $ft^{1/2}sec^{1/2}$. U.S. customary RTI values are 1.81 times the equivalent metric RTI values.

Laboratory determination of the RTIs of various devices has permitted the development of computer programs that predict the operating time of heat detectors and sprinklers based on the heat release history of a fire in conjunction with the ceiling height and radial distance of the detector or sprinkler from the fire.[5] These programs must be used with caution, since they represent only a rough correlation to actual conditions. It should also be noted that they are not appropriate for use with sprinklers following the start of water discharge.

The models of sprinkler sensitivity have recently been modified to account for conduction losses from the sprinkler operating mechanism to the sprinkler frame, fittings, and water in the adjacent piping. These new complexities are not taken into account by the original computer models.

The importance of conduction losses was established in 1986 sprinkler industry test work comparing various sprinklers.[6] These tests showed that the apparent RTI of some sprinklers increased at low velocities, particularly for sprinklers with high conductivity between the sprinkler operating mechanism and the sprinkler body. For example, Figure 16.1.5 shows response time indexes as a function of velocity.[6] In Figure 16.1.5, sprinklers D-P and D-S represent specific models of standard pendent and sidewall sprinklers, A and MA represent quick-response, flush-type pendent and sidewall sprinklers, and FR represents a specific quick-response sprinkler model with conventional frame arms.

Although it might seem beneficial to seek to control the conduction effect to maintain a constant RTI, the tests also demonstrated that the phenomenon could be helpful in preventing

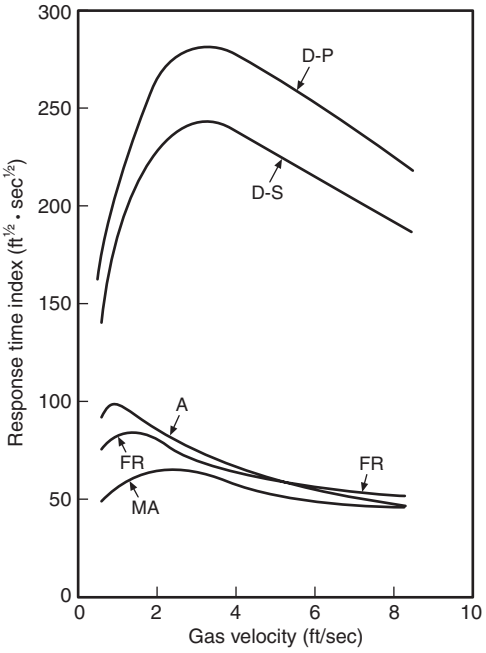


FIGURE 16.1.5 Response Time Indexes as a Function of Velocity (Courtesy of Tyco Fire & Building Products)

excessive sprinkler operations, since velocities tend to decrease with distance from the fire.

Following those tests, the FMRC researchers reviewed the original thermal response model and RTI concept and the plunge test devised for measuring RTI. They then introduced a modified model that incorporated a conductive heat loss factor.[7]

Additional testing using the plunge test apparatus yields a value for *C,* the conductivity factor. For purposes of using computer models to estimate the time of sprinkler activation, a value of "virtual RTI" can be calculated as:

$$\text{RTI}_v = \frac{\text{RTI}}{1 + C/u^{1/2}}$$

The virtual RTI can be used successfully whenever the gas velocity is fairly constant or does not change rapidly with time. With the exception of small turbulent fluctuations, this is usually the case with actual fires.

The revised model assumes that the sprinkler fitting is essentially at ambient temperature and that the conductive heat loss rate is proportional to the temperature rise of the sprinkler operating element. Experimental programs have demonstrated the accuracy of the revised model.

WATER DISTRIBUTION AND SPRAY COOLING CHARACTERISTICS OF SPRINKLERS

Relatively little can be accomplished from a design engineering standpoint with regard to the specific spray patterns produced by sprinklers. The distribution pattern of most types of sprinklers is tested only for overall coverage under specific geometric

conditions. At present, there is no method of predicting the actual amount of water that will be delivered to a specific unit of floor area under actual fire conditions, especially since spray patterns vary with water discharge pressures.

Figure 16.1.6 demonstrates the variability of the spray pattern of a typical pendent spray sprinkler with a nominal orifice coefficient of K = 5.6 (K_m = 80) when discharged under non-fire conditions at selected pressures. A 7 psi (0.5 bar) operating pressure is considered minimum by NFPA 13, *Standard for the Installation of Sprinkler Systems*. At that minimum pressure, the extent of the spray pattern roughly approximates that of the maximum light-hazard spacing permitted by NFPA 13, when the sprinkler is located 8 ft (2.4 m) above the floor. The spray pattern enlarges as the operating pressure is increased to about 70 psi (4.8 bar), then begins to contract at higher pressures, becoming more elliptical in shape at the upper end of the allowable pressure range. Within the wetting area, the water application rates vary considerably, such that the concept of an average density over the coverage area of a sprinkler provides only the roughest approximation of the amount of water that might actually be reaching a particular unit of floor area.

Some studies have been made of individual droplet size and motion. For geometrically similar sprinklers, the median droplet diameter in the sprinkler spray has been found to be inversely proportional to the one-third power of water pressure and directly proportional to the two-thirds power of sprinkler orifice diameter,[8] such that:

$$d_m \propto \frac{D^{2/3}}{\rho^{1/3}} \propto \frac{D^2}{Q^{2/3}}$$

where

d_m = Median droplet diameter

D = Orifice diameter

ρ = Pressure

Q = Rate of waterflow

Total droplet surface area is proportional to the total water discharge rate, divided by the median droplet diameter

$$A_s \propto Q / d_m$$

where A_s is the total droplet surface area.

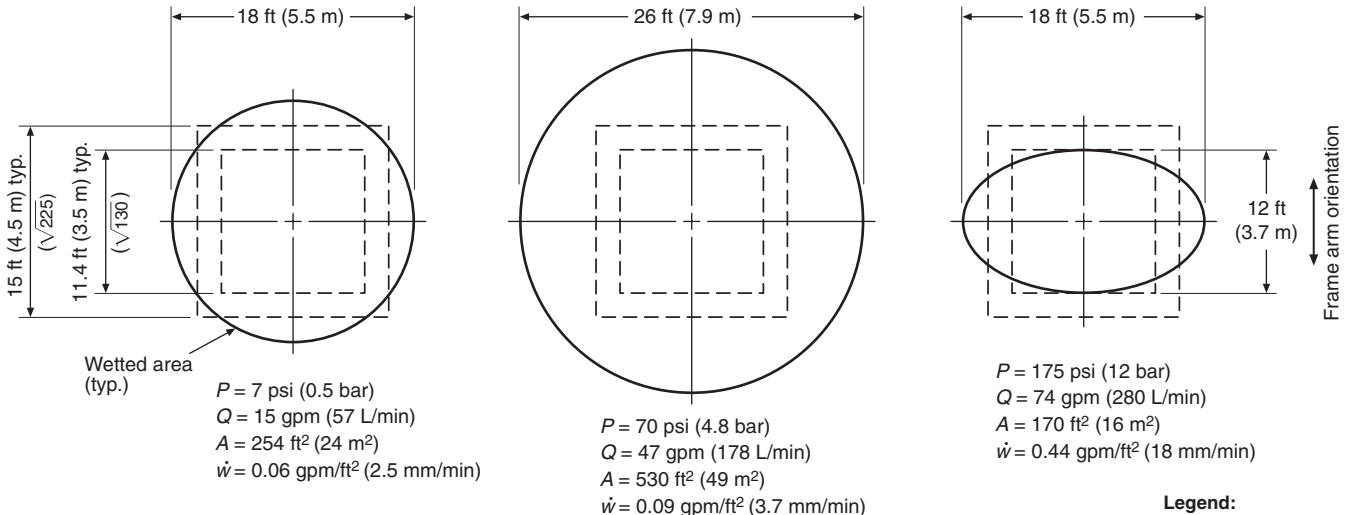
Combining these relationships, it can be seen that:

$$A_s \propto (Q^3 \rho D^{-2})^{1/3}$$

The heat absorption rate of a sprinkler spray can be expected to depend on the total surface area of the water droplets, A_s, and the temperature of the ceiling gas layer in excess of the droplet temperature. The total cooling ability of a sprinkler also depends on the depth of the ceiling jet or smoke layer through which the droplets pass.

INTERACTION OF SPRINKLER DISTRIBUTION AND BURNING FUEL

Sprinklers can be effective against fires in a number of ways. One of the most efficient, in terms of use of water, is simply through the cooling effects of the water spray. The production of a mist of fine water droplets can cause significant cooling, which reduces the radiative feedback to the fire below that which is needed to sustain combustion. In addition, the evaporation of water droplets can produce steam with a volume more than 1700 times that of the water and can deprive the fire of needed oxygen. This combination of "spray cooling" and "smothering," although efficient, has its limitations. It generally works well only if the fire is contained within an unventilated enclosure.[9]



Notes:
1. The sprinkler is mounted 8 ft (2.4 m) above the floor.
2. The smaller dashed square indicates the tributary area of the sprinkler at maximum uniform ordinary-hazard spacing, per NFPA 13.
3. The larger dashed square indicates the tributary area of the sprinkler at maximum uniform light-hazard spacing, per NFPA 13.

Legend:
P = pressure
Q = flow
A = area
$\dot{w}$ = average density over wetted area

FIGURE 16.1.6 Spray Pattern (Floor Level) Versus Discharge Pressure

The greatest efficiency is in the smallest enclosures, since almost all water droplets can be evaporated by contact with enclosing surfaces, and smothering is enhanced.[10]

In 1955, Nash and Rasbash[10] reviewed extensive tests of manual water extinguishment of fully developed room fires and suggested that there is a minimum "critical rate" of water application below which the fire cannot be extinguished. With increased rate of water application above the critical rate, the time needed to control or extinguish the fire falls rapidly. With further increases in the rate of water application, the time to extinguish diminishes more slowly (Figure 16.1.7).[10] Under the best of conditions, fires in model rooms could be extinguished with scanned jets or sprays with about 1 (imperial) gal per 1000 ft^3 (4.5 L/28.4 m^3) of room volume. It was found that a fixed spray with a medium degree of ventilation could extinguish the fire with about 2 (imperial) gal per 1000 ft^3 (9 L/28 m^3) of room volume.

Automatic sprinklers, of course, are expected to operate before total room involvement. To some extent, this makes their job more difficult, since the sprinkler spray is not readily evaporated to steam.

In a large, open, or well-ventilated area, a strong fire can create updrafts that sweep away the small droplets, making them ineffective. For this reason, traditional sprinkler system design is based on the idea of distributing a variety of droplet sizes over the burning fuel area to maintain relatively low ceiling temperatures while controlling or extinguishing the fire.

FIRE CONTROL BY SPRINKLERS

The traditional method by which sprinkler systems control fires currently is being termed the "fire control" approach. This method anticipates that a certain number of sprinklers will be opened surrounding the fire area. Although the sprinklers immediately over the fire may not be able to actually extinguish the fire, they will work with other open sprinklers to cool the atmosphere and to prevent sprinklers outside the general vicinity of the fire from operating. In the meantime, the open sprinklers outside the immediate fire area also can be expected to prewet adjacent combustibles, helping to prevent the spread of fire.

Figure 16.1.8 represents the fire control condition that can be achieved by sprinklers. In this steady-state condition, two separate energy balances must take place. At the level of the fuel, the water reaching the fire must be capable of reducing the burning rate to the point at which, in combination with the prewetting of adjacent combustibles that has taken place, the fire will not spread to additional fuel. Simultaneously, at the ceiling level, the cooling effect of the water spray from open sprinklers must be sufficient to absorb the heat of the fire plume so as to prevent additional sprinklers from operating and to maintain temperatures below those that would result in structural damage to the building.

In the fire control condition, the area over which sprinklers open generally exceeds the maximum area of the fire. The appendix of NFPA 13 provides typical examples of relative sizes of damaged areas of the test array and sprinkler operating areas (Table 16.1.1).

With sprinklers operating in the fire control mode, the central fuel package is eventually depleted and the fire is extinguished. For fire control by sprinklers, the heat release rate of the fire over time can be characterized, as shown in Figure 16.1.9.

Various studies have been made of the water application rate needed to extinguish or control fires in fully ventilated

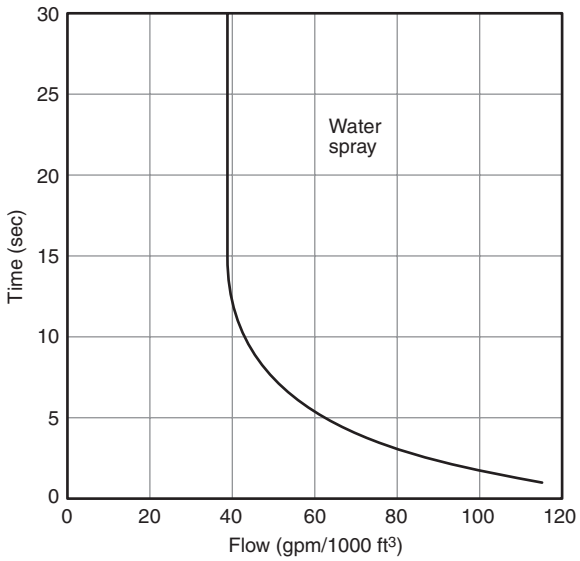


FIGURE 16.1.7 Time to Extinguish Fire in Model Room at Various Flows. For S.I. units: 1 gpm = 3.785 L/min; 1 ft^3 = 0.0283 m^3.

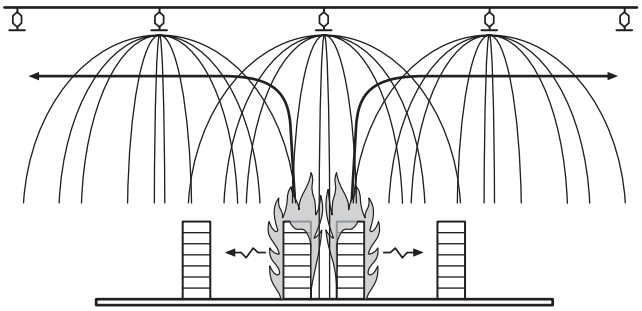


FIGURE 16.1.8 Fire Control by Sprinklers (Conceptual)

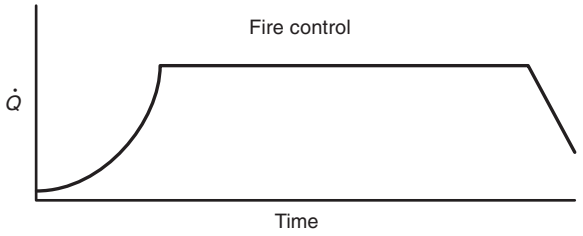


FIGURE 16.1.9 Representation of Fire Control by Sprinklers; Heat Release Rate ($\dot{Q}$) Versus Time

TABLE 16.1.1 Sprinkler Operation in Test Array

Density			Fire Damage in Test Array			Sprinkler Operation Area (165°F) (74°C)	
gpm/ft²	*mm/min*		*Percentage*	*ft²*	*m²*	*ft²*	*m²*
0.30	12.3	(Ceiling only)	22	395	37	4500–4800	420–450
0.375	15.4	(Ceiling only)	17	306	28	1800	167
0.45	18.4	(Ceiling only)	9	162	15	700	65
0.20	8.1	(Ceiling only)	28–36	504–648	47–60	13,100–14,000	1220–1300
0.20	8.1	(Sprinklers at ceiling and in racks)	8	144	13	4100	380
0.30	12.3	(Sprinklers at ceiling and in racks)	7	126	12	700	65

areas, both on simple surfaces and in complex fuel arrangements. The critical rate for wood appears to be between 0.0022 and 0.0044 gpm/ft^2 (0.09 and 0.18 mm/min), increasing to a degree with preburn.[11] For some plastic surfaces, the critical rate appears to be in the range of 0.02 to 0.065 gpm/ft^2 (0.82 and 2.67 mm/min), higher with external radiation.[12] These values are per unit of burning surface area, not floor area, and are determined under laboratory conditions.

For realistic fuel arrangements, the unit surface area of burning combustibles can be many multiples of the unit floor area protected by sprinklers. British fire tests have indicated that, for midsize wood cribs, water applied through impinging jet nozzles at rates less than 0.275 gpm/ft^2 (11.2 mm/min) of unit surface area had little effect on the actual burning zone.[13] The tests also indicated that application rates as low as 0.0625 gpm/ft^2 (2.56 mm/min) of unit surface area were found to be sufficient to limit flame spread within the crib.

Density/Area Curves

The density/area curves that form the basis of standard sprinkler system design can be considered to reflect historical experience with the fire control concept. Although most fires are extinguished or contained by only a few sprinklers, the more troublesome deep-seated fires historically have opened more sprinklers and justifiably have influenced the standards writers. System design criteria must address a reasonably worst-case situation.

The first edition of NFPA 13, published in 1896, contained simple pipe schedules that limited the maximum number of sprinklers that could be fed through each size of pipe. Combined with a minimum supply pressure of 25 psi (1.7 bar) at the highest line of sprinklers, the pipe schedule was expected to adequately provide water to at least 15 sprinklers.

The pipe schedule for sprinkler systems was altered many times, and the concept of different pipe schedules for various "hazards" was instituted with the development of "Class B" (later to become light-hazard) criteria in 1930 and the development of an extra-hazard pipe schedule in 1940.

The use of hydraulic calculation methods for fire sprinkler systems actually started in 1929, with the first formal compilation of Hazen-Williams friction loss tables and other hydraulic data in 1931.[14] NFPA 13 first addressed hydraulic calculations in its 1955 edition, but the use of such calculations was limited essentially to deluge system and water spray applications until the inclusion of density/area criteria in the 1972 edition of the standard. NFPA 231C, *Rack Storage of Materials,* the first standard developed based on fire test data, was adopted in 1971, and 1972 saw the insertion of density/area curves into NFPA 231, *Standard for General Storage,* although basic criteria had appeared as early as 1965. Density/area curves from NFPA 231 and 231C were merged into NFPA 13 beginning with the 1999 edition. The density/area curves in NFPA 13 were modified significantly in 1974 and again in 1991 as part of an overall reorganization and simplification of the standard. As developed in 1974, the curves reflect the hydraulic capability of pipe schedule designs that had proved satisfactory in nearly a century of experience.

The merging of ordinary-hazard groups 2 and 3 in the 1991 edition of NFPA 13 created a system design point of 0.2 gpm/ft^2 (8.1 mm/min) over 1500 ft^2 (135 m^2) for a hazard that could essentially be considered the processing and display of ordinary combustibles. This relates well to the historical development and use of the standard sprinkler system. The 1991 density/area curves are shown in Figure 16.1.10.

The density/area curves have traditionally provided some flexibility in system pipe sizing. Under provisions of NFPA 13, meeting any point on the appropriate curve is acceptable. This permits the use of higher densities over smaller areas or lower densities over larger areas. Higher densities with smaller areas will generally result in larger branch-line piping but lower main sizes and lower overall water supply requirements. For this reason, a high-density, small-area point is often selected as the most economical.

Modifications to the density/area curves have traditionally been made to reflect special conditions. The use of high-temperature sprinklers, where permitted for fast-developing fires, is expected to help limit the area over which sprinklers operate. The delay in water delivery resulting from the use of a dry-pipe system is expected to open additional sprinklers prior to the onset of fire control, necessitating a larger sprinkler design area.

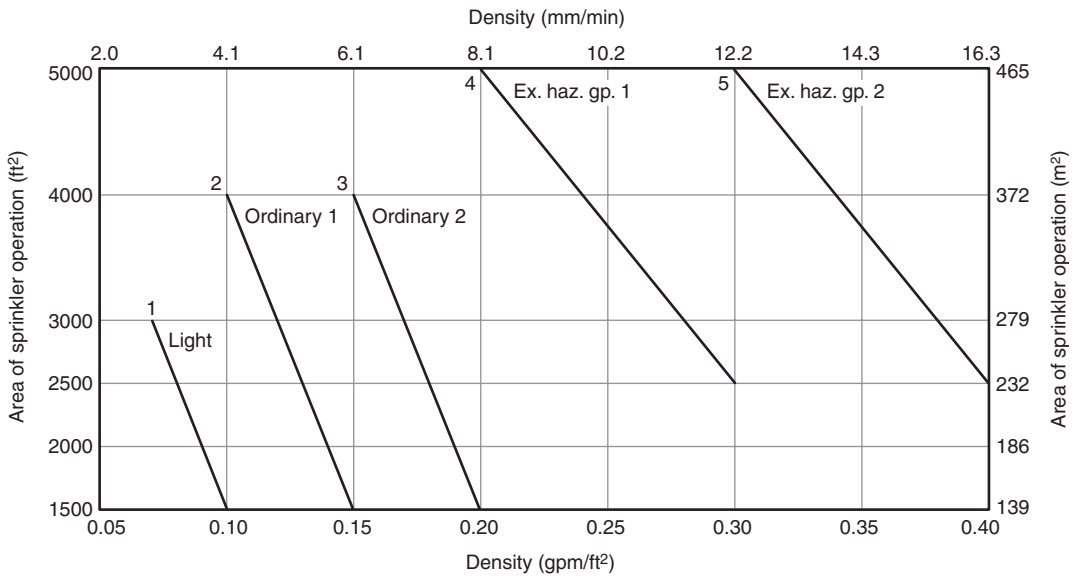


FIGURE 16.1.10 Density/Area Curves

Beginning with the 1996 edition of NFPA 13, a decrease in design area was permitted based on ceiling height with the use of quick-response sprinklers in wet-pipe systems in light and ordinary hazard occupancies. Although the faster actuation of quick-response sprinklers is expected to more quickly establish the conditions for fire control, the real basis for the area reduction is the recognition that ceiling height plays a major role in the fire control performance of sprinklers. Higher ceilings permit fires to grow larger prior to actuation of sprinklers. As far back as 1967, it was found that the size of the fire at the time of sprinkler operation increased with the square of ceiling height when the fire was located directly beneath a sprinkler and linearly with ceiling height when the fire was offset 5 ft (1.5 m) horizontally from the sprinkler.[13] The 1996 edition of NFPA 13 also introduced a corresponding design area increase for ceilings with slopes exceeding 2 in 12, based on modeling studies that showed operating patterns of sprinklers could be irregular under such conditions, causing larger numbers of sprinklers to operate.[15]

Tests conducted in 1998 suggested that fire control of high-challenge storage fires is better achieved through the use of larger orifice sprinklers. When standard orifice sprinklers were used to provide high-application densities, it was theorized that misting of the sprinkler discharge due to the high operating pressures reduced the effectiveness of the water spray in controlling the fire, allowing substantial fire damage despite the operation of few sprinklers.[16] For this reason, beginning with the 1999 edition of NFPA 13, minimum orifice sizes were specified for spray sprinklers protecting general storage, rack storage, rubber tire storage, roll paper storage, and baled cotton storage. For design densities of 0.34 gpm/ft^2 (13.9 mm/min) or less, standard-response sprinklers with a nominal orifice coefficient of K = 8.0 (K_m = 115) or larger must be used. For design densities exceeding 0.34 gpm/ft^2 (13.9 mm/min), standard-response sprinklers with a nominal orifice coefficient of K = 11.2 (K_m = 160) or larger and that are specifically listed for storage applications must be used.

Compartmentation and Fire Control

It has been observed in a number of test programs that walls tend to assist the sprinkler system in the control mode by limiting the number of sprinklers that can operate. If a fire takes place near a wall, the total number of sprinklers that operate will tend to be reduced by the fact that presumed "outer ring" sprinklers are not available on at least one side.

This will tend to conserve water for the operating sprinklers, resulting in higher application rates and earlier achievement of the fire control energy balances. Carried to an extreme, it is the benefit of walls that is recognized in the "room design method" permitted by NFPA 13 as an alternate to the area/density method.

However, one might ask how the same amount of heat can be absorbed by fewer operating sprinklers. In other words, if those fringe sprinklers are not available to operate and absorb some of the heat from the fire plume, doesn't that same heat flow back across the room in the other direction and simply open more sprinklers on the opposite side?

Two factors argue against this. One is that, unless the fire is almost exactly along the wall, it will entrain the same amount of air as a centered fire, producing the same amount of ceiling jet gases. However, the wall will prevent it from breaking into an axisymmetric ceiling jet, and the resulting ceiling jet or smoke layer will be thicker. The thicker smoke layer actually will permit more cooling to take place from the discharge of each sprinkler, since the path of each droplet through the layer is longer.

The other factor is that the spray cooling ability of each sprinkler is enhanced at higher pressures. Cooling depends on droplet surface area, which is increased with flow and with the

production of smaller-diameter droplets, both of which result from higher pressures. With fewer sprinklers operating in the vicinity of the fire, higher water supply pressures are available and more cooling takes place.

FIRE SUPPRESSION BY SPRINKLERS

Recent years have seen the development of new types of sprinklers that purport not only to control a fire but also to actively suppress the fire. To achieve fire suppression, water must be delivered by sprinklers to the burning fuel surface in sufficient quantity to disrupt the combustion process, knocking down the rate of heat release and preventing fire regrowth (Figure 16.1.11). If suppression is achieved at an early stage of the fire, only the sprinklers immediately over the fire area are expected to operate.

For this reason, the term "early suppression" has been developed. Today the term is being used both as the name for a concept and for a particular type of sprinkler. The concept is that fast response of sprinklers can produce an advantage in a fire if the response is accompanied by an effective discharge density—that is, a sprinkler spray capable of fighting its way down through the fire plume in sufficient quantities to suppress the burning fuel package.

The first sprinkler to include the term in its name, the early suppression fast-response (ESFR) sprinkler, was developed to apply the concept to a particular class of fire: protection of high-rack storage of FMRC's standardized plastic commodity, using ceiling sprinklers only. As part of the ESFR development program, FMRC researchers created new terms to investigate and to define the early suppression phenomenon: RDD and ADD.

Required Delivered Density

Required delivered density (RDD) is the minimum rate of water application that, if delivered to the top of the fuel package, is capable of providing early suppression. For the purposes of FMRC's ESFR program, early suppression was, in turn, defined as a sustained knockdown of the fire sufficient to prevent the operation of sprinklers beyond the initial ring.

Specialized test apparatus was developed by FMRC researchers to measure RDD. The apparatus consists of a series of perforated pipes suspended over the burning fuel package that are capable of spreading a fairly uniform water distribution directly over the top of the fuel, such that the water does not have to fight its way down through the fire plume (Figure 16.1.12). The pipes and fuel are all positioned below the fire products collector, a large calorimeter that collects all fire gases and determines the total rate of heat release of the fire as a function of time. The water application is initiated at a time simulating the operation of sprinklers, based on an assumed sprinkler location, sensitivity, and temperature rating. The heat release history generated while the water fights the fire can then be used to predict the operation of sprinklers beyond the first ring, based on their presumed location with respect to the fire.

Figure 16.1.13 shows the results of several RDD tests for a particular fuel package. Suppression can be considered to occur when the heat release rate of the fire is quickly knocked down and is prevented from resurging.

With regard to the standard plastic commodity stored in racks, FMRC confirmed that a relationship existed between RDD and height of storage (Table 16.1.2).

Under the sponsorship of the National Fire Protection Research Foundation, there has been an attempt to extend the early suppression concept to sprinkler protection of ordinary hazards.

Prior freeburn testing had been performed to determine the heat release histories of selected fuel packages. Among the fuel

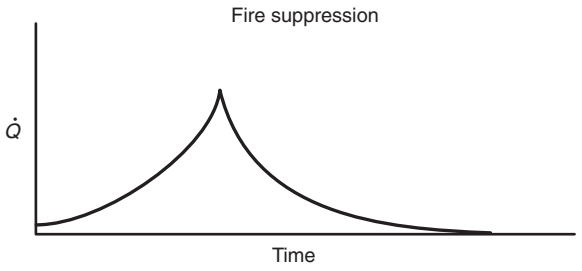


FIGURE 16.1.11 Representation of Fire Suppression by Sprinklers, Heat Release Rate ($\dot{Q}$) Versus Time

FIGURE 16.1.12 RDD Test Apparatus (© 2008 FM Global. Reprinted with permission. All rights reserved.)

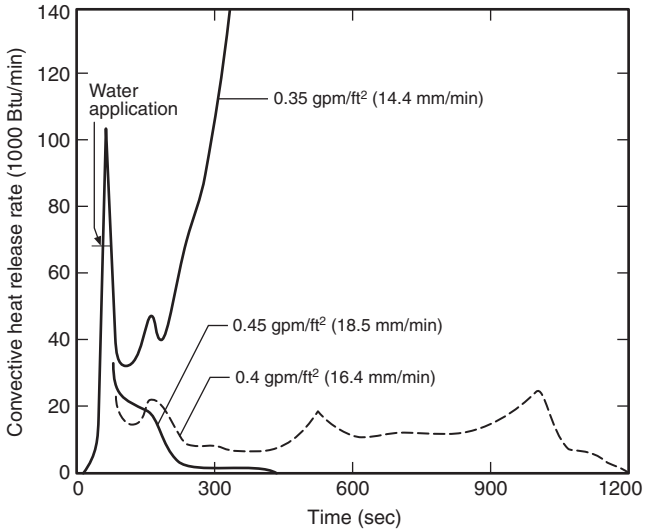


FIGURE 16.1.13 RDD Test Results Using Three Different Water Application Rates (© 2008 FM Global. Reprinted with permission. All rights reserved.)

TABLE 16.1.2 Standard Plastic Commodity—RDD Determination

Fast Response Sprinklers—30 ft (9.1 m) Racks	Storage Height in Racks		RDD Determination	
	ft	*m*	*gpm/ft²*	*mm/min*
3 tiers	15	4.6	0.35	14.4
4 tiers	20	6.1	0.45	18.5
5 tiers	25	7.6	0.65	26.7

packages tested were the upholstered furniture corner scenario used during the development of the residential sprinkler and a 6.7-ft (2.0-m) high storage configuration of the standardized plastic commodity in corrugated cardboard cartons that was used in the ESFR sprinkler program. Nineteen RDD tests were conducted by Underwriters Laboratories Inc. under the foundation's sponsorship to compare the relative suppressibilities of the two different fuel packages.[17,18]

In the freeburn testing, both these fuel packages were found to produce a total heat release history that could be approximated by an "ultrafast *t*-squared" fire, with a maximum heat release rate of about 5 MW. This refers to a standardized curve in which heat release grows proportionally to the square of time (Figure 16.1.14).

The specific water application rates needed to provide early suppression are still under study. However, it was observed clearly that the densities required for suppression of the plastic commodity were considerably higher than those required for the upholstered furniture for the same size fires. The tests conclusively demonstrated that some fuel packages are more easily

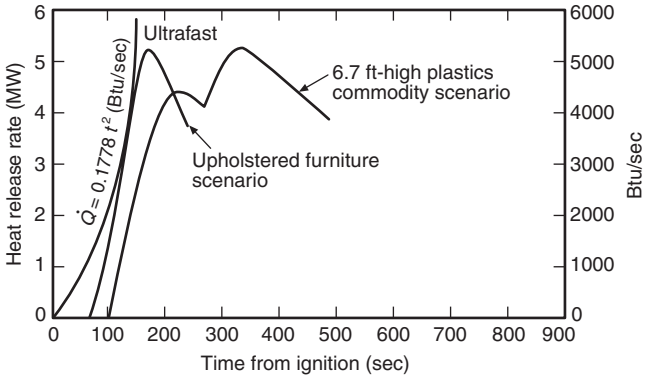


FIGURE 16.1.14 Comparison of Fire Growth Rates for Selected Fuel Packages and the "Ultrafast" t^2 Fire. For SI units: 1 ft = 0.305 m; 1 Btu = 0.055 kJ.

suppressed than others, even if their heat release rate histories appear to be similar.

Actual Delivered Density

Actual delivered density (ADD) is the actual rate of water application that a particular configuration of flowing sprinklers is capable of delivering to the top of a fuel package, depending on the strength of the upward fire plume.

The ADD measuring apparatus consists of a series of collection pans situated over a gas burner (Figure 16.1.15). The 0.5 m^2 pans simulate the top of a storage array and measure the rate at which each such area receives water from any particular configuration of flowing sprinklers. The gas burner is used to produce upward fire plume forces through the simulated flue spaces between the pans. In this manner, the ability of the flowing sprinkler(s) to deliver water to the fuel package can be checked against a wide range of fire strength conditions, simulating different points in the fire history. Typically, ADD decreases as the fire gets larger.

Since the water spray distribution of a sprinkler is not uniform, the collection pans collect different quantities of water during an ADD test. The development of ADD values from test results is accomplished using a probability distribution identified by, and named for, W. Weibull of Sweden. It was first applied to the distribution of liquid droplet sizes in 1951.[19] Using the Weibull distribution, the pan collections of each sprinkler spray acting through a fire plume of a given strength are fitted to a probability curve with a characteristic or average ADD θ and a uniformity value (*b*). The higher the uniformity value, the more likely it is that a characteristic ADD θ higher than the RDD will suppress the fire, since the needed water is being distributed in usable fashion.

The uniformity factor affects the basic shape of the probability distribution curve. Figures 16.1.16 and 16.1.17 indicate the relative effects of changing the scale parameter θ and the uniformity parameter *b* on the frequency distribution of the statistical model. These computer-generated figures demonstrate the superior ability of larger water droplets to penetrate the fire plume when a large fire is located directly below a sprinkler.

FIGURE 16.1.15 ADD Measuring Apparatus for Rack Storage (© 2008 FM Global. Reprinted with permission. All rights reserved.)

The variable x represents any given measurement. Typically, the ADD uniformity values range from about 1 to 7. A uniformity value of infinity would represent a perfectly uniform distribution.

The probability concept can also be applied to RDD data. A uniformity value b can be determined despite the fact that the RDD is measured in a test using the special water applicator intended to provide fairly uniform distribution. A "characteristic" RDD can be calculated as:

$$\theta_{RDD} = \frac{\text{RDD (proposed)}}{(1/b)!}$$

The probability distribution concept can also be used to rank the relative suppression capability of sprinklers. If ADD measurements are taken for three prototype sprinklers under the same fire, spacing, and flow conditions, and values of characteristic ADD and uniformity are found for each, the probability that each sprinkler will meet or exceed the characteristic RDD at any selected point on the fuel surface can be calculated from the relationship:

$$P(\text{ADD} \geq \theta_{RDD}) = \exp\left[-\left(\frac{\theta_{RDD}}{\theta_{ADD}}\right) b^{\text{ADD}}\right]$$

RECENT DEVELOPMENTS

The preceding discussion shows that the present understanding of the theory of fire sprinkler performance is incomplete. For some aspects of sprinkler system performance, such as thermal response and the hydraulics of water delivery, research has led to a good understanding of the mechanisms at work. On the other hand, the science of understanding how the water is dis-

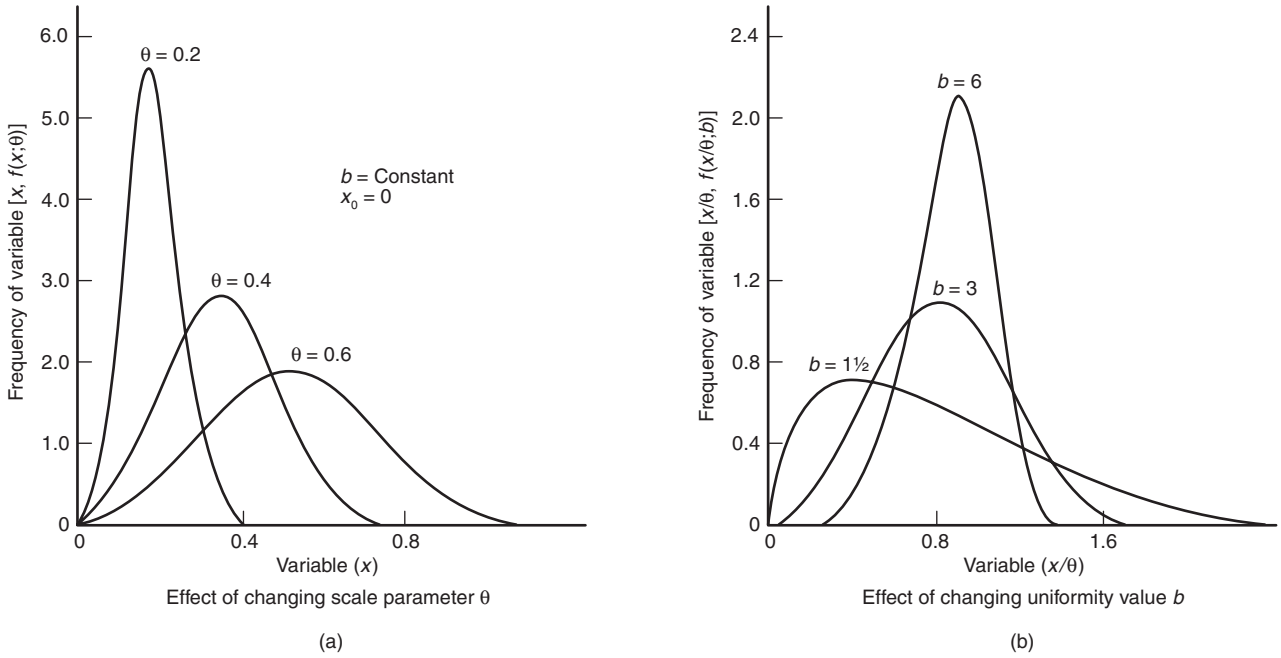


FIGURE 16.1.16 Effect of Changing (a) Scale Parameter θ; (b) Uniformity Value b

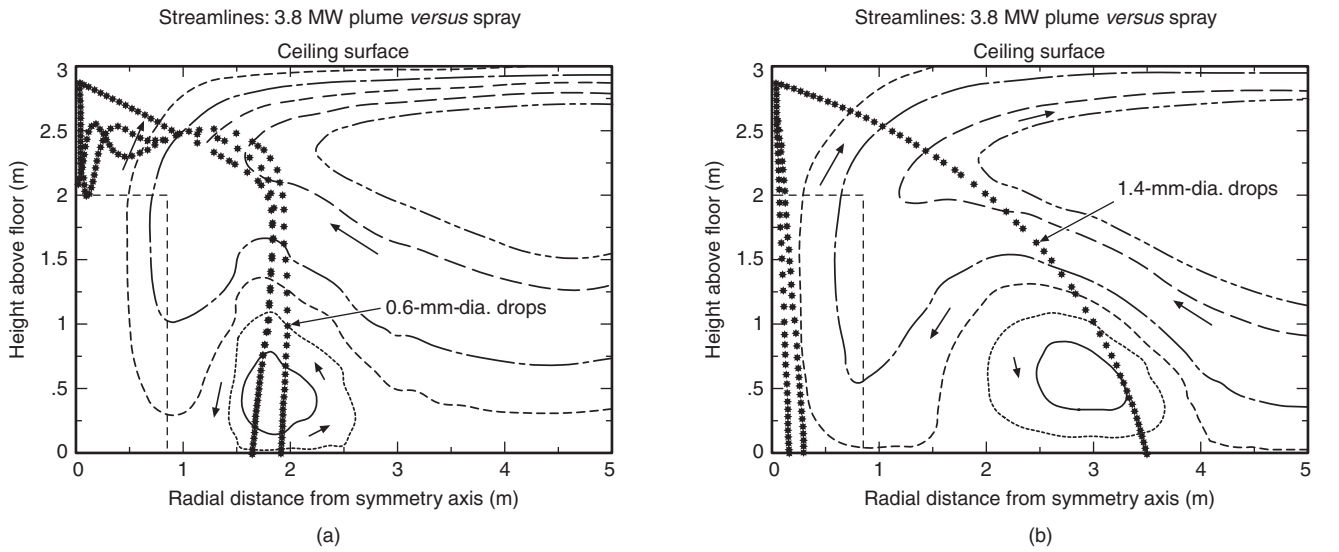


FIGURE 16.1.17 (a) Drops (0.6-mm diameter) Swept Away by the Upward Plume Velocities; (b) 1.4-mm Diameter Drops Following Their Trajectories.[19] For U.S. units: 1 in. = 25.4 mm; 1 ft = 0.305 m.

tributed remains very weak. Almost all the advances made in mathematical modeling of sprinkler performance in the past 25 years deal only with the time up to which the sprinkler starts to put water on the fire.

Research in the 1980s at FMRC, funded partly through the National Institute of Standards and Technology (NIST), began the effort of using computers to analyze the complex interactions between water droplet sprays and the gas flows induced by a building fire.[20] The work was based on very simplified assumptions, with the presumed fire located directly under a single sprinkler producing droplets of uniform size in a few specific directions (see Figure 16.1.17).

Continuing advances in computational fluid dynamics led to NIST efforts to model sprinkler response and suppression as part of a study of the interaction of sprinklers, vents, and draft curtains.[21] The NIST sprinkler/spray interaction model, now part of the Fire Dynamics Simulator, is currently accessible to practitioners through the NIST website at http://www.bfrl.nist.gov. However, potential users should be cautioned that there is still no accepted mechanism for measuring and characterizing sprinkler droplet size and distribution. Until such a mechanism is developed and validated, results of sprinkler system suppression modeling will be considered suspect. Recent work suggests that the suppression modeling problem is made even more difficult by the fact that the presence of water droplets tends to widen the fire plume and slow the upward velocity of the plume.[22]

SUMMARY

Automatic sprinkler systems are an effective means to control fires in enclosed areas, and in recent years models have been developed to perform early fire suppression. Continued improvements in design will require a greater understanding of the scientific principles involved in sprinkler performance. Whereas the thermal response and hydraulic mechanisms of sprinklers are well understood, the properties of water distribution are more complex and difficult to measure. Future advances in the fire suppression and control capability of automatic sprinkler systems will be the result of additional research based on computer analysis.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the principles of automatic sprinkler performance discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™,* 2006 edition
NFPA 13, *Standard for the Installation of Sprinkler Systems*

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Chapter 2

Automatic Sprinklers

Kenneth E. Isman

Chapter Contents

Sprinkler History
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Key Terms

automatic sprinkler system, deflector, early suppression fast response (ESFR) sprinkler, flush-type sprinkler, K-factor, large drop sprinkler, pendent sprinkler, recessed sprinkler, sidewall sprinkler, standard spray sprinkler, upright sprinkler

Automatic sprinklers are thermosensitive devices designed to react at predetermined temperatures by automatically releasing a stream of water and distributing it in specified patterns and quantities over designated areas. The automatic distribution of water is intended to extinguish a fire or to prevent its spread in the event that the initial fire is out of reach of the sprinkler's discharge or is of a type that cannot be extinguished by water discharged from sprinklers. The water is fed to the sprinklers through a system of piping, ordinarily overhead, with the sprinklers placed at intervals along the pipes.

This chapter covers the operating principles, including operating temperatures, of the various types of automatic sprinklers currently available and describes their construction in some detail. Sprinklers for special service conditions are also covered.

The National Fire Protection Association (NFPA) does not have standards that cover the manufacture of sprinklers. However, NFPA does maintain many fire protection standards (most important of which is NFPA 13, *Standard for the Installation of Sprinkler Systems,* hereinafter referred to as NFPA 13) that only allow sprinklers listed by reputable product evaluation organizations to be used in sprinkler systems. Listing of sprinklers in a national organization's listing service is an indication that the sprinklers have been scrutinized for their reliability and compliance with the organization's test criteria for sprinklers.

For related topics, see Section 16, Chapter 1, "Principles of Automatic Sprinkler System Performance"; and Section 16, Chapter 3, "Automatic Sprinkler Systems."

SPRINKLER HISTORY

Since they were introduced in the latter part of the nineteenth century, the performance and reliability of automatic sprinklers have been improved continually through experience and the efforts of manufacturers and testing organizations.

In 1952 and 1953, a new sprinkler was developed with a more efficient umbrella-shaped spray pattern. This "spray sprinkler" became the standard sprinkler in 1958 for use in conformance with NFPA 13; sprinklers of the older design became known as "old-style" or "conventional" sprinklers. Redesign of the deflector was the principal feature of the new standard sprinklers.

Due to the development of many new types of sprinklers during the 1980s, it became questionable whether any single type of sprinkler could be considered standard in the future. As such, the term *spray sprinkler* was brought back into use with the 1991 edition of NFPA 13. This also conforms better to internationally accepted terminology.

OPERATING PRINCIPLES OF AUTOMATIC SPRINKLERS

In order to appreciate the ruggedness, mechanical simplicity, reliability in operation, and freedom from premature operation of an automatic sprinkler, a familiarity with the basic principles of its design, construction, and operation is necessary.

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Operating Elements

Under normal conditions, the discharge of water from an automatic sprinkler is restrained by a cap or valve held tightly against the orifice by a system of levers and links or other releasing devices pressing down on the cap and anchored firmly by struts on the sprinkler.

Fusible Sprinklers. A common fusible-style automatic sprinkler operates when a metal alloy of predetermined melting point fuses. Various combinations of levers, struts, and links or other soldered members are used to reduce the force acting on the solder so that the sprinkler will be held closed with the smallest practical amount of metal and solder. This construction minimizes the time of operation by reducing the mass of fusible metal to be heated.

The solders used with automatic sprinklers are alloys of optimum fusibility composed principally of tin, lead, cadmium, and bismuth; all have sharply defined melting points. Alloys of two or more metals may have a melting point that is lower than that of the individual metal with the lower melting point. The mixture of two or more metals that gives the lowest melting point possible is called a "eutectic" alloy.

Bulb Sprinklers. A second style of operating element uses a frangible bulb (Figure 16.2.1). The small bulb, usually of glass, contains a liquid that does not completely fill the bulb, leaving a small air bubble trapped in it. As heat expands the liquid, the bubble is compressed and finally absorbed by the liquid. Once the bubble disappears, the pressure rises substantially, and the bulb shatters, releasing the valve cap. The exact operating temperature is regulated by adjusting the amount of liquid and the size of the bubble when the bulb is sealed.

Sprinkler Dynamics. Figure 16.2.2 shows how the mechanical force exists in a solder-type link-and-lever-style automatic sprinkler. The construction shown is diagrammatic and does not represent any particular sprinkler.

The mechanical force normally exerted on the top of the cap or valve is many times that developed by the water pressure below, so that the possibility of leakage, even from water hammer or exceptionally high water pressure, is practically

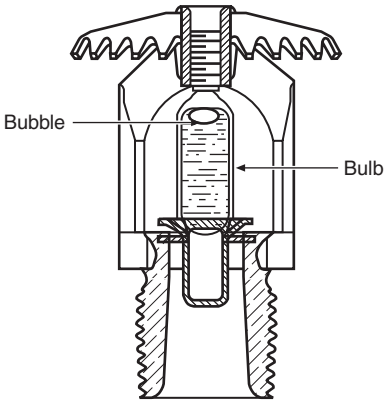


FIGURE 16.2.1 Grinnell Quartzoid, Issue D

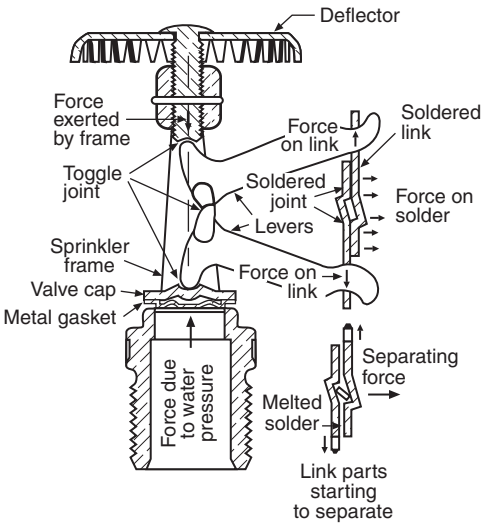


FIGURE 16.2.2 Representative Arrangement of a Solder-Type Link-and-Lever Automatic Sprinkler

eliminated. The mechanical force in a link-and-lever sprinkler is produced by tension in the sprinkler frame, usually created by tightening the screw that holds the deflector down against the toggle joint formed by the levers. This pressure is applied against the valve or cap, but the line of force is not direct. The eccentricity of the loading permits a leveraged reduction of the force, first by the toggle effect of the two levers, and second by the mechanism of the link parts. The force resisted by the solder is made relatively low because solder of the composition needed to give the desired operating temperatures is subject to cold flow under high stress. The sprinkler frame or other parts usually possess a degree of elasticity to provide the energy that produces a positive, sharp release of the operating parts.

Sprinklers illustrated in Figure 16.2.3 use modifications of the common link-and-lever construction, some of which employ solder under compression, tension, and shear.

To ensure that cold flow will not be a problem, the laboratories that test and list sprinklers use statistical methods to simulate long-term loading of heat-responsive elements. Statistical methods are also employed to ensure that the crush strength of glass bulbs is sufficiently higher than the frame loads that will be applied to the bulbs.

Deflector Design

Attached to the frame of the sprinkler is a deflector or distributor against which the stream of water is directed and converted into a spray designed to cover or protect a certain area. The amount of water discharged depends on the flowing water pressure and the size of the sprinkler orifice. A flowing pressure of 7 psi (48 kPa) is generally considered a minimum for development of a reasonable spray pattern. At this pressure, a sprinkler having a nominal ½ in. (12.7 mm) orifice (K = 5.6, or, in metric units, $K_m = 80$) will discharge approximately 15 gpm (58 L/min). (See Spray Sprinklers with Different Orifice Sizes in this chapter for the definition of K-factor.) At the same 7 psi

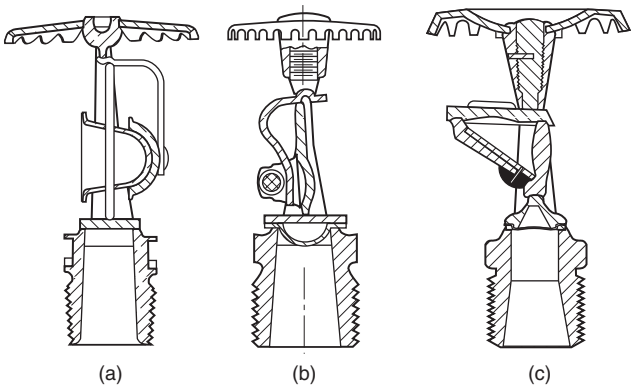


FIGURE 16.2.3 Some Modifications of the Common Link-and-Lever Construction: (a) Grinnell F950 Duraspeed, (b) Reliable Model G, and (c) Firematic Type S

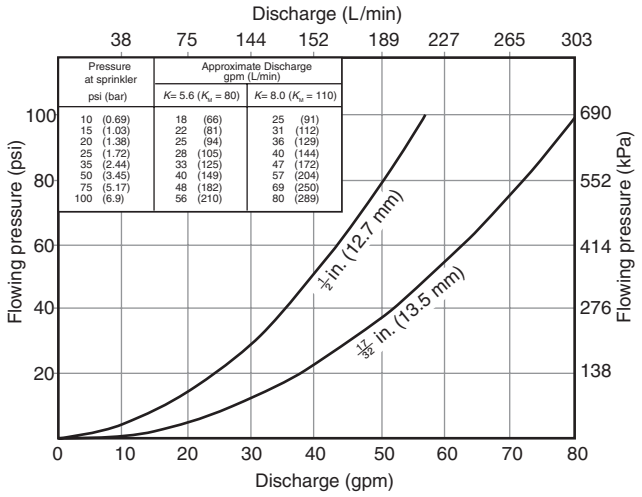


FIGURE 16.2.4 Water Discharge Rates of Typical Nominal K = 5.6 (K_m = 80) and K = 8.0 (K_m = 110) Automatic Sprinklers

(48 kPa) pressure, a nominal 17⁄32 in. (13.5 mm) orifice (K = 8.0, or, in metric units, K_m = 110) sprinkler will discharge approximately 21 gpm (79 L/min). (See Figure 16.2.4 for the quantity of water discharged at various water pressures.)

In order to have even the minimum flowing pressure at sprinklers that are remote from the point of water supply, especially when a number of sprinklers are operating simultaneously, water supply pressures in the range of 30 to 100 psi (316 to 690 kPa) are customarily provided. Hydraulically calculated systems are designed around the normally available water supply volume and pressure.

The distribution of water from a sprinkler is not expected to be axisymmetric, particularly because sprinkler frame arms obstruct the spray pattern and the serrated edges of the deflector create a "fingering" effect. A contour plot of the flow pattern of a pendent spray sprinkler is shown in Figure 16.2.5.[1]

Because the distribution of water from sprinklers is a complex phenomenon, the testing laboratories have fairly broad requirements in this area. For upright and pendent spray sprinklers, for example, Underwriters Laboratories Inc. (UL) requires a turntable test to "fingerprint" the spray pattern. For a sprinkler with an orifice of K = 5.6 (K_m = 80) or K = 8 (K_m = 110), water distribution is not permitted outside a 16-ft (4.9-m) diameter circle in a horizontal plane 4 ft (1.2 m) below the sprinkler when operating at minimum pressure. A separate "16 pan" distribution test checks the ability of four flowing sprinklers to cover the area between them with their overlapping spray patterns. Factory Mutual Research Corporation (FMRC) applies an additional six-sprinkler flow test, which looks at the area covered between two adjacent sprinklers.

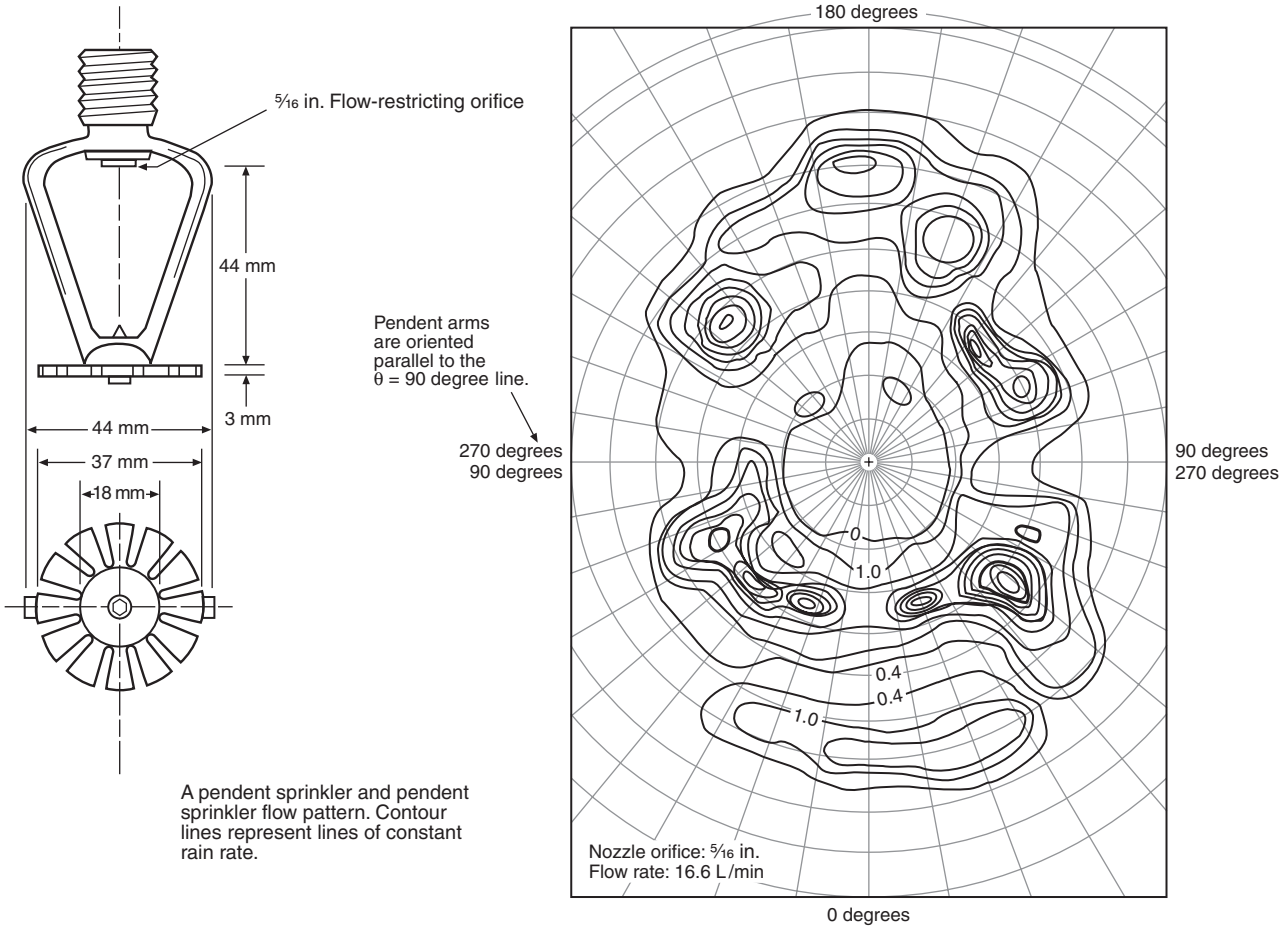
TEMPERATURE RATINGS OF AUTOMATIC SPRINKLERS

Automatic sprinklers have various temperature ratings that are based on the need to make sure that sprinklers do not operate when exposed to natural heat sources that are not a fire (Table 16.2.1). In order to make sure that sprinklers will open at the proper temperature, a sample sprinkler is immersed in a liquid

TABLE 16.2.1 Temperature Ratings, Classifications, and Color Codings

Maximum Ceiling Temperature		Temperature Rating				
°F	*°C*	*°F*	*°C*	*Temperature Classification*	*Color Code*	*Glass Bulb Colors*
100	38	135–170	57–77	Ordinary	Uncolored or black	Orange or red
150	66	175–225	79–107	Intermediate	White	Yellow or green
225	107	250–300	121–149	High	Blue	Blue
300	149	325–375	163–191	Extra high	Red	Purple
375	191	400–475	204–246	Very extra high	Green	Black
475	246	500–575	260–302	Ultra high	Orange	Black
625	329	650	343	Ultra high	Orange	Black

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*



A pendent sprinkler and pendent sprinkler flow pattern. Contour lines represent lines of constant rain rate.

FIGURE 16.2.5 Pendent Spray Sprinkler and Flow Contours

and the temperature of the liquid is raised very slowly until the sprinkler operates.

The temperature rating of all fusible-element-style automatic sprinklers is stamped on the soldered link. For bulb sprinklers, the temperature rating must be stamped or cast on some visible part. Color codes are also used for glass bulbs and for frame arms of fusible-element sprinklers.

The recommended maximum room temperature is restricted for both bulbs and fusible-element sprinklers. This restriction is because solder begins to lose its strength somewhat below its actual melting point. Premature operation of a solder sprinkler usually depends on the extent to which the normal room temperature is exceeded, the duration of the excessive temperature, and the load on the operating parts of the sprinkler. Although glass bulb sprinklers do not lose strength at temperatures close to their operating temperatures, using them at such temperatures can result in continuous loss and reforming of the air bubble, which creates stresses on the bulb.

The general rule of not using sprinklers of ordinary (135 to 170°F [57 to 77°C]) temperature rating where temperatures exceed 100°F (38°C) is necessary to provide a margin of safety. General practices regarding the use of automatic sprinklers of higher than the ordinary rating are given in Tables 16.2.2 and 16.2.3. Sprinklers of ordinary temperature rating can be used inside buildings and other places where they are not subject to direct sun rays, except in monitors and in blind attics without ventilation, under metal or tile roofs, near or above heat sources, or in confined spaces where normal temperatures may be exceeded.

When there is doubt as to maximum temperatures at sprinkler locations, maximum reading thermometers should be used and the temperature determined under conditions that would show the highest readings to be expected.

Sprinklers with high temperature ratings are often used in place of ordinary-rated sprinklers in situations where a high rate of heat release can be anticipated. The sprinklers rated for higher temperatures may have the advantage of reducing the number of sprinklers that would otherwise operate outside the fire area.

Automatic sprinklers may require a longer time period to operate when exposed to a slowly developing fire as opposed to the high heat release of a rapidly developing fire. They are designed to operate quickly enough to control a fire and prevent its spread.

The speed of operation depends on the physical properties of the sprinkler's mechanism. The time involved to operate depends, among other factors, on the shape, size, and mass

TABLE 16.2.2 Temperature Ratings of Sprinklers Based on Distance from Heat Sources

Type of Heat Condition	*Ordinary Degree Rating*	*Intermediate Degree Rating*	*High Degree Rating*
(a) Heating ducts			
1. Above	More than 2 ft 6 in.	2 ft 6 in. or less	
2. Side and below	More than 1 ft 0 in.	1 ft 0 in. or less	
3. Diffuser	Any distance except as shown under Intermediate Degree Rating column	*Downward discharge:* Cylinder with 1 ft 0 in. radius from edge extending 1 ft 0 in. below and 2 ft 6 in. above *Horizontal discharge:* Semicylinder with 2 ft 6 in. radius in direction of flow extending 1 ft 0 in. below and 2 ft 6 in. above	
(b) Unit heater			
1. Horizontal discharge		*Discharge side:* 7 ft 0 in. to 20 ft 0 in. radius pie-shaped cylinder extending 7 ft 0 in. above and 2 ft 0 in. below heater; also 7 ft 0 in. radius cylinder more than 7 ft 0 in. above unit heater	7 ft 0 in. radius cylinder extending 7 ft 0 in. above and 2 ft 0 in. below unit heater
2. Vertical downward discharge		7 ft 0 in. radius cylinder extending upward from an elevation 7 ft 0 in. above unit heater	7 ft 0 in. radius cylinder extending from the top of the unit heater to an elevation 7 ft 0 in. above unit heater
(c) Steam mains (uncovered)			
1. Above	More than 2 ft 6 in.	2 ft 6 in. or less	
2. Side and below	More than 1 ft 0 in.	1 ft 0 in. or less	
3. Blowoff valve	More than 7 ft 0 in.		7 ft 0 in. or less

For SI units: 1 in. = 25.4 mm; 1 ft = 0.305 m.
Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

TABLE 16.2.3 Ratings of Sprinklers in Specified Locations

Location	*Ordinary Degree Rating*	*Intermediate Degree Rating*	*High Degree Rating*
Skylights		Glass or plastic	
Attics	Ventilated	Unventilated	
Peaked roof: metal or thin boards, concealed or not concealed, insulated or uninsulated	Ventilated	Unventilated	
Flat roof: metal, not concealed	Ventilated or unventilated	Note: For uninsulated roof, climate and insulated or uninsulated occupancy can necessitate intermediate sprinklers. Check on job.	
Flat roof: metal, concealed, insulated or uninsulated	Ventilated	Unventilated	
Show windows	Ventilated	Unventilated	

Note: A check of job condition by means of thermometers may be necessary.
Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

of the thermosensitive mechanism; the temperature differential between the surrounding atmosphere and the operating temperature of the sprinkler; and the velocity of the heated fire gases past the sprinkler operating element.

In cases where extreme speed of operation is necessary owing to the likelihood of a rapidly developing and spreading fire as, for example, in explosives manufacturing, the practice is to use deluge systems incorporating open sprinklers. These systems can be activated by heat detectors, special detection systems using infrared or ultraviolet light detection, smoke detection, or other means to open a valve and quickly allow water to enter the system and discharge through the open sprinklers. In cases where extremely fast response is required, the sprinkler piping is prefilled with water up to the open sprinklers, which are equipped with blow-off plugs or caps. This system is sometimes referred to as a "hot" deluge system.

STANDARD SPRAY SPRINKLERS

Standard spray sprinklers are generally similar in appearance to old-style sprinklers and use the same style frame and linkage or other release mechanism. The essential difference is in the deflector; seemingly minor differences in deflector design make major differences in discharge characteristics. Several representative standard spray sprinklers are illustrated in Figure 16.2.6. Clockwise from upper left is a fusible link-and-lever style (Reliable Issue C); a perforated heat-collector style, which is a variation of the link-and-lever style (Grinnell F950 Duraspeed); a center-strut style with solder under compression (Chemetron Stargard Model H); and a frangible-bulb style (Viking Model M).

On the assumption that discharging water against the ceiling was essential to fire extinguishment, early research on automatic sprinklers was largely concerned with securing reasonably uniform distribution of water over the area protected by one sprinkler and with wetting the ceiling. Later research showed that more effective extinguishment and a larger area of coverage could be secured by directing all the water downward and horizontally. Research further showed that, with this pattern, discharge is effective even in controlling fires on the ceiling above the sprinklers because of the improved cooling effect of the spray, better high-level water distribution, and decreased exposure to the ceiling because of more effective direct discharge of water on burning materials below.[2]

The design of the deflector causes the solid stream of water issuing from the orifice of a standard sprinkler to break up to form an umbrella-shaped spray. The pattern is roughly that of a half-sphere filled with spray.

Standard spray sprinklers are made for installation in an upright or pendent position and must be installed in the position for which they are designed. (Note the difference in design of the deflectors shown in Figure 16.2.7.) It is customary to replace old-style sprinklers with spray sprinklers in existing installations, although NFPA 13 permits replacing old-style sprinklers with similar devices. Some manufacturers, however, have discontinued producing old-style sprinklers.

Several manufacturers developed a double deflector as their first design for use as standard spray upright sprinklers. A typical double deflector is shown in Figure 16.2.8. Such sprinklers are no longer manufactured but, if previously listed, are as acceptable as the currently approved upright spray sprinklers with a one-piece deflector.

FIGURE 16.2.6 Standard Spray Sprinklers Showing the Various Arrangements of Releasing Mechanisms

WATER DISCHARGE

The general patterns of water discharge from the old-style and from the standard spray sprinklers are shown in Figures 16.2.9 and 16.2.10, respectively.

FIGURE 16.2.7 Listed Sprinkler Showing Upright (Right) and Pendent (Left) Models of the Same Issue (Reliable Model G)

FIGURE 16.2.8 Standard Upright Spray Sprinkler with Double Deflector

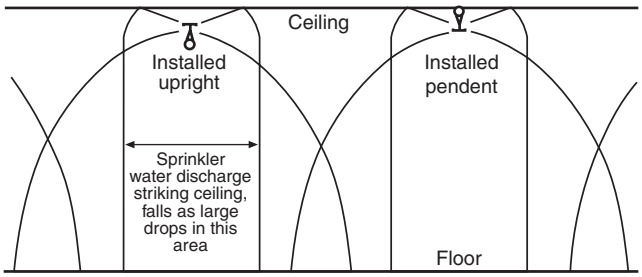


FIGURE 16.2.9 Principal Distribution Pattern of Water from Old-Style/Conventional Sprinklers

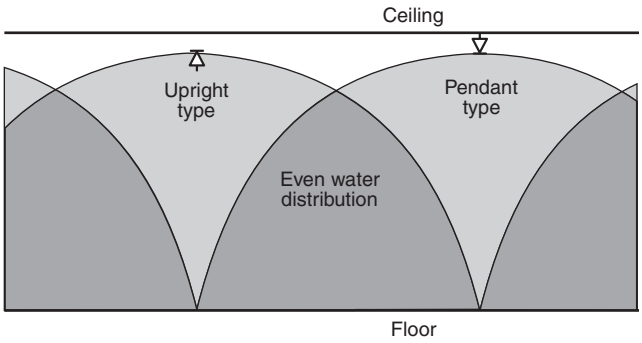


FIGURE 16.2.10 Principal Distribution Pattern of Water from Standard Spray Sprinklers

The water distribution characteristics of sidewall automatic sprinklers, picker trunk sprinklers, window sprinklers, and cornice sprinklers are described later in this chapter. The rate of water discharge from a sprinkler follows hydraulic laws and depends on the size of the orifice or nozzle and on the water pressure. Approximate rates of discharge at different pressures may be obtained from the plotted curve or from the table given in Figure 16.2.4.

Sprinklers discharging water through smaller or larger orifices are discussed later in this chapter. With similar forms of sprinkler nozzles and at the same water pressure, the discharge from these styles of sprinklers is approximately proportional to the nominal size of the orifice.

To obtain acceptance or approval of their sprinklers, manufacturers submit them to fire-testing organizations. After extensive tests and verification of the manufacturer's ability to manufacture the product properly, sprinklers found satisfactory are listed. Acceptance of a sprinkler by inspection departments or other regulatory agencies is based on such a listing.

Standard spray sprinklers are designed to be installed and operated in their proper position—that is, upright or pendent, as sometimes indicated by a stamping on the deflector bearing the appropriate word or the letters SSU (spray sprinkler upright) or SSP (spray sprinkler pendent).

Recessed Sprinklers

A recessed sprinkler is a type of ceiling sprinkler in which part or most of the body of the sprinkler, other than the part that connects to the piping, is mounted in a recessed housing. Its operation is similar to that of a standard pendent sprinkler (Figure 16.2.11).

Flush-Type Sprinklers

A typical flush-style sprinkler is shown in Figure 16.2.12. This style of sprinkler is used where appearance is considered to be

FIGURE 16.10.11 Central Model H Recessed Sprinkler

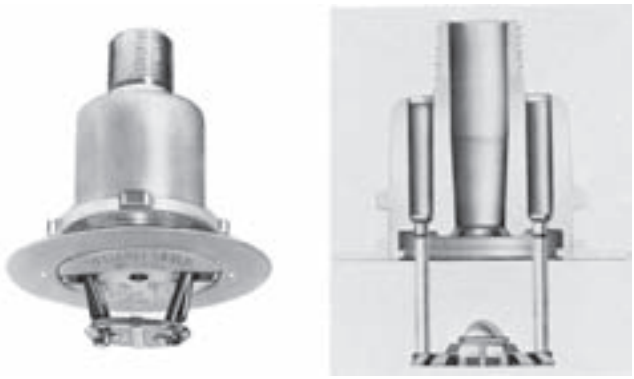


FIGURE 16.2.12 Flush-Style Ceiling Sprinkler (Reliable Model B)

of prime importance. (The diagram at the right shows the sprinkler after operation.) The special design of this type of ceiling sprinkler allows a minimum projection of the working parts of the sprinkler below the ceiling in which it is installed without adversely affecting the heat sensitivity or the pattern of water distribution.

In an effort to provide sprinkler protection in low-risk occupancies where aesthetics are important, sprinklers have been designed that attractively blend with the ceiling. Only the ceiling plate and thermosensitive assembly are visible from the floor when these sprinklers are installed. When a fire occurs and the thermosensitive element operates, the deflector drops to a position below the ceiling and water discharge commences.

Concealed Sprinklers

A concealed sprinkler is a type of ceiling sprinkler whose entire body, including the operating mechanism, is above its concealing cover plate. When a fire occurs, the cover plate drops, exposing the thermosensitive assembly. The subsequent operation of the thermosensitive assembly initiates discharge (Figure 16.2.13).

Ornamental Sprinklers

Ornamental sprinklers are automatic sprinklers that have been decorated by plating or enameling to give desired surface finishes. Ornamentation or special decorative design must not affect the operation or the water distribution unfavorably. Listed styles of ornamental sprinklers are for pendent installation in accordance with NFPA 13 (Figure 16.2.14). Such decorative coatings can be applied only by the manufacturer of the device.

Dry Pendent and Dry Upright Sprinklers

Dry pendent, dry upright, and dry-horizontal-sidewall sprinklers are used to provide sprinkler protection in unheated areas, such as freezers, where individual sprinklers are supplied from a wet-pipe system outside the unheated area. Dry pendent sprinklers must also be used on all dry-pipe systems where it is desirable to install pendent sprinklers.

A seal is provided at the entrance of the dry sprinkler to prevent water from entering until the sprinkler operates. The heat-sensitive operating mechanisms are adaptations of those used with automatic standard sprinklers.

See Figure 16.2.15 for an example of a dry pendent automatic sprinkler. When the ambient temperature rises beyond the operating temperature of the soldered link, the solder melts and the link plates separate on roller key. Levers held in place by a deflector screw are released, and the fixed tension of the frame, acting as a spring, ejects the levers and link parts clear of the sprinkler. Because the inner tube, which also serves as a discharge orifice, is no longer held in place by the levers, it moves to a predetermined position. With the support of the inner tube eliminated, the elements forming the watertight seal at the piping inlet pass through the inner tube and away from the sprinkler, allowing water to flow through the unobstructed waterway and strike the deflector, which distributes it in a spray pattern comparable to that of a ½ in. (12.7 mm) standard sprinkler. Shown is Reliable's Model C Dry Pendent. Other manufacturers have similar arrangements of proprietary equipment for dry-type sprinklers.

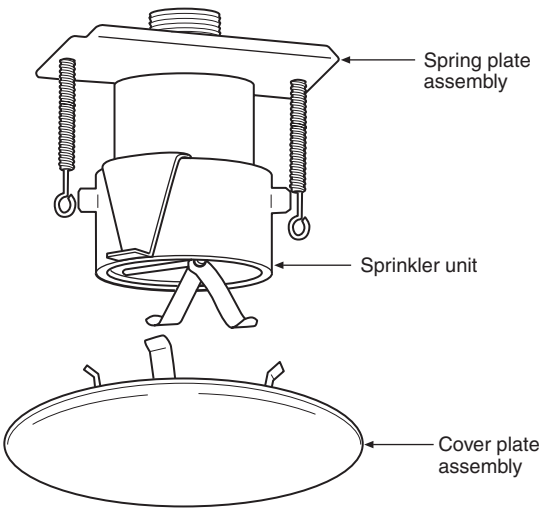


FIGURE 16.2.13 Concealed Ceiling Sprinkler (Stargard Model G)

FIGURE 16.2.14 Prussag SFH Glass-Bulb-Style Decorative Sprinkler

SPRINKLERS FOR SPECIAL SERVICE CONDITIONS

The sprinkler system using listed upright or pendent spray sprinklers is adaptable to a wide variety of conditions. However, there

FIGURE 16.2.15 Representative Dry Pendent Automatic Sprinkler

are situations for which special styles of sprinklers and special sprinkler arrangements are suited. In some cases, such as with sidewall sprinklers, special patterns of water distribution are necessary; in others, unusual ambient temperatures or corrosive atmospheres call for special design or construction features.

Residential Sprinklers

Residential sprinklers are sprinklers that have been specifically listed for use in residential occupancies. These fast-response sprinklers have special low-mass fusible links or bulbs that make the time of temperature actuation much less than that of a sprinkler with a conventional operating element.

Residential sprinklers also have different discharge characteristics than spray sprinklers. They are required to throw water within 18 in. (457 mm) of the ceiling. This high-wall wetting pattern, along with the faster response, helps the residential sprinkler control or suppress typical residential fires with flows much lower than standard spray sprinklers.

Because of the life safety aspects of fast response, these sprinklers can be used in a variety of residential occupancies. Where a conventional system installed according to the provisions of NFPA 13 might not be as practical, such as in a single-family dwelling or a low-rise residential property, NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes,* and NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height,* may be used. These standards have been developed specifically around the life safety capabilities of the residential sprinkler. A representative residential sprinkler is shown in Figure 16.2.16. (Residential sprinkler installations are discussed in detail in Section 16, Chapter 6, "Residential Sprinkler Systems.")

Large Drop Sprinklers

Large drop sprinklers are special sprinklers with a nominal K-factor of 11.2 ($K_m = 160$). (Nominal K-factors for standard ½ in. [12.7 mm] sprinklers are 5.6 [$K_m = 80$].) The deflector of a large drop sprinkler is specially designed and, combined with the greater discharge, produces large drops of such size and velocity as to enable the spray to penetrate strong updrafts generated by high-challenge fires. The special requirements for large drop sprinklers are found throughout NFPA 13 and are organized by subject category. These special requirements supersede the density/area requirements used for standard spray sprinklers. A representative large drop sprinkler is shown in Figure 16.2.17.

On/Off Sprinklers

On/off sprinklers have two separate operating mechanisms. The first is very similar to a standard sprinkler link. The second is a heat-operated valve or snap disk. When a fire occurs, both operating mechanisms sense the rise in temperature and open up. After the environment around the sprinkler cools, the secondary valve or snap disk senses the drop in pressure and automatically closes, stopping the flow of water. If the fire has not been suppressed and grows again, the secondary valve or snap disk reopens allowing water to flow.

Once an on/off sprinkler has activated, it does need to be replaced. The secondary valve or snap disk will not completely seal the valve and may leak. After activation, the sprinkler may also not be able to handle the surge pressures that might occur in the system.

Currently, no manufacturer makes an on/off sprinkler, but they have been described here because they have been manufactured in the past.

Sprinklers for Corrosive Conditions

Measures have been developed to protect automatic sprinklers from corrosive conditions, and testing organizations have studied the value of each method. A complete covering of wax that has a melting point slightly below the temperature at which the sprinkler operates is the protective coating most commonly used. A lead coating for the body of the sprinkler and the levers in combination with wax for protecting fusible elements is also common. Traditional coatings include wax only (Figure 16.2.18), asphalt only, lead only, wax over lead, and asphalt over lead. In recent years, sprinklers have been listed with enamel, polyester, and Teflon® coatings. Stainless steel sprinklers are available from some manufacturers. Other coatings are also available and should be selected on the basis of the expected environment.

Whatever the protective measures taken, they must not delay the operation of the sprinkler, nor interfere with the

FIGURE 16.2.16 Representative Residential Sprinkler

FIGURE 16.2.17 Representative Large Drop Sprinkler

FIGURE 16.2.18 Wax-Coated Upright Sprinkler for Corrosive Atmospheres (Source: Automatic Sprinkler Corporation of America)

FIGURE 16.2.19 Representative Selection of Listed Sidewall Sprinklers Showing Various Shapes of Deflectors

release of operating parts, nor significantly alter the pattern of water distribution. As with decorative sprinklers, these coatings may also be applied only by the manufacturer.

Sidewall Sprinklers

Sidewall sprinklers have the components of standard sprinklers except for a special deflector, which discharges most of the water toward one side in a pattern somewhat resembling one-quarter of a sphere. A small proportion of the discharge wets the wall behind the sprinkler. Located and mounted either vertically or horizontally along the junction between a ceiling and wall, sidewall sprinklers provide protection adequate for light-hazard occupancies, such as hotel lobbies, dining rooms, and executive offices. Some sidewall sprinklers have been tested and listed for use in ordinary-hazard occupancies.

Sidewall sprinklers are generally used where pipe would be difficult to install in a ceiling. This concern might be the case with certain types of ceiling construction or in retrofit situations in which the building owner does not want to disturb asbestos above an existing ceiling. Sidewall sprinklers are also sometimes used where the space above a ceiling is subjected to cold temperatures in order to keep the sprinkler pipe in a heated space in the wall, rather than in the ceiling space where freezing conditions could be encountered.

The directional character of the discharge from sidewall sprinklers makes them applicable to occasional special protection problems. They may be installed to give discharge in any desired direction.

Figure 16.2.19 shows typical sidewall sprinklers. Selection has been made to show the different shapes of a variety of deflectors. Many vertically mounted sidewall sprinklers may be installed in either the pendent or upright position.

Extended Coverage Sidewall Sprinklers

Extended coverage sidewall sprinklers are used in the horizontal position. They have larger areas of coverage than the areas of coverage allowed for standard sidewall sprinklers. They may be used in light-hazard occupancies, particularly in hotels and similar occupancies where a sprinkler system can be installed in an existing building without having piping exposed in living areas, which could be objectionable aesthetically.

The water pressure required to obtain the greater coverage is specified in the listings for the sprinklers and is greater than that required for standard sidewall sprinklers. Installation requirements are also a part of the listing.

An extended coverage sidewall sprinkler with a conventional link release is shown in Figure 16.2.20.

Open Sprinklers

Automatic sprinklers from which the valve cap and heat-responsive elements have been omitted are used in deluge sprinkler systems where the water supply is controlled by an automatic water control valve actuated independently of the automatic sprinklers (Figure 16.2.21). The water distribution pattern and the density of the discharge are designed to be appropriate for the hazard to be protected.

Small- and Large-Orifice Sprinklers

The terms *small orifice* and *large orifice* are used to describe sprinklers with orifice sizes other than ½ in. (K = 5.6). Automatic sprinklers having a water discharge rate greater or less than that of a standard K = 5.6 (K_m = 80) orifice sprinkler operating at the same pressure have characteristics desirable in protecting certain occupancies. High-discharge, large-orifice sprinklers operating at discharge densities of 0.45 gpm/ft^2 (18 [L/min]/m^2) and greater provide a quantity discharge not available from nominal

FIGURE 16.2.20 Representative Extended Coverage Sidewall Sprinkler

FIGURE 16.2.21 Standard Upright Sprinkler with Its Operating Elements Removed

FIGURE 16.2.22 Representative K = 4.2 (K_m = 60) Sprinkler in the Pendent Position

K = 5.6 (K_m = 80) orifice sprinklers. The pattern of the water discharge from small- and large-orifice sprinklers is similar to that of the standard K = 5.6 (K_m = 80) sprinkler.

Whenever sprinklers are replaced, care must be taken to replace them with the proper styles. Replacement of sprinklers with others of the correct orifice size is critical in hydraulically calculated systems.

Spray Sprinklers with Different Orifice Sizes

For many years, sprinklers have been manufactured with different orifice sizes to achieve different flows at available pressures. The smaller the orifice size, the lower the flow that will discharge from the sprinkler when it opens. The characteristic used for measuring the size of the orifice is called the K-factor, and it represents the mathematical constant relating the flow from the sprinkler at the available pressure as indicated in the following formula:

$$Q = K\sqrt{P}$$

where

Q = Flow in gpm (L/min)

K = Flow constant

P = Pressure in psi (bar)

The K-factor is constant for any given sprinkler, only changing with the diameter and shape of the orifice and waterway leading to the point where water gets discharged from the sprinkler. The standard spray sprinkler developed in the late 1950s had a K-factor in English units of 5.6. In metric units, this sprinkler has a K-factor of 80. Sprinklers with K-factors of 5.6 are still very commonly used.

Sprinklers with orifice sizes smaller than the standard K-factor of 5.6 are available when the designer wishes to restrict the flow into a space (Figure 16.2.22). Typically, this happens where a sprinkler protects a relatively small room, where the density can be achieved at a relatively small pressure. NFPA 13 allows the smaller orifice sprinklers to be used in light-hazard occupancies. The K-factors range from K = 1.4 (K_m = 20) to K = 4.2 (K_m = 60). Where the K-factor is less than 2.8 (K_m = 40), a strainer needs to be installed near the water supply to catch the sediment that might plug a sprinkler with a very small orifice.

Table 16.2.4 shows the various orifice sizes for the sprinklers smaller than the standard K = 5.6 (K_m = 80) sprinkler.

Sprinklers with orifice sizes larger than the standard K = 5.6 (K_m = 80) are available when the designer wishes to get larger flows from the sprinkler at the same pressure (Figure 16.2.23). Another way of looking at the advantages of these sprinklers is that the designer can get the required flow from the sprinkler at a lower pressure.

Sprinklers with larger orifice sizes tend to produce better size water droplets with better droplet momentum than K = 5.6 (K_m = 80) orifice size sprinklers. These larger orifice sprinklers are better at fighting high-challenge fires such as those in storage occupancies, where the water droplets from the sprinklers need to overcome the momentum of the fire plume in order to achieve fire control or suppression. For this reason, starting with the 1999 edition of NFPA 13, restrictions on the use of K = 5.6 (K_m = 80) and K = 8.0 (K_m = 110) sprinklers have been put in place. For storage occupancies, the K = 5.6 (K_m = 80) and K = 8.0 (K_m = 110) sprinklers can be used only where the design density necessary for fire control is relatively small. Table 16.2.5 summarizes the various orifice sizes for the sprinklers larger than the standard K = 5.6 (K_m = 80) sprinkler.

TABLE 16.2.4 Orifice Sizes for Sprinklers Smaller Than K = 5.6

Nominal K-Factor gpm/(psi)$^{1/2}$	*Nominal K-Factor L/min/(bar)$^{1/2}$*	*Percentage of Discharge at Same Pressure Compared to K = 5.6 (K_m = 80) Sprinkler*
1.4	20	25.0
1.9	30	33.3
2.8	40	50.0
4.2	60	75.0
5.6	80	100.0

FIGURE 16.2.23 K = 14 (K_m = 200) Spray Sprinkler (Source: Viking Corporation)

TABLE 16.2.5 Orifice Sizes for Sprinklers Larger Than K = 5.6

Nominal K-Factor gpm/(psi)$^{1/2}$	*Nominal K-Factor L/min/(bar)$^{1/2}$*	*Percentage of Discharge at Same Pressure Compared to K = 5.6 (K_m = 80) Sprinkler*
5.6	80	100
8.0	110	140
11.2	160	200
14.0	200	250
16.8	240	300
19.6	280	350
22.4	320	400
25.2	360	450
28.0	400	500

Discharge characteristics of various large- and small-orifice sprinklers are given in Table 16.2.6.

Picker Trunk Sprinklers

Picker trunk automatic sprinklers have a small, smooth deflector that aids in reducing collections of lint and fiber on the sprinklers when they are placed inside ducts or enclosures where moving air carries such foreign materials in suspension. Freedom from obstruction and a general breakup of the water stream are of more importance than any specific pattern of distribution (Figure 16.2.24).

Intermediate-Level Sprinklers

Intermediate-level sprinklers, also referred to as in-rack sprinklers, have large discs (shields) designed to protect the thermosensitive assembly from the spray of sprinklers suspended at higher levels. Without the protective shields, the impinging

FIGURE 16.2.24 Picker Trunk Sprinkler (Source: Tyco Fire & Building Products)

TABLE 16.2.6 Sprinkler Discharge Characteristics Identification

Nominal K-Factor gpm/(psi)$^{1/2}$	*K-Factor Range gpm/(psi)$^{1/2}$*	*K-Factor Range dm^3/min/(kPa)$^{1/2}$*	*Percentage of Nominal K = 5.6 Discharge*	*Thread Type*
1.4	1.3–1.5	1.9–2.2	25.0	½ in. NPT
1.9	1.8–2.0	2.6–2.9	33.3	½ in. NPT
2.8	2.6–2.9	3.8–4.2	50.0	½ in. NPT
4.2	4.0–4.4	5.9–6.4	75.0	½ in. NPT
5.6	5.3–5.8	7.6–8.4	100.0	½ in. NPT
8.0	7.4–8.2	10.7–11.8	140.0	¾ in. NPT or ½ in. NPT
11.2	11.0–11.5	15.9–16.6	200.0	½ in. NPT or ¾ in. NPT
14.0	13.5–14.5	19.5–20.9	250.0	¾ in. NPT
16.8	16.0–17.6	23.1–25.4	300.0	¾ in. NPT
19.6	18.6–20.6	27.2–30.1	350.0	1 in. NPT
22.4	21.3–23.5	31.1–34.3	400.0	1 in. NPT
25.2	23.9–26.5	34.9–38.7	450.0	1 in. NPT
28.0	26.6–29.4	38.9–43.0	500.0	1 in. NPT

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

water could cool the thermosensitive element and retard sprinkler operation. Both upright and pendent intermediate-level sprinklers are listed by testing organizations (Figure 16.2.25).

ESFR Sprinklers

The early suppression fast response (ESFR) sprinkler was developed in the late 1980s and came into widespread use starting in the 1990s for storage occupancies. The ESFR sprinkler was developed to provide fire suppression for high-challenge storage occupancies, usually without the use of in-rack sprinklers. Whereas most sprinklers are designed to provide fire control (and achieve fire suppression as a by-product of good design and extra safety factors), the ESFR sprinkler is designed specifically to provide fire suppression. Although the ESFR sprinkler has many advantages, it does not work for all types of buildings and ceiling construction, so architects and building owners need to make sure that the building and potential obstructions at the ceiling are closely coordinated with the sprinkler installation. Figure 16.2.26 compares an ESFR sprinkler to a standard K = 5.6 (K_m = 80) spray sprinkler.

Specific Application Control Mode Sprinklers

The specific application control mode sprinkler was developed in the beginning of the twenty-first century to provide more effective fire control of high-challenge storage occupancies, usually without in-rack sprinklers. The specific application control mode sprinkler produces good-quality water droplets with high mass and velocity. The combination of mass and velocity creates water droplets with sufficient momentum to penetrate the fire plumes developed by many storage commodities. Although this sprinkler provides improved protection over standard spray sprinklers, it still is considered a control mode sprinkler, meaning it is designed to control the fire, but may achieve suppression in some circumstances. It is not designed to promise suppression in all cases. Being the newest of the sprinklers developed for storage protection, the types of occupancies that can be protected with this sprinkler are constantly changing. Check with the manufacturer to see whether additional approvals have been developed. Figure 16.2.27 shows an example of a specific application control mode sprinkler.

FIGURE 16.2.25 Intermediate-Level (Rack Storage) Sprinklers Showing Integral Shields That Protect Operating Elements from the Discharge of Sprinklers Installed at Higher Levels (Star Model LD)

SUMMARY

The purpose of an automatic sprinkler system is to extinguish a fire or prevent its spread by automatically releasing a stream of water and distributing it over the protected area. The sprinklers

FIGURE 16.2.26 K = 14 (K_m = 200) ESFR Sprinkler (Left) Compared to K = 5.6 (K_m = 80) Standard Spray Sprinkler (Right) (Source: Victaulic® is a registered trademark of Victaulic Company)

FIGURE 16.2.27 Specific Application Control Mode Sprinkler (Source: Tyco International)

are fed water through a system of piping and are triggered by predetermined temperatures. Several different types of sprinkler systems have evolved over the years since their introduction in the latter half of the nineteenth century. The type of automatic sprinkler system installed and the settings used depend on many factors, including the purpose of the building (whether residential or commercial) and aesthetic considerations. As fire protection devices, automatic sprinklers have been found to be rugged, mechanically simple, reliable in operation, and generally free from premature operation.

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2. Thompson, N. J., *Fire Behavior and Sprinklers,* National Fire Protection Association, Quincy, MA, 1964.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on automatic sprinklers discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*
NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*

Chapter 3

Automatic Sprinkler Systems

Revised by
Roland Huggins

Chapter Contents

Development of Automatic Sprinklers
Value of Automatic Sprinkler Protection
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Standards for Installing Sprinklers
System Components and Materials
Installation Rules for Automatic Sprinkler Systems
Design Considerations for Automatic Sprinkler Systems
Plans, Calculations, and System Acceptance
Marine Applications

Key Terms

automatic sprinkler system, ceiling construction, control valve, deluge system, density/area curve, dry pipe system, K-factor, occupancy hazard classification, preaction system, sprinkler spacing, sprinkler system, wet pipe system

The first document published by NFPA, in 1896, provided the initial set of standardized rules for automatic sprinkler systems. The document was awkwardly titled *Rules and Regulations of the National Board of Fire Underwriters for Sprinkler Equipments, Automatic and Open Systems as Recommended by the National Fire Protection Association.* This NFPA document evolved to be NFPA 13, *Standard for the Installation of Sprinkler Systems*.

NFPA 13 provides standardized rules for the design, installation, and acceptance testing of sprinkler systems. Various options are presented for achieving effective sprinkler system performance, including among other considerations the selection of system components such as sprinklers, valves, and piping materials, as well as the determination of the fire hazard to be protected against and the calculation of system discharge rates.

The fundamental principles and assumptions about sprinkler systems have remained fairly consistent over the past century. However, the past 30 years have witnessed significant developments regarding the performance and effectiveness of sprinkler systems in providing life safety and property protection. Although the modern-day version of NFPA 13 is an expansion of the early principles of sprinkler system protection, it includes a much broader scope and addresses the application of many new technologies.

This chapter provides an introduction and overview to the fundamentals of automatic sprinkler systems and describes how the current edition of NFPA 13 has evolved to address a number of situations. The benefits of sprinklers are discussed followed by a review of current rules and practices that are associated with these systems.

Properly designed, installed, and maintained systems are a key element of many fire protection plans integral to modern building design and construction. Suppression, detection, and compartmentation are key safety features that allow buildings of a certain height or area to be constructed. A proper understanding of what sprinkler systems can and cannot do by those designing, installing, and approving such systems is critical to the overall effectiveness of the system.

See also Section 2, Chapter 7, "Theory of Fire Extinguishment"; Section 15, Chapter 1, "Fixed Water Storage Supplies for Fire Protection"; Section 15, Chapter 3, "Hydraulics for Fire Protection"; Section 15, Chapter 6, "Water Distribution"; Section 15, Chapter 7, "Fire Pump Controllers and Power Supply Arrangements for Motor-Driven Fire Pumps"; Section 16, Chapter 1, "Principles of Automatic Sprinkler Performance"; Section 16, Chapter 2, "Automatic Sprinklers"; Section 16, Chapter 5, "Sprinkler Systems for Storage Facilities"; and Section 16, Chapter 6, "Residential Sprinkler Systems."

DEVELOPMENT OF AUTOMATIC SPRINKLERS

A sprinkler is a thermosensitive device that is designed to discharge a certain amount of water in a certain pattern, is only activated when a fire generates a sufficient quantity of heat, and will control or suppress the fire once it has activated. NFPA 13 identifies and defines various types of sprinklers.

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Water is distributed to each sprinkler in the system through a series of specially sized pipes or tubes. Control valves are installed on the system to manually shut off waterflow to all or a portion of the system piping and the sprinklers.

The earliest sprinkler systems consisted of steel pipe networks with drilled holes or perforations provided along the length of pipe. This type of system often involved the use of a manually operated water supply. If the fire occurred when the building was not occupied, the system would be of little or no benefit. Additionally, the piping for these systems was often corroded, the holes were often plugged, and the water discharge from the pipe could generously be described as poor.

A derivative of the perforated pipe involved attachment of an open sprinkler device to the pipe. This improved the water distribution pattern of the system, but concerns with human intervention and corrosion remained.

The concept of employing a heat-actuated device dates back to approximately 1860. However, it was not until 1875 that Henry Parmelee incorporated this concept into a fire sprinkler device. The Parmelee sprinkler is credited as the first "automatic" sprinkler. Although the device was crude when compared to modern sprinklers, it established a specific water distribution pattern that was effective and efficient in controlling a fire. Figure 16.3.1 illustrates the discharge pattern from a Parmelee Number 3 sprinkler. The sprinkler consisted of a brass cap soldered over a perforated distributor and was designed to screw onto a nipple. Figure 16.3.2 shows a cross-sectional view of the Parmelee No. 3 sprinkler.

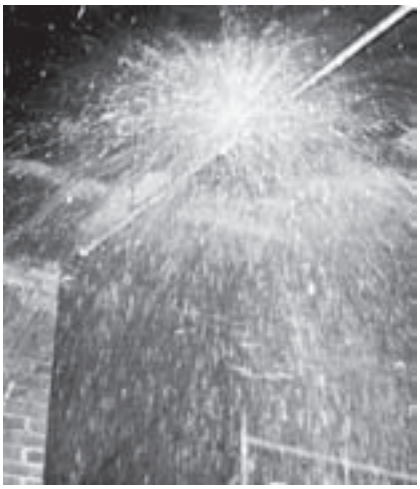


FIGURE 16.3.1 Discharge of an Early Automatic Sprinkler

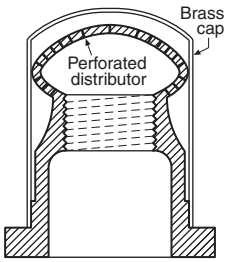


FIGURE 16.3.2 Cross-Sectional View of the Parmelee No. 3 Sprinkler

Other variations of the Parmelee sprinkler soon followed, and each one had a unique shape or form. Some of the sprinklers available when the 1896 edition of NFPA 13 was published include Neracher (Figure 16.3.3), National Manufacturing Company (Figure 16.3.4), New Grinnell (Figure 16.3.5), and Kane (Figure 16.3.6).

The introduction of these new automatic sprinkler devices that did not require human intervention to initiate waterflow prompted greater acceptance and use of sprinkler systems for factories and storage facilities.

VALUE OF AUTOMATIC SPRINKLER PROTECTION

The insurance industry in combination with the Industrial Revolution in the United States can be credited for promulgating and

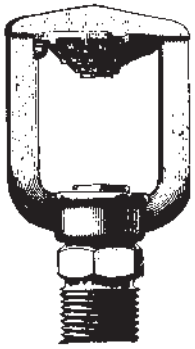


FIGURE 16.3.3 Neracher Sprinkler

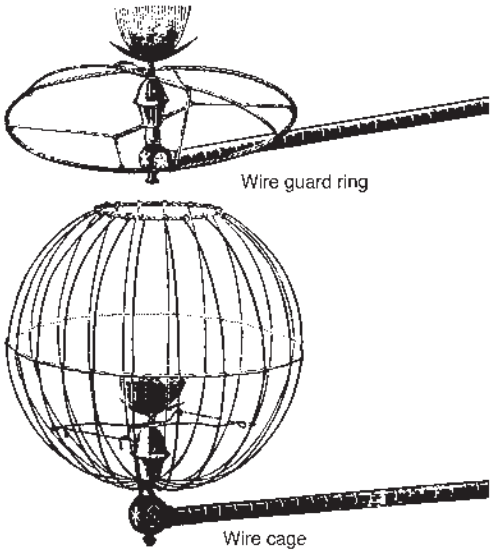


FIGURE 16.3.4 National Manufacturing Company Sprinkler

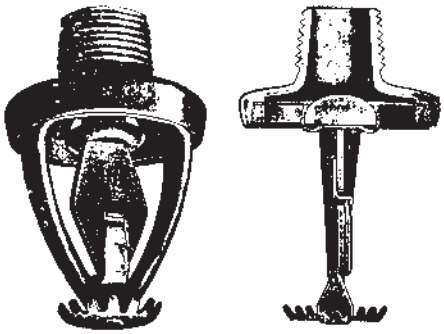


FIGURE 16.3.5 New Grinnell Sprinkler

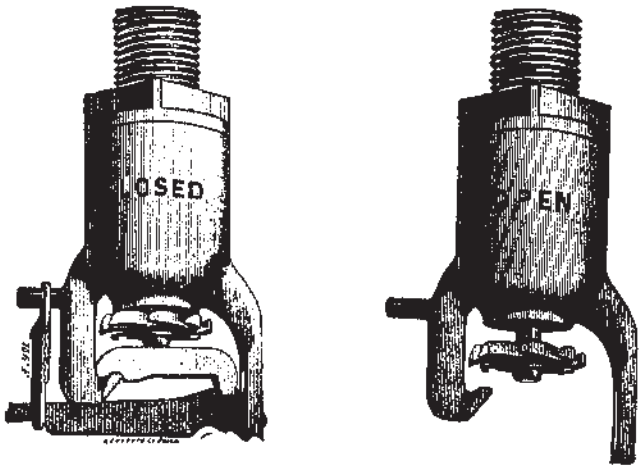


FIGURE 16.3.6 Kane Sprinkler

expanding the use of sprinkler systems. Initial system use was justified by the acute reduction in property loss that was evident in fires involving sprinkler systems when compared to those fire events in which no sprinkler systems were installed.

Because of their immediate recognition as greatly improving property protection risks, high-value facilities such as warehouses and industrial manufacturing facilities were particularly high-priority settings for protection by automatic sprinkler systems. This distinction could even mean the difference between a company staying in business versus not being able to recover from a fire and going out of business.

Although sprinklers were not immediately recognized for their life safety benefits, a trend indicating reductions in fire-related deaths in which sprinkler systems were present became apparent. Large-area, high-rise, high-value, and dense population structures soon became primary facilities where sprinkler systems would be of benefit.

Life Safety Benefits

The life safety benefit of sprinklers is intuitive since sprinkler discharge suppresses or controls a fire, thereby diminishing the threat to the occupants. Additionally, the operation of the sprinkler system sounds an alarm, warning building occupants of a fire condition. Although early sprinkler system designs focused primarily on property protection, the systems did improve the overall life safety features of the building. Current technology provides for numerous types of systems, some of which specifically focus on life safety with property protection as a secondary objective. The residential sprinkler system falls into this category. Section 16, Chapter 6, "Residential Sprinkler Systems," provides information on the development of the residential sprinkler. Although limited to residential occupancies, since its introduction to the marketplace in 1980, the application of the residential sprinkler has been expanded from use in single-family homes to high-rise occupancies such as hotels and apartments. NFPA *101*®, *Life Safety Code*®, and other building codes recognize the life safety benefits of sprinkler systems. Extended travel distances, reductions in rated wall assemblies, and interior finish materials with higher flame-spread ratings are permitted when sprinklers are present. NFPA *101* also mandates sprinkler systems in buildings that fit the high-rise category, as well as those buildings where evacuation of the occupants is impractical, such as health care facilities and some types of nursing homes.

Up until 1970, NFPA maintained a database on the performance and effectiveness of sprinkler systems. Unfortunately, collection of this type of information was discontinued when the data became skewed toward those instances in which large numbers of sprinklers tended to operate or in which the dollar losses were quite large. Such data appeared to indicate that sprinklers were only of marginal value and were not as effective as they actually were. Although substantial dollar losses can occur because of fires in sprinklered buildings, these large losses in sprinklered buildings represent a small percentage of overall fire losses. Furthermore, the majority of devastating fires in sprinklered buildings can usually be attributed to some type of human error, such as failure to maintain the system, rather than a mechanical failure of the system itself.

Even the skewed data, however, showed that a substantial number of fires in sprinklered buildings are controlled or even extinguished with the operation of only one or two sprinklers. Many more of these sprinkler successes control fires with such minimal damage that they are not reported to a fire department or insurance company. It is hoped another data collection program can be instituted in the future with the widespread use of central station alarm systems and the fact that most of today's sprinkler systems are equipped with some type of automatic alarm feature. However, at the time of this writing no formal efforts have been initiated.

Data Sources

Other data sources exist that provide some perspective on the number of sprinklers that operate in certain types of fires. The fewer the number of sprinklers that operate, the more likely that the fire is controlled by the sprinkler system. As previously indicated, the data suggest that a small number of sprinklers tend to control most fires.

NFPA's Fire Analysis and Research Division produces an annual report entitled *U.S. Experience with Sprinklers and Other Fire Extinguishing Equipment.* Table 16.3.1, based on Table 6 of that report, provides information on the number of

TABLE 16.3.1 Number of Sprinklers Operating in Structure Fires Where Sprinklers Were Present and Operated, 1999–2002 Structure Fires (Excluding Confined Fires) Reported in NFIRS Version 5.0 to U.S. Fire Departments

A. By Type of Sprinkler System

Number of Sprinklers Operating	*Wet Pipe (%)*	*Dry Pipe (%)*	*Other Type Sprinkler (%)*
1	65	41	55
2 or fewer	81	56	72
3 or fewer	88	65	83
4 or fewer	91	73	92
5 or fewer	93	77	92
6 or fewer	94	80	96
7 or fewer	95	80	100
8 or fewer	95	82	100
9 or fewer	96	83	100
10 or fewer	97	86	100

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Wet pipe systems outnumbered dry pipe systems 7 to 1. Wet pipe systems outnumbered "other type sprinkler" systems by nearly 30 to 1. However, 38 percent of the incidents had type of sprinkler system unreported. Percentages are based on fires where sprinklers were reported present and operating and there was reported information on number of sprinklers operating.

Source: Rohr, K., *U.S. Experience with Sprinklers and Other Fire Extinguishing Equipment,* Table 6, National Fire Protection Association, Quincy, MA, Aug. 2005.

sprinklers operating in structure fires. The report discusses the benefits of automatic sprinklers and provides comparisons of fires in sprinklered and nonsprinklered buildings.

One of the most compelling points made in the NFPA report is the life safety benefits of sprinkler systems. The following statements are taken directly from the 2005 report:

> NFPA has no record of a fire killing more than two people in a completely sprinklered building where the system was properly operating, except in an explosion or flash fire or where industrial fire brigade members or employees were killed during fire suppression operations.

Another statement that is directed at specific occupancies indicates that:

> NFPA has no record of a fire killing more than two people in a completely sprinklered public assembly, educational, institutional, or residential building where the system was properly operating.

The Fire Analysis and Research report indicates that when fatalities do occur in sprinklered buildings, the victims tend to be in close proximity to the fire or intimate with ignition. In other cases, the victim was incapacitated or otherwise incapable of self-preservation.

The "Fire Watch" column in the *NFPA Journal* usually summarizes one or two stories about sprinkler system performance during a fire. In addition, the information collection process through the National Fire Incident Reporting System (NFIRS), NFPA's data collection survey, and insurance summaries all indicate that sprinklers are a very effective means to reduce fire fatalities and damage. The Fire Analysis and Research report summarizes these data as indicating that sprinklers reduce the chances of dying if fire occurs and the average property damage per fire by one-third to two-thirds.

Because of their effectiveness, various building codes, insurance regulations, and local laws require sprinkler systems in numerous types of buildings. If properly designed, installed, and maintained, sprinkler systems remain among the best options for providing cost-effective life safety and property protection.

FINANCIAL IMPLICATIONS OF SPRINKLER SYSTEM INSTALLATIONS

A number of devastating fires have been investigated by NFPA over the years. In nearly every one of these incidents, findings indicate that the lack of a properly functioning automatic sprinkler system was a key factor in the accelerated rate of fire growth and spread.

When a fire occurs, a certain degree of damage to building contents and the building are expected. These property losses are tangible and can be measured in direct financial terms. However, a somewhat less tangible impact of a fire can be business interruption, which not only affects the business owner and the long-term viability of the enterprise but also the employees and local community. Catastrophic losses to large employers deteriorate the local tax base affecting community services.

Another undesirable outcome of a fire in financial terms can be impending lawsuits in which litigation expenses and judgments can be severe and, when they occur, can exceed other combined direct and indirect losses. This is especially true when a loss of life has occurred. Financial aspects of lawsuits, although typically not a key consideration to most building owners or business owners, can devastate a company, its employees, and ultimately the local community.

Automatic sprinkler systems are designed to operate during the early stages of fire development and minimize the fire's overall impact. In addition, most systems are provided with an electrically supervised waterflow alarm that can automatically notify the fire department when the sprinkler system operates. Although many systems will suppress or even extinguish a fire, it is anticipated that in most cases the fire department or fire brigade will completely extinguish a fire.

Contrary to some Hollywood portrayals and public perceptions of sprinkler system activation in which all sprinklers in a building appear to operate at once, only those sprinklers that are in close proximity to the fire will operate. As previously shown in Table 16.3.1, a relatively small number of sprinklers tend to operate in most fires. Because only those sprinklers near a fire operate, considerably less water damage occurs during a fire when a sprinkler system is present. Where sprinkler systems are not present, fire damage and the magnitude of damage from

master streams and other fire-fighting operations are typically more extensive, often considerably.

Nonetheless, water damage and inadvertent system discharge often concern building owners. Reports that cite collateral water damage as larger than the fire damage encourage a misleading comparison. For instance, some news accounts have been selectively prepared, indicating that the fire damage was limited to $1000 whereas the collateral water damage from sprinklers was perhaps $1500. No mention is made about the total value of the contents and the building; no mention is made about no one being injured; and no mention is made of the fatalities that did not occur.

Although inadvertent discharge of water from system piping, valves, or a sprinkler is rare, it can occur. To minimize this possibility, NFPA 13 controls system components to ensure integrity of the system. In addition, NFPA 13 governs a number of methods and techniques that help to protect against such problems. Quality control of installation practices and procedures is also an important consideration. Special materials and methods are specified for use in corrosive atmospheres, areas subject to freezing, and for systems installed in areas requiring seismic protection.

Some Incentives for Sprinklers

The major incentive for installing sprinkler systems can be directed toward the system's inherent highly effective and cost-efficient life safety and property protection features. However, direct financial benefits can also be realized by property owners. Many insurance carriers offer reduced premiums for fully sprinklered facilities. In addition, the cost of sprinkler system design and installation can often be amortized over the life of the building.

Although sprinkler systems are mandatory in many types of buildings, most building codes permit certain construction modifications when systems are installed. These modifications include increases to building heights and areas, reductions to fire-resistance ratings for partitions, and reductions in physical separations between adjacent structures. These changes often offset the cost of the sprinkler system.

Installing sprinkler systems in existing buildings also greatly improves overall fire and life safety and offsets previous fire protection concerns. Although installing sprinklers after building construction has been completed is more costly, laws mandating sprinkler systems on a retroactive basis usually allow for the installation to be phased over time. This permits building owners to coordinate the installation with other building upgrades and renovations.

STANDARDS FOR INSTALLING SPRINKLERS

NFPA 13, *Standard for the Installation of Sprinkler Systems,* is the principal document that addresses the design and installation of sprinkler systems. Although considered by some to be a variation of a plumbing system, they are not. Sprinkler systems are unique systems requiring specialized knowledge for their proper design, installation, and maintenance.

NFPA 13 is categorized as a standard and, therefore, specifies the rules and other information necessary for the proper design, layout, and installation of sprinkler systems. NFPA 13 does not specify the types of facilities or buildings in which sprinkler systems are required. This requirement is addressed by building codes, NFPA *101,* and other regulations.

In 1999, NFPA 13 underwent a major expansion and restructuring. Although still containing requirements concerning water supply, allowable materials and components, sprinkler placement and location, discharge criteria, working plans and calculation procedures, the document's scope has been greatly expanded to include sprinkler system information from over 40 other NFPA codes and standards. This extracted information, though, is still controlled by the original technical committee and is simply copied in NFPA 13.

Effective with the 1999 edition, all requirements pertaining to the design and installation of automatic sprinkler systems were, to the extent possible, centralized in NFPA 13. The scope of NFPA 13 was expanded to include sprinkler system design and installation requirements for storage facilities, formerly located in the NFPA 231 series of documents (NFPA 231 was titled *Standard for General Storage*). The design and installation requirements for underground piping and private fire service mains from NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances,* were also included.

The 1999 edition incorporated sprinkler system information copied from other NFPA standards to assist NFPA 13 users with the design and installation of automatic sprinkler systems for hazards and facilities not previously addressed by NFPA 13. Sprinkler system information from over 40 NFPA codes, standards, and recommended practices is cited in NFPA 13. For example, sprinkler system information specific to solvent extraction plans, laboratories using chemicals, and fixed guideway transit systems, among others, are included. The 2002 edition improved the ability to find this extracted information by incorporating it into one chapter. NFPA 13 continues to expand and refine criteria. Another change made in the 2002 edition was a restructuring of the hanging and bracing chapter. Restructuring continued into the 2007 edition where the presentation of the storage criteria was divided into nine chapters.

A number of assumptions have been employed in the writing of NFPA 13 to achieve an acceptable level of life safety and property protection while maintaining costs. For instance, the standard anticipates a single fire source, that is, no multiple ignitions in the building while the sprinkler system is operating. Nor does NFPA 13 address the likelihood of a fire occurring in one space area as opposed to another area. NFPA 13 treats the likelihood of a fire occurring in any given space on an equal footing regardless of the actual probabilities of ignition. For these reasons, the fundamental design principal that only a certain number of operating sprinklers are needed to control a given fire exists. In other words, it is only those sprinklers in the general vicinity of the fire that are expected to operate and discharge water.

A fundamental premise about buildings also serves as a basis for NFPA 13 criteria. Effective system design is a direct function of the building contents and the fire hazard associated with the contents. Building construction materials do not impact

the assigned discharge density. For example, a building of concrete construction does not receive any special preference when compared to a building of wood construction. The use and associated hazard of the contents of the building need to receive primary consideration when initiating a sprinkler system design. The structure does play a significant role in defining the type of allowed sprinklers, the minimum area of coverage, minimum starting pressure, and other installation criteria. For instance, an attic is a light-hazard occupancy but the area of coverage can be as low as 120 ft^2 (11.1 m^2) instead of the possible 400 ft^2 (37.2 m^2), as well as having a minimum starting pressure of 20 psi (1.4 bar) instead of the usual 7 psi (0.5 bar).

Although NFPA 13 serves as the primary resource for sprinkler system design and installation around the world, other documents also address sprinkler systems. Many of these documents fall within NFPA's fire codes set and address sprinkler system protection for specific hazards, building uses, and safety objectives. For example, NFPA 30, *Flammable and Combustible Liquids Code,* addresses the storage of flammable and combustible liquids; NFPA 851, *Recommended Practice for Fire Protection for Hydroelectric Generating Plants,* addresses hydroelectric generating plants; and NFPA *101* addresses the use of a sprinkler system solely for life safety purposes. Starting with the 1999 edition of NFPA 13, other NFPA documents that deal with sprinkler system design and installation are specifically referenced. In addition to NFPA's documents, local and national building codes may also address sprinkler system design and installation to some degree. Other nations and some insurance companies also maintain their own sprinkler system rules.

Terminology

Because of the complexity associated with the various aspects of sprinkler system design and installation, NFPA 13 defines various terms to establish a degree of consistency and uniformity. Some of the more prevalent terms are paraphrased here.

The most fundamental term, *sprinkler system,* is described as a combination of underground and overhead piping that is connected to an automatic water supply. The piping is specially sized or hydraulically designed with that portion of the piping within the building generally located overhead. Sprinklers are attached to the overhead piping in a systematic pattern and a valve controlling each riser is located either directly on the system riser or in the supply piping. The system is usually activated by heat from a fire and discharges water over the fire area. A device actuating an alarm when the system operates is located on the system riser. Figure 16.3.7 illustrates various aboveground and buried components that can comprise a fire sprinkler system. Note that the rules addressing fire pumps and water storage tanks can be found in NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection,* and NFPA 22, *Standard for Water Tanks for Private Fire Protection,* respectively. The criteria from NFPA 24 is repeated in NFPA 13.

System Types

Most sprinkler systems fall within one of four categories. These include (1) wet pipe, (2) dry pipe, (3) preaction, and (4) deluge with the wet pipe being the most common. The need to use one type of system rather than another depends on the environmental conditions in which the system will be used and the nature of the space being protected.

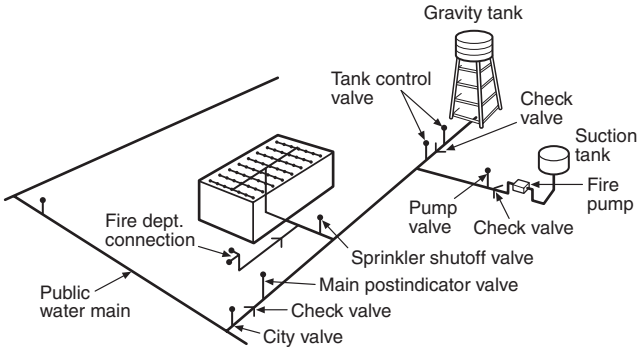


FIGURE 16.3.7 Hypothetical Sprinkler System Installation Illustrating Various Water Supply Sources and System Attachments

Wet Pipe System. This type of system is the preferred, most reliable option. It is also the easiest to design and install and the simplest to maintain. Wet pipe systems contain water under pressure at all times and utilize a series of closed sprinklers. When a fire occurs and produces a sufficient amount of heat to activate one or more sprinklers, because an automatic water supply is mandated, water immediately discharges from the open sprinklers. Wet pipe systems should be the first choice of designers and installers because they are more inherently reliable and less costly to maintain. However, wet pipe systems should not be considered when temperatures to which the system could be exposed fall below 40°F (4°C). Figure 16.3.8 illustrates a basic wet pipe system.

Dry Pipe System. These systems should only be used when system components will be exposed to temperatures below 40°F (4°C). System piping contains no water prior to system activation but rather is charged with air or nitrogen under pressure. These systems experience more internal corrosion than a wet pipe system due to moisture in the air and constant replenishment of oxygen. A dry pipe valve holds back the water supply and serves as the water/air interface. Most listed dry pipe valves act on a pressure differential principle, in which the surface area of the valve face on the air side is greater than the surface area on the water side. Figure 16.3.9 shows a typical dry pipe valve. There are also many dry pipe valves that use a latching mechanism and a pressure differential.

If a fire occurs and a sufficient amount of heat is generated, one or more sprinklers operate, causing system air pressure to drop. Once the air pressure falls below a predetermined level, the dry pipe valve opens, allowing water to flow through the system to the open sprinklers. Dry pipe systems are more complex than wet pipe systems. They require a reliable air supply source and, because of the delay associated with water delivery from

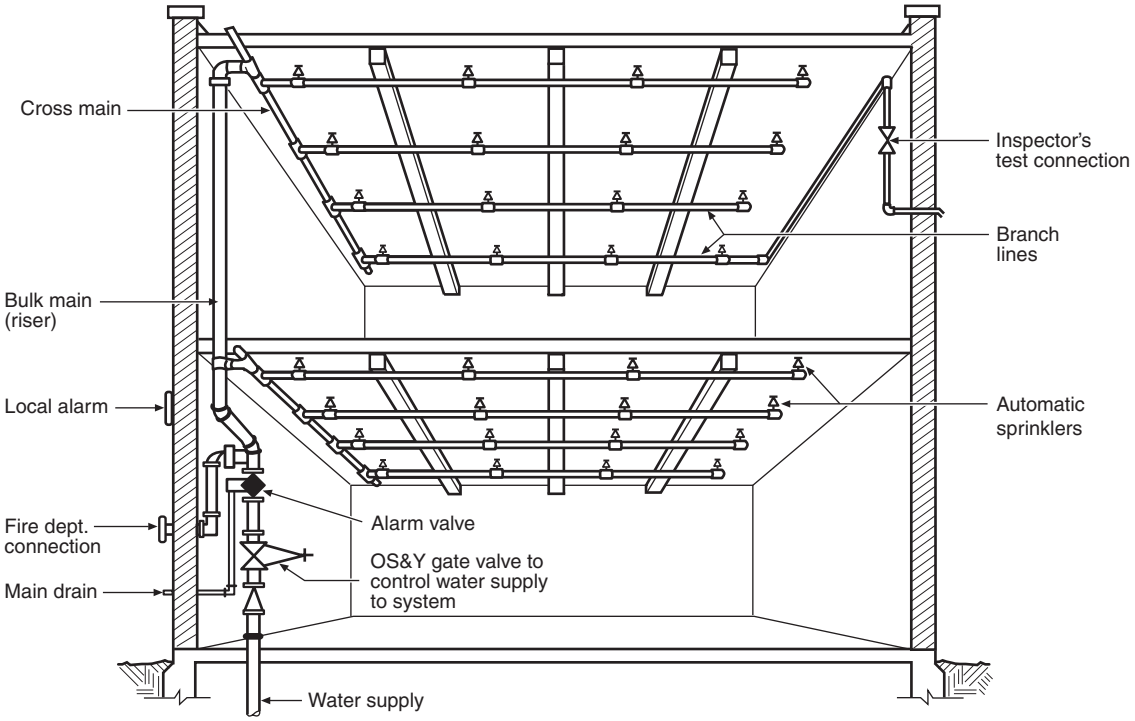


FIGURE 16.3.8 Basic Components of a Wet Pipe Sprinkler System

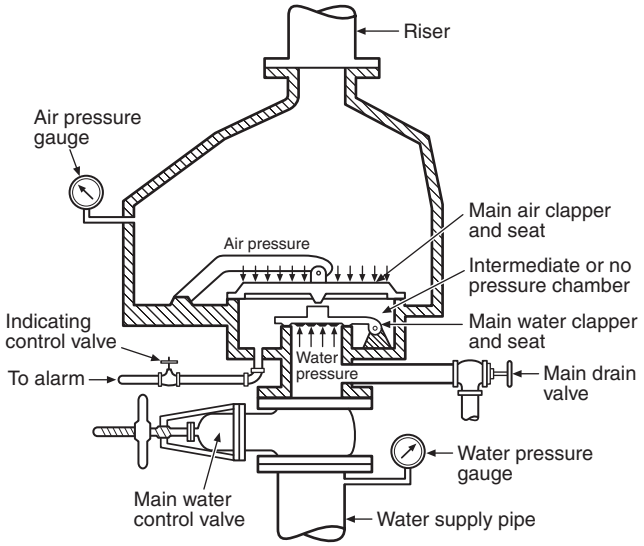


FIGURE 16.3.9 Typical Dry Pipe Valve

the dry pipe valve to the open sprinklers, are subject to certain design limitations. These limitations can include restriction of system size, the need for additional components such as accelerators, and the need for a larger design area due to an increase in the number of anticipated operating sprinklers.

In addition to serving as stand-alone systems, dry pipe systems can comprise a subsystem of a larger wet pipe system in which small coolers and loading docks need to be protected. Figure 16.3.10 illustrates a hypothetical dry pipe system.

Preaction System. Similar to a dry pipe system, a standard or single-interlock preaction system piping is charged with air under pressure rather than water. However, the air pressure associated with preaction systems is generally less than that for dry pipe systems. It also experiences a greater amount of internal corrosion. The water supply is held back by means of a preaction valve. The system is equipped with a supplemental detection system. Operation of the detection system allows the preaction valve to automatically open and admit water into the pipe network. Water will not discharge from the system until a fire has generated a sufficient quantity of heat to cause operation of one or more sprinklers. In essence, the system appears as a wet pipe system once the preaction valve operates. Figure 16.3.11 shows a typical preaction system.

Air pressure maintained in the piping is used to monitor the integrity of the pipe. If the pipe develops a leak, the air pressure will drop and an alarm will sound, indicating a low air-pressure condition. Because water is held back with a preaction valve rather than a dry pipe valve, water will not flow into the system until the supplemental fire detection system operates, signaling the preaction valve to open. The preaction valve stays in its normal position until the detection system is activated.

A variation of the single-interlock preaction system is the double-interlock preaction system. The double-interlock system has characteristics of both the single-interlock system and the dry pipe system. For water to enter the system piping both the

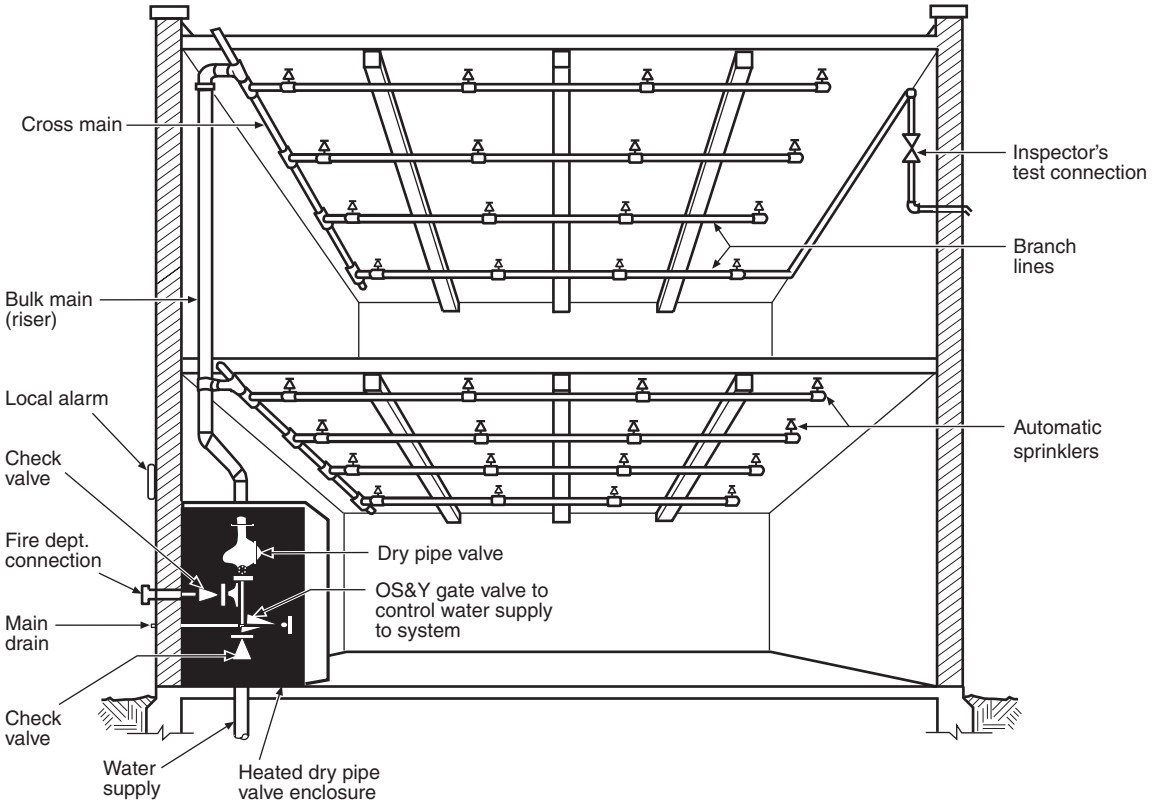


FIGURE 16.3.10 Hypothetical Dry Pipe System

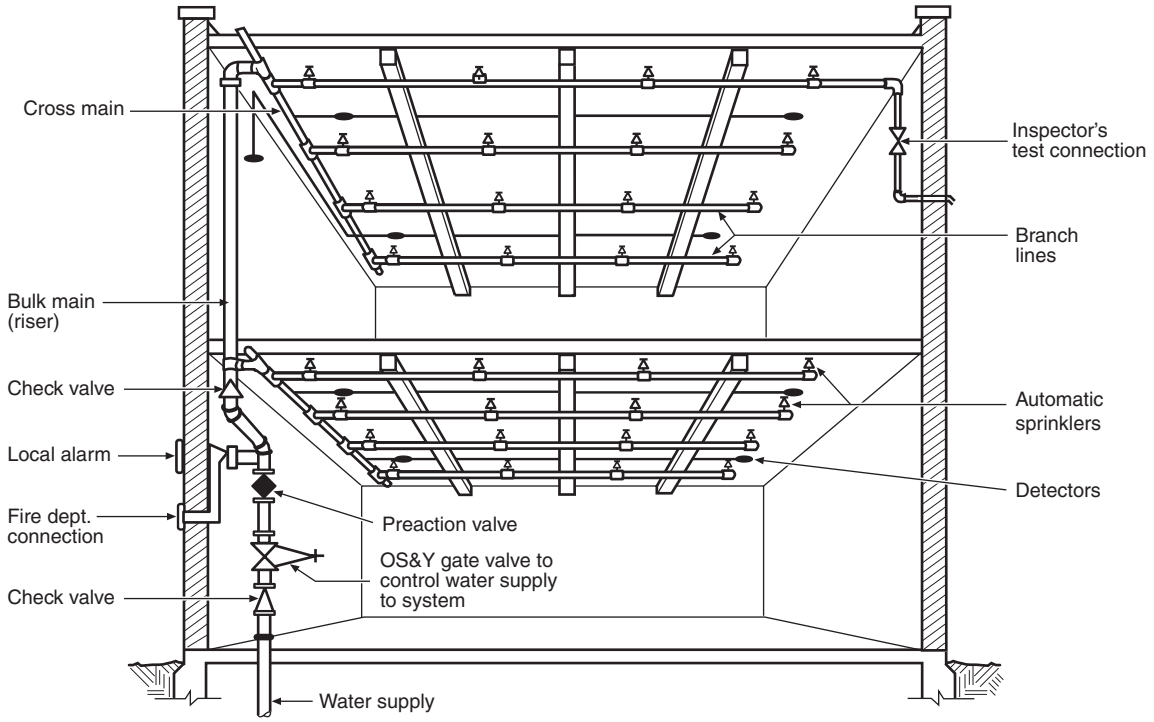


FIGURE 16.3.11 Typical Preaction Sprinkler System

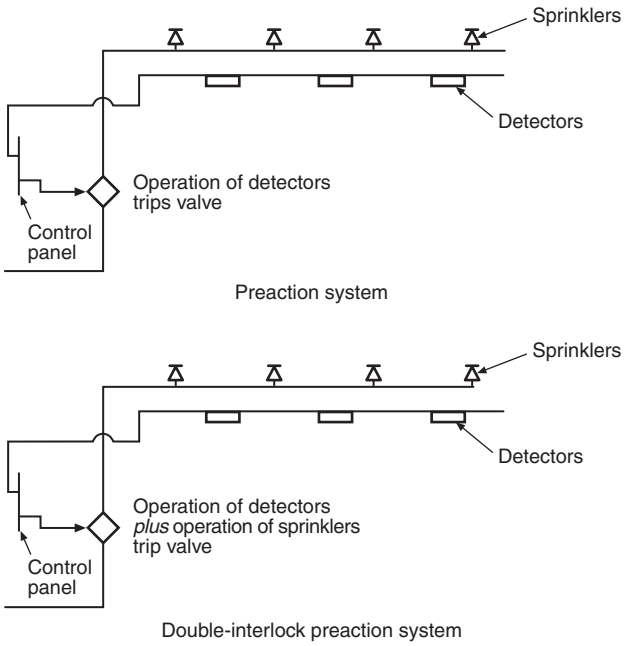


FIGURE 16.3.12 Comparison of Operating Features for the Types of Preaction Systems

supplemental detection system and the sprinklers on the system must operate. Figure 16.3.12 illustrates the double-interlock arrangement. Another variation of a preaction system is the non-interlock system in which either activation of the supplemental detection system or a sprinkler initiates waterflow through the system. Preaction systems are typically found in spaces containing computer or communications equipment, museums, and other facilities where inadvertent water leakage from system piping is of major concern. The double-interlock system is most common in deep-freeze facilities where accidental valve operation can result in the almost immediate freezing and damage of system piping.

Deluge Systems. Deluge systems, as the name implies, deliver large quantities of water over specified areas in a relatively short period of time. These systems are used to protect against rapidly growing and spreading fires. Sprinklers used in a deluge system do not contain thermally sensitive operating elements and are referred to as open sprinklers. A deluge valve controls the system water supply and is activated by a supplemental fire detection system. Because open sprinklers are employed, system piping is at atmospheric pressure. As water reaches each sprinkler in the system, it is immediately discharged from the system.

The nature of this system makes it appropriate for facilities in which significant amounts of highly combustible materials are present. The system is also used for situations in which thermal damage is likely to occur in a relatively short period of time. Aircraft hangars are one area of application of deluge systems. Figure 16.3.13 shows a typical deluge system.

Other Systems. Several variations to each one of these four basic systems exist. One such system is the antifreeze system that is essentially a wet pipe system with a certain amount of antifreeze concentrate added to provide a degree of protection

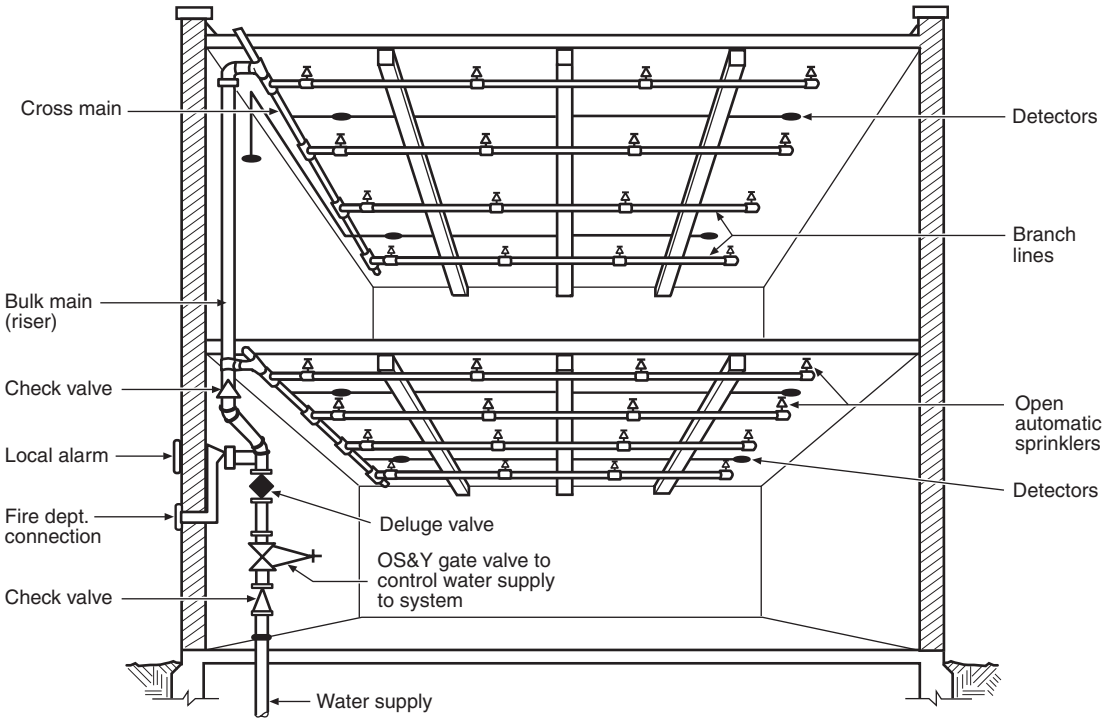


FIGURE 16.3.13 Deluge System

against freezing. Because of the cost associated with these systems, antifreeze systems are usually used to protect smaller spaces exposed to cold temperatures such as outside loading docks or exterior canopies. There has been an increased use of antifreeze for large systems protecting freezers with early suppression fast-response (ESFR) sprinklers. NFPA 13 specifies which types of antifreeze can be used and the percentage of concentrate needed.

Design Objectives

In general terms of property protection, sprinkler systems are typically designed to achieve fire control, although certain types of sprinklers allow for fire suppression to be attained in certain storage arrangements. Fire control can be described as limiting the fire size by decreasing the rate of heat release and prewetting adjacent combustibles, while maintaining ceiling gas temperatures so as to avoid structural damage. Fire suppression can be described as a sharp reduction in the heat release rate to a point at which regrowth is not possible as a result of the application of large quantities of water through the fire plume to the surface of the burning fuel. Figure 16.3.14 provides a graphical representation of these phenomena in terms of the rate of heat release as a function of time.

Where property protection is a secondary objective, options for designing systems targeted principally at life safety within the room of fire origin exist for certain types of facilities. Because property protection is typically more difficult to achieve than is life safety, more cost-effective systems can be considered, but it must be recognized that these systems might not provide the same degree of property protection in all circumstances. Systems targeted for life safety employ residential sprinklers that are intended to maintain a tenable environment in the room of fire origin. The use of residential sprinklers is limited to residential-type facilities. Since their development in the mid-1980s, building codes and NFPA *101* have mandated the use of residential sprinklers or quick-response sprinklers in apartments, hotels, and patient care rooms in health care environments. Both property protection and a higher level of life safety can be provided where facilities are protected throughout in accordance with NFPA 13 and quick-response sprinklers are used.

Occupancy Hazard Classification

To a large degree, the occupancy hazard classifications form the basis of the design and installation criteria of NFPA 13. The occupancy hazards provide a convenient means of categorizing the fuel loads and fire severity associated with certain building operations. The classifications also present a relationship between the burning characteristics of these fuels and the ability of a sprinkler system to control the associated types of fires. The likelihood of ignition is not considered in the occupancy classifications.

NFPA 13 defines three fundamental hazard levels: (1) light hazard, (2) ordinary hazard, and (3) extra hazard. These are defined in a subjective manner and generally focus on the heat release rate and the quantity of combustible fuel. The ordinary-hazard and extra-hazard categories are both subdivided into Group 1 and Group 2 categories. Larger quantities of fuel are typically present in the respective Group 2 categories. As previously stated, the properties of the contents in the building rather than the materials of construction of the building determine the classification. An extensive list of examples of various buildings is placed in the annex of NFPA 13. Defining the hazard is, thus, the first step in selecting and designing the system.

Some examples of occupancies in each of these classifications are as follows:

Light Hazard

- Office buildings
- Schools

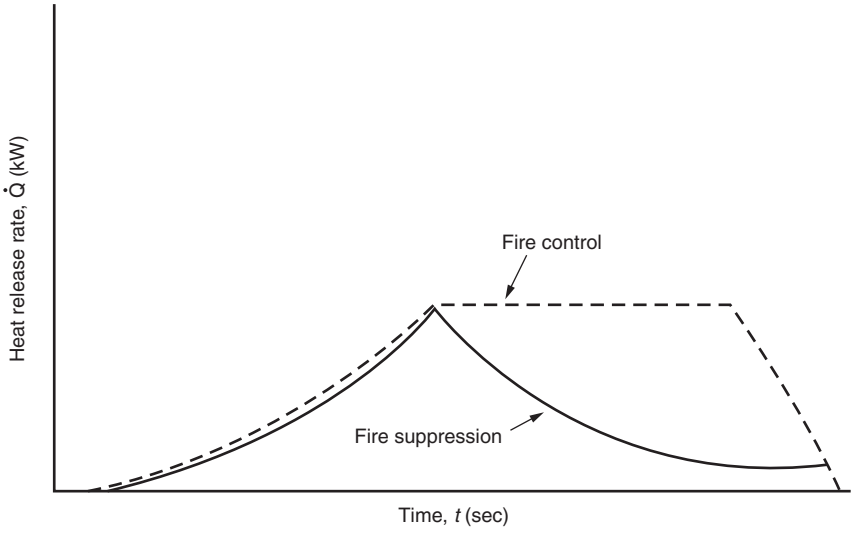


FIGURE 16.3.14 Simplified Fire Control/Fire Suppression Analogy

- Residential occupancies
- Public assembly

Ordinary Hazard

- Canneries (Group 1)
- Electronics plants (Group 1)
- Restaurant service areas (Group 1)
- Dry cleaners (Group 2)
- Library—large stack rooms (Group 2)
- Repair garages (Group 2)
- Wood product assembly (Group 2)

Extra Hazard

- Combustible fluid use area (Group 1)
- Printing that uses inks with flashpoints below 100°F (38°C) (Group 1)
- Upholstering with plastic foams (Group 1)
- Flammable liquids spraying (Group 2)
- Manufactured home assembly (Group 2)
- Plastics processing (Group 2)

Although the occupancy hazard classifications in NFPA 13 address a large majority of building operations, they are not all-encompassing. Certain building operations fall outside the scope of the occupancy hazard classifications and must be treated differently. One such instance includes storage facilities. Where large amounts of materials are stored in a building, the associated fire hazard of the contents in terms of determining appropriate sprinkler system protection is described through commodity classifications. Section 16, Chapter 5, "Sprinkler Systems for Storage Facilities," provides more information in this regard. A similar situation also holds true where flammable and combustible liquids are stored. NFPA 30 provides more information in this regard. Additionally, NFPA 13 further identifies those building operations that require special consideration in terms of either sprinkler system design or installation.

Ceiling Construction

Ceiling construction in terms of the depth, spacing, and openness of the structural and other members affects a sprinkler's activation time and discharge pattern and, therefore, must be considered when placing and positioning sprinklers throughout the building. A sprinkler's allowable area of coverage and the distance below the ceiling will be affected by the ceiling construction classification.

NFPA 13 considers two types of ceiling construction: (1) obstructed and (2) unobstructed. Obstructed construction includes ceiling members that can substantially impede heat flow or water distribution in such a manner that the ability of the sprinkler to suppress or control the fire can be more easily compromised. Under unobstructed construction, ceiling members have less of an impact on sprinkler activation and discharge pattern. NFPA 13 defines unobstructed construction as follows:

- Openings in the member must be at least 70 percent of the cross-sectional area.
- Depth of the member does not exceed the smallest dimension of the openings.
- The members are spaced more than 7 ft 6 in. (2.3 m) on center.

Figure 16.3.15 illustrates an example of obstructed and unobstructed general construction. Within the unobstructed ceiling types, there is a subcategory called smooth ceilings. Some sprinklers, such as the sidewall type, are restricted to just smooth ceilings.

SYSTEM COMPONENTS AND MATERIALS

Maintaining integrity and reliability of a sprinkler system is accomplished in a number of ways. This includes restricting the types and quality of materials and components that comprise the system. As a general rule, NFPA 13 requires that almost all system components, such as sprinklers, valves, and pipe hangers, be listed. While specifically defined by NFPA 13, being listed implies that the equipment and materials to be used on the system have been evaluated by a third party for their intended purpose and marked as such.

Sprinklers

Sprinklers must be listed, and only new sprinklers are permitted for use. Various types of sprinklers are available on the worldwide market. Table 16.3.2 identifies certain sprinkler characteristics. One of these characteristics is the K-factor, which describes the size and angle for the inlet of the sprinkler's orifice (Table 16.3.3). Although sprinklers can be used to protect against various types of fire hazards as classified by NFPA 13, it must be recognized that there might be limitations on the use of a given sprinkler. For example, sprinklers with a K-factor smaller than 5.6 are limited to light-hazard occupancies. Additionally,

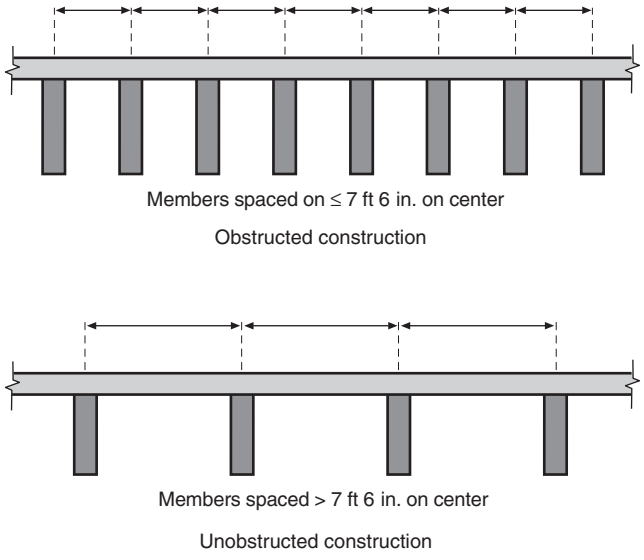


FIGURE 16.3.15 (Top) Obstructed Construction, (Bottom) Unobstructed Construction

TABLE 16.3.2 Sprinkler Discharge Characteristics Identification

Nominal K-Factor $gpm/(psi)^{1/2}$	*K-Factor Range* $gpm/(psi)^{1/2}$	*K-Factor Range* $dm^3/min/(kPa)^{1/2}$	*Percentage of Nominal K = 5.6 Discharge*	*Thread Type*
1.4	1.3–1.5	1.9–2.2	25.0	½ in. NPT
1.9	1.8–2.0	2.6–2.9	33.3	½ in. NPT
2.8	2.6–2.9	3.8–4.2	50.0	½ in. NPT
4.2	4.0–4.4	5.9–6.4	75.0	½ in. NPT
5.6	5.3–5.8	7.6–8.4	100.0	½ in. NPT
8.0	7.4–8.2	10.7–11.8	140.0	¾ in. NPT
				½ in. NPT
11.2	11.0–11.5	15.9–16.6	200.0	½ in. NPT
				¾ in. NPT
14.0	13.5–14.5	19.5–20.9	250.0	¾ in. NPT
16.8	16.0–17.6	23.1–25.4	300.0	¾ in. NPT
19.6	18.6–20.6	27.2–30.1	350.0	1 in. NPT
22.4	21.3–23.5	31.1–34.3	400.0	1 in. NPT
25.2	23.9–26.5	34.9–38.7	450.0	1 in. NPT
28.0	26.6–29.4	38.9–43.0	500.0	1 in. NPT

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

TABLE 16.3.3 Nominal Sprinkler Orifice Sizes

Nominal K-Factor	Nominal Orifice Size *in.*	*mm*
1.4	1/4	6.4
1.9	5/16	8.0
2.8	3/8	9.5
4.2	7/16	11.0
5.6	1/2	12.7
8.0	17/3	13.5
11.2	5/8	15.9
14.0	3/4	19.0
16.8	—	—
19.6	—	—
22.4	—	—
25.2	—	—
28.0	—	—

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

the type of system, such as dry pipe, can require the use of a minimum K-factor value.

The 5.6 K-factor or ½-inch (12.7-mm) orifice sprinkler is considered the standard orifice sprinkler and generally serves as a benchmark against which to compare the discharge of other sprinklers. Sprinklers with K-factors less than 5.6 have traditionally been considered small orifice sprinklers. Sprinklers with K-factors larger than 5.6 traditionally have been referred to as large, extra large, and very extra large orifice sprinklers. However, the current trend is to develop sprinklers with larger and larger K-factors, the largest currently at 25. Thus, the terms *large orifice* and *extra large orifice* have lost their meaning and are no longer used.

Sprinklers must also satisfy other criteria concerning thread type and marking. Sprinkler manufacturers and listing laboratories are bound to some degree to the limits of NFPA 13. For example, a sprinkler with a K-factor of 14 cannot have a ½ in. (12.7 mm) NPT thread. Restrictions on thread type and orifice diameter are imposed on larger sprinklers because of the poor hydraulic features associated with flowing large quantities of water through a relatively small opening.

Another feature of the sprinkler that is governed by NFPA 13 is the temperature rating, as indicated in Table 16.3.4. The first column indicates the maximum ambient temperature to which the sprinkler is expected to be exposed. As the expected ambient temperature increases, sprinklers with higher temperature ratings need to be used. For example, where the ambient temperature during any given day can be expected to exceed 100°F, such as a non-air-conditioned warehouse in one of the southern states, ordinary temperature rated sprinklers cannot be used. For the most part, sprinklers with higher temperature ratings, such as ultrahigh, are intended for use around process equipment that generates substantial amounts of heat.

Although the general provisions outlined in Table 16.3.4 apply in most situations, there are additional situations in which higher temperature ratings are necessary. The installation rules in NFPA 13 govern these situations and identify conditions in which higher temperature rated sprinklers are needed, such as under skylights.

As noted in Table 16.3.4, sprinklers are color coded to facilitate the identification of the temperature rating. Eutectic metal or solder-type sprinklers use the color scheme in the next to last column, whereas glass-bulb sprinklers use the color scheme in the last column. The liquid in a glass-bulb sprinkler is basically a low-boiling-point alcohol. An air bubble within the glass bulb

TABLE 16.3.4 Temperature Ratings, Classifications, and Color Codings

Maximum Ceiling Temperature		Temperature Rating				
°F	°C	°F	°C	*Temperature Classification*	*Color Code*	*Glass Bulb Colors*
100	38	135–170	57–77	Ordinary	Uncolored or black	Orange or red
150	66	175–225	79–107	Intermediate	White	Yellow or green
225	107	250–300	121–149	High	Blue	Blue
300	149	325–375	163–191	Extra high	Red	Purple
375	191	400–475	204–246	Very extra high	Green	Black
475	246	500–575	260–302	Ultrahigh	Orange	Black
625	329	650	343	Ultrahigh	Orange	Black

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

is volume controlled to achieve a certain temperature rating. The larger the bubble, the higher the operating temperature. The liquid is dyed the appropriate color to correspond to the color code system in the table. Selection of the correct temperature rating for the environment is critical to ensure that sprinklers will not operate during nonfire conditions.

Sprinklers can be manufactured with special coatings to improve their corrosion resistance or aesthetic qualities. Sprinklers installed in corrosive atmospheres can be lead- or wax-coated or made of stainless steel to provide protection against premature corrosion. Sprinklers with special finish coatings are also available and can enhance the architectural features of a space. The choice of coating can be restricted by the type of sprinkler. For instance, quick-response sprinklers cannot be wax-coated.

In both the case of listed corrosion-resistant sprinklers and sprinklers with special decorative finishes, such finishes may only be applied by the manufacturer. Under no circumstance can sprinklers be "field coated" with any type of material. Sprinklers that have been coated or painted must be replaced. Such coatings may impair the spray pattern of the sprinkler or they may react with some functional part of the sprinkler assembly, such as the operating element or the Teflon® seal, which is used to seat the orifice cap on the orifice.

Pipe and Tube

A number of piping materials are acceptable for use in sprinkler systems. Steel, copper, and nonmetallic pipe materials are currently addressed by NFPA 13. These pipe materials must meet certain pipe manufacturing standards, certain listing requirements, or both. Limiting the types of pipe that are acceptable for use will increase reliability of not only the system installation, but it will also ensure the integrity of the system piping during a fire. In addition to identifying the type of pipe materials that can be used, NFPA 13 also specifies how the pipe is to be joined.

Steel Pipe. Steel pipe has been a viable option for use in sprinkler systems since the first edition of NFPA 13, published in 1896. Steel pipe of at least schedule 10 wall thickness manufactured in compliance with certain ASTM (American Society for Testing and Materials) standards as specified by NFPA 13 and summarized in Table 16.3.5 is not required to be listed. However, this does not preclude a manufacturer from having steel pipe specifically listed for fire protection service.

Copper Tube. Copper tube was first discussed as an optional material for sprinkler systems in 1954. Concern over the failure of solder materials or the brazing materials used to join the copper tube was expressed as being a potential failure point of the system during a fire. Joint research by the listing laboratories and the Copper Development Association addressed those concerns, and recommendations were made to restrict the types of brazing material and solder materials. Table 16.3.6 indicates the relevant standards for both copper tube and the joining materials. Copper tube systems have been installed in a large number of buildings. Some notable buildings with copper systems are the Trans-America building in San Francisco, the Monterey Aquarium, and the Library of Congress.

Nonmetallic Pipe. NFPA 13 previously identified two types of plastic pipe for use in sprinkler systems. Polybutylene (PB)

TABLE 16.3.5 Pipe or Tube Materials and Dimensions

Materials and Dimensions	*Standard*
Ferrous Piping (Welded and Seamless)	
Specification for Black and Hot-Dipped Zinc Coated (Galvanized) Welded and Seamless Steel Pipe for Fire Protection Use	ASTM A795
Specification for Welded and Seamless Steel Pipe	ANSI/ASTM A53
Wrought Steel Pipe	ANSI B36.10M
Specification for Elec.-Resistance Welded Steel Pipe	ASTM A135

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

TABLE 16.3.6 Pipe or Tube Materials and Dimensions

Materials and Dimensions	*Standard*
Copper Tube (Drawn, Seamless)	
Specification for Seamless Copper Tube	ASTM B75
Specification for Seamless Copper Water Tube	ASTM B88
Specification for General Requirements for Wrought Seamless Copper and Copper-Alloy Tube	ASTM B251
Fluxes for Soldering Applications of Copper and Copper Alloy Tube	ASTM B813
Brazing Filler Metal (Classification BCuP-3 or BCuP-4)	AWS A5.8
Solder Metal, 95-5 (Tin-Antimony-Grade 95TA)	ASTM B32
Alloy Materials	ASTM B446

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

pipe was first listed for use in systems in NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes,* in 1984. An obvious concern with plastic pipe is failure when exposed to fire and even its possible contribution to fire growth. This concern was addressed by requiring the pipe to be installed behind a protective membrane. Such a protective barrier would shield the pipe from direct heat exposure. The exposing temperature would be expected to be substantially decreased, since the operating sprinkler would be controlling the fire. Although PB pipe can still be used for sprinkler systems, since April 1996, the resin used to manufacture the pipe is no longer available. All reference to polybutylene pipe was removed from the 2007 edition of NFPA 13.

A second type of nonmetallic pipe, chlorinated polyvinyl chloride (CPVC), was introduced in 1986. CPVC pipe was listed for use in systems complying with NFPA 13D and for systems complying with NFPA 13 for light-hazard occupancies.

CPVC piping materials must be manufactured in accordance with the piping standard in ASTM F442 *and* must be specifically listed for use in automatic sprinkler systems. The listing criteria include a number of conditions and restrictions. Some of these conditions are as follows:

- Limited for use in systems that comply with NFPA 13D; NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height;* and NFPA 13 (light-hazard occupancies only)
- Can be used in all wet pipe systems but limited for dry pipe and preaction systems
- Must be installed behind a thermal barrier. Note that CPVC pipe may be installed exposed if used with listed residential sprinklers that are installed in accordance with their listing or if used with listed quick-response (QR) sprinklers, where the QR sprinklers are installed within 8 in. (203 mm) of the ceiling
- Must be joined with listed fittings or materials
- Not permitted to be installed in concealed combustible spaces that require sprinkler protection by NFPA 13

NFPA 13 requires that all of the manufacturer's installation instructions be followed in addition to the design and installation rules of NFPA 13.

Specially Listed Steel Pipe. In the same manner that NFPA 13 previously allowed manufacturers to produce pipe with materials other than steel and copper, a similar provision also permits the use of other types of steel pipe that have a thickness of less than schedule 10. These materials are typically referred to as thin-wall steel pipe and may have a wall thickness similar to that for schedule 5. They must be specifically listed for use in automatic sprinkler systems.

The listing process evaluates a number of pipe properties such as hydraulic characteristics, corrosion resistance, beam strength (for determining hanger spacing for piping support), and joining methods of joining the pipe, among others.

System Valves

Automatic sprinkler systems are required to have at least one listed valve installed to allow for the system to be shut down. As a matter of course, sprinkler systems should never be shut down except when system modifications are being accomplished or during the time following a fire to allow for replacement of any sprinklers that operated. The types of valves used in a sprinkler system vary with the location of the valve in the water supply system or portion thereof.

Valves may be of the isolation type to shut the system off, they may be a one-way or check valve to prevent flow of water in one direction, or they may be a pressure-regulating valve to permit the pressure entering part of the system to be maintained at a certain level. In all cases, the valves must be listed for use in fire protection systems, they must be supervised in their normally open position, and they must be identified as to the area or segment of the system that they control.

Listed control valves are evaluated for such characteristics as the maximum working pressure to which they can be exposed, the hydraulic profile or equivalent pipe lengths that result, and the means of supervising equipment that they may use.

Indicating Features. The purpose of an indicating feature on a valve is to allow a method to quickly determine if the valve is in the open or closed position. One of the more common methods for accomplishing this is the use of a listed outside screw and yoke (OS&Y) valve. The rising stem feature of this valve is the indicator if the valve is open or closed. The stem rises as the valve is set to the open position. The opposite end of the stem is equipped with a gate valve that raises out of the pipe network as the valve wheel is operated. OS&Y valves are often installed at, or near, the system riser.

A postindicator valve (PIV) is frequently installed outside of the structure. The indicating feature on this device is a viewing window with a sliding metal plate. As the valve is operated with the special wrench, the stem, which is connected to the gate device on the end of the stem (the stem is internal to the post

on a PIV), also repositions the sign. When the valve is in the open position, the sign labeled "OPEN" will be evident in the small viewing window on the side of the PIV housing. Likewise, when the valve is operated to the closed position, the sign labeled "CLOSED" will be evident in the viewing window. Figure 16.3.16 illustrates two types of control valves.

Listed indicating butterfly valves (IBV) do not have the same type of physical features of either the OS&Y valve or the PIV valve; thus, it must use an indicating feature that is substantially different from either of the first two valves. The indicating feature with an IBV is usually a directional arrow, mounted on the housing of the valve. This feature points in the "position" of the valve. For example, when the valve is open, the arrow is aligned with the flow direction of the water. When the valve is in the closed position, the arrow points in a direction perpendicular to the pipe, indicating that water cannot travel beyond the valve.

Supervisory Features. Another requirement of NFPA 13 is to provide some means to ensure that the valve remains in its normal position. Supervision of system valves dates back to the 1896 edition of NFPA 13, in which Rule 60 stated "All gate valves in supply pipes to sprinklers to be of indicator pattern, and to be strapped open with riveted leather straps passing around the riser and spoke of the wheel, or secured open with a seal." The methods for supervising valves include the following:

- Electrically supervised in a manner to allow a signal to be heard at a central station facility
- Electrically supervised in a manner to allow a signal to be heard at a constantly attended point at the protected facility
- Locking valves in the open position
- Sealing valves in the open position, with a weekly surveillance program

It is important to remember that, although NFPA 13 allows any of these options, for sprinkler systems required by other building codes, the code typically dictates that the valve be electrically supervised at a central station.

In addition to those valves used to control the system supplies or a portion of the system supply, other types of valves are used to test the system or drain the system pipe. Although such valves are not required to meet the same level of reliability as control valves, they must still be installed to facilitate testing of the system, as well as to allow for the system to be drained during a period of maintenance. The main drain or test valve is located at the system riser. Its purpose is twofold. First, it may be used as a central point to drain water from the entire system. Its second purpose is to conduct the main drain test. This test is done when the system is commissioned, in order to allow for a set of baseline values to be established. The points of interest are (1) the static pressure and (2) the residual pressure when the valve is fully open. Figure 16.3.17 shows the common arrangement of the main drain valve.

Another type of valve used is the inspector's test valve, or the alarm test connection. The location of the valve depends on the type of system. When installed on a wet pipe system, the main purpose of this device is to test the operation of the waterflow device. Although it can be located anywhere after the waterflow device, the preferred location is as close to the system riser as possible. This limits the extent of corrosion within the system. When installed on a dry pipe system, its purpose is twofold. First, it is used to establish the trip time of the dry pipe valve and the transit time of the water to the connection. Second, it establishes the time for the waterflow device to operate and the actual operation of the alarm device. For these reasons, it must be located at the end of the most remote branch line.

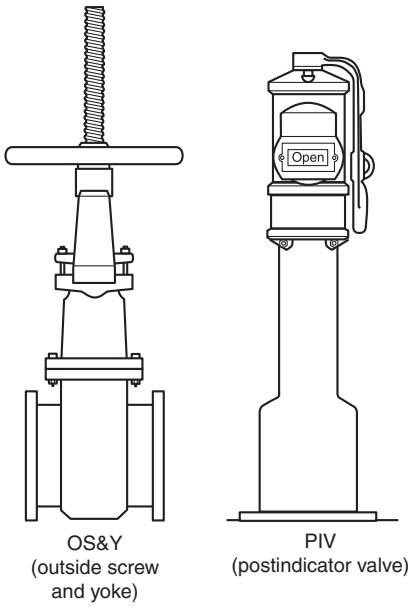


FIGURE 16.3.16 Two Sprinkler System Indicating Control Valves

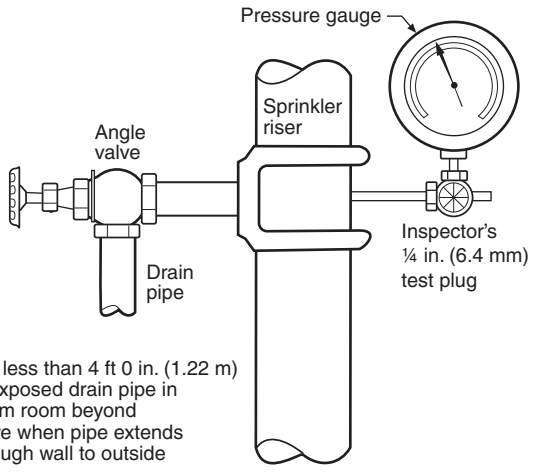


FIGURE 16.3.17 Main Drain Connection for System Riser

INSTALLATION RULES FOR AUTOMATIC SPRINKLER SYSTEMS

The basic principles of NFPA 13 concerning sprinkler system installation are as follows:

1. Sprinklers are to be installed throughout the premises.
2. The maximum allowed protection area per sprinkler is not to be exceeded.
3. Sprinklers are to be positioned to allow for timely operation and distribution.

Installing Sprinklers Throughout the Premises

Installing sprinklers throughout the premises is necessary in order to achieve the desired level of life safety and property protection. Since there are no standardized methods to predict where a fire is likely to start in a structure, the basic rules of NFPA 13 require sprinklers to be installed in most areas of the building. In general, a fire that originates in an unsprinklered area is expected to overpower the capabilities of a system that may be installed in a nearby or adjacent space. In general, this correlation holds true. There have been instances in which sprinklers did actually contain or extinguish a fire that originated in an unsprinklered space. The most notable of these fires was the One Meridian Plaza fire in Philadelphia in 1991. In this incident, an uncontrolled fire had spread between eight stories in a high-rise office building. On reaching the thirtieth floor, which had been equipped with sprinklers, a total of nine sprinklers operated to completely stop the further spread of the fire.

Some codes that focus exclusively on life safety might not require sprinklers in all areas of the building. This is in recognition of the assumption that the threat to life or injury as a result of fire in these spaces is considered minimal. Because NFPA 13 focuses on both property protection and life safety, very few exceptions for omitting sprinkler coverage exist.

Some areas that do not require sprinkler coverage include bathrooms in residential-type occupancies that are not over 55 ft^2 (5.1 m^2) in area and are composed of noncombustible or limited-combustible materials. Small closets in hotel occupancies are also not required to be protected with sprinklers. In both instances, there is recognition that the fuel loading in such spaces is minimal and that fires that originate in such spaces do not normally become threatening to either the occupants or the structure.

Two other exceptions to sprinkler protection center on electrical equipment rooms and elevator shafts. Electrical equipment rooms that (1) use dry-type equipment, (2) are used for no other purpose, and (3) are separated by 2-hour fire-rated construction are not required to be protected with automatic sprinklers. In this instance, strict controls are imposed on the use of the room and the materials of construction.

Passenger elevator shafts that use noncombustible construction and utilize elevator cabs constructed in accordance with ASME 17.1, *Safety Code for Elevators and Escalators,* are not required to be provided with a sprinkler at the top of the shaft. Sprinklers are not required at the bottom of similar shafts, unless the elevator lift mechanism uses hydraulic fluid. It is important to note that such exceptions do not extend to the elevator equipment or machine rooms.

Concealed spaces, such as those found above a ceiling within the building, do not require sprinklers, provided the space is constructed of noncombustible materials. Conversely, concealed spaces of combustible construction or materials require sprinkler protection. There are a number of exceptions to this general rule, however. Exceptions to sprinkler protection center on two basic ideas: (1) that physical limitations within a space may prevent a meaningful arrangement of sprinklers to be installed, and (2) that the nature and arrangement of the combustible materials may have some inherent fire resistance. The 2007 edition of NFPA 13 contains 14 exceptions that address the specific instances in which sprinklers can be omitted from concealed combustible spaces. Buildings are still considered to be sprinklered throughout when these exceptions are applied.

Areas of Coverage

A number of limits are imposed on the size of the area that a particular type of sprinkler can protect. In arriving at the area of coverage for a particular type of sprinkler, a number of variables are considered. These include the type of sprinkler in question, the nature of the hazard being protected, the type of construction contemplated, and the spacing of the construction members. Tables 16.3.7 through 16.3.10 summarize the maximum areas of coverage permitted for standard upright and standard pendent spray sprinklers. Protection areas for other types of sprinklers are provided in NFPA 13. Exceeding the area of coverage limits specified by NFPA 13 can result in failure of the sprinkler to control the fire.

The area of coverage of a sprinkler is established through a set of principles based on an evaluation of the relationship between the distance between sprinklers located on the branch line and the distance between sprinklers on adjacent branch lines. The first value is defined as "S" (along the branch line), whereas the second value is defined as "L" (between adjacent branch lines). In the same manner that maximum limits are imposed on the overall area of coverage, limits are also placed on these distances. Once again, the type of sprinkler, the hazard to be protected, and the characteristics of the construction are factored into these limits. Tables 16.3.7 through 16.3.10 show the permitted values for "S" and "L" identified as the maximum spacing.

The area of coverage is then determined by multiplying the "L" and "S" values together. It should be noted that sprinklers installed on the ends of a branch line near a wall and those sprinklers installed on the branch line that runs closest to a wall receive special treatment and may alter the selected values for "S" and "L." (See NFPA 13 for a further discussion on this issue.) Even a slight deviation in these limits may result in the sprinkler system not being able to adequately control the fire.

Extended coverage (EC) sprinklers use a slightly different method of determining their area of coverage. In essence, the area of coverage is identical to whatever the sprinkler is listed to. Pendant-mounted extended coverage sprinklers are listed with equal-sided, even-numbered dimensions. An EC sprinkler

TABLE 16.3.7 Protection Areas and Maximum Spacing (Standard Spray Upright/Standard Spray Pendent) for Light Hazard

Construction Type	*System Type*	Protection Area		Spacing (Maximum)	
		ft^2	*m*^{2}	*ft*	*m*
Noncombustible obstructed and unobstructed and combustible unobstructed with members less than 3 ft (0.9 m) on center	Pipe schedule Hydraulically calculated	200 225	18.6 20.9	15 15	4.60 4.60
Combustible obstructed with members less than 3 ft (0.9 m) on center	All	168	15.6	15	4.60
Combustible with members less than 3 ft (0.9 m) on center	All	130	12.1	15	4.60
Combustible concealed space under a pitched roof having combustible wood joist or wood truss construction with members less than 3 ft (0.9 m) on center with slopes having a pitch of 4 in 12 or greater	All	120	11.1	15 parallel to the slope 10 perpendicular to the slope	4.60 parallel to the slope 3.05 perpendicular to the slope

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

TABLE 16.3.8 Protection Areas and Maximum Spacing (Standard Spray Upright/Standard Spray Pendent) for Ordinary Hazard

Construction Type	*System Type*	Protection Area		Spacing (Maximum)	
		ft^2	*m*^{2}	*ft*	*m*
All	All	130	12.1	15	4.6

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

that is listed for 16 ft × 16 ft (4.9 m × 4.9 m) has an area of coverage of 256 ft^2 (23.8 m^2). These values become fixed with respect to system design. For example, even if this type of sprinkler is used in an area or room with dimensions of 15 ft × 15 ft (4.6 m × 4.6 m), it must still be designed for the listed spacing of 16 ft × 16 ft (4.9 m × 4.9 m), or 256 ft^2 (23.8 m^2). Sidewall sprinklers are treated in a similar manner but the area can be a rectangle with changes in either dimension limited to 2 ft increments. There is an exception to the area of coverage rule. Extended coverage pendent sprinklers listed for an extra-hazard occupancy and storage shall apply the S × L rule.

TABLE 16.3.9 Protection Areas and Maximum Spacing (Standard Spray Upright/Standard Spray Pendent) for Extra Hazard

Construction Type	*System Type*	Protection Area		Spacing (Maximum)	
		ft^2	*m*^{2}	*ft*	*m*
All	Pipe schedule	90	8.4	12 (In buildings with storage bays 25 ft [7.6 m] wide, 12 ft 6 in. [3.8 m] shall be permitted)	3.7
All	Hydraulically calculated with density ≥0.25	100	9.3	12 (In buildings with storage bays 25 ft [7.6 m] wide, 12 ft 6 in. [3.8 m] shall be permitted)	3.7
All	Hydraulically calculated with density <0.25	130	12.1	15	4.6

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

TABLE 16.3.10 Protection Areas and Maximum Spacing (Standard Spray Upright/Standard Spray Pendent) for High-Piled Storage

Construction Type	*System Type*	Protection Area		Spacing (Maximum)	
		ft²	*m²*	*ft*	*m*
All	Hydraulically calculated with density ≥0.25	100	9.3	12 (In buildings with storage bays 25 ft [7.6 m] wide, 12 ft 6 in. [3.8 m] shall be permitted)	3.7
All	Hydraulically calculated with density <0.25	130	12.1	15	4.6

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

Sprinkler Activation and Discharge Characteristics

The position of the sprinkler with respect to the ceiling and any nearby construction features, such as lighting fixtures, construction elements, and the like, can impact the performance of the sprinkler in two distinct ways. First, if the sprinkler is located in a manner so that it is not directly exposed to the heat from the fire, the subsequent delay in sprinkler operation may result in the fire becoming too large for proper control by the sprinkler. To minimize this possibility, NFPA 13 controls the positioning of the sprinkler with respect to walls and ceilings.

The second area of concern lies within the distribution pattern of the sprinkler. In other words, once the sprinkler operates, is it likely that the water that discharges from the sprinkler will be able to reach the fire and surrounding objects. NFPA 13 deals with this by specifying obstruction rules for each type of sprinkler. The requirements of NFPA 13 that address sprinkler activation are specific to the type of sprinkler involved. Although specific requirements for a given type of sprinkler vary, the fundamental principles remain the same: (1) control the distance between the sprinkler deflector and the ceiling/roof, and (2) determine if the ceiling construction features will impede heat flow from the fire to the sprinkler. Ceiling construction features were previously discussed. The position of the sprinkler beneath the ceiling is predicated on the principle that a dynamic heat layer consisting of hot gases from the fire develops below the ceiling and ultimately contains a sufficient amount of energy in terms of heat to activate the sprinkler. In essence, heat from the fire rises to the ceiling surface where, if unobstructed, it spreads out across the ceiling. As the layer builds because of the developing fire, the thermally sensitive components of the sprinklers eventually activate, allowing for the discharge of water. For this reason, NFPA 13 limits the distance that the sprinkler can be positioned below the ceiling.

Dealing with obstructions to sprinkler discharge can be a rather complex issue. A building with a completely smooth, flat, horizontal ceiling that utilizes recessed lighting fixtures, or flush-mounted heating, ventilating, and air-conditioning (HVAC) exhaust grilles, and that otherwise has no projections from the ceiling is the most desirable in terms of sprinkler discharge. However, this situation is rare.

The many combinations of architectural features, lighting components, structural members, and related building systems can create detrimental obstructions to sprinkler discharge. Since the first edition of NFPA 13 in 1896, many rules and requirements have been added to address the issue. The fundamental philosophy concerning obstructions has not changed in over 100 years, but details concerning type, size, and shape of obstruction are important as well as how close that obstruction has to be before it becomes a concern.

NFPA 13 addresses three general areas of concern with regard to obstructions. However, rules are specific for each category of sprinkler identified by NFPA 13. The first concern is the overall objective, which is to ensure that a sufficient amount of water from the sprinkler reaches the fire. The concern was previously referred to as a horizontal obstruction and dealt primarily with continuous obstructions such as beams, top chord members, and ducts that are tight or very near the ceiling and in close proximity to the sprinkler.

The second concern deals with the obstruction to sprinkler discharge pattern development. This concern addresses continuous and noncontinuous obstructions such as piping, light fixtures, truss webs, or building columns located within the first 18 in. (457 mm) below the sprinkler deflector. Obstructions located in this zone prevent the proper sprinkler discharge pattern from developing. As a result sprinklers are required to be positioned so that they are located a certain radial distance away from the obstruction. NFPA 13 addresses the correct position for each type of sprinkler.

The 18 in. (457 mm) distance was established in 1952 as the clearance below the newly developed spray sprinkler. It was determined that this volume of clear space was necessary for proper spray pattern development. Starting with the 1996

edition of NFPA 13, the rules for obstructions went through a significant change. Within the 18 in. zone, spray sprinklers are to be separated a radial distance equal to three times the larger dimension of the obstruction. For some types of sprinklers such as extended coverage sprinklers, the separation is increased to four times the dimension. The sensitivity to obstructions is not only affected by the type of sprinkler but also by the occupancy hazard classification. As added in the 1999 edition of NFPA 13, when using standard pendent or upright sprinklers in light- and ordinary-hazard occupancies, only structural members in this zone need be accounted for as obstructions. In general, the obstruction rules in NFPA 13 allow for a portion of the sprinkler's spray pattern to be impacted.

The third area of concern deals with obstructions that prevent the sprinkler discharge from reaching the hazard. These obstructions typically consist of continuous and noncontinuous obstructions that interrupt the water spray pattern once it is below the 18 in. (457 mm) discharge pattern development zone. These types of obstructions can include overhead doors, ducts, or decks. When the width of these obstructions exceeds 4 ft, additional sprinklers are required to be installed beneath them. As indicated by such a large dimension being acceptable, once the pattern has developed, obstructions present much less of a threat to acceptable sprinkler performance.

Another category of obstruction applicable to certain types of sprinklers includes obstructions that are suspended from the ceiling, such as privacy curtains in a hospital or floor-mounted partitions that do not reach the ceiling, such as those found in offices. In both cases, sprinklers must be positioned so that a sufficient portion of the sprinkler discharge sprays over the obstruction.

It is important to note that certain types of sprinklers are more "obstruction sensitive," in that they have little or no tolerance for objects that disrupt the spray pattern. Large-drop and ESFR sprinklers both fit into this category, and their performance can be severely affected by relatively small obstructions.

DESIGN CONSIDERATIONS FOR AUTOMATIC SPRINKLER SYSTEMS

The basic design consideration for sprinkler systems is to verify that the sprinkler system can discharge a sufficient amount of water for the period of time necessary to either control or suppress the types of fires anticipated. Determination of the appropriate occupancy hazard classification is critical in this regard. However, certain installation criteria also play a role. For example, ceiling construction, whether obstructed or unobstructed, influences the area of coverage for a particular sprinkler and this bears on the overall water demand requirements of the system. Another instance focuses on the presence of concealed combustible spaces, which can increase the overall system design area. In protecting a single building or within a single floor area, multiple designs options can be applied. Each option is treated independently.

Two general design methods exist in NFPA 13: (1) the pipe schedule method and (2) the hydraulic design method. The pipe schedule method dates back to the late 1800s. It basically uses a prescribed schedule that specifies the number of sprinklers that can be supplied by a given size pipe. NFPA 13 contains schedules for both copper tube and steel pipe. The use of this particular design method is severely restricted by NFPA 13, almost to the point where it is impractical in most instances.

In addition to the schedule or table that is provided for a light-hazard or ordinary-hazard occupancy (pipe schedule design is no longer permitted for extra hazard), a second table is used to specify the minimum flow and pressure at the base of the system riser (Table 16.3.11). This table is limited to installations no larger than 5000 ft^2 (464.7 m^2). The flow is a minimum, and in the case of a light-hazard occupancy, that flow must be made available at the base of the system riser at a pressure of 15 psi (103.4 kPa) plus the pressure that is necessary to reach the highest sprinkler. In the case of a light-hazard occupancy that has its highest sprinkler positioned 38 ft (11.2 m) above the base of the riser, the minimum flow would have to be available at a pressure of 31.5 psi (217.2 kPa). Table 16.3.11 indicates that not less than 500 gpm (1892.5 L/min) must be provided at this point. If the installation was greater than 5000 ft^2 (464.7 m^2), the minimum residual pressure is increased to 50 psi (344.8 kPa). The above example would require 66.5 psi (458.5 kPa). Such flows are not typical of most municipal water supplies.

The more accurate method of determining the demand for a sprinkler system is through hydraulic calculation. Additionally, this method provides the designer and the building owner with a more cost-effective system. This method offers a number of other advantages in that it is not limited to use with a particular type of pipe, a particular type of sprinkler, or a particular type of occupancy hazard. These are all limitations associated with the pipe schedule approach.

The process by which the calculations are completed is based on an evaluation of the sprinkler system from the hydraulically most remote point. This is that portion of the system that is expected to produce the greatest demand on and tax the system to its greatest extent. It sometimes, but not always, coincides with the physically most remote point in the system (i.e., the point farthest away from the base of the system riser). The concept here is that, if one can satisfy the most demanding point hydraulically, then one can also satisfy any point that is hydraulically closer to the system water supply.

TABLE 16.3.11 Water Supply Requirements for Pipe Schedule Sprinkler Systems

Occupancy Classification	Minimum Residual Pressure Required		Acceptable Flow at Base of Riser		*Duration in Minutes*
	psi	*bar*	*gpm*	*L/min*	
Light hazard	15	1.03	500–750	1892–2839	30–60
Ordinary hazard	20	1.38	850–1500	3217–5677	60–90

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

In determining this most remote point, a design area or system area of operation must be established based on the criteria of NFPA 13. This area should take the shape of a rectangle with a minimum area of 1500 ft^2 (139.4 m^2) for light- and ordinary-hazard occupancies and 2500 ft^2 (232.3 m^2) for extra-hazard occupancies. The selected area is then matched to a corresponding discharge density in accordance with Figure 16.3.18, which is taken from NFPA 13. The designer needs only to satisfy a single point on this curve in order to produce an acceptable design.

A designer is free to select a matching area of sprinkler operation and density along the representative curves. However, it is more advantageous to select the smallest corresponding area of operation (vertical axis) and highest density (horizontal axis). Other points higher on the curve are acceptable but only result in the system requiring more water overall. Interestingly, less water is made available to any given area on the floor when such points are selected.

Up until this point in the design process, the only fixed parameter is the occupancy hazard to be protected. Once the demand point has been selected from the curve, other influencing factors come into play. One of these factors involves the protection (or lack thereof) of concealed combustible spaces. In some instances, the design area must be increased from 1500 to 3000 ft^2 (139.4 to 278.7 m^2). Another factor is the area of coverage for each sprinkler and the spacing that is provided between sprinklers on each branch line (dimension "S," which was previously described).

This type of information becomes critical since the area of system operation is to be converted to a number of sprinklers expected to operate. The number of sprinklers expected to operate is the result of the system area of operation (in units of ft^2) divided by the area of coverage for a sprinkler (in units of ft^2 per sprinkler) (1 ft^2 = 0.0929 m^2). A sprinkler that covers a 200 ft^2 (18.6 m^2) area in a light-hazard occupancy, and in which a system area of operation was selected to be 1500 ft^2 (139.4 m^2), could also be said to have a system area of operation of 1500 ft^2 (139.4 m^2) divided by 200 ft^2 (18.6 m^2) per sprinkler or 7.5 sprinklers. In this process, any fractional amount is always rounded up to the next whole number. In this case, the 1500 ft^2 (139.4 m^2) hydraulically most remote area may also be described as being an eight-sprinkler hydraulically most remote area. This translates to the need to provide a sufficient amount of water to these eight sprinklers in order to control a fire.

The longer dimension of the rectangular area should be parallel to the system branch lines and its length, represented by the number of sprinklers along the branch line in the design area, is determined by the following formula:

$$\frac{1.2\sqrt{A}}{S}$$

where A represents the system design area and S represents the distance between sprinklers along the branch lines. Considering the example in which the design area is 1500 ft^2 and sprinklers are spaced 10 ft (3.1 m) apart along the branch line, the longer side of the design area will contain five sprinklers as follows:

$$\frac{1.2\sqrt{1500}}{10} = 4.6 \text{ sprinklers}$$

(1 ft = 0.305 m)

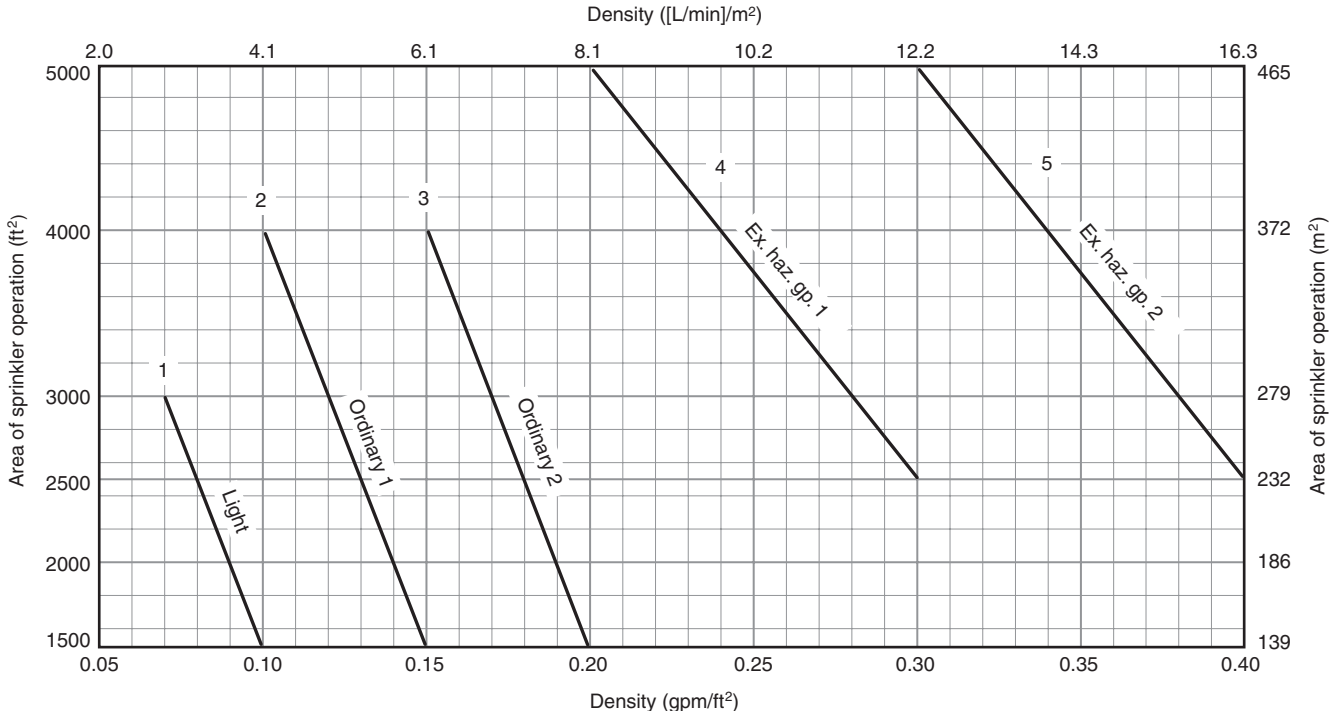


FIGURE 16.3.18 Density/Area Curve (Source: NFPA 13, *Standard for the Installation of Sprinkler Systems*)

As noted before, it is necessary to always round the calculated value up to the nearest whole number of sprinklers—in this case, five. In this example, the remote area consists of a total of eight sprinklers, five on the first branch line in the remote area and three on the second branch line in the remote area.

Using the number of sprinklers is a good means to estimate the size of the remote area. The actual floor area covered must still be verified. This becomes an issue when the distance to the adjacent wall(s) is not symmetrical with the distance to the opposite branch line or sprinklers. When this happens, the assigned area of sprinkler coverage is greater than the actual floor area covered, resulting in a remote area that is too small.

Once the shape and size of the remote area are established, the hydraulic calculation procedures can be initiated. The flow from the most remote sprinkler in the design area can be determined by multiplying the area of coverage of the sprinkler by the selected density. For example, if a density of 0.01 gpm/ft^2 was selected from the design curves and the sprinkler spacing is 200 ft^2 (18.6 m^2) per sprinkler, the flow from the sprinkler is:

$$Q = A \times \text{Density} = 200 \times 0.01 = 20 \text{ gpm}$$

This gives the flow from the most remote sprinkler. The pressure for that first sprinkler is then determined by the following formula, which describes the relationship between the sprinkler orifice (K-factor), the flow (Q), and the pressure (P):

$$Q = \text{K}\sqrt{P}$$

rearranged to $P = (Q/\text{K})^2$.

The flow from the hydraulically most remote sprinkler is then carried upstream to the next sprinkler. The pressure at this sprinkler can then be determined. This pressure is the pressure for the hydraulically most remote sprinkler plus the pressure needed to overcome the losses due to friction for the flow through the pipe connecting the second remote sprinkler on the branch line. Additionally, pressure losses for any fittings and elevation changes are also considered. Once again, the relationship between flow (Q), sprinkler characteristic (K), and pressure (P) is used. The K-factor for the sprinklers used is known as is the pressure; thus, the flow from that sprinkler can be determined.

The total system flow at this point is the additive discharge from these two sprinklers. The flow for these two sprinklers is used to calculate up to the next sprinkler, and the process is repeated as previously described.

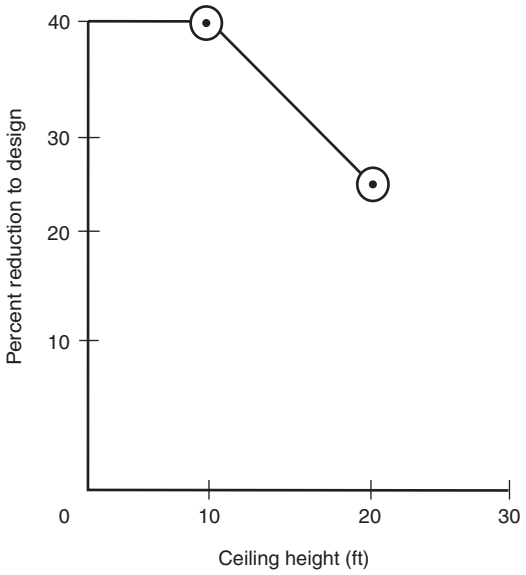
This method of conducting hydraulic calculation uses the Hazen-Williams equation. It was developed in the 1920s and provides sufficiently accurate results for sprinkler systems. The hydraulic design can be completed through the application of formulas, hydraulic tables as indicated in Table 16.3.12, or computer programs. Refer to related chapters of this handbook, the *NFPA Sprinkler Systems Handbook,* or a hydraulics text for more detailed information.

Special Design Features

Where sprinkler systems are used to protect hazards that are not classified by the occupancy hazard classifications specified in NFPA 13, other approaches should be used. Additionally, the approach just described applies to spray sprinklers only. Where other types of sprinklers such as ESFR, large-drop, or residential sprinklers are used, other methods need to be used. See the chapters on sprinklers, residential sprinkler systems, and sprinkler systems for storage applications in this handbook for additional information in this regard.

Under certain circumstances, adjustments to the area/density curve might be necessary. For example, where extended coverage sprinklers are used, NFPA 13 mandates that no fewer than five sprinklers be included in the design of a system. Without this rule, a system that used an extended-coverage sprinkler listed for 400 ft^2 (37.1 m^2) could be designed with only four sprinklers (1500 ft^2 ÷ 400 ft^2 = 3.75 or 4 sprinklers) (1 ft^2 = 0.0929 m^2). Other adjustments require a 30 percent increase to the design area where excessive roof slopes exist or when dry pipe systems are being considered.

A reduction in the system area of operation is permitted where quick-response (QR) sprinklers are used. This provision is limited to those situations in which the occupancy is either a light or ordinary hazard and in which certain ceiling configurations are present. Figure 16.3.19 shows the allowable reduction. The application of this reduction is further limited to spaces containing smooth, flat ceilings that are no higher than 20 ft (6.1 m). Where the ceiling is sloped, the maximum roof height needs to be used. When the size of the remote area is reduced, the density for whatever size was initially selected from Figure 16.3.18 is applied. This special rule was developed as the result



Note: $y = \frac{-3x}{2} + 55$

For ceiling height ≥ 10 ft and ≤ 20 ft, $y = \frac{-3x}{2} + 55$;
For ceiling height < 10 ft, $y = 40$;
For ceiling height > 20 ft, $y = 0$.
For SI units: 1 ft = 0.31 m.

FIGURE 16.3.19 Allowable Reduction in System Area When Quick-Response Sprinklers Are Used (Source: NFPA 13, *Standard for the Installation of Sprinkler Systems*)

TABLE 16.3.12 Friction Loss—PSI per Lineal Foot of Pipe, American Standard Weight, Black Steel Pipe

gpm	*1 in. (1.049 mm)*	*1¼ in. (1.380 mm)*	*1½ in. (1.610 mm)*	*2 in. (2.067 mm)*	*2½ in. (2.469 mm)*	*3 in. (3.068 mm)*	*3½ in. (3.548 mm)*
1	0.0005	0.0001	0.0001	—	—	—	—
2	0.0018	0.0005	0.0002	0.0001	—	—	—
3	0.0039	0.0010	0.0005	0.0001	0.0001	—	—
4	0.0066	0.0017	0.0008	0.0002	0.0001	—	—
5	0.0100	0.0026	0.0012	0.0004	0.0002	0.0001	—
6	0.0140	0.0037	0.0017	0.0005	0.0002	0.0001	—
7	0.0187	0.0049	0.0023	0.0007	0.0003	0.0001	—
8	0.0239	0.0063	0.0030	0.0009	0.0004	0.0001	0.0001
9	0.0297	0.0078	0.0037	0.0011	0.0005	0.0002	0.0001
10	0.0361	0.0095	0.0045	0.0013	0.0006	0.0002	0.0001
11	0.0431	0.0113	0.0053	0.0016	0.0007	0.0002	0.0001
12	0.0506	0.0133	0.0063	0.0019	0.0008	0.0003	0.0001
13	0.0587	0.0154	0.0073	0.0022	0.0009	0.0003	0.0002
14	0.0673	0.0177	0.0084	0.0025	0.0010	0.0004	0.0002
15	0.0764	0.0201	0.0095	0.0028	0.0012	0.0004	0.0002
16	0.0861	0.0226	0.0107	0.0032	0.0013	0.0005	0.0002
17	0.0963	0.0253	0.0120	0.0035	0.0015	0.0005	0.0003
18	0.1070	0.0282	0.0133	0.0039	0.0017	0.0006	0.0003
19	0.1180	0.0311	0.0147	0.0044	0.0018	0.0006	0.0003
20	0.1300	0.0342	0.0162	0.0048	0.0020	0.0007	0.0003
21	0.1420	0.0375	0.0177	0.0052	0.0022	0.0008	0.0004
22	0.1550	0.0408	0.0193	0.0057	0.0024	0.0008	0.0004
23	0.1690	0.0443	0.0209	0.0062	0.0026	0.0009	0.0004
24	0.1820	0.0480	0.0226	0.0067	0.0028	0.0010	0.0005
25	0.1970	0.0517	0.0244	0.0072	0.0030	0.0011	0.0005
26	0.2110	0.0556	0.0262	0.0078	0.0033	0.0011	0.0006
27	0.2270	0.0596	0.0281	0.0083	0.0035	0.0012	0.0006
28	0.2430	0.0638	0.0301	0.0089	0.0038	0.0013	0.0006
29	0.2590	0.0681	0.0321	0.0095	0.0040	0.0014	0.0007
30	0.2760	0.0725	0.0342	0.0101	0.0043	0.0015	0.0007
31	0.2930	0.0770	0.0363	0.0108	0.0045	0.0016	0.0008
32	0.3100	0.0817	0.0385	0.0114	0.0048	0.0017	0.0008
33	0.3290	0.0864	0.0408	0.0121	0.0051	0.0018	0.0009
34	0.3470	0.0913	0.0431	0.0128	0.0054	0.0019	0.0009
35	0.3660	0.0964	0.0455	0.0135	0.0057	0.0020	0.0010
36	0.3860	0.1020	0.0479	0.0142	0.0060	0.0021	0.0010
37	0.4060	0.1070	0.0504	0.0149	0.0063	0.0022	0.0011
38	0.4270	0.1120	0.0530	0.0157	0.0066	0.0023	0.0011
39	0.4480	0.1180	0.0556	0.0165	0.0069	0.0024	0.0012
40	0.4690	0.1230	0.0582	0.0172	0.0073	0.0025	0.0012
41	0.4910	0.1290	0.0610	0.0181	0.0076	0.0026	0.0013
42	0.5130	0.1350	0.0637	0.0189	0.0079	0.0028	0.0014
43	0.5360	0.1410	0.0666	0.0197	0.0083	0.0029	0.0014
44	0.5600	0.1470	0.0695	0.0206	0.0087	0.0030	0.0015
45	0.5830	0.1530	0.0724	0.0214	0.0090	0.0031	0.0015
46	0.6080	0.1600	—	0.0223	0.0094	0.0033	0.0016
47	0.6320	0.1660	0.0785	0.0232	0.0098	0.0034	0.0017
48	0.1730	—	0.0816	0.0242	0.0102	0.0035	0.0017
49	0.6830	0.1800	0.0848	0.0251	0.0106	0.0037	0.0018
50	0.7090	0.1860	0.0880	0.0261	0.0110	0.0038	0.0019

of a series of tests done in 1988, which compared the number of QR sprinklers operating to the number of standard-response sprinklers operating under similar fire scenarios.

One final point on system design involves fire department operations. This chapter has addressed considerations for correct operation of the system, which entail control or suppression of a fire. Final extinguishment of the fire, which can be accomplished by the sprinkler system in many cases, is normally contemplated as a function of the fire department. To ensure that water is available for fire department use while the sprinkler system is operating, NFPA 13 requires an allowance for hose streams. NFPA 13E, *Recommended Practice for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems,* provides guidance on the fire department interaction with the sprinkler system.

PLANS, CALCULATIONS, AND SYSTEM ACCEPTANCE

Plans

Factors impacting system design and installation must be documented. Knowledgeable designers need to present the design plans and specifications to the authority having jurisdiction (AHJ) for review and/or approval prior to the commencement of any installation work. The purpose of such documents is to ascertain that the appropriate system elements have been considered and incorporated. Detailed plans should include items such as the layout of the pipe, the location of the sprinklers, the location or spacing of supports, the location of the system riser, the location of any water supply control valves, and the location of the system water supply source, among other items, as required by NFPA 13.

Hydraulic Calculations

Where hydraulic calculations were conducted, they should be detailed and comprehensive. A summary sheet showing the design area of operation, the design density, the occupancy hazard, the hose stream allowance, the water supply information, and the total system demand should also be included. Detailed calculation sheets that document the proper sequence of sprinkler demand points must also be provided. These calculations must originate in the hydraulically most demanding portion of the system and reflect the hydraulic characteristics between that point and the water supply source.

Acceptance Test

The system acceptance or checkout test is used to verify that items previously submitted on the contract plans and reviewed by the AHJ were indeed provided, installed, incorporated, and located as indicated. Test provisions can include items such as a hydrostatic test of the system piping. This test is used to verify the quality of the pipe and fitting installation. In addition to being hydrostatically tested, dry pipe systems must also be pneumatically tested for 24 hours to make sure that air is not being lost to faulty installation of fittings or pipe.

On completion of the acceptance test described in NFPA 13, the contractor's material and test certificate is signed by the installing contractor, the AHJ, and the building owner (or the designated representative). This certificate becomes the basis for final acceptance and commissioning of the system and often becomes a determining factor in allowing the certificate of occupancy to be issued for the building.

Once system acceptance has occurred, it is now incumbent on the building owner to follow up with periodic inspection, testing, and maintenance of the system as specified in NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems.* Future changes to the building or the contents are likely to impact the sprinkler system and need to be accounted for. Ignoring changes to the system and the associated fire hazard can lead to inadequate system performance during a fire. For example, relatively minor architectural changes can create severe obstructions to a sprinkler's discharge pattern and prevent water from reaching the fire area.

MARINE APPLICATIONS

Marine applications of sprinkler systems were formally introduced for the 1996 edition of NFPA 13.

Since 1991, the U.S. Coast Guard has provided a circular on merchant vessel sprinkler systems. This circular basically requires the use of a NFPA 13–type sprinkler system on certain categories of vessels. The prevalence of gaming-type excursion vessels on both inland and coastal routes has been a motivating factor in this aspect of sprinkler protection.

Sprinkler systems are not exclusively limited to these vessel types. The span of marine vessels that will require systems in the near future includes not only excursion boats for both gaming and pleasure but also cruise ships and merchant vessels used to haul various commodities. The Safety of Life at Sea (SOLAS) regulations, promulgated by the International Maritime Organization (IMO), also require sprinkler systems.

The marine chapter in NFPA 13 deals with the unique aspects of a ship's operating environment. In general, all of the current rules of NFPA 13 will still be applicable, except those that are amended or modified by this particular chapter. Many design considerations are similar between a ship and building, but differences exist. These include references to decks instead of floors, shore connections instead of fire department connections, and sprinkler pumps instead of fire pumps. The terms and connotations are similar but the arrangement and importance of each will differ.

One aspect of the design of a sprinkler system on a merchant vessel that is underway, as compared to a building, is that the ship must be entirely self-reliant. That is, occupants cannot be readily evacuated; the fire department cannot be summoned to assist with manual fire suppression; and a maintenance contractor cannot be called in at a moment's notice to repair a system fault. Because of these factors, additional redundant features will be found on the ship that otherwise would not be considered in the design of a land-based structure.

Other conditions that must be considered include the potential for the heaving and rolling that a ship may experience and the resulting impact it would have on sprinkler system piping.

This problem can be dealt with by incorporating some of the seismic design features that are discussed in NFPA 13.

The exposure of certain pipe materials and sprinklers to corrosive atmospheres is also a concern. The use of nonmetallic pipe and the special corrosion-protection measures that are discussed in NFPA 13 are applicable to this situation.

Perhaps the most crucial design consideration is the arrangement and reliability of the water supply. In most circumstances, a nearly infinite supply is readily available to a merchant vessel, but how it is arranged and supplied to the ship's sprinkler system is of paramount importance. A number of water supplies (never less than two) are deemed acceptable, and each must be arranged to ensure that a high level of reliability is obtained. A pressure tank is considered an acceptable method to satisfy part of the water supply requirements. This source must be charged with a quantity of fresh water that will supply the system for a period of at least 1 minute, in the case of a wet pipe system. The supply for a dry pipe system should be adequate to allow for complete filling of the pipe volume plus a quantity of water to permit 1 minute of system discharge.

A sprinkler pump is one of the supply sources that must always be provided. The sprinkler pump has characteristics that are similar to a fire pump, and it must be specifically listed for marine application. The power supply for a sprinkler pump must be arranged to minimize the chances of a fire affecting the starting or operation of the pump. This is done by obtaining the power supply for the pump from the main switchboard on the ship. A backup source of power from a generator must also be provided.

In addition to these arrangements, the water supply for the onboard sprinkler system must also be interconnected with the ship's fire main system. The fire main system is the equivalent of an underground distribution system that is also used to supply strategically located hose outlets on the ship. Figure 16.3.20 shows one basic configuration of a pressure tank, a fire pump, and the ship's fire main.

The fire department connection depicted in Figure 16.3.20 should typically be of the same style and size of those used on fixed structures. Such connections may be supplied by land-based fire department pumpers. In other cases, the source of supply for this connection may be from a fireboat when the vessel is in or near a port area. The companion international shore connection (ISC) is a universal water supply hookup for vessels operating outside of their home port at the time of a fire. As shown in Figure 16.3.20, both types of connections may be used to supplement the other automatic sources of supply for the sprinkler system.

Another feature associated with this unique operating environment is the need to carry additional spare parts to facilitate basic repairs while the vessel is underway. Certain merchant vessels and cruise ships may be as much as four days away from the nearest port capable of repairing system impairments.

SUMMARY

Automatic sprinkler systems serve as one of the most effective methods for providing fire protection and life safety. Sprinkler systems can be installed in various types of buildings and facilities such as manufactured homes, high-rise buildings, warehouse facilities, manufacturing facilities, and, more recently, merchant vessels. Technological advances continue with piping materials, sprinklers, fittings, and hangers both in terms of the products offered and the manner in which they are installed. Advances in technology will continue to produce more effective and cost-efficient sprinkler systems for an increasing number of applications. The greatest obstacle to even broader

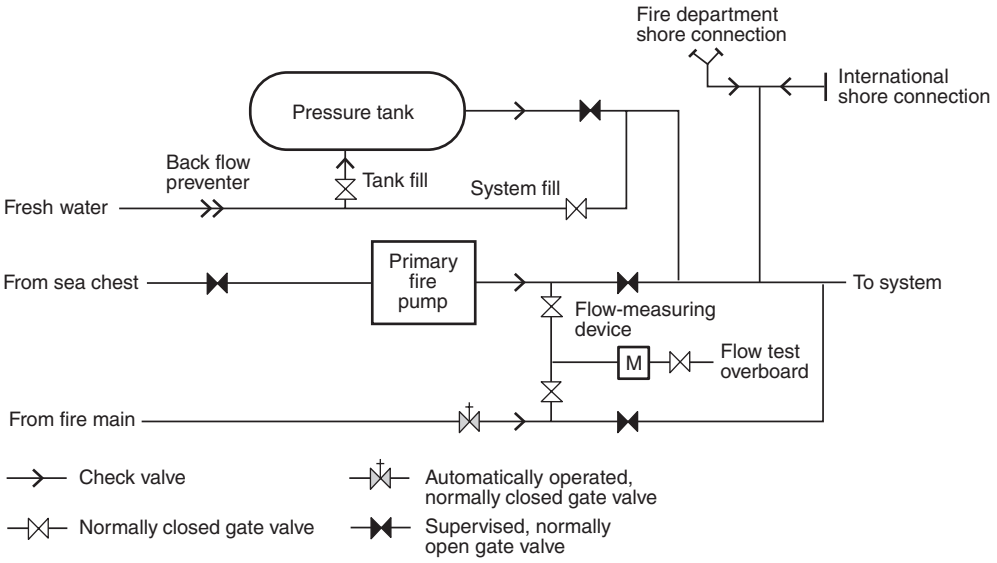


FIGURE 16.3.20 Abbreviated Example of a Water Supply with Fire Pump Backup for Marine Applications

use of sprinkler systems is public perception rather than limitations with available technology.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on automatic sprinkler systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*
NFPA 13E, *Recommended Practice for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems*
NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 22, *Standard for Water Tanks for Fire Protection*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 30, *Flammable and Combustible Liquids Code*
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Chapter 4

Hanging and Bracing of Water-Based Systems

Russell P. Fleming

Chapter Contents

Hangers
Hanger Installation
Earthquake Bracing
Joint Restraint of Underground Piping

Key Terms

automatic sprinkler system, bracing, earthquake, floor-mounted support, hanger, piping (underground), restrained joint system, thrust block, water-based fire protection

Physical support of a water-based fire suppression system is considered essential to the system's proper operation, and specific requirements addressing hanging of automatic sprinkler systems have been included in NFPA 13, *Standard for the Installation of Sprinkler Systems,* since the first edition of the standard was published in 1896. This chapter identifies the various aspects of hanging and bracing that apply to water-based systems, and provides an understanding of some of the assumptions and conventions that underlie the specific rules contained in the NFPA system installation standards.

The earliest sprinkler system hanger rules called for either U-type hangers made of round wrought iron or malleable cast iron, ring clips, or approved adjustable hangers. Flat U-type hangers were permitted if they were at least 3⁄16 in. (5 mm) thick. Hangers were required to be at least 12 in. (300 mm) from sprinklers to avoid interference with water distribution, except that round hangers were permitted as close as 3 in. (75 mm). For concrete construction, cast iron inserts were recommended, although expansion bolts could be used in existing buildings, preferably in a horizontal position. Those familiar with current hanger rules will recognize that some of these rules are still in place.

Guidance for protecting automatic sprinkler systems against earthquakes was first included in the 1947 edition of NFPA 13. The insurance rating bureaus on the West Coast of the United States had urged that special features be included in systems installed in earthquake-prone areas. Yet there were no major earthquakes in the continental United States between 1940 and 1970, and it was not until the San Fernando earthquake in California in 1971 that the NFPA 13 guidance was tested. Following that earthquake it was observed that the performance of the sprinkler system obviously depended on how well the building itself survived the ground movement—if the sprinklered building fared well, so did the sprinkler system. Studies of the performance of sprinkler systems in the Loma Prieta earthquake in the San Francisco area in 1989 and the Northridge earthquake in the Los Angeles area in 1994 were the basis of additional refinements to sprinkler system rules, which are also often applied to other water-based fire protection systems.

The hanger rules of NFPA 13 are also directly referenced or at least serve as the basis for rules within NFPA standards for other water-based fire suppression systems. For this reason, the committee responsible for the hanging and bracing criteria is designated the Committee on Hanging and Bracing of Water-Based Fire Protection Systems. Today, the rules within NFPA 13 that address structural support can be considered in four parts: rules for hangers, rules for hanger installation, rules for bracing systems against earthquake movement, and rules for joint restraint of underground piping systems.

For related topics, see the following chapters in Section 16: Chapter 1, "Principles of Automatic Sprinkler System Performance"; Chapter 2, "Automatic Sprinklers"; and Chapter 3, "Automatic Sprinkler Systems."

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TABLE 16.4.1 Maximum Pipe Stand Heights

		Pipe Stand Diameter									
Diameter of Pipe		*1½ in.*		*2 in.*		*2½ in.*		*3 in.*		*4 in.*	
1½ in.	(40 mm)	10 ft	(3.0 m)	14 ft	(4.3 m)	18 ft	(5.5 m)	28 ft	(8.5 m)	30 ft	(9.1 m)
2 in.	(50 mm)	8 ft	(2.4 m)	12 ft	(3.7 m)	16 ft	(4.9 m)	26 ft	(7.9 m)	30 ft	(9.1 m)
2½ in.	(65 mm)	6 ft	(1.8 m)	10 ft	(3.0 m)	14 ft	(4.3 m)	24 ft	(7.3 m)	30 ft	(9.1 m)
3 in.	(75 mm)	—	—	8 ft	(2.4 m)	12 ft	(3.7 m)	22 ft	(6.7 m)	30 ft	(9.1 m)
>3 in.	(>75 mm)	—	—	—	—	—	—	—	—	10 ft	(3.0 m)

Source: NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection.*

HANGERS

Hanger Types

Various types of hangers (Figure 16.4.1) are used to support fire protection piping, with a variety of components used to attach to the building structure or to attach to the piping. Some types of hangers combine the building attachment component and the pipe attachment component. This would include U-type hangers and short straps, sometimes referred to as clips. Adjustable swivel ring hangers (also commonly known as adjustable steel band hangers), clevis hangers, and split ring hangers are the pipe attachment components used most commonly for suspending horizontal fire protection piping. C-type clamps are the most common structure attachment components for steel structures, and attach rigidly to one edge of the top or bottom flange of a structural member. All-thread mild steel rods are commonly used between the structural attachment and the piping attachment.

Listing of Hangers

Hanger components that attach directly to the building structure or to the piping are required by NFPA standards to be listed for use in fire protection systems. An exception is made within NFPA 13 for components that are made of ferrous metal, are certified by a professional engineer to meet the load requirements stated previously, and are supported adequately and in conformance with the maximum spacing rules.

Hangers made from mild steel rod, such as U-hooks and eye rods, are not required to be listed. Mild steel rods are considered to have demonstrated through practice their ability to support the required loads with adequate safety factors. Pipe straps are not included in the exception and therefore must be listed. Typical fasteners such as screws and bolts are also exempt from the listing requirement.

Special listed pipe can be required to use special hangers or hanger spacing as part of its listing limitations and restrictions. Manufacturers are obligated to make such product data available.

Floor-Mounted Supports

NFPA system installation standards have not traditionally discussed floor supports. Because most fire protection piping systems are located within buildings and because it is desirable to maximize usable floor space, piping is usually supported on hangers from overhead structural members. Nevertheless, floor-mounted supports have often been used for risers other than those protruding straight upward through the floor. A floor support usually includes some type of saddle to help avoid slippage of the pipe.

NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection,* provides rules governing sizing of pipe stands used to support fire protection piping in the absence of a building structure (Tables 16.4.1 and 16.4.2). The criteria include allowance to increase spacing between vertical supports by up to half of the length of braces extending from the vertical supports to the horizontal piping (Figure 16.4.2).

Hanger Loads

There is a difference between the safety factors applied to the hanger versus those for the building structure. In general, the hanger components are expected to support five times the weight of the water-filled piping plus a load of 250 lb (114 kg) at any point of piping support. The intent is not to simultaneously require loading of all hangers, but to represent the possibility of an individual using the piping to support the weight of a human body. This has often been the case in industrial occupancies, where sprinkler system piping may be temporarily loaded during maintenance operations such as ceiling cleaning or painting. The 250 lb (114 kg) load is specified at the point of

TABLE 16.4.2 Pipe Stand Distance

Loop Size		Distance Between Pipe Stands	
in.	*mm*	*ft*	*m*
1	25	10	3.0
1½	40	12	3.7
2	50	14	4.3
2½–8	65–200	15	4.6

Source: NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection.*

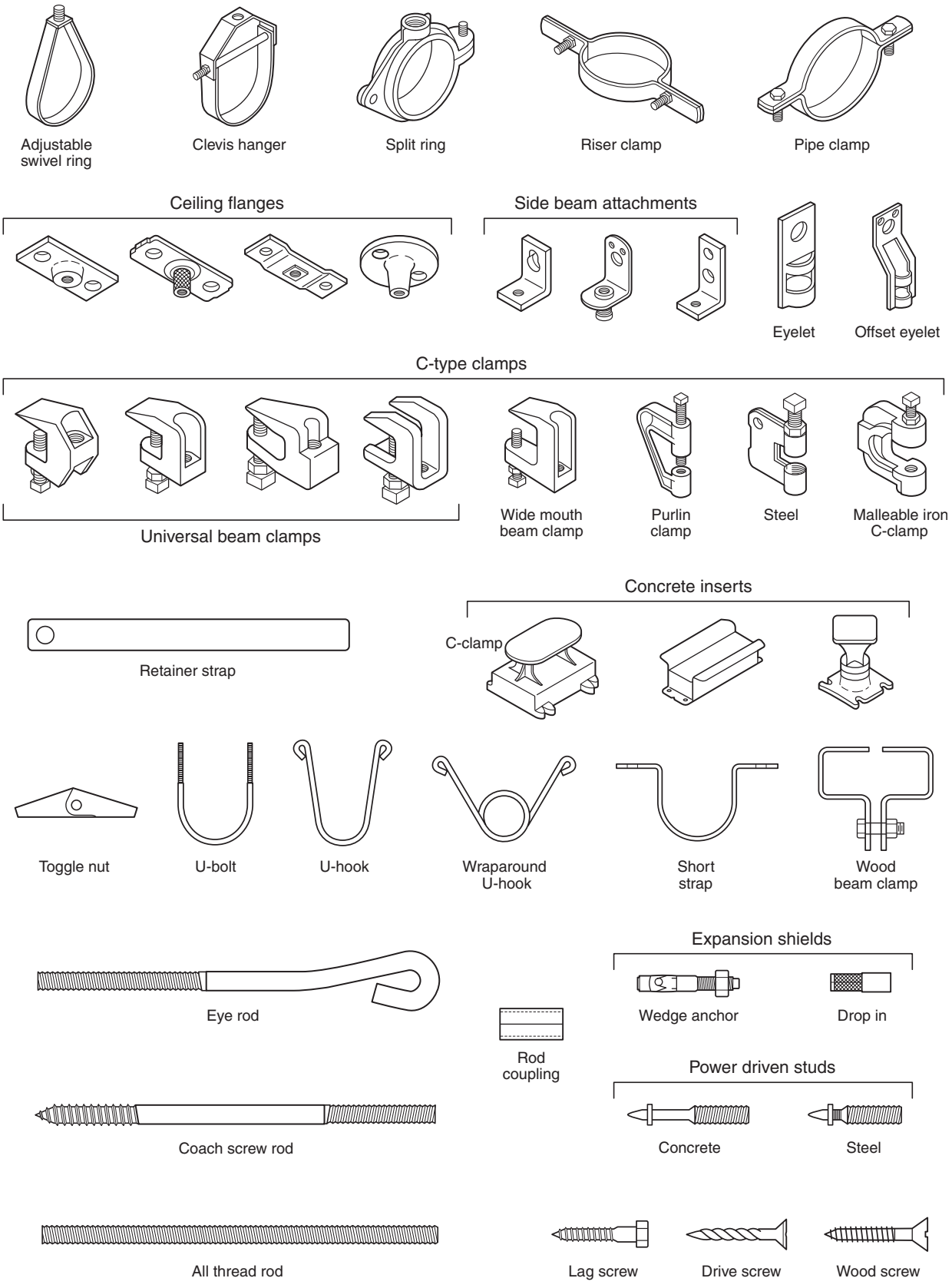
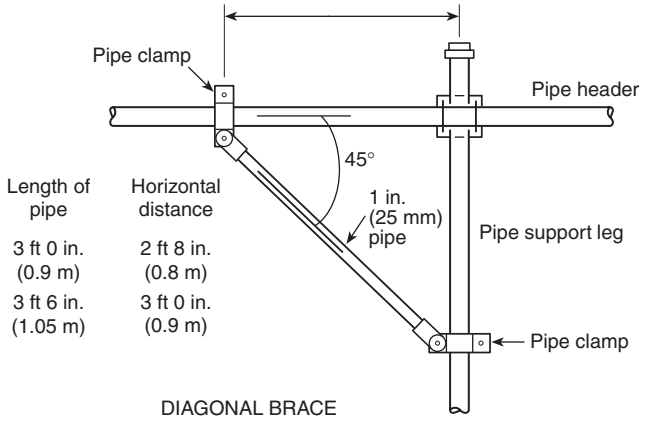


FIGURE 16.4.1 Common Types of Acceptable Hangers



Note: When using diagonal braces as supports, the maximum dimension between support legs can be exceeded by one-half the total horizontal distance of the diagonal braces.

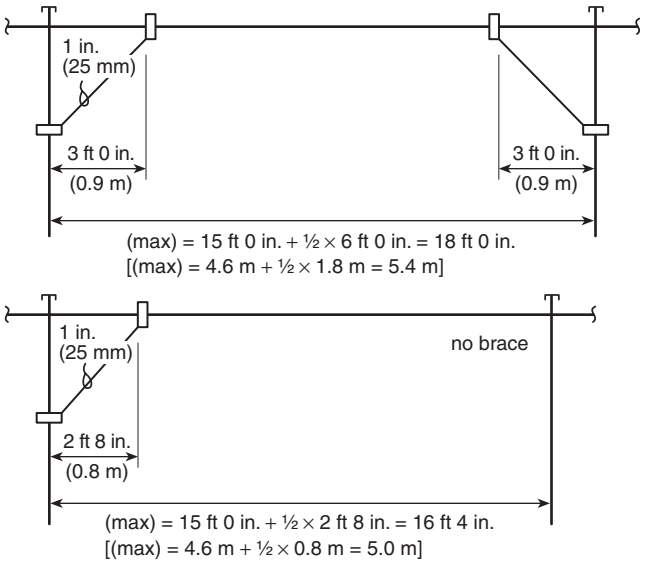


FIGURE 16.4.2 Sway/Support Brace

hanging because it is recognized that some types of piping will not support the additional load at midspan.

The structure itself must be capable of supporting the weight of the water-filled pipe plus a load of 250 lb (114 kg) at each point of support. The safety factor of five is not applied so as to permit the installation of systems in a wider number of existing buildings. There are two exceptions to the structural support requirements stated within the standard. One permits toggle hangers for piping 1½ in. (40 mm) or smaller under ceilings of hollow tile or metal lath and plaster. The other permits drilling or punching vertical members of metal deck for support of pipe 1 in. (25 mm) and smaller and using through bolts. Neither of these special options would be expected to carry the 250 lb (114 kg) load in addition to the weight of the water-filled pipe. The use of a suspended ceiling to support a listed flexible sprinkler drop is another exception, although not specifically addressed as such within NFPA 13.

Trapeze Hangers

Trapeze hangers are used where there is a need to provide a support for hangers between the structural members of the building. Like the trapeze that supports an acrobat, a trapeze hanger provides a span for the support of a sprinkler system or other fire protection piping (Figure 16.4.3).

In a fire sprinkler system, trapeze hangers usually support the larger piping, or mains. This is because it is most efficient to run the branch lines perpendicular to the closely spaced joists or purlins. In this manner, the joists or purlins provide ready points of attachment for hangers for most of the system piping. This means that the mains must generally be supported from the primary structural members that are supporting the joists, or purlins. Where there is a need for points of support between the primary structural members, trapeze hangers can be provided, attached on both ends to adjacent joists or purlins.

NFPA 13 treats trapeze hangers as an extension of the building structure, based on the fact that a trapeze hanger is always an alternative to a modification of the structure that would permit an acceptable point of hanging. This is especially true with wood frame structures. Joists are sometimes added where needed to attach system hangers. Some manufacturers of composite wood joists publish details showing how wood trapeze members are to be affixed between adjacent joists to provide attachment points for sprinkler piping. Because trapeze hangers are considered an extension of the building structure, their requirements are not based on the "five times" safety factor used for hangers, but rather on the requirement used for the building structure, that is, the weight of the water-filled piping plus 250 lb (114 kg).

NFPA 13 contains two tables that simplify the selection of trapeze hangers. Both tables are based on the concept of the trapeze hanger as a simple center-loaded span. Based on the use of steel with a tensile strength of 15 ksi supporting a maximum 15 ft (5 m) of pipe, Table 16.4.3 provides the minimum section modulus needed based on the span of the trapeze and the diameter of the pipe to be supported. Values are separately provided for Schedule 10 pipe and for Schedule 40 pipe, or Schedule 30 for sizes 8 in. (200 mm) and larger. A formula in Appendix A of

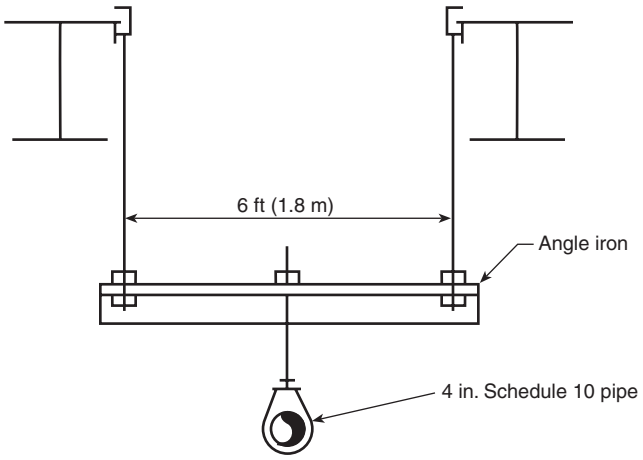


FIGURE 16.4.3 Trapeze Hanger

TABLE 16.4.3 Section Modulus Required for Trapeze Members (in.^{3})

Span of Trapeze	*1 in.*	*1¼ in.*	*1½ in.*	*2 in.*	*2½ in.*	*3 in.*	*3½ in.*	*4 in.*	*5 in.*	*6 in.*	*8 in.*	*10 in.*
1 ft 6 in.	0.08	0.09	0.09	0.09	0.10	0.11	0.12	0.13	0.15	0.18	0.24	0.32
	0.08	0.09	0.09	0.10	0.11	0.12	0.13	0.15	0.18	0.22	0.30	0.41
2 ft 0 in.	0.11	0.12	0.12	0.13	0.13	0.15	0.16	0.17	0.20	0.24	0.32	0.43
	0.11	0.12	0.12	0.13	0.15	0.16	0.18	0.20	0.24	0.29	0.40	0.55
2 ft 6 in.	0.14	0.14	0.15	0.16	0.17	0.18	0.20	0.21	0.25	0.30	0.40	0.54
	0.14	0.15	0.15	0.16	0.18	0.21	0.22	0.25	0.30	0.36	0.50	0.68
3 ft 0 in.	0.17	0.17	0.18	0.19	0.20	0.22	0.24	0.26	0.31	0.36	0.48	0.65
	0.17	0.18	0.18	0.20	0.22	0.25	0.27	0.30	0.36	0.43	0.60	0.82
4 ft 0 in.	0.22	0.23	0.24	0.25	0.27	0.29	0.32	0.34	0.41	0.48	0.64	0.87
	0.22	0.24	0.24	0.26	0.29	0.33	0.36	0.40	0.48	0.58	0.80	1.09
5 ft 0 in.	0.28	0.29	0.30	0.31	0.34	0.37	0.40	0.43	0.51	0.59	0.80	1.08
	0.29	0.29	0.30	0.33	0.37	0.41	0.45	0.49	0.60	0.72	1.00	1.37
6 ft 0 in.	0.33	0.35	0.36	0.38	0.41	0.44	0.48	0.51	0.61	0.71	0.97	1.30
	0.34	0.35	0.36	0.39	0.44	0.49	0.54	0.59	0.72	0.87	1.20	1.64
7 ft 0 in.	0.39	0.40	0.41	0.44	0.47	0.52	0.55	0.60	0.71	0.83	1.13	1.52
	0.39	0.41	0.43	0.46	0.51	0.58	0.63	0.69	0.84	1.01	1.40	1.92
8 ft 0 in.	0.44	0.46	0.47	0.50	0.54	0.59	0.63	0.68	0.81	0.95	1.29	1.73
	0.45	0.47	0.49	0.52	0.59	0.66	0.74	0.79	0.96	1.16	1.61	2.19
9 ft 0 in.	0.50	0.52	0.53	0.56	0.61	0.66	0.71	0.77	0.92	1.07	1.45	1.95
	0.50	0.53	0.55	0.59	0.66	0.74	0.81	0.89	1.08	1.30	1.81	2.46
10 ft 0 in.	0.56	0.58	0.59	0.63	0.68	0.74	0.79	0.85	1.02	1.19	1.61	2.17
	0.56	0.59	0.61	0.65	0.74	0.82	0.90	0.99	1.20	1.44	2.01	2.74

Notes:
1. Top values are for Schedule 10 pipe; bottom values are for Schedule 40 pipe.
2. The table is based on a maximum allowable bending stress of 15 ksi and a midspan concentrated load from 15 ft (4.6 m) of water-filled pipe, plus 250 lb (114 kg).

For SI units, 1 in. = 25.4 mm; 1 in.^{3} = 16,387 mm^3; 1 ft = 0.3048 m.

Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

NFPA 13 can be used to compute a shorter equivalent length of span where it can be established that the load will be to one side as opposed to the center of the trapeze span.

Table 16.4.4 provides the section modulus available using Schedule 10 pipe, Schedule 40 pipe, or selected steel angles as the trapeze member. It is only necessary to ensure that the trapeze selected from Table 16.4.4 has a section modulus greater than or equal to that needed from Table 16.4.3.

NFPA 13 requires that the trapeze member be secured to prevent slippage. Because pipe is readily available to sprinkler contractors, it is the most common type of trapeze member, and it is typically a smaller pipe size than the pipe being supported. To ensure adequate strength of hanger components, NFPA 13 requires that all ring, strap, or clevis hangers supporting the larger pipe be sized for the larger pipe. The ring or strap must be shaped to accommodate the smaller pipe size. Otherwise the potential exists for the ring or strap to elongate over time with the load, which could result in a change of pitch of the piping.

Aside from steel pipe and angles, other types of structural members are used as trapeze members, provided the section modulus is acceptable. This allows the use of such things as steel channels, where the manufacturers or specifiers would be expected to ensure the minimum tensile strength and to provide information on the available section modulus. Because the section modulus of a nonsymmetrical member changes with orientation, it is important that orientation be considered.

The NFPA 13 language does not specifically allow the use of wood trapeze members, and the language in the standard calling for ferrous hangers and banning the use of nails as fasteners might appear to prohibit their use. This is when it must be recognized that the building designer always has the option of allowing a modification of the building structure to provide a built-in trapeze. The manner in which extensions are made to the building structure must be acceptable to the responsible design professional.

HANGER INSTALLATION

Spacing of hangers is based essentially on the expected beam strength of the piping. For this reason, NFPA 13 and related standards reduce allowable spans for piping with less beam strength than traditional standard weight (Schedule 40) steel pipe. Table 16.4.5 shows the maximum distance between hangers based on type of piping. Other rules, such as the general requirement that hangers be provided on crossmains between every two branch lines, can supersede these maximum spacings.

Special rules relate to hanger installation. For example, nails are not permitted to fasten hangers. Holes must be predrilled for

TABLE 16.4.4 Available Section Moduli of Common Trapeze Hangers (in.^{3})

Pipe (in.)	*Modulus*	*Angles*	*Modulus*	*Pipe (in.)*	*Modulus*	*Angles*	*Modulus*
Schedule 10				Schedule 40			
1	0.12	1½ × 1½ × 3/16	0.10	1	0.13	3 × 2½ × 3/16	0.43
1¼	0.19	2 × 2 × ⅛	0.13	1¼	0.23	3 × 3 × 3/16	0.44
1½	0.26	2 × 1½ × 3/16	0.18	1½	0.33	2½ × 2½ × 5/16	0.48
2	0.42	2 × 2 × 3/16	0.19	2	0.56	3 × 2 × ¼	0.54
2½	0.69	2 × 2 × ¼	0.25	2½	1.06	2½ × 2 × ⅜	0.55
3	1.04	2½ × 1½ × 3/16	0.28	3	1.72	2½ × 2½ × ⅜	0.57
3½	1.38	2½ × 2 × 3/16	0.29	3½	2.39	3 × 3 × ¼	0.58
4	1.76	2 × 2 × 5/16	0.30	4	3.21	3 × 3 × 5/16	0.71
5	3.03	2½ × 2½ × 3/16	0.30	5	5.45	2½ × 2½ × ½	0.72
6	4.35	2 × 2 × ⅜	0.35	6	8.50	3½ × 2½ × ¼	0.75
		2½ × 2½ × ¼	0.39			3 × 2½ × ⅜	0.81
		3 × 2 × 3/16	0.41			3 × 3 × ⅜	0.83
						3½ × 2½ × 5/16	0.93
						3 × 3 × 7/16	0.95
						4 × 4 × ¼	1.05
						3 × 3 × ½	1.07
						4 × 3 × 5/16	1.23
						4 × 4 × 5/16	1.29
						4 × 3 × ⅜	1.46
						4 × 4 × ⅜	1.52
						5 × 3½ × 5/16	1.94
						4 × 4 × ½	1.97
						4 × 4 × ⅝	2.40
						4 × 4 × ¾	2.81
						6 × 4 × ⅜	3.32
						6 × 4 × ½	4.33
						6 × 4 × ¾	6.25
						6 × 6 × 1	8.57

For SI units, 1 in. = 25.4 mm; 1 in.^{3} = 16,387 mm^3; 1 ft = 0.3048 m.
Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

TABLE 16.4.5 Maximum Distance Between Hangers (ft-in.)

	Nominal Pipe Size (in.)											
	¾	*1*	*1¼*	*1½*	*2*	*2½*	*3*	*3½*	*4*	*5*	*6*	*8*
Steel pipe except threaded lightwall	NA	12-0	12-0	15-0	15-0	15-0	15-0	15-0	15-0	15-0	15-0	15-0
Threaded lightwall steel pipe	NA	12-0	12-0	12-0	12-0	12-0	12-0	NA	NA	NA	NA	NA
Copper tube	8-0	8-0	10-0	10-0	12-0	12-0	12-0	15-0	15-0	15-0	15-0	15-0
CPVC	5-6	6-0	6-6	7-0	8-0	9-0	10-0	NA	NA	NA	NA	NA
Polybutylene (IPS)	NA	3-9	4-7	5-0	5-11	NA	NA	NA	NA	NA	NA	NA
Polybutylene (CTS)	2-11	3-4	3-11	4-5	5-5	NA	NA	NA	NA	NA	NA	NA
Ductile Iron Pipe	NA	NA	NA	NA	NA	NA	15-0	NA	15-0	NA	15-0	15-0

For SI units, 1 in. = 25.4 mm; 1 ft = 0.3048 m.
Note: IPS = iron pipe size; CTS = copper tube size.
Source: NFPA 13, *Standard for the Installation of Sprinkler Systems.*

proper installation of lag screws and coach screw rods. Wood screws must be installed with a screwdriver. Drive screws are permitted only in the horizontal position and only for pipe 2 in. (50 mm) and smaller.

Hangers in Earthquake Areas

Special limitations apply to hangers in areas considered subject to earthquakes. Retaining straps must be provided for all C-type clamps. The retaining strap either must be listed as part of the hanger listing or must meet specified minimum dimensions. In the absence of an adequate lip on the structural member to hold the retaining strap, the strap can be secured with a bolt or screw.

Unless they are specially listed for use in high-risk earthquake areas, powder-driven fasteners are not permitted to attach hangers where the assigned earthquake accelerations exceed half of gravity, or, in other words, where the lateral forces to be resisted exceed half the weight of the water-filled pipe.

Momentum Restraint

Relatively little attention has been given to the subject of restraint or bracing against momentum of waterflow within water-based fire suppression systems. Because linear momentum of fluid flow is conserved, unbalanced momentum forces can occur at changes in piping direction when water surges into a deluge, dry, or preaction system, and to a lesser extent can take place within a wet pipe system as well. However, it is generally believed that the safety factors inherent in the system to resist hydrostatic forces adequately handle such momentum forces, especially with regard to threaded and mechanical joints. To resist permanent shifting of the piping the system relies on the structural attachment components, in combination with the rigidity of the system piping. Where flexible couplings allow angular displacement and the pipe is therefore not capable of resisting loads internally, the hanger attachments must provide sufficient resistance through their method of attachment to avoid being pulled off the building structural component.

Beginning in 1987, NFPA 13 was modified to recognize the impulse force that is the reaction to flow of water through individual sprinklers. Concern was expressed that a single pendent sprinkler extending through a ceiling and operated under high pressure could be lifted above the ceiling from the thrust forces. Subsequent tests showed that a standard K = 5.6 (K_m = 8.0) orifice spray pendent sprinkler operating at 150 psi (10.3 bar) would experience a thrust force of 70–90 lb (10–13 N). Figure 16.4.4 shows the upward deflection of 1 in. (25.4 mm) Schedule 40 pipe under steady state flow of sprinklers with nominal orifice coefficients K = 5.6 (K_m = 80) and K = 8.0 (K_m = 115) at various pressures in the absence of any special restraint.

A pendent sprinkler at the end of a branch line should be given special restraint where the maximum pressure at the sprinkler exceeds 100 psi (6.9 bar) and the sprinkler extends downward through a ceiling. The special restraint involves use of a hanger assembly that prevents upward movement of the sprinkler, located no more than 12 in. (300 mm) from the end of steel pipe branch line, or no more than 6 in. (150 mm) from the end of a copper tube branch line. If these limits are exceeded, the branch line can be extended beyond the last sprinkler on the branch line. A parallel provision applies to pendent sprinklers through ceilings located on armovers.

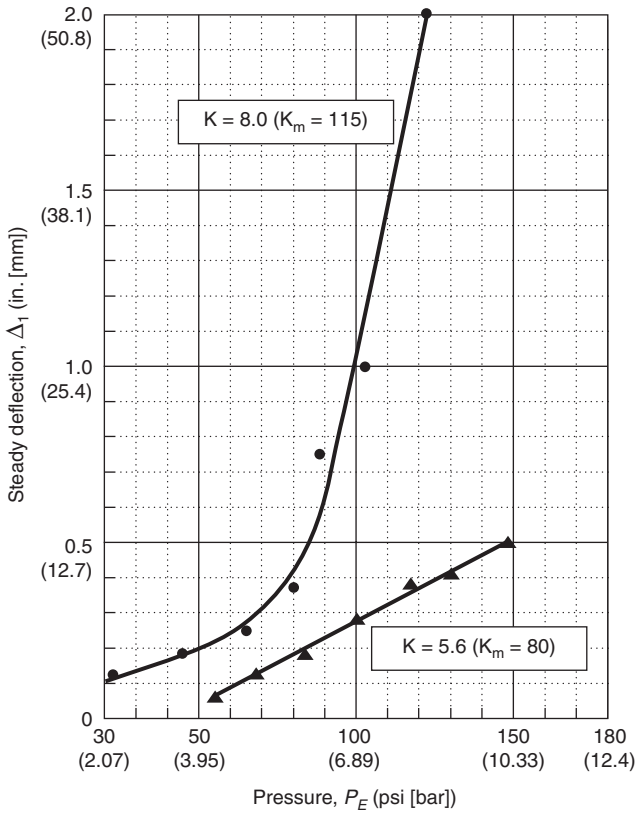


FIGURE 16.4.4 Pipe Deflection

The uplift phenomenon occurs only with the end sprinkler operating. The uplift is considerably reduced with a second sprinkler flowing, and is negligible for the next-to-end sprinkler flowing alone. A formal interpretation was issued by the Committee on Automatic Sprinklers to clarify that the 100 psi (6.9 bar) trigger does not include potential pressure supplied through the fire department connection.

EARTHQUAKE BRACING

Bracing is only one aspect of protecting fire sprinkler systems against earthquakes, but it is probably the most visible aspect. The others are providing necessary flexibility through the use of flexible couplings and clearances and providing restraint. Like bracing, restraint helps to hold piping in place, but to a lesser degree.

Successful bracing of fire protection systems involves determination of appropriate force factors, tentative placement of sway bracing, determination of loads to braces, and verification that the loads can be carried by the sway brace components.

Determination of Force Factors

The determination of seismic force levels is of primary significance in providing bracing, because bracing must be sized and spaced to resist the anticipated forces. NFPA 13 has never dealt

with the issue of where earthquake protection is to be required, but only provided a means of protecting the system. The decision to require protection of sprinkler systems or other mechanical systems against earthquake forces, as well as the magnitude of those forces, is generally stated within building codes, or determined by other authorities having jurisdiction. The decision is based on the past seismic activity of an area and its potential for future earthquakes.

Changes in Protection Criteria. Since past building codes were not always specific with regard to anticipated earthquake forces, NFPA 13 protection criteria traditionally were based on an assumed horizontal acceleration of half of gravity or 0.5 g. This acceleration resulted in a horizontal force factor of $F_p = 0.5W_p$ or a horizontal force equivalent to half the weight of the water-filled piping. This acceleration was judged to be suitably conservative for even highly active earthquake areas, and it was not considered economically justified to fine-tune system bracing loads to accommodate lower expected earthquake forces in some localities. The 0.5 g value continues to serve as the default value for bracing criteria. However, since the 1994 edition, NFPA 13 has permitted the use of other force factors to accommodate code requirements that specify the use of higher or lower horizontal acceleration values. Use of alternative force factors is becoming common for the following two reasons:

1. Both the 1989 Loma Prieta and 1994 Northridge earthquakes in California demonstrated horizontal accelerations in excess of 0.5 g.
2. Earthquake protection of sprinkler systems is now mandated in many areas where expected maximum accelerations are less than 0.5 g.

Essentially, the force equation became $F_p = C_pW_p$, where the value of C_p was determined by the code or other authority, and could be higher or lower than 0.5.

Coordination of Earthquake Protection Provisions. In a tentative interim amendment (TIA) to the 2002 edition, which became effective August 6, 2003, and to an even greater extent in the changes to the 2007 edition, additional changes were made to better coordinate the earthquake protection provisions of NFPA 13 with those of the National Earthquake Hazards Reduction Program's *Recommended Provisions for Seismic Regulations for New Buildings and Other Structures.*[1] These provisions, which have themselves gone through several iterations, were developed through the Building Seismic Safety Council of the National Institute of Building Sciences, with funding from the U.S. Federal Emergency Management Agency. The provisions have served as the basis of successive changes to model building codes in the United States and are now incorporated in ASCE 7, *Minimum Design Loads for Buildings and Other Structures.*[2] ASCE 7 is in turn adopted by reference in current model building codes, with the 2005 edition (ASCE 7-05) adopted by the 2006 editions of both the International Building Code®[3] and *NFPA 5000®, Building Construction and Safety Code®.*

Seismic Design Force Formula. The 2003 TIA to NFPA 13 reduced the allowable fastener loads to match current industry standards, limited the maximum spacing of lateral braces to 40 ft (12.2 m) on center, and provided clarification of how NFPA 13 could be used in conjunction with the seismic design force formula contained in ASCE 7 for use with nonstructural components:

$$F_p = 0.4a_pS_{DS}W_p\frac{1+2(z/h)}{R_p/I_p}$$

where

F_p = Seismic design force

S_{DS} = Design spectral acceleration, short period, found as $S_{DS} = ⅔S_{MS}$, where S_{MS} is the maximum considered earthquake (MCE) acceleration, and is in turn found as $S_{MS} = F_aS_S$, where F_a is an acceleration-based site coefficient and S_S is the short period mapped acceleration (Figure 16.4.5)

W_p = Component weight, in this case the sprinkler piping contributing to the load on a brace

a_p = Component amplification factor affected by the type of seismic attachment

z = Height in the structure of the point of attachment of the component

h = Average roof height of the structure

R_p = Component response modification factor

I_p = Component importance factor

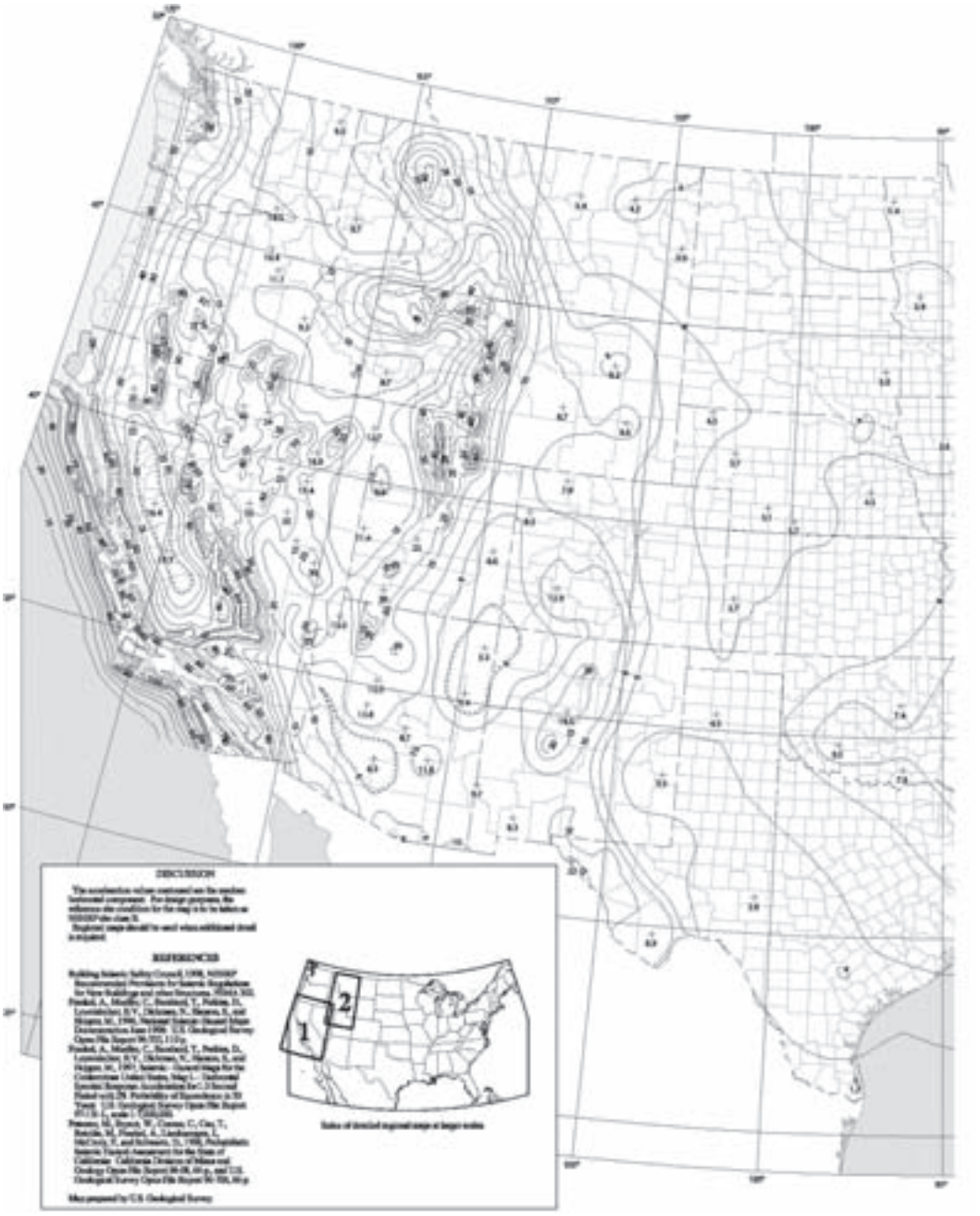
Applying the Force Formula. In using this equation, certain values are assigned for fire sprinkler systems in ASCE 7-05. The importance factor I_p is 1.5. The component response modification factor R_p for a steel piping system is 4.5, and the component amplification factor a_p is 2.5. It is worth noting that these values changed between the 2002 and 2005 editions of ASCE 7. The TIA issued on the 2002 edition of NFPA 13 in 2003 suggested the use of $R_p = 3.5$, correlating with the 2002 edition of ASCE 7. ASCE 7-02 also specified a value of 1.0 for a_p compared to the value of 2.5 specified in the 2005 edition.

As noted above, ASCE 7–05 is the standard referenced by the 2006 editions of the International Building Code and *NFPA 5000,* whereas ASCE 7-02 is referenced for use by the 2003 editions of the International Building Code and *NFPA 5000.* The 2000 edition of the International Building Code also included text parallel to the 2002 edition of ASCE 7. As such, compliance with the 2000 or 2003 editions of these codes would produce an a_p/R_p ratio of 1.0/3.5 = 0.29, whereas compliance with the 2006 editions of these codes produces a ratio of 2.5/4.5 = 0.55, resulting in significantly higher forces with the use of the equation. To some extent this has been offset by the clarification that the calculated design force can be reduced by a factor of 1.4 in recognition of the fact that ASCE 7 is based on strength design, whereas NFPA 13 uses allowable stress design. Prior to the 2007 edition, all loads in NFPA 13 were at allowable stress levels with the exception of the buckling loads for brace members. In the 2007 edition, tables that contained the allowable loads on braces were reduced to add a factor of safety appropriate to the use of allowable stress design.

The $1+2(z/h)$ factor in the design force equation leads to force levels that are three times as high at the top of the building

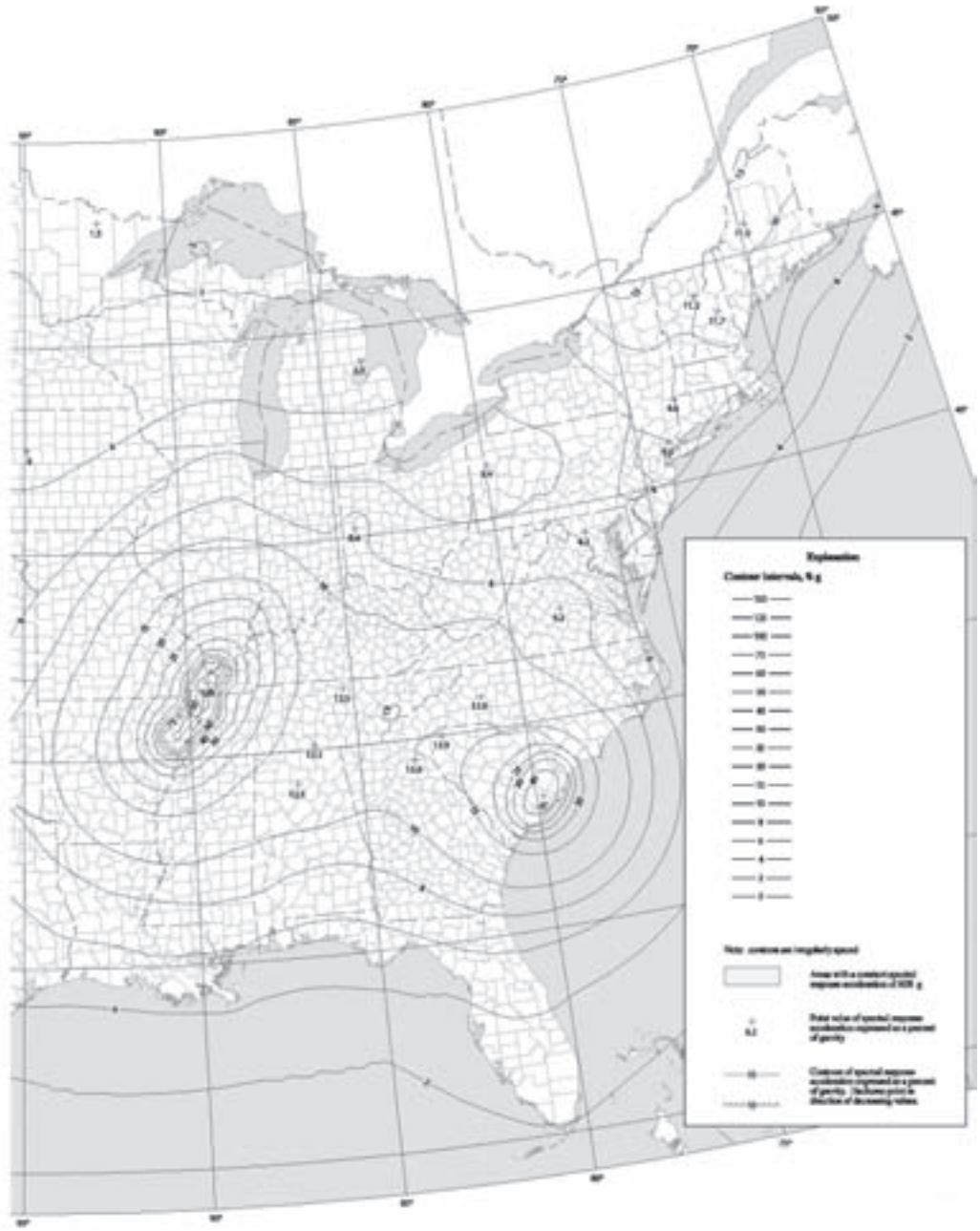
than at the base, regardless of building height. Because it is presumed that sprinkler systems are installed through the building, the simplifying assumption generally used is that $1+2(z/h) = 3$, with forces determined on the basis of the worst case, or, in other words, the highest level.

The Soil Factor. In the determination of $S_{DS} = \frac{2}{3} S_{MS} = \frac{2}{3} F_a S_S$, F_a is a site-specific soil factor. This factor can range from 0.8 for hard rock up to 2.5 in areas with softer soil and low seismic accelerations. S_S is the short period (0.2 second or 5 cycles per second) seismic acceleration representing a 2 percent probability of being exceeded in 50 years. The 0.2 second period is considered reasonably representative of the shortest effective period of buildings and structures, and the 2 percent probability of being exceeded in 50 years means that it relates to the 2500 year earthquake. Values of S_S are available on maps developed by the U.S. Geological Survey (USGS) and can be accessed at the USGS website. Figures 16.4.5 (a)



(a)

FIGURE 16.4.5 Values of S_S for (a and b) the Continental United States and (c and d) Region 1 of the United States (Courtesy U.S. Geological Survey)



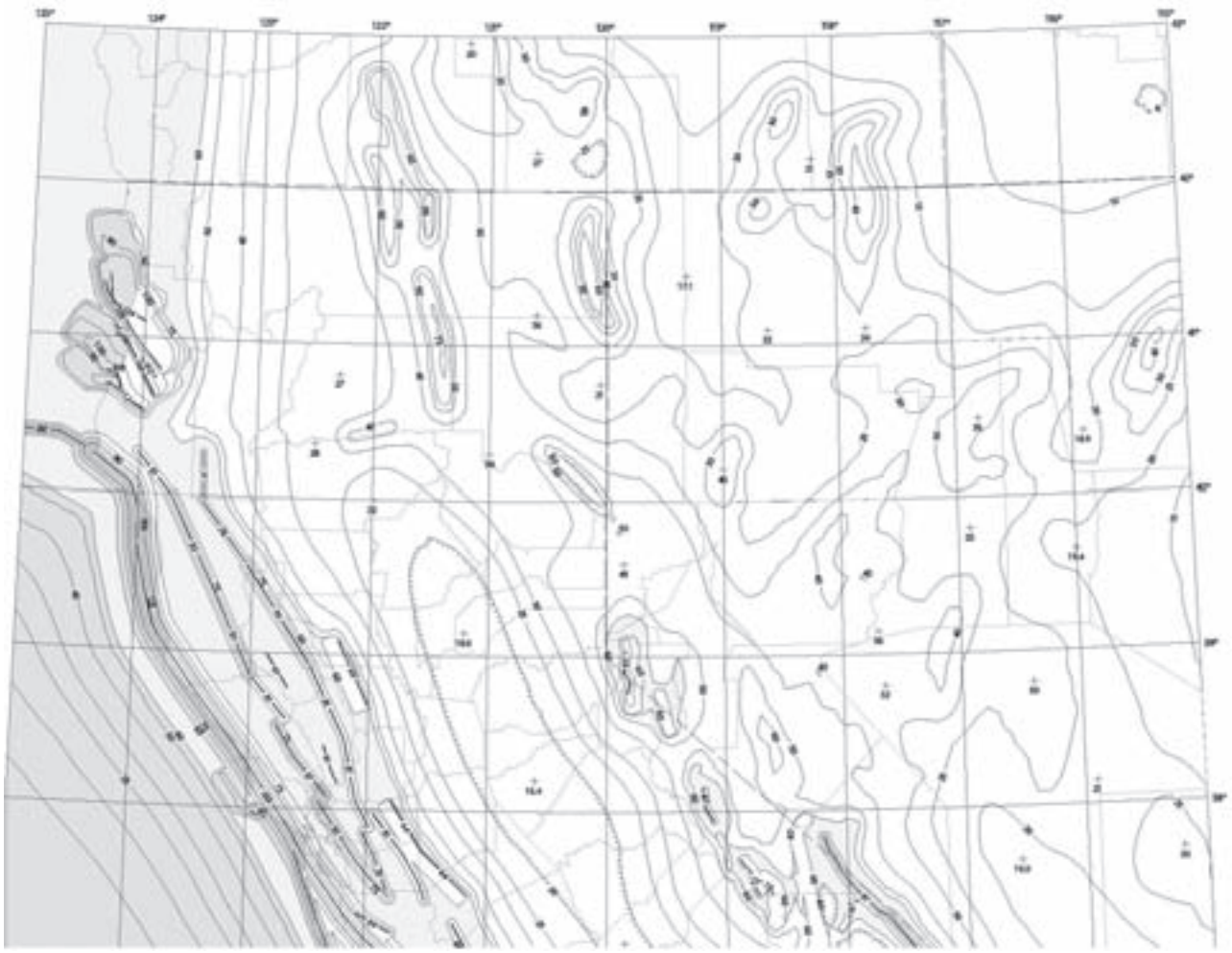
(b)

FIGURE 16.4.5 Continued

through (d) show the values of S_S for the continental United States and in more specific detail for the seismically active state of California. Figures 16.4.5 (a) and (b) show the maximum considered earthquake ground motion for the coterminous United States of 1.0 second spectral response acceleration (5 percent of critical damping), Site Class B. Figures 16.4.5 (c) and (d) show the maximum considered earthquake ground motion of 1.0 second spectral response acceleration (5 percent of critical damping), Site Class B for Region 1 of the United States.

Using a Seismic Coefficient. A simplified approach to determining seismic forces on sprinkler systems was developed for the 2007 edition of NFPA 13 and involves the factors shown in Table 16.4.6. The table assigns the "seismic coefficient " or acceleration factor C_P based directly on the mapped value of S_S from Figures 16.4.5(a), (b), (c), or (d). Multiplying the acceleration factor C_P by the contributing system weight W_p gives the force that must be resisted by an earthquake brace.

A number of conservative assumptions were used in the development of the NFPA 13 simplified approach. In addition



(c)

FIGURE 16.4.5 Continued

TABLE 16.4.6 Seismic Coefficient Table

S_s	C_p
0.33 or less	0.31
0.50	0.40
0.75	0.43
0.95	0.50
1.00	0.52
1.25	0.60
1.50	0.71
2.00	0.95
2.40	1.14
3.00	1.43

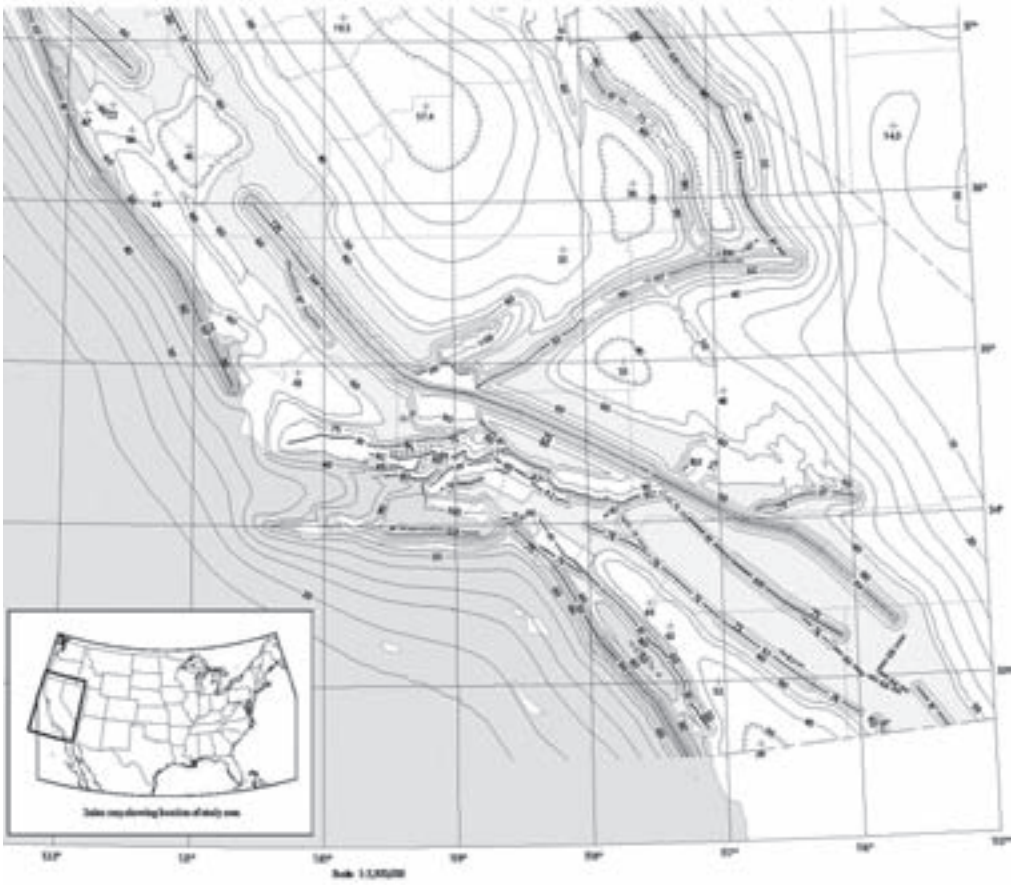
Source: NFPA 13, *Standard for the Installation of Sprinkler Systems,* Table 9.3.5.6.2, 2007, p. 13-101.

to the top-story assumption discussed above, the table is based on the maximum value of F_a for a given range of S_S, or in other words, poor soil conditions. The user of the standard always has the option to determine lateral forces in accordance with the actual equation of ASCE 7-05, as part of a more detailed analysis allowed by NFPA 13. For mapped acceleration values of S_S less than or equal to 0.33, the table provides a minimum lateral design acceleration of $C_P = 0.31$, which is less than the traditional default value of 0.5, but higher than would be obtained through the use of the ASCE 7 equation in many low-risk seismic areas.

Sway Bracing Placement

Sprinkler systems are provided with sway bracing to resist both lateral and longitudinal horizontal seismic loads as well as to prevent vertical motion resulting from strong seismic loads. The structural components to which bracing is attached must be capable of carrying the added applied loads.

Earthquake bracing can be either lateral (preventing motion perpendicular to the run of the pipe) or longitudinal (parallel to



(d)

FIGURE 16.4.5 Continued

the run of the pipe). A four-way brace is one that prevents both lateral and longitudinal movement.

Both lateral and longitudinal (four-way) bracing is required at the top of the riser. This keeps the top of the riser lined up with the floor/ceiling assembly.

Longitudinal bracing must be provided for all feed and cross mains at maximum 80 ft (24.4 m) intervals. The last brace must be within 40 ft (12.2 m) of the end of the main.

Lateral bracing must be provided for all feed and cross mains, and for branch lines with diameters 2½ in. (65 mm) and larger, although 2½ in. (65 mm) branch line starter pieces are not required to be braced if they do not exceed 12 ft (6.1 m) in length. A major change to the 2007 edition was the limitation of maximum lateral sway brace spacing based on the size of the pipe being braced and the contributory load. The traditional maximum brace spacing of 40 ft (12.2 m) still applies, but in situations involving high lateral forces or heavy branch lines, the maximum spacing may need to be reduced. This reduction is in recognition of the fact that maximum lateral brace spacing is related to the beam strength of the piping and in an attempt to limit pipe deflection as well as pipe stresses.

An exception allows the elimination of lateral bracing where piping is supported by hanger rods less than 6 in. (150 mm) in length. This length is measured between the top of the pipe and the point of attachment to the building structure.

For both longitudinal and lateral bracing, pipe runs less than 12 ft (3.6 m) are allowed to be included with adjacent runs and do not require their own braces provided the maximum distance between braces is observed. Braces within 2 ft (0.6 m) of a turn in the piping run can serve as both a lateral brace for one run and a longitudinal brace for the perpendicular run.

Determination of Loads

Prior to 1999, NFPA 13 permitted two methods of determining the loads to be carried by braces: the assigned load table and the zone of influence method. These two methods somewhat paralleled the pipe schedule method and hydraulic calculation method used to size pipe in sprinkler systems. Just as the role of pipe schedule systems has diminished in favor of consideration of actual water pressures, the assigned load table was deleted in favor of consideration of actual loads.

Using the zone of influence method involves evaluating the load that contributes to each brace. A longitudinal brace is expected to carry the load of the main to which it is connected in a length halfway to the adjacent braces in each direction. A

lateral brace is similarly expected to carry the loads from the piping halfway to the next brace in both directions. However, for the lateral brace this includes the contributions of branch lines as well as mains. During an earthquake, the branch lines are not expected to move uniformly, preventing the contribution of their loads to the longitudinal braces on mains.

The weights of the piping contributing to each brace are accumulated and the total horizontal force calculated as $F_p = C_p W_p$ as explained above. A brace acting as both a lateral brace for one main and a longitudinal brace for another would be expected to carry the combined load simultaneously. Beginning with the 2002 edition of NFPA 13, the value of W_p was specified to be 1.15 times the nominal weight of the water-filled piping to account for the additional weight that might be imposed by fittings or sectional valves. Table 16.4.7 includes piping weights with the 1.15 multiplier.

Where multiple braces are to be installed with the same configuration along a main, it is standard practice to select the worst-case brace for purposes of determining the load to be carried. This would be the brace with the zone of influence that includes the heaviest total piping.

Loads on Sway Brace Components

The sway braces themselves are generally constructed of pipe, but can be of angles, rods, flats, channels, or other structural members with slenderness ratio limited to a maximum of 300. The slenderness ratio is found as l/r where l is the length and r is the least radius of gyration. Traditional bracing resists movement in both tension and compression, but tension-only cable bracing is now also available. Such tension-only bracing systems must be specially listed for use with sprinkler systems. Because the cables can only provide resistance to movement in tension, they must be provided on both sides of the piping at each point of support.

The sway braces are used as part of a sway brace assembly, which in addition to the brace typically consists of the sway brace fitting (the attachment to the pipe being braced) and the structure attachment fitting. These fittings must be listed and have been assigned maximum allowable loads. The allowable loads must be reduced where braces are installed, other than at the full horizontal (90 degree) position. Similar reductions in allowable loads for braces and fasteners are built into the tables contained in NFPA 13. The allowable load for a sway brace assembly is based on the weakest link of the brace, the sway brace fitting, the structure attachment fitting, and the fastener. The allowable load for a brace assembly must meet or exceed the load determined using the assigned load table or zone of influence method.

Sway braces are to be fastened tight and concentric, with eccentric loadings avoided. Welded tab attachments are acceptable for use in connecting longitudinal braces. Pipe must not be braced to building sections that will move differentially. Fastener load tables within the standard are based on various orientation/angle conditions of lag screws in wood, through bolts in wood, expansion shields in concrete and through bolts in steel.

NFPA 13 contains special rules for the fastening of sway braces. C-type clamps (with or without retaining straps) are prohibited from use in attaching sway braces to the building structure. Power-driven fasteners are also prohibited from use in attaching braces unless specifically listed for this service.

An appendix section cautions that although most current concrete fasteners in the marketplace are expansion anchors, the table within the standard is based on the use of "shield-type" or "lead cinch" concrete anchors. Professional engineers may specify alternative fastening arrangements.

Although NFPA 13 states its intent to prevent vertical motion resulting from seismic loads, it is generally expected that the downward force of gravity will sufficiently offset any

TABLE 16.4.7 Piping Weights

Nominal Dimensions		Weight of Water-Filled Pipe		1.15 Weight of Water-Filled Pipe		Nominal Dimensions		Weight of Water-Filled Pipe		1.15 Weight of Water-Filled Pipe	
in.	*mm*	*lb/ft*	*kg/m*	*lb/ft*	*kg/m*	*in.*	*mm*	*lb/ft*	*kg/m*	*lb/ft*	*kg/m*
Schedule 40 Pipe (in.)						Schedule 10 Pipe (in.)					
1	25	2.05	3.05	2.36	3.51	1	25	1.81	2.69	2.08	3.09
1¼	32	2.93	4.36	3.37	5.01	1¼	32	2.52	3.75	2.90	4.31
1½	40	3.61	5.37	4.15	6.18	1½	40	3.04	4.52	3.50	5.20
2	50	5.13	7.63	5.90	8.77	2	50	4.22	6.28	4.85	7.22
2½	65	7.89	11.74	9.07	13.50	2½	65	5.89	8.77	6.77	10.09
3	80	10.82	16.10	12.44	18.52	3	80	7.94	11.82	9.13	13.59
3½	90	13.48	20.06	15.50	23.07	3½	90	9.78	14.55	11.25	16.73
4	100	16.40	24.41	18.86	28.07	4	100	11.78	17.53	13.55	20.16
5	125	23.47	34.93	26.99	40.17	5	125	17.30	25.75	19.90	29.61
6	150	31.69	47.16	36.44	54.23	6	150	23.03	34.27	26.48	39.41
8*	200	47.70	70.99	54.86	81.64	8	200	40.08	59.65	46.09	68.60

*Schedule 30.

upward vertical earthquake loads, and that system hangers have sufficient safety factors to handle any downward vertical earthquake loads. As a result, the standard only addresses the net vertical reaction that would result from strong horizontal loads where the brace angle from vertical is relatively low. Where the horizontal force factor exceeds $0.5W_P$ and the brace angle is less than 45 degrees from vertical, or where the horizontal force factor exceeds $1.0W_P$ and the brace angle is less than 60 degrees from vertical, the braces are to be arranged to resist the net vertical reaction. For traditional rigid braces, this can be accomplished by providing an additional brace on the opposite side of the main. For special listed cable type braces, this can be accomplished by reinforcing the hanger rods to prevent buckling as well as upward movement.

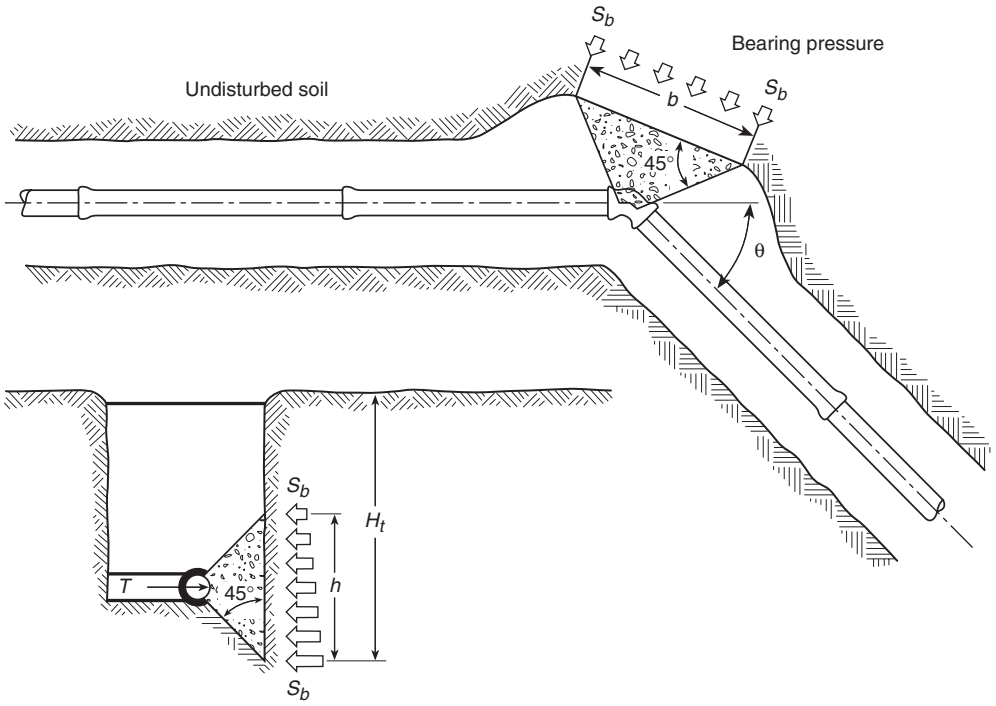
JOINT RESTRAINT OF UNDERGROUND PIPING

Traditional bell and spigot underground piping using push-on joints relies on the resistance provided by the surrounding soil to hold it in place. This is sufficient for straight runs, but the forces at changes in direction must be resisted. For this reason, NFPA standards require all tees, plugs, caps, bends, and hydrant branches to be restrained against movement. NFPA 13 and NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances,* share the criteria for underground piping, including joint restraint.

Like most overhead piping, underground piping with fused joint systems, including welded, soldered, brazed, and threaded pipe, requires no additional joint restraint. Otherwise, joint restraint must be provided through the use of thrust or restrained joint systems.

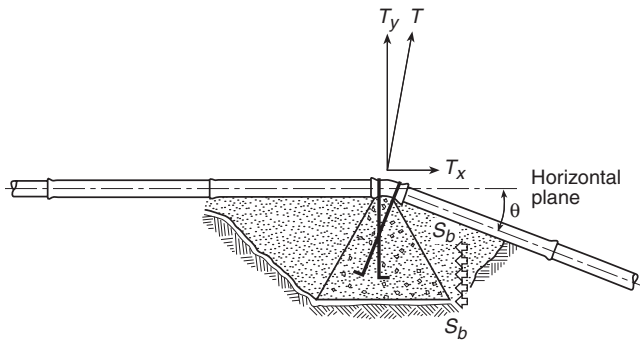
Thrust Blocks

Thrust blocks are large concrete blocks used to transfer horizontal loads to undisturbed soil or to resist upward vertical loads by means of their mass. Thrust blocks must be made of a concrete mix that is not leaner than one part cement, two and a half parts sand, and five parts stone aggregate. If possible, thrust blocks must be placed so that the joints are accessible for repair. (See Annex A in NFPA 13 for additional guidance, including formulas that can be used to size horizontal [bearing] and vertical [gravity] thrust blocks based on the bearing strength of the undisturbed soil, size and orientation of pipe, and maximum expected water pressures [Figures 16.4.6 and 16.4.7].) Care should be taken when obtaining soil bearing strength values because they are often not the same in the horizontal and vertical planes.



T = Thrust force resulting from the change in direction of flow
S_b = Horizontal bearing strength of the soil
h = Block height
H_t = Total depth to bottom of block

FIGURE 16.4.6 Bearing Thrust Block



T = Thrust force resulting from the change of direction of flow
T_x = Horizontal component of the thrust force
T_y = Vertical component of the thrust force
S_b = Horizontal bearing strength of the soil

FIGURE 16.4.7 Gravity Thrust Block

Restrained Joint Systems

Fused joint systems and threaded joints are considered acceptable as restrained joint systems, as are locking mechanical joints, joints using setscrew retainer glands, bolted flange joints, pipe clamps and tie rods, and other methods and devices approved by the authority having jurisdiction. NFPA standards provide specific guidance for sizing the clamps, rods, bolts, and washers associated with restrained joint systems. After installation, all rods, clamps, bolts, nuts, and washers must be cleaned and coated with a bituminous or other material to help prevent corrosion.

Some confusion has been caused in the past by the figure within NFPA 13 showing the "typical connection to a fire protection system riser" (Figure 16.4.8). In this depiction of an underground stub-up, rods are shown as necessary to hold the base of the flange and spigot piece within the bell opening of the last length of bell and spigot piping at the base of the riser. However, such rods and clamps are not necessary if other measures are taken to ensure that sufficient restraint is provided.

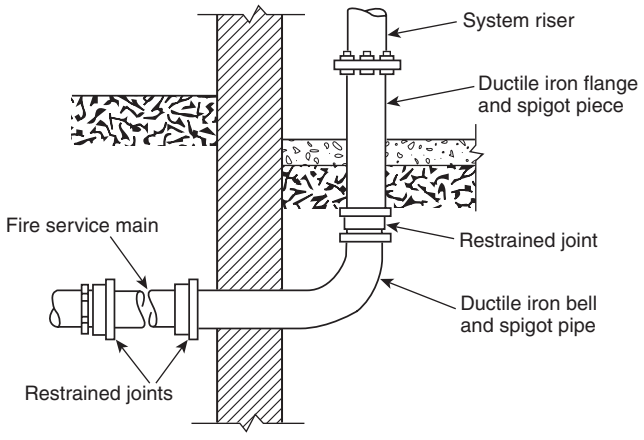


FIGURE 16.4.8 Typical Connection to a Fire Protection System Riser Illustrating Restrained Joints

Adequacy of joint restraint is verified by means of a 2 hour hydrostatic test, at not less than 200 psi (13.8 bar), but at least 50 psi (3.4 bar) above the maximum expected static pressure. The piping between an exterior fire department connection and the check valve in the connection's inlet pipe must also be hydrostatically tested. All thrust blocks should be hardened before testing, and the trench must be backfilled between joints to prevent movement of the pipe. Where necessary to hold the pipe in place, joints can also be backfilled as long as the contractor remains responsible for locating and correcting leaks.

Appendix sections of NFPA 13 and 24 recommend that the underground piping be filled with water for a 24 hour period prior to the hydrostatic test to stabilize the system. These appendix sections also recommend that the test pressure be held for 1 hour, that the pressure then be decreased to zero to look for signs of leakage, and that it then be repressurized for the second hour.

SUMMARY

In the development and application of rules for structural support of fire protection system piping, fire sprinkler systems have received great attention. This is expected given their widespread use. But the features related to hanging and bracing can also readily be applied to other types of fire protection systems and components, including pumps and tanks. The weight of any components required to be braced could be substituted for the weight of system piping in the application of the rules for braces and fasteners. The NFPA 13 hanging and bracing criteria, continually improved over decades based on practical experience, represents the best available guidance on supporting fire systems and protecting them from earthquake damage.

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3. *International Building Code,* International Code Council, Country Club Hills, IL, 2000, 2003, and 2006 editions.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on hanging and bracing of water-based systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 5000®, Building Construction and Safety Code®

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Chapter 5

Sprinkler Systems for Storage Facilities

James E. Golinveaux

Chapter Contents

NFPA Storage Standards
Commodity Classification
Storage Arrangement
Storage Height and Clearance
Automatic Sprinkler Protection
Water Supply
Special Commodities

Key Terms

automatic sprinkler system, bulk storage, commodity classification, pallet, pile storage, plastic, rack storage, storage, warehouse, water supply

This chapter addresses sprinkler system protection for storage operations. It is an unfortunate fact that many of the factors that enhance the efficiency of a storage facility also increase the fire risk presented by that storage. The more efficiently storage volume is used, the more combustible materials there are in that volume, and the more material there is to burn.

Access to the stored materials requires space between storage units. Efficient use of storage space requires that these spaces (flues) be as small as possible. The result is an array that could hardly be any more conducive to maximum burning rate and fire spread than if it had been designed with that purpose in mind. Therefore, well-designed, properly installed, and carefully maintained fire protection is critical if a catastrophic fire is to be avoided.

This chapter reviews basic fire protection principles primarily in the context of NFPA sprinkler system and storage standards. It begins with a discussion of commodity classification and storage arrangement, height, and clearance and then discusses sprinkler systems and associated design factors unique to storage operations. Then it presents an overview of special commodities and special storage facilities. The remaining sections highlight other fire protection features that a comprehensive fire protection program needs and fire safety problems of construction.

This chapter covers fire protection for a broad range of materials and storage arrangements, but it does not discuss the protection of special hazards such as flammable liquids and gases, explosives, and so on. For protection of special hazards, see Section 6, Chapter 10, "Gases"; Section 6, Chapter 12, "Flammable and Combustible Liquids"; Section 16, Chapter 3, "Automatic Sprinkler Systems"; and Section 17, Chapter 8, "Explosion Prevention and Protection."

NFPA STORAGE STANDARDS

NFPA standards outline methods for providing effective fire protection for various types of storage occupancies. These standards include NFPA 13, *Standard for the Installation of Sprinkler Systems.* For the most part, sprinkler systems are the backbone of an effective fire protection strategy for storage facilities. The changing footprint and potential pile collapse in storage facilities make manual fire fighting difficult. A well-designed and properly maintained automatic sprinkler system is the best means of fire control in storage facilities.

NFPA storage standards are based on full-scale fire tests and past loss experience. The standards address storage situations in which test data are available or in which conclusions could be drawn from the extrapolation of available data, judgment, or experience. Not all recognized protection technologies are equal. The NFPA standards identify the minimum acceptable level of protection for storage facilities. Operational planning or type of construction may limit the use of some recognized technologies. For this reason it is very important to understand certain protection scheme limitations before selecting a design method. For storage situations beyond the scope of a specific NFPA document, engineering judgment and other sources may be used but only with care and by professionals with an in-depth knowledge of fire protection science and practice. NFPA

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storage documents and this chapter outline basic fire protection concepts for storage operations and can provide guidance where specific standards are not available.

To effectively prepare a fire protection plan for a storage occupancy, the following steps should be followed:

- Determine the commodity classification.
- Identify the storage arrangement.
- Establish the storage height and clearance from the top of storage to sprinklers.
- Develop a protection scheme (automatic sprinkler system).

In addition to the basic steps just outlined consideration also is needed for the following:

- Water supply
- Special commodities
- Special storage facilities
- Supplemental means of fire protection
- Construction

Changes to any one of the above, whether daily, weekly, seasonally, or over the life of the building can seriously impact the adequacy of protection. For this reason, it is very important to consider all of the storage variables that are known to exist or are expected to exist due to normal operations.

COMMODITY CLASSIFICATION

Proper design of sprinkler systems requires that the commodities to be stored are identified and categorized according to their burning characteristics. Categorizing commodities is a difficult task because a wide variety of products can be found within stored commodities. Some storage facilities are designed to support seasonal changes in commodity types and packaging. This has to be taken into consideration in selecting the worst case commodity classification. Additionally and probably the most difficult is to consider possible planned commodity changes, such as replacing steel parts with plastic. Although these changes can be handled through system upgrades in the future, it is much more cost-effective to address the known variables during the initial system design.

The classification of a commodity is based on a unit of storage of the commodity. For the most typical commodities, the unit of storage is the pallet load and includes the pallet, the packaging of the commodity, and the commodity itself. Commodity classification does not take into account mixed storage of commodities. For example, a storage area containing pallet loads of paper products, which are Class III commodities, mixed with pallet loads of Group A plastic commodities cannot be classified as Class IV storage based on the relative number of pallet loads of each commodity. The most challenging commodity (highest class number) determines protection for everything in an undivided, unseparated area. The paper products must be protected as a plastic commodity, unless the commodities are separated and each is properly protected.

The reason for this is quite simple. The fire tests on which NFPA 13 is based involve no more than a 200 ft^2 (18.6 m^2) fire area. Fires that were not confined to that size by sprinklers were typically not controlled. So the severity of a fire in mixed commodity storage is dictated by where the fire starts, not the overall mix of commodities. And, since any point of origin is possible, the most challenging point—near the most challenging commodities—sets the need for protection of the entire space.

Classifications reflect the burning rate and heat release rate of a commodity, as well as the effect of water (from sprinklers) on the commodity. For this reason, small-scale tests, which measure heat of combustion or relative horizontal burning rates, are of little use in determining commodity classification.

Full-scale fire tests can be used to determine commodity classification, but full-scale tests can be quite expensive. Intermediate-scale test methods (such as the fire products collector commodity classification method developed by Factory Mutual Research and used by FM Global and Underwriters Laboratories) provide a more economical means to accurately determine commodity classification.

NFPA Categories

NFPA 13 provides an approach that categorizes materials into one of seven major categories—Classes I through IV and Groups A, B, and C plastics. (NFPA 13 contains a comprehensive list of commodities and their classifications.) The definitions of the various commodity classifications are as follows:

- *Class I.* Class I commodities are noncombustible products in corrugated containers with or without single-thickness cardboard dividers, stored on wood pallets. The standard Class I test commodity is glass jars in compartmented cardboard cartons on wood pallets.
- *Class II.* Class II commodities are Class I products with slightly increased amounts of combustible packaging (such as multiple-layer cartons) or trim (such as plastic knobs). The standard Class II test commodity is a metal-lined double triwall corrugated carton on a wood pallet (Figure 16.5.1).
- *Class III.* Class III commodities include ordinary combustibles (wood, paper, natural fiber cloth) in cardboard cartons on wood pallets. The standard Class III test commodity is paper cups in compartmented cardboard cartons on wood pallets.
- *Class IV.* Class IV commodities are Class I, II, or III products containing limited amounts of Group A plastics in corrugated cartons and Class I, II, and III products in ordinary corrugated cartons, with limited amounts of expanded Group A plastic packaging on wood pallets. Limited amounts of Group A plastics are considered to be 5 to 15 percent by weight and 5 to 25 percent by volume. The standard Class IV test commodity is a mixture of paper and plastic cups (15 percent plastic by weight) on wood pallets.

Classification of Class I through IV commodities is based on the assumption that they are stored on wood pallets. When *unreinforced* polypropylene or high-density polyethylene plastic pallets are used, the classification of the commodity unit is increased one class (e.g., Class III will become Class IV, and Class IV will become cartoned unexpanded Group A plastics). When *reinforced* polypropylene or high-density polyethylene plastic pallets are used, the classification of the commodity unit is increased two classes, except for Class IV commodity, which will be increased to a cartoned unexpanded Group A plastic

FIGURE 16.5.1 Standard Class II Test Commodity (Source: Underwriters Laboratories)

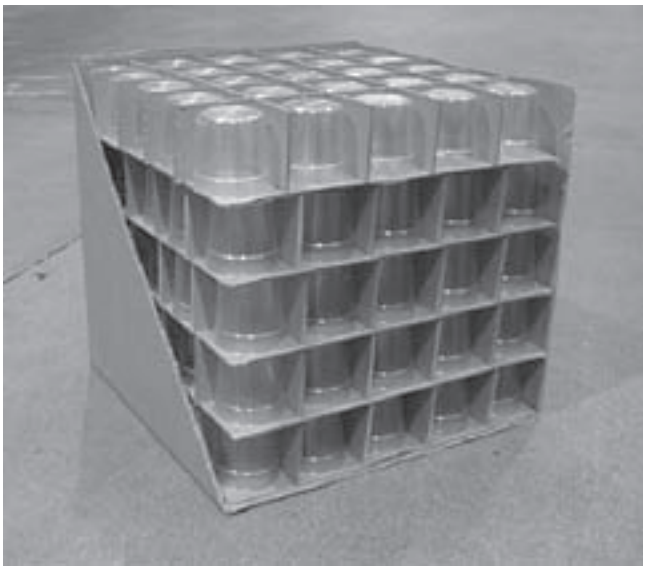


FIGURE 16.5.2 Nonexpanded Group A Test Commodity—16 oz (473 mL) Polystyrene Plastic Jars Individually Separated by Cardboard (Source: Underwriters Laboratories)

commodity (e.g., Class II will become Class IV and Class III and IV will become a cartoned unexpanded Group A plastic commodity). Plastic pallets are assumed to be reinforced if no permanent marking or manufacturer's certification of nonreinforcement is provided. This can complicate the decision to convert from wood pallets to plastic pallets in storage areas, as the existing sprinkler protection probably will no longer be adequate and will require modification. However, there now exist listed plastic pallets that can be treated as standard wood pallets for determining the commodity type.

Plastics

Plastics present a greater fire protection challenge because their combustion can produce about 1½ to 3 times as much heat per unit of weight as wood or paper. In addition, plastics can burn at a much faster rate, resulting in a very challenging, high heat release rate fire.

Plastic materials are categorized in NFPA standards into one of three groups: A, B, or C. Group A plastics present the most severe hazard (Figure 16.5.2), whereas Group C plastics present the least severe. Group B plastics behave similarly to Class IV commodities, and Group C plastics behave similarly to Class III commodities.

The following list identifies a number of plastics according to their potential fire severity. The list contains unmodified plastic materials. Although fire-retardant modifiers and other additives can inhibit ignition, once ignited, heat release is usually the same as for unmodified plastic. Intermediate or full-scale testing is the best means to determine a modified material's classification. The plastics are categorized as follows:

Group A

- ABS (acrylonitrile-butadiene-styrene copolymer)
- Acrylic (polymethyl methacrylate)
- Acetal (polyformaldehyde)
- Butyl rubber
- EPDM (ethylene-propylene rubber)
- FRP (fiberglass-reinforced polyester)
- Natural rubber (if expanded)
- Nitrile rubber (acrylonitrile-butadiene rubber)
- Polybutadiene
- Polycarbonate
- Polyester elastomer
- Polyethylene
- Polypropylene
- Polystyrene
- Polyurethane
- PVC (polyvinyl chloride—highly plasticized—e.g., coated fabric, unsupported film)
- SAN (styrene acrylonitrile)
- SBR (styrene-butadiene rubber)

Group B

- Cellulosics (cellulose acetate, cellulose acetate butyrate, ethyl cellulose)
- Chloroprene rubber
- Fluoroplastics (ECTFE—ethylene-chlorotrifluorethylene copolymer, ETFE—ethylene-tetrafluoroethylene copolymer, FEP—fluorinated ethylene-propylene copolymer)
- Natural rubber (not expanded)
- Nylon (nylon 6, nylon 6/6)
- PET (thermoplastic polyester)
- Silicone rubber

Group C

- Fluoroplastics (PCTFE—polychlorotrifluoroethylene, PTFE—polytetrafluoroethylene)

- Melamine (melamine formaldehyde)
- Phenolic
- PVC (polyvinyl chloride—rigid or lightly plasticized—e.g., pipe, pipe fittings)
- PVDC (polyvinylidene chloride)
- PVF (polyvinyl fluoride)
- PVDF (polyvinylidene fluoride)
- Urea (urea formaldehyde)

In determining the classification of a commodity that is a mixture of different materials, the amount of the most hazardous material and its effect on a fire must be considered. If the most hazardous material dominates the behavior of the burning commodity, then the product must be classified the same as the most hazardous material. For instance, thick, expanded Group A plastic packing material surrounding a Class IV commodity in a corrugated carton will completely dominate fire behavior in the early stages of the fire, when the protection battle is won or lost. So the commodity must be classified as an expanded Group A plastic.

STORAGE ARRANGEMENT

Storage configuration has a major impact on how a fire burns. Therefore, a commodity's storage arrangement must be considered when preparing the fire protection plan. Materials are most commonly arranged as bulk storage, solid pile, palletized pile, or rack storage. Bins and narrow shelves also are used, more commonly in smaller stockrooms holding moderate quantities of product. Most warehouses combine these various storage arrangements.

The most critical factor among the various storage arrangements that affect fire behavior and the difficulty of controlling a fire is the presence of flue spaces. Storage configurations create these horizontal and vertical air spaces. Air passes through flue spaces, oxidizing the fire. Although flue spaces are not desirable, they should not be obstructed when present. Obstructed flue spaces can prevent heat and combustion products from reaching a fire detector or sprinkler and also can prevent water or other fire protection media from reaching the fire.

Bulk Storage

Bulk storage consists of piles of loose, free-flowing materials, including powder, granules, pellets, or flakes, and agricultural items, such as peanuts. The materials are typically stored in silos, bins, tanks, or in large piles on the floor. Flue spaces are typically not present. Fires in large piles tend to burrow down into the pile, making them difficult to extinguish. This type of fire requires prolonged soaking to reach the seat of the fire. Bulk storage arrangements are also subject to spontaneous ignition. Fires starting inside the piles are difficult to locate, unless heat sensors immersed in the pile continually monitor internal heating.

Material handling equipment, such as belt conveyors, air-fluidizing ducts, and bucket conveyors ("legs") are often employed to transfer the material to and from its storage location. This moving process agitates and disturbs material. Airborne combustible material presents an explosion hazard. This concern is significant, especially in grain storage facilities. In addition, conveyor belts and other components can be combustible and can burn together with the commodity in inaccessible places high above the floor, in tunnels, and in housings around conveying equipment.

Solid Pile Storage

Solid piling consists of cartons, boxes, bales, bags, and so on in direct contact with each other. Air spaces, or flues, exist only where contact is imperfect, or where a pile is close to, but not touching, another pile. Because pallets are not typically used, stacking is done by hand or by lift trucks using side clamps or prongs, which are pried between packages or bales without damaging the product.

Figure 16.5.3 illustrates a type of solid piling in which spaces left between cartons accommodate lift-truck prongs. Wide aisles give the lift truck plenty of room to maneuver. The dark pipes at the ceiling are sprinkler lines.

Relative to palletized and rack storage arrangements, solid piling gives fire the least opportunity to develop and spread due to restricted air access for burning, resulting in a fire challenge less than that for palletized or rack storage. Still, high piling presents a significant fire hazard, especially where the pile's surface consists of a material susceptible to rapid flame spread properties. Also, the higher the pile, the more difficult it is to break up and separate during a fire.

Palletized Pile Storage

Palletized storage consists of unit loads placed on pallets that are then stacked on top of one another. A pallet load usually takes the form of a cube, with sides of about 4 to 5 ft (1.22 to 1.52 m), consisting of a single package or multiple packages. The top surface of the pallet load must adequately support other pallet loads so that the commodity is not crushed or so that the pile does not become unstable. Due to these considerations, the maximum height of palletized storage usually does not exceed 30 ft (9.1 m).

FIGURE 16.5.3 Example of Solid Pile Storage

Pallets contain open horizontal spaces for forklift trucks. These horizontal spaces make this storage arrangement functional, but they increase the fire hazard. Air spaces usually continue in one direction along the entire width of a pile. Like vertical flue spaces, horizontal spaces let air easily pass to the fire. In addition, their configuration lets a fire burn in the space while shielding it from the water from an overhead sprinkler system.

Early fire collapse can be a positive factor in protection of solid pile and palletized storage, but the key word is early. In order for early pile collapse to be a positive factor for fire protection, it must occur within 2 to 3 minutes of the time the first sprinkler operates. Almost any commodity in solid pile storage will ultimately collapse, but credit can be given only if it can be assured that early pile collapse will occur. In general, the great majority of stored commodities will not qualify for credit for pile collapse.

Rack Storage

A storage rack is a structural framework in which a commodity is placed, usually as a pallet load. The design of rack storage systems maximizes vertical storage capability. The ceiling height or the vertical reach of materials-handling equipment limits storage heights. Some rack storage arrangements are over 100 ft (9.3 m) high.

The most common racking configurations are single-row and double-row racks. Single-row racks include racks up to 6 ft (1.83 m) wide, separated from other storage by at least 3.5 ft (1.07 m) aisles. Double-row racks consist of two single-row racks placed back-to-back, with a combined width up to 12 ft (3.66 m) and aisles at least 3.5 ft (1.05 m) wide on each side (Figures 16.5.4 and 16.5.5). Multiple-row racks, which can use a flow-through or drive-in configuration, are also becoming more widely used. They consist of racks greater than 12 ft (3.66 m) wide, or single- or double-row racks separated by aisles less than 3.5 ft (1.07 m) wide whose overall width exceeds 12 ft (3.66 m) (Figures 16.5.6 and 16.5.7). Note that with the multiple-row, drive-in storage racks pictured in Figure 16.5.7, forklift trucks drive into the rack to deposit and withdraw loads in the depth of the rack.

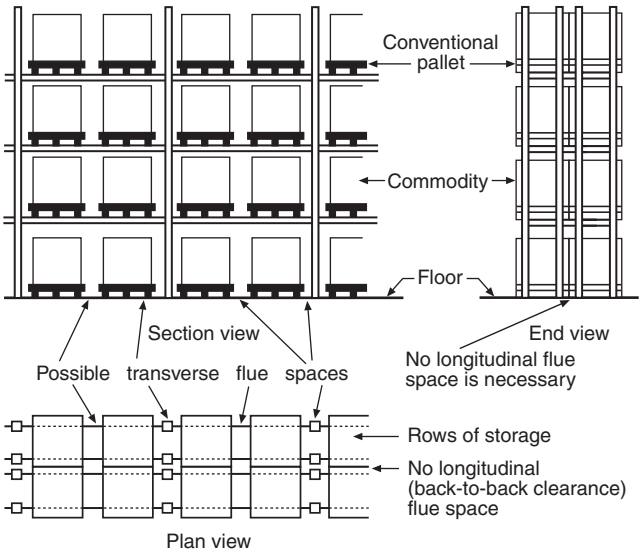
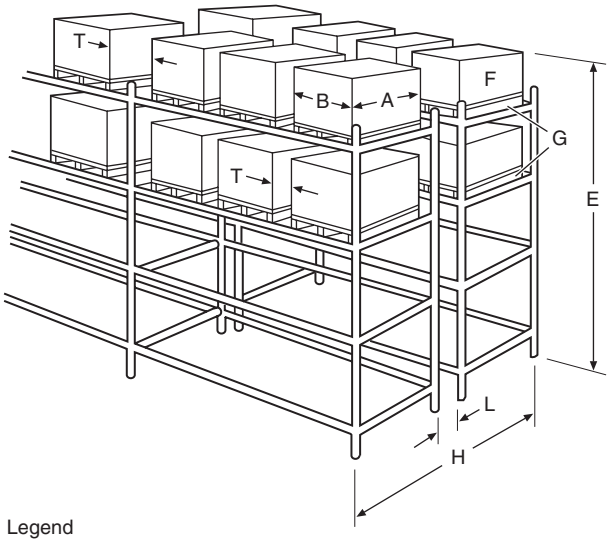


FIGURE 16.5.4 Typical Double-Row Rack with Back-to-Back Loads



Legend

A = Load depth	G = Pallet
B = Load width	H = Rack depth
E = Storage height	L = Longitudinal flue space
F = Commodity	T = Transverse flue space

FIGURE 16.5.5 Double-Row Rack Holding Pallet Loads

Bin Box Storage. Bin box storage is a variation of rack storage in which substantial (wood or metal) vertical dividers create five-sided storage bins where the only open side faces an aisle. There are no gaps between the top, bottom, sides, and the back of the bin. Bins are usually no more than 3 ft (0.91 m) wide, 3 ft (0.91 m) high, and 3 ft (0.91 m) deep, and the stored commodity does not extend into the aisle beyond the face of the bin. Storage height is usually less than 20 ft (6.1 m). This storage arrangement creates the equivalent of solid five-sided storage

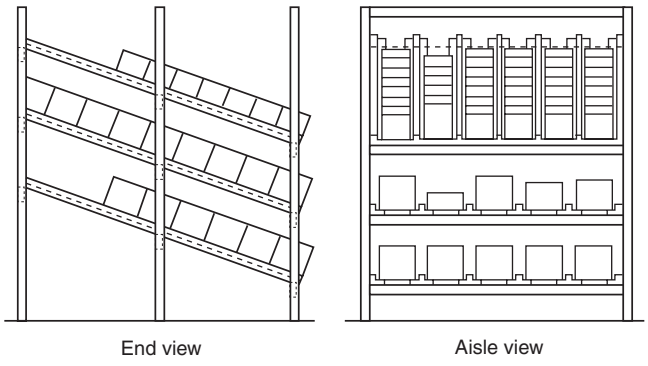


FIGURE 16.5.6 Multiple-Row Flow-Through Rack

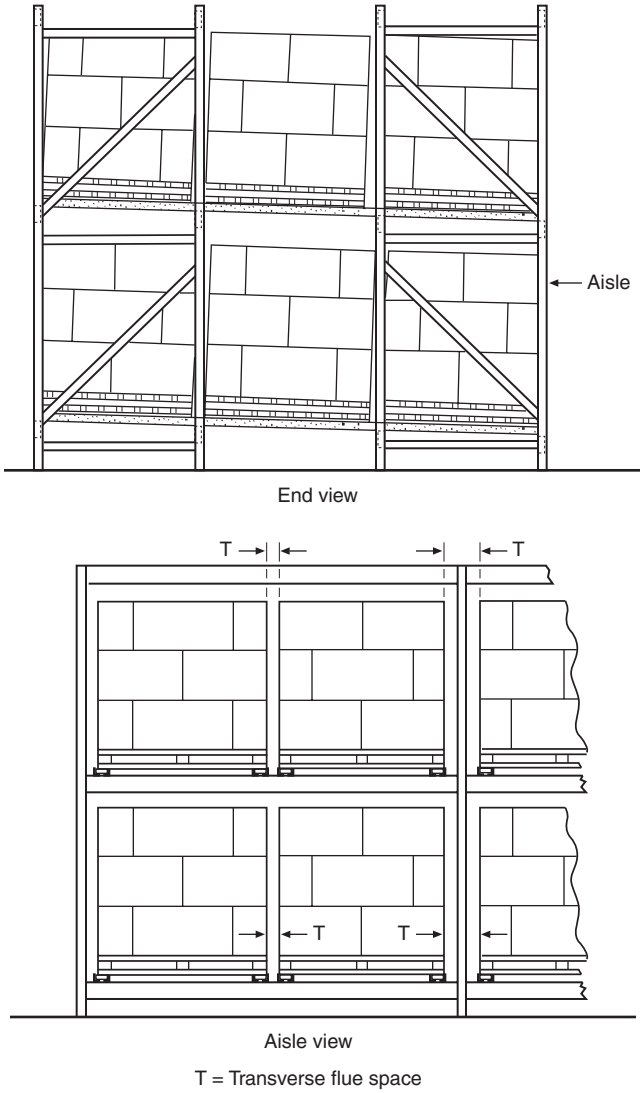


FIGURE 16.5.7 Multiple-Row, Drive-In Storage Rack, Two or More Pallets Deep

containers that limit vertical and horizontal fire spread. As a result, although the storage resembles rack storage, it can be protected as if it were solid-piled or palletized storage.

Shelf Storage. Shelf storage is another variation of rack storage, where the shelves are solid but narrow, measuring 30 in. (0.76 m) or less, and the racks are arranged in single rows, so that there is a maximum dimension of 30 in. (0.76 m) between aisles. Aisles are usually 24 in. (0.61 m) to 36 in. (0.91 m) wide. Shelves are typically less than 2 ft (0.61 m) apart vertically. And storage height is usually not greater than 15 ft (4.57 m). This storage can be protected as if it were solid-piled or palletized storage, so long as the shelf width (as measured from aisle to aisle) does not exceed 30 in. (0.76 m).

Other Types of Storage Racks. Other types of storage racks are also used. These include cantilever racks in which arms that extend horizontally from columns support the load. The load can rest on the arms or on shelves the arms support (Figure 16.5.8). Movable racks are connected to fixed rails or guides. They can be moved back and forth only on a horizontal, two-dimensional plane. A moving aisle is created as abutting racks are loaded or unloaded and then moved across the aisle to abut other racks (Figure 16.5.9). Portable racks are also used. They are not fixed in place and can be arranged in a number of configurations, as shown in Figure 16.5.10. A combination of rack and palletized storage can also be used (Figure 16.5.11).

Depending on the height and type of the rack structure, various types of materials-handling equipment can be used. These include manual and automated devices, as shown in Figures 16.5.12 through 16.5.14. Note that with the high storage racks pictured in Figure 16.5.13, stacker machines ride on floor rail, guided from the top.

Rack structures inherently create flue spaces within the storage arrangement allowing air to reach the fire. Racks also provide stability during a fire so that the burning commodity cannot collapse upon itself. As a result, fires in rack storage configurations can be the most difficult to control and extinguish.

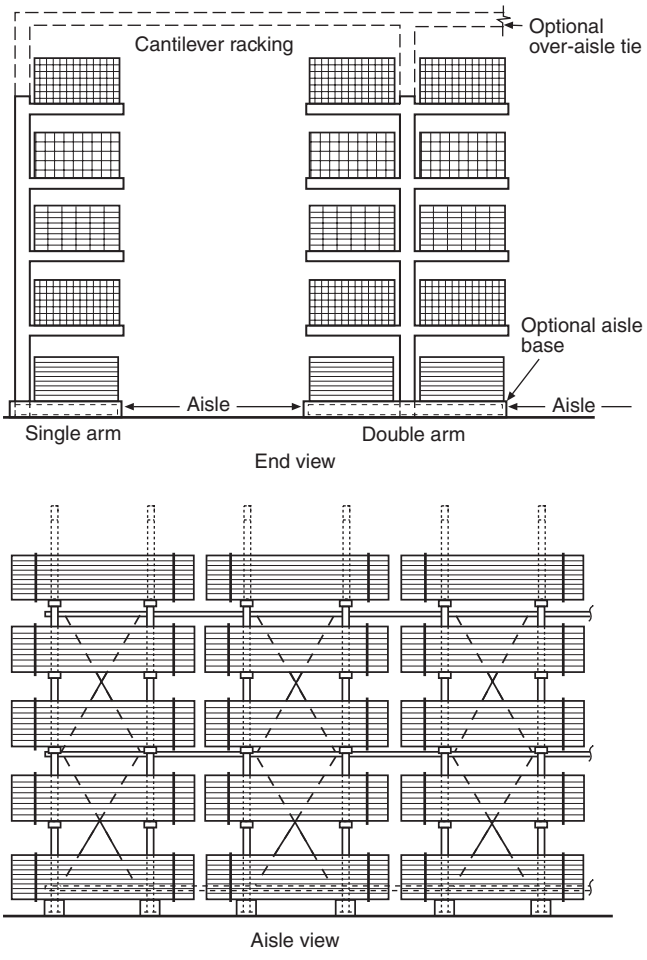


FIGURE 16.5.8 Cantilever Storage Rack

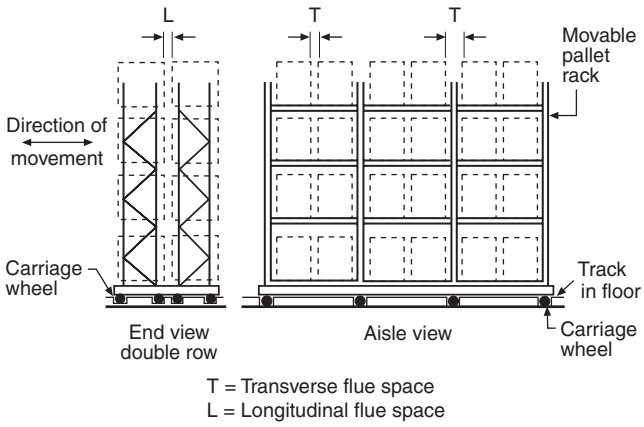


FIGURE 16.5.9 Movable Racks

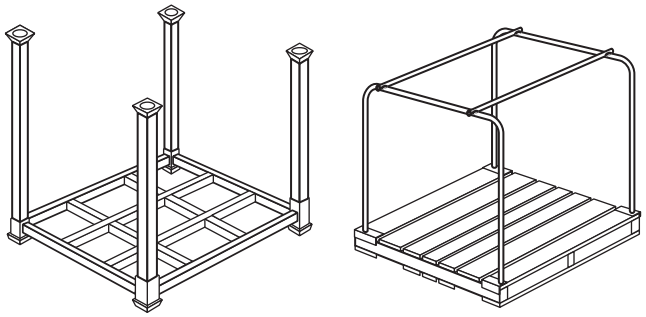


FIGURE 16.5.10 Portable Racks

Fires in racks typically burn up through flue spaces while consuming products on the racks. However, flue spaces should be kept unobstructed because they let heat from the fire reach and activate sprinklers. Flue spaces also provide a means for sprinkler discharge to penetrate the rack structure, prewet uninvolved material, and reach the fire.

Even if content damage is not severe in high-rack storage fires, heat from the fire can make the rack structure vulnerable to distortion and warping. This adversely affects materials-handling equipment because it must be accurately aligned to function properly. Such damage can impair the entire warehouse operation. Fortunately, storage racks are usually permanent structures that can support in-rack sprinklers. In-rack sprinklers are designed to contain fire to a small, localized area by reducing the horizontal and vertical spread of fire. Without in-rack sprinklers, fires in high-rack configurations can pose an impossible situation for a conventional sprinkler system installed at the ceiling. (Refer to the discussion of in-rack sprinklers later in this chapter.)

Aisle Width. Aisle spaces between stored materials let water from the ceiling sprinklers reach the fire and mitigate its spread from one storage pile or rack to another. The wider the aisle, the more advantageous it is to fire protection. In addition, aisles provide access for fire-fighting and salvage operations. Aisle widths are also a key factor in determining whether the rack arrangement is single, double, or multiple row.

For rack storage up to 25 ft (7.6 m) high, aisle widths significantly impact sprinkler system requirements. NFPA 13 provides sprinkler criteria for single- and double-row racks with 4 ft (1.22 m) and 8 ft (2.44 m) aisles as indicated in Figure 16.5.15. Interpolation is required for aisle widths between 4 ft (1.22 m) and 8 ft (2.44 m).

Racks incorporating 4 ft (1.22 m) aisles require greater sprinkler protection than those using 8 ft (2.44 m) aisles. Aisles wider than 8 ft (2.44 m) provide no more benefit than an 8-ft (2.44-m) wide aisle and, therefore, no reduction in sprinkler criteria is provided. If aisles are narrower than 3.5 ft (1.07 m), then

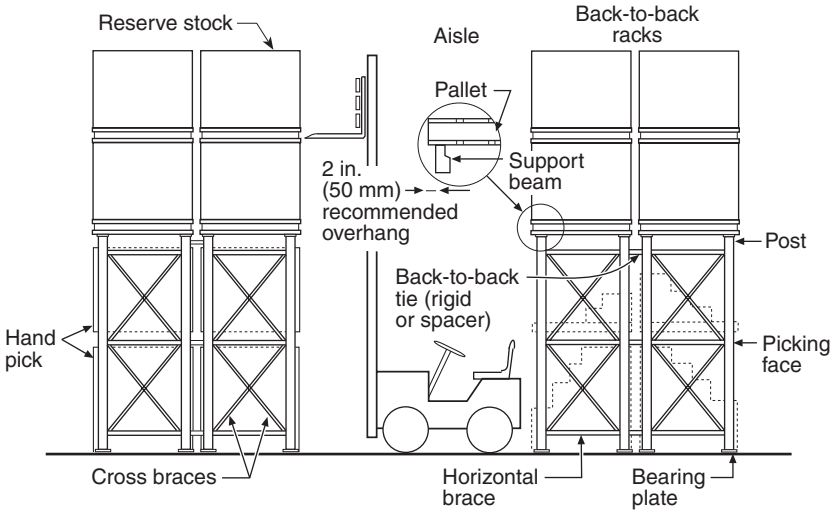
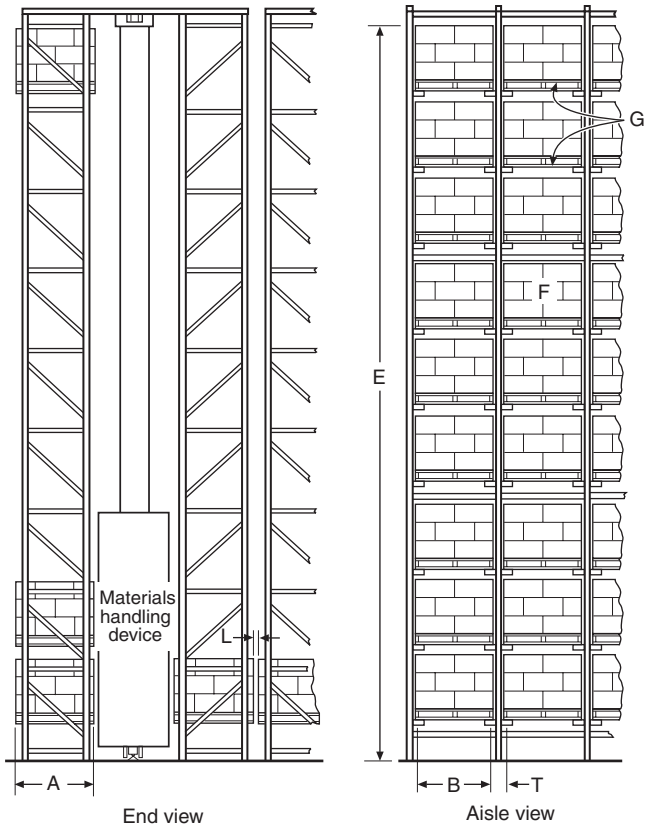


FIGURE 16.5.11 Common Arrangement of Double-Row Storage Racks with Palletized Storage Atop (Source: Unarco Material Handling, Inc.)

FIGURE 16.5.12 Unusual Storage Racks with Three Pallets Between Uprights—Three Transverse Flues (Source: Clark Material Handling Company)

FIGURE 16.5.13 High Storage Racks (53 ft [16 m]) with Narrow Aisle (Source: Unarco Material Handling, Inc.)

the rack arrangement is considered multiple row. Multiple-row racks demand a more powerful sprinkler system than double-row racks: the narrower aisles increase the likelihood of a fire spreading from rack to rack.



Legend

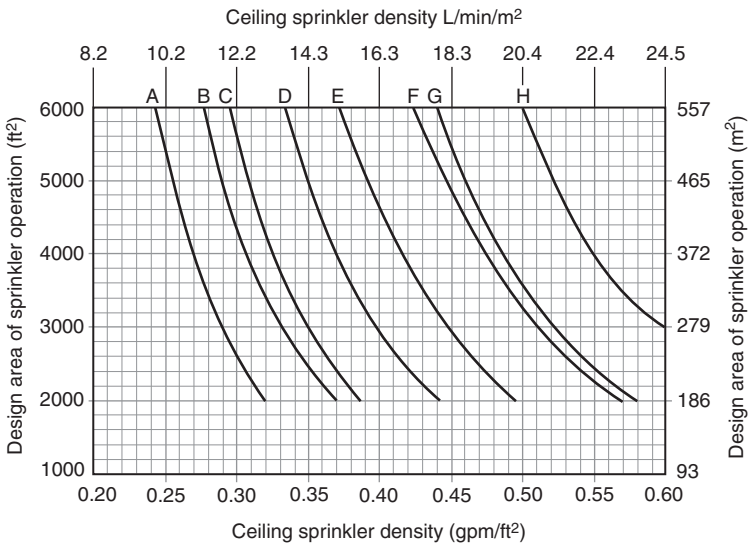
A = Load depth
B = Load width
E = Storage height
F = Commodity
G = Pallet
L = Longitudinal flue space
T = Transverse flue space

FIGURE 16.5.14 Automatic Storage-Type Rack

Aisles between palletized storage piles should not be more than 50 ft (15.2 m) wide. This lets streams from small hose lines penetrate 25 ft (7.6 m) into the center of the pile. Although NFPA 13 does not specially consider wide or frequent aisles, it assumes the presence of aisles. The aisles should be at least 8 ft (2.4 m) wide. This requirement is not unreasonable, considering that aisles are necessary for materials-handling operations and 8 ft (2.4 m) are typically needed to maneuver a lift truck. When judging the adequacy of existing sprinkler protection, aisle spacing and frequency need consideration.

STORAGE HEIGHT AND CLEARANCE

After commodity classification and storage arrangement, probably no other factor more profoundly influences a fire and its controllability than does storage height and clearance from the top of storage to sprinklers. As expected, the higher the storage arrangement, the more challenging the fire is. This is because an increase in storage height results in a larger fire size (heat release rate) at the time sprinklers operate, which in turn requires increased sprinkler performance to control.



Legend

A = Single- or double-row racks with 8 ft (2.44 m) aisles with 286°F (141°C) ceiling sprinklers and 165°F (74°C) in-rack sprinklers.

B = Single- or double-row racks with 8 ft (2.44 m) aisles with 165°F (74°C) ceiling sprinklers and 165°F (74°C) in-rack sprinklers.

C = Single- or double-row racks with 4 ft (1.22 m) aisles or multiple-row racks with 286°F (141°C) ceiling sprinklers and 165°F (74°C) in-rack sprinklers.

D = Single- or double-row racks with 4 ft (1.22 m) aisles or multiple-row racks with 165°F (74°C) ceiling sprinklers and 165°F (74°C) in-rack sprinklers.

E = Single- or double-row racks with 8 ft (2.44 m) aisles and 286°F (141°C) ceiling sprinklers.

F = Single- or double-row racks with 8 ft (2.44 m) aisles and 165°F (74°C) in-rack sprinklers.

G = Single- or double-row racks with 4 ft (1.22 m) aisles and 286°F (141°C) ceiling sprinklers.

H = Single- or double-row racks with 4 ft (1.22 m) aisles and 165°F (74°C) ceiling sprinklers.

FIGURE 16.5.15 Sprinkler System Design Curves for 20-ft (6.1-m) High Rack Storage of Class IV Unencapsulated Commodities Using Conventional Pallets

Clearance also produces a significant effect on fire challenge. Increasing clearance from the top of storage to sprinklers increases the time required for sprinklers to operate in a fire of a given commodity and storage height, resulting in a larger fire size at the time sprinklers operate. Increased clearance also results in a larger fire plume above the top of storage, which reduces the ability of water from sprinklers to reach the seat of a fire.

In designing protection for a storage facility, the protection scheme must properly account for both storage height and clearance. The storage height used for design should be the maximum height expected. What may not be as obvious is that the clearance used for design should also be the maximum anticipated clearance.

NFPA 13 requires that, when ceiling heights exceed 30 ft (9.14 m) and the distance between the ceiling height and top of storage exceeds 20 ft (6.1 m), protection be provided for the storage height that would result in a 20 ft (6.1 m) distance between the ceiling height and top of storage. The clearance between the storage and the roof/ceiling is an important factor for control-mode density/area protection. Implicit in storage protection requirements is that protection for a given storage height in a building of a given height must also be adequate to protect any lesser storage height in that building. This requirement becomes necessary because warehouses are never completely full, and storage heights can fluctuate widely over both the short and long term. Clearances greater than 20 ft (6.1 m) are beyond the scope of testing used to develop the protection requirements for control-mode density/area sprinklers. Therefore, protection adequate for a storage height that results in a clearance of less than 20 ft (6.1 m) will be adequate for lesser storage heights, despite the fact that clearance exceeds 20 ft (6.1 m).

Warehouses are highly transient facilities, with the amounts of products varying widely from morning to night, week to week, and season to season. A sprinkler design cannot take advantage of low clearance (i.e., design area reductions for clearance from ceiling to top of storage less than 4½ ft [1.37 m]) unless the clearance will never be greater than that used in determining the sprinkler system design.

The minimum clearance of 18 in. (0.46 m) required below ceiling sprinkler deflectors is the minimum that will allow the proper spray pattern to develop. When early-suppression fast-response (ESFR) or specific-application control-mode sprinklers are used, the minimum clearance required is 36 in. (0.91 m).

AUTOMATIC SPRINKLER PROTECTION

Automatic sprinkler protection supplemented by manual fire-fighting operations and sound storage and housekeeping practices is the most effective and practical means of fire protection. Properly designed, installed, and maintained systems will perform their intended tasks. However, a fire protection plan incorporating an inadequate, impaired, or partial sprinkler system cannot be expected to produce good results.

Recent advances in sprinkler technology provide three basic approaches for sprinkler protection of storage operations. These include the use of (1) control-mode density-area sprinklers, (2) control-mode specific-application sprinklers, and (3) suppression-mode (ESFR) sprinklers. Each of the three approaches is associated with varying sprinkler types, sizes, and installation arrangements, thus providing a number of possible alternatives for sprinkler system design for most storage situations. There is no single "best" method for protecting a given storage arrangement, as each design must take into consideration the overall effectiveness, flexibility, and cost in relation to the design goals. Any of the protection alternatives specified in NFPA 13 for storage facilities will meet the basic goals of fire control. However, certain alternatives more effectively minimize property damage, maximize flexibility in relation to future changes in storage arrangement, or minimize cost.

The most common design approach is to determine the design that satisfies the minimum requirements of NFPA 13 at the least initial cost. Implicit in this approach is the assumption that any design that satisfies the requirements of NFPA 13 is equivalent to any other, and that the initial cost of installation is the only factor of consequence. In actual fact, minimizing the original cost of installation often doesn't even minimize the true cost of the sprinkler system over its useful life, much less maximize its overall cost effectiveness. The best approach, therefore, is to establish a comprehensive design that takes into consideration in a rational way clearly identified long-term operational and fire protection goals. This requires, in addition to an understanding of the requirements of NFPA 13 and sprinkler systems, in-depth knowledge of the strengths and limitations of the wide variety of sprinkler hardware and designs currently available and an understanding of the associated fire hazards.

Miscellaneous Storage

Most every occupancy outside of storage occupancies have some type/amount of storage. It is not the intent of the NFPA standards to trigger stringent storage rules every time incidental storage occurs in occupancy hazards. Storage protection per NFPA 13 can occur in occupancy hazards such as ordinary and extra hazards without changing the occupancy classification if the storage is incidental to the occupancy and meets the following definition:

> Storage that does not exceed 12 ft (3.66 m) in height and is incidental to another occupancy use group. Such storage will not constitute more than 10 percent of the building area or 4000 ft^2 (372 m^2) of the sprinklered area, whichever is greater. Such storage will not exceed 1000 ft^2 (93 m^2) in one pile or area, and each such pile or area will be separated from other storage areas by at least 25 ft (7.62 m).

Meeting this definition will result in an occupancy (ordinary or extra hazard) method of protection rather than a storage method of protection.

Control-Mode Density-Area Sprinklers

Control-mode density-area sprinklers are the oldest technology used to protect current storage methods. One key indicator of a control-mode density-area sprinkler is the description of the design area by a density, such as 0.3 gpm (12.2 mm/min), over an area of 2000 ft^2 (186 m^2). Control-mode density-area sprinklers are the only sprinklers that can change their minimum operating pressure by changing the spacing. The area of protection for each sprinkler dictates the minimum operating pressure, unlike control-mode specific-application and ESFR sprinklers that have a minimum operating pressure regardless of sprinkler spacing. The control-mode density-area category includes sprinklers with K-factors ranging from 5.6 (80.6) to 25.2 (362.9) in which discharge densities operating over a certain size area are selected from NFPA 13. The performance of these sprinklers in the protection of storage is characterized by the fact that the first sprinklers that operate work to contain or rather control the fire. Through a combination of prewetting of combustibles surrounding the initial fire area and cooling at roof/ceiling level, the fire is confined to a relatively small area until it is manually extinguished or burns itself out. Recent full-scale fire tests have shown that larger K-factor sprinklers have a distinct performance advantage.[1] That fact, coupled with the fact that the larger K-factor sprinklers require less pressure to achieve a specified discharge density, means that the minimum K-factor for sprinklers used to protect storage should be no less than 8.0 (115.2) and preferably 11.2 (161.4) or greater for certain applications.

NFPA 13 specifies both ceiling-only and ceiling-plus-in-rack sprinkler designs for protection of certain rack storage configurations using control-mode density-area sprinklers. Although there are a number of negative aspects associated with in-rack sprinkler protection (chief among which are installation cost and the potential for leakage due to mechanical damage), it remains the most effective and reliable method for protecting rack storage.

Control-Mode Specific-Application Sprinklers

Control-mode specific-application sprinklers are control-mode sprinklers whose performance characteristics have been enhanced through the use of orifice/deflector designs that produce larger water droplets that better penetrate a fire plume. This enhanced performance provides certain advantages over traditional control-mode density-area sprinklers. The discharge criterion for this type of sprinkler is specified as a number of sprinklers operating at a minimum pressure rather than a minimum density and design area.

The first control-mode specific-application sprinkler was the large-drop sprinkler. More recently, control-mode specific-application sprinklers with larger K-factors have been developed. The design requirements and applications of various types of control-mode specific-application sprinklers can differ and are based on fire testing. It cannot be assumed that, because one type of control-mode specific-application sprinkler is permitted by standards for protection of a type of storage, other types of control-mode specific-application sprinklers may be used.

Suppression-Mode Sprinklers

Suppression-mode, or ESFR, sprinklers are a radical departure from control-mode sprinkler technology and come with their own unique set of strengths and limitations. The fundamental premise of suppression-mode sprinkler protection is that a sensitive sprinkler capable of producing an optimized high-volume, high-momentum discharge can actually suppress (rather than simply control) a fire in storage. The primary advantage of suppression-mode sprinklers is their ability to protect many rack storage arrangements without the need for in-rack sprinklers. Although they are much more effective in protecting such storage than ceiling-only control-mode sprinklers, they are no more effective than a ceiling/in-rack sprinkler design using control-mode sprinklers. They also have their own quite complex and sensitive installation rules.

Comparison of Types of Sprinkler Protection

Looking at the design requirements for 20-ft (6.1-m) high storage of Class I to IV storage protection provided by the previously referenced technologies will help to develop an understanding of the different protection options available. Tables 16.5.1 through 16.5.7 show the design requirements for the protection of 20-ft (6.1-m) high storage of Class I to IV storage using the three types of sprinkler protection. Notice the effect of storage arrangements and encapsulation on control-mode density-area sprinklers, whereas there is little effect on control-mode specific-application sprinklers and no effect on suppression-mode sprinklers. Although there are many other commodities and storage heights, these simple comparisons will give the user a better understanding of the different protection methods available for a single commodity class.

TABLE 16.5.1 Sprinkler System Design Density for Palletized, Solid-Piled, in Bin Boxes, or in Shelf Storage of Class IV Commodity Storage 20 ft (6.1 m) High

		Sprinkler Temp.			
		High Temp.		Ordinary Temp.	
Storage Height	*Commodity Class*	*gpm/ft²*	*mm/min*	*gpm/ft²*	*mm/min*
20 ft (6.1 m)	IV	0.30	12.2	0.39	15.9

Control-Mode Density-Area Sprinklers. The effect of the storage arrangement is shown for control-mode density-area sprinklers by interpreting the design density curves in NFPA 13 for 20-ft (6.1-m) high Class IV storage. Tables 16.5.1, 16.5.2, and 16.5.3 show the design densities required at a 2000 ft² (186 m²) hydraulically remote area (unless noted otherwise) for palletized/solid-piled, single-/double-row rack, and multiple-row rack, respectively. Minimum operating pressure changes with spacing. Density is applied based on the actual floor coverage area. Although clearance or ceiling height limitation are not in the protection table for control-mode density-area sprinklers, the clearance is limited to a 20 ft (6.1 m) maximum (see the previous discussion in Storage Height and Clearance).

Control-Mode Specific-Application Sprinklers. Spacing of control-mode specific-application sprinklers (from their

TABLE 16.5.2 Sprinkler System Design Density for Single- or Double-Row Racks—Class IV Commodities—Storage Height 20 ft (6.1 m) Without Solid Shelves

					20 ft (6.1 m)							
					With In-Rack				Without In-Rack			
					High Temp.		Ordinary Temp.		High Temp.		Ordinary Temp.	
Commodity Class	*Encapsulated*	*Sprinklers Mandatory in Racks*	Aisles *ft*	Aisles *m*	*gpm/ft²*	*mm/min*	*gpm/ft²*	*mm/min*	*gpm/ft²*	*mm/min*	*gpm/ft²*	*mm/min*
IV	No	No	4	1.2	0.39	15.9	0.44	17.9	0.58	23.6	0.60*	24.5
			8	2.4	0.32	13.0	0.37	15.1	0.50	20.4	0.57	23.2
	Yes	1 level	4	1.2	0.48	19.6	0.55	22.4	NA	NA	NA	NA
			8	2.4	0.39	15.9	0.45	18.3	NA	NA	NA	NA

*Design area = 3000 ft² (278.7 m²).
NA = Not available.

TABLE 16.5.3 Sprinkler System Design Density for Multiple-Row Racks (Class IV Commodities)—Rack Depth up to and Including 16 ft (4.9 m), Aisles 8 ft (2.4 m) or Wider, Storage Height 20 ft (6.1 m)

			20 ft (6.1 m)					
			With In-Rack				Without In-Rack	
			High Temp.		Ordinary Temp.			
Commodity Class	*Encapsulated*	*Sprinklers Mandatory in Racks*	*gpm/ft²*	*mm/min*	*gpm/ft²*	*mm/min*	*High Temp.*	*Ordinary Temp.*
IV	No	1 level	0.39	15.9	0.44	17.9	NA	NA
	Yes	1 level	0.48	19.6	0.56	22.8	NA	NA

NA = Not available.

minimum to maximum allowable spacing) does not affect the minimum operating pressure required in the tables. Notice the addition of ceiling/roof height to Tables 16.5.4 and 16.5.5, which is important to the system design.

Suppression-Mode Early-Suppression Fast-Response (ESFR) Sprinklers. Notice that the ceiling/roof height is now the primary factor in determining the appropriate design criteria (see Tables 16.5.6 and 16.5.7). Unlike control-mode technology, the ESFR is not affected by clearance between the top of the storage and the sprinkler at the ceiling. It is one of the first technologies providing protection for the full height of the building and will not be affected by changes in storage heights. Spacing of ESFR sprinklers (from their minimum to maximum allowable spacing) does not affect the minimum operating pressure required in the tables.

In-Rack Sprinklers

Rack structures inherently create obstructions to rising heat and combustion products from a fire and to water discharge from a ceiling sprinkler system. As a result, a fire in racks can become very challenging, quickly overpowering most ceiling sprinkler systems. This phenomenon becomes more pronounced when storage heights increase and when both horizontal and structural flue spaces become obstructed. Sprinklers installed in racks alleviate this concern.

In-rack sprinklers work to contain a fire in a small, localized area. Once activated, they discharge water on or near the fire's source, without the delay associated with conventional ceiling sprinklers. In-rack sprinklers also prewet the area directly near the fire, thus reducing horizontal and vertical fire spread. In-rack sprinklers also minimize the potential water damage to stock because water is only applied to the localized area of the fire, usually eliminating the activation of the ceiling sprinkler system. Using in-rack sprinkler systems also reduces the demand on the ceiling sprinkler system and uses water supply more efficiently.

In-rack sprinklers are installed in the longitudinal flue spaces of the rack structure. As rack height increases, additional in-rack sprinklers may also be needed in the transverse flue spaces within 18 in. (0.49 m) of the aisle. Such in-rack sprinklers, referred to as "face sprinklers," protect against fire spread over the rack's vertical face and help prevent a fire from jump-

TABLE 16.5.4 Specific-Application Control-Mode Sprinkler Design Criteria for Palletized and Solid-Piled Storage of Class I Through IV Commodities Stored 20 ft (6.1 m) in Height

Storage Arrangement	*Commodity Class*	*Nominal K-Factor*	Maximum Storage Height		Maximum Ceiling/Roof Height		*Type of System*	Number of Design Sprinklers/ Minimum Pressure	
			ft	*m*	*ft*	*m*		*psi*	*bar*
Palletized	IV	11.2	20	6.1	30	9.1	Wet Dry	20/25 NA	20/1.7 NA
Solid pile	IV	11.2	20	6.1	30	9.1	Wet Dry	15/50 NA	15/3.4 NA
		11.2	20	6.1	30	9.1	Wet Dry	15/50 NA	15/3.4 NA

NA = Not available.

TABLE 16.5.5 Specific-Application Control-Mode Sprinkler Design Criteria for Single-, Double-, and Multiple-Row Racks Without Solid Shelves of Class IV Commodities Stored 20 ft (6.1 m) in Height

Commodity Class	*Nominal K-Factor*	Maximum Storage Height		Maximum Ceiling/Roof Height		*Type of System*	Number of Design Sprinklers/ Minimum Pressure	
		ft	*m*	*ft*	*m*		*psi*	*bar*
IV	11.2	20	6.1	25	7.6	Wet Dry	15/50 NA	15/3.4 NA
IV	11.2	20	6.1	30	9.1	Wet Dry	20/25 NA	20/3.4 NA
IV	11.2	20	6.1	30	9.1	Wet Dry	15/75 NA	15/5.2 NA

NA = Not available.

TABLE 16.5.6 ESFR Protection of Palletized and Solid-Pile Storage of Class IV Commodities

Commodity	Maximum Storage Height ft	Maximum Storage Height m	Maximum Ceiling/Roof Height ft	Maximum Ceiling/Roof Height m	Nominal K-Factor	Minimum Operating Pressure psi	Minimum Operating Pressure bar
Class IV, encapsulated or unencapsulated (no open-top containers or solid shelves)	20	6.1	25	7.6	11	50	3.4
					14	50	3.4
					25.2	20	1.4
	25	7.6	30	9.1	14	50	3.4
					25.2	20	1.4
	30	9.1	35	10.7	14	75	5.2
					25.2	30	2.1
	35	10.7	40	12.2	14	75	5.2
					25.2	40	2.8
	40	12.2	45	13.7	25.2	50	3.4

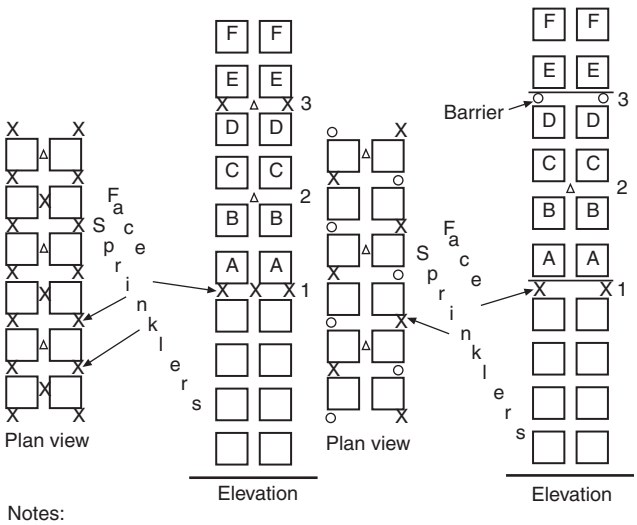
TABLE 16.5.7 ESFR Protection of Rack Storage Without Solid Shelves of Class IV Commodities Stored up to and Including 25 ft (7.6 m) in Height

Storage Arrangement	Commodity	Maximum Storage Height ft	Maximum Storage Height m	Maximum Ceiling/Roof Height ft	Maximum Ceiling/Roof Height m	Nominal K-Factor	Minimum Operating Pressure psi	Minimum Operating Pressure bar
Single-row, double-row, and multiple-row rack (no open-top containers)	Class IV, encapsulated or unencapsulated	20	6.1	25	7.6	11	50	3.4
						14	50	3.4
						25.2	20	1.4
		25	7.6	30	9.1	14	50	3.4
						25.2	20	1.4
						25.2	50	3.4
		30	9.1	35	10.7	14	75	5.2
						25.2	30	2.1
		35	10.7	40	12.2	14	75	5.2
						25.2	40	2.8
		40	12.2	45	13.7	25.2	50	3.4

ing across the aisle to an adjacent rack. In some cases solid horizontal barriers covering the rack's entire length and width are also used with in-rack sprinklers. These barriers help activate the in-rack sprinklers and reduce the number of in-rack sprinklers needed. Figure 16.5.16 illustrates these concepts. Note in Figure 16.5.16 how horizontal barriers within the racks (right) reduce the number of in-rack sprinklers required (left). The symbols O, Δ, and X indicate sprinklers installed in a vertical or horizontal alternating or staggered arrangement on the sprinkler piping.

Sprinklers installed in racks can be standard or fast-response type with standard or large orifices. Ordinary-temperature-rated sprinklers should be used. However, intermediate-temperature- and high-temperature-rated sprinklers are required near heat sources. Water shields are required to guard against cooling or cold soldering of unactivated sprinklers by the water spray from in-rack sprinklers located higher in the rack. Figure 16.5.17 illustrates typical in-rack sprinklers. The upright standard-response sprinkler is shown on the left and the upright fast-response sprinkler is shown on the right. Pendent sprinklers can be field-equipped with water shields. The fast-response type is appropriate for protection under open-girded catwalks between racks, shelves, or bins.

The need for in-rack sprinklers depends on a number of factors, including the condition and type of ceiling sprinkler system, commodity type, and storage height. Generally, when spray sprinklers are used, in-rack sprinklers are required for rack storage over 25 ft (7.6 m), regardless of the commodity. For storage up to 25 ft (7.6 m), the need for in-rack sprinklers varies. When ESFR sprinklers are used, in-rack sprinklers are



Notes:
1. Sprinklers labeled 1 required where loads labeled A or B represent top of storage.
2. Sprinklers labeled 1 and 2 required where loads labeled C or D represent top of storage.
3. Sprinklers labeled 1 and 3 required where loads labeled E or F represent top of storage.
4. For storage higher than represented by loads labeled F, the cycle defined by Notes 2 and 3 is repeated.
5. Symbols O, Δ, and X indicate sprinklers on vertical or horizontal stagger.
6. Each square in the figure represents a storage cube measuring 4 to 5 ft (1.25 to 1.56 m) on a side.

FIGURE 16.5.16 In-Rack Sprinkler Arrangement for Class I, II, or III Commodities, with Storage Heights over 25 ft (7.6 m)

FIGURE 16.5.17 Typical In-Rack Sprinklers (Source: Grinnell Fire Protection Systems Co., Inc.)

not required in most cases. (See the discussion of sprinkler response time later in this chapter.)

NFPA 13 provides criteria to determine if in-rack sprinklers are necessary, their number, and arrangement. Various combinations of in-rack sprinkler installations have been found effective, so several design options are available.

Sprinkler Spacing

NFPA 13 provides the minimum and maximum spacing for the different types of sprinklers. It is just as important to recognize the minimum spacing requirements as the maximum spacing requirements to prevent the cold solder and skipping of adjacent rings of sprinklers in the event of a fire. The maximum spacing for most sprinklers is 100 ft^2 (9.3 m^2), whereas extended coverage sprinklers may be spaced at 196 ft^2 (59.7 m^2) for storage applications.

Temperature Rating of Ceiling Sprinklers

In control-mode sprinkler protection, the temperature rating of a sprinkler can exert a significant effect on the number of sprinklers that operate. Due to the comparatively weak performance of smaller-orifice sprinklers, ceiling gas temperatures can be high, even though control is achieved. This means that sprinklers further away from a fire can operate, and that fact must be taken into consideration in design. For larger-orifice control-mode and ESFR sprinklers, this effect is minimized and lower-temperature-rated sprinklers do not pose as great a concern.

Sprinkler Response Time

With the exception of ESFR sprinklers, testing has shown[2] that quick-response sprinklers offer neither significant advantages nor disadvantages in the protection of storage. However, NFPA 13 specifies the use of standard-response sprinklers unless quick-response sprinklers listed for storage applications are to be used. The same design requirements apply equally to both types.

Protection System Types

Dry Pipe Versus Wet Pipe Sprinkler Systems. In a wet pipe sprinkler system, the piping attached to the automatic sprinklers contains water under pressure at all times. In a dry pipe system, the piping contains air or nitrogen under pressure. When a sprinkler operates in a dry pipe system, air pressure is reduced, a dry pipe valve opens, water enters the piping, and after a short delay flows out the open sprinklers. Dry pipe systems should only be used in areas subject to freezing temperatures. Refer to Section 16, Chapter 3, "Automatic Sprinkler Systems," for discussions of various types of sprinkler systems.

Where dry pipe systems are used, the time delay associated with water delivery lets a fire grow and spread heat that in turn can activate more sprinklers beyond the immediate fire area. To compensate, the required design area of sprinkler operation usually increases by 30 percent for dry pipe systems. Density should be selected so that, after the 30 percent increase, the design area does not exceed the maximum allowable design area of sprinkler operation.

High-Expansion Foam. Although automatic high-expansion foam extinguishing systems can independently suppress a fire, some are reluctant to use them as the sole means of automatic fire control in certain cases. They are usually more expensive and more complicated than sprinkler systems, do not protect the roof structure until foam reaches it, involve the entire contents of a protected area regardless of the fire's size, and leave foam residue on unburned materials. However, they can be desirable when used with automatic sprinklers for certain high-challenge storage occupancies. A high-expansion foam system uses a series of foam-makers at ceiling level. When activated by the fire detection system throughout the area, the foam system sprays

water mixed with special foam concentrate in each foam-maker and strikes a screen while a fan blows through it. The system produces many uniformly sized bubbles, which cascade down into and gradually fill the warehouse area. The foam's expansion ratio is up to 1000:1. It flashes to steam on contact with burning material and engulfs other material, keeping it from burning. Building doors should automatically close when the system activates.

When high-expansion foam systems combine with ceiling sprinkler systems, the ceiling sprinkler discharge density may be reduced to one-half the density otherwise required. However, the density cannot be less than the following:

- 0.15 gpm/ft^2 (6.1 L/min/m^2) for Class I through IV solid-piled or palletized commodities, including idle pallets or plastics
- 0.24 gpm/ft^2 (9.8 L/min/m^2) for rubber tire storage
- 0.25 gpm/ft^2 (10.2 L/min/m^2) for roll paper storage

In-rack sprinklers are not required for rack storage when high-expansion foam is installed. In addition, ceiling density can be reduced to 0.2 gpm/ft^2 (8.1 L/min/m^2) for Class I, II, and III commodities, and to 0.25 gpm/ft^2 (10.2 L/min/m^2) for Class IV commodities.

WATER SUPPLY

The water supply must adequately supply the demands of the ceiling sprinklers, in-rack sprinklers if used, and hose streams. NFPA 13 outlines hydraulic calculations for determining the demand of the sprinkler system, including in-rack sprinklers. Sprinkler demand is expressed as a flow rate, such as gal/min (L/min), at a corresponding minimum residual pressure. Typically 500 gpm (1894 L/min) is added to the sprinkler demand for large and small hose streams. Hose streams are intended to operate concurrently with the sprinkler system, so the residual pressure demand for the sprinklers is typically used.

The sprinkler system piping design (i.e., pipe size, fittings, and material), affects the residual pressure. In general, at least 30 to 50 psi (207 to 345 kPa) pressure is needed at the ceiling-level distribution point or top of the riser. When greater pressure is available, more economic system design is possible. However, exposing the most remote conventional sprinkler to pressures over 60 psi (414 kPa) is undesirable. High pressures may create very fine, but not very effective, spray patterns.

The water supply needs to be available long enough for the sprinklers to control the fire, manual fire fighting, and mop-up operations. Two hours are typically required. However, if a central station monitors the fire alarms, this period can be reduced to 90 minutes.

The reliability of available water supplies also needs consideration, especially for high-value locations. A multiple-supply arrangement (e.g., a fire pump connected to a suction tank in conjunction with an adequate public supply) might be advantageous. Such redundancy is based on engineering judgment. For example, a $100 million warehouse may be connected to a single city water main. Although the supply may be adequate, it is possible that supply could be out of service for some time or deteriorate.

The layout of yard mains, tanks, pump houses, power supply to pumps, hydrants, and valves warrants qualified fire protection engineering attention in the planning stage. To correct a water supply deficiency, alternate methods can be considered. The factors discussed earlier offer such alternatives. Adding a booster fire pump may be an economical alternative for a sprinkler system requiring high pressure. On the other hand, it may be more economical to do one of the following:

- Upgrade the piping layout only in that system
- Replace ceiling sprinklers for that system with ones of a different temperature rating
- Install in-rack sprinklers in that area
- Lower pile heights in that area (not a good long-range solution)
- Combine methods

SPECIAL COMMODITIES

Many commodities have been studied separately because of the fire properties associated with their physical form, method of storage, and difficulty of fire control. The following describes some of the unique characteristics of special commodities.

Idle Pallets

Pallets used as storage aids are considered part of the commodity classification. Pallets are approximately 4 in. (102 mm) high and usually composed of wood or plastic, although some are metal or cardboard. A pallet's main purpose is to aid storage practices by allowing products to be moved easily by forklift trucks and to provide stability. The commodity classification does not include idle pallets because of their unique combustion characteristics. When stored outdoors, all types of pallets should be located away from a building at the distances indicated in Table 16.5.8.

Wood Pallets. Stockpiling idle pallets indoors or outdoors presents a very severe fire hazard. Wooden pallets tend to dry out so their edges become frayed and splintered. In this condition, a relatively small ignition source can ignite them. Their dried-out condition, high rate of heat release, and overall arrangement result in a quickly developing fire. The undersides of the slats or planks, shielded from the discharge of automatic sprinklers, make controlling or extinguishing a fire difficult. Figure 16.5.18 shows a conventional wooden pallet.

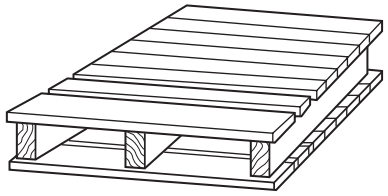


FIGURE 16.5.18 Conventional Wooden Pallet

TABLE 16.5.8 Recommended Clearances Between Outside Idle Pallet Storage and Building

Wall Construction		Minimum Distance (ft [m]) of Wall from Storage Of		
Wall Type	*Openings*	*Under 50 Pallets*	*50 to 200 Pallets*	*Over 200 Pallets*
Masonry	None	0	0	0
	Wired glass with outside sprinklers 1 hour doors	0	10 (3.0)	20 (6.1)
	Wired or plain glass with outside sprinklers ¾ hour doors	10 (3.0)	20 (6.1)	30 (9.1)
Wood or metal with outside sprinklers		10 (3.0)	20 (6.1)	30 (9.1)
Wood, metal, or other		20 (6.1)	30 (9.1)	50 (15.2)

The fire hazard idle pallets present can be mitigated by strictly limiting storage arrangements and employing an appropriate sprinkler system or by moving idle pallets outside and away from the building. Tables 16.5.9, 16.5.10, and 16.5.11 list protection criteria found to be effective for pallets stored indoors. However, the provisions of these tables need not be applied if the idle pallets meet any of the following conditions:

- Stacked no higher than 6 ft (1.8 m)
- Stored in piles not exceeding four stacks
- Stored in piles separated by a distance of 8 ft (2.4 m) from one another or by 25 ft (7.62 m) of commodity

Plastic Pallets. Plastic pallets other than nonexpanded polyethylene solid-deck pallets present an even greater fire hazard. Additional precautions must be taken. Refer to NFPA 13 for details.

Rubber Tires

Fires in rubber tires are very hot, smoky, and difficult to control and extinguish. High sprinkler densities are needed to control the fire and protect the building. (See NFPA 13.)

Tires are stored in piled form, in compact portable racks referred to as pallets, and in racks. They may be arranged on tread,

TABLE 16.5.9 Control-Mode Area-Density Protection of Indoor Storage of Idle Wood Pallets

Type of Sprinkler	*Location of Storage*	Maximum Storage Height		Sprinkler Density		Areas of Operation: High Temperature		Areas of Operation: Ordinary Temperature	
		ft	*m*	*gpm/ft²*	*mm/min*	*ft²*	*m²*	*ft²*	*m²*
Control mode area-density	On floor	Up to 6	Up to 1.8	0.2	8.2	2000	186	3000	279
		6 to 8	1.8 to 2.4	0.3	12.2	2500	232	4000	372
		8 to 12	2.4 to 3.7	0.6	24.5	3500	325	6000	557
		12 to 20	3.7 to 6.1	0.6	24.5	4500	418	—	—

TABLE 16.5.10 Control-Mode Specific-Application Protection of Indoor Storage of Idle Wood Pallets

Type of Sprinkler	*Location of Storage*	*Nominal K-Factor*	Maximum Storage Height		Maximum Ceiling/Roof Height		*Type of System*	Number of Design Sprinklers by Minimum Pressure		
			ft	*m*	*ft*	*m*		*25 psi (1.7 bar)*	*50 psi (3.4 bar)*	*75 psi (5.2 bar)*
Large drop	On floor	11.2	20	6.1	30	9.1	Wet	15	15	15
							Dry	25	25	25

TABLE 16.5.11 ESFR Protection of Indoor Storage of Idle Wood Pallets

Type of Sprinkler	*Location of Storage*	*Nominal K-Factor*	Maximum Storage Height		Maximum Ceiling/Roof Height		Minimum Operating Pressure	
			ft	*m*	*ft*	*m*	*psi*	*bar*
ESFR	On floor or rack without solid shelves	14.0	25 35	7.6 10.7	30 40	9.1 12.2	50 75	3.4 5.2

on side, or in a laced configuration (Figure 16.5.19). Because tires are not packaged, they contribute their own circular air space to the storage, forming considerable horizontal or vertical flues. Interiors of tire carcasses can flame vigorously, mostly beyond the reach of water from sprinklers. Final extinguishment involves laboriously applying water to individual tires, usually after removing them from the building.

Combined with sprinklers, high-expansion foam is very effective on rubber tires and causes minimal water damage or contamination. To fully penetrate the inner reaches of the tires, an additional hour of foam soaking is advised after the sprinklers are shut off to maintain the foam level.

Roll Paper

Roll paper is stored on its side or, more commonly, on end. One might assume that the latter arrangement permits easier paths for sprinkler water to penetrate the vertical air spaces and slow the fire, but experience with roll paper shows otherwise. In storage on end, peeling or exfoliation during a fire is a major concern. This phenomenon can be abated somewhat by metal banding, tightly applying steel baling wire by hand, covering ends as well as sides with fire-retardant-treated tight paper wrappers or closely spacing the columns of rolls. In effective close spacing, stacks or columns are less than 4 in. (101 mm) apart.

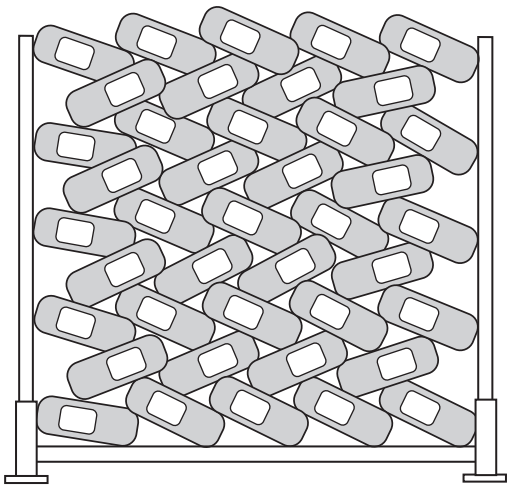


FIGURE 16.5.19 Laced Tire Configuration

NFPA 13 prescribes sprinkler density-area requirements according to the rolls' arrangement, whether they are banded or unbanded, the piles' height, and the paper's weight (i.e., heavy, medium, light, or tissue). Because rolled paper tends to absorb water from a discharging sprinkler and swells in size, it should be stored with sufficient clearance from walls.

Carpet Storage

Rugs or carpeting in rolls are generally stored in racks that accommodate 12- to 15-ft (3.7- to 4.6-m) long rolls. Therefore, racks are at least that deep and sometimes placed back-to-back, forming a total width of 24 to 30 ft (7.3 to 9.1 m) between aisles. Of course, small carpet pieces and rolls may be placed in cartons and stored in regular solid or palletized piles or conventional racks.

Long carpet rolls will deflect if their length is not supported, so solid or slatted shelves are used in wide racks, or in some cases, rolls of carpet are stored in paperboard tubes. A strict application of NFPA 13 requirements for solid-shelf rack storage would require in-rack sprinklers under each solid or slatted shelf in racks, unless transverse flue spaces at least 6 in. (152 mm) wide are provided no more than 4 ft (1.22 m) apart. With carpet racks having only one tier for each roll of carpet, installation of in-rack sprinklers becomes problematic. A reasonable compromise is to provide minimum 3-in. (51-mm) wide transverse flue at all vertical supports, which are normally 10 to 12 ft (3 to 3.7 m) apart, and providing in-rack sprinklers (including face sprinklers) at approximately every third tier, with a maximum vertical dimension of 10 ft (3.05 m) between levels of in-rack sprinklers.

Figure 16.5.20 illustrates racks for storing carpeting on slatted shelves. The tiers' closeness to each other, plus their depth, complicates problems of providing in-rack sprinkler protection.

Carpet Padding

Padding or backing for carpet is typically expanded plastic. When stored in carpet warehouses, it should be protected as an expanded plastic, which will typically require in-rack sprinklers at every level of storage.

Baled Fibers

The main hazard of baled cotton and other fibers of vegetable origin comes from the multitude of exposed minute fibers on

FIGURE 16.5.20 Racks for Storing Carpeting on Slatted Shelves (Source: Clark Material Handling Company)

the surfaces of the bales. Fire can flash quickly over these vertical surfaces, loose particles on the floor, and lint on overhead piping and structure. Fire on one side of an automatic-closing fire door can progress through the open doorway on loose floor scraps before the door can close automatically. Housekeeping, therefore, is especially important.

Fire also can easily penetrate between and into bales, requiring their removal from the building for extinguishment. Considerable smoke emission can complicate fire fighting. Certain fibers, such as jute, swell when wet, so they should be piled with regard to stability in a fire and with proper clearance from walls.

NFPA 13 limits the height of tiered or rack storage to 15 ft (4.6 m) and pile sizes to 700 bales, with a 12 ft (3.7 m) main aisle and 4 ft (1.2 m) cross aisles, in maximum fire divisions of 10,000 bales. The standard calls for large operating areas for sprinklers. (Factory Mutual Research Corporation's Loss Prevention Data Sheet 8-7 covers baled combustible fibers generally, including wool, which burns much more slowly than most fibers.)

Ordinary dry chemical (BC-type) fire extinguishers very effectively knock down surface fires on bales. However, they should be backed up by water spray from small hose or garden hose or by water-type extinguishers with spray nozzle attachments to extinguish smaller fires that may have penetrated the bales. Preferably, "wet water," which is water with a chemical additive that increases its penetrating and spreading ability, should be used.

Baled Waste Paper

Like baled fibers, baled wastepaper is typically stored in solid piles in which fire can easily burrow. Fire can flash over the surface of finely shredded paper bales, as it does over baled fiber. Wastepaper becomes mushy and difficult to handle when wet; in fact, the bales' integrity slowly disappears as the hose stream application progresses, making removal of burning bales difficult. Smoke can also be troublesome. Baled paper sometimes is stored at great heights because of its low unit value, but fire protection standards utilizing conventional sprinklers do not apply to storage over 30 ft (9.1 m) high, except in racks. Baled wastepaper is often stored in sheds with only partial walls, if any. Anecdotal loss experience suggests that even relatively light winds can significantly increase the intensity of baled wastepaper fires. It is best that, wherever possible, baled waste storage be well separated by distance or substantial walls from valuable equipment or finished goods.

Pesticides

Poisonous to insects and small animals, pesticides can harm and even kill humans when ingested or breathed as combustion products. They are stored as solutions in flammable or combustible liquids, as powders or granules in combustible packages, or as compressed gases for fumigation. Special attention must be given to the personnel hazard in addition to the commodity's combustibility. Pesticide fires can endanger persons fighting the fire or standing nearby, and poisonous runoff from fire fighting can pollute water or soil in the area.

Automatic sprinkler protection is advisable with provision for safe accumulation and disposal of water runoff. Fire-fighting strategy should include plans to use protective clothing and respiratory equipment, spray nozzles rather than straight streams to reduce water runoff, and specialized medical backup services. Container breakup and pesticide dispersal must be avoided. NFPA 434, *Code for the Storage of Pesticides,* gives general requirements for both inside and outside storage of pesticides.

SUMMARY

Protecting storage facilities from fire presents a particular challenge. An efficient use of space, such as small flues between stored materials, is also conducive to maximum burning rate and fire spread. An effective fire protection strategy needs to take into account various factors, including the commodity classification, the storage arrangement, the storage height and clearance from top of storage to sprinklers, water supply, and construction. These factors and others determine the sprinkler types, designs, sizes, and installation arrangements of the automatic sprinkler system.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on sprinkler systems for storage facilities discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 25, *Standard for Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 30B, *Code for the Manufacture and Storage of Aerosol Products*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 72®, *National Fire Alarm Code®*
NFPA 88A, *Standard for Parking Structures*
NFPA 102, *Standard for Grandstands, Folding and Telescopic Seating, Tents, and Membrane Structures*
NFPA 204, *Standard for Smoke and Heat Venting*
NFPA 307, *Standard for the Construction and Fire Protection of Marine Terminals, Piers, and Wharves*
NFPA 434, *Code for the Storage of Pesticides*
NFPA 505, *Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operations*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 601, *Standard for Security Services in Fire Loss Prevention*

Chapter 6

Residential Sprinkler Systems

Daniel Madrzykowski ❏ Russell P. Fleming

Chapter Contents

Developing a Sprinkler System in Response to the Home Fire Problem
Residential Sprinkler Standards
New Technology in Residential Sprinkler Systems
Residential Sprinkler Experience
Incentives for More Widespread Use of Residential Sprinklers

Key Terms

automatic sprinkler system, Home Fire Sprinkler Coalition, quick-response (QR) sprinkler, residential sprinkler system, response time index (RTI)

Automatic sprinkler systems have been successfully used to protect industrial and commercial buildings and their occupants for more than 100 years. Historically, the place that has offered the least amount of fire protection to occupants was and still is their own home. This situation was brought to light in 1973 by the Report of the National Commission on Fire Prevention and Control, *America Burning.*[1] At the time of the report, approximately 8000 people died in fires every year in the United States. Eight out of ten of those victims died in their homes.

In the more than 30 years since *America Burning* was published, the number of lives lost in fires in the United States has decreased to less than 4000 per year. Unfortunately, 8 out of 10 victims still die in home structure fires.[2] Although residential sprinkler installations are increasing, it is estimated that less than 3 percent of all residential dwellings in the United States have them installed.[3]

In response to the information from the *America Burning* report, the National Fire Protection Association's Technical Committee on Automatic Sprinklers assigned a subcommittee to develop a standard for residential sprinkler systems in 1973. NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes,* was adopted in May 1975, based on expert judgment and the best information available at that time.

Significant testing and development of residential sprinkler systems has continued since then, resulting in the evolution of NFPA 13D and the development of NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height.*

The purpose of a residential sprinkler system built to the standard is to "provide a sprinkler system that aids in detection and control of residential fires, and thus provides improved protection against injury, life loss, and property damage."[4] From a performance perspective, if the room of fire origin is sprinklered, a sprinkler system designed and installed in accordance with the residential sprinkler standards is expected to prevent flashover and improve the occupant's opportunity to escape or to be rescued.[4]

Residential sprinkler systems designed and installed in accordance with NFPA 13D or NFPA 13R have significantly different requirements than those for residential occupancies designed in accordance with NFPA 13, *Standard for the Installation of Sprinkler Systems.* NFPA 13D and NFPA 13R systems have been optimized for certain types of residential occupancy buildings in an effort to minimize the cost of the system while improving the degree of fire safety.

New developments in residential sprinkler system technology continue to be made in an effort to increase the ease of installation and reduce the cost of installation while maintaining the effectiveness and reliability of the system. Residential sprinkler systems have been required in dwellings in several communities for more than a decade. Information from these communities is providing compelling data concerning the effectiveness of residential sprinkler systems. These data, in addition to code requirements and other incentives, are increasing the numbers of sprinkler installations around the country.

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For related topics, see Section 3, Chapter 1, "An Overview of the Fire Problem and Fire Protection"; and Section 16, Chapter 8, "Water Mist Fire Suppression Systems."

DEVELOPING A SPRINKLER SYSTEM IN RESPONSE TO THE HOME FIRE PROBLEM

The development of a residential sprinkler standard with the main focus on life safety required a multifaceted approach. Fire incident data had to be collected and analyzed to obtain an understanding of the nature of the residential fire safety problem. In addition, technical challenges had to be overcome to develop an effective, practical, and economically acceptable residential sprinkler system design.

The more common home fire hazards had to be characterized in terms of leading areas of origin. The rankings and percentages have changed little since then, and more recent data are shown in Table 16.6.1, which demonstrates the number of fire fatalities and injuries based on the area of origin. Over 50 percent of home fires, over 70 percent of home fire fatalities, and over 70 percent of home fire injuries are the result of

TABLE 16.6.1 Structure Fires in Homes by Area of Origin, 1999–2002 Annual Averages

Area of Origin	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Kitchen or cooking area	95,200	(26%)	460	(16%)	4620	(30%)	761	(14%)
Bedroom	44,800	(12%)	760	(26%)	3820	(25%)	928	(17%)
Confined cooking fire	29,800	(8%)	0	(0%)	470	(3%)	10	(0%)
Common room, living room, family room, lounge, or den	23,600	(6%)	870	(29%)	1900	(12%)	596	(11%)
Laundry room or area	15,800	(4%)	30	(1%)	390	(3%)	170	(3%)
Exterior wall surface	13,300	(4%)	10	(0%)	140	(1%)	168	(3%)
Attic or ceiling/roof assembly or concealed space	10,600	(3%)	10	(0%)	110	(1%)	290	(5%)
Confined chimney fire	10,600	(3%)	0	(0%)	10	(0%)	7	(0%)
Garage or vehicle storage area	9,900	(3%)	40	(1%)	340	(2%)	314	(6%)
Heating equipment room	9,600	(3%)	30	(1%)	270	(2%)	128	(2%)
Chimney	9,600	(3%)	10	(0%)	30	(0%)	57	(1%)
Lavatory or bathroom	9,400	(3%)	40	(1%)	350	(2%)	107	(2%)
Crawl space or substructure space	8,600	(2%)	50	(2%)	300	(2%)	202	(4%)
Wall assembly or concealed space	7,600	(2%)	30	(1%)	120	(1%)	146	(3%)
Exterior balcony or open porch	7,100	(2%)	30	(1%)	210	(1%)	180	(3%)
Unclassified structural area	5,100	(1%)	70	(2%)	150	(1%)	162	(3%)
Unclassified	4,800	(1%)	50	(2%)	140	(1%)	141	(3%)
Closet	4,400	(1%)	20	(1%)	180	(1%)	71	(1%)
Unclassified function area	4,200	(1%)	110	(4%)	300	(2%)	102	(2%)
Ceiling/floor assembly or concealed space	4,000	(1%)	30	(1%)	90	(1%)	107	(2%)
Hallway, corridor, or mall	3,100	(1%)	40	(1%)	160	(1%)	39	(1%)
Confined fuel burner or boiler fire or malfunction	2,900	(1%)	0	(0%)	10	(0%)	2	(0%)
Exterior roof surface	2,600	(1%)	0	(0%)	20	(0%)	61	(1%)
Dining room, bar, or beverage area	2,600	(1%)	40	(1%)	160	(1%)	59	(1%)
Unclassified storage area	2,600	(1%)	10	(0%)	80	(1%)	44	(1%)
Storage of supplies or tools or dead storage	2,500	(1%)	20	(1%)	100	(1%)	50	(1%)
Multiple areas of origin	2,100	(1%)	30	(1%)	60	(0%)	68	(1%)
Trash or rubbish chute, area, or container	2,000	(1%)	0	(0%)	30	(0%)	15	(0%)
Other known means of egress	5,700	(2%)	50	(2%)	220	(1%)	96	(2%)
Other known outside area	4,200	(1%)	10	(0%)	70	(0%)	64	(1%)
Other known service or equipment area	3,400	(1%)	0	(0%)	50	(0%)	64	(1%)
Other known area	6,600	(2%)	100	(3%)	350	(2%)	171	(3%)
Contained trash or rubbish fire	4,600	(1%)	0	(0%)	20	(0%)	1	(0%)
Other confined or contained area	200	(0%)	0	(0%)	0	(0%)	1	(0%)
Total	372,900	(100%)	2,960	(100%)	15,300	(100%)	5,383	(100%)

Source: Marty Ahrens, *U.S. Fires in Selected Occupancies: Homes,* National Fire Protection Association, Quincy, MA, Mar. 2006, Table 8.

fires starting in a living room, bedroom, or kitchen. The impact sprinklers would have in these locations was clear. Analysis of this data was used to determine those rooms of a residence in which sprinkler protection would have the most positive impact on life safety. Table 16.6.2 shows the first items ignited in home fires.[4] It shows that over one-fourth of all home fire deaths involved the initial ignition of furniture or bedding. Other data showed that these ignitions were most often caused by a smoldering heat source (e.g., cigarette) or a small open flame source (e.g., match or lighter). This information provided a sense of the types of fire hazards that residential sprinklers would have to mitigate.

Another aspect of the residential fire problem concerns those who typically die in residential fires. Figure 16.6.1 presents the number of fire deaths per million people of a given age range, and Figure 16.6.2 presents the relative risk of dying in a fire by age.[3] Both figures show the trends that children 4 years of age and under and adults 65 years of age and older are more likely to die in a residential fire than are other segments of the population. For adults 65 and older, the risk increases significantly with age. Because these high-risk groups may depend on assistance to exit the dwelling, anything less than automatic suppression may not be enough to save them.[5]

TABLE 16.6.2 Structure Fires in Homes by Item First Ignited, 1999–2002 Annual Averages

Item First Ignited	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Cooking materials, including food	59,600	(16%)	140	(5%)	3110	(20%)	296	(6%)
Confined cooking fire	29,800	(8%)	0	(0%)	470	(3%)	10	(0%)
Structural member or framing	29,300	(8%)	210	(7%)	610	(4%)	917	(17%)
Electrical wire or cable insulation	23,500	(6%)	90	(3%)	480	(3%)	297	(6%)
Mattress or bedding	18,000	(5%)	410	(14%)	2000	(13%)	358	(7%)
Rubbish, trash, or waste	17,400	(5%)	50	(2%)	360	(2%)	135	(3%)
Unclassified	16,700	(4%)	120	(4%)	550	(4%)	171	(3%)
Exterior wall covering or finish	14,900	(4%)	30	(1%)	190	(1%)	281	(5%)
Interior wall covering, excluding drapes	13,100	(4%)	140	(5%)	510	(3%)	321	(6%)
Clothing	13,000	(3%)	200	(7%)	780	(5%)	160	(3%)
Confined chimney fire	10,600	(3%)	0	(0%)	10	(0%)	7	(0%)
Flammable or combustible liquid or gas, filter, or piping	10,500	(3%)	170	(6%)	980	(6%)	244	(5%)
Multiple items first ignited	10,500	(3%)	190	(6%)	480	(3%)	350	(6%)
Upholstered furniture or vehicle seat	10,200	(3%)	560	(19%)	1130	(7%)	283	(5%)
Floor covering, rug, carpet, or mat	8,100	(2%)	110	(4%)	350	(2%)	159	(3%)
Unclassified structural component or finish	7,500	(2%)	60	(2%)	200	(1%)	245	(5%)
Cabinetry, including built-in	6,900	(2%)	40	(1%)	400	(3%)	136	(3%)
Unclassified furniture or utensils	6,000	(2%)	130	(5%)	530	(3%)	136	(3%)
Insulation within structural area	5,200	(1%)	10	(0%)	90	(1%)	71	(1%)
Appliance housing or casing	4,900	(1%)	20	(1%)	180	(1%)	50	(1%)
Magazine, newspaper, or writing paper	4,600	(1%)	60	(2%)	230	(2%)	71	(1%)
Contained trash or rubbish fire	4,600	(1%)	0	(0%)	20	(0%)	1	(0%)
Box, carton, bag, basket, or barrel	4,300	(1%)	30	(1%)	190	(1%)	64	(1%)
Dust, fiber, lint, sawdust, or excelsior	4,300	(1%)	0	(0%)	70	(0%)	26	(0%)
Unclassified soft goods or wearing apparel	3,900	(1%)	60	(2%)	200	(1%)	66	(1%)
Exterior roof covering or finish	3,700	(1%)	0	(0%)	40	(0%)	118	(2%)
Curtains, blinds, drapes, or tapestry	3,600	(1%)	20	(1%)	280	(2%)	57	(1%)
Exterior trim, including doors	3,400	(1%)	10	(0%)	40	(0%)	51	(1%)
Linen other than bedding	3,400	(1%)	20	(1%)	140	(1%)	33	(1%)
Confined fuel burner or boiler fire or malfunction	2,900	(1%)	0	(0%)	10	(0%)	2	(0%)
Interior ceiling cover or finish	2,500	(1%)	10	(0%)	60	(0%)	56	(1%)
Light vegetation, including grass	2,000	(1%)	0	(0%)	20	(0%)	25	(0%)
Other known item	13,800	(4%)	60	(2%)	570	(4%)	186	(3%)
Other confined fire	200	(0%)	0	(0%)	0	(0%)	1	(0%)
Total	372,900	(100%)	2,960	(100%)	15,300	(100%)	5,383	(100%)

Source: Marty Ahrens, *U.S. Fires in Selected Occupancies: Homes,* National Fire Protection Association, Quincy, MA, Mar. 2006, Table 9.

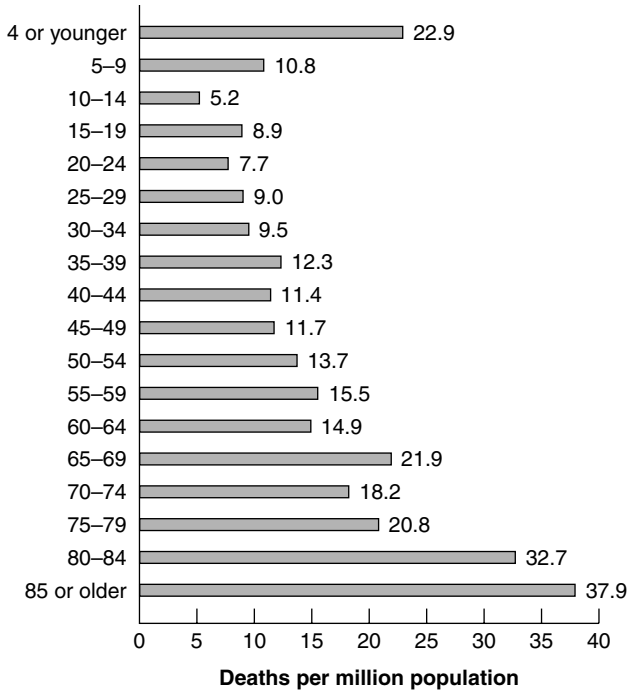

FIGURE 16.6.1 Home Fire Deaths per Million Population by Age from 1992 to 2001. Note: Data have been adjusted to account for unknown or unspecified ages. (Source: Data from NFIRS, NFPA, and U.S. Census Bureau; in *Fire in the United States 1992–2001,* 13th ed., Federal Emergency Management Agency, United States Fire Administration, National Fire Data Center, FA-286, Oct. 2004, Figure 10, p. 42.)

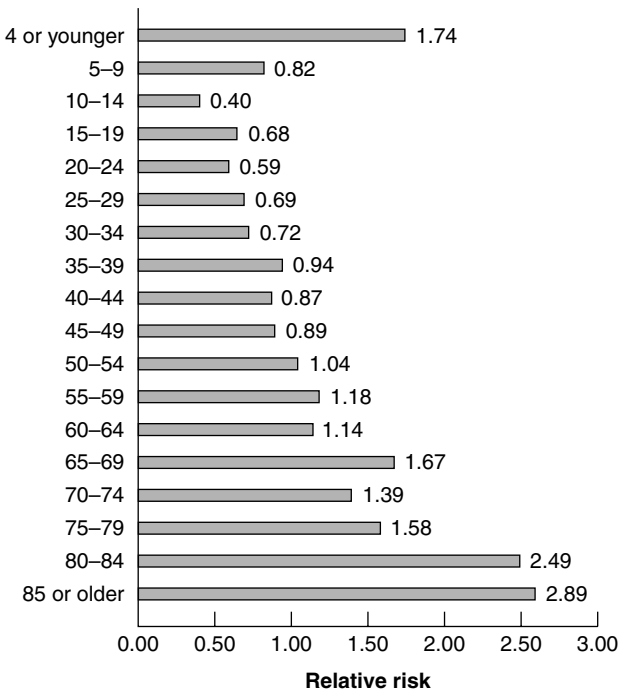

FIGURE 16.6.2 Relative Risk of Home Fire Deaths by Age from 1992 to 2001. Notes: 1. *Relative risk* compares the per capita rate (Figure 16.6.1) for a particular group (here, an age group) to the overall per capita rate (i.e., the general population). For the general population, the relative risk is set at 7. 2. Data have been adjusted to account for unknown or unspecified ages. (Source: Data from NFIRS, NFPA, and U.S. Census Bureau; in *Fire in the United States 1992–2001,* 13th ed., Federal Emergency Management Agency, United States Fire Administration, National Fire Data Center, FA-286, Oct. 2004, Figure 11, p. 43.)

Once it was determined where sprinklers in a home would be most effective in reducing life loss, the technical challenge of developing an effective and economically viable sprinkler system was pursued. The sprinkler system would have to activate automatically while a fire was small and the smoke and heat conditions in the home were survivable. Once the system was activated, it needed to control the fire with a smaller amount of water relative to a commercial sprinkler system, because the water supply to a home is typically less than the water supply to a commercial or industrial occupancy.

NFPA 13D, First Edition, 1975

Based on the review of then-available fire incident data, NFPA's Technical Committee on Sprinkler Systems developed a residential sprinkler installation standard that covered the principally occupied areas of a dwelling and that met the goals of (1) preventing flashover, (2) providing sufficient time for safe egress or rescue, and (3) economic viability.

As specified in the initial version of NFPA 13D, a residential sprinkler system would use a ½ in. (12.7 mm) orifice, standard response sprinkler, with a maximum of 256 ft^2 (23.8 m^2) coverage, and a spray density of 0.10 gpm/ft^2 (4.1 L/m^2), yielding a flow rate of 25 gpm (94.6 L/m^2). If the system was not supplied by an adequate public water source, a 250 gal (946.3 L) stored water supply was required to provide a 10-minute water supply.

To keep costs down, it was proposed that sprinklers be located only in principally occupied rooms. For this reason, sprinklers were not required in bathrooms 40 ft^2 (3.7 m^2) or less, small closets 24 ft^2 (2.2 m^2) or less, attics not used as a living space, porches, carports, garages, and foyers. Table 16.6.1 shows how much of the home fire problem begins in these excluded spaces, as well as in or on concealed spaces and exterior surfaces, which were also excluded. The system was to have a local waterflow alarm. NFPA 13D permitted sprinklers to be omitted from certain areas where the incidence of life loss from fires was statistically shown to be low. NFPA 13 had always required complete sprinkler protection in order to safeguard property adequately. In departing from the concept of complete coverage, the 1975 edition of NFPA 13D became the first "life safety" sprinkler standard. In spite of these concessions, actual installations based on this standard were rare, primarily due to cost.

The initial residential sprinkler system was crafted from existing technology and improvements were needed. Jensen noted that "much of this first edition was based on the collective experience of the committee members; little was based on real-world fire testing."[6]

Residential Sprinkler Research

Beginning in 1976, the National Fire Prevention and Control Administration, renamed the United States Fire Administration (USFA) in 1979, supported a significant number of research programs on a wide variety of topics relating to residential sprinkler systems. The objective of the USFA research program was to assess the impact sprinklers would have on reducing deaths and injuries in residential fires.[7] The USFA—working in conjunction with the National Fire Protection Association, Factory Mutual Research Corporation, Underwriters Laboratories, and many other groups and individuals—evaluated the design, installation, practical usage, and water acceptance factors that would have an impact on achieving reliable and acceptable systems,[8] the minimum water discharge rates and automatic sprinkler flow required; and response sensitivity and design criteria.[9–11] Full-scale fire experiments were conducted to develop residential sprinkler designs and validate their effectiveness.[12–16] In addition, standards for testing and evaluating residential sprinklers were developed. These included tenability criteria for occupants that the sprinklers were required to maintain in the room of fire origin.

Residential Sprinkler Sensitivity and Response

Although researchers at the Factory Mutual Fire Insurance Companies recognized the need for "faster" or more "sensitive" sprinklers in 1884, it was not until the late 1960s that a "quick-response sprinkler" subcommittee was formed within the NFPA 13 technical committee.

Research showed that a more sensitive sprinkler was needed to respond faster to both smoldering and fast-developing home fires for two reasons. First, fires had to be controlled quickly in order to prevent the development of lethal conditions in typically small home compartments. In addition, fires had to be attacked while still small if they were to be controlled with the water supplies typically available in single-family dwellings, that is, 20 to 30 gpm (76 to 114 L/min).

Measuring Sprinkler Sensitivity

Much of the original work in the area of measuring sprinkler sensitivity was done at FM Global Research under the sponsorship of the United States Fire Administration (USFA) during the development of the residential sprinkler.[17,18] Important contributing research was also performed at the British Fire Research Station and the National Institute of Standards and Technology (NIST).[19–22]

The progress in this area climaxed late in 1990, when an agreement was reached within the working group on sprinkler and water spray equipment of the International Standards Organization (ISO) for a standardized approach to sprinkler sensitivity requirements and testing. The agreement, included in ISO 6182/1, "Requirements and Methods of Test for Sprinklers," uses a combination of sprinkler test procedures developed by laboratories in the United States and Europe and establishes the three ranges of sprinkler sensitivity characteristics, shown in Figure 16.6.3.

These ranges of sensitivity are based both on the response time index (RTI) of the device and on its conductivity (C). RTI is a measure of pure thermal sensitivity, which indicates how fast the sprinkler can absorb heat from its surroundings sufficient to cause activation. The conductivity factor is important in measuring how much of the heat picked up from the surrounding air will be lost to the sprinkler fittings and waterway.[23] Figure 16.6.3 shows three broad ranges of sprinkler sensitivity: standard, special, and fast response. Traditional sprinkler hardware falls into the standard-response category. The fast-response category is used for new types of sprinklers for which fast response is considered important. The special-response category is used in some countries for special types of sprinklers that may be installed in conformance with appropriate national installation standards. In the United States, this category includes some of the extended coverage sprinklers.

Sprinkler response time as a function of the temperature rating of the operating element is well understood; that is, a 165°F (74°C) rated sprinkler will operate when its temperature reaches 165°F (74°C), plus or minus a few degrees. Because of the "thermal lag" of the link or bulb mass, however, the air temperature may be significantly higher before the element operates. The

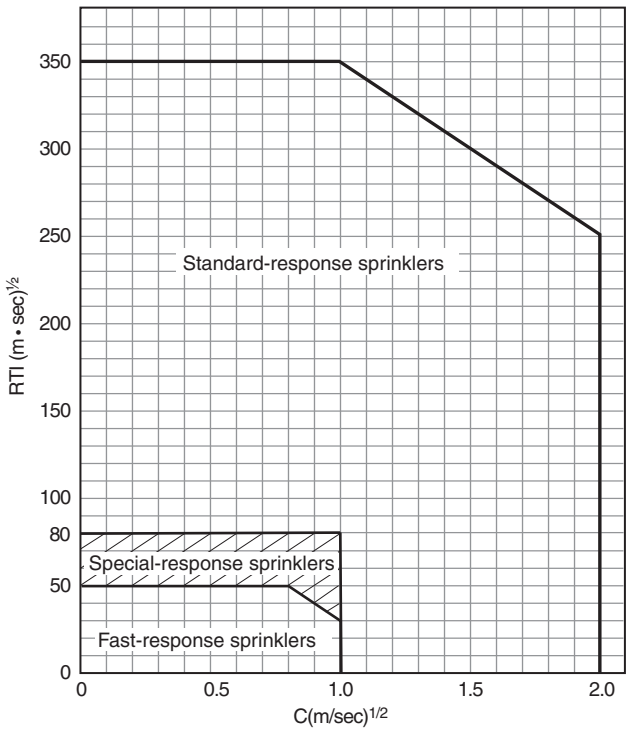

FIGURE 16.6.3 International Sprinkler Sensitivity Ranges, Response Time Index (RTI) versus Conductivity (C). For SI units: 1 ft = 0.305 m.

smaller mass of the operating element of a fast-response sprinkler permits it to follow a temperature rise in the surrounding air more rapidly, resulting in faster operation. The actual sensitivity requirements of the first fast-response sprinklers, intended as residential sprinklers, were arrived at somewhat by trial and error during developmental test work. To measure sensitivity, FM Global Research researchers first applied the concept of the "tau" (τ) factor and later developed the RTI.

Sensitivity Testing

Both the τ factor and RTI refer to the performance of a sprinkler or its operating element in a standardized air oven tunnel or thermal sensitivity test. The test is known as a "plunge" test because a sprinkler at room temperature is plunged into a heated airstream of known constant temperature and velocity.[17,18] In the plunge test, the τ factor is the time at which the temperature of the sensing element of the sprinkler is approximately 63 percent of the difference between the hot gas temperature and the original temperature of the sensing element. In other words, the τ factor is the time at which the temperature of the sprinkler thermal element has risen 63 percent of the way to the higher temperature of the heated air. The smaller the τ factor, the faster the sprinkler sensing element heats up and operates. Figure 16.6.4 shows a time-temperature graph for several τ values ranging from 25 to 200.[24]

The τ factor is independent of the air temperature used in the plunge test, but is inversely proportional to the square root of the air velocity. During the early development of the residential sprinkler, a τ factor of 21 seconds was considered to indicate the needed level of sensitivity, but this was associated with the specific velocity of 5 ft/sec (1.52 m/sec) used in the FM Global Research plunge test. Since the τ factor changes with the velocity of heated air moving past the sprinkler, it is a fairly inconvenient measure of sprinkler sensitivity.

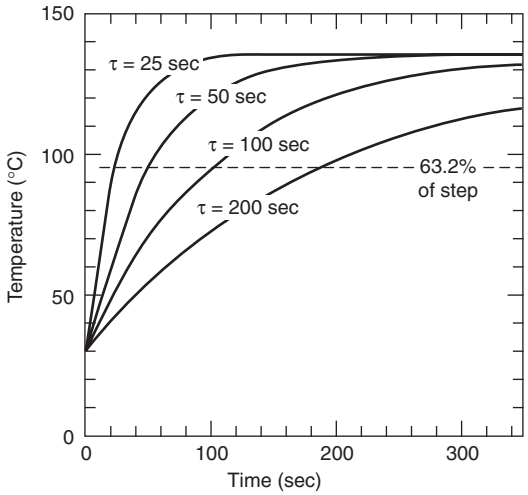

FIGURE 16.6.4 Calculated Sprinkler τ Values Responding to a Step Change Temperature Increase of 105°C with a Gas Velocity of 8.33 ft/sec (2.54 m/sec)

The RTI has replaced the τ factor as the measure of sensitivity and is determined simply by multiplying the τ factor by the square root of the air velocity at which it is found. The RTI is therefore practically independent of both air temperature and air velocity. Comparisons of RTI give a good indication of relative sprinkler sensitivity. The smaller the RTI, the faster the sprinkler operation. Standard-response sprinklers have RTIs in the range of 180 to 650 $sec^{½}ft^{½}$ (100 to 350 $sec^{½}m^{½}$), whereas the RTI range for residential sprinklers is about 50 to 90 $sec^{½}ft^{½}$ (28 to 50 $sec^{½}m^{½}$).

The need to add a conductivity term to the model of sprinkler response was recognized in 1986.[23,25] The conductivity term accounts for the loss of heat from the sprinkler operating element to the sprinkler frame, its mounting, and even the water in the pipe. These losses can become significant under low-velocity conditions, particularly for some of the flush-type sprinkler designs with little insulation between the operating element and the sprinkler body.

Fast-Response Sprinkler

Full-scale tests conducted by FM Global Research resulted in the development of a prototype fast-response sprinkler that could control or suppress typical residential fires with the operation of not more than two sprinklers. It could also operate fast enough to maintain survivable conditions within the room of fire origin.[12] Survivable conditions were established as follows:

- Maximum gas temperature at eye level of 200°F (93°C)
- Maximum ceiling surface temperature of 500°F (260°C)
- Maximum carbon monoxide concentration of 1500 ppm

Thus, the sprinkler concept expanded from the traditional role of property protection to include life safety. Full-scale field tests were then conducted in Los Angeles to establish system design parameters using the new prototype fast-response residential sprinkler.[13–16] Data from these tests were studied by the National Fire Protection Association Technical Committee on Automatic Sprinklers and used to establish the criteria for the 1980 edition of NFPA 13D.

RESIDENTIAL SPRINKLER STANDARDS

It is important to recognize that, in addition to their fast-response characteristics, residential sprinklers have a special water distribution pattern. Because the effective control of residential fires often depends on a single sprinkler in the room of fire origin, the distribution of residential sprinklers must be more uniform than that of standard spray sprinklers, which in large areas can rely on the overlapping patterns of several sprinklers to make up for voids. Additionally, residential sprinklers must protect sofas, drapes, and similar furnishings at the periphery of the room. In their discharge patterns, therefore, sprinklers must not only be capable of delivering water to the walls of their assigned areas but also be high enough up on the walls to prevent the fire from getting "above" the sprinklers. The water delivered close to the ceiling not only protects the portion of the wall close to the ceiling but also enhances the capacity of the spray to cool gases at

the ceiling level, thus reducing the likelihood of excessive sprinkler openings.

Residential Sprinkler Testing

Because of their differences, residential sprinklers are not listed by product evaluation organizations under the same product standards as standard sprinklers. Underwriters Laboratories Inc., for example, has developed UL 1626, *Standard for Safety for Residential Sprinklers for Fire-Protection Service,* for residential sprinklers, and FM Global Research has published Approval Standard FM 2030, *Research Approval Standard for Residential Automatic Sprinklers,* for residential sprinklers. Both of these standards include a plunge test with specific sensitivity requirements and a distribution test that checks the spray pattern in the vertical plane as well as the horizontal plane. Product standards for standard spray sprinklers contain neither test. Both UL 1626 and FM 2030 also include a fire test that is intended to simulate a residential fire in the corner of a room containing combustible materials representative of a living room environment.

UL 1626 Test Procedures. The UL 1626 fuel package and test procedure was recently revised to (1) enhance the reproducibility of the tests and (2) increase the similarity between the fire performance of the fuel package used in the standard tests and that of the fuel packages used as part of the principal residential sprinkler research effort.[13,15,16] Details of the UL 1626 simulated furniture are shown in Figure 16.6.5. The arrangement of the fuel package within the test room is shown at the upper left of the figure.

The three fire test configurations are shown in Figures 16.6.6, 16.6.7, and 16.6.8. Figure 16.6.6 shows the configuration used to test pendent, upright, flush, recessed pendent, and concealed sprinklers. Figures 16.6.7 and 16.6.8 present the configurations used to test sidewall sprinklers; in the first case the sprinklers are located opposite the fuel package, and in the second case the sprinklers are located on the same wall as the fuel package.

The floor plan dimensions of the test room depend on the rated sprinkler coverage. As shown in Figure 16.6.5, the width of the test room, w, equals the rated sprinkler coverage width, and the length of the test room equals twice the rated coverage length, L. For the sidewall sprinkler configurations, the dimensions of the test room should be the rated sprinkler coverage length, L, by 1½ times the sprinkler coverage width, w, plus 9 ft (2.7 m). The ceiling height in all cases is a nominal 8 ft (2.4 m). The fuel package is composed of several different components: a wood crib, two simulated sofa ends covered with foam, two sheets of ¼ in. (6.3 mm) Douglas fir plywood, a pan with heptane, and two heptane-soaked cotton wicks. The wood crib is composed of 16 pieces of nominal 1½ in. by 1½ in. (38 mm by 38 mm) kiln-dried spruce or fir lumber 12 in. (300 mm) in length and 5.5 to 7.0 lb (2.5 to 3.2 kg) in weight. The pieces of lumber are to be arranged in four layers, with four pieces of wood per layer. The pieces of lumber should be evenly spaced along the length of the previous layer of wood members and stapled in place. The layers of lumber are to be placed at right angles to the layer below. The finished size of the wood crib is approximately 12 in. (305 mm) on a side and 6 in. (152 mm) high.

The simulated sofa ends are composed of a wood frame support and a ½-in. (12.7-mm) thick piece of plywood, 33 in. by 31 in. (840 mm by 790 mm) high in a vertical position. The plywood has 3-in. (76-mm) thick uncovered urethane foam cushions 30 in. (760 mm) high by 32 in. (810 mm) wide attached to the side facing the crib. The foam has a density of 1.70 to 1.90 lb/ft^3 (27.2 to 30.4 kg/m^3). The walls of the test room are covered with 4 ft by 8 ft by ¼ in. (1.2 m by 2.4 m by 6.4 mm) Douglas fir plywood paneling (flame spread rating 130 ± 30) attached to wood furring strips. The ceiling of the test room is 8 ft (2.4 m) high and covered with 2-ft by 4-ft by ½-in. (0.61-m by 1.20-m by 12.7-mm) thick acoustical panels (flame spread rating 25 or less) with a density of 13.5 ± 1.5 lb/ft^3 (216 ± 24 kg/m^3) attached to wood furring strips.

A 12-in. by 12-in. by 4-in. (305-mm by 305-mm by 104-mm) high steel pan containing 16 oz. (0.5 L) of water and 8 oz. (0.24 L) of heptane is positioned under the wood crib and ignited to start the test.

Fire Control Requirements. To meet the UL 1626 test criteria, residential sprinklers, installed in a fire test enclosure with an 8-ft (2.4-m) ceiling, are required to control a fire for 10 minutes with the following limits:

1. The maximum gas or air temperature adjacent to the sprinkler—3 in. (76.2 mm) below the ceiling and 8 in. (203 mm) horizontally away from the sprinkler—must not exceed 600°F (316°C).
2. The maximum temperature—5 ft 3 in. (1.6 m) above the floor and half the room length away from each wall—must be less than 200°F (93°C) during the entire test. This temperature must not exceed 130°F (54°C) for more than a 2 minute period.
3. The maximum temperature—¼ in. (6.3 mm) behind the finished surface of the ceiling material directly above the test fire—must not exceed 500°F (260°C).
4. No more than two residential sprinklers in the test enclosure can operate.

The enclosure is kept at an initial ambient temperature of 80°F (27°C) ± 5°F (3°C) and it is ventilated through two door openings on opposite walls. The fire test is conducted for 10 minutes after the ignition of the wood crib. The waterflow to the first sprinkler that operates and the total waterflow when the second sprinkler operates are specified as part of the listing limitations for the sprinklers in the test. The total waterflow for two sprinklers must be a minimum of 1.2 times the minimum flow for a single sprinkler.

Water Distribution Requirements. The water distribution test requirements are based on the distribution pattern of the prototype residential sprinkler used in the Los Angeles test fires.[16] The distribution requirements involve collections in both the horizontal and vertical planes. All residential sprinklers in the test must discharge water at the flow rate specified by the manufacturer for a 10 minute period simulating one sprinkler operating and two sprinklers operating. The quantity of water collected on both the horizontal and vertical surfaces is measured and recorded.

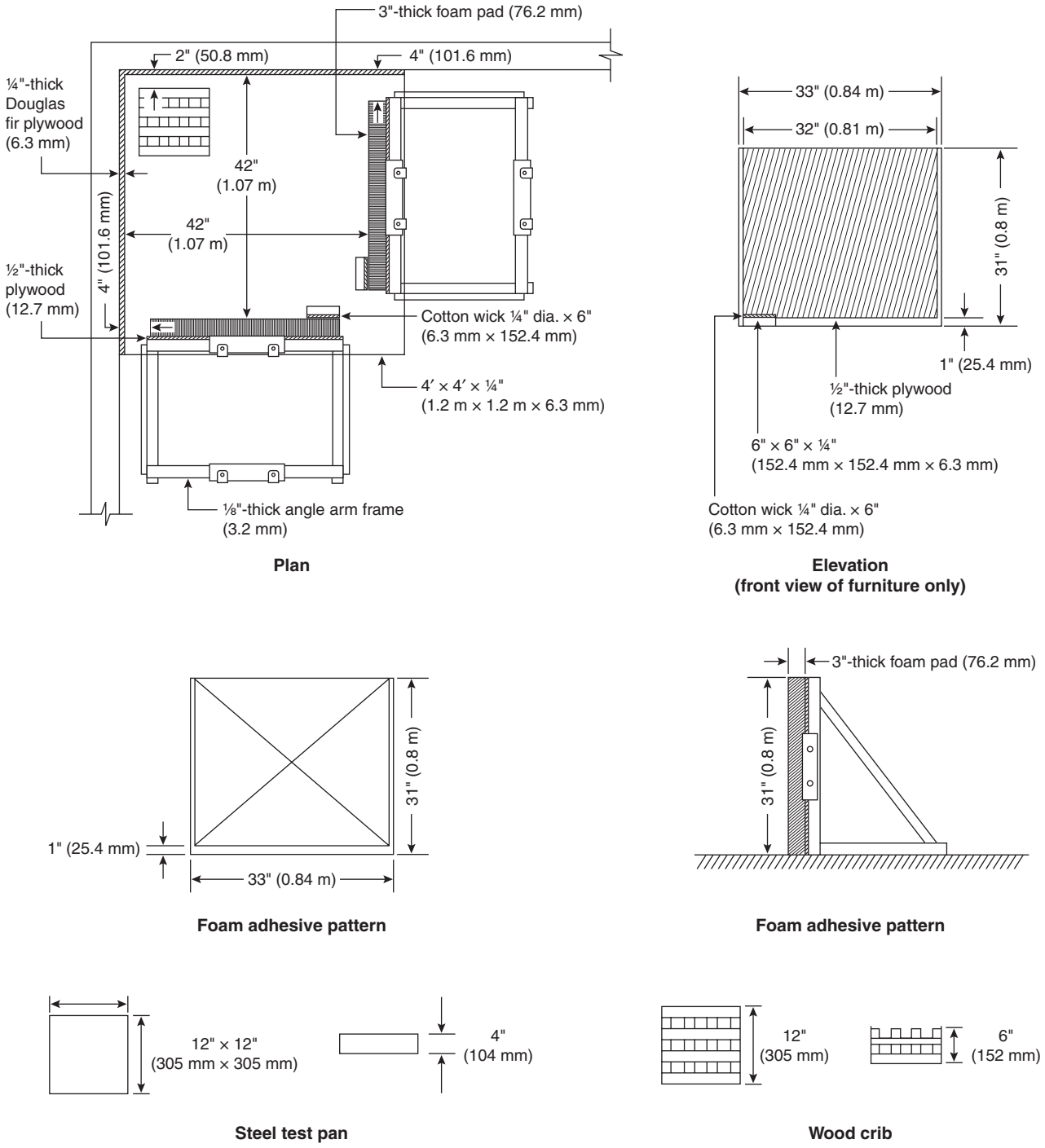

FIGURE 16.6.5 Simulated Fuel Package from UL 1626

Sprinklers being tested are required to discharge a minimum of 0.02 gpm/ft^2 [(0.8[L/min]/m^2) over the entire horizontal design area, with the exception that no more than four 1-ft^2 (0.09-m^2) areas shall be allowed to be at least 0.015 gpm/ft^2 (0.6[L/min]/m^2). They must also wet the walls of the test enclosure to a height not less than 28 in. (711 mm) below the ceiling with one sprinkler operating. Each wall surrounding the coverage area is required to be wetted with a minimum of 5 percent of the sprinkler flow.

Changes to the 2002 editions of NFPA 13D and NFPA 13R were coordinated with revised listings for residential sprinklers, calling for a minimum water spray density of 0.05 gpm/ft^2 (2.05 mm/min). Although the number of sprinklers to be included in the design area did not change for the 13D and 13R standards, the concept of the reduced multiple-sprinkler flow rate was abandoned. Residential sprinklers are now listed with a single minimum flow rate for a given area of coverage.

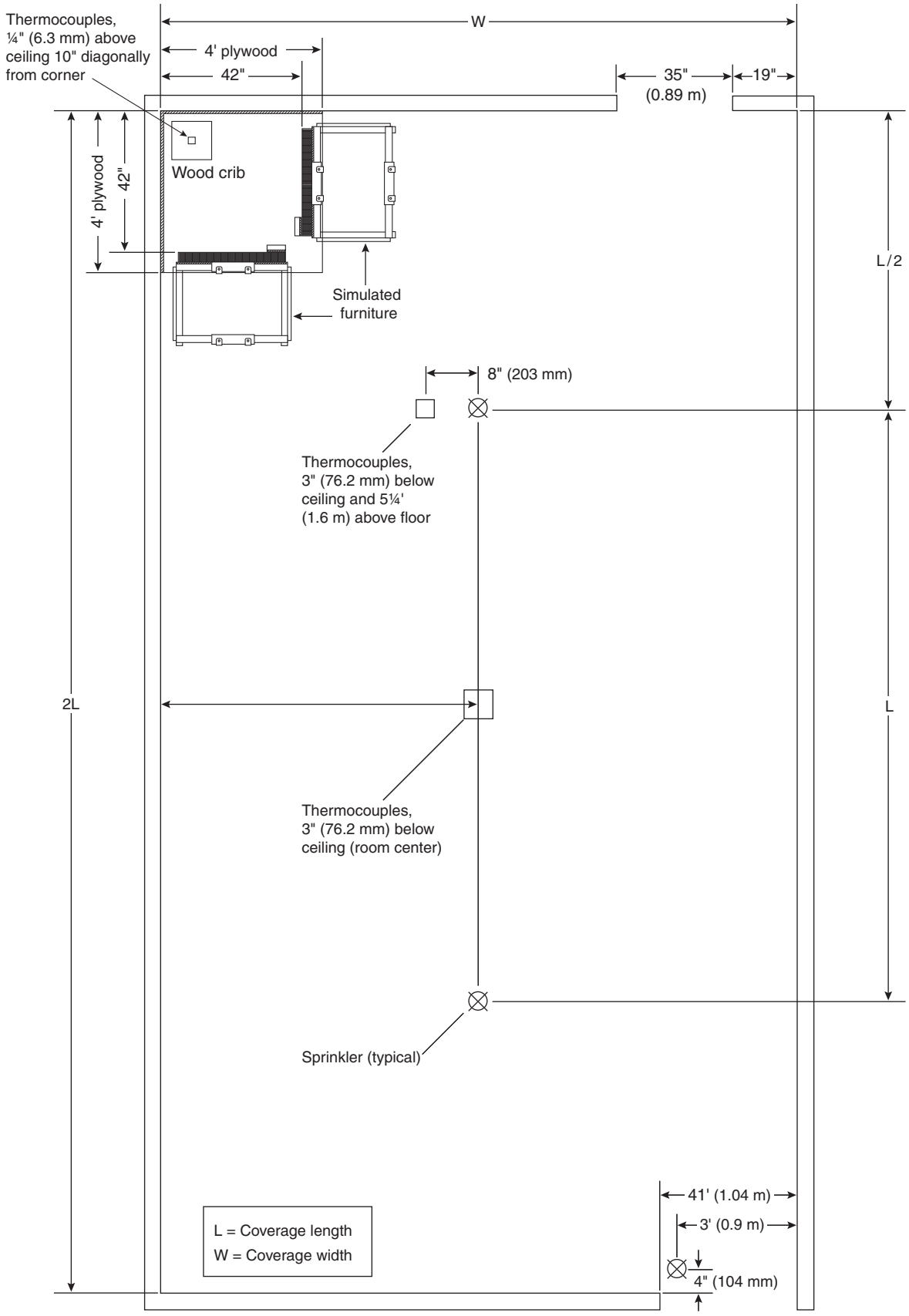

FIGURE 16.6.6 Fire Test Arrangement from UL 1626 for Pendent, Upright, Flush, Recessed Pendent, and Concealed Sprinklers

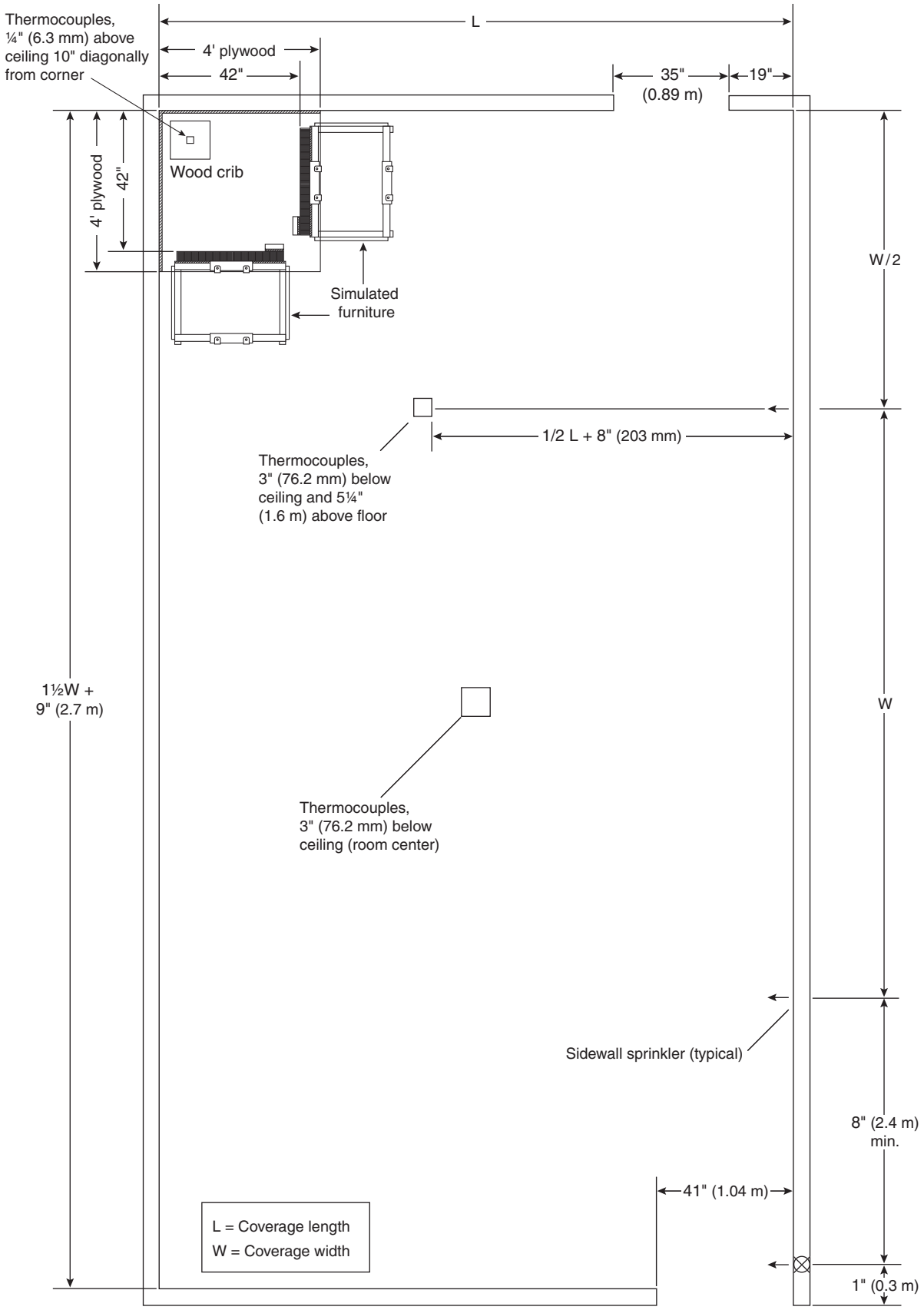

FIGURE 16.6.7 Fire Test Arrangement from UL 1626 for Sidewall Sprinklers, Test Arrangement 1

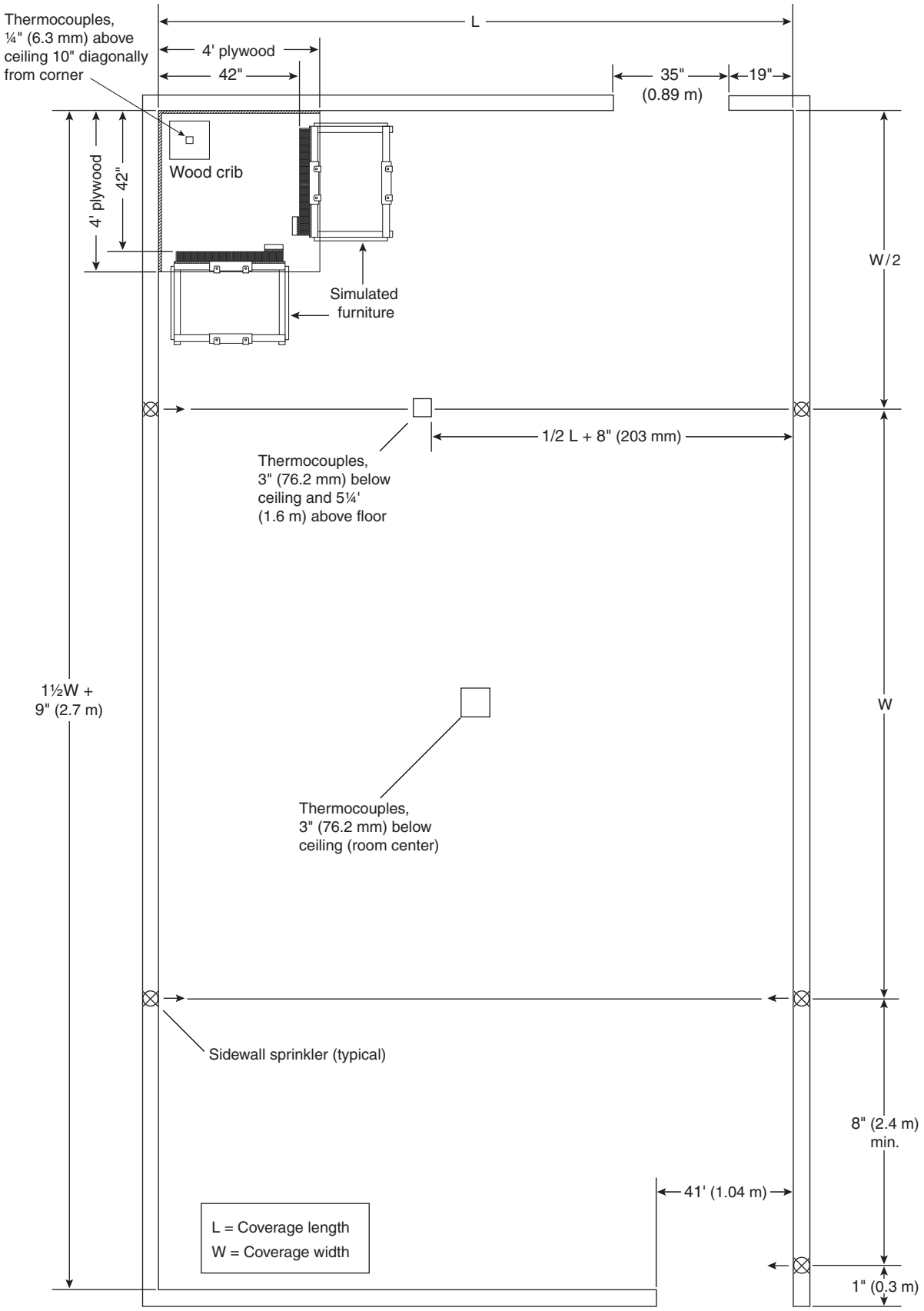

FIGURE 16.6.8 Fire Test Arrangement from UL 1626 for Sidewall Sprinklers, Test Arrangement 2

Research on residential and domestic sprinklers outside the United States supports the trend toward a single minimum flow rate for residential sprinklers. Swedish research published in 2001 indicated that the minimum water application rate of 0.05 gpm/ft^2 (2.05 mm/min) was sufficient to achieve reasonably good protection when the fire test scenario involved upholstered furniture.[26]

Revised NFPA 13D Design Requirements

The design criteria in the 1980 edition of NFPA 13D included for the first time the requirement that all sprinklers be "listed residential sprinklers" (Figure 16.6.9). Other initial basic design requirements in the revamped NFPA 13D were as follows.

Performance Criteria. To prevent flashover in the room of fire origin, when sprinklered, and to improve the chance for occupants to escape or be evacuated.

Design Criteria. Design criteria include the following:

- Only listed residential sprinklers to be used
- Minimum 18 gpm (68 L/min) to any single operating sprinkler and 13 gpm (49 L/min) to all operating sprinklers in the design area up to a maximum of two sprinklers
- Maximum area protected by a single sprinkler of 144 ft^2 (13.4 m^2)
- Maximum distance between sprinklers of 12 ft (3.7 m)
- Minimum distance between sprinklers of 8 ft (2.4 m)
- Maximum distance from a sprinkler to a wall or partition of 6 ft (1.8 m)

Application rates, design areas, areas of coverage, and minimum design pressures other than those specified above were permitted to be used with special sprinklers listed for such special residential installation conditions.

Sprinkler Coverage. Sprinklers to be installed in all areas, with the following exceptions:

- Sprinklers allowed to be omitted from bathrooms no larger than 55 ft^2 (5.1 m^2)

FIGURE 16.6.9 Listed Residential Sprinkler

- Sprinklers allowed to be omitted from closets where the least dimension does not exceed 3 ft (0.9 m), the area does not exceed 24 ft^2 (2.2 m^2), and the walls and ceiling are surfaced with noncombustible materials
- Sprinklers allowed to be omitted from open-attached porches, garages, carports, and similar structures
- Sprinklers allowed to be omitted from attics and crawl spaces that are not used or intended for living purposes or storage
- Sprinklers allowed to be omitted from entrance foyers that are not the only means of egress

In the 30 years following the development of the residential sprinkler, special listings involving expanded protection areas and reduced flows proliferated to the point that the original flow and spacing criteria have become all but obsolete. Residential sprinklers are now listed for coverage areas up to 400 ft^2 (37.2 m^2) per sprinkler.

Since 1985, the use of residential sprinklers has also been permitted under some conditions in accordance with NFPA 13. Essentially, NFPA 13 allows residential sprinklers in dwelling units located in any occupancy, provided they are installed in conformance with the requirements of their listing and the positioning requirements of NFPA 13D. A dwelling unit is defined as one or more rooms arranged for the use of one or more individuals living together, as in a single housekeeping unit, normally having cooking, living, sanitary, and sleeping facilities. Dwelling units include hotel rooms, dormitory rooms, sleeping rooms in nursing homes, and similar living units. Occupancies encompassing dwelling units include apartment buildings, board and care facilities, dormitories, condominiums, lodging and rooming houses, and other multiple-family dwellings. For NFPA 13 applications involving residential sprinklers in dwelling units, the design area must consist of the four most hydraulically demanding sprinklers (Figure 16.6.10).

Other areas, such as attics, basements, or other types of occupancies outside of dwelling units but within the same structure, must be protected in accordance with regular provisions of NFPA 13, including the appropriate water supply requirements. The decision as to which areas are to be protected with sprinklers is also regulated in accordance with the normal provisions of NFPA 13. This protection means, for example, that combustible concealed spaces generally require sprinklers. For NFPA 13 applications, although the four-sprinkler design area can be used in the dwelling units when protected with residential sprinklers, any sprinklers installed within such concealed spaces would have to use a different design approach.

Residential sprinklers installed in systems designed to NFPA 13 requirements are spaced and positioned in accordance with their residential listings, not with the spacing requirements of NFPA 13. The water demands for the residential sprinklers are the same as in NFPA 13 applications, except that the multiple-sprinkler flow requirement is extended to four sprinklers rather than the two stipulated for one- and two-family dwellings and manufactured homes in NFPA 13D. The more liberal piping, component, hanger, location, and water supply duration allowances of NFPA 13D are not permitted in these systems. Beginning in 1996, NFPA 13 requires residential sprinklers or quick-response sprinklers in residential areas.

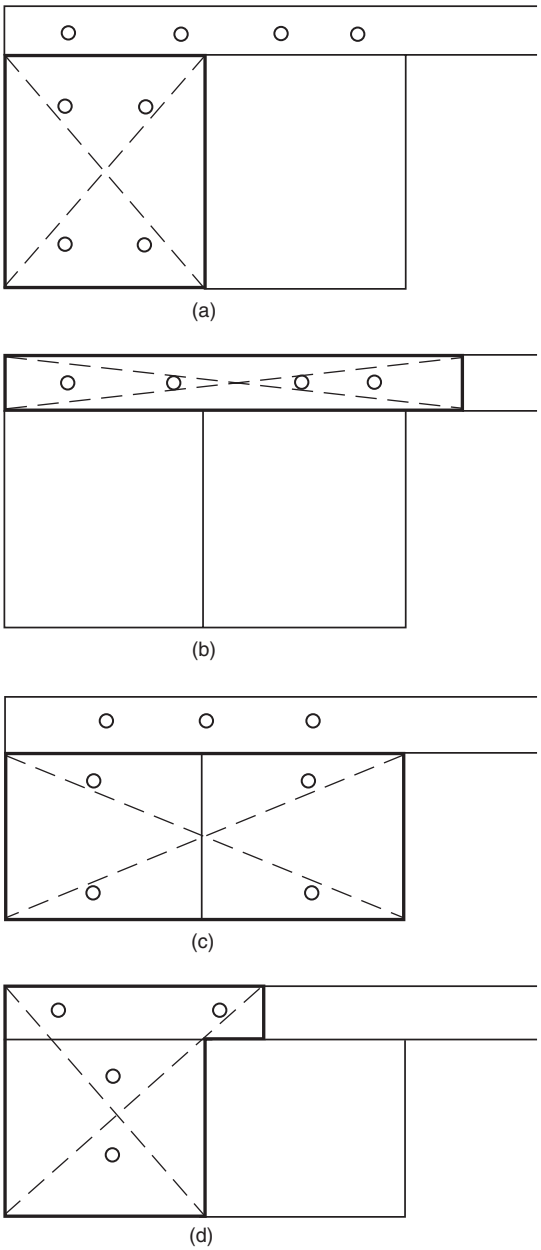

FIGURE 16.6.10 Design Areas for Dwelling Units

Ceiling Fan Criteria. Technical improvements to NFPA 13D are made with each new edition. One of the major areas of improvement to the 2007 edition was the development of criteria for the obstructions created by ceiling fans. Figure 16.6.11 shows a sprinkler obstructed by a ceiling fan. Research conducted in 2005 by the National Fire Sprinkler Association at the facilities of the Viking Corporation involved distribution and fire testing using three different styles of ceiling fans, one with the housing tight against the ceiling, one with a suspended housing, and one with large blades obstructing half of the plan view of the area swept by the blades.[27] Based on the results of the tests, the Committee on Residential Sprinkler Systems agreed that the minimum distance from a sprinkler to the center of a ceiling fan should be 3 ft (0.9 m) for pendent sprinklers and 5 ft (1.5 m) for sidewall sprinklers.

FIGURE 16.6.11 Residential Sprinkler Obstructed by Ceiling Fan

Development of NFPA 13R

Like NFPA 13D, NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height,* is oriented toward economical life safety protection from fire. Sprinklers can be omitted from building areas that have been found to have a low incidence of fatal fires, including combustible concealed spaces, small bathrooms and closets, and attached porches. As with NFPA 13D, residential sprinklers are required throughout dwelling units, with some minor exceptions. A four-sprinkler design area is required unless the largest compartment contains fewer sprinklers.

In recognition of the greater risk associated with multifamily occupancies, NFPA 13R is more conservative than NFPA 13D in some areas. Requirements for plans, hydraulic calculations, and system acceptance certificates parallel those of NFPA 13. Unlike NFPA 13D, NFPA 13R requires a consideration of the likelihood that simultaneous domestic flows might occur through combined service piping. In addition, pumps and other key equipment are required to be listed. In NFPA 13R systems, areas outside dwelling units can be protected with standard spray sprinklers, using NFPA 13 design criteria.

NEW TECHNOLOGY IN RESIDENTIAL SPRINKLER SYSTEMS

Multipurpose Piping Systems

Although NFPA 13D has had the option for a combined or multipurpose piping system for many years, in 1999 the committee further encouraged the use of this option by allowing nonlisted pipe to be connected to the sprinkler system for the purpose of supplying plumbing fixtures and by specifying a working pressure requirement of not less than 130 psi (8.9 bar) at not less than 120°F (49°C). The combined system may be a means to

integrate the sprinkler system into new homes as a standard feature instead of as an option.

The multipurpose system uses the cold water piping to serve as a supply for both the domestic fixtures, such as sinks and showers, and the fire sprinklers. Given the potential for a reduced amount of pipe and fittings, there is a potential for reduced system cost. Supplying the sprinklers from the domestic water system can provide increased system reliability because any impairment to the water supply would be more quickly recognized. In addition, a combined system eliminates the need for backflow prevention devices. This setup also helps to reduce the cost of the system and eliminates any water pressure losses that would be incurred by a backflow prevention device.

New piping materials composed of cross-linked polyethylene have recently been listed by UL for use in residential sprinkler systems.[28] This piping is similar to piping already used in domestic plumbing systems and is therefore easily used in combined systems.

Residential Water Mist System

Residential fire suppression/control systems are also being developed under NFPA 750, *Standard on Water Mist Fire Protection Systems.* A water mist system uses very fine water sprays to control or extinguish fires by cooling of the flame and fire plume, oxygen displacement by water vapor, and radiant heat attenuation.[29]

Water mist systems typically use smaller amounts of water at significantly higher pressures when compared to a NFPA 13D residential sprinkler system. The spacing of water mist nozzles tends to be smaller than the spacing of residential sprinklers; hence more nozzles are needed to provide fire protection for a given area. Studies sponsored by the U.S. Fire Administration showed that in some cases water mist systems could provide equivalent levels of fire safety relative to a residential sprinkler system, however, at a significantly higher cost.[30,31] (For further information, see Section 16, Chapter 8, "Water Mist Fire Suppression Systems.")

RESIDENTIAL SPRINKLER EXPERIENCE

Scottsdale, Arizona

Due to the proven effectiveness of residential fire sprinklers, communities in 25 states require sprinklers in one- and two-family homes.[32] One of these communities, Scottsdale, Arizona, has conducted a detailed 10 year study on the impact of residential fire sprinklers on its community. In June 1985, the city of Scottsdale passed a comprehensive fire sprinkler ordinance that required all new multifamily and commercial structures to be protected by sprinklers, beginning in July 1985, and all new single-family homes, beginning in January 1986.[33]

The results of the study held some surprises. The average installation cost of a residential sprinkler system decreased significantly over the 10 year period. In 1986, the average installation cost was $\$1.14/ft^2$. By January 1996, the average cost was $\$0.59/ft^2$, a decrease of approximately 45 percent.[33]

Surveys of the home insurance companies in the Scottsdale area yielded an average discount of 10 percent for homes with residential sprinkler systems installed.[33] The Scottsdale study also examined the issue of water usage during a fire incident. The first 38 sprinklered fire incidents, a combination of fires in commercial, multifamily, and single-family units, were investigated. Based on the incident time lines, the waterflow times for the sprinkler systems were determined and the total waterflow was calculated. The average amount of water used per fire was 357 gal. Assuming that manual suppression could be accomplished in the same amount of time as the sprinkler flow time, the average amount of water used per fire incident by the fire department would amount to more than 4800 gal.[33]

In 1996, a review of the 109 fires that had occurred in sprinklered buildings in Scottsdale included 44 residential fires. In over 90 percent of the incidents, the fire was controlled with one or two sprinklers activated. The average amount of water flowed by the sprinklers was 299 gal per fire versus an estimated manual suppression usage of approximately 6000 gal per fire.

In 2001, the Scottsdale data were updated to include 15 years of experience with the Scottsdale sprinkler ordinance.[34] The updated data show the trends continuing, with the average fire loss in a sprinklered home to be $2166, as compared to $45,019 in a home without sprinklers. Efforts are under way to update the study to include 20 years of experience.

Prince Georges County. Maryland

Prince Georges County, Maryland, enacted an ordinance in 1990 by which all new residential structures were required to be sprinklered beginning in January 1, 1992. A report of the first 8 years' experience was compiled in January 2001.[35] The total fire loss in 117 fire incidents in which sprinklers were involved was reported as $401,220, as compared to an estimated $38,230,000 had sprinklers not been present. Although 7 minor injuries were reported in these fires, 154 lives were reported as having been saved by the sprinkler systems.

Among the 121 reported fire incidents, more than one residential sprinkler operated in only 11. In 7 of those, more than two sprinklers operated. An investigation revealed that those 7 involved some extenuating circumstance, such as the use of an accelerant or human intervention, which contributed to the operation of the additional sprinklers. During this same time period, there were only 4 incidents of sprinkler discharge for reasons other than a fire.

Residential Fire Sprinkler Activation Project

Starting in July 2003, the National Association of State Fire Marshals established a residential fire sprinkler activation reporting system on its website (http://www.firemarshals.org). The objective of the project is to collect current and detailed data pertaining to residential sprinkler activations.[36] There are 18 data fields, which include the type of occupancy, number of stories, story of origin, room of origin, area of the room of fire origin, number of sprinklers installed in room of origin, number of sprinklers activated, type of sprinkler activated, and reason for activation. Other inputs regard smoke detectors, and esti-

mates for lives saved, dollar loss due to fire, and dollars saved by sprinkler activation.

During the first two years of the project, 448 incidents were submitted by 167 different fire departments. Over 60 percent of the sprinkler activations documented occurred in apartment buildings. The sprinkler activations in kitchens accounted for 40 percent of the recorded incidents. Of the incidents where the number of sprinklers was reported, approximately 83 percent of the activations involved only a single sprinkler. This project is supported by a grant from the U.S. Fire Administration.

INCENTIVES FOR MORE WIDESPREAD USE OF RESIDENTIAL SPRINKLERS

Certain incentives can stimulate interest in residential sprinklers. These incentives are discussed in the following paragraphs.

Reduction in Government Spending

Reduction in all forms of government spending, resulting from public pressure to reduce property taxes, is a prime factor in the future growth of the residential sprinkler concept. Many fire departments are forced to protect larger areas and more subdivisions with the same number of or even fewer people because financial restrictions hamper a fire department's ability to grow with the community. As a result, alternatives to traditional firefighting techniques must be found. One of them is the use of residential sprinklers. San Clemente, California, was the first community in the United States to pass a residential sprinkler ordinance in 1980 as part of the fire department's master plan. This ordinance requires automatic sprinkler systems to be installed in all new residential construction. The prime motivation for the passage of this ordinance was San Clemente's cutbacks in government spending brought about by Proposition 13, the state's tax-capping measure. Many communities across the country face similar situations. Automatic sprinklers in residences may be the answer to fewer fire fighters and longer response times from the fire department.

Insurance Savings

Although the greatest benefit from widespread installation of residential sprinklers will be the lives saved and injuries prevented, lower property losses will be a secondary and substantial benefit. An ad hoc committee from the insurance industry sponsored a number of test fires in Los Angeles during the early 1980s and concluded that residential sprinklers have the potential for reducing homeowners' claim payment expenses.[37] As a result, the Insurance Services Office (ISO) Personal Lines Committee recommended that a 15 percent reduction in the homeowner's policy premium be given for installation of an NFPA 13D residential sprinkler system. Although this would not pay for the system over a short period of time, as is the case in many commercial installations, the continuing increases in the cost of insuring a single-family home make this a significant incentive nonetheless. NFPA analysis indicates that home sprinklers, like other sprinkler installations, reduce average fire loss per home fire by a much larger one-half to two-thirds.[38]

Real Estate Tax Reductions

In 1981, the state of Alaska enacted into law a significant piece of legislation that has a dramatic impact on the installation of sprinkler systems throughout that state. The law provides that 2 percent of the assessed value of any structure is exempt from taxation if the structure is protected with a fire protection system. The word *structure* is significant in the law, because it also applies to homes. In effect, if a home were assessed at $100,000 for purposes of taxation, the assessed value would be computed at $98,000, provided that it contained a fire protection system.

It actually may be considered an incentive simply to add the value of a fire sprinkler system to the assessed value of a property. In a national poll commissioned by the Home Fire Sprinkler Coalition in December 2000, it was found that 69 percent of homeowners believe having a fire sprinkler system increases the value of a home, and 38 percent said they would be more likely to purchase a new home with sprinklers than one without.[39]

Zoning

Greater land use may be possible with zoning changes that would permit fully sprinklered residences to be built on smaller parcels of land. The assumption is that the space between houses will not be as important from a fire protection standpoint if an entire street or neighborhood is fully sprinklered. One could argue, however, that if the sprinkler system fails, the resultant fire involving a number of residences could be much greater. The more complex analysis required to assess the net effects of full sprinklering of a neighborhood with smaller lot sizes has yet to be conducted.

Sprinkler Legislation

In addition to the San Clemente ordinance, a number of other California communities have passed residential sprinkler legislation, including Orange County and Los Angeles County. In 1993, more than 4 million Californians lived in communities in which residential sprinklers were mandated in all new homes.[40] Since 1982, Greenburgh, New York, and several surrounding communities have enacted sprinkler ordinances that require the installation of automatic sprinklers in virtually all new construction, including all new multiple-, one-, and two-family dwellings. A similar law went into effect in Prince George's County, Maryland, in 1992.

The state of Florida in 1983 passed a law requiring that all public lodging and time-share units three or more stories high in the state be sprinklered. It also required that all existing units be sprinklered by 1988.

In 1983, the city of Honolulu, Hawaii, adopted legislation that required all new and existing high-rise hotels, which are those more than 75 ft (23 m) above grade, to be sprinklered.

In the late 1980s, additional jurisdictions, including Atlanta, Georgia, the state of Connecticut, and the commonwealth of Massachusetts, acted to require retroactively the installation of sprinkler systems in high-rise residential buildings. In 1990, the federal government enacted the Hotel and Motel Fire Safety Act, which contains strong incentives for complete sprinkler

protection of hotels, because only hotels with satisfactory levels of fire protection are eligible for federal employee travel.

The Federal Fire Safety Act of 1992 requires automatic sprinkler systems or an equivalent level of safety in all federally assisted housing four or more stories in height, as well as in office buildings owned or leased for more than 25 federal employees. Perhaps the most significant legislation promoting the use of sprinkler systems, however, is the 1990 Americans with Disabilities Act. In 1991, the U.S. Department of Justice published criteria that became mandatory for places of public accommodation and commercial facilities designed for first occupation after January 26, 1993. Alterations to existing buildings must also comply. A key feature of the criteria is the need for areas of refuge. Floors of buildings that do not have direct access to the exterior at grade must provide areas of rescue assistance, except those buildings that have a supervised automatic sprinkler system.

Adoption of fire sprinkler ordinances continues in various areas. One of the most active areas in the early twenty-first century are the suburbs of Chicago. Between 2000 and 2005 the number of communities that had adopted an NFPA 13D ordinance grew from 3 to 35, with 14 of those adopted in 2005.[41] Lessons learned from the experience of communities that have adopted ordinances is being used to provide guidance to others that might wish to pursue their own ordinances.[42]

Construction

Many authorities having jurisdiction have used building code modifications as an incentive to install sprinklers. Cobb County, Georgia, was one of the first communities to amend its Buildings and Construction Code to include such an approach for multifamily structures equipped with residential sprinkler systems. Although these construction alterations can be a major incentive to install residential sprinklers, the disaster potential must always be considered if a fire, for whatever reason, should overpower the sprinkler system. This possibility of disaster is especially true if the system is designed with the minimal water supplies required by NFPA 13D.

The city of Dallas, Texas, adopted a building code that requires all new buildings or those undergoing major renovation, having an area greater than 7500 ft^2 (697 m^2), to have automatic sprinklers. At the same time, this building code encourages the installation of sprinkler systems by allowing design options that may allow different levels of "passive" fire protection features in exchange for "active" automatic sprinkler alternatives.

Code Requirements

Beginning with the 1991 edition, NFPA *101*®, *Life Safety Code*®, required the use of quick-response or residential sprinklers in new health care occupancies in smoke compartments that contain patient sleeping rooms. This generally means all patient rooms and their adjacent corridors. Beginning with the 1994 edition, quick-response or residential sprinklers were also required in all new hotel and dormitory guest rooms and guest room suites. Beginning in 1996, NFPA 13 requires quick-response or residential sprinklers in all new light hazard construction.

Because of these and other incentives, the use of new technology, such as residential and quick-response sprinklers, increased by a factor of 15 in the United States between 1990 and 2000, while the total number of sprinklers installed nearly doubled.[43] There is growing recognition of the enhanced ability of residential and other types of fast-response sprinklers to protect life and property from fires.

A major milestone for residential sprinkler came in August 2005 with the issuance of the 2006 editions of NFPA *101*® and *NFPA 5000*®, *Building Construction and Safety Code*®, both of which require fire sprinkler systems in all new one- and two-family dwellings.

SUMMARY

Residential sprinkler systems are an effective means of controlling fire in the home, allowing occupants the time to escape or be rescued. Several different systems exist, and research is ongoing to develop systems that are more efficient and cost-effective. The design and installation must take into account where sprinklers in a home are most effective in reducing the risk to life and property. The sprinkler system needs to activate automatically while a fire is small and the smoke and heat conditions in the home are survivable. Once the system is activated, it needs to control the fire with a smaller amount of water relative to a commercial sprinkler system.

Although most fire-related deaths in the United States occur in the home, it is estimated that less than 3 percent of one- and two-family dwellings have sprinkler systems installed. This percentage will rise as more legislation is passed requiring new homes to have sprinkler systems and as technology and costs continue to improve.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on residential sprinkler technology discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*
NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA *101®, Life Safety Code®*
NFPA 750, *Standard on Water Mist Fire Protection Systems*
NFPA 5000®, Building Construction and Safety Code®

Chapter 7

Ultra-High-Speed Water Spray Systems

Robert M. Gagnon

Chapter Contents

System Definition and Application
Reaction to Fire Events
General System Concerns
Detection System Selection
The Munitions Manufacturing Process
Squib-Actuated Systems
Pilot-Actuated Systems
Portable Systems
Explosive Sphere-High-Rate-Discharge (HRD) Devices
Explosion Suppression Systems
Explosion Venting
Research and Development

Key Terms

area protection, deluge system, detection system, explosion suppression, explosion venting, flame detection, point protection, reaction time, ultra-high-speed water spray systems, water spray system

Ultra-high-speed suppression systems for explosive hazards have come to symbolize many things to different people. To fire protection engineers, they are the cutting edge of today's fire protection technology. To some contractors, they may be too difficult to install. To the general public, they may connote an air of mystery and foreboding. Clients may consider them to be temperamental or hard to maintain. It is this diversity of impressions that has necessitated further developments in ultra-high-speed fire suppression system technology.

Two fundamental types of suppression systems are available to fire protection professionals for the control or extinguishment of explosive hazards: (1) ultra-high-speed water spray systems, which are discussed in significant detail in this chapter, and (2) explosion suppression systems, covered briefly in this chapter and well detailed in Section 17, Chapter 8, "Explosion Prevention and Protection."

Since the ultra-high-speed water spray system is essentially a highly sophisticated water spray system, a review of the fundamentals of water spray system design may be of considerable assistance. See Section 16, Chapter 9, "Water Spray Protection."

Further information is available in Section 2, Chapter 8, "Explosions"; Section 6, Chapter 15, "Explosives and Blasting Agents"; Section 14, Chapter 2, "Automatic Fire Detectors"; Section 16, Chapter 9, "Water Spray Protection"; Section 17, Chapter 8, "Explosion Prevention and Protection"; and Section 18, Chapter 4, "Venting Practices."

SYSTEM DEFINITION AND APPLICATION

Definition

An ultra-high-speed water spray system is defined by NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection,* as one that can commence the initiation of discharge of water to a volatile commodity within 100 milliseconds of detection, measured from presentation of an energy source to the detector to flow of water from the nozzle being tested. This level of response is required where materials of very high flame spread and heat release, such as propellants and pyrotechnic materials, are involved. With recent advancements in detection and electronic technology, ultra-high-speed water spray system response times in the 10 millisecond range are achievable, with 10 milliseconds being a mandatory response time for very rapidly spreading fires.

The NFPA Technical Committee on Water Spray Fixed Systems has determined that a line of demarcation must exist between ultra-high-speed water spray systems, covered in NFPA 15,

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and explosion suppression systems, covered in NFPA 69, *Standard on Explosion Prevention Systems.* Explosion suppression systems are required to be designed in accordance with NFPA 69 for enclosed vessels or other devices or conveyances where overpressurization or rupture is the primary concern. Ultra-high-speed water spray systems are predominantly designed in accordance with NFPA 15 for rooms or open, unconfined areas where rupture resulting from overpressurization is not the primary concern. Tightly sealed rooms and enclosed, or partially enclosed, process equipment are examples of applications that may be appropriate for the design of either ultra-high-speed water spray systems or explosion suppression systems, depending on the configuration of the commodity and its associated manufacturing process. Explosion suppression systems are not normally used in ordinance operations, because their response time is slower than ultra-high-speed water spray systems for the volume of the space requiring protection.

When personnel are present in a room with the potential for a rapidly spreading fire, room overpressurization and rupture are not the primary concerns because personnel are in jeopardy well in advance of an impending room rupture. An ultra-high-speed water spray system is needed to halt the expanding flame front before room overpressurization becomes a concern.

Both ultra-high-speed water spray systems and explosion suppression systems can be satisfactorily designed for the suppression of deflagrations or fires where the expanding flame front travels at a velocity less than the speed of sound. Neither system has been found to be effective for applications where a detonation, or a fire where the expanding flame front travels at a velocity greater than the speed of sound, could occur. Laboratory test data or empirical field testing of the commodity with respect to flame spread and heat release may be necessary before selecting a suppression system for a particular explosive hazard.

Application

Examples of facilities where ultra-high-speed water spray systems are advantageous include rocket fuel manufacturing or processing; solid propellant manufacturing or handling; paint spray can filling; ammunition manufacturing; pyrotechnics manufacturing; maintenance/renovation/demilitarization of ordinance items containing pyrotechnic materials; and the manufacture or handling of other volatile solids, chemicals, dusts, and gases. An example of a situation where an ultra-high-speed suppression system is not likely to be effective would be the protection of stored munitions whose manufacture has been completed.

Certain types of munitions, such as C-4 explosives, may promote a fire scenario that transitions from a deflagration to a detonation. An ultra-high-speed water spray system has been found to be effective for the suppression of such fires when the expansion of the flame front has been halted in its incipient stages.[1]

For military applications, it has become customary to use a nine-hazard classification system developed by the United Nations Organization (UNO) to promote the safe manufacture, storage, and transport of explosives. Class 1 contains the majority of energetic materials that are ordinarily protected by ultra-high-speed water spray systems. Class 1 is subdivided into six divisions, with Divisions 3 and 4 providing the most opportunity for high-speed suppression (Table 16.7.1).

REACTION TO FIRE EVENTS

Reaction Time

Reaction time is defined as the total time required from initiation of combustion and detection to the presence of water at the nozzle. It can be broken down into 11 segments for clarity as to what is included in reaction time and what is currently not being considered during the testing of ultra-high-speed water spray systems (Table 16.7.2).[2]

The 100 millisecond maximum response time required by NFPA 15 considers the period from detector reaction to flow at nozzles, or the time elapsed from segments 4 through 9. Since different detectors have differing reaction times, it is imperative that a detector be chosen with the shortest reaction time available, that the detectors be placed as close as possible to the target, and that no retards or delays be present.

Of great concern to fire protection engineers is the time required for the water to travel from the nozzle to the target, segment 10. To minimize water travel time, nozzles must be placed as close as physically or practically possible to the target. Increased nozzle pressure can increase water velocity and decrease travel time. It is highly recommended that the water travel time be considered in the total response time where feasible. High-speed photographic equipment or other sophisticated

TABLE 16.7.1 Classification of Explosives

Class 1, Division 1	Mass detonation. Includes explosives, ammunition, and liquid propellants that are too energetic to be protected by an ultra-high-speed water spray system.
Class 1, Division 2	Explosion with fragments. Includes ammunition and explosives that may be too energetic to be protected by an ultra-high-speed water spray system.
Class 1, Division 3	Mass fire. Includes ammunition and explosives that may be extinguished during manufacture if suppressed at an early stage. The majority of ultra-high-speed water spray systems protect commodities within this division.
Class 1, Division 4	Moderate fire. Includes ammunition and explosives that can be extinguished by an ultra-high-speed water spray system.
Class 1, Division 5	Very insensitive explosives
Class 1, Division 6	Extremely insensitive ammunition

TABLE 16.7.2 Reaction Time

1 The energetic material is subject to excessive energy input.
2 Deflagration begins.
3 The deflagration develops to a point that puts it in the detector's field of vision.
4 The detector begins to react to the fire.
5 The detector determines that there is sufficient light energy to be considered a fire.
6 The detector sends out a fire signal.
7 A high-speed module on the control panel receives the signal from the detector and activates the squib or solenoid-actuated valve.
8 Mechanical components associated with the ultra-high-speed water spray system go into motion.
9 Water leaves the nozzle and travels toward the target.
10 Water spray impinges on the target.
11 Waterflow is maintained to achieve cooling, dispersion, or extinguishment.

time measurement tools are needed to measure water travel time as a component of the total response time.

When no explicit guidance is given for specific situations, 36 in. (914.4 mm) is frequently used as a default distance between a point hazard and ultra-high-speed water spray system nozzles and detectors. Although increased nozzle pressure can reduce water travel time, pressurization of a nozzle beyond its effective range can result in distorted and inefficient nozzle spray patterns.

General Detection Concerns

To achieve the aforementioned rapid response time, optical flame detection for open areas or pressure detection for areas subject to overpressurization is necessary. Examples of optical flame detection devices include ultraviolet (UV) or infrared (IR) detectors placed in close proximity to the hazard. Such detectors instantaneously detect flashes of light associated with the wavelengths normally found in combustion. Pressure detectors sense a buildup of explosive pressure in an enclosure; they are very effective but generally provide slower actuation times than optical flame detectors.

Multiple-band optical detectors are now being specified for use with ultra-high-speed water spray systems. The U.S. Army's Advanced Fire Protection Deluge System Project (AFPDS) investigated multiband IR/IR and UV/IR multiple-band optical detectors as possible replacements for UV detectors and found that they can be as fast as the UV detectors and less likely to falsely actuate. False actuations of ultra-high-speed water spray systems are a major concern for defense and industrial applications. Furthermore, environmental concerns relative to containment and disposal of potential pollutants mixed with water from ultra-high-speed water spray systems may also be a major concern and a rationale for selection of multiple-band optical detectors.

The signal emitted by a detector is received by a high-speed module on the fire alarm control unit. To enhance actuation response times, it is necessary that the control unit be specifically designed for ultra-high-speed systems. It is the fire alarm control unit and its associated detection system that makes an ultra-high-speed suppression system unique from other types of water-delivery fire protection systems. The proper choice and design of supervisory equipment is essential to the successful functioning of the system.

NFPA 70, *National Electrical Code®*, and *NFPA 72®, National Fire Alarm Code®,* must be followed closely for all detection system wiring, component placement, and connections. Circuits between sensing devices and their controllers must be continuous with no splices and must be individually shielded.

GENERAL SYSTEM CONCERNS

Piping Methods

The piping methods associated with agent delivery to the hazard are as varied as the hazards they protect. The nozzles should be in very close proximity to the hazard with water in the piping and primed up to the nozzle, prepared for quick delivery of water to the hazard. One type of ultra-high-speed water spray system, the squib-actuated system, involves loosely capped nozzles, and/or a rupture disc at each nozzle, a preprimed piping system, and a deluge valve with an explosive squib (Figure 16.7.1). Another type, the solenoid-actuated system, involves pilot-actuated nozzles with a solenoid valve or system of solenoid valves installed on the pilot piping, which actuate upon receiving a signal from the detection system (Figure 16.7.2). A third type, possessing explosive squibs at each nozzle, is a variation of the squib-actuated system. Its distinguishing features (i.e., prepriming and squib actuation) will be covered in detail in this chapter.

Approaches to Detection

Two general design approaches, point protection and area protection, will apply to ultra-high-speed water spray system design. Point protection is the application of concentrated high-speed water spray onto a fixed point of ignition, such as a band saw blade for cutting solid munitions, and is accomplished by providing two or more counteropposed nozzles at positions as close as physically possible to the point of ignition (Figure 16.7.3). Area protection is the application of high-speed water spray over the area of a room or over the surface area of an object (Figure 16.7.4). In both cases, the nozzles must be as close to the intended target as possible to minimize the time for the water to travel from the nozzle to the target. Some hazards may be conducive to using the attributes of both point protection and area protection. This hybrid system is referred to as a combination system (Figure 16.7.5).

Nozzles and detectors should be placed no further than 36 in. (914.4 mm) from a point hazard and must be carefully coordinated with the process to avoid interference with the hazardous operation. Nozzles placed for point protection should have very narrow water spray angles for the efficient application of water density onto the point of hazard.

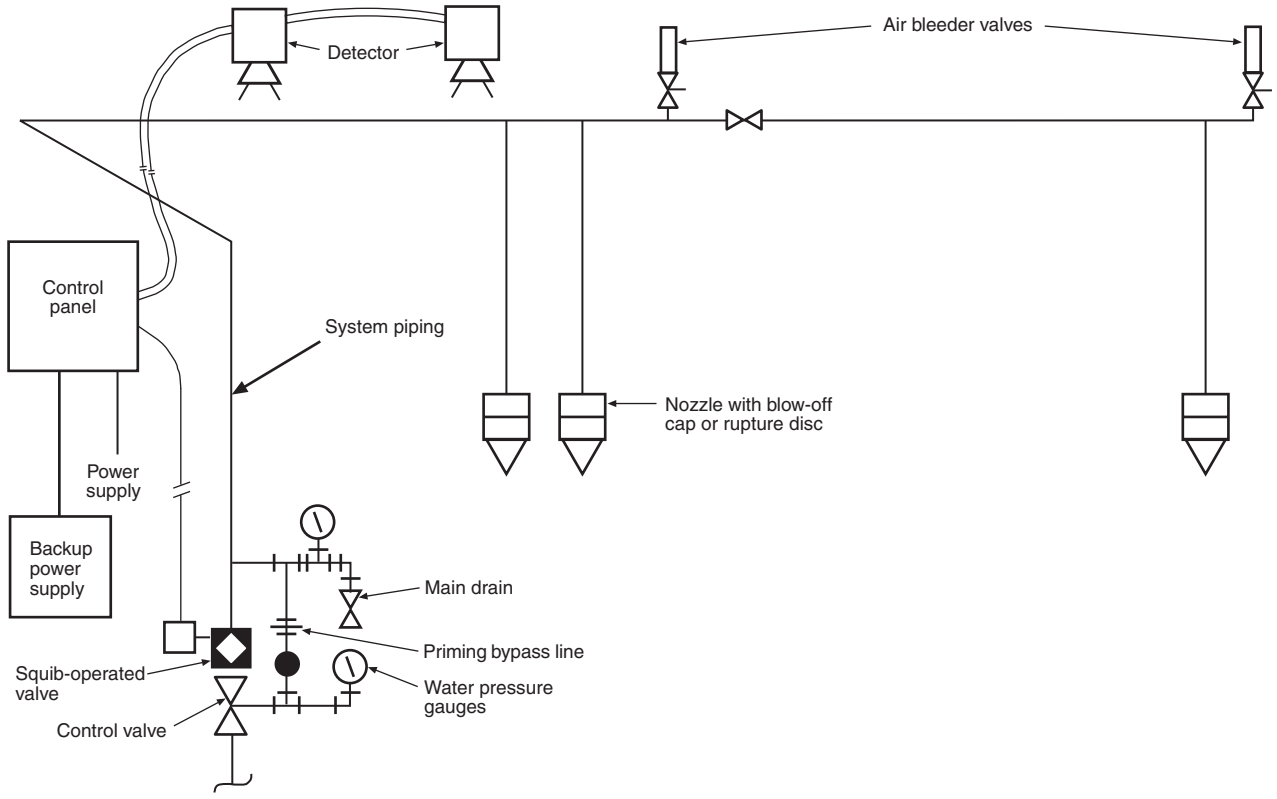


FIGURE 16.7.1 Squib-Actuated System

Nozzles spaced for an area hazard must be placed at a distance from the floor that permits the overlap of nozzle spray patterns on the floor or on the surface of interest. Although wide nozzle spray angles (about 120°) are likely to easily overlap, narrower spray angles (60° or 90°), spaced closely together, are more likely to provide efficient spray density, water velocity, and enhanced water travel time.

The process of detection, transfer of signal to the fire alarm control unit, interpretation of the signal, transmission of signal to the valve, and delivery of water to the hazard happens before one's senses are aware of a problem. It is not unusual for an installer to receive complaints of false trips after the installation of an ultra-high-speed water spray system. These occurrences may actually be real fires, undetectable by human senses. It is recommended that a diary of events be kept before and after system installation for analysis.

The first high-speed systems that protected munitions and propellant facilities were primarily preprimed deluge systems that used standard deluge valves, pneumatic detection, and enhanced pressurization. Response times for such systems were in the vicinity of 1 second. This type of system can still be used when it is desired that standard water spray deluge systems have an enhanced response time. The movement of the deluge valve clapper slows system actuation time considerably. However, improvements and innovations were developed to protect processes involving materials that require faster response times than the preprimed deluge system. The currently available ultra-high-speed water spray systems are covered in the sections that follow.

DETECTION SYSTEM SELECTION

In order to provide the best possible results in protecting munitions and other hazards requiring rapid-response technology, it is recommended that a four-step method be used to select a detection system:[3]

1. Choose a detector capable of reacting to the wavelengths expected to be encountered in a fire involving the hazardous material in question. For example, a UV detector will respond to a hydrogen fire, but an IR detector operating in the 4.4 micron range will not.
2. Survey the hazard area, the process, and the adjoining areas to determine sources of false signals that may exist. For example, if arc welding is expected to occur within the view of a detector, UV detectors must be either shielded from view or repositioned.
3. Determine elements that could interfere with the optimum operation of the detector. Dust or ice could severely hamper the detector's ability to function in accordance with its design parameters and will determine a detector's features or placement. Detectors with air shields to automatically clear dust from the detector lens are available.
4. Using test data or empirical results, ascertain the speed with which the detector is required to respond.

Two basic categories of flame detection systems are used as releasing systems for ultra-high-speed water spray systems. One type, UV detectors, responds to radiation in the range of 1850 to

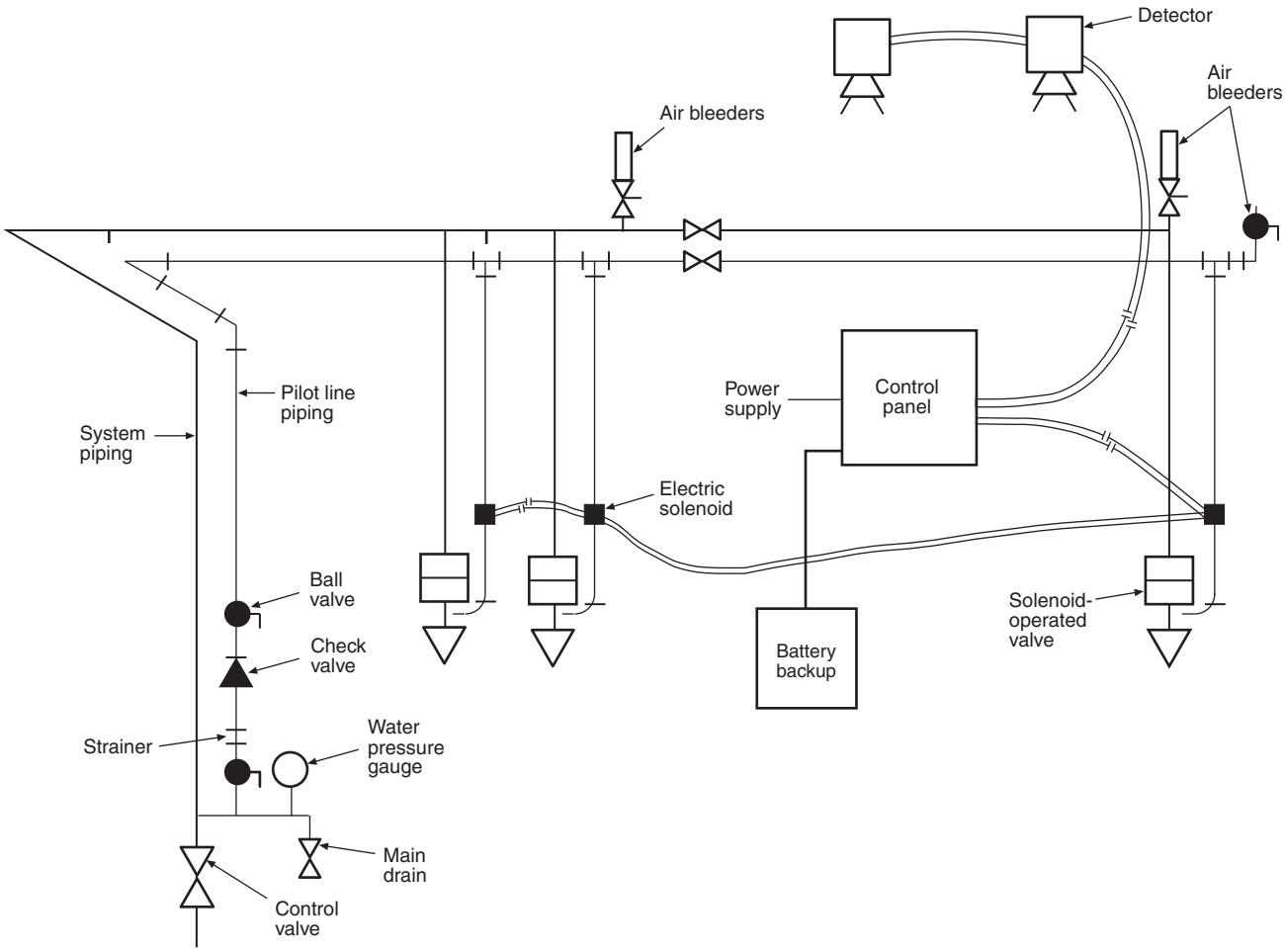


FIGURE 16.7.2 Solenoid-Actuated System

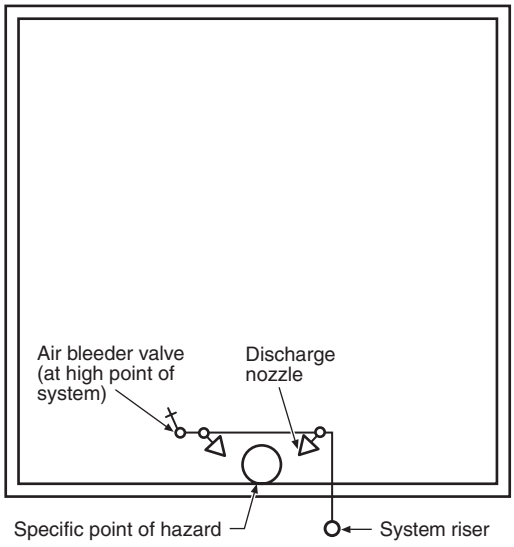


FIGURE 16.7.3 Local Point Application Design

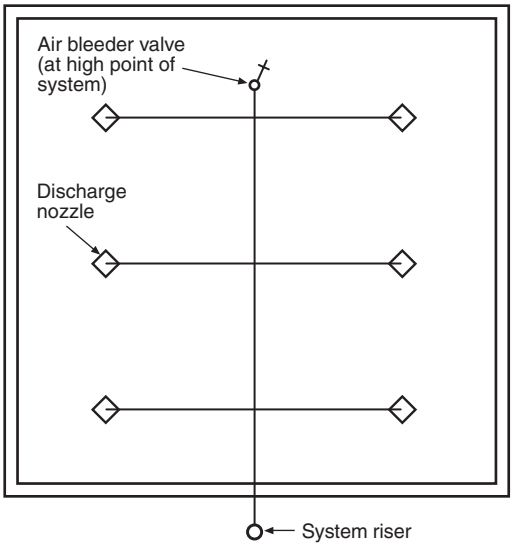


FIGURE 16.7.4 Area Application Design

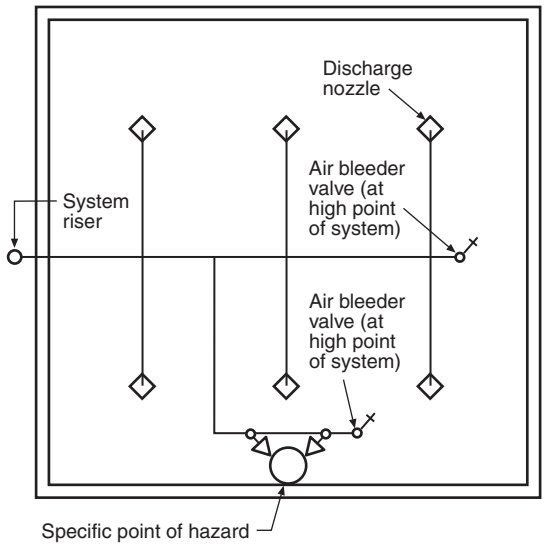


FIGURE 16.7.5 Combination Application

2850 angstroms (0.185 to 0.285 microns). Detection ranges are graphically shown on a radiation spectrum chart (Figure 16.7.6). The other type of flame detector is the IR detector.

Multiple-band optical detectors, such as dual-band or triple-band IR or UV detectors and dual-band UV/IR detectors, may also be used. A multiple-band IR detector, for example, searches a hazard for more than one band of IR radiation from the IR spectrum, providing the potential for a more reliable detection signal.

Note how the radiation spectrum chart shows an intersection between the IR detector sensitivity (between 0.8 and 1.0 microns) and the graph of solar radiation that reaches the earth. One can surmise by this intersection that an IR detector would be receptive to and would be adversely affected by sunlight radiation. This radiation spectrum correlation will strongly affect the manner in which IR detectors are used. UV detectors are not affected by sunlight, according to the graph, and can be located without regard to sun exposure. High-intensity lights and high-temperature bodies will affect IR detectors with no effect on UV detectors. However, arc welding, lightning, X-rays, and gamma rays will affect UV detectors more than IR detectors that have been properly aimed and shielded.

Since the two predominant types of ultra-high-speed system detectors (i.e., UV and IR) are searching for differing types of radiation and are affected by differing interfering media, their applications are generally quite different. UV detectors, being insensitive to sunlight, would be well suited for surveillance of an entire process area or a process requiring a wide angle of vision, whereas IR detectors would be better suited for close surveillance of a specific contact point within a processing machine or supervision of the interior of an enclosed vessel (Figure 16.7.7).

UV detectors are subject to the inverse square laws of optics, where detector sensitivity varies inversely with the distance between the detector and the energy source:

$$S = \frac{(\mathrm{K})pe^{cd}}{d^2}$$

where

S = Radiation power reaching the detector

K = Constant

p = Radiation power emitted by the fire, which is a function of the fuel characteristics and fire size

e = Base logarithm

c = Extinction coefficient of air, or the radiation energy absorbed or diffused by air, a function of humidity, dust, and so on

d = Lineal distance from the fire to the detector

From this famous law of physics, one can see that doubling the sight distance of the detector results in a dramatic reduction in the radiation received by the detector. Conversely, reducing the sight distance greatly increases the radiation received by the detector.

In cases where the point of ignition could be anywhere in a room, the wisest use of UV detectors is to provide area detection of the entire process by overlapping the area detection system

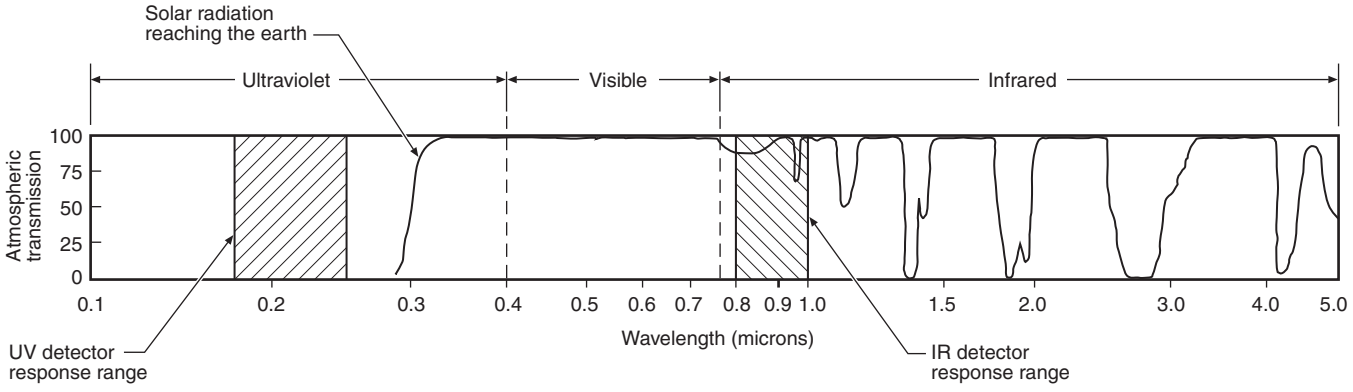


FIGURE 16.7.6 Radiation Spectrum Chart

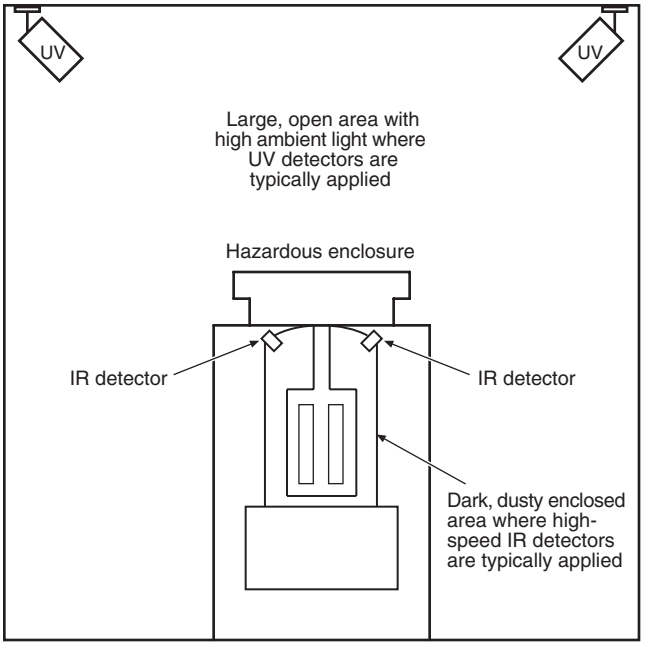


FIGURE 16.7.7 UV and IR Detectors

to cover all room areas, with additional detectors that closely view critical points in the process. For point protection, reliability increases dramatically when critical areas are viewed by overlapping cones of vision from counteropposed detectors in the same detection zone.

Because of their sensitivity to sunlight, IR detectors are best located in enclosed spaces, partially enclosed spaces, or spaces shielded from sunlight. Although IR detectors also obey the inverse square law, the hazard of receiving unwanted sunlight signals negatively affects their performance at extended detection distances. Shields are available to restrict the cone of vision of an IR detector to prevent unwanted actuation, and downward positioning reduces dust buildup on the lens.

The actuation or release apparatus for an ultra-high-speed suppression system consists of detectors (Figure 16.7.8), a specialized high-speed controller capable of monitoring and supervising up to eight detectors (Figure 16.7.9), a relay module to alert personnel and provide remote annunciation capability, and a detonator module that activates the squibs or solenoids that release an ultra-high-speed deluge system. Figure 16.7.10 illustrates the wiring of the detector and the controller shown in Figures 16.7.8 and 16.7.9. The modular control components are installed in a mounting cage and are served by a voltage converter that transforms ac building current into dc system current.

THE MUNITIONS MANUFACTURING PROCESS

The munitions manufacturing process is one of the most prominent applications for ultra-high-speed water spray systems and is among the most hazardous fire protection challenges that a

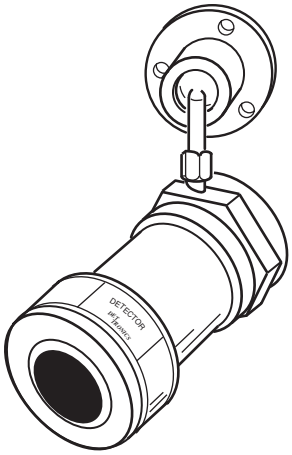


FIGURE 16.7.8 Ultraviolet Optical Detector on Swivel-Mount Base

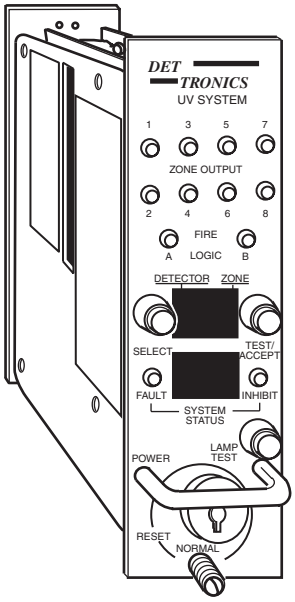


FIGURE 16.7.9 High-Speed Module

system designer or contractor can encounter. A delay of only a few milliseconds can mean disaster. The stakes are frighteningly high, and munitions manufacturing personnel are routinely required to perform operations involving significant risk. The U.S. Army Operations Support Command and its army ammunition plants and depots have played a leading role in the development and improvement of ultra-high-speed water spray systems.

Ultra-high-speed water spray systems have been successfully employed to protect the manufacture of many types of munitions, including propellants, diazodinitropherol (DDNP), trinitrotoluene (TNT), tetranitromethylaniline (TETRYL), tetranitrocellulose-type explosives (RDX), C-4, black powder,

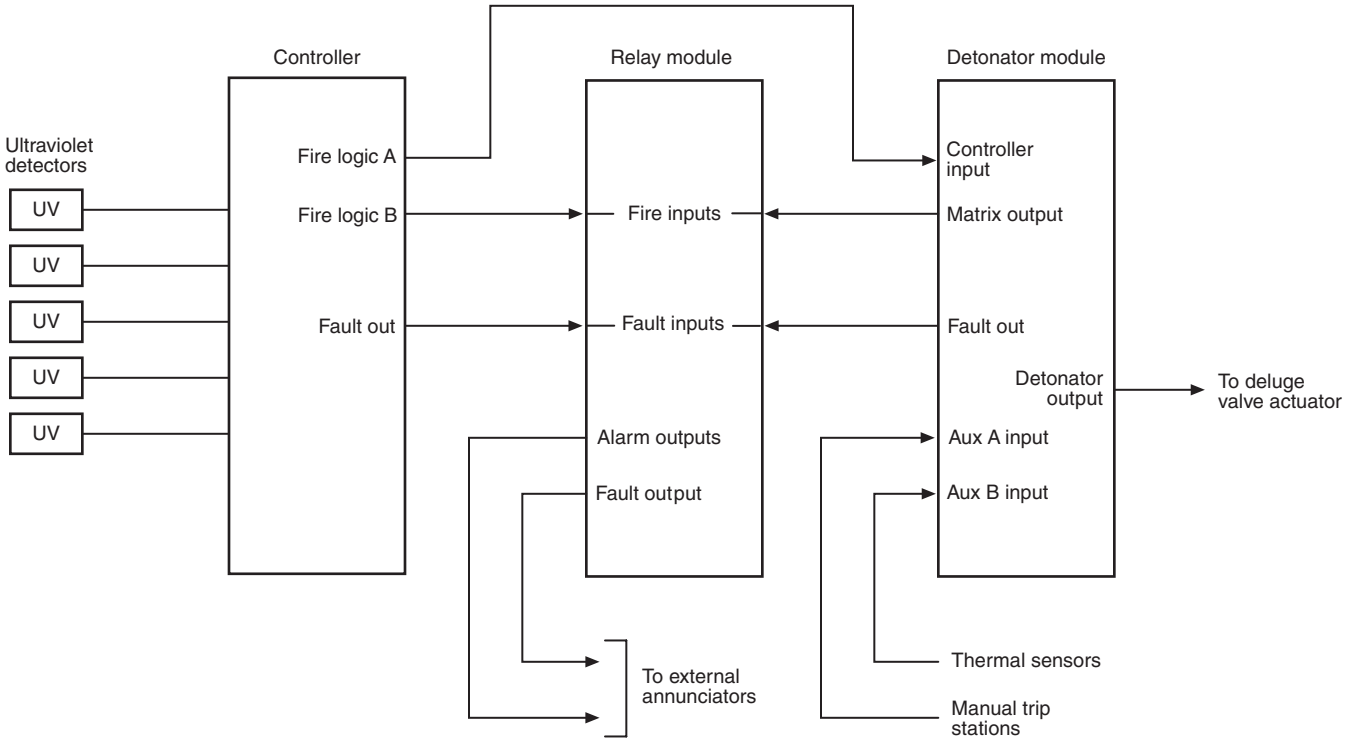


FIGURE 16.7.10 UV Block Diagram

pyrotechnics, fireworks, magnesium Teflon™ flares, and smoke-generating devices. Each commodity involves differing manufacturing processes and protection schemes.

Manufacturing Operations

In general, the 14 processes[1,4] that describe most munitions manufacturing operations include the following:

1. Weighing
2. Pressing
3. Pelletizing
4. Propellant loading
5. Melting
6. Extrusion
7. Mixing
8. Blending
9. Screening
10. Sawing
11. Granulating
12. Drying
13. Pouring
14. Machining

Each of these munitions manufacturing operations requires individual consideration and careful engineering to fully analyze the entire munitions manufacturing process and determine the proper and appropriate protection measures. In each case, the specifying engineer or designer must determine the objective of the system.

The three performance objectives that are to be considered in ultra-high-speed suppression system design are (1) life safety and personnel protection, (2) equipment protection and facility protection, and (3) total extinguishment or propagation cessation. The location and extent of protection and detection varies with the size of the operation, location of critical friction points, and the presence and location of the operating crew. A thorough risk analysis of the hazard is required and an evaluation of the financial and life safety effects of a catastrophic event in a processing area must be completed in advance of selecting the choice of objective or combination of objectives. If a catastrophic event would have a major effect on any objective, then prevention of such an event is a critical component of ultra-high-speed system design.

A strong consideration to be given in the choice of general area protection versus specific point protection is the mobility of the equipment. In many cases munitions processing machinery can be moved from one location to another, making protection at specific contact points impractical or impossible. It is recommended that a combination of area protection and point protection be provided wherever feasible and that protection for personnel be provided in all cases. Perhaps a way of solving the dilemma of frequently relocated point hazards is to provide area protection at the ceiling, supplemented by a portable ultra-high-speed water spray system, as discussed later in this chapter, for protection of the movable point hazard.

Weighing. If the munition is a powder, a special situation will arise as a result of the dust created by the operation. Ungrounded

static charges could result in ignition of the dust. The detection system should be as close to the hazard as possible, while maintaining the ability to perform and observe the pouring operation. Nozzles should be placed in such a way as to wet down the entire operation, including the operator, with overlapping sprays from opposing angles and with as heavy a density as possible. Extra nozzles may be required at critical points in the process. Solid weighing processes will involve, in general, detectors and nozzles placed throughout the hazard area. By protecting the entire room, the pathways between operations will be supervised and protected by heavy-density water spray.

Pressing and Pelletizing. A major risk in pressing and pelletizing operations is associated with ignition of the munition at the contact points of the operation and propagation of flame to the bulk storage of the munition. Detection and protection must be located as close to the points of contact as possible. Normally, the operator's arms will be protected by water spray applied to the contact points. Strong consideration should also be given to adding nozzles for the protection of the entire machine and the operator. Also, the designer should ensure that the bulk storage of the commodity is physically isolated from the manufacturing operation, or is otherwise protected.

Propellant Loading. The fire protection objective in explosive propellant loading is to halt the flame front caused by an ignition of propellant, thereby preventing propagation from the loading area to the main hopper, preventing a deflagration in the hopper.

Area protection and detection is recommended for the loading area, the storage area, and the travel routes between the munitions operation, the storage area, and the loading area. Additional point protection is recommended for critical friction or contact points.

Melting. Kettles are used to melt munitions, employing steam or hot water as the predominant energy source. One or more detectors, placed as close to the kettle as possible, and nozzles directed over the exterior of the kettle, especially at the opening where materials are added, will be required. The close proximity of detection and nozzles with respect to the kettle is critical to successful fire protection during a melting operation.

Detectors are never placed within melt kettles. Such environments are conducive to severe fogging of the detector lenses, negating their value in a very short time. Furthermore, the temperature encountered within melt kettles often exceeds the upper operating limits of most detectors and will not permit the internal installation of detectors. For such applications, mount the optical detectors on the exterior of the melt kettle as close as physically possible.

Extrusion of Explosives, Pyrotechnics, and Propellants. Extrusion involves the process of pressing the propellant or pyrotechnic material through an opening or die to form it into a desired shape. The point of fire protection interest here is the opening through which the munition exits. Detection and nozzle placement close to this point should prevent any ignited munition from spreading to the bulk storage area of the machine. Personnel and machine protection should also be considered.

Mixing and Blending. Mixing and blending of munitions can take place in an open vat or in a closed container. The open mixing or blending process may be approached in a manner similar to the melting process. If the container is closed, the detector and nozzle should penetrate the enclosure, with appropriate precautions taken to avoid dust loading or obscuration of the detector and nozzle. Heat, mechanical damage, and dust must be considered when placing detectors or nozzles within closed containers.

Screening, Sawing, and Granulating. Common hazards to be considered in these processes are friction, dust, and sparks that can occur during these operations. Points of contact must be completely observed by detection and protected with point-protection ultra-high-speed water spray. Locating the nozzle as close to the point of contact as possible will enhance timely delivery of water to the critical point most likely to support ignition.

Drying, Pouring, and Machining. Drying operations are usually done in ovens or heating cabinets, with area nozzle protection over the surface area of the cabinets, especially where the operator opens the cabinet to remove or add items to be dried. Pouring requires point nozzle protection, and area nozzle protection is also often required. Machining operations require point nozzle protection similar to extrusion operations with area coverage also often required.

Choice of Agent for Munitions Manufacturing Protection

Water is the agent of choice in the protection of explosive munitions hazards for its ability to cool the combustible, insulate the exposed surfaces, dilute a hazardous material, knock down suspended dust, and cool the expanding flame front. Water is an inexpensive and readily available suppressant.

Munitions and propellants differ from most fire protection hazardous commodities in that they contain a built-in supply of their own oxidizer mixed in with the fuel. The oxidizer is needed to ensure rapid burning of the material on demand in tightly enclosed areas or oxygen-deficient atmospheres, such as rocket motor combustion chambers or artillery gun tubes. Most oxidizer additives in the munitions industry fall under the general classification of nitrates and chlorates, such as potassium nitrate and potassium chlorate.

In the choice of an agent for munitions manufacturing, the presence of this built-in oxygen supply effectively eliminates from consideration the commonly available smothering or blanketing agents, such as carbon dioxide. Halon clean agents and other gaseous suppressants typically fail to stop the flame front in munitions fires. These agents begin to chemically break down and, therefore, fail to provide the cooling necessary to inhibit propagation. It must, therefore, be concluded that the primary objective in munitions protection is cooling by using water, not unlike most hazards encountered

by the fire protection engineer. By introducing a cooling agent in the early stages of a deflagration, one prevents the feedback of heat energy from spreading to unburnt fuel, thus effectively limiting and then ceasing combustion. Failure to apply water in the very early stages of munitions combustion could result in burrowing or flame propagation within a pile of munitions mixture covered by extinguished and water-soaked munitions material.[1]

Also to be considered are the combustion gases produced by burning munitions. There exists in munitions fires a point of no return, where the production of combustion gases creates a barrier sufficient to prevent water spray from reaching the fuel. This explains why sophisticated mechanical and electrical fire protection equipment, designed for response in a few milliseconds, is essential for the protection of munitions hazards. Retardation of ultra-high-speed fire suppression system response time from 100 milliseconds to 1 second or more can create a scenario whereby the deflagration reaches a point that the expanding flame front gets out of control, negating the effectiveness of the suppression system and resulting in the loss of the process.

An automatic sprinkler system should be specified for adjacent storage or operations areas if there is a possibility of a fire occurring in other materials that could result in a fire propagating to the munitions, such as a fire starting in combustible packaging material and spreading to a munitions item.

Flame Detection Devices

Flame detection is the detection method of choice for ultra-high-speed deluge systems. Two types of flame detectors in common usage are UV detectors and IR detectors, both consisting of a photoelectric cell and a photoconductive cell.

Ultraviolet Detectors (UV). UV detectors are designed to detect radiation falling within the ultraviolet wavelengths below 4000 angstroms (0.4 microns). Fires emitting radiation with wavelengths of this nature generally have high-intensity flames associated with diffusion flame combustion. Close proximity of the detector to the source of the combustion is critical to operation within its intended range of sensitivity.

Shielding or screening may be necessary to isolate the UV detector from unwanted signals, such as lightning and welding arcs. It should be noted that a UV detector is an efficient flame detector, but must see the fire to be effective. An anticipated fire that is preceded by or accompanied by significant quantities of thick or dark smoke may not be amenable for UV detection, since the smoke could prevent or delay the operation of a UV detector. UV detectors cannot see through Lexan shielding. It is, therefore, necessary to ensure that each area bounded by shielding is individually detected within the shielded zone.

A limitation to the use of UV detectors is the fogging or loading of the lens that can occur when these detectors are used in dusty or moist atmospheres, adversely affecting their reaction time. Unless special arrangements are provided, such as air shields to divert dust away from the lens, or a tightly controlled 24 hour maintenance and supervision program, UV detectors may be unsuitable for some dusty or greasy environments.

Infrared Detectors (IR). IR detectors are amenable for use at distances up to 50 ft (15.3 m), and respond to infrared radiation involving wavelengths from 8500 to 12,000 angstroms (0.8 to 1.2 microns). Using IR detectors at extended distances is generally not recommended for ultra-high-speed suppression systems for explosive hazards. There is, however, research currently under way on possibly using some of the newer IR detectors that show great promise as a possible detection source for ultra-high-speed water spray systems for specialized applications.

Some common heat sources that can be sources of false alarms for IR detectors include automobile headlights, direct or reflected sunlight, room lighting, heaters, lighted tobacco products, and matches. IR detectors may not be able to discriminate between a common heat source and a combustion scenario.

Most IR detectors have a built-in timing unit that can delay actuation by as much as 1 to 30 seconds. This length of delay is usually unsuitable for the detection of munitions fires. If IR detectors are used, the distance between hazard and detector must be kept to a minimum, effectively screening out most sources of unwanted signals, and the time delay must be eliminated or minimized. A special ultra-high-speed IR detector is available with the delay feature eliminated.

Detector Listing. Most UV and IR detectors are listed by Underwriters Laboratories Inc. (UL) and are approved by Factory Mutual Research Corporation (FMRC) for fire protection use. Although they are approved for both indoor and outdoor use, it is recommended that they not be used outdoors for ultra-high-speed detection, so that unwanted signals can be minimized. Sources of flickering light, such as lights mounted on operating or vibrating machinery, may be perceived as being a fire by the detector and should be screened or eliminated.

Multiband Detectors. Multiband IR/IR and UV/IR detectors are commercially available, and recently manufactured units have been found to provide rapid response times while lowering incidences of false actuation. Multiband detectors search for more than one band of spectral radiation and confirm receipt of such signals in advance of notification of the fire alarm control unit of a fire.

SQUIB-ACTUATED SYSTEMS

The squib-actuated ultra-high-speed deluge system is a preprimed deluge system with a squib-operated deluge valve, a system of piping preprimed with water, specially capped nozzles and/or rupture discs, and an ultra-high-speed flame detection system. Developed in the early 1960s, it was the first commercially available ultra-high-speed water spray system and continues to be in active use today.

It is recommended that this system be used for hazards such as ammunition loading, explosive powder drying operations, high-energy fuel processing, self-oxidizing fuel processing and storage, silane containment cells, explosive dust collecting and conveying operations, roll mills, and casting pits. Other hazards requiring enhanced reaction times may be suitable for the squib-actuated ultra-high-speed water spray system.

Preprimed Piping System

The preprimed piping system on a squib-actuated system is supplied by a priming bypass valve that provides a water head of up to a maximum of 12 psi (82.74 kPa) to the blow-off caps installed to hold back the pressurized priming water. Water pressure required to remove the blow-off caps will vary with the make and model of cap used. A wire retains the blow-off cap to the nozzle for ease of retrieval and to prevent it from falling into material or devices being protected. It is recommended that the nozzles be as close as possible to the hazard being protected, and directed toward the critical points of the hazard (Figure 16.7.11).

Allowing the water to be preprimed in the piping has a strong advantage over standard evacuated piping deluge systems. The time it would have taken for the water to travel from the deluge valve to the nozzle has been eliminated. This can be a significant difference, especially for systems requiring the deluge valve to be remote from the hazard. The preprimed aspect of this system requires that the hazard area and valve riser be heated. Heat tracing of the piping is not recommended because loss of power, improper tracing installation, cracking or crimping of the tracing wire, or other potential failures of the tracing would damage and compromise the ability of the system to function when required.

The priming static pressure that can be maintained on the blow-off caps for a squib-actuated system, without danger of accidental leakage, is 12 psi (82.74 kPa) or less, depending on the cap manufacturer. Rupture discs or other devices capable of maintaining a minimum system static pressure of 50 psi (344.75 kPa) are strongly recommended. The system must be hydraulically designed to ensure a minimum residual pressure of 50 psi (344.75 kPa) at each nozzle, with sufficient static pressure to allow for automatic removal of all blow-off caps or rupture of all rupture discs on system actuation (Figure 16.7.12).

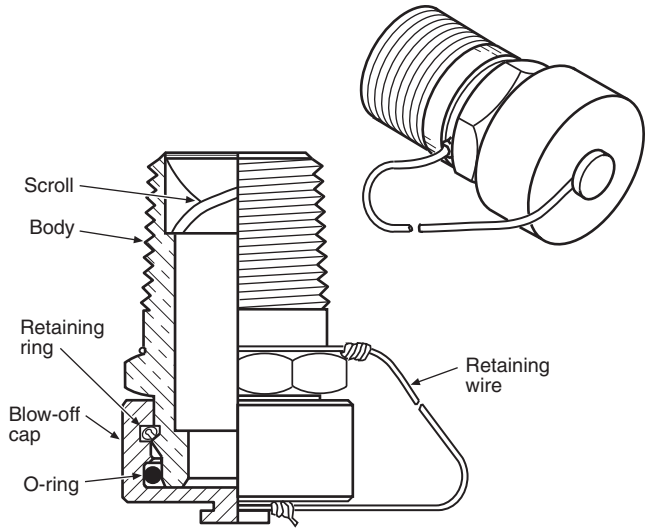


FIGURE 16.7.11 Nozzles and Blow-Off Caps

Squib-Actuated Valve

The squib-actuated valve is an electrically actuated valve with two explosive primers wired in parallel (Figure 16.7.13). The

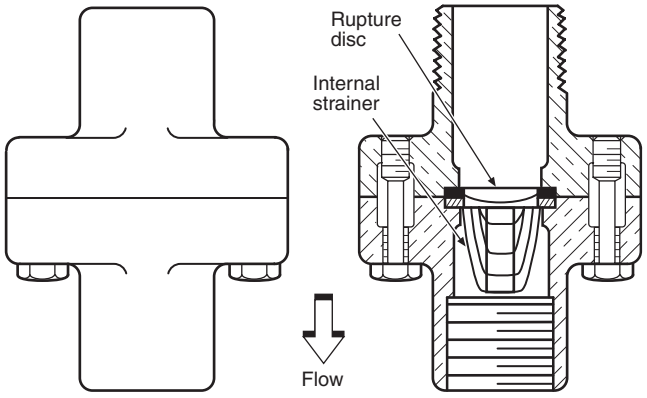


FIGURE 16.7.12 Rupture Discs

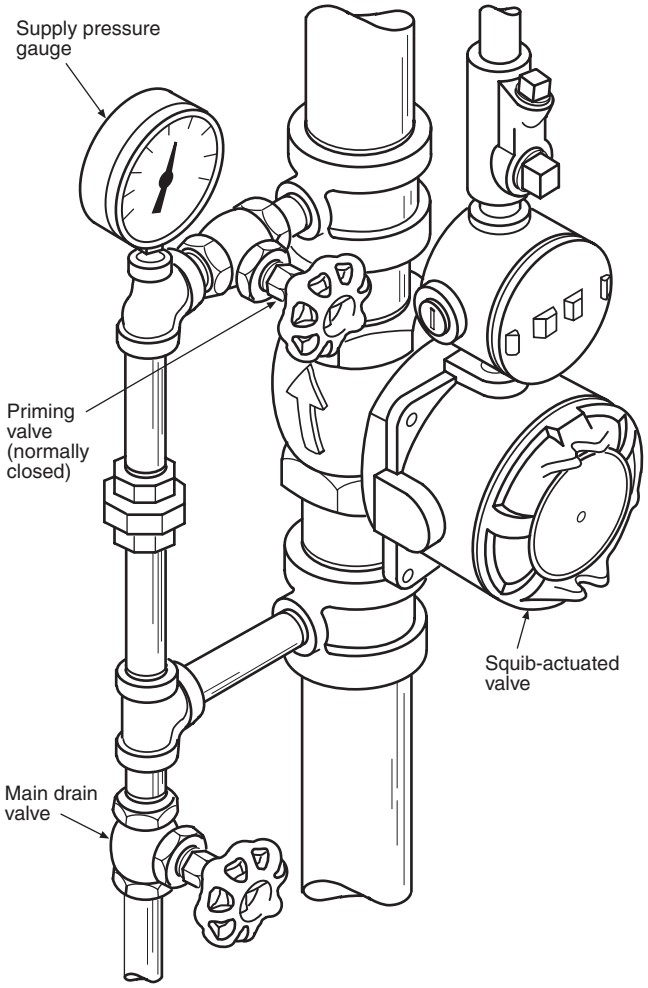


FIGURE 16.7.13 Squib-Actuated Valve

valve is intended to be installed vertically but will also function with increased response times in the horizontal position. The primers consist of 0.004 oz (0.12 g) of lead styphnate charge and actuate upon the receipt of an electric signal from the detection system.

The primers are designed so that the force of only one primer is needed to actuate the system. Firing of the primers shears a rod holding the clapper latch, allowing the plunger to rise, resulting in the rapid movement of the clapper and rapid pressurization of the priming water as water begins to flow through the valve. The blow-off caps are ejected or rupture discs broken once their inlet pressure exceeds their respective release pressure (Figure 16.7.14).

Although squib-actuated valves are rated for use in Class II (electrical rating) locations, it is recommended that the valve not be located directly adjacent to a hazardous process and in a nonhazardous area, if physically possible.

Squib-actuated valves are available for use with 2 in. (51 mm) and 2½ in. (64 mm) risers, and releases are available for 4 in. (102 mm) and 6 in. (152 mm) deluge valves. Increased system size has a very strong effect on the increasing of response time. A 500 gal (1893 L) water-holding capacity is recommended as the maximum system size, and best results would be obtained by subdividing the systems such that the number of nozzles served by one squib-actuated valve is between two and six nozzles with separate detection systems and suppression system actuation valves.

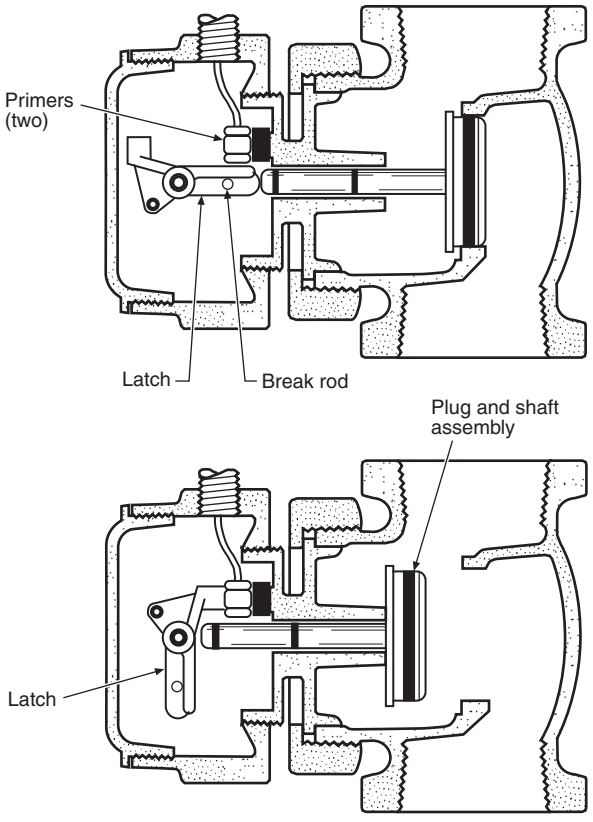


FIGURE 16.7.14 Squib-Actuated Valve Unlatching

Squib-Actuated Detection System

The detection system for a squib-actuated system (Figure 16.7.15) is ordinarily an optical flame detection system. These photoconductive cells monitor the hazard and can detect small amounts of radiant energy emitted by a fire in the hazard area. Such detectors are monitoring light within certain predetermined wavelengths normally associated with fire. Should the photoconductive cells receive more light than was specified to be ambient, the cells' resistance will change, sending a signal to an amplifier in the control panel. This amplifier increases the signal's strength and sends it to the primer for actuation. Signal transmission time is normally 2 or 3 milliseconds.

Normal actuation times for a squib-actuated system can vary with piping configuration, size of the system, distance from the valve to the nozzles, water pressure, and hazard conditions. Response times in the 100 millisecond range are possible for very small systems with risers very close to the hazard and with high water supply pressures.

Resetting a Squib-Actuated System

After operation, the two primers and primer holders are replaced, and a new break rod installed. Nozzles are then recapped or plugged or rupture discs replaced. Breakglasses must be replaced if the system was operated manually. The system is then reprimed by slowly opening the priming bypass valve and bleeding the air from bleeder valves located at high points in the piping system. Care must be taken to purge all air to ensure complete priming of the system. The control panel is then reset and returned to service. It is recommended that spare primers, holders, rods, blow-off caps, rupture discs, and breakglasses be kept in a convenient nearby location for ease of resetting. It is essential that the system be functionally tested and operated at least once a year to ensure that all parts are functioning properly and ready for use.

System Actuation Time

The piping in a preprimed deluge system must be sloped, with air bleed valves placed at the piping high points, to facilitate the

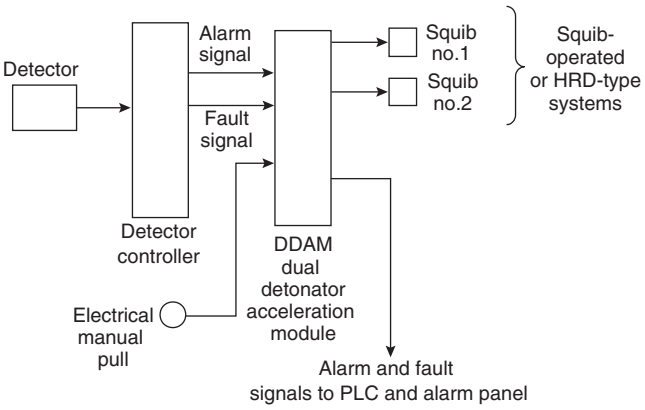


FIGURE 16.7.15 Squib-Operated Electrical Flow Diagram (Source: Pyrotech International)

removal of trapped air bubbles in the piping, which are known to have the effect of increasing response time.

Another major factor influencing actuation time is the system water supply pressure. When all other variables are held constant, the actuation time decreases with increasing water supply pressure. For example, if one could double the supply pressure from 50 to 100 psi (344.75 to 689.5 kPa), the actuation time would decrease by about 20 to 25 percent. Actuation times assume that the priming water is at rest at the nozzle orifices. The system pressure and the resulting enhanced actuation times, therefore, result from inertia effects and are effectively independent of pipe friction, head elevation, and nozzle orifice coefficients.

Other factors influencing the effectiveness of a squib-actuated system are the quantity of nozzles on the system, orifice diameter of the nozzles, length of piping from deluge valve to the nozzles, number of fittings on the supply and branch pipes, cap or disc blow-off pressure, and cross-sectional area of the supply pipe.

Actuation time for squib-actuated systems is shown in Figure 16.7.16. The valve unlatching time and cap blow-off time are strong functions of system pressure. The graph also shows that 4- and 6-in. (102- and 152-mm) squib-actuated valves take 3 milliseconds longer to unlatch than the 2- and 2½-in. (51- and 64-mm) valves.

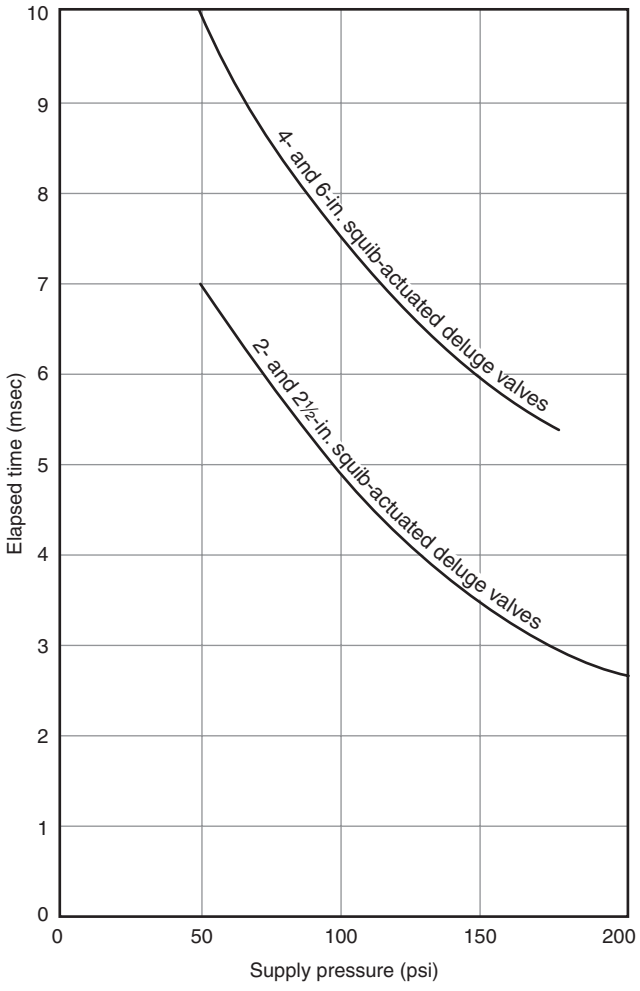


FIGURE 16.7.16 Valve-Unlatching Time

Most U.S. Army ammunition plants maintain static pressure for ultra-high-speed water spray systems in the range of 50 to 75 psi (344.75 to 517.13 kPa), usually supplied by elevated gravity tanks, to enhance actuation time.

Squib-Actuated Ultra-High-Speed Water Spray System Design

Recommendations for a squib-actuated ultra-high-speed water spray system design are as follows:

1. It is recommended that the squib-actuated valves be installed in the vertical position, even though a horizontal position is possible. Installation in the horizontal position could trap air, negatively affecting actuation time.

2. Care should be taken to make the pipe routing from squib-actuated valve to the nozzles as direct as possible, with as few fittings and bends as possible.

3. Slope all piping up to vent valves at piping high points to facilitate the elimination of air from the system. The pipe should be sloped as radically as possible, especially for smaller pipe sizes.

4. For point protection, position the nozzles into counter-opposed groups of no fewer than two nozzles for efficient delivery of water to a likely source of ignition. Counteropposition of the nozzles involves nozzles aimed from differing directions at a common point.

5. Ensure the highest possible water supply static pressure, enhancing system pressure with a surge (pressure) tank or an excess pressure pump if city or plant supply is insufficient. A minimum of 50 psi (344.75 kPa) static pressure is recommended.

6. Perform hydraulic calculations of the system to verify pipe sizes and ensure minimum nozzle discharge pressures of 50 psi (344.75 kPa). Densities must be calculated based on water that actually impinges on the hazard area. Unless the nozzles are wisely placed, the spray that impinges on areas of little consequence could be considerable, reducing the actual delivered density on the hazard area. Also care must be taken to overlap sprays as much as possible to supplement the lighter densities that are normally found along the outside perimeters of the conical spray patterns. For spot protection, it is recommended that the concept of average density (raw gal [L] available at nozzle divided by total ft^2 [m^2] of floor area covered) be replaced by experienced engineering evaluation of actual nozzle distribution to the hazard area in question. Each nozzle is required by NFPA 15 to discharge no less than 25 gpm (95 L/min) per nozzle for point protection, nor less than 0.50 gpm/ft^2 (20.37 L/min·m^2) for area protection. Some commodities, such as especially volatile pyrotechnics, may require densities as high as 3.0 gpm/ft^2 (122.24 L/min·m^2).

PILOT-ACTUATED SYSTEMS

Early Development

The first pilot-actuated nozzle was introduced in the early 1960s. This early system (Figure 16.7.17) has as its basis mechanical

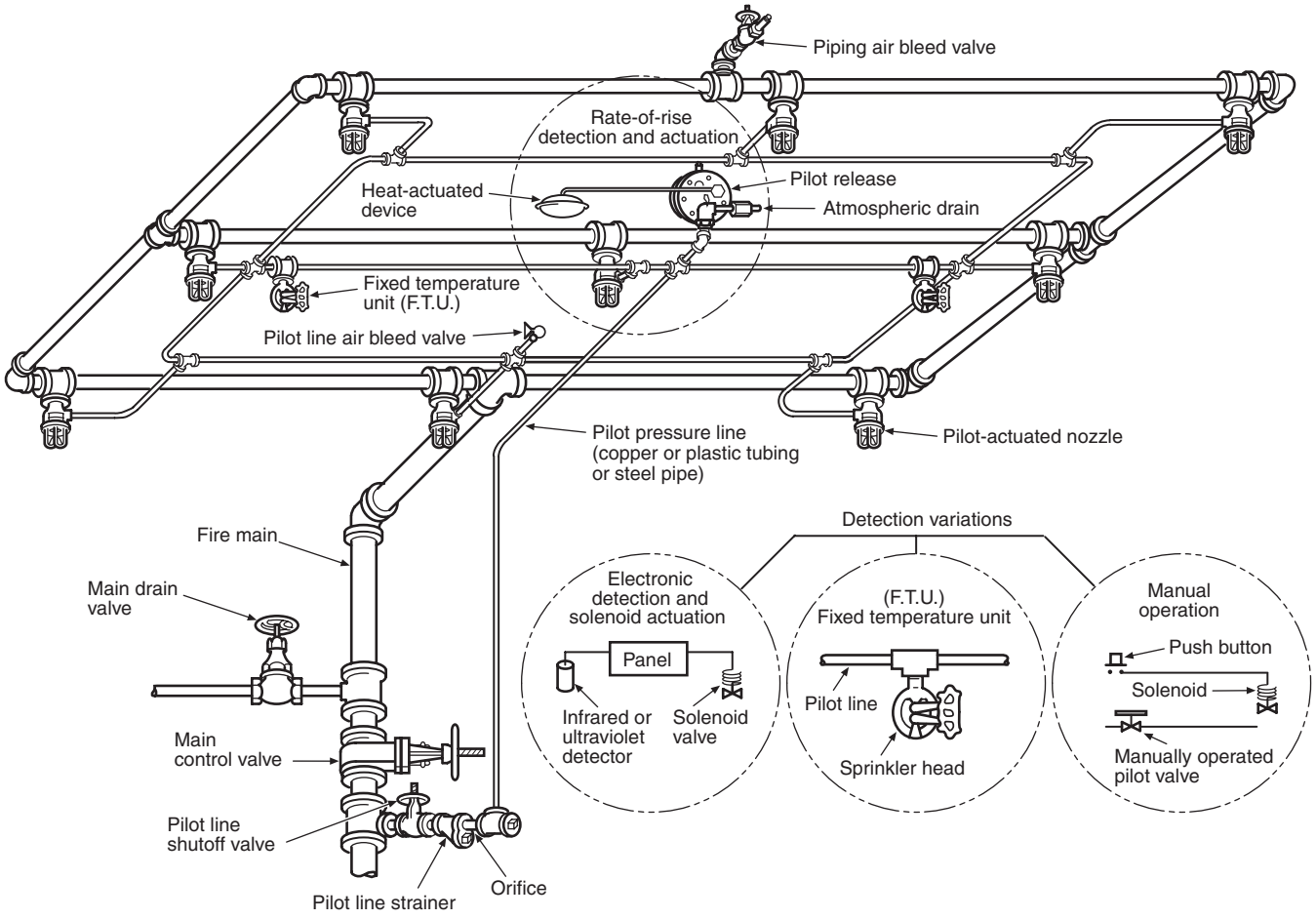


FIGURE 16.7.17 Early Pilot-Actuated System (Obsolete)

components similar to types in the present system. Each revision to the early concept was in the interest of speed, which became possible with the advent of more sophisticated electronic technology.

The first pilot-actuated nozzles had an integral deflector attached to the lower body with a male adapter for connection of a water spray nozzle. Today the integral deflector has been augmented by the addition of other bodies capable of accommodating a wide variety of water spray nozzles, allowing engineering flexibility. Each nozzle individually functions similarly to a wet-pilot-actuated deluge valve. In its earliest incarnation, the pilot-actuated nozzle was called the "aerospace" nozzle, as a result of its use in hyperbaric chambers for the space program[5] (Figure 16.7.18).

The standard detection arrangement for early systems was a system of pilot piping with a heat-actuated pilot release. This method was developed specifically for and became commonly employed with naval ship munitions magazine protection systems. The naval requirement for the early pilot-actuated system response was 150 milliseconds, with an operation time, measured from release of the pilot line to delivery of water, in the 10- to 20-millisecond range. The time that it took for the heat-actuated device to actuate and commence evacuation of the pilot line was not included in this time. The heat-actuated means of detection eventually gave way to ultraviolet electronic detection with solenoids on the pilot line as the method of choice, once the electronic detection and control technology became available.

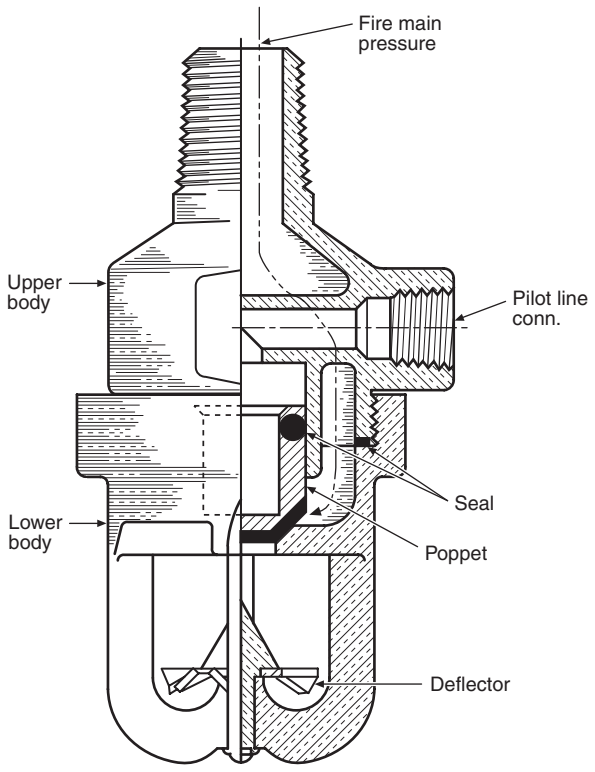


FIGURE 16.7.18 Early Pilot-Actuated Nozzle

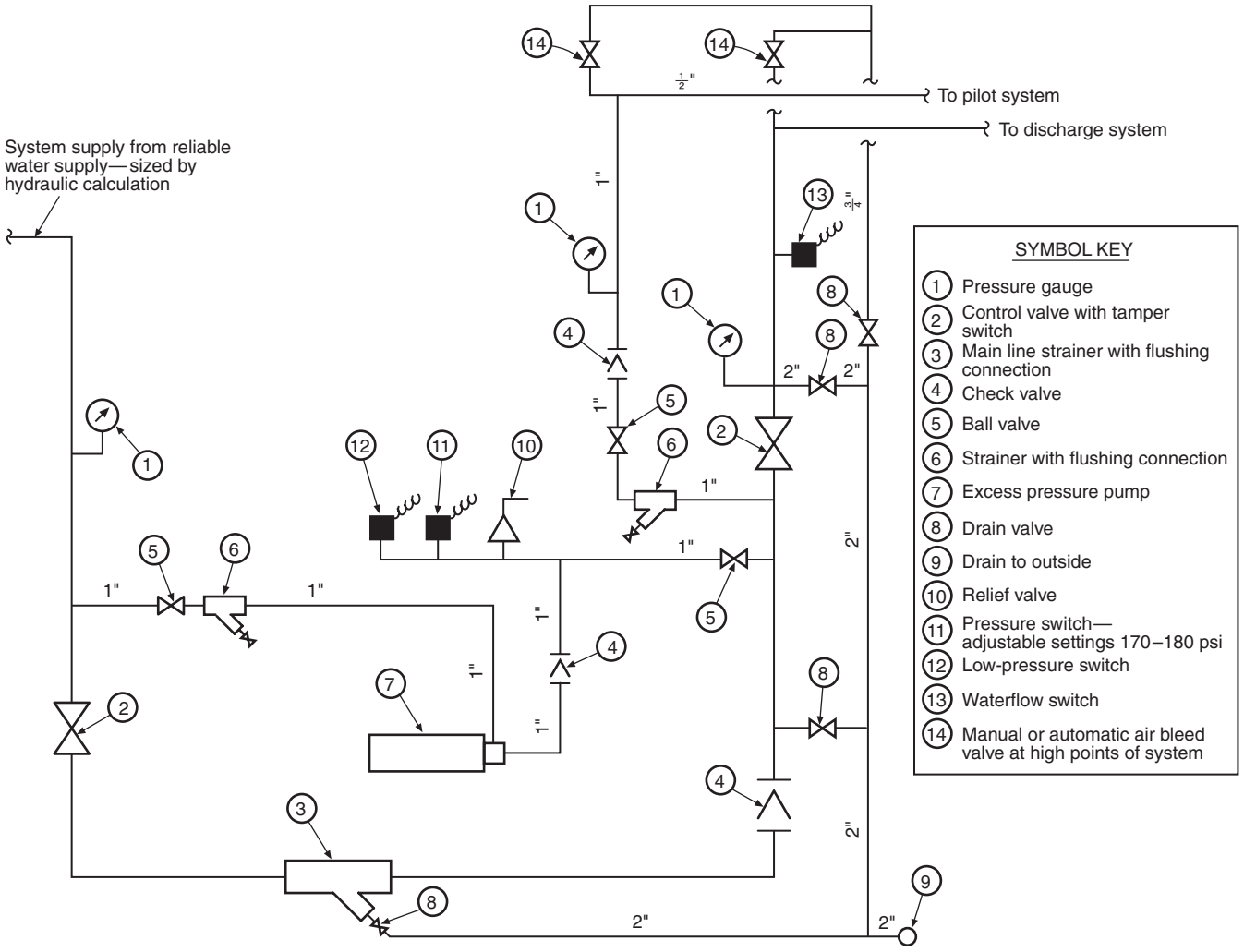


FIGURE 16.7.19 Control Riser Solenoid Operating System

What made the pilot-actuated system different was its positive priming at fire main pressure, its poppet-valve nozzle and pilot system, and simultaneous opening of all nozzles connected to one pilot line. The basic system in its earliest form had certain similarities to the pneumatically actuated deluge system and also bears a strong resemblance to a wet-pilot-actuated deluge system.

Pneumatic heat-actuated and eutectic heat-actuated devices are significantly slower than an electronic UV-actuated release system. With the development of more sophisticated circuit boards, microprocessors, high-speed release modules, solenoid improvements and other response time innovations, improvements in system actuation time were possible.

Current Arrangement

A fixed pilot-actuated ultra-high-speed water spray system consists of a primed discharge system with pilot-actuated nozzles; a hydraulic wet pilot system, supervised and discharged by high-speed solenoid valves; a UV or IR flame detection system; and a central fire alarm control unit with standby batteries and charger (Figures 16.7.19 and 16.7.20).

Discharge System. Although the pilot-actuated nozzle has been available for many years, recent developments in control modules and panels make the pilot-actuated system more amenable to hazards requiring extremely rapid response times. The pilot-actuated nozzle consists of a two-piece body, with ½ in., 1 in., or 1¼ in. (12.7 mm, 25.4 mm, 31.8 mm) male National Pipe Thread (NPT) threaded connection for attachment to the deluge piping system, a ¼ in. (6.4 mm) female inlet for connection to the pilot piping system, and an outlet for the insertion of water spray nozzles with male NPT connections.

The pilot-actuated nozzle is connected to two piping systems, discharge and pilot (Figure 16.7.21). The discharge piping system, normally filled with water to the nozzle, delivers the water for distribution to the hazard. The pilot piping system applies pressure onto a poppet valve in such a way that water in the discharge system, in its standby state, is prevented from flowing through the nozzle. The nozzles are located as close to the hazard as possible. Release of pilot pressure allows the deluge system to overcome the pressure differential, forcing the poppet valve up and initiating instantaneous discharge.

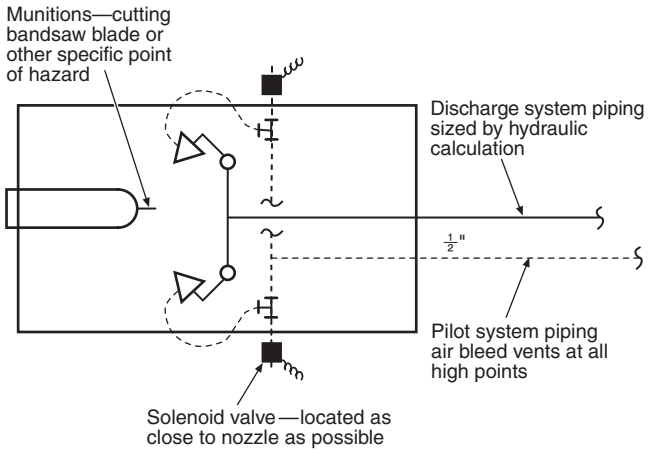


FIGURE 16.7.20 Plan View

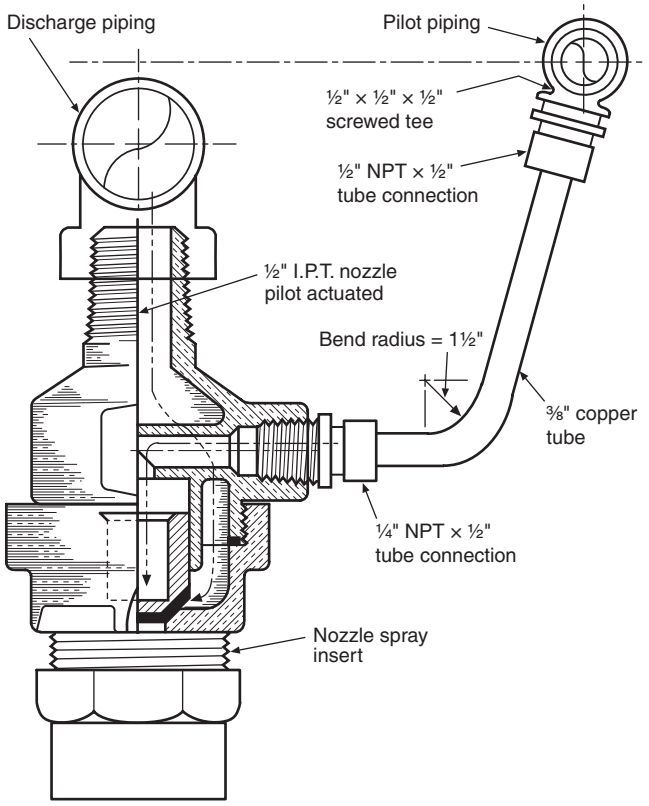


FIGURE 16.7.21 Pilot Connection

Pilot-actuated nozzles are capable of accepting inserts that allow custom designing of water application to the specific hazard in question. Discharge piping can be gridded when an area protection concept is employed. A strainer is required on the main riser of the discharge system to minimize debris that may accumulate between the poppet and the poppet seat and may cause leakage from the nozzle and possible system actuation. Sloping of the discharge system to air vents will serve to purge air from the discharge system and reduce system discharge time. Discharge and pilot piping is required by NFPA 15 to be sloped a minimum of 1 in. (25.4 mm) per 10 ft (3.1 m) of pipe.

Pilot System. The pilot system is monitored by normally closed two-way solenoid valves spaced throughout the system (Figure 16.7.22). Ideally, a solenoid valve should be provided for every pilot-actuated nozzle, but in certain cases one solenoid valve could control up to three nozzles. Engineering judgment must be exercised in determining a solenoid-to-nozzle ratio, since the response time increases as the distance between the pilot-actuated nozzle and the solenoid increases. Solenoids should be equipped with an enclosure-rated NEMA type 4 (watertight), NEMA type 7 (hazardous locations Class I, Group C or D), and NEMA type 9 (E, F, or G hazardous locations, Class II, Group E, F, or G). Detectors and detector housings should be rated for Class I and Class II locations.

It is essential that every effort be made to minimize air pockets in the pilot line, with piping radically sloped to air vents placed at all high points, facilitating the bleeding of air from the pilot system and enhancing the speed of reaction. The pilot line slope should be equal to or greater than the discharge piping slope, but should not be less than 1 in. (25.4 mm) per 10 ft (3.1 m) of pipe. For best results, keep branch lines and their associated pilot lines very short and slope them as radically as possible.

Air in the pilot line is of paramount concern because of its effect on the function of the pilot valve operation. The larger the air cushion, the longer the delay in response time. An automatic air vent is an option (Figure 16.7.23). To protect the solenoid orifices, a strainer must be installed on the pilot line feed.

The two systems of piping (i.e., pilot line and discharge) can be simultaneously pressurized by an excess pressure pump or some other pressure maintenance device, with static system pressure normally ranging from 170 to 180 psi (1172.2 to 1241.1 kPa), with a relief valve and pressure-limiting switch ensuring this range. An elevated gravity tank with a minimum static pressure of 75 psi (517.13 kPa) may provide acceptable response times. A specially designed orifice union in the pilot line maintains the pressure ratio necessary to keep the pilot-actuated nozzles open and allow smooth operation of all solenoid-

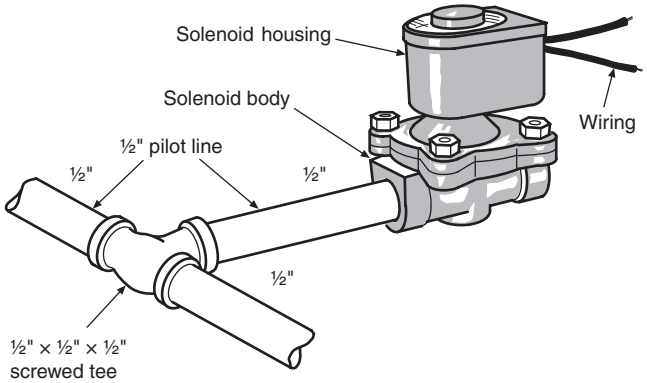


FIGURE 16.7.22 Solenoid Valve

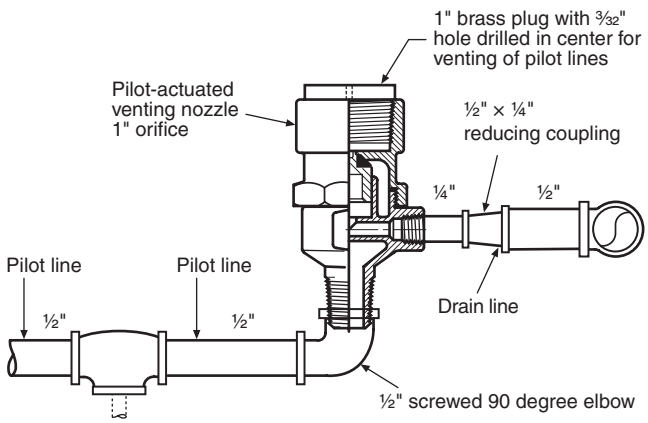


FIGURE 16.7.23 Automatic Pilot Vent

operated valves. The orifice retards the rush of pilot pressure so that the solenoids can exhaust enough water to permit full and even opening.

The Detection System. UV, IR/IR, and UV/IR detectors currently used on the pilot-actuated systems shown in Figures 16.7.24 and 16.7.25 comprise an extrasensitive detection tube housed in a stainless steel, brass, or aluminum explosionproof housing. The detector is mounted on a swivel base to give maximum field adjustment up to an angle of 240 degrees. Most UV and IR detectors have a field of vision between 80 and 90 degrees.

Flame detectors are installed as close to the points of anticipated hazard as practicable and angled and spaced so that all areas where the volatile substance might be found are observed by the detectors. Placement of detectors on an ultra-high-speed water spray system requires experienced judgment and thorough field inspection.

Fire Alarm Control Unit. The control unit, with its sensitive high-speed modules, is kept in a protected area remote from the hazard, usually an area classified safe for nonexplosionproof equipment. Where it is necessary or required to install the control unit in the hazard area, it must be installed in a rated enclosure. The detector, module, and control unit system are specifically designed and customized for the hazard in question. The primary concern of each component is speed, and, as a result, the telemetry system is considerably faster than the systems of the early 1960s. The control system is designed to provide supervision over all electronic devices.

A fire alarm control unit that is placed outside or otherwise exposed to the elements must be installed within a weatherproof enclosure. It is possible that a weatherproof enclosure might be needed for an interior location if it is possible that roof leakage, sprinkler discharge, or other potential waterflow could enter the control unit.

The control unit should include a controller, high-speed modules, control relays, a lamp test push button, trouble silence switch, panel reset button, ac power fail light, waterflow lamp, tamper switch fault lamps, alarm lights, and indicators for special functions for pumps and tanks, with terminals for other functions, if required. The controller powers and monitors the ultraviolet detectors and their signals and notifies the high-speed modules of a trouble or fire signal from the detectors. The high-speed module receives a signal from the controller and will operate the high-speed solenoids on receipt of a fire signal, thus purging the pilot system of hydraulic pressure and opening the nozzles. An example of a currently manufactured ultra-high-speed water spray system module is the Response Acceleration Module (RAM), shown in Figure 16.7.25.

Control relays supervise gate valves, pressure switches, alarm bells or other notification appliances, and the control unit operation. Electrical contacts can be provided for customer functions, such as shutting down equipment. An automatic reset capability option allows the high-speed module to cease water

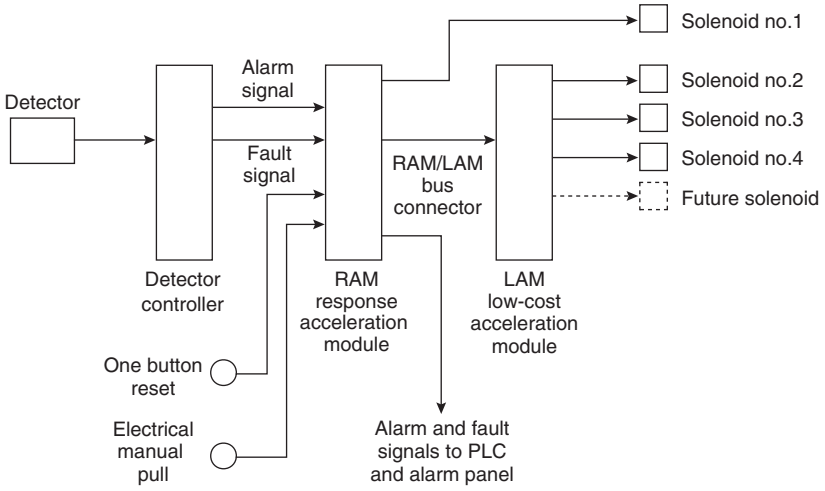
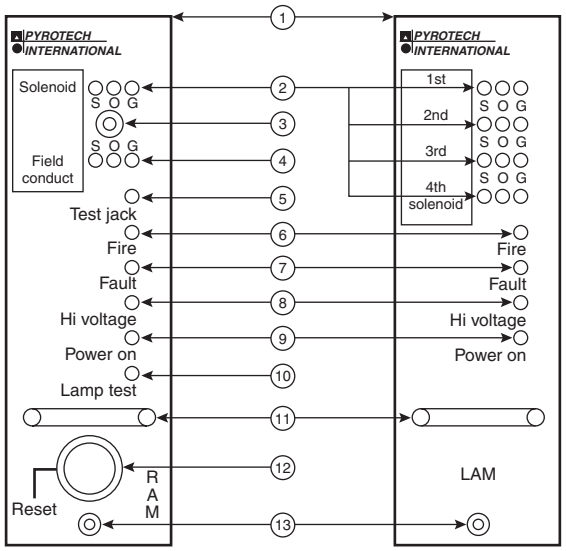


FIGURE 16.7.24 Pilot-Operated Electrical Flow Diagram (Source: Pyrotech International)



1. RAM/LAM frontplate
2. RAM/LAM short, open and ground solenoid status
3. RAM reset timing adjustment
4. RAM short, open and ground field alarm contact status
5. RAM response time test jack
6. RAM/LAM fire LED
7. RAM/LAM fault LED
8. RAM/LAM high-voltage LED (normally on)
9. RAM/LAM power on LED (normally on)
10. RAM lamp test button
11. RAM/LAM service handles
12. RAM reset/bypass key switch (normally in vertical position)
13. RAM/LAM fastener cap screw (4 mm)

FIGURE 16.7.25 RAM/LAM Frontplates (Response Acceleration Module) (Source: Pyrotech International)

distribution after a predetermined period of time (usually 2 minutes), provided that the detectors no longer view a hazard. Electric push buttons and LED indicators annunciate the control functions of the panel and display the status of the pilot-actuated system. The control unit should be equipped with a capability for resetting the solenoids automatically from the unit, eliminating lengthy system shutdowns.

A battery charger recharges the batteries when needed and rectifies the 120 V ac input power to 24 V dc for system use. Upon loss of primary 120 V ac power, the charger will transfer to the secondary 24 V dc battery supply.

Sequence of Operation for a Pilot-Actuated System

The flame detectors constantly view the hazard areas, searching for changes in light intensity. The status is reported to the controller for analysis. Light intensities are screened by the detectors' ability to recognize common signals, such as house lighting and sunlight. Physical screening may be necessary to prevent detector signals from such intermittent light sources as welding torches, lightning, or sun reflecting from the windshield of a car.

Upon detection of a valid signal, the controller, constantly interpreting system status, receives the signal. The signal is interpreted and relayed to the appropriate high-speed module. Indicator lights and indicating devices commence operation, and a signal is sent simultaneously to all the high-speed solenoids on the system.

The normally closed solenoids open, allowing water to flow through the solenoids, thus purging the pilot system of water and relieving the pilot pressure. The pressure drop allows the poppet valves in the pilot-actuated nozzles to move, allowing water to flow through the nozzle and onto the hazard, as shown in Figure 16.7.26 and Figure 16.7.27. The pilot-actuated nozzle insert directs the waterflow into a wide-, medium-, or narrow-angle spray. Minimum static pressure at each nozzle should be no less than 50 psi (344.75 kPa), with 180 psi (1241.1 kPa) strongly recommended.

Factors Influencing Speed of a Pilot-Actuated System

There are many variables that can enhance the speed of a pilot-actuated system, and all are considered in each engineered layout. For example, trapped air in the pilot line can be a significant hindrance to the hydraulic evacuation of the pilot line. To prevent this, the pilot line is sloped as radically as possible, with air-release vents, either manual or automatic, at all high points of the pilot system. It is a common practice to bleed air from the system after it is reset and repeat the process at the start of the next working day to ensure that all air is removed from the system.

Excess system volumetric capacity of a pilot-actuated system is a substantial contributor to increasing the response time of the system. It is important to maintain a maximum system volumetric capacity of less than 500 gal (1892.5 L), as required by NFPA 15. Where response times of less than 100 milliseconds are required, it may be necessary where possible to subdivide the systems such that the maximum number of nozzles on a single system is about 10. It is also advantageous to minimize the number of fittings and changes of water direction and to minimize the length of the feed main to the system.

The distance from the solenoid valve on the pilot line to the pilot connection of the pilot-actuated nozzle can be a major factor in the speed of evacuation of the pilot line. The ideal situation would be to place a solenoid on the pilot line adjacent to each nozzle. This would release the pilot pressure to the noz-

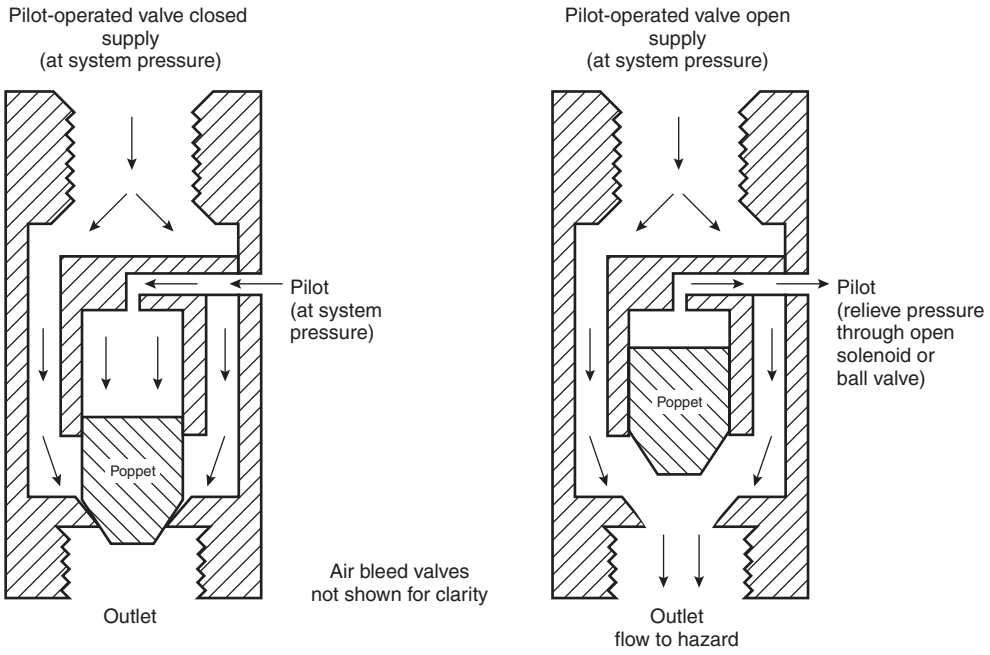


FIGURE 16.7.26 Modern Pilot Valve Operation (Source: Pyrotech International)

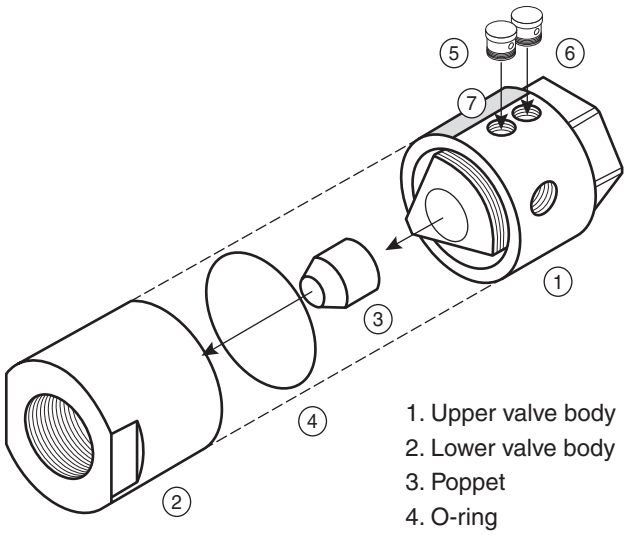


FIGURE 16.7.27 Pilot-Operated Valve (Source: Pyrotech International)

zle almost immediately, and evacuation of the entire pilot line would not become a factor. When large systems are necessary, it may be electronically impractical to provide a ratio of one solenoid per nozzle.

System pressure can be a major factor in response time. An excess pressure pump can be provided for each system or group of systems to maintain 170 to 180 psi (1172.2 to 1241.1 kPa) static pressure on the system piping and pilot line. Pressure of this magnitude at each nozzle provides the impetus for rapid evacuation of pilot pressure and rapid delivery of water to the hazard. Another alternative is the use of an elevated gravity tank that would provide a minimum of 75 psi (517.13 kPa) static pressure on the system. An orifice restriction device, either an orifice union or a drilled ball valve, is placed in the pilot line at the riser to maintain proper functioning of the pilot valves. Once the solenoids open, residual pressure drop in the pilot line is minimized by this restrictor, increasing the speed of pilot evacuation. The diameter of the pilot line can also be a factor in pilot evacuation. For short runs of pilot piping, ½ in. (12.7 mm) galvanized steel pipe is sufficient, with a very short run of ⅜ in. (9.5 mm) internal diameter copper piping for the nozzle pilot connections.

To increase the speed of solenoid actuation, the initial voltage provided to the solenoids from the panel, upon receipt of a signal from the detectors, should provide delivery of a high-voltage signal, enhancing the solenoid operating time. Although the voltage eventually levels off to 24 V dc, which is the normal control system operating voltage, the initial burst of energy may damage solenoids rated for less than the maximum voltage encountered.

No less than 25 gpm (95 L/min) per nozzle is required by NFPA 15 to be designed for point protection, nor less than 0.50 gpm/ft^2 (20.37 L/min·m^2) of exposed area for area protection. Point protection should be accomplished with no fewer than two counteropposed nozzles per point of likely ignition, and area protection should be accomplished with a nozzle spacing of between 30 and 60 ft^2 (2.8 and 5.6 m^2), depending on the configuration of the hazardous commodity or process.

Counteropposition of the nozzles involves nozzles aimed from differing directions at a common point. Some commodities, such as certain pyrotechnics, may require densities as high as 3.0 gpm/ft^2 (122.24 L/min·m^2).

Response Time for Pilot-Actuated Systems

Specifications written for pilot-actuated systems mandate a response time not to exceed 100 milliseconds, measured from presentation of an energy source to the detector to water discharge from the most distant pilot-actuated nozzle. Whenever possible, travel time for the water to hit its intended target should be included in the total response time. Research is ongoing that would evaluate and further define this time span.[1,6] The specifying engineer should evaluate test data and lower the required response time where warranted.

Method of Timing Response of a Pilot-Actuated System

The following procedure can be used to perform a functional time test of a pilot-actuated system:

1. Install a pressure switch on the nozzle being tested. Each nozzle on the system must be tested to ensure that the solenoids are functioning properly and that operation speeds are being maintained at each nozzle.
2. Slowly fill the system piping.
3. Bleed all air from the pilot system through air vent valves. Opening these valves too quickly may operate the system.
4. Close the air vent valves and record the static system pressure at the riser.
5. Connect the timer to the nozzle pressure switch and to the timing test jack on the RAM or high-speed module. High-speed photography is also an effective timing device.
6. Take three consecutive readings for each system.
7. Record the static pressure at the riser before and after each test.
8. A UV light source will be used to activate a UV detector for the system being tested. UV, IR, and UV/IR testing lamps for tripping ultra-high-speed water spray systems are commercially available.
9. An electrical impulse from the RAM time test jack will start the timers.
10. Two timers should be used in order to ensure accuracy.
11. The timers will be stopped by the water discharge reaching the pressure switch.
12. Record the test results, including residual pressure at the riser.
13. Reset the system at the control panel.

It has been found that when an ultra-high-speed water spray system has been discharged repeatedly, response times usually increase somewhat. This is the result of air bubbles created by the rapid movement of water through the piping collecting into pockets of air in critical segments of the piping system. When this phenomenon is identified through the observation of repeated declining response times, it may take several hours to permit air bubbles to migrate to positions in the piping where they can be completely expelled through the air bleeders.

Other Applications for Pilot-Actuated Systems

Although munitions provide the largest share of current pilot-actuated system applications, this system has been used with a preset timer to limit discharge to protect valuable commodities such as mail conveyors and chutes, ovens, and antique book storage facilities. Where enhanced system response is desired, but where a 100 millisecond response time is unnecessary, the system can be modified to resemble the early pilot-actuated system with thermal, pneumatic, or electric detection and standard control modules.

PORTABLE SYSTEMS

Portable ultra-high-speed water spray systems shown in Figure 16.7.28 have been created to supply cost-efficient, mobile, short-term protection for U.S. Army ammunition plants and other facilities requiring enhanced actuation times for exposed energetic materials.[7] This system is a portable, self-contained fire detection and suppression system capable of delivering water to the nozzles within 50 to 100 milliseconds from time of detection and can protect an area up to 100 ft^2 (9.3 m^2). The system features UV detection with a high-speed controller, a solenoid-actuated deluge valve, and a portable pressurized water storage tank that is capable of being temporarily cross-connected to a building water supply, if available.

Some portable ultra-high-speed water spray systems for use in explosive production facilities are supplied with 20 ft (6 m) extension hoses and are capable of reacting to a fire in less than 50 milliseconds. Reaction time interval is the time from the point of detection to flow at the nozzle. Because of their mobility, the portable units are well suited for use on short production runs where a fixed system is not practical. They can be rolled by one person and are designed with channels for forklift transport. Some units are of a size that allows them to be rolled through a

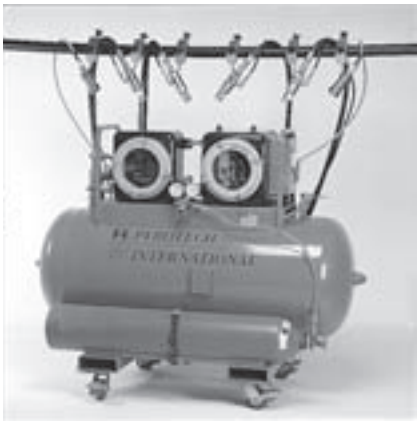


FIGURE 16.7.28 Portable Ultra-High-Speed Water Spray Systems (Source: Pyrotech International)

36 in. (91 cm) door with water tank capacity up to 100 gal (397 L) pressurized by a nitrogen bottle.

Units are provided with supervised ultraviolet detectors, solenoids, and pilot-operated valves, with tank pressure and water level also supervised. An integral power supply/charger and battery pack are normally provided. Electrical components should be housed in explosionproof enclosures with appropriate ratings. All necessary controls for normal operation (power switch and reset switch) are located on the outside of the explosionproof enclosure. The system could be reset with a switch or by means of automatic reset.

Applications for portable units include the following:

- Explosive or pyrotechnic spills, in which case the portable unit could be rolled into the hazard area and used to protect an area during the cleanup operation, where fixed fire protection may not normally be present
- Hazards for which there is not sufficient time or funding to install fixed fire protection quickly enough to satisfy the need
- Depot rework, where maintenance or operations often change and machinery is moved or replaced with different equipment. In some cases, fixed systems may not be practical from an operational, safety, or economic standpoint.
- Machining, milling, blending, or drying, where the portable unit could be attached to the machinery
- When the existing fixed system is shut down and production must go on; portable units can bridge the time involved in getting fixed systems back on line
- Cleanup and decontamination operations, when equipment is torn down or if there is fear of residual explosives. This presents one of the more hazardous conditions for operators at explosives facilities.
- Evaluation and burn testing of the design of fixed fire protection systems to prove the effectiveness of such configurations. This system would allow for easy modification and variations providing more comprehensive test results.
- Research, evaluation, and quality control laboratories. Hazards often vary in severity as do the processes and material to which the technicians are exposed. In most cases, the energetic material has known properties such as sensitivity to spark, friction, or impact. Sometimes in the case of experimental compounds the properties (possibly hazardous) are unknown. In either case, it would be advantageous to be able to roll in a portable unit to protect personnel and equipment. Processes in the laboratory environment are also quite likely to change, for example, blending, mixing, granulating, extruding, and drying. Changing operations (if hazardous) require an adaptable explosion or fire suppression system. Although personnel are more highly skilled and quantities often much smaller, the explosives laboratory can be a hazardous environment and in some cases warrants the use of such a system.
- Temporary depot and staging areas, possibly offshore or overseas, where fixed deluge systems could not have been considered possible because of installation time, lack of water supply, or varying processes
- Temporary storage protection for in-process work, in the situation of production overruns where surplus munitions ingredients must be stored and normal adequate fire protection is not available, or in the case of rejected production runs where the product must be stored until it can be reworked or destroyed
- Additional backup for existing systems or unforeseen changes in process

Additives can be included with the water supply. Antifreeze and wetting agents or water coloring may be added to help evaluate different spray patterns utilizing high-speed video (for added clarity). Possible advantages of water gels, "sticky water," could be tested.

Portable units can be moved to a shop or maintenance area for service, allowing them to leave the restricted (hazardous) area. Nozzles with different spray patterns can be adapted, moved, and configured depending on operation.

EXPLOSIVE SPHERE-HIGH-RATE-DISCHARGE (HRD) DEVICES

The explosive sphere-HRD-type device (Figure 16.7.29) is for rapid response deluge suppression in the munitions and explosives industries. It is an explosive squib-operated, high-pressure vessel (400 psi [27.579 bar]) with a rupture disk. It is compatible with all forms of high-speed detection and is actuated by the DDAM (Dual Detonator Acceleration Module) (Figure 16.7.30). Although the sphere-HRD-type device can achieve a reaction time under 15 milliseconds, it is limited to approximately 7 gal (26.5 L) of flow. For this reason, it is not a stand-alone device and must be used in conjunction with other rapid response deluge systems. These devices are often used for point protection.

When designing such systems, consideration must first be given to bringing explosive devices into a hazardous location to arm and reset the sphere. A source of high-pressure inert gas must also be available to prime the sphere-HRD-type device.

When a detector sends an alarm signal to the appropriate DDAM, the squib in the sphere-HRD-type device is detonated,

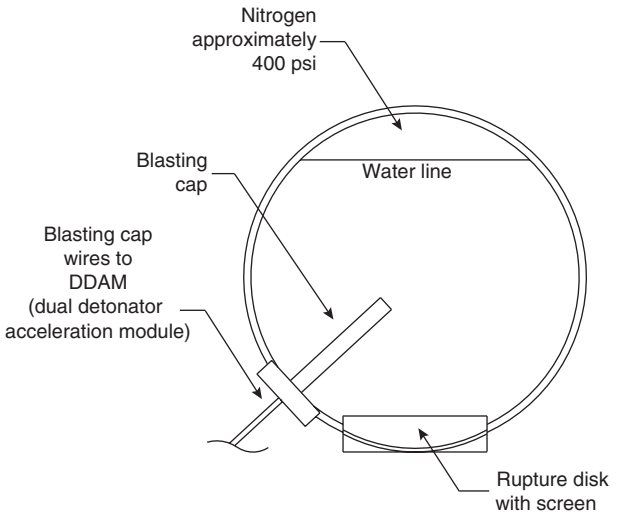
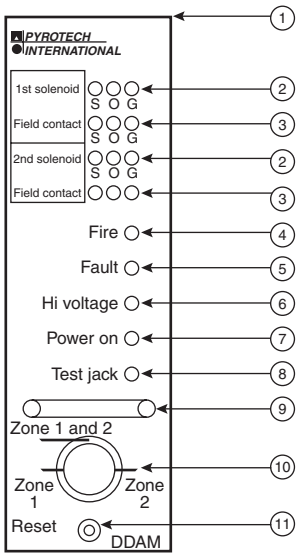


FIGURE 16.7.29 Explosive Sphere-HRD-Type Device (Source: Pyrotech International)



1. Frontplate
2. Short, open, and ground solenoid status or normal, open, and ground squib status
3. Short, open, and ground field alarm contact status
4. Fire LED
5. Fault LED
6. High-voltage LED (normally on)
7. Power on LED (normally on)
8. Response time test jack
9. Service handle
10. Reset/bypass key switch
11. Fastener cap screw (4 mm)

FIGURE 16.7.30 DDAM (Dual Detonator Acceleration Module) Frontplate (Source: Pyrotech International)

the rupture disk is broken, and the high-pressure chamber is emptied. Simultaneously, backup deluge is also discharged to the hazard. Even though the backup deluge may reset automatically, the sphere-HRD-type device must be reset manually. Sphere-HRD-type devices are squib actuated. Response time testing of the sphere-HRD-type device is best accomplished by the use of high-speed video.

EXPLOSION SUPPRESSION SYSTEMS

The first explosion suppression systems were introduced by the British in the late 1940s for protection of aircraft and were later extended to industrial use. Explosion suppression systems consist of a cylinder filled with a suppressing agent, a detection system, and a system of control circuitry. They can ordinarily be visually differentiated from ultra-high-speed water spray systems by their lack of system piping, by the existence of uniquely shaped agent containers, and by the use of a wide variety of agents, including water, that can be employed with such systems. Halon, which was once a commonly used agent for explosion suppression systems, has been scheduled for elimination by the Montréal Protocol.[8] A clean agent or halon substitute, in accordance with NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems,* may be required for a new explosion suppression system. Explosion suppression systems are designed in accordance with NFPA 69 to protect enclosed vessels or containers from rupture due to overpressurization resulting from a deflagration.

EXPLOSION VENTING

An enhancement to the effectiveness of an ultra-high-speed water spray system or an explosion suppression system is explosion venting. These passive vents are sometimes used in lieu of an ultra-high-speed water spray system or an explosion suppression system. Venting, however, will relieve pressure without any active effort to control the continued burning of the fuel in the hazard area. Care must be taken to avoid placing explosion venting louvers in a location where an operator or passerby could be injured by an explosion relief blast. NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* should be used when designing an explosion venting system.

An alternative to a suppression system could be to provide no protection of any kind. In a facility with an enclosed and separated or isolated automatic process that is normally unoccupied, where vessels are manufactured with sufficient strength to withstand overpressurization resulting from a deflagration, or where there is enough process redundancy to avoid process stoppage, a firm may consider the option of no protection. Repair or replacement of a process area, the spreading of fire or blast damage to adjacent areas with a corresponding result of possible deaths or injuries, unfavorable publicity, and loss of income could prove to be significantly more costly than an ultra-high-speed suppression system or an explosion suppression system.

RESEARCH AND DEVELOPMENT

The Air Force Research Lab's (AFRL) Fire Research Group at Tyndall Air Force Base, Florida, has been working to invent a more effective deluge system capable of stopping high-velocity fires caused by deflagration of explosives, propellants, and pyrotechnic materials. Initially, a system similar to that described in the section on explosive sphere-HRD-type devices was used. Compared to the NFPA requirement of 100 millisecond response from detection to initiation of waterflow, AFRL's Advanced Fire Protection Deluge System (AFPDS) reduced response time to about 8 milliseconds (6 milliseconds detection time and 2 milliseconds initiation time) and put water on a fire 36 in. (0.9 m) away from the nozzles in 18 milliseconds. Close behind, back-up water from a pressurized tank with solenoid-operated nozzles reached the fire in about 130 milliseconds. In 100 trials using ¼- to ½-lb (0.113- to 0.226-kg) samples of various pyrotechnic materials, most fires were extinguished by the initial water from the explosive sphere-HRD device, and the back-up water was redundant.

Effective as the AFPDS is on most propellants and pyrotechnic materials, it is not fast enough to stop fires from the fastest burning materials, exemplified by magnesium-Teflon pyrotechnic flare material. A new phototransistor-circuit flame detector was developed that cut detection time from 3 to 5 milliseconds to less than 1 millisecond, and a novel deluge system, the blast-initiated deluge system (BIDS), was developed that discharged water at nearly 500 ft/sec (152.4 m/sec). The heart of the BIDS consists of a steel cone set inside a steel cylinder (Figure 16.7.31). On detection of a fire, the controller sends an electrical signal to a small explosive charge fixed at the apex of the cone. Detonation of the charge causes a rapid rise in pressure inside the cone that forces the initial water out a burst disk and onto the fire. Holes in the side of the cone allow follow-on water

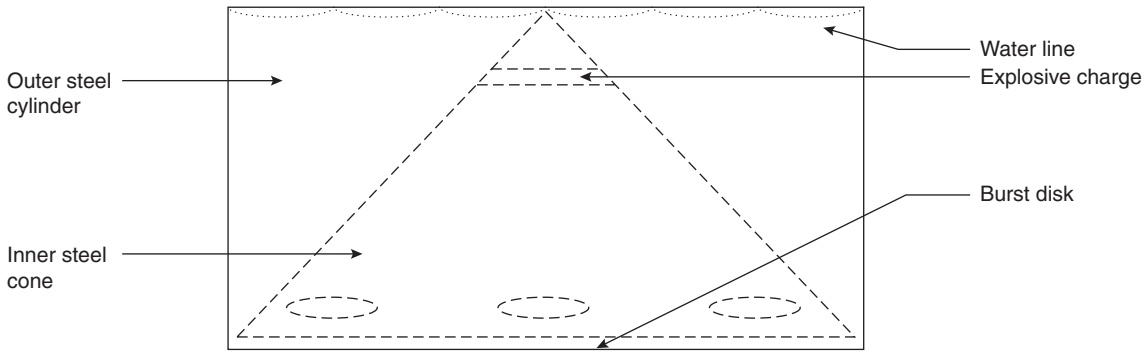


FIGURE 16.7.31 Blast-Initiated Deluge System (BIDS)

to flow through the cone and onto the fire. The BIDS reduced time from detection to water on a fire 36 in. (0.9 m) from the nozzle to 7 milliseconds, as compared to about 26 milliseconds for the AFPDS, and 130 milliseconds or longer for solenoid-activated systems. The BIDS extinguished 1 lb (0.453 kg) samples of magnesium-Teflon in an average of 15 milliseconds and 4 lb (1.81 kg) samples in 40 to 50 milliseconds, and significantly reduced heat flux levels.

SUMMARY

A major difference exists between ultra-high-speed water spray systems and explosion suppression systems. Even though both systems suppress explosive hazards, ultra-high-speed water spray systems are used predominantly for open machine protection or room area protection, whereas ultra-high-speed explosion suppression systems protect enclosed vessels. Although system names are sometimes used interchangeably, this chapter helps clarify correct terminology.

There is relatively little information available on practical testing of various munitions manufacturing explosive levels for differing munitions commodities and processes. However, years of successful field performance and experience, as well as system time and reliability testing demonstrate the effectiveness of ultra-high-speed water spray systems with respect to the suppression of munitions explosive hazards. Artificial retardation of the normal actuation times of ultra-high-speed water spray systems means the difference between extinguishment and total loss of control in the explosive process. A comparison of ultra-high-speed water spray systems is shown in Table 16.7.3.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on ultra-high-speed water spray systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 18, *Standard on Wetting Agents*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 22, *Standard for Water Tanks for Private Fire Protection*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 72®, *National Fire Alarm Code®*

TABLE 16.7.3 Comparison of Squib-Operated, Pilot-Operated, Explosive Sphere-HRD, and Portable Deluge Systems

	Squib-Operated	*Pilot-Operated*	*Explosive HRD*	*Portable*	
Complete electrical supervision		*		*	Solenoids are supervised for shorts, opens, and grounds. On a squib-operated system the igniter wire can be supervised but condition of explosive is not known.
Response time not affected by air in supply pipe		*	NA	*	Due to low-pressure prime and the remote location of the valve, air in the piping of a squib-operated valve can cause slow and fluctuating response times.
No recurring cost or replacement parts needed after each firing		*		*	After firing of the squib-operated systems, disc or caps must be replaced and explosive devices reinstalled. Nitrogen or other inert gas must be accessible to recharge a sphere-type device.
Programmable automatic reset feature available		*		*	An optional automatic reset feature is available. This allows automatic system reset after a present time as long as no fire is present.
System does not require explosives for operation		*		*	Pilot-operated valves do not present the problem of bringing explosives (squibs) into the hazard area.
System can be reset and back on line in less than 30 seconds		*		*	Primac and HRD-sphere type devices may require caps, discs, squibs, blocks, or pins
Limited shelf life of components	*		*		Squibs have a shelf life and should be periodically replaced.
Requires pilot line piping		*		*	Pilot line connections are necessary for pilot-operated valves to function.
Mechanical manual operation available		*		*	Mechanical manual release is possible even in the event of total power failure (including loss of primary power and battery backup).
Each head acts as an individual deluge valve (safety through redundancy)		*		*	The system does not depend completely on one device for operation. Redundancy of solenoids and valves provides a more reliable system.
Response time not affected by system size		*	*	*	Since each nozzle can be considered an individual deluge valve, system size does not affect response time.
Compatible with all forms of detection	*	*	*	*	Systems can be interfaced with any of the available detection devices.
System can be preprimed with high pressure		*	*	*	Since valve is at the nozzle, a high-pressure prime can be accomplished.
Unlimited available water supply	*	*		*	HRD-type devices require backup systems to be in place. Portable deluge may be connected to existing supply. A backup system must be fast enough to provide full waterflow before HRD system empties (approximately 250 milliseconds).
Nozzles can be directed very close to the hazard	*	*		*	Due to the size of the HRD-type devices, it may be physically impossible to locate the HRD close to the hazard. Water travel time may greatly compromise safety.
Adapts to various response time test equipment	*	*		*	HRD-type systems can only be response time tested by use of high-speed video.
Contaminants discharged with deluge	*		*		Squib and HRD-sphere type systems may contain debris from rupture discs, blasting caps, and/or blasting cap holders.

NA = Not available.

Source: Pyrotechnic International.

NFPA 77, *Recommended Practice on Static Electricity*
NFPA 495, *Explosive Materials Code*
NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*

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Chapter 8

Water Mist Fire Suppression Systems

Jack R. Mawhinney

Chapter Contents

Applications of Water Mist Systems
Summary of Water Mist System Features
General Principles of Water Mist Systems
Design of Water Mist Systems
Methods of Generating Water Mist
Design Calculations for Water Mist Systems
System Types
System Components
System Water Supply and Atomizing Medium Considerations
System Maintenance Considerations

Key Terms

atomization, constant pressure system, declining pressure system, drop size distribution, enclosure effects, fire test protocols, flame cooling, local application, nozzles, oxygen displacement, positive displacement pump, radiant heat blocking, single fluid, spray momentum, thermal management, total flooding, tunnel fire protection, twin fluid, vapor dilution, water mist, water vapor

Interest in the use of very fine water sprays (water mist) in fire suppression systems has been intense for the last 15 years. The economic force behind this interest has been driven by two major fire protection needs. First, in the early 1990s the international maritime regulatory organizations mandated the installation of sprinkler systems on passenger ships. This mandate inspired a search for a system that could be considered equivalent to sprinklers but that would discharge less water, use smaller-diameter piping, have lower overall weight than a standard sprinkler system, and hopefully cost less. The second driving force was the need to find a replacement for ozone-depleting substances such as the halons, which had been used for decades to protect machinery spaces, flammable liquids rooms, computer rooms, and rooms for materials sensitive to water damage. The halon alternative search included the possibility of using water in applications where water was not previously considered practical. Thus, a technology that could minimize droplet size and application rate, enhance evaporation, and help reduce oxygen levels to extinguish hidden fires began to have marketable value.

Spurred by receptive market conditions, innovative fire suppression systems have been conceptualized, tested against specific fire scenarios, and installed as working systems. A large number of the world's passenger ships are now equipped with marine water mist systems. Much of the early work in developing fire tests and performance criteria occurred in Europe at laboratories such as SP in Sweden, SINTEF in Norway, VTT in Finland, and the Danish Fire Research Institute. In North America, practical research was conducted in Canada at the National Research Council National Fire Laboratory and in the United States by Hughes Associates, Inc., with U.S. Navy and Coast Guard support. In 1993, the National Fire Protection Association (NFPA) began work on a design and installation standard, NFPA 750, *Standard on Water Mist Fire Protection Systems,* to consolidate design concepts emerging from the research and development work. In the last decade a number of European companies have obtained approvals from North American listing agencies such as FM Global Research and Underwriters Laboratories (UL) for machinery spaces, turbine enclosures, and wet benches. Several North American fire protection manufacturers have developed specialized water mist equipment with their own nozzle designs. There are now formal fire test protocols not only for marine applications, such as machinery rooms, turbine enclosures, accommodations, public spaces, and service areas, but also for land-based applications involving very large machinery spaces, local application systems, light and ordinary hazard applications, and "wet benches" for electronics manufacturing. Although the marine market for water mist systems remains the strongest, there is a steady growth in land-based applications.

The first chapter on water mist technology appeared in the 18th edition of the *Fire Protection Handbook* released in 1997. Since then, the technology has advanced from "potential" to "actual." There are installed systems in process modules in the Alaskan oil fields and in heritage buildings, hotels, art galleries, and computer rooms worldwide. Experience with design, installation, commissioning, and maintenance of systems has advanced steadily. The handbook chapter has been revised to reflect the changes and advances made. It must be noted that the growing experience

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has not changed one important factor in water mist system design. As indicated in the first edition, there still is no generalized "first principles" approach to design of water mist systems. Design criteria for each manufacturer's equipment are determined through full-scale fire testing to internationally recognized test protocols. The flux densities differ sufficiently among manufacturers so that one cannot enforce a single generic criterion on all manufacturers. Full-scale testing continues to be justified.

This chapter reviews the salient features of water mist fire protection systems. It discusses the general extinguishing mechanisms and the influence of fuel type and compartment conditions on effectiveness. The chapter provides details on the components, types of systems, calculation methods for single- and twin-fluid systems, pump selection and application of positive displacement pumps, and maintenance issues.

For related topics, see the following chapters in Section 16: Chapter 1, "Principles of Automatic Sprinkler System Performance"; Chapter 2, "Automatic Sprinklers"; and Chapter 3, "Automatic Sprinkler Systems."

APPLICATIONS OF WATER MIST SYSTEMS

Before discussing the details and general principles of water mist systems, it is instructive to review several applications of water mist systems. Some of the applications have been studied in detail by various technical groups seeking to develop consensus fire test protocols to set design criteria. Others were developed through ad hoc testing by a group interested in solving a specific problem. The following examples represent the proving ground for water mist fire suppression systems technology.

Machinery Spaces

Fires in machinery compartments involve diesel fuel and lubricating or hydraulic oil spills, ignited by hot engine parts, overheated bearings, or electrical arcing. Pool or spray hydrocarbon fires can be fast developing, very hot, and have the potential to cripple or destroy a ship. International shipping safety regulations, developed by the International Maritime Organization (IMO) and as written in the rules of SOLAS (Safety of Life at Sea), have for many years required that machinery spaces on large vessels be equipped with either CO_2 or halon fire suppression systems. With the phase-out of halon and increased awareness of the safety hazard that CO_2 represents, there is strong interest in finding an alternative fire suppression agent for machinery compartments on ships. Further incentive for improved suppression systems for machinery spaces comes from IMO regulation enacted in the 1990s that required all ships capable of carrying more than 36 passengers to be equipped with automatic sprinkler systems by 1997. Where the necessary pumps and water supplies must be provided for general sprinklering of the ship, the use of a water-based suppression system in lieu of a gaseous agent in the machinery space becomes economically viable. The requirement to retrofit existing ships with sprinkler systems raised concerns, however, about creating stability problems due to adding weight of piping or large volumes of water to the superstructure of a ship. Those potential problems could be addressed by water mist fire suppression systems that promise to use small-diameter piping and deliver minimum quantities of water.

The potential to use finely divided water sprays to suppress hydrocarbon pool and spray fires has been known for some time, at least since the 1950s.[1,2] Since 1990, a number of companies have developed water mist systems for marine machinery compartments, in which the primary fire hazard involves hydrocarbon spray or pool fires. The International Maritime Organization (IMO) test protocols and amendments dating from 1994 and 1996 established the baseline for machinery space water mist fire suppression systems (IMO MSC/Circular 668: Alternative Arrangements for Halon Fire Extinguishing Systems in Machinery Spaces and Pump-rooms).[3,4] The tests address liquid fuel fires in machinery compartments of 500 m^3, main diesel machinery in spaces up to 3000 m^3, and in larger-volume diesel machinery spaces on oil tankers and container ships. These test protocols are described in NFPA 750. There are 13 test scenarios involving shielded pool and spray fires of different size around a mockup of a diesel engine. There is a void space under the diesel mockup intended to simulate a bilge space with a shielded fire. There is also a 2 m by 2 m ventilation opening in the lower quarter of the test compartment. In order to pass the IMO test protocol a water mist system must extinguish all 13 of the test fires, from the largest 6 MW spray fire to the smallest pool fire (500 kW) within 15 minutes. The test fires involve both low- and high-flashpoint hydrocarbon fuels. One test involves a small wood crib and heptane igniter. Since 1999, the International Maritime Organization has issued test standard IMO MSC/Circular 913[5] for local application systems to protect specific equipment in large machinery spaces. In 2005, IMO produced MSC/Circular 1165,[6] which sets criteria for water mist systems for very large machinery spaces, for example, up to 3300 cubic meters. IMO MSC/Circular 1165 includes most of the fire tests used in MSC/Circular 668 but eliminates the need to extinguish the very smallest fire.

Experience has shown that extinguishing large fires in a compartment with limited ventilation is relatively easy.[7–9] A large fire consumes oxygen and generates enough heat to convert water droplets to water vapor, reducing the oxygen concentration in the compartment. The fire extinguishes itself due to oxygen starvation. Small fires are more difficult (take longer) to extinguish, because they do not consume the available oxygen fast enough (relative to the inflow through the ventilation opening), nor do they generate enough heat to evaporate much of the water mist.[7] For these reasons the IMO machinery compartment tests become increasingly difficult to pass as the compartment becomes larger and the fires become smaller. The IMO test protocol requires full extinguishment of all fires. Systems that have passed the IMO machinery space test protocol are permitted to utilize combinations of total flooding ceiling nozzles and screening nozzles over the ventilation opening, as well as the addition of a surfactant to the water supply. To a certain extent the successful system designs may be customized to pass the IMO test specifically. Some systems may be dependent on controlling the ventilation through the specific ventilation opening. If the actual application does not have such a well-defined ventilation opening, it is unknown whether the system would still achieve the same results. Furthermore, the IMO test structure

does not include the clutter of overhead piping, cable trays, and ducts found in real machinery spaces. The extent to which the additional obstructions might increase extinguishment times is not evaluated by the test protocol.

The IMO regulations also require the installation of local application fire suppression systems on certain machinery space equipment, in particular, large diesel engines. The IMO MSC/Circular 913, Local Application test protocol[5] defines the performance requirements. For ships that utilize carbon dioxide for the engine room suppression system, the requirement to install the water-based local application system represents an additional cost. For passenger ships that utilize water mist to comply with the IMO requirements, the water supply and pumping capacity are already provided. The local application system represents only a small cost increase.

Both FM Global Research and Underwriters Laboratories (UL) have developed their own versions of the IMO test series. The FM Global Research and UL test programs differ from the IMO tests in certain ways. The FM Global Research and UL test protocols, for example, relax the requirement to extinguish the smallest pan fire in the bilge. The relaxation recognizes the level of control achieved by the suppression system—the small shielded fire can be approached and extinguished by hand.

Water mist systems have been installed in land-based machinery spaces in Alaska's North Slope. There are differences between machinery spaces on land and on ships. On ships, the concept of a single 2 m by 2 m ventilation opening is valid because of the nature of compartmentation on ships. In land-based facilities, the ventilation openings may be distributed differently. The designer must understand the conditions and the performance objectives of each test protocol in order to make an appropriate adaptation to a real installation.

Machinery compartment water mist systems can be characterized as follows:

- *Safety objectives.* Replace halon or CO_2 extinguishing agents. Extinguish all fires involving spilled or sprayed diesel fuel or hydraulic oils and provide cooling of hot gases using a limited amount of water. Fire sizes range between 0.5 and 10.0 MW. Extinguishment times must be within 15 minutes (IMO) or 30 to 60 minutes (UL or FM Global Research).
- *Mechanisms.* Mechanisms include convective cooling of flame, hot gases, and fuel; steam displacement of oxygen and dilution of air-fuel vapor mixtures; and blocking convective and radiant heat transfer to surfaces of unburned fuels and surrounding objects. The ability to ensure optimum conditions for any of the extinguishing mechanisms decreases as compartment size, ventilation, fuel complexity, and number of obstructions increase.
- *System features.* Deluge systems with open nozzles in grid at ceiling and sometimes at intermediate levels are used for flooding the total compartment with water mist. Local application systems around equipment also utilize open nozzles. Nozzles may be high- or low-pressure jet, twin-fluid, or impingement types and may be combined with other suppression systems (e.g., bilge foam systems) where control is beyond the capability of mist alone. A separate detection system is used for activation. Water supply is preferably fresh water, but systems are designed to permit switching to seawater after fresh-water supplies are depleted. Maritime regulations (IMO) require a minimum 30 minute water supply.
- *Industry acceptance.* Water mist systems are accepted worldwide by the International Maritime Organization (IMO) as a replacement for halon or CO_2 in marine machinery spaces. Maritime insurance societies such as Det Norske Veritas and Lloyd's inspect and commission the systems. For passenger cruise ships, which must be sprinklered throughout, water mist is frequently used to comply with Solas requirements for the machinery space. For cargo shipping, carbon dioxide systems are more widely used. The petroleum resource industries worldwide are using water mist systems in machinery spaces such as process modules at production sites.

BP Alaska, Phillips Petroleum, and ARCO Alaska have installed water mist systems in machinery modules on Alaska's North Slope as a replacement for halon 1301 systems. The designs of these land-based machinery space systems are based on IMO, FM Global Research, or UL protocols for machinery spaces.

Turbine Enclosures

Turbine enclosures are a type of machinery space. Unlike general machinery spaces, which may contain many potential fire sources, the source of fire in a turbine enclosure is limited to the turbine and its fuel lines. Large diesel or gas-driven turbines are standard equipment in offshore drilling platforms. Fuel line breaks may lead to spray fires or three-dimensional spill fires with pool fires in a bilge area under the turbine. The rotating turbine blades are susceptible to serious damage if the surrounding casing is cooled rapidly and contracts. For that reason, it was in the past considered dangerous to apply water to turbine fires, at least until the machine had stopped rotating. The turbines are enclosed in ventilation-controlled compartments. Halon 1301 and CO_2 total flooding systems have been the preferred method of providing automatic fire suppression for turbine enclosures.

Wighus et al.[7] confirmed the ability of a water mist fire suppression system to extinguish fires in a turbine enclosure. Subsequent test protocols have been developed by FM Global Research to address concerns about the use of water spray on hot turbines. The FM Global Research fire test protocol for turbines in enclosures incorporates a test to measure the rate of cooling of a thick metal plate. The test results in convective heat transfer coefficients for different segments of the heated plate. The heat transfer coefficients can then be used in a finite element analysis of the turbine casing to evaluate clearances between casing and turbine blades. As turbines are typically installed inside enclosures, the test protocols have been developed for enclosed conditions. A number of water mist equipment manufacturers have obtained FM Global Research listings for water mist systems in turbine enclosures up to 260 m^3. Other turbine enclosure test protocols exist in Europe and Australia. The manufacturers have adopted various strategies in order to pass the cooling test in the FM Global Research test protocol. These include orienting the nozzles to project the spray horizontally, parallel with the axis

of the turbine, to minimize direct-spray impingement on the casing, or cycling the spray on and off for short intervals.

The turbine enclosure water mist system can be characterized as follows:

- *Safety objectives.* The safety objectives are to rapidly extinguish a fire involving spilled or sprayed diesel fuel on or under an operating diesel turbine, using a limited amount of water, and without damaging the turbine blades through thermal shock; provide cooling of hot gases in the compartment; and replace halon 1301 or CO_2.
- *Mechanisms.* Mechanisms include convective cooling of flame, hot gases, and fuel; steam displacement of oxygen and dilution of air/fuel vapor mixtures; blocking convective and radiant heat transfer to surfaces of unburned fuels and other objects; and cooling hot metal surfaces.
- *System features.* These include total compartment flooding systems with open nozzles on a preengineered piping system. Both low-pressure and high-pressure systems utilize stored water and compressed gas to deliver the water to the nozzles. Nozzle locations and orientation are important to overall performance. Cycling (on/off cycles) are sometimes used to minimize the cooling rate of the turbine casing. A separate heat or optical detection system is used to control release of the system and to activate interlocks. Water storage volume is based on either the FM Global Research minimum requirement for 10 minutes' duration or the NFPA 750 requirement for two complete discharges for preengineered systems (20 minutes).
- *Industry acceptance.* Norwegian and Australian petroleum industry operators and regulators accept water mist as an alternative to halon or CO_2 in turbine enclosures on offshore platforms. The Alaska North Slope oil field regulators also accept the use of water mist in land-based turbine enclosures. Most turbine manufacturers accept the use of water mist around their turbines provided they have passed the FM Global plate cooling test.

Marine Accommodation, Public Spaces, and Service Areas

The IMO maritime regulations that require installation of sprinkler systems on passenger-carrying ships have stimulated interest in developing water-based suppression systems that require less water than standard sprinklers, can use smaller-diameter piping, and be compatible with the water supplies, detection, and control systems on a ship. To that end, considerable effort has gone into developing water mist systems that operate in the same manner as sprinkler systems.

Test protocols have been developed by IMO to evaluate the use of water mist in crew's quarters and ship corridors.[10–12] Testing to date has focused on small cabins (i.e., 12 m^2 for crew's quarters, and 25 m^2 for luxury cabins). Unlike the water mist systems intended for application to Class B (hydrocarbon fuel) fires, the crew's quarters fire scenario involves Class A combustibles. Whereas large droplets are a disadvantage for hydrocarbon fires, they are beneficial to the extinguishment of Class A combustibles due to wetting of unburned fuel. Mist intended for suppression of Class A combustibles can have more large droplets than sprays intended for liquid fuel fires.

Water mist systems incorporating thermally released nozzles were recognized under IMO as equivalent to sprinklers for application in crew's quarters and passenger cabins.[10] Additional tests have been developed by IMO for the more severe fuel loading associated with shopping and service areas on ships.[11–14] The fire tests developed by IMO for the Class A hazards on ships have become the basis for generalized systems intended for land-based "light and ordinary hazard" and "residential" occupancies.[15,16]

The light and ordinary hazard occupancy applications of water mist systems can be characterized as follows:

- *Safety objectives.* The safety objectives are to save lives by suppressing and controlling fires in Class A combustibles and to prevent fire spread from the compartment of origin into adjacent compartments.
- *Mechanisms.* Mechanisms include wetting of wood, paper, cloth, and plastic fuels in furnishings and wall coverings; some steam displacement of oxygen; convective cooling of flame, hot gases, and fuel; and blocking convective and radiant heat transfer to surfaces of unburned fuels and other objects, thereby preventing flashover.
- *System features.* The system is similar to wet-pipe sprinkler systems with normally closed, fast-response, thermally activated nozzles. The nozzles produce a higher percentage of finer drops than standard sprinklers.
- *Industry acceptance.* As of 2006, almost all cruise ships are protected with marine water mist systems tested under the IMO test protocols for accommodation, public spaces, and service areas. The systems are recognized by most national coast guard authorities and marine classification societies.

Hotels, Heritage Buildings, and Galleries

Nonmarine applications of water mist systems include hotels, heritage buildings, and art galleries. The IMO test protocols for accommodation, public spaces, and service areas provide the design basis for many of these systems. Rooms with corridors on cruise ships are similar to rooms with corridors in land-based hotels. Since 2000, two hotels in the United Kingdom have been retrofitted with high-pressure water mist sprinkler systems for the purpose of increasing life safety. High-pressure water mist systems were selected because of the advantages of using small-diameter tubing and a small waterflow requirement compared to standard sprinklers. The water mist systems were cost competitive with standard sprinklers.

Water mist systems have been installed to protect remote heritage buildings in Norway and Finland. The 1000-year-old wood stave churches are located in remote areas with minimal or no water supply. There was a need to provide an automatic detection and suppression system that could protect the structures with a minimum amount of water and without damaging the icons painted with water-soluble paint on the wood walls. A water mist system was developed using nozzles at ceiling height to achieve flashover suppression by delivering enough water to take the heat out of the hot gas layer but not to wet the walls.[17,18] Supplementary nozzles with higher flow rates were mounted at floor level to extinguish the accelerant fires. Testing was performed in Norway to validate the concept, and

Norwegian authorities responsible for preservation of national treasures were pleased to have a means of protecting the structures.[19] The National Gallery of Art in Washington, DC, has installed a preaction, high-pressure water mist system in a series of galleries. The galleries are primarily period rooms with combustible walls or ceilings. A fire in these galleries would threaten all other areas of the gallery with smoke and fire damage. The combustible walls and ceilings were not considered to be irreplaceable because the woodwork could be recreated if damaged by water. The objective was to provide fire protection with minimal water use, so that other areas of the gallery would not be flooded or damaged. Water mist nozzles were selected to project spray horizontally along the underside of the ceiling in the concealed spaces above the ceiling and in wall cavities. The nozzles are thermally activated, although the fire pump unit does not start unless there is an alarm signal from at least two smoke detectors.

Water mist systems for hotels and heritage buildings can be characterized as follows:

- *Safety objectives.* For hotels, the objective is life safety, although property protection is also important. For remote heritage buildings and galleries, the objective is primarily property protection and heritage preservation.
- *Mechanisms.* Mechanisms used include cooling of hot gases near the ceiling to minimize the occurrence of flashover and direct wetting of Class A combustibles.
- *System features.* For hotels and galleries, high-pressure pump water supplies are used for a minimum 30 minute duration. For remote heritage buildings, compressed gas–driven systems with 10 minutes' stored water are used. Open nozzles on deluge systems for flashover suppression, thermally activated (automatic) nozzles on preaction systems for gallery protection, and automatic nozzles on wet-pipe systems for hotels are used. Preaction and deluge systems would also include the use of a supplemental fire or smoke detection system and interconnected alarm panel.
- *Industry acceptance.* Acceptance by authorities having jurisdiction (AHJ) in Europe is based on collaborative development work involving AHJ, design engineers, and manufacturers. Acceptance is growing rapidly in North America.

Electrical Equipment Rooms, Computer Rooms, and Wet Benches

Water mist has been viewed as a possible alternative to halon 1301 for use in electrical equipment rooms. Potential applications include telecommunications central office facilities, control rooms, and computer rooms. Developments in these areas are limited. There is strong interest worldwide in the use of water mist systems in control rooms, particularly since several European authorities mandated the removal of all halon systems. Consensus on a general design approach and performance objectives for water mist on fires in electronic equipment has not yet been reached.

Testing has been performed by the U.S. Navy and by manufacturers to demonstrate that water mist may be used on high-voltage electrical equipment if precautions are taken with regard to stand-off distances.[20] Electrical charge does not transmit through an atomized spray. Water mist may be used in switchboard compartments for 10 minutes or more before leakage currents reach dangerous levels.[21]

Although FM Global has shown support for the use of water mist for telecommunications central offices, general acceptance by end users has been slow in North America. Similarly, the use of water mist as a halon replacement for computer rooms has been mixed. The fundamental issue has to do with comparing the performance of total flooding gaseous clean agents that can penetrate into electronic cabinets with water mist that cannot extinguish fire inside a cabinet, at least not in a total compartment flooding mode.

One water mist manufacturer markets a water mist system intended to capture smoke in a computer room subfloor and direct it into tubes where it can be scrubbed of acidic gases. This computer room "smoke scrubbing" subfloor system has been approved by FM Global for the protection of computer room subfloors, not as a general computer room fire protection system. For general fire protection in the computer room above the subfloor, standard water mist nozzles are distributed according to light hazard spacing rules. In general, water mist may provide the level of protection afforded by sprinklers against Class A fire hazards in a computer room but with discharge of smaller volumes of water. The objective of extinguishing a small fire inside an electrical cabinet without causing extensive wetting of sensitive electronics can be better achieved with gaseous clean agents.

It should be stated that the subfloor "smoke scrubbing" takes place inside a 100-mm-diameter tube where thorough mixing and washout are possible. The system captures smoke from the subfloor in 100-mm-diameter tubes. A water mist nozzle placed inside the tube creates a positive differential pressure downstream of the nozzle and a negative differential pressure upstream of the nozzle relative to the pressure in the subfloor. In the positive-pressure end, nitrogen and very fine mist are pushed out of holes in the pipe into the subfloor. In the negative-pressure end of the pipe, air and smoke from the subfloor are drawn into the pipe. Nitrogen rises into the computer cabinets above the subfloor where it extinguishes small telltale fires inside a computer cabinet. For the smoke that is drawn into the scrubbing tube, the vigorous mixing causes soluble corrosive gases such as HCl to be washed out.

In contrast, it is not true that water mist has a general smoke-scrubbing benefit when injected into a smoky fire compartment from ceiling nozzles. Unfortunately, some water mist manufacturers make the general claim that water mist provides a smoke-scrubbing benefit, making it suitable for use in electronic spaces. This erroneous claim of generalized smoke-scrubbing benefit is promoted for electronic spaces, art galleries, highway tunnels, and buildings in general. In a study conducted for the U.S. Navy, Mawhinney et al. measured the optical density of smoke before and after passing through water mist screens.[22] The study noted that optical densities decreased as a result of the water mist but not enough to materially improve visibility. Furthermore, nonsoluble toxic gases in the smoke are not washed out, so the toxicity of smoke is not reduced by the water mist. Recently, an Austrian group claimed that water mist provided

scrubbing benefits for fires in a highway tunnel—the perceived benefits include improved visibility and increased "breathability."[23] Such claims are not supported by experimentation and may lead to a dangerous misunderstanding of the benefits of water mist.

Wet benches are used for the manufacture of electronic computer chips. They are traditionally protected by carbon dioxide systems. The hazard includes confined spaces under the wet bench, vats of flammable liquid on the polypropylene surface of the work bench, and the collector hoods. Two water mist manufacturing companies have developed water mist systems for installation in wet benches. FM Global Research developed a test protocol for evaluation of the system.[24] The system consists of open nozzles in zones connected to a water storage cylinder connected to a cylinder of compressed gas. It is activated by optical detectors. Because of the high corrosivity of the etching acids used in the process, corrosion-resistant pipe and fittings are needed. One company manufactured a twin-fluid nozzle out of the equivalent of Teflon plastic to meet the corrosion-resistance requirement.

Water mist systems for electronic equipment, computer rooms, and wet benches can be characterized as follows:

- *Safety objective.* The safety objective is to provide property protection by extinguishing small fires and removing acid gases from smoke generated in subfloor areas.
- *Mechanisms.* Mechanisms include direct wetting of Class A combustibles in electrical wiring and normal combustible items found in computer rooms and washing out of soluble acid gases in subfloor smoke.
- *System features.* For computer rooms and electrical equipment rooms, closed nozzles equivalent to sprinklers are used. For subfloor smoke scrubbing, a custom-designed grid of large-diameter tubes for distribution and collection of the combined nitrogen/fine mist gas is used. Small water storage cylinders and cylinders of nitrogen gas provide a 10 minute operation of the subfloor system.
- *Industry acceptance.* Acceptance by authorities having jurisdiction in Europe is based on collaborative development work involving AHJ, design engineers, and manufacturers of water mist equipment. Consensus on test protocols and design criteria for water mist systems for computer rooms has not yet been reached. Wet bench systems have approval by FM Global.

Tunnels

Tunnels are likely to be an important direction of development for water mist fire protection systems in the next 10 years. Fire testing has been performed to evaluate the use of water mist against electrical cable fires in tunnels.[25] After a decade of serious highway and rail tunnel fires in Europe that resulted in heavy loss of life and financial losses totaling in the billions of dollars, the tunnel authorities in Europe have begun to lessen their reluctance to employ active water-based fire suppression systems in tunnels.[26,27]

In North America and Europe the fire protection strategies for highway tunnels have been based on providing ventilation to remove smoke and hot gases, using spall-resistant concrete, and providing traffic control and evacuation exits at certain distances along the tunnel. Water-based fire suppression systems were until recently viewed as undesirable, possibly because of incomplete risk evaluations. The body of opinion on which the designers of fire safety systems for tunnels have relied was reflected in NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways*.[28] That standard also provided estimated fire sizes for different types of vehicles for use as design fires for designing ventilation systems and protective linings. Remarks in the Appendix to NFPA 502 gave dire warnings against the use of sprinklers or suppression systems.

A series of full-scale fire tests conducted in Norway in 2003 presented a challenge for the traditional design assumptions for fire safety in tunnels. The Runehamar Tunnel[29] fire tests demonstrated that a typical HGV lorry transporting furniture or foam mattresses could create a fire ranging from 75 to 200 MW. NFPA 502 suggested design fire size for a HGV is 30 MW. Ventilation systems designed on the basis of an assumed 30 MW fire are going to be ineffective against 150 MW fires. This fivefold underestimate in the size of the design fire for ventilation system design suggests that water-based suppression systems are in fact necessary in order to reduce the impact of fire in a tunnel to a level that the ventilation systems or other safety features can handle.

Since 2003 the tunnel fire safety authorities in Europe have realized that water-based active fire suppression systems may be essential to ensure the assumed (public expectation) minimum level of life safety in road tunnels. This change in attitude has motivated significant spending on the part of manufacturers of water mist fire suppression systems in full-scale testing. In the last 5 years, systems including high expansion foam, compressed air foam (CAF), and water mist have been tested. Fire testing of water mist systems has been and continues to be carried out at the Runehamar test tunnel in Norway, the IF tunnel research facility also in Norway,[30] the Hagerbach tunnel research facility in Switzerland,[31] and the San Pedro de Anes tunnel safety research facility in Spain.[32] Recently, contracts have been let to begin installation of water mist systems in several highway tunnels in Europe. One result of the extensive full-scale fire testing conducted to satisfy tunnel authorities will be some standardization of the performance objectives for the suppression system, against standard design fires, versus against very severe heavy goods vehicle fires such as identified in the Runehamar testing. Due to a lack of consensus among tunnel authorities in different countries as to how to set realistic performance objectives for a tunnel fire suppression system, there may be significant differences in the design features of systems developed by different manufacturers. The benefits of water mist in highway tunnels include cooling the gases to reduce the thermal threat to people, prevention of fire propagation beyond the first one or two vehicles involved, and reduced buoyant smoke spread. Reduced buoyancy makes it easier for existing ventilation equipment to function and for fire fighters to force smoke back into a tunnel as they try to approach the fire area. It should be noted that water mist applied generally from ceiling nozzles does not provide a smoke-scrubbing benefit. Although some soot is washed out of the smoke, the visibility does not improve sufficiently to improve existing conditions, and nonsoluble toxic gases such as CO are not re-

moved.[33] Water mist can be used to cool tunnel ventilation fans so that they survive longer and continue to remove smoke from the tunnel.

Tunnels can be very long with limited space for equipment such as pumps and water reservoirs. The challenge of providing adequate flow and pressure of water to the mid-sections of a tunnel that might be 10 km or more in length presents a unique opportunity for water mist systems, which use smaller-diameter piping than traditional water-based suppression systems. Extensive full-scale fire testing of water mist systems in highway tunnels in the last 5 years has shown that water mist can provide satisfactory protection of life and property against even catastrophic fires in heavy goods vehicles. Cost-effective engineering designs to achieve the required waterflow rates at the three most remote zones in the tunnel have been realized.

Water mist systems for tunnels can be characterized as follows:

- *Safety objectives.* For electrical cable tunnels, the primary objective is property protection, although life safety is an issue for workers in the tunnel. For railway tunnels, both life safety and property protection are important**.** For highway tunnels, the property protection objective is to limit thermal damage to the tunnel lining to the area of a single burning vehicle and to prevent propagation of fire to adjacent vehicles. Reduced temperatures and smoke buoyancy will increase the effectiveness of ventilation systems in tunnels and make it easier for the fire fighters to enter the tunnel to fight the fire and aid rescue.
- *Mechanisms.* Mechanisms include direct wetting of Class A combustibles in electrical wiring or commodities carried in vehicles, cooling of hot gases; reduced smoke buoyancy, hence, smoke spread; and direct cooling of gases entering the smoke exhaust system to prolong functionality of equipment.
- *System features.* Features include generally high-pressure water mist systems with stainless steel tubing and several positive displacement pump stations, special detection systems, zoning of systems fixed to the tunnel, or systems fixed to a moving vehicle.
- *Industry acceptance.* Acceptance by local authorities having jurisdiction is on the basis of special fire testing directed by end users.

Aircraft Passenger Compartments

Starting in 1985, the Civil Aviation Administration (CAA) in the United Kingdom and the Federal Aviation Administration (FAA) in the United States, with the involvement of Transport Canada, Airbus, Boeing, and other aviation industry agencies, developed a fine water spray fire control system for aircraft passenger compartments.[34] The objective of this international research and development effort was to find a way to decrease the number of fatalities in air crashes that involve fuel spill fires (i.e., the postcrash fire scenario). The Manchester, United Kingdom, air crash of 1984 was the particular incident that sparked this interest. In that incident, the fatalities were not caused by the crash but by the fire from spilled fuel that engulfed the fuselage and spread into the passenger compartment. Aircraft are not at present equipped with fixed systems to protect against a postcrash fire.

The testing program verified that the aircraft passenger compartment water mist system met or exceeded the researchers' objectives for the postcrash fire scenario.[35] Having determined the details of the design, a cost-benefit study was conducted. The study concluded that the cost of outfitting a fleet of aircraft with passenger compartment water mist systems would be too high relative to the number of lives that would be saved to justify mandatory requirements for their installation.[34] As a result, both industry and regulatory partners in the aviation industry decided not to make it mandatory to install such systems on existing or new aircraft. Instead, focus has shifted to the problem of developing water mist systems for onboard cargo compartment fires during flight.

The aircraft passenger cabin water spray system can be characterized as follows:

- *Safety objective.* The primary safety objective is saving lives by protecting an aircraft passenger compartment from a postcrash, external fire threat and extending the survivable evacuation time.
- *Mechanisms.* Mechanisms include blocking convective and radiant heat transfer, cooling of hot fire gases, and wetting of fuels (plastic and cloth).
- *System features.* The system features zoned piping, automatic thermal activation of each zone, 3 minute supply of stored water in pressurized cylinders, single discharge, with limited duration of protection adequate for a well-defined performance objective.
- *Industry acceptance.* Developed through collaboration between aviation industry and regulatory authorities, the system has not been made mandatory on the basis of an unfavorable cost-benefit study.

SUMMARY OF WATER MIST SYSTEM FEATURES

From the preceding descriptions, it is evident that there are wide variations in the objectives, fire scenarios, system details, and levels of acceptance for water mist fire suppression systems. These can be summarized as follows:

Objectives

1. Protect lives and property in a compartment from external fire threat.
2. Control fire temperatures in a compartment to prevent flashover and fire spread to adjacent compartments.
3. Extinguish Class A and Class B fires.
4. Use water to provide protection where there was no previous protection (aircraft passenger compartments).
5. Use water where halon or CO_2 was previously used (Class B fires in machinery rooms).
6. Provide freedom from sprinkler system design constraints (e.g., allow use of smaller pipe sizes) with equivalent level of safety.

Fire Scenarios

1. Large external pool fire threatening to spread into a compartment

2. Liquid hydrocarbon fuels with high- and low-flashpoint liquids, in spray, spill, and pool fires, outdoors and in compartments
3. Class A combustibles (furniture, bedding, books on fixed shelving) in small compartments
4. Machinery compartments, underventilated liquid fuel fires
5. Large machinery compartments with obstructions, well-ventilated conditions, and small to large fire sizes
6. Tunnels with very large fuel loads of wood and plastic commodities on heavy goods vehicles or passenger vehicles

System Details

1. Low-pressure to high-pressure systems: 5 to 140 bar (75 to 2000 psi)
2. Single- and twin-fluid systems
3. Normally open nozzles, deluge-type systems, with separate detection system for activation
4. Normally closed, thermally activated nozzles
5. Continuous discharge
6. Repeated short discharges (cycling)
7. Declining pressure systems (gas driven)
8. Constant pressure systems (pump driven)

Levels of Acceptance

1. IMO full-scale fire test protocols, to be conducted by national laboratories, have been in place since 1996. Systems that meet the fire performance criteria in the IMO test protocols will be acceptable to national and international maritime authorities. Water mist is widely used on passenger ships, less so on commercial cargo ships.
2. FM Global Research approved a preengineered system for turbine enclosures in a compartment of fixed maximum dimensions. The performance evaluation includes not only the suppression effectiveness but also the performance of the detection system, effects of water on the equipment being protected, the performance of the detection/actuation equipment, flow duration, and sensitivity to partial dysfunction.
3. The components of water mist systems, including nozzles, pumps, actuators, gas cylinders, pressure control equipment, detection system panel, control valves, and so on, must meet IMO component testing criteria or be listed by Underwriters Laboratories Inc. (UL 2167) or FM Global Research (FM 5560 Test Protocols) for use in water mist systems.
4. Acceptance of water mist systems in land-based applications continues to grow. Authorities having jurisdiction are accepting more and more systems for industrial process modules, highway tunnels, hotels, and heritage buildings.
5. NFPA 750 describes what must be taken into account in full-scale fire test evaluations of water mist systems but defers to testing agencies to conduct those tests. If tests conducted by a credible laboratory demonstrate that the proposed design will meet the performance objectives, then it is expected that authorities having jurisdiction will accept the design.

Having reviewed the types of water mist systems that have achieved a level of recognition, the fundamental principles involved in extinguishing fires with water mist can be addressed. Ultimately, an understanding of the first principles governing the performance of water mist systems will allow the designer to adapt the range of misting technologies to the range of fire scenarios to meet a variety of system objectives.

GENERAL PRINCIPLES OF WATER MIST SYSTEMS

This section describes the general principles of water mist fire suppression systems technology and includes extinguishing mechanisms, spray characteristics, generic design elements, and methods of generating water mist. Extinguishing mechanisms are discussed first, as they are the basis on which the importance of specific spray characteristics can be appreciated. Technical details relating to spray characteristics are presented next. General principles governing the performance of water mist systems are outlined, and methods of generating water mist are described.

Extinguishing Mechanisms

A basic description of how water mist extinguishes fires was provided as early as 1955 by Braidech[1] and confirmed by Rasbash et al.[2] To quote Braidech:

> The extinguishing action of sprays of finely divided water applied to commonly encountered fires appears to be due predominantly to dilution of the air (oxygen) supply in the zone of burning with vapor (steam) resulting from evaporation of water droplets in the heated area surrounding the fire. The cooling effects of the water may also be important factors in extinguishment in many cases. In order to obtain extinguishment, the water droplets comprising the spray must be relatively small, and the amount of water applied must be adequate in relation to the specific fire.

Research conducted more than four decades later has not altered the accuracy of this description. The recent work has, however, suggested other processes that are involved and has identified the mechanisms that are most important for the design of effective fire suppression systems.

Figures 16.8.1 and 16.8.2 illustrate the mechanisms involved in extinguishing fire with mist. The mechanisms that act together to extinguish fire can be described as three primary and two secondary mechanisms.[36] The primary mechanisms are (1) heat extraction, (2) oxygen displacement, and (3) blocking of radiant heat. Wighus[7] and Hanauska and Back[37] described the mechanisms as "gas-phase cooling and steam inerting," making no reference to radiant heat attenuation. Although all three mechanisms are involved to some degree in every extinguishment, in tests conducted at the National Research Council, some fires were extinguished predominantly through heat extraction (cooling) and others predominantly through displacement of oxygen. The difference depends on whether the fire was poorly or well ventilated and on the properties of the fuel. The benefit of radiation attenuation in a compartment is evi-

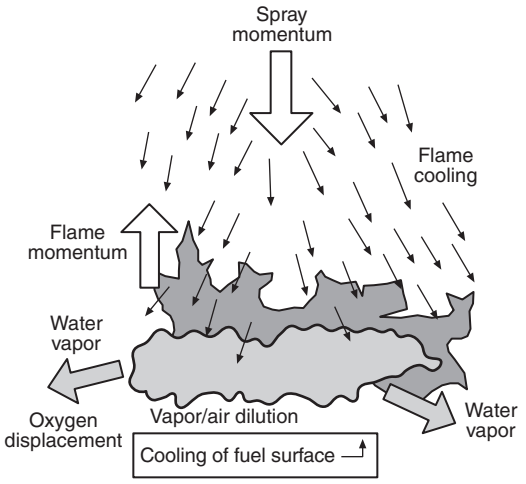


FIGURE 16.8.1 Interaction of Mist with Pool Fire Flame, Showing the Extinguishing Mechanisms

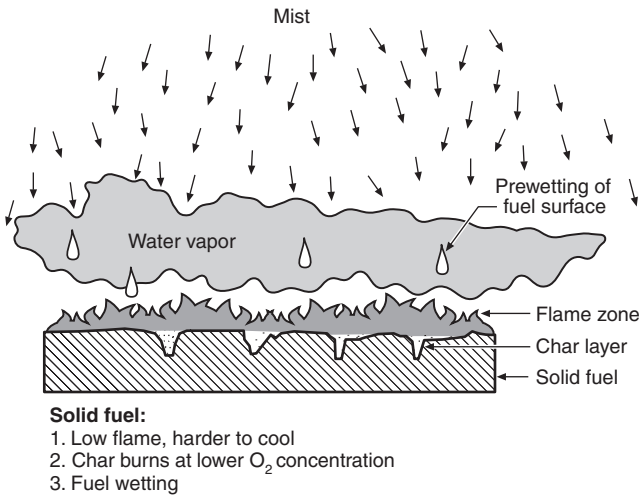


FIGURE 16.8.2 Flame on a Solid Fuel with Charring and Mist

dent in reduced thermal feedback to burning and unburned fuel surfaces. In the National Research Council of Canada (NRCC) experiments, however, radiation attenuation could not be identified as the dominant mechanism of extinguishment.

There are two secondary mechanisms that play a role in extinguishment, but it is difficult to quantify their importance. These are (1) vapor/air dilution, and (2) kinetic effects. The dilution of vapor/air mixtures by the mixing of water vapor and entrained air in the flammable vapor zone above a fuel surface can be deduced to have some effect on pool fires. Also, the velocity of the flame front in a flammable gas mixture may be inhibited (or accelerated) by the presence of small water droplets dispersed in a volume of flame, and this phenomenon may play a role in the extinguishment of spray fires and in inhibiting deflagrations.[38]

For engineering design of reliable water mist fire suppression systems, it may be sufficient to understand the three dominant mechanisms (i.e., heat extraction, oxygen displacement, and radiation attenuation). For scientific purposes, computer modelers need to consider all extinguishing mechanisms in order to develop algorithms to simulate the extinction of fire by mist. An ideal computer model would account for flame and fuel cooling, oxygen reduction, concentration changes in vapor/air mixtures at the fuel surface, reduced radiant feedback from flame to fuel surface, and possible kinetic effects caused by the interaction of mist with a moving flame front. Computational fluid dynamics (CFD) modeling to that level of detail is, at this time, in its early stages of development.[39–42] Recently zone models have been developed that predict extinguishing time based on oxygen depletion and cooling.[43] The mechanisms of extinguishment are described in detail in the sections that follow. Table 16.8.1 summarizes the points to be discussed.

Heat Extraction (Cooling). When water is applied to a fire, heat is absorbed in three areas: (1) from the hot gases and flames, (2) from the fuel, and (3) from the objects and surfaces in the vicinity of the fire. Cooling of the fuel and nearby objects contributes to reducing fire spread, but it does not necessarily require fine drop sizes. In fact, wetting and cooling of solid fuels are easier to achieve by using larger droplets (400 microns) and delivering more water than can usually be delivered as water mist.

Compared with coarser sprays, finely divided water sprays enhance the speed at which the spray extracts heat from the hot gases and flame. Reducing the drop size increases the surface area of the water mass and thereby increases the rate of heat transfer. The conversion of water droplets to steam absorbs heat. If sufficient heat is withdrawn, the gas-phase temperature of the flame can be dropped to a level that is below that necessary to sustain the combustion reaction, and flame will be extinguished. Theoretical considerations suggest that the combustion reaction in a diffusion flame will cease if the flame temperature drops below approximately 1600°K (1327°C).[1,2,36]

As for what constitutes "sufficient" heat absorption, various authors note that it is not necessary to absorb all of the heat given off by the fire at the rate of burning. Absorbing 30 to 60 percent may be enough to cause burning to stop.[44] An estimate of the minimum evaporation rate to extinguish a fire of a given heat release rate (HRR) is of little practical value, however, because extinguishment usually involves more than just flame cooling. The concurrent effect of oxygen reduction could mean the fire could be extinguished with only a fraction of the theoretical minimum required for flame cooling.

For liquid fuel fires, the evaporation of mist cools the flame, which, in turn, reduces the radiant heat flux to the surface of the fuel, resulting in a reduction in the evolution of flammable vapors. The combination of reduced flame temperature and reduced evolution of vapors results in a reduced burning rate and, in some cases, complete extinction. Fires in liquid fuels with flashpoints (FPs) above normal ambient temperatures, for example, diesel fuel (FP ~ 60°C), can be extinguished with relative ease by flame cooling and reduced radiation to the surface. Fires in liquid fuels with flashpoints below normal

TABLE 16.8.1 Mechanisms of Extinguishment by Water Mist and Their Application

Mechanism	*Principle of Application*
Primary	
Heat extraction	The drop size distribution, momentum, and mass flow rate delivered to the fire, after losses to interior surfaces and obstructions, must be sufficient to absorb a critical percentage of the heat released by the fire.
Oxygen displacement	Designed to: 1. Enclose fire to contain evaporated water 2. Use nozzle dynamics to force water vapor into the base of the fire
Radiant heat attenuation: 1. To unburned surfaces 2. To burning surfaces	Mist must: 1. Surround the fire 2. Penetrate the flame
Secondary	
Vapor/air dilution: 1. By water vapor 2. By entrained air	Significant for liquid fuel pool or spray fires. Must have enclosure or control of dynamic spray properties to distribute diluent over the fuel surface. Nozzle design may influence air entrainment, hence, dilution.
Kinetic effects: 1. Reduce flame velocity 2. Accelerate combustion reactions	Difficult to predict or control. Applies to deflagration control by reducing velocity of the flame front, hence, explosion overpressure. Unpredictable: mist may suppress or invigorate combustion.

ambient temperatures, for example, heptane (C_7H_{16}, FP ~ –4°C), are much harder to extinguish by cooling alone because temperatures cannot be reduced enough to reduce the vapor/air mixture above the surface of the fuel to below the lean flammability limit.[45] Any hot object or fragment of flame can cause reignition.

The cooling of flames above solid fuels also reduces the radiant heat flux to the fuel surface and the rate of pyrolysis of the fuel. As illustrated in Figure 16.8.2, however, with charring substances, the combustion reaction occurs within the carbon-rich porous zone that forms on the fuel surface.[46] Cooling of the diffusion flame above an established char zone may not suppress radiant feedback within the crevices of the char. Either water mist must be applied early in the fire, before a deep char zone has developed, or water droplets must penetrate the char zone and reach the actual interface between burning and unburned fuel. On the other hand, the flame height and plume velocities for glowing combustion are relatively low, so that the larger drop sizes in a spray may not be evaporated and will wet the fuel surface.

Extinguishment of solid fuels such as Class A combustibles, therefore, depends on the geometry of the fuel arrangement and the depth of the char layer. Exposed surfaces facing the source of the spray might be extinguished, whereas shielded surfaces (such as within a wood crib) will be almost impossible to extinguish by cooling alone.

Oxygen Displacement. Braidech et al.[1] concluded correctly in 1955 that the suppression effect of water mist "appears to be due predominantly to dilution of the air (oxygen) supply in the zone of burning with vapor (steam)." That is to say, oxygen displacement appears to play a stronger role than flame cooling. Water droplets expand approximately 1900-fold upon evaporation (at 95°C, 1 atm pressure). If evaporation occurs rapidly, the water vapor displaces the air in the vicinity of the drop. Injection of a finely divided water spray into a hot compartment results in rapid evaporation, expansion, and displacement of the air in the compartment by steam. If the amount of oxygen available for combustion is reduced below a critical level, the fire burns inefficiently and will be easier to extinguish by cooling.

The average temperature of the gases in the compartment limits the dilution of oxygen by water vapor in a suppression scenario.[42] As illustrated in Figure 16.8.3, the absolute concentration of water vapor that can be held in air at 60°C is 20 percent by volume—that is high enough to reduce the oxygen concentration in a compartment to about 16.8 percent, which begins to affect combustion. But at 45°C, the amount of water vapor in saturated air falls below 10 percent, which would only reduce the oxygen concentration to about 19 percent, which is not enough to extinguish the fire. This fact helps explain why water mist is more effective at extinguishing large fires than small fires in a given compartment. The higher the compartment temperature, the more water vapor dilutes the oxygen. It also explains why cycling sprays on and off, in closed compartments, reduces extinguishing time compared to systems with continuous discharge. More water is evaporated because of the increase in compartment temperature during the "off" stage of the cycle. Water mist is likely to act as gaseous extinguishing agent if the average compartment temperature is between 60 and 70°C. In a cooler compartment, the effectiveness of oxygen depletion is reduced. Flame and fuel cooling and wetting become the primary mechanisms of extinguishment.

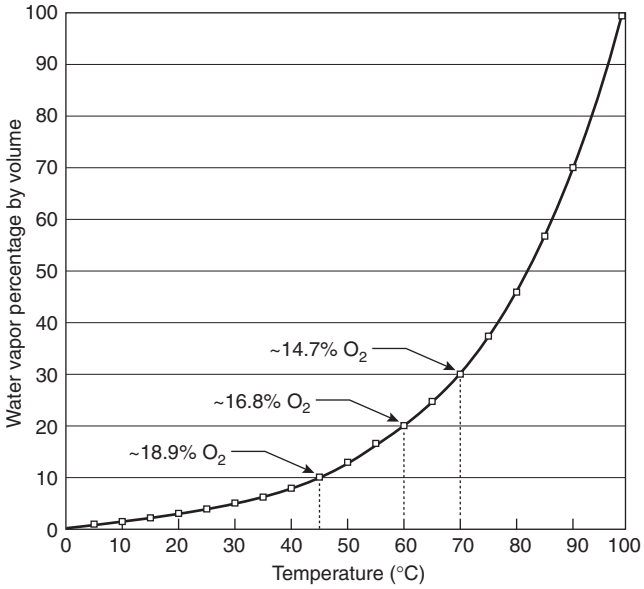


FIGURE 16.8.3 Relationship Between Gas Temperature and Volume Concentration of Water Vapor in Saturated Air. Approximate resulting oxygen concentration is indicated.

The Braidech et al.[1] study, as with most studies of the extinguishment of fires with water mist, concentrates on hydrocarbon pool fires with a few tests on wood cribs. Recent tests by Wighus et al.,[7,44] Mawhinney,[47] and Hanauska and Back[37] on diesel and heptane pool and spray fires confirmed that oxygen displacement ("steam inerting") was the dominant mechanism by which water mist extinguished the flames, both in compartments and in open-area pool fires. The confinement of heat allowed the water vapor concentration to build up so that hidden and shielded fires could be extinguished. Hanauska and Back[37] used a very fine spray with low momentum and flow rate to extinguish heptane pool and spray fires, after 30 to 50 seconds of mist application, in a 28 m^3 compartment. Fires in such enclosures can be extinguished with about one-tenth the mass flux of water needed for pool fires in open areas.[7,44] In open-area fire tests at National Research Council Canada (NRCC), extinguishment of pool fires could not be achieved unless the spray was oriented and applied with enough force to push water vapor created in the outer regions of a flame onto the fuel surface. The open-area fires required high-momentum sprays, properly oriented with respect to the plume direction. This fact suggests that the water vapor concentration at the fuel surface can be increased by either confining the fire in an enclosure or by using spray momentum to push the water vapor against the surface. In the NRCC plenum tests,[48] turbulent mixing alone did not bring about extinction if there was no component of the spray velocity directed toward the fuel surface.

The minimum amount of free oxygen needed to support combustion varies with the type of fuel. In general, hydrocarbon gases and vapors cease burning at oxygen concentrations below 13 percent, whereas charring solid fuels may burn with oxygen concentrations as low as 7 percent.[46] This explains why it is easier to extinguish hydrocarbon pool fires (diesel and heptane) than wood crib fires; the reduction in oxygen needed to extinguish a hydrocarbon flame is easy to obtain compared to that needed to arrest combustion in burning wood.

Figure 16.8.3 also explains why it is easier to extinguish large fires than small fires. The terms *small* and *large* refer to the size of the fire relative to the size of the enclosure. The observation is explained by the fact that a small fire has little effect on the average oxygen concentration in the enclosure (initially, at least), whereas the effect of a large fire on oxygen concentration is quickly evident. Compared to a small fire, a large fire generates more heat and creates a higher compartment temperature that in turn supports a higher absolute concentration of water vapor and reduces the average oxygen concentration more rapidly. To be useful in a compartment that cannot tolerate the damage that could be done by a small fire, perhaps due to flame impinging directly on a critical piece of equipment, careful thought must be given as to when or if it is necessary to extinguish small fires early.

Radiant Heat Blocking. Blocking radiant heat plays a role in stopping the fire from spreading to unignited fuel surfaces and reduces the vaporization or pyrolysis rate at the fuel surface. On a macro scale, radiation attenuation provided by water mist protects objects and personnel in a space from radiant heat damage, whether or not extinguishment occurs.

Theoretical work on radiation attenuation by water sprays[49,50] indicates that the attenuation of radiation depends on drop diameter and mass density of the droplets. As the concentration of drops with diameters smaller than 50 microns increases, the degree of attenuation of radiant heat increases.[49] This is one reason why water mists, having high concentrations of very fine drops, prove to be very effective at reducing radiant heat transfer. One question that arises is how much of the reduction in radiation to surfaces is due to the reduced size of the flame and what proportion is due to actual attenuation of radiant heat due to the presence of mist. Theoretical considerations suggest that mist or steam that enters the space between a flame and the fuel surface will reduce the radiant heat flux to that surface.[38] This is difficult to measure, but it is hypothesized that radiant heat from the flame could be absorbed by unevaporated droplets and steam, which reradiate at the lower temperature of the droplets or vapor. With some liquids, such as diesel fuel (FP ~ 60°C), this reduction in the heat flux to the fuel surface may reduce the vaporization rate of the liquid fuel and contribute to the extinguishment. Reducing energy transfer to the fuel surface reduces the rate of generation of volatile vapors.

Radiant heat attenuation between flame and fuel surface is important for computer modeling of fire suppression using computational fluid dynamics (CFD). In developing a CFD model of fire suppression using water mist, An et al.[51] calculated the heat release rate of a liquid pool fire, taking into account the coefficient of absorption of water vapor in each control volume. A reduction of radiant heat transfer to the fuel pan was predicted to measurably reduce the vaporization rate, hence, the heat release rate of the burning vapors. More experiments are needed to compare measurements of heat flux in this zone to predictions of radiant heat attenuation obtained using the CFD models.

Vapor/Air Mixture Dilution. Air and water vapor entrained in a water spray may dilute the vapor/air mixture to below the lean flammability limit. With diesel fuels (FP ~ 60°C), cooling of the flame reduces the thermal energy to the fuel surface, which in turn reduces the rate of evaporation. Coupled with a dilution of the vapors by the addition of entrained air, the vapor/air concentration falls below the lean flammability limit. In contrast, it is much harder to reduce a heptane/air mixture to below its lean flammability limit because of the low-flashpoint temperature (–4°C) and high vapor pressure of heptane. Dilution of pyrolized vapors emitted from solid fuels may also contribute to extinction and is referred to as a secondary mechanism because it is difficult to see how dilution alone could result in extinguishment. It requires uniform mixing of mist and entrained air throughout the space between the flame and the fuel surface to dilute all of the vapor/air mixture within the vaporization region. Mixing at fuel surfaces is often turbulent and nonuniform, so it is likely that there will always be some region of the vapor/air cloud that is in the flammable range.

For purposes of designing suppression systems, it is not yet feasible to quantify the relationship among the flammability limits of different fuels, the fuel vaporization rates, spray evaporation rate, and the mass flow rates of water mist and entrained air. A knowledge of dilution effects can, however, be used to explain differences in the effectiveness of water mist on different fuels as, for example, diesel and heptane. It should in principle be possible to calculate dilution effects on gas concentrations using computer field models based on computational fluid dynamics.

Kinetic Effects of Mist on Flames. A liquid pool fire is sometimes intensified by the application of water spray. A flare-up often occurs during the first moments of contact with the water mist, and it is evident in some fire tests that the burning rate is increased for longer periods. The general flare-up at the instant of application of water spray on liquid fuel fires is familiar to fire fighters. In many cases, the flare-up is followed by a quick knockdown and extinguishment of the flames. If the spray dynamics are insufficient to bring about extinguishment, the fire will continue to burn violently in spite of the mist.

The momentary intensification of the fire has been attributed by some authors to the effect of droplets striking the fuel surface and causing splashing and increased vaporization rate. Kokkala[52] referred to a "flame ball" that occurred when a sprinkler spray hit a hot, high-boiling-point liquid and explosively vaporized. In a study performed at WPI, the intensification of high-flashpoint oil fires on application of water spray was attributed largely to the disturbance of the fuel surface.[53] The same phenomenon was noted by Mawhinney[48] during suppression tests in which a fine water mist was applied from below a diesel pan fire in a direction concurrent with the fire plume, such that very few droplets could reach the surface of the diesel fuel. The visual evidence, supported by thermocouple readings, was that the flame within the plenum became violently turbulent and appeared to intensify during the time of application of the mist. One possible explanation for the observed intensification is that the turbulence acted to introduce more air into the combustion zone and thereby increased the burning rate of the fuel.

Mawhinney et al.,[36] at NRCC, measured the heat release rate of open-area heptane and diesel pan fires during the application of water mist. Figure 16.8.4 shows the measurements of heat release rate (HRR) during the suppression of a diesel pool fire and a heptane pool fire, respectively, using the same downward-oriented water spray in both cases. The HRR curves under suppressed conditions are plotted with the curves for unsuppressed fires in the same pans. In the case of diesel fuel, there is a brief spike in the HRR, followed by complete extinguishment within 60 seconds once the system is activated. For the heptane fire, a brief spike also occurred, followed by a partial suppression of the fire, and then by a continued increase in the burning rate of the heptane. The water spray failed to extinguish the fire, and turbulent flaming continued until the fuel was consumed. Over a portion of the burning time, the HRR of the fire with mist exceeded the HRR for the unsuppressed fire although, as expected, the overall burning time was reduced by the interval of intensified combustion. It is possible that the combustion process benefited from the additional air brought into the flame zone by the turbulent spray.

Jones and Thomas[38] report intensification of the rate of combustion in the use of water mists to quench gaseous explosions. The mist suppresses the maximum overpressure in an enclosed gaseous ignition, but the peak pressure may be attained sooner than for an unsuppressed explosion. Furthermore, the authors report that it is "never immediately obvious whether application of a water spray will quell or invigorate an explosion."

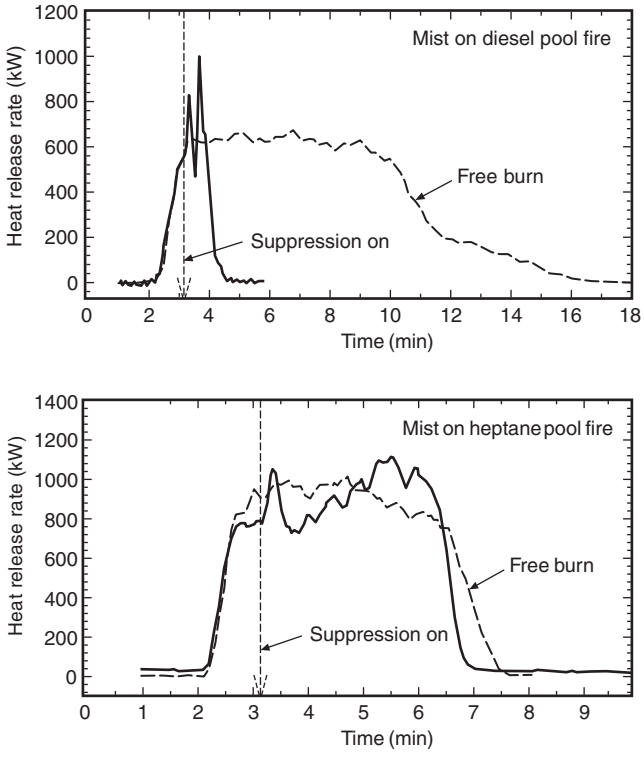


FIGURE 16.8.4 Momentary and Sustained Increases in the Heat Release Rate of Diesel and Heptane Pool Fires with Application of Water Mist

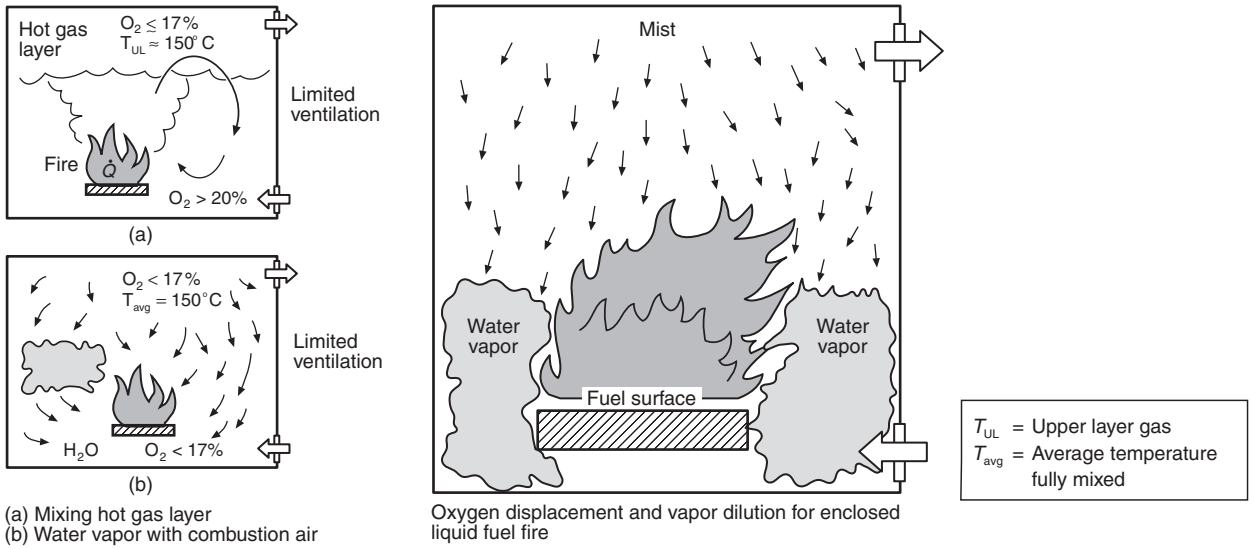


FIGURE 16.8.5 Enclosure Effects

The conflicting influences of cooling, inerting, dilution, and enhanced turbulence and fuel mixing lead to a degree of unpredictability in the effects of water mist on gas-phase burning.

There is reason to be concerned that a water mist system that is unable to extinguish a liquid fuel pool or spray fire could instead increase the heat release rate of the fire. Further research is needed to investigate the conditions under which flare-up or flame invigoration occurs.

Enclosure Effects. Enclosure effects enhance the performance of water mist systems. The enhanced performance can be attributed to restricted ventilation and heat entrapment. A fire in a small compartment reduces the average oxygen concentration in the compartment by several percentage points within the first few minutes of growth. Thus, a fire that is large enough to quickly reduce the average oxygen concentration in a compartment could be considered to be poorly ventilated. The addition of a small amount of water mist and resulting increase in water vapor further reduce the oxygen available to support combustion. Thus, an underventilated fire in an enclosure is "easier" to extinguish than a well-ventilated unenclosed fire.

Figure 16.8.5 illustrates how enclosure effects contribute to fire suppression with water mist. Heat from the fire trapped in the compartment evaporates the finest portion of the mist, so that the expanding water vapor pushes the air out of the compartment. Then oxygen-depleted, hot fire gases at the ceiling of the compartment are cooled by the mist and pushed down to floor level, mixing water vapor, oxygen-depleted air, and water drops with the fire. The combined effects of reduced combustion efficiency and flame cooling usually result in extinguishment. With enclosure effects, it is possible to extinguish even shielded fires with low-momentum sprays in heavily obstructed compartments. Where enclosure effects can be relied on, the flux density required for extinguishment can be as much as 10 times lower than that required for unconfined, well-ventilated fires.[7,44]

A phenomenon associated with enclosure effects can lead to very rapid pressure change between the fire compartment and the surrounding spaces. Water mist injected by a deluge system uniformly through the hot gas layer causes a rapid cooling of the gas layer. The accompanying volume change of the cooled gases creates a negative pressure inside the compartment relative to surrounding spaces. This is illustrated in Figure 16.8.6.[54] Depending on the temperature and depth of the hot layer, the rapid cooling results in an instantaneous volume reduction and

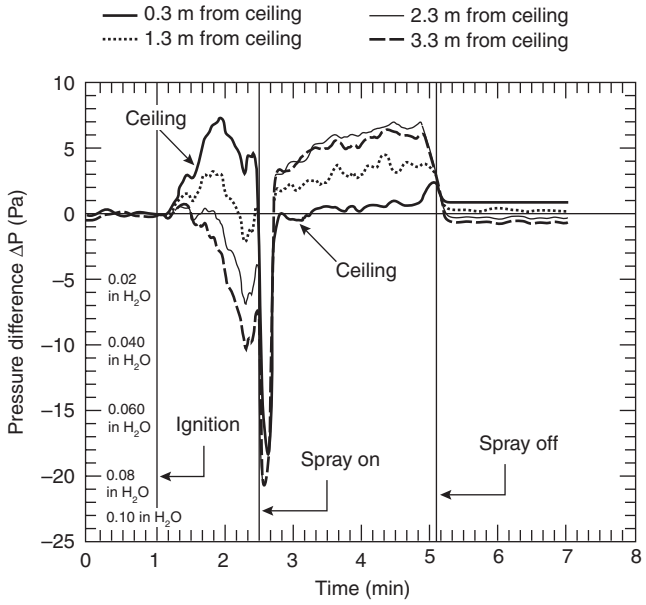


FIGURE 16.8.6 Generation of a Negative-Pressure Pulse in an Enclosure After the Injection of Water Mist into a Hot Gas Layer

negative pressure change that can suck in the windows or walls of a tight enclosure. The potential damage to a compartment is minimized by early release of the water mist system. If there is a delay in activation of the mist system, such as may occur with manual release of a local application system, the negative-pressure spike may be severe enough to damage the compartment ceiling, walls, windows, or doors.

In the case of an unconfined and, therefore, well-ventilated fire there are no enclosure effects to create conditions favorable to extinguishment. Water mist can achieve extinguishment only if the spray has strong enough momentum to push water droplets and vapor into the flame to the fuel surface. Thus, the absence of enclosure effects creates the need for a local application system. Local application systems typically have different spray characteristics, higher flow rates, and closer nozzle spacing than total-compartment application systems. Nozzle dynamics must compensate for the lack of confinement of vitiated gases, heat, and water vapor.

Time to Extinguishment. The time needed to extinguish a fire with water mist varies with the fuel type, compartment geometry, drop size distribution, momentum, and application rate of the water mist. Water mist extinguishes liquid fuel pool fires in 10 to 20 seconds, using small amounts of water. The top part of Figure 16.8.4, for example, shows a 600-kW, unenclosed diesel pool fire that was extinguished in less than 60 seconds by water mist. Such successes occur in circumstances in which all suppression properties act together (i.e., oxygen displacement, flame cooling, radiant heat blocking, and vapor dilution).

Rapid extinguishment is not characteristic of all water mist fire suppression systems, however. There are circumstances in which it can take several minutes to extinguish a fire without it being considered a failure. For example, the IMO machinery space test protocol requires extinguishment within 15 minutes. One example is where flame cooling cannot extinguish the fire immediately but, after several minutes, the buildup of water vapor in the compartment (an enclosure effect) combines with flame cooling to bring about extinguishment. With combustibles that form a char layer (e.g., fabric, wood, plastics, or electrical wiring), the fire may not be extinguished immediately. Fuel wetting begins to reduce the size of the fire and it is eventually extinguished. As long as the mist limits the heat release rate, causes the fire to progressively diminish in intensity, and cools the compartment, the level of fire control can be considered adequate.[55]

The relationships among fire size, compartment volume, and time to extinguishment are well described in work by Back et al.[56] Figure 16.8.7[56] shows test results for a series of machinery room fire tests conducted for the U.S. Coast Guard. The data were analyzed to develop a prediction for time to extinguishment as a function of fire size in different size compartments.[56] Fires were extinguished solely through the mechanism of oxygen depletion. It is evident from Figure 16.8.7 that smaller fires take longer to extinguish than larger fires and that increasing the compartment volume increases the time to extinguishment. For each size of compartment shown, there is a fire that is too small to extinguish (i.e., an "unextinguishable fire"). The size of the unextinguishable fire is a function of the size of the compartment. The relationship illustrates that there is a practical limit to what can be achieved through extinguishment by total flooding alone. That limit is reached when the unextinguishable fire is either too large to be extinguished by hand or when it is likely to do unacceptably severe damage to the contents of the space.

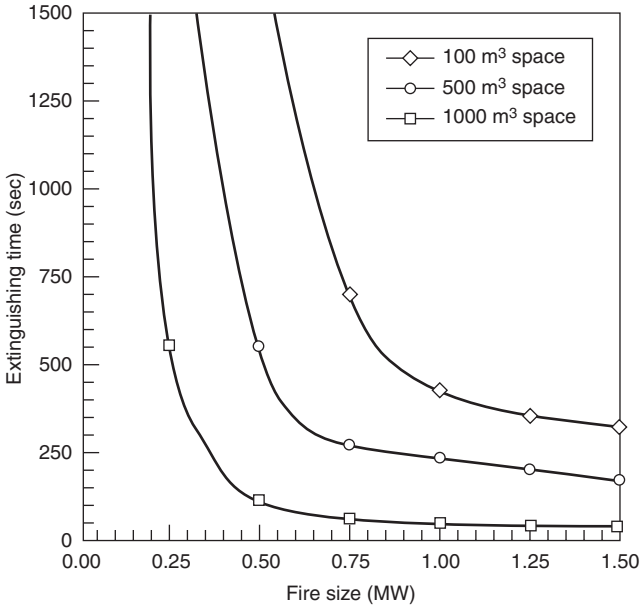


FIGURE 16.8.7 Relationship Between Fire Size, Enclosure Volume, and Time to Extinguishment of Fires in an IMO Machinery Room Test Enclosure

If the damage expected to be caused by the unextinguishable fire is unacceptably high, the system design must convert to a combination of total flooding and local application. It means that it is not sufficient to rely solely on the oxygen depletion mechanism of extinguishment. The other extinguishing mechanisms permitted by direct local application of spray must be unleashed.

Duration of Discharge. There are reasons to flow water from a system for a longer period of time than the minimum extinguishing time. First, extinguishment times vary even under controlled test conditions, and conditions in real compartments cannot be closely controlled. Second, with liquid fuel fires, reignition may occur if hot surfaces are not sufficiently cooled or if there is a remnant of flame in a shielded area. In principle, the flow should be sustained until it is confirmed that all fire has been extinguished and reignition will not occur. Such confirmation is difficult to obtain in real fire conditions. Practically, it is tempting to assign an arbitrary minimum flow duration, based on conservative assumptions about the probability of fire being extinguished. NFPA 750 recommends that the water supply be sized based on a 30 minute minimum flow duration. An exception is provided for preengineered systems, for which the minimum duration must be sufficient for two complete discharges. The length of one complete discharge is determined by the full-scale testing on which the listing was based. A second exception allows a fire protection engineer to use standard methods of fire

hazard analysis to determine the appropriate design duration. The author's experience has been that a careful fire hazard analysis for a specific application invariably results in a decision to enforce the 30 minute minimum duration.

Spray Characteristics

The term *water mist* implies a very fine water spray that remains suspended in air for an extended period of time. The term reflects one of the qualities of a spray (i.e., the drop sizes are small) relative to rain or to sprinkler sprays, for example. This one characteristic of drop size is not the only characteristic of a spray that must be controlled in order to generate an effective fire suppression medium. There are three other characteristics that influence its effectiveness as an extinguishing agent: (1) the density of the spray (mass of suspended water per unit volume of space), (2) the velocity with which it is delivered to the seat of the fire, and (3) the quality of the water itself (which may contain dissolved additives to enhance suppression effectiveness). The following discussion includes all four characteristics of a water mist for fire suppression purposes:

1. Drop size distribution
2. Flux density
3. Spray momentum
4. Additives

Drop Size Distribution. It is difficult to discuss water mist without measuring and analyzing its most notable feature, the fact that it is made up of very small water drops. At the time of this writing, except for computer modeling, the drop size distribution of the spray cannot be used explicitly as a variable in the design of a water mist system. That stage awaits the results of further research work. The value in knowing the drop size distribution (and other characteristics) of a water spray lies in the fact that it relates directly to system performance: how spray is affected by obstructions, the dynamics of the spray interaction with the fire, and how extinguishment occurs. For computer modeling of the dynamics of suppression with water mist, a quantitative measure of the drop size characteristics of the spray is essential.

The term *drop size distribution* refers to the range of drop sizes contained in a representative sample of a spray or mist. There is a distribution of small and large drops, which varies with location in the spray as well as with time. For a continuous discharge, the distribution of drop sizes changes with distance from the source as drops collide, evaporate, or hit surfaces and fall out. For a short-duration discharge, the distribution measured at a point in space changes with time as the larger drops pass through quickly, leaving increasingly finer drops, which move at lower velocity.

There are a number of ways to present data about drop size distributions of sprays.[42,57,58] It is customary in some fields to refer to the size of particles in a spray by a single drop size parameter, such as a "Sauter Mean Diameter (SMD)" or "Volumetric Median Diameter (VMD)." Such terms reveal little about the *range* of drop sizes in a spray, however. It is important to know about the presence of larger-diameter drops in a spray to avoid splashing on the surface of a liquid fuel, for example, or perhaps to know about the potential to achieve fuel wetting.

NFPA 750 has adopted the cumulative percent volume (CPV) versus diameter curve to represent the distribution of drop sizes in a water mist. Reasons for this choice are that (1) the cumulative percent volume plot visually reveals the range of sizes, and (2) the volume distribution converts readily to mass distribution, which is the most relevant term for analyzing heat transfer and evaporation rates using computer modeling. Figure 16.8.8 illustrates cumulative percent volume curves, measured 3 ft (0.9 m) from the nozzle, for several nozzles used in water mist systems.[22] The weighted average CPV curves were obtained using the method described in NFPA 750.

Commercial software conforming to ASTM E799, *Standard Practice for Determining Data Criteria and Processing for Liquid Drop Size Analysis,* for particle size measurement,[57] provides output in several formats, one of which is the cumulative percent volume versus diameter curve. For comparison with other sprays, the "S" shape of the curve can be roughly

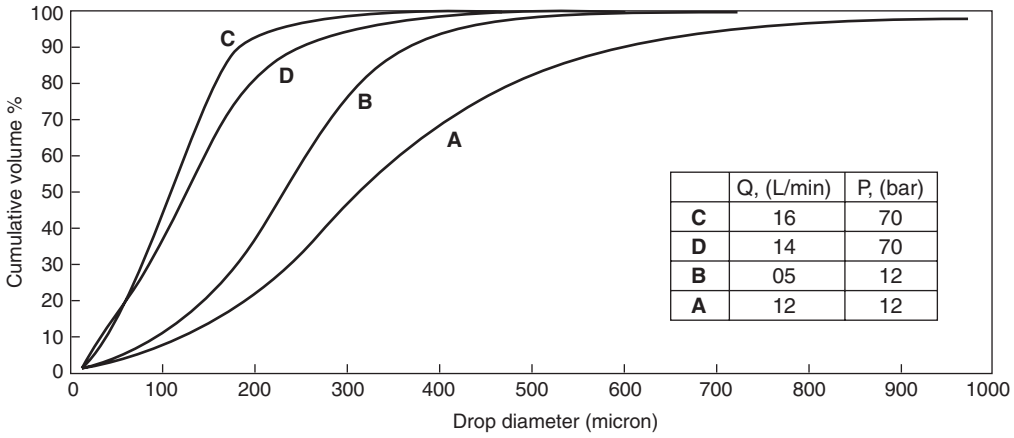


FIGURE 16.8.8 Statistically Weighted Cumulative Percent Volume Versus Drop Size Distribution Plots for Two Low-Pressure (A and B) and Two High-Pressure (C and D) Water Mist Nozzles

described using only three representative diameters: Dv0.1, Dv0.5, and Dv0.9. These parameters appear as standard output from a particle size analyzer conforming to ASTM E799. For a spray with a Dv0.9 of 400 microns, it means that "90 percent of the volume of a sample of the spray, at the sampling location, is contained in drops with diameters less than 400 microns." The cumulative percent volume distribution versus diameter curves can also be expressed as a mathematical function, which can be used in computer modeling of water spray/fire plume interactions.[42,58,59]

A method of obtaining a statistically representative measure of drop size distribution is described in the Appendix of NFPA 750. It is intended that the listing agency conduct drop size distribution measurements as part of component testing. The listing agency would then use the initial distribution readings as a baseline for ongoing checking for consistency in manufactured nozzles. The drop size distribution is measured 1 m from the nozzle, where the spray is expected to have the average properties of the spray elsewhere in the compartment. At that distance the cone is close to its maximum diameter, the entrained air has acquired a velocity, and the velocities of large- and small-diameter drops equalize.

This weighting approach, as described in NFPA 750, is necessary because individual readings may vary widely. If listing laboratories checked drop size distributions of manufacturers' nozzles annually, based on single point readings, they could see large variations that suggest changes in manufacturing quality, where in fact the variation could be due to the randomness of single point measurements. In contrast, a statistically blended curve will be more reproducible over time. Figure 16.8.8 shows statistically weighted cumulative percent volume distribution curves for two low-pressure and two high-pressure commercially available water mist nozzles.

Early research with fine water sprays was motivated by interest in using small drop sizes to enhance evaporation and heat extraction, using small volumes of water.[1,2] The research focused primarily on liquid fuel pool fires, for which the desired benefits are achievable with sprays that have most of the mass contained in drops of diameters of 400 microns or less.[48] Recent interest in using water mist for applications involving solid fuels, however, suggests that sprays with drop sizes greater than 400 microns need to be included. Drop sizes larger than 400 microns provide for fuel wetting, an important mechanism in extinguishing fires in solid fuels and charring substances. For that reason, the definition of water mist in NFPA 750 includes sprays for which 99 percent of the volume of the spray is contained in droplets less than 1000 microns in diameter ($Dv0.99 < 1000\ \mu$). Water mist systems, therefore, are applicable to a wide range of fire scenarios, including both liquid and solid fuels.

Classification of Water Sprays by Drop Size Distribution. The definition of water mist in NFPA 750 is so broad that some important differences in the qualities of sprays are disguised. It includes, for example, all water sprays used in NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection,* sprays produced by standard sprinklers operating at high pressure, and light mists suitable for greenhouse misting and HVAC humidification systems. In addition, the sprays referred to here are much coarser than what a meteorologist or physicist would view as a true mist.

The drop size distribution that will be most effective in one fire scenario will not necessarily be the best for a second scenario. There is no "one size fits all." The type of fuel (solid or liquid), the compartment dimensions, the velocity at which the mist is delivered, and the performance objective (e.g., temperature control versus extinguishment) collectively determine the most appropriate drop size distribution for a given application.

As a means of allowing distinctions to be made among coarser and finer sprays across the 1000 micron spectrum of the NFPA 750 definition of water mist, this chapter adopts a classification system that subdivides water mist into Class 1, 2, or 3 mists, according to their representative cumulative percent volume (CPV) versus diameter distribution curve (Figure 16.8.9).

This classification is introduced as a utilitarian necessity. It facilitates talking and thinking about sprays of significantly different character without referring to single-point parameters such as Sauter Mean diameter, volumetric, or numeric mean diameters. If a spray is reported as having a volumetric median diameter of 500 microns or a Sauter Mean diameter of 400 microns, the information is incomplete. Those single-point parameters do not tell us about the range of drop sizes in the spray or the steepness of the curve. Furthermore, it is difficult to say whether a 100-micron difference in volumetric mean diameter is significant in any way with respect to suppression effectiveness. The classifications of Classes 1, 2, and 3 set broad bands that describe the range of drop sizes and the relative steepness of the CPV curve. The classifications permit immediate visualization of the range of drop sizes in a spray.

The NFPA 750 committee agreed to delete reference to the spray classification system that was originally published in the Appendix of NFPA 750 in 1996 for the reason that some authorities having jurisdiction and specifying engineers imposed an interpretation on the system that Class 1 mists were superior in some way to Classes 2 and 3 mists. This misinterpretation of the meaning of spray drop size characteristics was used by some manufacturers to unjustifiably denigrate the products of their competitors. This misinterpretation of Classes 1, 2, and 3 sprays was damaging to some parties and to the promulgation of sensible engineering for water mist system design in general.

On the basis that the description of sprays as Class 1, 2, or 3 is of practical value to fire protection engineers working with water sprays, the classification system is described here. The boundaries defining the three classifications are shown in Figure 16.8.9.

A spray for which the $Dv0.9 \leq 200$ microns is a Class 1 mist, that is, $({}^{1}Dv0.9) \leq 200$. This category includes the finest water mists. In general, one expects that the fineness of a spray is obtained at the expense of mass flow rate and spray velocity. As shown in Figure 16.8.8, however, there are a number of commercial water mist nozzles that produce Class 1 sprays at the same mass flow rate as Class 3 sprays and with a higher initial velocity.[22] Class 1 sprays can be generated at low pressures or high pressures with twin-fluid, single-fluid, pressure jet, and impingement nozzles and flashing of superheated water.

Again with reference to Figure 16.8.9, the CPV curve for a Class 2 mist falls in the range $200 < ({}^{2}Dv0.9) \leq 400$ microns.

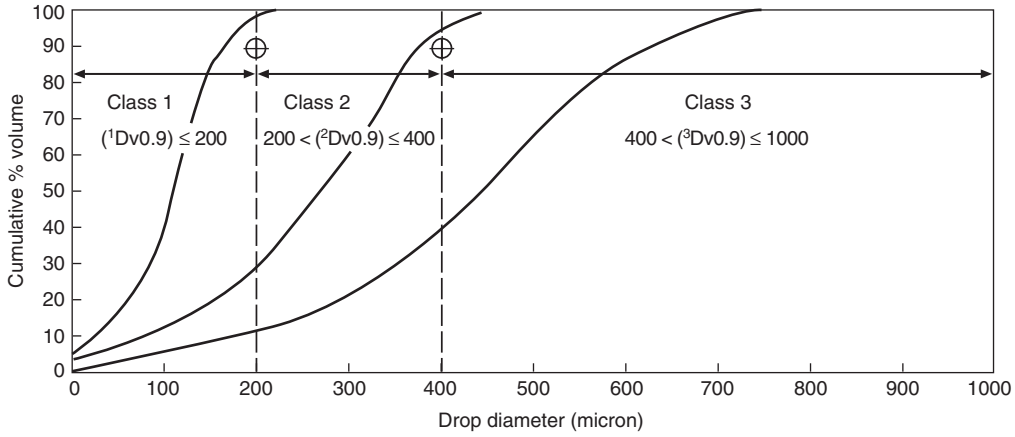


FIGURE 16.8.9 Classification of Drop Size Distributions—Classes 1, 2, and 3

Such sprays can be generated by low- and intermediate-pressure, pressure-jet nozzles; twin-fluid nozzles; and impingement nozzles.

A Class 3 mist has a CPV curve that lies in the range $400 < ({}^{3}Dv0.9) \leq 1000$ microns. Such sprays are typically generated by impingement nozzles of various sorts, including low- and intermediate-pressure, small-orifice nozzles. High mass flow rates are possible.

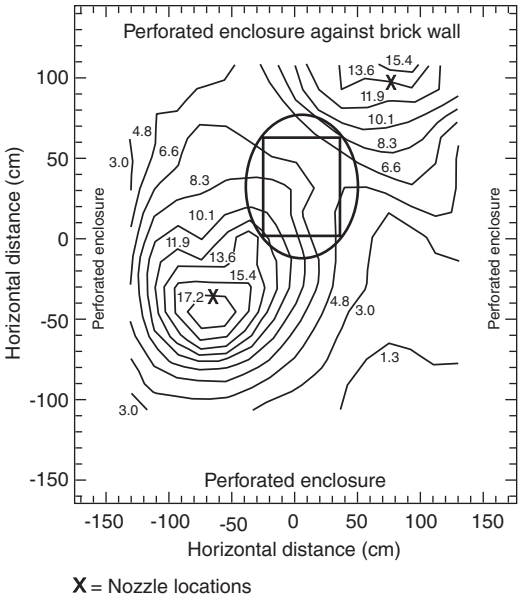
The relationship between drop size distribution and extinguishing capacity of a water mist is complex. In general, Class 1 and Class 2 mists are successful at extinguishing liquid fuel pool fires and spray fires without agitation of liquid pool surfaces. Class 3 sprays also extinguished pool fires. Class A fires can be extinguished with Class 1 mists if the velocity is high, the burning is surficial, or enclosure effects enhance the degree of oxygen reduction. This evidence confirms that drop size distribution alone does not determine the ability of a spray to extinguish a given fire. Factors such as fuel properties, enclosure effects, spray flux density, and spray velocity (momentum) are all involved in determining whether a fire will be extinguished. For this reason, NFPA 750 could not assign an optimum drop size distribution as a universal design variable for water mist systems for a specific hazard. Unlike with standard sprinklers, the flux density that successfully achieves the performance criteria of a fire test will vary depending on the drop size distribution, spray velocity, and mass flow rate of the nozzle.

Flux Density. The ability of water mist to extinguish a fire depends only partly on having the appropriate drop size and spray velocity. It also requires that the mass of water spray that interacts with the fire be sufficient to absorb a critical portion of the heat given off by the fire. Spray flux density is, therefore, an important characteristic of water mist for fire suppression systems. It can be expressed in *volume units* of gpm/ft^3 (L/min/m^3), although it is more practical to measure it as *area units* of gpm/ft^2 (L/min/m^2).

Expression of spray density in volume units is useful for the limited case of a total-flooding system in a compartment with no obstructions and nozzles with uniform distribution within their spray cones. With few exceptions, the flux density distribution of mist within a single spray cone is nonhomogeneous. When mixed with overlapping spray cones, air movement caused by the fire plume and the nozzles themselves and the deposition of mist on obstructions results in an unpredictable volume concentration of spray at any point in the compartment. It is, therefore, difficult to establish a meaningful correlation between volume concentration of mist and extinguishing effectiveness.

On the other hand, the average flux density in area units of gpm/ft^2 (L/min/m^2) can be measured easily using a grid of collection cups to measure the volume of liquid collected per unit of area per unit time. It is possible to relate success or failure to extinguish a fire to the flux density measured at that point (under nonfire conditions). It is, therefore, more useful to express flux density in area units, as a design variable, than to express it in volume units. Both representations are poor approximations of the actual flux density during extinguishment, however. That number is likely to vary dynamically with fire conditions and spray velocity and, therefore, can at best be used only as a rough design guide.

The density distributions from spray nozzles are far from uniform. Figure 16.8.10 shows an example of the flux density distribution on a plane 9.9 ft (3.0 m) below two SSC ¾ 7G5 nozzles, spaced 6.6 ft (2.0 m) apart, discharging 9.2 gpm (35 L/min) each.[60] These nozzles have been proposed for a "waterfog" system in a hydraulic equipment compartment on British (Royal Navy) submarines. At 100 psi (6.8 bar), the nozzles produce a Class 2 spray. The area covered by the spray cone at the level of collection was about 5 ft (1.5 m) square, for an area of 25 ft^2 (2.25 m^2). The nominal flux density for this array is calculated as the nozzle discharge divided by the coverage area of the spray cone at the plane of interest. In this case, the nominal flux density was 0.37 gpm/ft^2 (15.1 L/min/m^2). The measured flux density ranged from 0.42 gpm/ft^2 (17.2 L/min/m^2) directly below the nozzle, to 0.07 gpm/ft^2 (3 L/min/m^2) at the outer edge, and about 0.16 gpm/ft^2 (6.6 L/min/m^2) midway between the two nozzles. Thus, within a distance of less than 3.3 ft (1 m), the flux density distribution from these two nozzles ranged from 0.2 to 1.1 times the nominal flux density.



L/min / m²	gpm / ft²
17.2	4.2
15.4	3.8
13.6	3.3
11.9	2.9
10.1	2.5
8.3	2.0
6.6	1.6
4.8	1.2
3.0	0.7

FIGURE 16.8.10 Actual Flux Density Measured 9.9 ft (3.0 m) Below Two SSC ¾ 7G5 Nozzles, Spaced 6.6 ft (2.0 m) Apart, Discharging at a Nominal Flux Density of 0.37 gpm/ft^2 (15.1 L/min/m^2)

The extinguishing effectiveness of these two nozzles on heptane and diesel fuel pan fires varied with fire location.[60] Directly beneath the nozzles, where both flux density and spray direction (momentum) were sufficient to overpower the fire plume, all fires were extinguished in less than 10 seconds. Placed midway between the nozzles, the diesel fires took longer to extinguish, and some heptane fires were not extinguished. Midway between nozzles, the overlapping spray cones create a zone of turbulence in which spray goes in all directions. The flux density of 0.16 gpm/ft^2 (6.6 L/min/m^2) would likely have been sufficient had the spray momentum been better aimed against the fire plume. The strong heptane fire plume could rise through the mist and deflect the rest of the spray cone.[59]

These results illustrate that the extinguishing effectiveness of water mist can only be related to actual, not nominal, flux density. Many nozzles concentrate a high percentage of the water spray into the center of the cone area. This occurs because a negative pressure develops in the inner core of a hollow-cone spray, which draws droplets from the outer fringes into the center. Further distortion of actual from nominal flux densities occurs because of obstructions. Obstructions scrub water mist from suspension, drastically reducing the flux density. Obstructions also deflect the spray randomly, reducing its momentum and rendering it less effective.

Spray Momentum. The difference between success and failure of a fire suppression test can often be attributed to variations in spray *momentum.* Three factors that constitute the momentum of the spray are (1) the spray velocity, (2) its direction relative to the fire plume, and (3) the mass of the water droplets transported into the flame or onto the fuel surface. Velocity is a vector quantity, which has both magnitude and direction. The more control that can be exercised over momentum, the greater the ability to control total water requirements, time to extinguishment, water damage, and overall system reliability.

The extinguishing capacity of water mist is the result of a complex interaction of fuel properties, enclosure effects, drop size distribution, flux density, and spray momentum. Of course, the velocity cannot be too great or liquid fuels could be displaced, worsening fire conditions. The efficiency of a spray generation method is highest when the maximum amount of the spray has the desired directional properties relative to the fire plume. Control over momentum, then, depends not only on the nozzle characteristics but also on the degree to which nozzles can be strategically positioned around the fire.

One very important aspect of the selection of a mist generation method is the degree of control it allows over the directionality of the spray produced. If oriented strategically, narrow-cone-angle sprays direct more of their flow toward the fire source than wide-angle-spray cones. This was demonstrated in a series of tests conducted by NIST[61] and at NRCC, involving fires in computer cabinets.[62] The fire was located between two parallel printed circuit boards in an array of circuit boards, as illustrated in Figure 16.8.11. The fires were extinguished only when the spray direction was close to parallel to the circuit boards. A single, wide-spray-angle nozzle mounted in an open space above the circuit boards could only extinguish fires in a narrow band on either side of the vertical axis of the cone, in which the spray could enter the narrow spaces between the circuit boards.[62] As the horizontal component of the spray increased toward the edges of the array, the spray could not penetrate the space between the circuit boards. Increasing the nozzle pressure and mass flow rate did not widen the effective zone: it simply increased its depth. When the wide-angle nozzle was replaced with a series of closely spaced, narrow-spray-angle nozzles, the effective zone was widened to include the entire cabinet. By converting from a "fan-shaped" distribution of spray to a linear distribution of parallel sprays, it became possible to extinguish fires between any of the circuit boards with very little water.

The experiment described here illustrates that controlling the directionality of the spray can be more important than controlling the drop size distribution or mass flow rate. Drop size distributions can vary by 100 microns (Dv0.9) or more and be apparently equally effective. Most water supply systems deliver more water than is needed for the minimum performance of a single nozzle, so there is no penalty for being overdesigned on flow rate. There is little to be gained by designing to narrow tolerances on those parameters. On the other hand, small modifications to the direction of application of the spray can mean the difference between success or failure to extinguish.

Additives. The chemical nature of the water supplied to the nozzles influences the performance of water mist as a fire suppressant. Experiments at NRCC demonstrated that the extinguishing effectiveness of a water mist was enhanced by addition of sodium chloride to the water.[48] Mist made with seawater (2.5% by weight sodium chloride solution) extinguished diesel fuel pan fires at lower flux densities, and 40 to 50 percent faster,

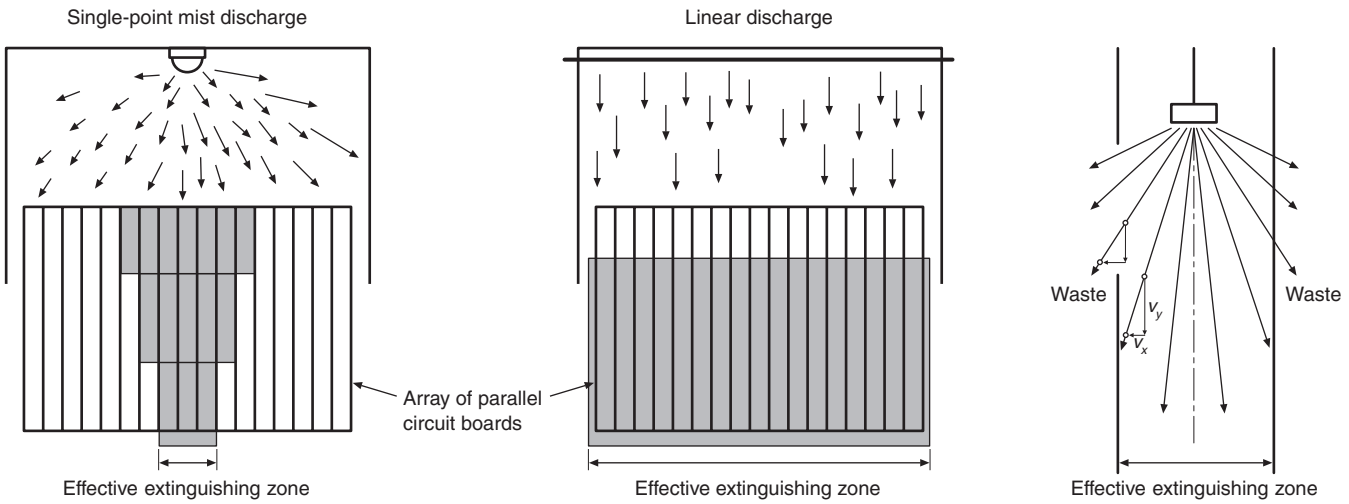


FIGURE 16.8.11 Effect of Controlling Spray Directionality or Momentum in Extinguishing Fires in Printed Circuit Boards

than mist made with fresh water. In addition, the seawater mist was less influenced by obstructions than fresh-water mist. One possible explanation for the improved performance is that dissolved alkali salts crystallize in the flame zone as drops evaporate. The salt crystals are small enough to be in the optimum effectiveness range of dry chemical extinguishing agents,[63] many of which are alkali salts. This hypothesis suggests that other alkali salts, which are better dry chemical fire suppressants than sodium chloride, could significantly improve the extinguishing effectiveness of water mist. Various products are already sold on the basis of their ability to enhance suppression effectiveness of water sprays.

The addition of a low percentage of a film-forming agent (e.g., 0.3% AFFF) greatly improves the effectiveness of water mist on hydrocarbon pool fires. This is particularly useful for suppressing spill fires in bilge areas that are sheltered from the water spray.

The chemicals that could be added to the water supply for a water mist system include antifreeze, film-forming agents, Class A or B foaming agents, surfactants, or emulsifiers to increase penetration of water into solid fuels, fire-retardant salts, biocides to prevent algae growth in stored water, and so on. The benefit provided by the additive may be offset by the introduction of secondary problems, for example, such as increased corrosivity or increased toxicity. The tolerance of equipment for increased corrosivity must be evaluated by the property owner/insurer on the basis of degree of corrosivity and the acceptable level of loss. Toxicity concerns, on the other hand, invoke government regulation. At the time of the aviation industry studies on aircraft passenger cabin water mist systems,[35] the U.S. surgeon general expressed concerns about the effects of inhalation of fine water spray on people. Those concerns were raised also by the U.S. Environmental Protection Agency (EPA) when water mist was being evaluated under the Significant New Alternatives Policy Program (SNAP) as a halon replacement. In response to the EPA concerns, the Halon Alternatives Research Committee (HARC), with the participation of the NFPA 750 committee, convened a health panel of medical experts to review data on this potential hazard.

The HARC Health Panel Report[64] concluded that water mist supplied by water, equivalent in quality to potable water (i.e., containing no additives other than those used in drinking water), or by natural seawater, poses no health risk to persons exposed to it, either under circumstances of a fire or due to nonfire actuation. The EPA found the panel's findings were credible and adopted its conclusions as the basis to a ruling. The resultant U.S. Federal Register regulation[65] recognizes that water mist systems supplied by potable water or natural seawater are "acceptable without restriction," as both a halon 1301 substitute in occupied spaces and as a streaming agent to replace halon 1211.

Water mist systems with additives are of interest for applications such as the engine compartments of vehicles and in machinery spaces. The EPA has accepted the use of water mist combined with a small percentage of a surfactant (water mist/Surfactant Blend A) for such applications in unoccupied areas.[65] Recent tests of surfactants used to improve suppression effectiveness by DuPont confirmed that their particular additive is not harmful to health.[66] Other additives, such as antifreeze, foaming agents, and fire-retardant salts, will be limited to unoccupied spaces unless the proponent provides EPA with the results of a medical peer review panel study addressing the toxicity question.

DESIGN OF WATER MIST SYSTEMS

The present level of understanding of the interaction of water mist with fire, obstructions, ventilation conditions, and compartment features is not sufficient to permit design of water mist systems by "first principles." Ideally, a first principles design would assume that there was a fixed relationship between the fire scenario, compartment geometry, ventilation, and application rate of water mist with a given drop size distribution. This relationship would hold regardless of the specific details of individual

manufacturers' equipment. Such an ideal relationship has not been established for water mist systems. There is considerable variation in the design parameters associated with the systems of different manufacturers, even when they have supposedly optimized their systems to the same fire test protocol.[67] In the absence of a large empirical database of design criteria and of a set of general principles that applies to all water mist hardware, NFPA 750 requires that all water mist system designs be linked to formal fire tests. Testing has shown that the performance of water mist systems is dependent on the specific manufacturer's equipment, particularly the nozzle design. One manufacturer might pass a fire test program at a particular flow rate and nozzle spacing. Another might operate at a lower pressure but have a higher flow rate and closer nozzle spacing to pass the same test. If one calculates the average flux density for the two systems, they may differ by a factor of three![67] Consequently, it is not yet possible to see convergence between manufacturers' systems toward generic design criteria such as a consistent nominal flux density for a particular fire scenario. The criteria are dependent on the manufacturer's choice of equipment. It appears that barely perceptible differences in atomization, spray cone angle, and velocity influence the performance of the system. The only way to be sure that a particular manufacturer's water mist system will work in a given application is to conduct fire tests with the manufacturer's equipment.

If a water mist system is listed for an application, the system design criteria and performance objectives have been validated through fire tests conducted by a recognized testing laboratory. Table 16.8.2 shows a list of fire test protocols recognized in North America and Europe. Test protocols are intended to test the limits of performance of systems against a realistic range of conditions, including worst-case scenarios, and to establish agreed-on and measurable performance objectives. Considerable thought and experience go into achieving consensus on the test scenarios. In North America, end users of water mist technology tend to rely on third-party listings by Factory Mutual Research Corporation (FM Global Research) or Underwriters Laboratories (UL) to confirm suitability. In Europe end users are likely to accept the results of ad hoc or specially designed fire testing. It is always important that the test program put sufficient effort into looking for failure conditions, limits of applicability, and breadth of criteria for judging acceptability. Ad hoc tests will be very specific to an application. There are many ad hoc water mist test efforts that form the basis of design for water mist systems. Examples include local application systems;[68] high-voltage cable tunnels; railway tunnels;[69,70] heritage properties, libraries, and archival storage on fixed shelving,[71,72] electronic equipment rooms,[73] computer room underfloor areas;[74] aircraft cargo bays;[75] and outdoor transformers.[76] Many of the ad hoc test programs have the potential to become formal or consensus test protocols.

NFPA 750 describes a number of fire test protocols in detail. It should be noted that the criteria by which systems are deemed acceptable are decided by consensus of a committee. Successful performance does not necessarily mean extinguishment of the fire. For example, the IMO tests for accommodation spaces and public spaces on ships require only that the fire be controlled for a period of 10 minutes. At the end of 10 minutes, the fire is manually extinguished and a damage assessment made. Fire extent and damage to the test materials must be within certain limits. During that 10 minutes, the fire continues to burn, and if the water mist system is shut off, the fire will regrow. The IMO machinery space protocol, on the other hand, does require extinguishment of all fires, including small, hidden bilge fires. Both FM Global Research and UL have their own versions of the original IMO machinery space tests. They have listed systems without requiring extinguishment of the smallest shielded pan fire. Unfortunately, it is not certain that the designer and the end user will understand the significance of such differences for the application at hand.

It is not advisable to rely on a generalized listing without checking that the performance promised by the listing meets the end user's actual needs. The fire protection engineer must confirm that the application is similar to the conditions of the test protocol. He or she must also check that the performance criteria used to judge pass or fail in the test protocol are compatible with the end user's needs in the actual installation. In some cases the performance requirements of the listing may be lower than what the end user really needs. Measures to upgrade performance will be required. To determine exactly what upgrade measures might be required to raise the level of performance without doing further testing the designer will have to apply first principles of fire science.

A second problem with the current approach is that a simplified test protocol can never capture the details of all possible field conditions. For example, the IMO Machinery Space test compartment contains only a mockup of a large engine; it does not contain any of the ducts, cable trays, and overhead piping that may clutter a real machinery space. Yet the design spacing determined in the mockup is applied rigorously in all applications. Furthermore, the manufacturers may be able to fine-tune their systems to meet the narrow performance criteria of the test protocol. The tolerance for differences between the test arrangement and real spaces is not known. Rather than achieving better performance through more efficient mist nozzles, we may simply be peeling away the safety margin. Once installed in a real machinery compartment with more overhead clutter or different ventilation opening than the test setup, one manufacturer's system may be within a hair's breadth of losing control. Another manufacturer's system may be more tolerant of variances. It would be reassuring if we were not so entirely dependent on the formalized "design by fire testing" approach.

METHODS OF GENERATING WATER MIST

Methods to generate water mist range from simple to elaborate. Some of the more elaborate methods include high-speed spinning discs, ultrasonic vibrations, flashing and recondensation of superheated liquids, rapid release of dissolved gases, and explosives. For fire suppression purposes, the choice of method is narrowed by the fact that the mass flow rates and velocities needed to be effective are beyond the capacity of some methods. The methods that are practical for fire suppression systems are those that break up water into drops smaller than 1000 microns at mass flow rates and spray velocities

TABLE 16.8.2 Fire Test Protocols for Water Mist Fire Protection Systems as of May 2006

Agency	*Water Mist Fire Tests Protocol*
1. International Maritime Organization (IMO)	IMO MSC/Circular 668: Alternative Arrangements for Halon Fire Extinguishing Systems in Machinery Spaces and Pump-Rooms. a. Appendix A: Component Manufacturing Standards of Equivalent Water-Based Fire Extinguishing Systems (1994). b. Appendix B: Interim Test Method for Fire Testing Equivalent Water-Based Fire-Extinguishing Systems for Machinery Spaces of Category A and Cargo Pump-Rooms (1994). As amended in MSC/Circ. 728: Amendments to the Test Method for Equivalent Water-Based Fire-Extinguishing Systems for Machinery Spaces of Category A and Cargo Pump-Rooms contained in MSC/Circ. 668, Appendix B (June 1996). IMO Res. A.800 (19) Revised Guidelines for Approval of Sprinkler Systems Equivalent to that referred to in SOLAS Regulations II-2/12. a. Appendix 1—Component Manufacturing Standards for Water Mist Nozzles. b. Appendix 2—Fire Test Procedures for Equivalent Sprinkler Systems in Accommodation, Public Space and Service Areas on Passenger Ships (December 1995). MSC/Circ. 913, Guidelines for the Approval of Fixed Water Based Local Application Systems for Use in Category A Machinery Spaces, 4 June 1999. MSC/Circ. 914, Guidelines for the Approval of Alternative Fixed Water Based Fire-Fighting Systems for Special Category Spaces, 4 June 1999.
2. FM Global, Approval Standard for Water Mist Systems, Class Number 5560, May 2005	a. Appendix A, B, C: Fire Tests for Water Mist Systems for the Protection of Machinery Spaces, Special Hazard Machinery Spaces, Combustion Turbines with Volumes Up to and Including 2825 ft^3 (80 m^3) (respectively). b. Appendices D, E, F: Fire Tests for Water Mist Systems for the Protection of Machinery Spaces, Special Hazard Machinery Spaces, Combustion Turbines with Volumes Up to and Including 9175 ft^3 (260 m^3) (respectively). c. Appendix G: Fire Tests for Water Mist Systems for the Protection of Machinery Spaces and Special Hazard Machinery Spaces with Volumes Exceeding 9175 ft^3 (260 m^3). d. Appendix H: Fire Tests for Water Mist Systems for the Protection of Combustion Turbines with Volumes Exceeding 9175 ft^3 (260 m^3). e. Appendix I: Fire Tests for Water Mist Systems for the Protection of Light Hazard Occupancies. f. Appendix J: Fire Tests for Water Mist Systems for the Protection of Wet Benches and Other Similar Processing Equipment. g. Appendix K: Fire Tests for Water Mist Systems for the Protection of Local Applications. h. Appendix L: Fire Tests for Water Mist Systems for the Protection of Industrial Oil Cookers. i. Appendix M: Fire Tests for Water Mist Systems for the Protection of Computer Room Subfloors. j. Appendix N: Other Occupancies Which FM Global Has an Interest in Protecting with Water Mist Systems.
3. Underwriters Laboratories Inc., Northbrook, IL, USA	UL 2167, Proposed First Edition of the Standard for Water Mist Nozzles for Fire Protection Service, June 1998. a. Machinery Spaces b. Passenger Cabin Fire Tests c. Passenger Cabins Greater than 12 m^2 d. Public Space Fire Tests e. Residential Area Fire Tests f. Light Hazard Area Fire Tests g. Ordinary Hazard I and II Tests h. Nozzle Construction Design, Marking and Performance Requirements
4. Verband der Schadenversichen e.V. (VDS, Germany)	VDS 2498 Guidelines for Water Extinguishing Systems Requirements and Test Methods for Fine Spray Nozzles, 8/96 Edition. a. Fine Spray Nozzles for Cable Conduits

appropriate for full-scale fire scenarios, which can be protected against plugging and which reliably sustain that flow as long as required. The economics of providing the stored energy, or installing special pumps and piping systems, are also determinants in selection of a mist-generating technology for a given application.

Water mist nozzle designs involve one of three basic principles: (1) impingement of a jet of water on a deflector (impingement), (2) expulsion of a high-velocity jet from an orifice (pressure jet), or (3) use of compressed air or nitrogen to shear water into fine spray (twin-fluid or air-atomizing nozzles). All three methods have been used by manufacturers of spray nozzles. The innovations being made by manufacturers interested in fire suppression are intended to improve efficiency or to optimize some spray characteristics such as mass flow rate, spray velocity, drop size, or cone shape. NFPA 750 distinguishes among the pressure regimes at which mist-generating technologies operate by introducing terms for low-, intermediate-, and high-pressure systems. Low-pressure systems operate at pressures of 175 psi (12 bar) or less; intermediate-pressure systems involve pressures greater than 175 psi (12 bar) but less than 500 psi (34 bar); and high-pressure systems operate at pressures of 500 psi (34 bar) or greater. The operating range of low-pressure systems is similar to standard fire protection systems, such as sprinklers and standpipes. The requirements for pipe, fittings, valves, pumps, or hydraulic calculations can be met by conventional materials and installation practices. Pipe, fittings, and valves for intermediate-pressure systems are also commonly available, although there may be no listed centrifugal fire pumps that produce pressures in the range of 500 psi (34 bar). Therefore, there are some aspects of intermediate-pressure systems that lie outside of standard fire protection engineering experience. Special requirements are invoked with high-pressure systems for pipe, fittings, pumps, valves, pressure regulators, cylinders, and tanks. The technology of high-pressure systems, although new to fire protection engineering practice, is well developed in other industries, such as the hydraulics and offshore petroleum drilling industries.

The method of generating mist does not uniquely determine suppression capability. Matching the spray characteristics of drop size distribution, flux density, and spray momentum to the fire hazard is more important. The choice of mist-generating method does influence factors such as the cost-effectiveness and reliability of a system.

Impingement Nozzles

Impingement nozzles operate on the principle of a solid jet of water striking a deflector and breaking up into small drops. They include standard sprinklers, nozzles used in traditional (see NFPA 15) water spray and deluge systems, and nozzles used for a myriad of industrial applications. The jet velocity and the shape of the impingement surface determine the cone angle, drop size distribution, flux uniformity, and spray momentum. Figure 16.8.12 shows several types of impingement-style nozzles used in water mist systems.

Impingement nozzles operating at low pressures are simple in design and, therefore, cost less to construct than nozzles that require more precise machining. In 1992, NRCC[77] measured the

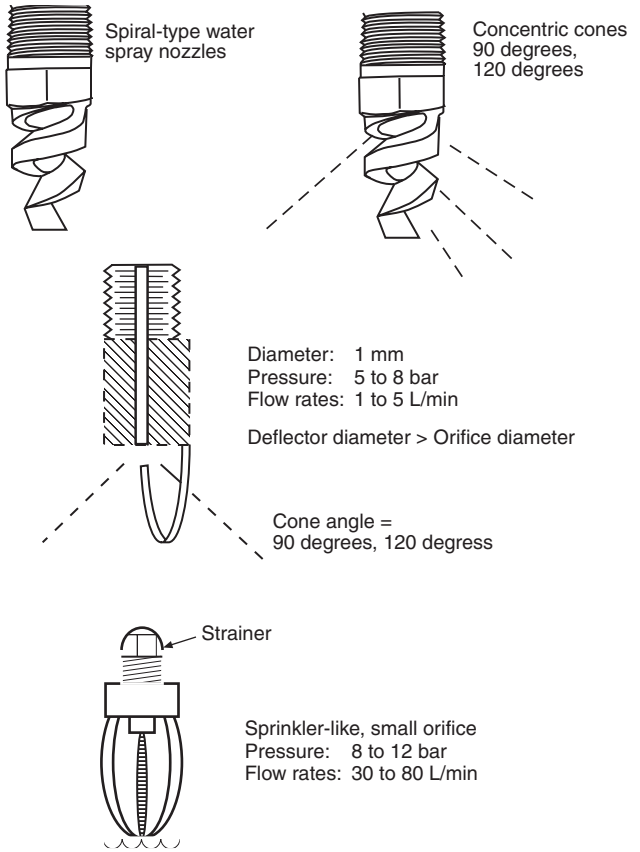


FIGURE 16.8.12 Several Types of Impingement Nozzles for Fine Sprays

spray characteristics of several commercially available impingement nozzles, including sprinkler-type deflector plates, spiral deflectors, and pin-type deflectors, operating at pressures less than 175 psi (12 bar). These nozzles produced Classes 2 and 3 sprays, with cone angles between 60 degrees and 120 degrees. The size and shape of the deflector determined the cone angle. The tests revealed that impingement nozzles have a limited axial spray projection distance because of the energy lost as the jet strikes the deflector. A slight tilt in the deflector plate will skew the spray distribution in one direction. Deflector supports can cause shadow effects, and irregularities in the impingement surface can magnify to large variation in the spray distribution patterns. These sprays controlled or extinguished fires, not only with Class A combustibles, but also in liquid fuel fires in enclosures, where enclosure effects made spray momentum less critical. Overall, the reduced forward spray momentum and irregular flux distribution, which were typical of the impingement nozzles tested, were limitations on their potential use in a water mist system for large machinery spaces.

The relationship between nozzle pressure and discharge rate for impingement nozzles is reliably calculated using the expression familiar to sprinkler system designers: where q is the discharge rate, P is the gauge pressure at the orifice, and k is a coefficient characterizing the nozzle.

Impinging Jets

The term *impinging jets* is used to describe a type of water mist nozzle that creates mist by forcing two thin jets of water to collide after exiting the orifice. Machining of the very small orifices must be very accurate to achieve correct alignment for collision of the jets. A German company has an impinging jet that creates a Class 2 mist at approximately 5 L/min at 175 psi (12 bar) operating pressure. It is an intermediate-pressure nozzle. The nozzle is used in turbine enclosure systems. It was tested in a cable tunnel fire scenario in New Zealand and performed very well.[25]

Pressure Jet Nozzles

Pressure jet nozzles work by pushing a jet of water through a relatively small-diameter orifice at a high velocity. As the jet leaves the orifice, complex physical events occur, involving the fluid viscosity and the jet diameter and velocity relative to the air.[58] The breakup of the thin jet of water into droplets begins within a few millimeters of the orifice. Figure 16.8.13 illustrates several pressure jet nozzles. The disintegration of the jet into droplets can be enhanced by inserting swirl devices in a chamber inside the nozzle to impart a rotation to the jet as it emerges from the orifice. If water is pushed through a narrow slot instead of a circular orifice, the jet takes the form of a sheet, which becomes unstable and disintegrates into droplets.

Individual pressure jet orifices can be assembled in groups on a single base or at intervals along a pipe (linear arrangement). Where several pressure jets are assembled in close proximity on a single base, the combined effect of all jets entrains air into the composite spray cone. The diameter of the fully developed composite cone is not a simple function of initial jet velocity and direction. The trajectory of drops from the individual jets is influenced by the pressure regime within the spray cone, which depends on the manner in which air is drawn toward the nozzle and entrained into the cone. With some nozzles, the spray cone may not become fully developed if free air movement to the back of the nozzle is restricted.

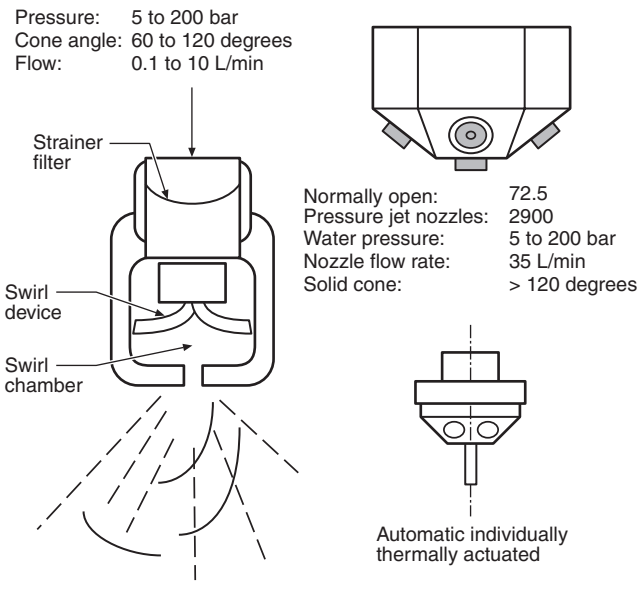


FIGURE 16.8.13 Pressure Jet Nozzles

Pressure jet nozzles operate over a wide range of pressures from 75 to 4000 psi (12 to 272 bar). Pressure jet nozzles require higher operating pressures than impingement nozzles. Up to a limit, the drop size distribution becomes finer as pressure increases. Often there is an upper limit, at which further increase in pressure has little effect on the drop size distribution. There may be incremental increase in mass flow rate or momentum but with no significant improvement in the coverage area of the spray cone. The listing agency will provide information about the operating pressure range needed to produce the desired spray qualities.

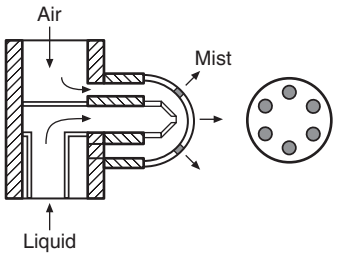
The relationship between pressure and flow from multiorifice pressure jet nozzles follows the simple formula used for single-orifice nozzles, such as sprinklers. Again, the listing agency must provide information on how to calculate discharge rates as a function of pressure from pressure jet nozzles.

Twin-Fluid Nozzles

Twin-fluid nozzles are also referred to as air-atomizing nozzles. They combine compressed gas with a water stream to shear the water into fine droplets. The resulting mist can be directed through one or more orifices to shape a conical spray of any desired cone angle. Twin-fluid nozzles allow for efficient control over drop size distribution, cone angle, spray momentum, and discharge rate. Nozzle manufacturers have produced twin-fluid nozzles for a wide variety of industrial applications, including spray painting, agricultural spraying, and humidification systems. One company markets a twin-fluid nozzle based on a design developed by British Petroleum (BP) Ventures in the 1980s. This nozzle operates with compressed gas and water pressures in the 65- to 90-psi (4.5- to 6.2-bar) range. For fire protection systems (which may require many nozzles), it is an advantage to minimize the total required flow rate of compressed gas. Although typical industrial twin-fluid nozzles operate at air-to-liquid mass ratios (ALR mass) of 0.20 or greater, this particular water mist nozzle operates with ALR mass values of 0.05 to 0.10. Figure 16.8.14 illustrates the mixing arrangement for two types of twin-fluid nozzles.

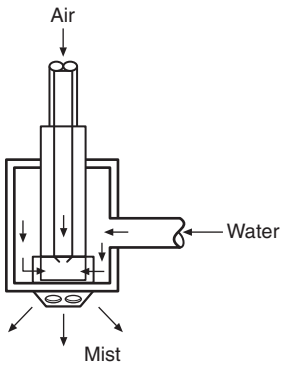
The relationship between water discharge and atomizing medium (air) discharge from a twin-fluid nozzle cannot be characterized by the expression used for simple orifice nozzles. Because the air and water lines are joined (inside the nozzle), the pressure in one line works against the pressure in the other line. As air pressure increases, the airflow increases, which, in turn, forces a reduction in the waterflow and modifies the water system pressure. Conversely, if the water pressure is increased, it reduces the airflow.

Figure 16.8.15 shows a plot of atomizing medium and waterflow rates for a commercial twin-fluid nozzle. The term *air to liquid ratio* (ALR) is used to describe the balance of atomizing medium and liquid demand across the nozzle. To adjust a system in the field and to determine air and water discharge rates from manufacturers' data sheets, it is convenient to use the air-to-liquid pressure ratio, ALR_p. For comparing



Typical commercial air atomizing nozzle

Cone angle:	72 degrees
Nozzle flow rate:	5.3 gpm
Air/liquid ratio (mass):	0.27
Water pressure:	65 psi
Air pressure:	75 psi



Securiplex

Cone angle:	90 degrees, 120 degrees
Nozzle flow rate:	5 to 25 L/min
Air/liquid ratio (mass):	0.10
Water pressure:	4 to 5 bar
Air pressure:	5 to 7 bar

FIGURE 16.8.14 Two Designs for Twin-Fluid Nozzles

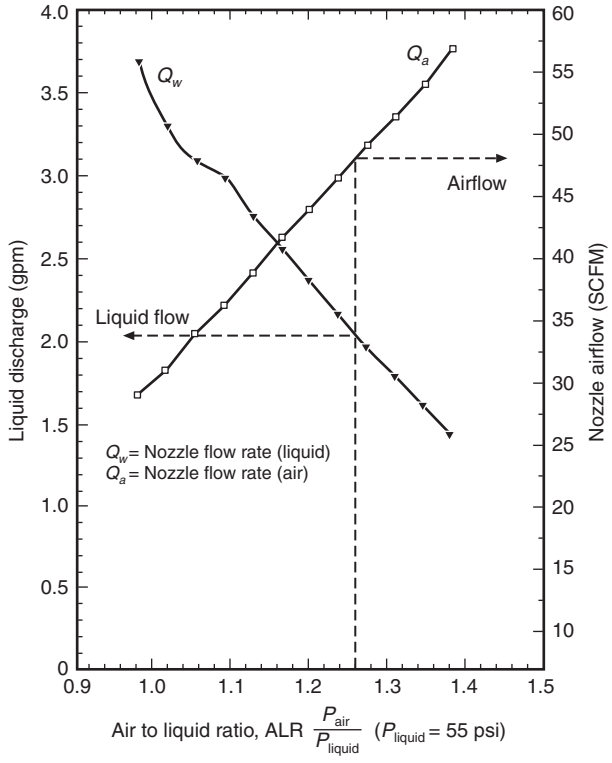


FIGURE 16.8.15 Air- and Waterflow Rates in Twin-Fluid Nozzles

the efficiencies of different nozzles and performing pneumatic system calculations to determine pipe sizes, pressure regulator settings, and the total quantity of compressed gas required for a system, it is better to work with an air-to-liquid ratio expressed in terms of mass flow rates, ALR_m. It is interesting to note that FM Global Loss Prevention Data Sheet 4-2, Water Mist Systems,[74] simply recommends calculating the pneumatic and the hydraulic piping separately to show that the nominal required flow can be delivered at an acceptable minimum pressure. The approach is simpler than the method described previously, and for some types of nozzles it may be sufficiently accurate for practical purposes. A functional discharge test of the installed system will be needed, however, as a final check on the system design.

$$ALR_p = \frac{P_a}{P_w} \qquad ALR_m = \frac{M_a}{M_w}$$

where

ALR_p = Air-to-liquid pressure ratio

ALR_m = Air-to-liquid mass ratio

P_a = Air pressure, gauge, psi (bar)

M_a = Mass of air per unit time, lb/min (kg/sec)

P_w = Water pressure, gauge, psi (bar)

M_w = Mass of water per unit time, lb/min (kg/sec)

The nozzle manufacturer should identify the range of air-to-liquid ratios (pressure and mass) over which the nozzle achieves the optimum spray characteristics. The total compressed gas demand of many nozzles in an open-nozzle system can be costly, so it is desirable to minimize the demand for atomizing medium. An efficient operating point for a twin-fluid nozzle is one that produces the desired spray characteristics at as low an ALR_m as possible (e.g., between 0.05 and 0.10).

Innovations in Mist Generation

The term *innovation* as used here applies to nozzles that incorporate unusual features to improve efficiency or to optimize some characteristic of the spray or that produce spray by a different physical mechanism than those described previously.

Combined Nitrogen and Water Discharge. One company has developed a two-stroke piston pump unit that is driven by compressed nitrogen. It has advantages for applications where electrical power for pumps may be unavailable. It is referred to as a GPU unit and has been listed for machinery spaces, turbine enclosures, and light hazard applications. At each stroke of the piston pump, either water or nitrogen gas is pushed into the piping. It is not clear how to do hydraulic calculations for a distribution system using this system. As the unit discharges air or nitrogen gas in one stroke and water on the next stroke, the flow of mixed gas and water in the piping system has unknown properties with respect to friction loss.

It may be undesirable to use the GPU system for nozzles at different elevations, as the balance of gas and water delivered from the nozzles is unpredictable. It is recommended to conduct a full discharge test of the system to ensure that the quantity of compressed gas is sufficient for the required duration of protection.

Linear Sprays. Water mist is usually delivered from nozzles with a 360° circular spray cone. Nozzles are distributed in a grid at ceiling level. This delivery pattern is typical of sprinkler systems and is suitable for most applications. Some applications, however, require that water mist be delivered to protect a well-defined geometry. Spray that is discharged in any direction other than that dictated by the fuel arrangement would be wasted. Fixed shelving in rows, cable trays, or electronic cabinets with parallel circuit boards are examples of applications in which circular distribution patterns lead to inefficient application of water. Placing small pressure jet orifices at close intervals along a tube creates a linear spray. The nozzle then is actually a length of tube with discharge orifices spaced along its entire length. The K-factor for such an elongated nozzle is different than for a conventional nozzle with orifices situated around a circular metal base. The discharge characteristic of a linear system is a function of the flow rate per orifice, the number of orifices per meter, the total length of each line, and whether water is supplied from one end or both ends.

Flashing of Superheated Water. The "flashing of superheated liquid" phenomenon is usually associated with gaseous fire suppression agents, but it occurs with water as well. A superheated liquid is one that is maintained by pressure in its liquid state at a temperature above its boiling point. When released suddenly from the pressurized container, the liquid partly flashes to vapor and partly disintegrates into spray by the shearing effect of rapidly expanding bubbles.[78–80] The pressure in the closed container is determined by the vapor pressure of the liquid at the given temperature. For water, standard steam tables indicate that at 348°F (176°C) the gauge pressure inside the container will be 118 psi (8 bar). This self-generated pressure is enough to discharge the water from the cylinder. The storage cylinder can be further pressurized by addition of compressed nitrogen, if necessary.

Once released to atmospheric pressure through a simple orifice, superheated water boils instantaneously. Tiny gas bubbles form, expand, and then explode in a powerful release of energy that fractures still-liquid water to small droplets. The rapid release of energy propels the mist throughout the compartment. The percentage of the water that flashes to vapor can be estimated from standard steam tables and could be as high as 14 percent at 348°F (176°C). The flashed water vapor promptly cools and condenses, forming an opaque fog of aerosol-sized (20 micron) water drops. These ultra-fine drops are the result of condensation, not the physical breakup of liquid water by mechanical energy. Within the cloud of white fog, the portion of the liquid that does not flash to vapor is distributed as a "rainout" of Class 1 mist ($^1Dv0.9 \leq$ 200 microns).[62,80]

The rapid generation of mist by the flashing process has been demonstrated to be effective in quenching dust explosions. For hydrocarbon pool fires in enclosures, tests conducted at NRCC[62] showed that the spray was no more effective than other Class 1 sprays. Research into the possible application of this technology continues.

Nano-Mist[81] is an ultra-fine mist with very uniform drop size distribution with a volumetric mean droplet diameter in the 10 micron range. The technology combines an ultrasonic transducer assembly and a process technology for aerosolization, extraction, and transport of mist. The throughput capacity of the mist generator is in the range of 0.25 Lpm (0.06 gpm). The opaque cloud of low-momentum mist can achieve suspended mass of water droplets in excess of 240 g/m^3 (0.015 lb/ft^3). No conventional water mist nozzle approaches that level of suspended water droplets. The Nano-Mist can be transported through smooth ducts to confined areas. In a series of tests conducted for the U.S. Navy to develop a hybrid system (nitrogen plus water mist),[82] Nano-Mist was tested in a mock computer-room subfloor (false deck) against telltale fires.[81] Various combinations of inert gas (nitrogen) and water mist were used to extinguish the test fires. The concentration of nitrogen needed to inert the space and extinguish the fires was first determined. Then water mist was added to the nitrogen. The water mist reduced the concentration of nitrogen needed to extinguish the fires by as much as 40 percent.[83] However, water mist itself could not extinguish the concealed fires in the subfloor. The Nano-Mist, however, was able to extinguish the telltale fires itself without addition of any nitrogen.

The Nano-Mist technology appears to be able to achieve the suspended mass of water droplets needed to bring about extinguishment of hydrocarbon fires if it can be delivered to the seat of the fire. As it is a low-momentum mist, it needs to be transported to the flame region by controlled air movement. Research and development work continues, seeking to increase the rate of generation of the mist to flow rates needed for large spaces, to improve the means of transporting the cloud to the flame area, and to reduce the cost of the ultrasonic generators.

Automatic, Nonautomatic, and Hybrid Nozzles

NFPA 750 introduces the terms *automatic, nonautomatic,* and *hybrid nozzles* to distinguish among three types of nozzles that are already on the market.

Automatic Nozzles. Automatic nozzles operate independently of other nozzles by means of a detection/activation device built into each nozzle. A heat-activated link or bulb is built into the nozzle that, when exposed to heat, releases and allows discharge from that single nozzle in exactly the same manner as a sprinkler. Automatic water mist nozzles use fast-response glass bulb elements, some of 2.5 mm diameter or less. The temperature ratings of the automatic nozzles are selected according to the

application. Automatic water mist nozzles may also be referred to as "water mist sprinklers," as they are used in exactly the same manner as standard sprinklers.

Nonautomatic Nozzles. Nonautomatic nozzles are open nozzles used in deluge-type systems. Water mist systems intended for total compartment flooding are designed to discharge mist from all nozzles in the compartment. A separate detection system is required to detect the fire and release the system. Some local application systems in marine machinery space systems are permitted to be released manually. Once the main control valve is opened, water discharges from all nozzles. Nonautomatic nozzles for use in machinery spaces or aggressive environments are often equipped with blow-off caps to keep moisture and grime from getting into the nozzle orifices and piping. Release of water into the piping system creates enough force to dislodge the blow-off caps, allowing water to discharge freely.

Hybrid Nozzles. The term *hybrid nozzle* was introduced in NFPA 750 to recognize nozzles that were designed with a thermal element so that they would release if exposed to fire in the same manner as an automatic nozzle but which could also be released by a signal from a separate detection system. Hybrid nozzle hardware was developed for experimental work in the 1990s but has not been commercialized or undergone formal component testing associated with the official fire test protocols. It should be noted that the means of generation of Nano-Mist does not involve a nozzle as defined by NFPA 750. The ultrasonic generator, chamber, and associated delivery tubing might be viewed as a hybrid conception.

Choice of Mist-Generation Method

Full-scale fire testing has shown that it is not possible to say categorically that one mist-generation method is better than another with respect to fire suppression. Manufacturers working in different pressure ranges and employing different nozzle designs have all passed the IMO and FM Global Research machinery space and turbine enclosure tests. In general it can be stated that there is a tendency to favor higher rather than lower operating pressures. Nozzles that were at one time thought of as low-pressure nozzles require 185 psi (12.8 bar) minimum nozzle pressure. This means that the normal system operating pressure will be at a higher pressure, putting the system functionally in the intermediate-pressure range (12 to 34 bar). Only the twin-fluid system operates entirely in the low-pressure range for water pressure—the compressed gas provides the additional energy needed to produce a suitable spray. For manufacturers, the choice of mist-generation method for their product line is largely dictated by availability of unpatented technology and the ability to be cost competitive. The designer of water mist systems should be free to choose a mist-generation method according to the engineering merits and the cost of each.

Ultimately the best choice of mist-generation method will be determined by the following:

- Evidence of acceptable performance in a recognized fire test protocol relevant to the application
- Number of nozzles required at the manufacturer's spacing, hence, pipe and fitting materials and labor costs
- Total water demand—storage requirements, potential water damage, and environmental regulations for water retention
- Pump details—suction supply, pump capacity, power requirements, and emergency backup power
- Reliability considerations taking into account the ability to maintain water supply quality, compressed gas cylinder management, electrical circuit supervision, details of specific equipment, and degree of effort involved in scheduled maintenance tasks
- Cost

Reliability Considerations

Water mist systems incorporate a number of features that traditionally have been avoided in water-based fire protection systems. The use of small orifices increases the risk of nozzle plugging. The use of higher operating pressures than traditional sprinkler or water spray systems increases the risk of piping system failure. Control systems rely on electrical release of solenoid valves on compressed gas cylinders or on sectional control valves—a failure of the electrical control circuit will cause failure of the entire system. The use of positive displacement pumps to meet a variable system demand involves programming control logic in a programmable controller. Design procedures to calculate the correct storage volumes of compressed gas and water to deliver water to the nozzles at the specified pressure for the minimum discharge duration have not been fully developed. Design criteria for such systems are based on empirical testing. The use of multiple small storage reservoirs of water instead of a single large tank introduces concerns about maintaining the quality of stored water. The features unique to water mist systems introduce many potential failure modes. Measures must be taken in the design process and in ongoing maintenance to counter each identified failure possibility. Table 16.8.3 tabulates recommended countermeasures to improve system reliability.

DESIGN CALCULATIONS FOR WATER MIST SYSTEMS

Calculation Fundamentals

The calculation procedures for water mist systems range from fundamental methods for single-fluid, low-pressure systems to somewhat more complex methods for twin-fluid and high-pressure systems.

As for any engineered hydraulic system, the designer must select pipe sizes, confirm flows and pressures at discharge points, and determine total flow and pressure requirements for the system in order to select pumps and size storage reservoirs. Such calculations are done routinely for sprinkler systems and water spray systems. Water mist systems introduce problems

TABLE 16.8.3 Potential Failure Concerns and Suggested Countermeasures to Improve Reliability in Water Mist Systems

Potential Failure Concern	*Suggested Countermeasures to Improve Reliability*
Plugging of small orifices in nozzles and small-diameter passages in valves	• Set water quality standards = potable water. • Require screens or filters or both on inlet to storage tanks and on the outlet if algae growth could occur. • Treat stored water to prevent bacterial activity—either chlorination or bromination of UV light. Avoid chlorination where stainless steel tubing is used. • Provide screens on each individual nozzle. • Use corrosion resistant liners in water storage vessels. • Monitor water quality quarterly as part of regular maintenance. Drain and refill stored water cylinders semiannually. • Use corrosion-resistant pipe and fittings; mandate cleaning and flushing measures as installation practice and acceptance testing. • Use blow-off caps to prevent external grime from getting into open nozzles.
Start-up problems with positive displacement (PD) pumps (overcurrent trip)	• Modify NFPA 20 to specify controller design appropriate for PD pumps. • Conform to NFPA 20 with respect to duplicate power supplies and overcurrent protection.
Normally closed valves: Failure of electrical solenoid valves to release compressed gas or open sectional control valves	• Mandate emergency backup power supplies, apply process industry reliability standards, and ensure component testing as part of listing. • Duplicate release capability with hydraulic or pneumatic and manual release features. • Perform regular maintenance to check functionality of solenoid valves.
Normally open valves: Failure to identify a closed valve due to use of nonindicating type valves.	• Mandate use of open/closed indicators on all control valves. • Develop supervisory circuits and scheduled maintenance tasks to confirm water supply valves are open.
Inadequate capacity of stored gas to sustain discharge for the minimum duration	• Mandate calculation procedures to determine required capacity of compressed gas. • Confirm capacity of gas storage vessels by discharge test through system piping or test orifice with equivalent K-factor.
Accident while handling compressed gas cylinders	• Mandate safe handling and storage practices for compressed gas cylinders. • Secure support frames; provide minimum width of access aisle.
Loss of pressure in compressed gas cylinders due to slow leak	• Mandate electrical supervision of gas pressurized piping. • Mandate microleakage control on cylinder headers.
Failure of pressure regulator	• Require component testing of regulators and control valves as part of listing.
Install incorrect size of replacement cylinder	• Post specifications for all replacement cylinders on support rack.
Failure of stored water supply due to: — error in design calculation — loss of water from tank — deterioration in quality (algae growth) — tank corrosion	• Confirm correct capacity of water storage vessels by full discharge test through system piping or test orifice with equivalent K-factor. • Provide duplicate capacity of stored water. • Mandate supervision of water level or visual indicators. • Establish monthly, semiannual, and annual maintenance procedures to monitor water quality.
Failure of detection system for deluge and preaction systems	• Confirm functionality of all detectors, control panel, and interlocks at acceptance test.
Failure of interlocks to shut down ventilation and operate other ancillary devices	• Design and commission detection system to NFPA 72 and conduct regular maintenance as per industry standards.

that are not commonly encountered in calculations for sprinkler systems, however. For example, high-pressure systems may involve positive displacement pumps or stored pressure reservoirs with continuously declining pressure during the discharge. Twin-fluid systems involve the use of pressure-regulating and solenoid valves on both liquid and compressed gas lines. This section reviews some of the special calculation problems encountered in design of water mist systems.

Calculations Involving the Hazen-Williams Equation

NFPA 750 defines a low-pressure water mist system as one that operates at 175 psi (11.9 bar) or less. The operating range of low-pressure systems is similar to standard fire protection systems, such as sprinklers (see NFPA 13, *Standard for the Installation of Sprinkler Systems*), standpipes (see NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*), and water spray systems (see NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*). The requirements for pipe, fittings, valves, pumps, and hydraulic calculations, then, can be met by conventional materials and design practices. Based on this assumed similarity with sprinkler piping, NFPA 750 accepts the use of the Hazen-Williams equation to calculate pressure losses in piping provided that fluid velocity never exceeds 25 ft/sec (7.6 m/sec) (Table 16.8.4).

Values of the friction loss coefficient, *C,* used in the Hazen-Williams equation, are accurate only if the flow velocity is close to that at which the value of *C* was measured.[84] It is a matter of judgment as to what velocity is "too high" for the Hazen-Williams equation. American Water Works Association (AWWA) data, quoted in Titus,[84] list *C* factors measured at a velocity of 3 ft/sec (0.9 m/sec), yet it is standard practice in sprinkler calculations to accept velocities in sprinkler piping between 10 and 20 ft/sec (3.05 and 6.1 m/sec). Similarly, the tables of equivalent lengths for fittings and valves, used by sprinkler system designers, are based on fittings and valve types typical of sprinkler systems. Water mist systems may incorporate different types of fittings and valves, for which the Hazen-Williams–based equivalent length values commonly accepted for sprinkler piping will be incorrect.

Calculations Involving the Darcy-Weisbach Equation

The Hazen-Williams (H-W) equation contains no terms that allow one to change the temperature, density, or viscosity of the liquid. It assumes that the water contains no additives and is close to 60°F (15.6°C). The Darcy-Weisbach (D-W) equation does allow for variation in fluid properties, and for that reason it is widely used by mechanical engineers designing fluid systems.

TABLE 16.8.4 Hazen-Williams Equation for Calculation of Pressure Loss Due to Friction

U.S. Customary Units	*SI Units*
$p = \frac{4.52\,Q^{1.85}}{C^{1.85}d^{4.87}}$	$p_m = 6.05\left(\frac{Q_m^{1.85}}{C^{1.85}d_m^{4.87}}\right)10^5$
p = Frictional resistance, psi per foot of pipe	p_m = Friction resistance, bars per m of pipe
Q = Flow, gpm	Q_m = Flow, L/min
C = Friction loss coefficient	C = Friction loss coefficient
d = Actual internal diameter, in.	d_m = Actual internal diameter, mm

It also allows input of more detail to account for differences in pipe materials from standard sprinkler pipe and fittings. For water mist systems, if viscosity or water temperature departs significantly from typical sprinkler system water supply conditions, the Darcy-Weisbach equation should be used. NFPA 750 requires the use of D-W equation if fluid velocity exceeds 25 ft/sec (7.6 m/sec). The limiting velocity was selected after review of calculations comparing the agreement between H-W and D-W calculations and measured head losses in 1- to 3-in. (25- to 80-mm) diameter black steel pipe, over a range of velocities.[85] Table 16.8.5 shows the Darcy-Weisbach and related equations for use in calculating friction loss in pipe and tubing.

Most of the parameters in the Darcy-Weisbach equation will be known by the designer, such as the diameters and lengths of pipe (including equivalent lengths for fittings) and the density of the fluid. Density may vary according to water source (seawater or potable water) and the possible presence of additives such as wetting agents, fire retardant salts, or antifreeze. The flow rates (Q) will be determined by the nozzle characteristics, such as the K-factor. The unknown value f (friction factor) must be derived through a three-step process as follows:

1. Equation 2 in Table 16.8.5 is used to calculate the Reynolds number (Re).
2. Equation 3 in Table 16.8.5 is used to calculate the relative roughness factor

TABLE 16.8.5 Darcy-Weisbach and Associated Equations for Pressure Loss in Piping

U.S. Customary Units	*SI Units*
Darcy-Weisbach Equation: $\Delta p = 0.000216\,\frac{fL\rho Q^2}{d^5}$	Darcy-Weisbach Equation: $\Delta p_m = 2.252\,\frac{fL_m\rho_m Q_m^2}{d_m^5}$
Reynolds Number: $\mathrm{Re} = 50.6\,\frac{Q\rho}{d\mu}$	Reynolds Number: $\mathrm{Re} = 21.22\,\frac{Q_m\rho_m}{d_m\mu}$
Relative Roughness: $\textit{Relative roughness} = \frac{\varepsilon}{D}$	Relative Roughness: $\textit{Relative roughness} = \frac{\varepsilon_m}{d_m}$
Δp = Frictional loss, psi gauge	Δp_m = Frictional loss, bars gauge
f = Friction factor, psi/ft	f = Friction factor, bars/m
L = Length of pipe, ft	L = Length of pipe, m
ρ = Weight density of fluid, lb/ft^3	μ = Absolute (dynamic) viscosity, centipoise (cP)
Q = Flow, gpm	Q = Flow, L/min
d = Internal pipe diameter, in.	d_m = Internal pipe diameter, mm
ε = Pipe wall roughness, ft	ρ = Weight density of fluid, kg/m^3
D = Internal pipe diameter, ft	ε = Pipe wall roughness, mm
μ = Absolute (dynamic) viscosity, centipoise (cP)	

3. The Moody diagram (Figure 16.8.16) is used to obtain a value for the friction factor

Tables 16.8.6 and 16.8.7 provide values of water density dynamic viscosity and absolute roughness for use in solving equations 2 and 3. Once the Reynolds number and the relative roughness are determined, the values are located in the Moody diagram (see Figure 16.8.16). The intersection point for the Re and values is located on the diagram. A horizontal line is projected from the intersection point to the left axis of the Moody diagram, which provides a value for the friction factor

The value of f and other known parameters are then used in the equation in Table 16.8.5 to calculate a total pressure loss over each length of pipe. The value of f changes as flow quantities accumulate along the pipe length and as pipe diameters change across the system. From this point on the hydraulic calculation procedures are comparable to standard sprinkler calculations—discharges and pressure losses are accumulated over the entire piping network to provide an estimate of the total waterflow rate and pressure required at the water source (pump). Computerized calculation procedures based on the Darcy-Weisbach equations are available.

The equivalent length tables available in many NFPA standards are based on the Hazen-Williams equation and should be checked before being used with the Darcy-Weisbach equation. The head losses incurred across valves and fittings not found in standard tables may be calculated using resistance coefficients (K) and equivalent lengths and flow coefficients, C_v.[86] Valve manufacturers should provide C_v values with data sheets on their valves.

Calculations for Declining Pressure Systems

Systems that utilize stored energy from compressed gas cylinders will operate in one of two ways. Low-pressure systems use a pressure regulator to sustain a constant pressure in the system 7piping. High-pressure systems do not regulate the pressure—all the gas is directed into the piping system, which instantly sees a high pressure that then decays steadily. In either case, the driving pressure in the compressed gas cylinders decreases throughout the discharge. The end of discharge is determined when the compressed gas can no longer deliver the minimum pressure to meet the minimum design flow condition.

For single-fluid systems, calculations to determine pipe sizing are the same as for any constant-pressure system. The engineering question of greater interest is how to determine the number of compressed gas cylinders needed to meet the flow/pressure/duration requirements of the water mist system. For the most part, systems utilizing compressed gas as a driving force are preengineered systems. The manufacturer has determined in

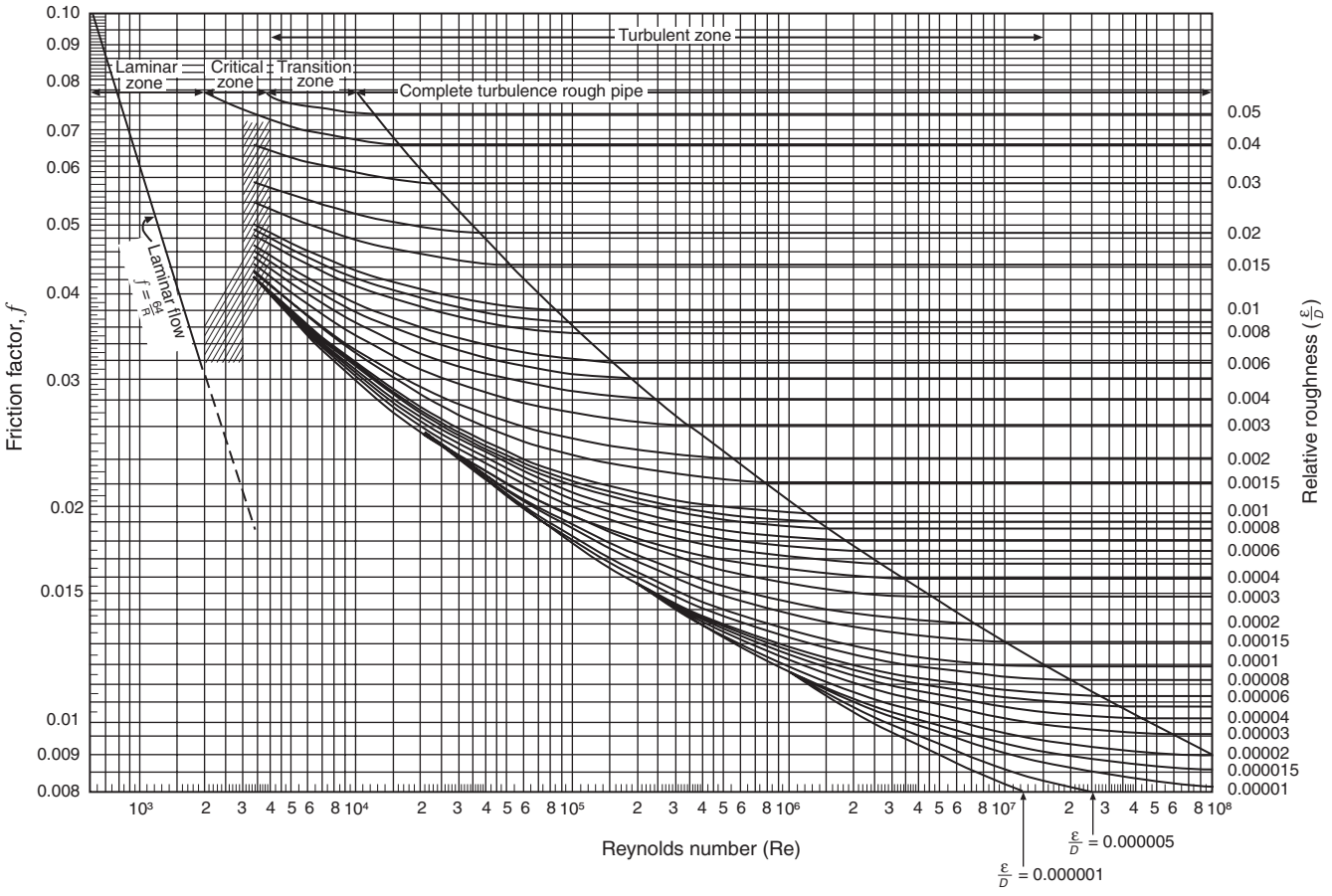


FIGURE 16.8.16 Moody Diagram

TABLE 16.8.6 Approximate Values of μ, Absolute (dynamic) Viscosity, and ρ for Clean Water, over the Temperature Range 40 to 100°F (4.4 to 37.8°C)

Temperature (°F)	*Temperature (°C)*	*Weight Density of Water (lb/ft³) p*	*Weight Density of Water (kg/m³) p_m*	*Absolute (dynamic) Viscosity, μ (centipoise)*
40	4.4	62.42	999.9	1.50
50	10.0	62.38	999.7	1.30
60	15.6	62.34	998.8	1.10
70	21.1	62.27	998.0	0.95
80	26.7	62.19	996.6	0.85
90	32.2	62.11	995.4	0.74
100	37.8	62.00	993.6	0.66

previous trials how many cylinders are needed to meet the design flow and the choice has been validated by the listing tests. However, if the number of nozzles increases and the piping layout is changed to adapt to an actual space, the compressed gas demand must be calculated. The designer is interested in knowing the length of time each nozzle will discharge in the pressure range needed for producing the design spray characteristics, the settings for pressure regulators, and how much water must be stored.

Practical calculation procedures for predetermining quantities of compressed gas cylinders for compressed gas–driven systems are not yet available. Manufacturers generally work out the gas requirements from basic assumptions about the volume of gas in a cylinder at a given pressure, the ideal gas law, and trial and error. If it is not possible to check design adequacy by reviewing the designer's calculations, there is no better means of confirming adequacy of compressed gas supply than a full system discharge test.

Figure 16.8.17A shows the results of pressure measurements taken at the hydraulically most remote nozzle in a twin-fluid system. The measurements were taken as part of the final acceptance test for the system. The system was designed to deliver six discharges of 50 second duration each. The manufacturer's specification for minimum nozzle operating pressure, for both water and compressed gas lines, was 66 psi (4.6 bar). The test plot shows that the system completed five discharge episodes at the desired pressure range, but the sixth discharge could not achieve the minimum operating pressure. The compressed gas supply was exhausted before the design duration was achieved. Adding one cylinder to the compressed gas bank extended the discharge to the minimum required duration.

In this case the manufacturer's method of estimating compressed gas requirements was inaccurate. The problem could be due to unavoidable imbalances in the system piping, so that more compressed gas than necessary was flowing through nozzles closest to the source. Thus, the characteristics of the pip-

TABLE 16.8.7 Recommended Values of Absolute Roughness or Effective Height of Pipe Wall Irregularities, for Use in Relative Roughness Equation

Pipe Material (new)	*Design Value of ε (ft)*	*Design Value of ε (mm)*
Copper, copper nickel, drawn tubing	0.000005	0.0015
Stainless steel, commercial steel, wrought iron	0.000150	0.0450
Galvanized iron	0.000500	0.1500

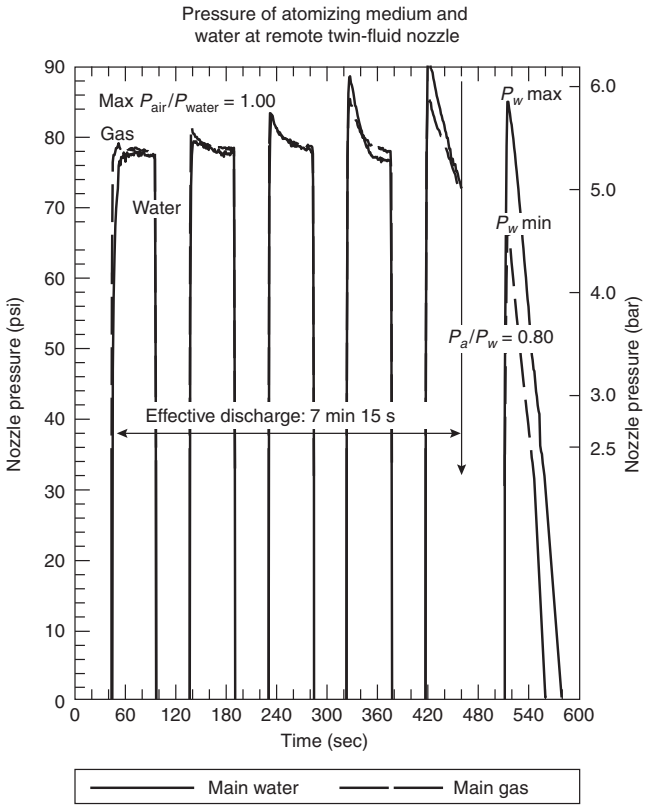


FIGURE 16.8.17A Discharge Test Results for a Twin-Fluid Water Mist System. Test objective was to confirm that the compressed gas supply was sufficient to sustain pressure greater than minimum 4.6 bar (66 psig) for 30 minutes. Pressures measured at remote twin-fluid nozzle.

ing system will directly affect the rate at which compressed gas supply is depleted. Since there were no calculations to confirm the adequacy of gas supply, the full discharge test was the only means of verification. In contrast, Figure 16.8.17B[87] shows the results of a full system discharge test of a gas-driven pump unit. The objective of the test was to ensure the adequacy of the compressed gas supply to achieve a 30 minute discharge duration, with the final system pressure not less than the end-of-discharge pressure in the FM approval test, which was 15 bar (215 psi).

Compressed gas cylinders are used on a variety of preengineered water mist systems. For all of these systems, the manufacturer is responsible for ensuring that the compressed gas supply is adequate for the design performance. Because industry practice is still founded in trial and error, it is highly advisable to verify design adequacy by means of a full system discharge test. The noise, sputter, and poor visibility in the compartment make it difficult to identify the end of discharge by visual observation. There must be actual measurements of nozzle pressure—the end of discharge is clearly identified when the nozzle pressure falls below its minimum operating pressure.

If circumstances do not permit a full system discharge for acceptance testing, the absence of a verifying calculation procedure is a serious problem. Such systems should be equipped with a test connection that simulates the system K-factor.

Calculations for Twin-Fluid Systems

Twin-fluid systems require sources of pressurized water and compressed gas in order for the nozzles to produce spray as required for fire suppression. The two "fluids" are delivered to the nozzles through two independent piping systems. The designer must calculate the pressure losses in each piping system in order to ensure that nozzles perform as intended and to determine the minimum storage quantities and pressure for each agent. The quantities of water and of compressed gas ("air") discharged at each nozzle depend on the air-to-liquid ratio (ALR) characteristics of the nozzle. If the air pressure is too high, it could prevent water from entering the nozzle. If the water pressure is too high, not enough air will enter the nozzle and the spray quality will deteriorate. Both air- and waterflow rates are very sensitive to the balance between their respective pressures. For that reason, summing the nominal flow rates of air and water is not the correct way to determine the required quantities of stored water or gas. Twin-fluid systems require special calculation procedures in order to ensure adequate nozzle performance, select pipe sizes, and determine agent storage requirements.

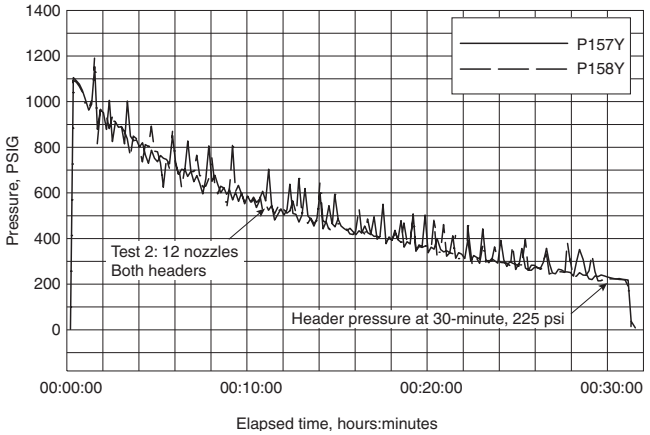


FIGURE 16.8.17B Results of Acceptance Test of a Decaying Pressure, Gas-Driven Pump System over a 30 Minute Discharge Period. Test objective was to confirm that the compressed gas supply was sufficient to sustain pressure greater than minimum 15 bar (215 psi) for 30 minutes. Pressures measured at pump discharge header.

One approach to the problem is to perform both the hydraulic and the pneumatic calculations simultaneously, checking to ensure that the gauge pressures, and pressure differences between liquid and compressed gas, at each nozzle, fall within a specified range. The listing information for a twin-fluid nozzle identifies the maximum and minimum operating pressures for both liquid and atomizing media. The designer's task is to select preliminary pipe sizes on both piping systems and then to work methodically through two sets of calculations, comparing the conditions at each nozzle. The H-W equation can be used for the water distribution piping. The calculations for the compressed gas line should follow standard engineering practice as described in references.[88] At any point, if the pressure/flow conditions exceed or fall outside of the desired operating range, an adjustment to the piping system should be made. After several iterations, it is possible to arrive at a reasonable estimate of total system demand.

The key step in the calculation procedure involves confirming that the ALR_m, that is, the mass ratio of the water discharge and the atomizing media discharge, at each nozzle, is within an acceptable range. That is,

$$ALR_m \text{ (min)} < ALR_m \text{ (actual)} < ALR_m \text{ (max)}$$

Figure 16.8.18 illustrates one model for this calculation procedure. Values for the water pressure and flow rate and air pressure and flow rate, at the most hydraulically remote nozzle, are set based on the manufacturer's recommended values. Flow rates must be converted from volumetric to mass units, for example, gpm to lb/min (L/min to kg/min), and SCFM to lb/min (m^3/min to kg/min). The ALR_m value (ALR_1 in Figure 16.8.18) is calculated. Then, for the given flow rates through the pipes supplying the most remote nozzle, the total pressure losses in each leg are calculated using the appropriate equations and added to the beginning pressures. The new pressures at the upstream nozzle (Pw_2 and Pa_2 in Figure 16.8.18) are used, with the manufacturer's nozzle data, as shown in Figure 16.8.15, to determine the new flow rates, Qw_2 and Qa_2. These values are converted to mass units to calculate ALR_{m2}. If ALR_{m2} is not within the acceptable range, then one of the pipe diameters should be increased or decreased and the calculation repeated. If it is within the acceptable range, the flows are accumulated and the calculation proceeds to the next nozzle until all nozzles have been included.

It is expected that manufacturers of twin-fluid systems will develop computerized methods for performing hydraulic and pneumatic calculations in combined piping systems. As noted earlier, FM Global accepts calculating the hydraulic and pneumatic piping independently.[74]

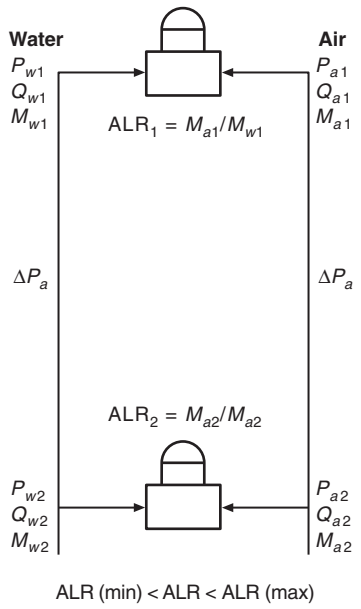


FIGURE 16.8.18 Simplified Air-to-Liquid Ratio Model

Calculations for High-Pressure Pump Systems

Water mist systems for large spaces or where a long duration of flow is needed require the use of pumps rather than compressed gas cylinders. For high-pressure systems, positive displacement (PD) pumps are normally used. Positive displacement refers to the fact that at each rotation of a gear or a piston, a fixed quantity of water is displaced. Although it is possible to use centrifugal pumps to generate high pressures, either by operating at very high speeds or by adding pumps in stages, it is more cost-effective to use PD pumps. The output pressure of a PD pump is limited only by the power of the motor and the strength of materials used. Centrifugal pump systems automatically vary both the pressure and discharge according to the demand of the fire suppression system. In contrast, PD pumps put out a constant Q but at varying pressure. Herein lies the engineering challenge: the hydraulic demand for a water mist system is seldom constant. Demand varies depending on the number of nozzles that open, as is the case when automatic nozzles are thermally released. It is also the case when several deluge systems of different sizes are supplied by a single pump source. The pump system must be able to supply both the largest and the smallest system demands. Calculations are needed to match the pump supply curve to the range of system demands and to develop a control program to manage the system.

The key to design involving PD pumps is to incorporate a pressure unloading valve, or unloader valve, with each pump. Figure 16.8.19 is an ISO symbol diagram showing a PD water mist pump assembly with unloader valves on each pump. The diagram shows two PD pumps driven by a single electric motor using direct-drive couplings at each end of the drive shaft.

An unloader valve incorporates a spring-operated valve and a check valve. When the system pressure exceeds the setting on the spring, the valve bypasses all output from the pump(s) that cannot be discharged by the system. The designer selects a pump with a specified volumetric output (L/min) at the set motor speed. The pump is coupled with an unloader valve that can "unload" up to the full output capacity of the pump. One approach is to design with one or more pumps to provide the desired Q output (equal to the maximum system demand) and a single large-capacity unloader valve. Several water mist pump manufacturers' systems are designed on this basis. In this case, the "pump curve" appears as shown in Figure 16.8.20, where the maximum pressure of the system is determined by the setting of the single unloader or pressure relief valve.

Another approach is to divide the total system demand among a number of small pumps, each with its own unloader valve and

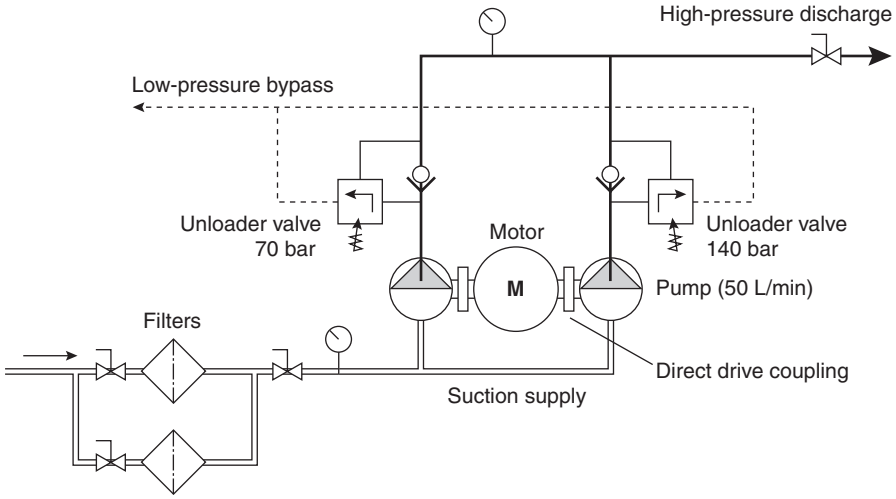


FIGURE 16.8.19 ISO Symbol Diagram of a High-Pressure Pump Assembly with Unloader Valves on Each Pump

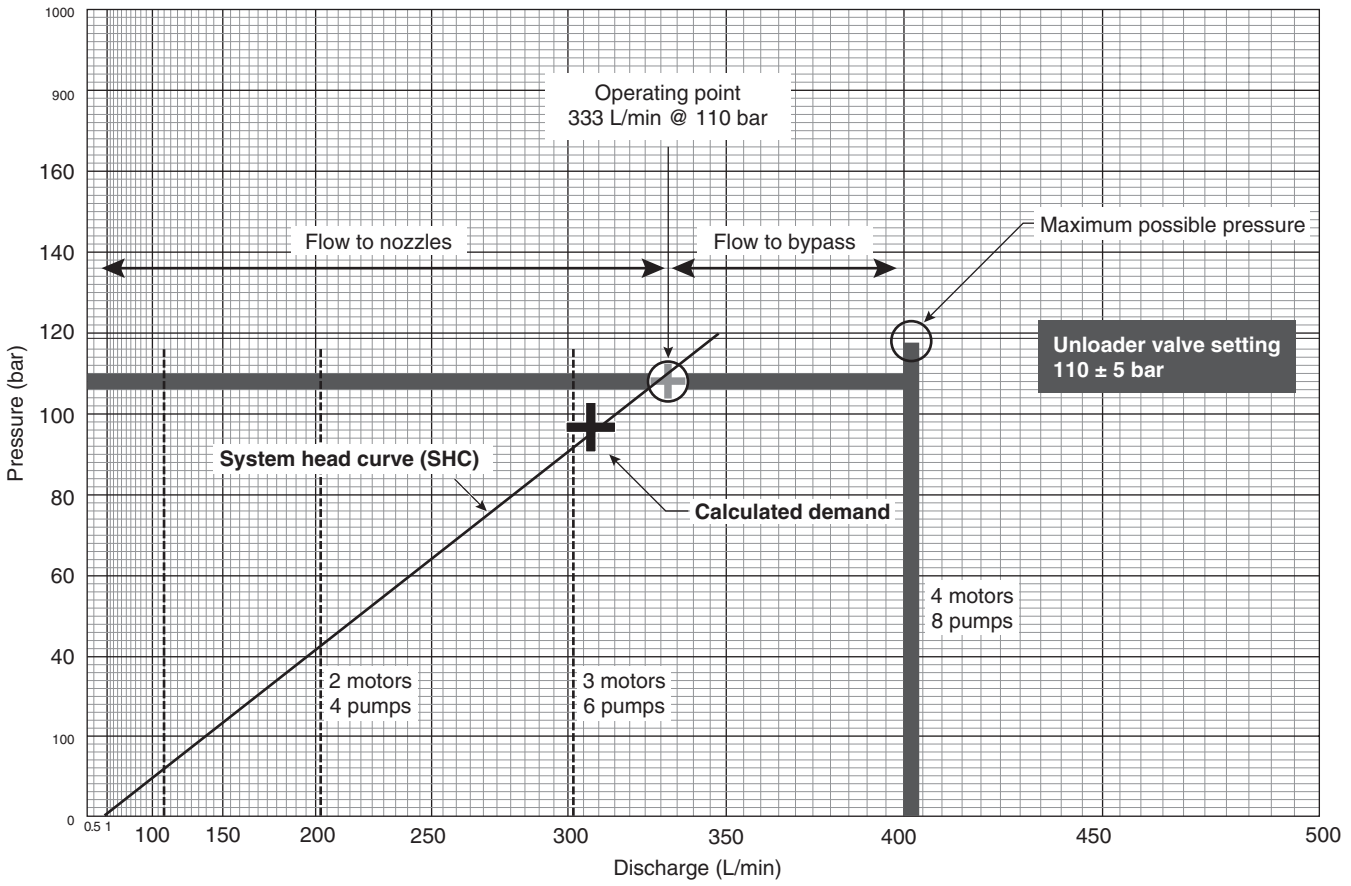


FIGURE 16.8.20 Composite Pump Curve for an 8 Pump Assembly with Single or Multiple Unloader Valves Set at 110 Bar

unique setting, and then bring different numbers of pumps on line as needed to match the demand. If one unloader valve is set at one-half the setting of the other unloader valve, the pump curve has a stepped appearance, as shown in Figure 16.8.21.

Suppliers of high-pressure water mist pumps and pump assemblies use both of these strategies. A German company uses a motor driving a single-piston pump of 120 L/min volumetric output at 1800 rpm as its basic unit. To meet larger demands several motor/pump combinations are connected in parallel to a common header. An unloader valve is connected to the common header—it is sized to pass the total output of all pumps connected to the header, for example, 120, 240, 360 L/min or more. Figure 16.8.20 illustrates the resulting pump curve. One difficulty presented by using a single large-capacity unloader valve is that, with small flows such as with a single water mist sprinkler flowing, the unloader valve may "chatter," causing uneven flow to the single nozzle. The arrangement is adequate for deluge-type water mist systems for which a relatively large flow rate is required, but it is less suitable for sprinkler-type water mist systems with automatic nozzles, in which only one or several nozzles will be opened. It should also be noted that settings on unloader valves may vary by 5 bar or more (75 psi) above or below the set pressure. It is imperative to test the installed equipment to determine the as-built capacity of the combination of pump(s) and unloader(s).

A European manufacturer of high-pressure water mist systems uses a different strategy. A piston pump with a volumetric output of about 50 L/min at 1800 rpm is used as the basic unit. A single electric motor may drive from one to four such pumps. Each pump is equipped with its own unloader valve, and each unloader valve can be set to different pressure. This approach allows the pump assembly to provide small flows at very high pressure and larger flows at a lower pressure, usually one-half the pressure of the lower flow regime. Figure 16.8.21 shows the two-step pump curve for the arrangement.

Each piston pump has an output of 13 gpm (50 L/min) discharge capacity at 1800 rpm. Assume, for example, that the largest demand on a system is 19.8 gpm (75 L/min), and the smallest demand is one nozzle at, say, 5.3 gpm (20 L/min). Both pumps would be required to meet the largest demand, at 70-bar pressure and some flow going to waste. The smallest demand of a single nozzle is less than the output of one pump. The unloader set at 70 bar will send all of its flow to the bypass, and the unloader set at 140 bar will allow 20 L/min to flow to the nozzle and the unused 30 L/min to bypass to waste. Even though the constant Q output of a single pump at 13 gpm (50 L/min) exceeds the smallest demand, the unloader valves allow partial output flows.

Table 16.8.8 displays the equations needed to design a PD pump system. Equation 1 calculates the power required of a motor to achieve a specified pressure/flow condition. Equation 2

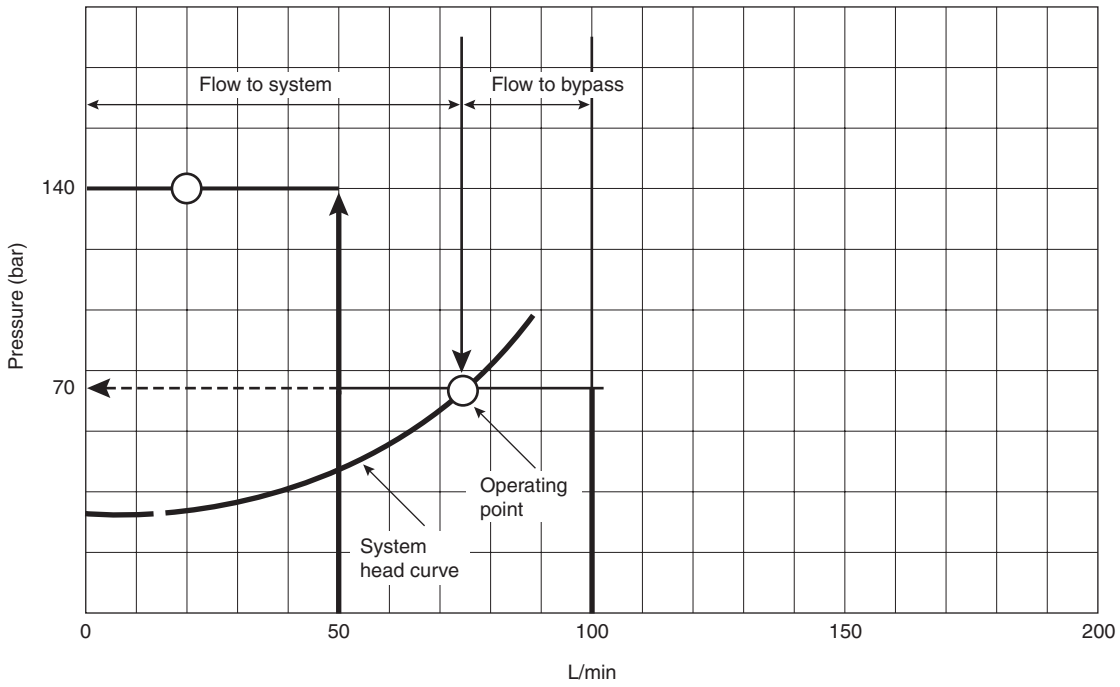


FIGURE 16.8.21 Composite Pump Curve for Two PD Pumps with Unloader Valves Driven by a Single Motor

TABLE 16.8.8 Basic Equations to Be Used in Design of PD Pump Assemblies

Pump Equations—Metric Units

$$kw = \frac{Ql \times H}{600 \times Em \times Ed} \quad \text{Eq. 1}$$

$$H_{max} = \frac{kW \times 600 \times Em \times Ed}{Ql} \quad \text{Eq. 2}$$

$$\text{Amp} = \frac{kW \times 1000}{Em \times Pf \times V \times \sqrt{N}} \quad \text{Eq. 3}$$

kW = Motor power, kW
Ql = Discharge flow, L/min
H = Discharge pressure, bar
600 = Coefficient of 598.8 ~ 600
Em = Efficiency of motor (0.88 to 0.92)
Ed = Efficiency of drive gear (<0.85)
Amp = Full load amp draw
Pf = Power factor (~0.85 depends on motor)
V = Volts
N = Number of phases in supply ($N = 3$)

Pump Equations—U.S. Units

$$bHp = \frac{Qg \times P \times 2.31}{3960 \times Em \times Ed} \quad \text{Eq. 4}$$

$$P_{max} = \frac{bHP \times 3960 \times Em \times Ed}{Qg \times 2.31} \quad \text{Eq. 5}$$

$$\text{Amp} = \frac{bHP \times 746}{Em \times Pf \times V \times \sqrt{N}} \quad \text{Eq. 6}$$

bHP = Brake horsepower
Qg = Discharge flow, gal/min
P = Discharge pressure, psi gauge
3960 = Coefficient for U.S. units
Em = Efficiency of motor (0.88 to 0.92)
Ed = Efficiency of drive gear (<0.85)
Amp = Full load amp draw
Pf = Power factor (~0.85 depends on motor)
V = Volts
N = Number of phases in supply ($N = 3$)

calculates the maximum pressure that could be achieved using a specific motor with a specific PD pump. Equation 3 is used to calculate the full-load amp draw in order to size the electrical supply. All electrical equations assume 60 Hz frequency power.

Some very large water mist systems, such as those installed on cruise ships and in the oil and gas processing industry, make use of multiple assemblies of motors and PD pumps capable of providing specific flow rates to different zones. A controller is programmed to start a specified number of electric motors depending on which system is activated. Each system of nozzles will have its unique hydraulic characteristic, referred to as a system head curve (SHC). The SHC for any system is obtained by performing hydraulic calculations on the piping system to determine the total head losses at a given discharge rate. When the water supply is activated, the actual operating point can be determined by plotting the system head curve (SHC) for the piping system on the plot of pump curves. In Figure 16.8.21, which is a Cartesian plot, the SHC has an actual curve shape. When plotted on $N = 1.85$ hydraulic graph paper, as in Figure 16.8.20, the SHC is a straight line. For a complex assembly of multiple pumps and unloader-valve settings, the hydraulic plot looks like Figure 16.8.22.[89]

Figure 16.8.22 shows a plot of an assembly that includes 6 motors and 24 pumps. The assembly was designed to meet the different demands of many separate water mist systems in machinery modules of different sizes. The composite pump curve is determined by summing the number of motors, the number of pumps per motor, the volumetric capacity of each pump, and the settings on the unloader valves on individual pumps. The demand for each water mist system must be calculated separately and plotted on the graph. The SHC represented by the constant K line (dashed line) for the calculated point is projected to where it intersects the supply curve. This determines the operating point for the system and how many motors and pumps will be needed. A programmable controller is used to start the correct number of motors for a given water mist system demand. When a separate detection system calls for release of a water mist system in a given machinery module, the controller starts the number of motors needed to meet the precalculated demand. Figure 16.8.22 was used for acceptance testing to confirm that the PD pump system design for a large facility in Alaska was correct.[89]

As recommended by NFPA 750, when conditions permit, a full system discharge should be performed with recordings of critical pressures throughout the duration of the test. In the case shown, the actual measured operating point was above the calculated value, indicating either an error in the calculation or a significant difference between design and as-built piping. There

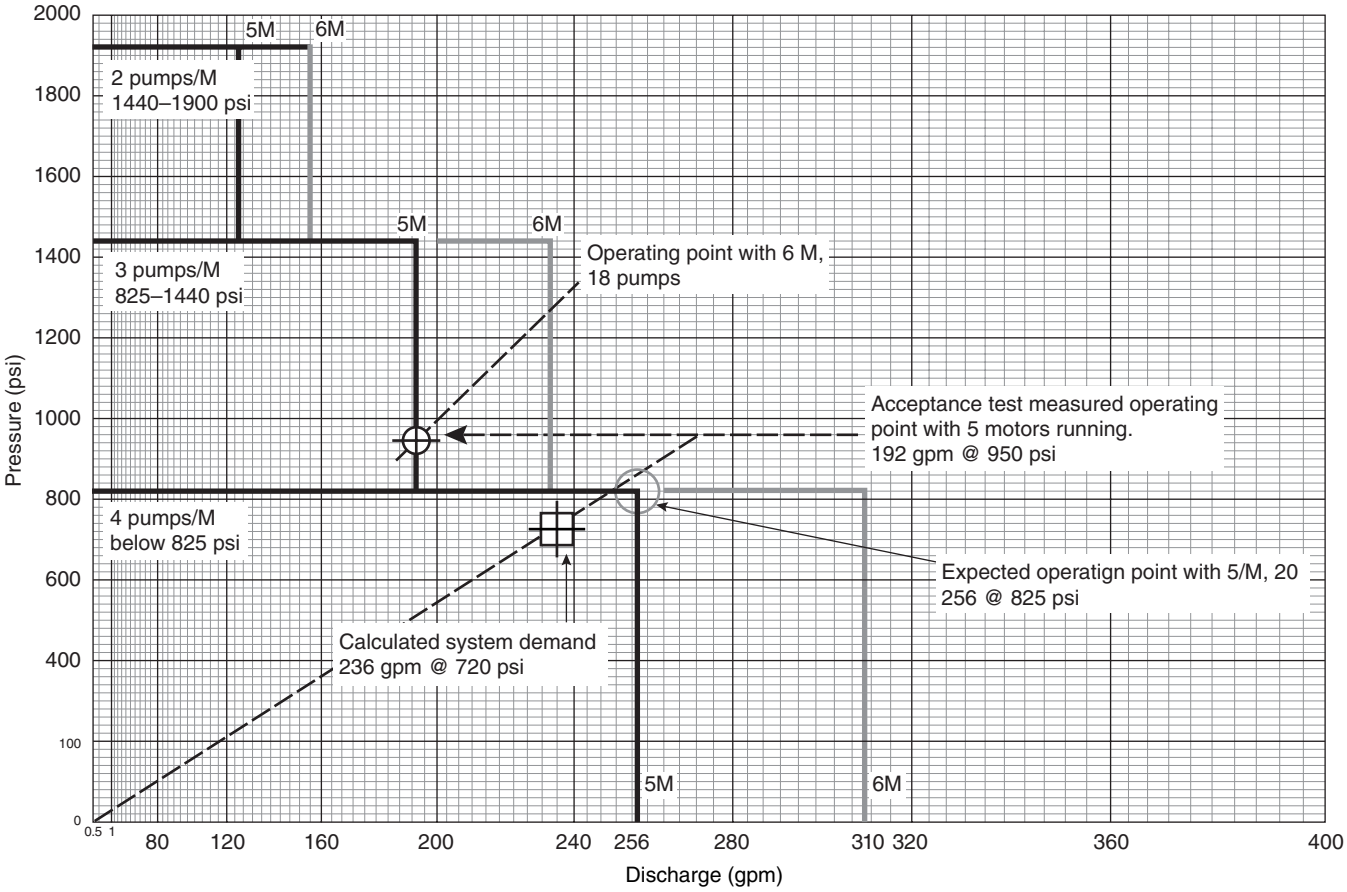


FIGURE 16.8.22 Hydraulic Diagram for Acceptance Test of a Water Mist System. Measured operating point indicates piping system is more restricted than calculated. Solution was to program system to operate six rather than five motors.

is a tendency to interpret a higher pressure on a system as corresponding to a higher discharge from the system. That interpretation only applies for a demand curve (i.e., a system head curve), for which a pressure increase corresponds to an increase in discharge. But a discharge pressure measured as part of a pump test represents the operating point of the system, where the demand curve intersects the supply curve. For a supply curve, a higher than expected pressure corresponds to a lower discharge rate. This principle applies for both centrifugal and PD pumps. Therefore, the operating point plotted in Figure 16.8.22 lies on the vertical portion of the pump curve above the lowest pressure setting of the fourth unloader, for which the total flow rate is *less than* the design flow rater for the system. In this case plotting the results of the full-system discharge test on the hydraulic graph sheet revealed the problem. After confirming that the hydraulic calculations were correct, the possible remedial actions were to (a) investigate the piping system to find and remove any restrictions, and (b) change the control program to start six motors instead of five motors for this system. In the particular case, the control program was changed to start another motor to increase the flow to at least the minimum design flow rate.

SYSTEM TYPES

NFPA 750 has introduced descriptive terms that classify water mist systems according to four basic characteristics of their design. The four parameters used as the basis of description are (1) system operation method, (2) operating pressure, (3) application, and (4) nozzle type. The reasons for classifying systems according to these four classifications are presented in the following sections.

System Operation Method

Systems may be described as deluge, dry-pipe, preaction, or wet-pipe systems. These descriptions are the same as those used for automatic sprinkler systems.

Deluge Systems. Deluge systems utilize open nozzles spaced throughout a compartment or around an object to be protected. Water is held out of the piping system by a *deluge* valve, which can be automatically released on a signal from a control panel. The system requires a separate fire detection system, which provides the signal to the control panel to release the water. Manual release features are always provided as well. When the deluge valve opens, water fills the piping system and discharges from all water mist nozzles simultaneously. The deluge system operation is widely used for machinery compartments and other applications where it is necessary to completely surround a fire with mist.

Dry-Pipe Systems. Dry-pipe systems utilize normally closed automatic nozzles on a closed piping system. The piping is pressurized with compressed gas. Some low-pressure water mist systems may use a differential-type dry-pipe valve held closed by the gas pressure. Such systems are then exactly equivalent to a standard dry-pipe sprinkler system. In the case of high-pressure water mist systems, there are no differential-type sectional control valves. The control valve is electrically activated and must be released by the fire alarm control panel (FACP). The signal to open the valve may come from a pressure sensor that responds to decreasing system pressure when an automatic nozzle is opened by heat. Pneumatic valves designed to open on a differential pressure are available.

Preaction Systems. A preaction system is similar to a dry-pipe system in that it utilizes closed nozzles on a piping system that contains no water. Water is prevented from entering the piping network by means of a valve that can be opened automatically by a control panel. A supplementary detection system is required to signal that there is a fire in the compartment and to open the valve. Water then enters and fills the piping, at which point the system operation is identical to a wet-pipe system. Water is not discharged until the heat is sufficient to actuate a nozzle. Just like a standard preaction sprinkler system, a low air pressure in the piping can be monitored to supervise the integrity of the piping system. A loss of air pressure would reveal a leak in the piping without resulting in a discharge of water.

Wet-Pipe Systems. A wet-pipe system consists of an array of closed nozzles on a piping network that is filled with water. Each nozzle is equipped with a thermal sensing element, like a sprinkler, which opens the nozzle when exposed to fire (hence, an *automatic* nozzle). As nozzles are opened by heat, water discharges immediately. This sprinkler-system-like configuration is suitable for many applications.

Operating Pressure

A second characteristic that differentiates system types is the range of operating pressure. Three categories have been defined by NFPA 750 as (1) low-pressure, (2) intermediate-pressure, and (3) high-pressure systems.

Low-Pressure System. In this water mist system the distribution piping is exposed to pressures of 175 psi (12.1 bar) or less.

Intermediate-Pressure System. In this water mist system the distribution system piping is exposed to pressures greater than 175 psi (12.1 bar) but less than 500 psi (34.5 bar).

High-Pressure System. In this water mist system the distribution system piping is exposed to pressures of 500 psi (34.5 bar) or greater. The working pressure regime of a water mist system is determined by the manufacturer's choice of nozzle. It is possible to create water mist with suitable spray characteristics in all three pressure regimes. With the exception of twin-fluid systems (and Nano-Mist), most commercial water mist systems operate in either the intermediate- or high-pressure range. Even if the nozzle is rated for 175 psi (12 bar) minimum operating pressure, which is the limit of low-pressure water mist, the operating pressure will by definition be higher than the minimum nozzle pressure; hence, it will be an intermediate-pressure system. Most of the advantages and disadvantages of high- versus low-pressure systems have already been discussed. In general, the use of high-pressure nozzles may increase spray velocity,

which may translate to greater nozzle spacings and lower overall flow rates than low-pressure systems.

Although not introduced in NFPA 750, further distinction can be made between constant pressure systems and declining pressure systems. In general the distinction is between a pumped system versus one driven by cylinders of compressed gas. For water mist systems utilizing centrifugal-type pumps, or positive displacement pumps with a single unloader valve on the common header, the nozzle pressures remain approximately constant over the design area throughout the 30-minute discharge. In gas-driven systems, the nozzle pressure declines continuously over the duration of protection. In performing acceptance testing of declining pressure systems, the author has used the minimum pressure available at the end of the discharge in the approval test report as the criterion for minimum operating pressure.

Not all pumped systems are necessarily constant pressure systems, however. For marine water mist sprinkler systems utilizing pumps with a single unloader valve, a constant pressure system is designed on the basis of a minimum operating pressure at the most remote nozzle in a 180 m^2 (2000 ft^2) design area. The minimum operating pressure is the pressure that was used in the approval tests. For systems designed to use assemblies of positive displacement pumps with unloader valves on individual pumps, it is possible to design for at least two pressure regions, one higher than the other (see Figure 16.8.21). During the early stages of a fire, a few automatic nozzles may open. The pump assembly can deliver the required volume of water at a very high pressure. As more automatic nozzles open, the pump assembly can deliver the larger flow but at a lower pressure (determined by the pressure setting on the unloader valves). The system might be designed then for a design area of 100 m^2 (1100 ft^2) at 120 bar (1740 psi) and 180 m^2 (2000 ft^2) at 60 bar (870 psi). A similar concept of having to prove hydraulic capacity for two design conditions has been applied to sprinkler system designs in the past.[90]

Application

Three different types of applications are described in NFPA 750. These are (1) local, (2) total compartment, and (3) zoned applications.

Local Application. This configuration is used to protect a specific hazard or object. An example may be the protection of a piece of equipment in a large compartment. The system would be designed to discharge water mist directly onto the object. Figure 16.8.23 depicts a local application system.

Total Compartment Application. This type of system provides protection to all fire hazards and all areas in a compartment. The open nozzles are positioned in a grid so that water mist discharges approximately uniformly throughout the entire volume. Figure 16.8.24 illustrates a total compartment application system.

Zoned Application. This type of system is configured to discharge mist from portions of a larger system as required to control fire in a specific part of a compartment. It would be considered, for example, in circumstances where the water demand for a total compartment system (i.e., a deluge system), would be beyond the capability of the water supply. Zoning the water mist piping network, however, requires the installation of a detection system capable of pinpointing the exact location of the fire in the compartment or portion of a tunnel and a piping control system capable of opening or closing specific valves in the distribution network. Research focused on achieving accurate fire detection and location for zoning purposes continues.[91]

Figure 16.8.25 illustrates elements of a zoned application system. Clearly, water mist systems for tunnels must be zoned

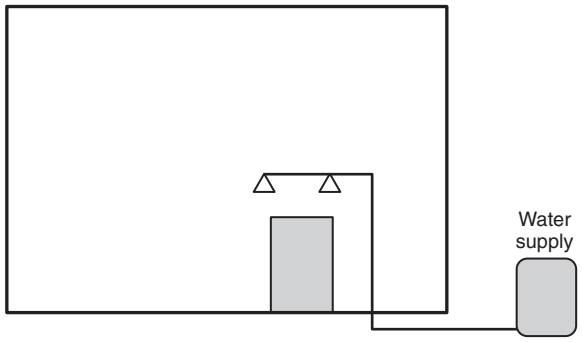


FIGURE 16.8.23 Local Application System

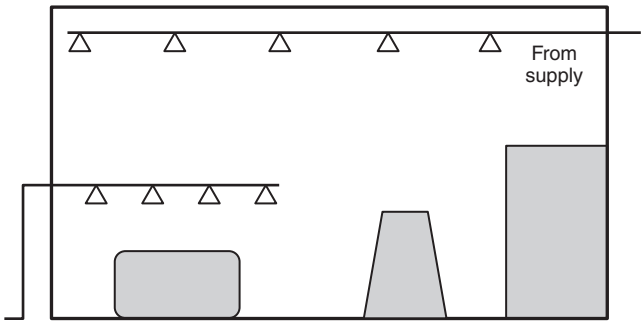


FIGURE 16.8.24 Total Compartment Application with Local Application System

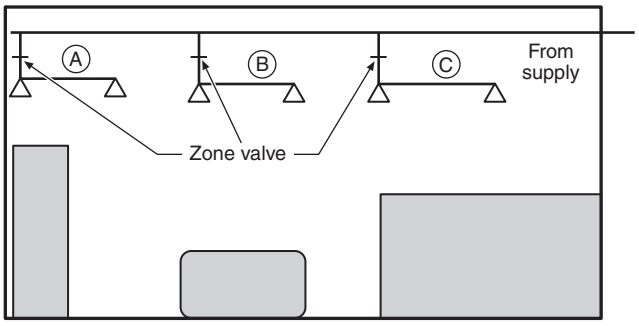


FIGURE 16.8.25 Zoned Application

in order to limit the total waterflow requirement. Typically, the design is based on the flow required for three zones—the zone where the fire is detected, plus one zone upstream and one zone downstream, to accommodate the possibility of a fire occurring at the boundary between two zones.

Nozzle Type

The nozzle type constitutes the fourth parameter for classifying water mist systems. Nozzles have been described as "open" or "closed" in previous text. Open nozzles have also been referred to as "nonautomatic" nozzles because they play no role in whether water is released. That is determined by the supplemental detection system. However, closed nozzles are designed with thermal sensing elements or other features that allow them to open, individually and automatically, in the presence of fire. Thus, NFPA 750 has adopted the terms (1) *nonautomatic,* (2) *automatic,* and (3) *hybrid* to describe the operation principle of types of nozzles. Characteristics of the types of nozzles are described elsewhere in this chapter.

SYSTEM COMPONENTS

As with all fire protection systems, water mist systems require their own unique set of hardware features, components, and materials. Basic components include but are not limited to pipe, fittings, valves, hangers, gas and water containers, nozzles, strainers, pumps, and detection system components.

The quality of system components and the overall reliability of water mist systems can be enhanced by using materials and components that comply with internationally recognized standards or material specifications. This is addressed in NFPA 750 by requirements for most components of systems to be listed for specific duty in water mist systems. The requirement of listing is particularly emphasized in North America. Marine authorities and European users have accepted water mist system technology on the basis of component testing done under the auspices of the International Maritime Organization (IMO) test protocols. The first water mist systems installed in North America contain components that were not listed at the time of installation but were part of systems being marketed internationally. Examples include pumps, motors, controllers, and the tubing clamps used on stainless steel tubing systems. As the acceptance of water mist systems increases, manufacturers continue to complete the North American listing requirements for their components.

It is important to ensure that all components in a water mist system, not just the water mist nozzles, are evaluated for functionality and reliability as part of the listing process. FM Global Approval standard number 5560 contains comprehensive requirements for listing of water mist system components, including positive displacement pump assemblies and controllers. Some additional design considerations for selection of pumps, detection, actuation and supervision of control equipment, and miscellaneous components are offered here.

Pumps

Pumps used to deliver the necessary flow and pressure to system pipe networks will be of the centrifugal type or the positive displacement type. The reliability of centrifugal fire pumps, pump drivers, and controllers are well regulated by NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection.* Centrifugal pumps are suitable for use in low-pressure and possibly intermediate-pressure systems. They are not practical, however, for water pressures in the high-pressure regime (500 psi [34.5 bar]). High-pressure water mist systems utilize positive displacement (PD) pumps.

A number of issues relating to control of positive displacement pumps require close attention. For example, the controller functions necessary for an assembly of positive displacement pumps are not compatible with NFPA 20 requirements for fire pump controllers. Traditional centrifugal fire pump installations did not consider the need to operate many small motors, so each motor has its own controller. For multipump assemblies with many motors, there is one controller for the assembly, not for each motor. This difference invokes a need to modify requirements in NFPA 20 pertaining to locked rotor current and to permit timed shutdown of individual motors. The idea of starting and stopping individual motors in an assembly of motors conflicts with the basic practice of automatic start/manual stop for fire pumps. System features such as the electrical power supply connections, location and sizing of circuit breakers, and supervision are no different than conventional fire pump installations, and NFPA 20 should be followed. Acceptance testing of PD pump assemblies can prove problematic due to the difficulty of achieving accurate pressure setting on unloader valves. Variances of 5 bar (75 psi) or more over nominal settings are common; as a result the measured performance curve for the pump may not match its theoretical value. It is important to evaluate the adequacy of the PD pump or pump assembly on the as-built performance curve.

Table 16.8.9 compares technical features of centrifugal and PD pumps that should be taken into consideration by a designer of water mist systems (from NFPA 750).

Detection, Actuation, Alarm, and Control Equipment

Detection systems for water mist systems must be designed and installed in accordance with *NFPA 72, National Fire Alarm Code®* (CAN/ULC S524-M86 and S529-M87). The releasing device must also comply with these codes when appropriate. All the detection and control equipment used to activate a preaction system or a deluge system must work at the time of the fire. In addition to increasing the reliability of the system, evaluations and performance tests evaluate system controls to ensure that the possibility of inadvertent activation is minimized.

In the same manner that fire pumps require a specific set of features to be supervised, supervision of certain detection and control features is also necessary. System alarm, trouble signals, or both are necessary for critical parts of the electrical control system. These alarms include the following:

- System activation (alarm)
- Power failure (supervisory)
- Valve position (supervisory)
- Detector operation (alarm)
- Detector status (supervisory)

TABLE 16.8.9 Design Considerations for Centrifugal and Positive Displacement Pumps

Feature	*Centrifugal Pump*	*Positive Displacement Pump*
Ability to achieve high pressure	High pressure requires high speed and or multistage design.	High pressure limited only by the power of the driver (brake horsepower or kilowatts) and strength of materials.
Pressure and flow pulsation	Pressure and flow are smooth, varying only with system backpressure or pump speed. Pulsation dampers are unnecessary. Gauges and instruments can be directly mounted on piping or pump skid.	Pressure and flow are sinusoidal, varying with each plunger stroke or gear rotation. Pulsation damper in the suction piping can improve NPSH. Pulsation damper in the discharge piping can reduce vibratory stress to system and relief valve. Gauges and instruments should take their signals via flexible tubing or wiring and should not be mounted on the piping at the pump skid. *Note: Pulsation is not a problem at 1750 rev/min. Use of variable speed drivers in a PD pump system may introduce pulsation problems at slow motor speeds.*
Head curve	Flow from pump depends on backpressure from system. For any given pump speed, there is a maximum pressure that can be achieved. If operated at no-flow shutoff condition and maximum pressure, pump will vibrate and experience accelerated wear but will not fail catastrophically. Churning may heat water to boiling, but small bypass flow sufficient is to prevent boiling.	Flow from PD pump is proportional to pump speed and nearly independent of system backpressure. If flow from the pump is blocked partially or completely, discharge pressure will increase until full flow is forced past the blockage or something breaks. "Multistep pump curve" results when unloader valves are provided on each pump in a multipump assembly.
Relief valve	Not needed if the piping is designed to accommodate the maximum pressure achievable from the pump plus static suction head.	Pressure relief valve is needed. Relief valve must tolerate pressure pulsation produced by the pump.
Net positive suction head (NPSH)	Most centrifugal pumps used in fire service can tolerate a wide range of available NPSH. Ordinary design of suction piping is acceptable.	In general, PD pumps are more sensitive to NPSH than centrifugal pumps. Special care with the design of the suction piping must be taken to provide as much NPSH as possible.
Pump start-up	Conventional pump start-up strategies. Soft-start controllers.	Maximum pressure can be achieved with the first plunger stroke. Use of an unloader valve in the discharge piping is common. Manufacturers recommend motors with high starting torque. Constant torque motors required.
Strainers, sensitivity to dirty water	Silty water is not critical for pump flow passages. Some pumps have water lubricated surfaces that could be adversely affected. Strainer for the protection of water mist nozzles could be on suction or discharge side of the pump.	Silty or murky water is less critical for pump flow passages. Pumps are oil lubricated. Strainers and/or filters for the protection of water mist nozzles are required on the suction side of the pump. Strainers and filters reduce NPSH available. A suction booster pump may be required to meet minimum NPSH for pumps.
Foundation	Ordinary	Compared to centrifugal pumps additional rigidity and mass are helpful because of vibration caused by pulsating flow.
Pump motor link	Typically operate at motor speed. Close-coupled or direct drive via flexible coupling.	May operate at less than motor speed. Belt drive or geared speed reducer is typical. Pulsations and starting torque are considerations in the design of the speed reducer. Possible to have multiple pumps on one motor, with one pump driven directly by the shaft and the other(s) driven by chain drives.

Some systems may use pneumatic lines to activate system valves. These control lines should be protected against mechanical damage as well as fire damage. A means of supervising such pneumatic lines for integrity is necessary.

Water mist systems should also be equipped with a manual means of operation, for those situations in which the fire is discovered by people in the vicinity of the fire, prior to the fire being detected by the detection system. The manual means of activation should be independent of the automatic features, to the extent possible, to allow for the system to operate in the event of a catastrophic control failure. Manual releasing stations should be provided at the main system control valves or at other conspicuous areas within or near the protected hazard.

Miscellaneous Components

The discussion so far has centered on those components that are different than those used in similar types of water-based fire protection systems or special hazard systems.

Water mist systems may use a variety of valves that control everything from the discharge of the water to the discharge of the atomizing medium. Valves should be selected for their particular function and should be capable of sustaining the system pressure to which they will be subjected. All valves should be labeled as to the portion of the system that they control, and they should be supervised in the normal (open or closed) position.

Electrically activated sectional control valves are used on high-pressure systems. These valves can have very high head losses. Manufacturers should provide data on hydraulic performance of such valves to the designer. Electrically activated valves should be supervised. Special methods of supervision may be required where electrical valves operate on AC current. Where possible, valves should be of the indicating type and allow for manual release. Pressure-regulating devices will be found on any part of a system that may subject the valve, pipe, fitting, or nozzle to an operating pressure higher than the working pressure of the device.

Check valves may be necessary in a number of locations on water mist systems. Check valves should be installed in the following locations:

- At the point between the system piping and the system water supply
- On twin-fluid systems, in the pipe network, to prevent atomizing medium from entering the water supply pipe and to prevent the water supply from entering the atomizing medium

Pressure gauges are necessary to monitor key points within the system to verify that proper water pressure or atomizing medium pressure is available. These locations include the following:

- Pressurized side of all water and atomizing media connections
- Pressurized side of all system control valves
- Pressurized storage containers
- Suction side of all pumps

In general, the gauges are used to verify system status as part of a preventive maintenance program. Gauges should be selected such that they can withstand at least two times the working pressure associated with the particular system.

SYSTEM WATER SUPPLY AND ATOMIZING MEDIUM CONSIDERATIONS

Reliability of the water supply and atomizing medium is crucial to the performance of a water mist system. There are various engineering factors that affect reliability. For water, the major issues are whether it is free of silt or debris that could plug nozzles and free of bacteria that could cause algae growth in water storage vessels. For compressed gas media gas-driven systems, the major issue is whether the quantity is sufficient to meet the flow rate and duration required.

Water Supplies

For pumped water supplies there should be an automatic water supply to feed the pump. NFPA dictates that the supply should be at least equivalent to potable water, or natural seawater, with respect to particulates. Screens and filters are required on the supply connection to ensure that particulate matter in the water does not get into the piping and nozzles. Marine systems are equipped with a seawater connection, so that supply can be switched to a seawater source after the fresh-water supply is depleted. Seawater intakes typically draw marine life into the inlet. The IMO dirty water component test is intended to demonstrate that dirty water can be pumped through the screens and filters and not plug the nozzles.

Duration of water supply has been an interesting problem for end users. NFPA 750 requires a minimum supply duration of 30 minutes, except for preengineered systems with stored water supplies, for which there must be capacity to support two complete discharges of 10 minutes each. A problem has arisen in the field: FM Global Research and UL have listed systems for turbine enclosures and machinery spaces. These systems are expected to extinguish fire in less than 5 minutes and provide for 10 minute discharge time. The manufacturer has sold systems to end users with capacity for a 10 minute discharge duration, quoting the fact that the systems are FM approved. The FM Global Research approval documents state that discharge time shall be 10 minutes or the “coast down time of the turbine” (or by implication, the shutdown time of process lines containing hazardous fluids or gases). The systems installed provide only a 10-minute protection time. The installers have ignored the NFPA 750 requirement for either backup discharge or 30 minutes.

The NFPA 750 requirement for a minimum 30 minute discharge time should be observed in all cases. There may be circumstances where the facility is next door to a fire department where a 10-minute total capacity of the system is adequate. In many circumstances, however, 10 minutes is barely enough time for competent persons with necessary resources to react to the reality that a fire exists. To mobilize effective response in that time is unlikely. The fire test protocols for machinery spaces, for example, are based on fires in a compartment with a mockup of a diesel engine and bilge space. There are no overhead pipes, cable trays, or ducts in the test compartment. Real

machinery spaces, in contrast, are filled with pipe, cable trays, and ducts. The clutter in a real machinery space is not simulated in the test compartment. Therefore, the performance of fire extinguishment in "less than 5 minutes" cannot be guaranteed in real spaces.

The time to extinguishment for a given fire size is a function of the fire size and compartment volume (see Figure 16.8.7). New FM Global Research test protocols for large machinery spaces (e.g., 1000 m^3) mandate minimum water supply durations of 60 minutes.

For pumped water supplies on high-pressure systems, it is sometimes necessary to utilize suction booster pumps on the suction supply to the fire pumps. The need arises because of the head losses created by the screens and filters that are required on the infeed to the pumps. Positive displacement pumps are particularly sensitive to low net positive suction head (NPSH) so attention to suction line details is necessary. Control over the additional pump must be worked into the control program to ensure that it operates when required.

In brief, water supplies for water mist systems must provide sufficient quantity (flow rate) at the pressure needed to supply pumps or refill reservoirs in a reasonable time. Minimum duration at design flow should be 30 minutes—shorter durations should only be considered for special cases after a fire protection engineering evaluation. Screens, strainers, and filters are needed to ensure the water is free from particulates that could plug the nozzles.

Water Quality

NFPA 750 mandates that water supplies for water mist systems must be at least equivalent to potable water or natural seawater with respect to particulates and dissolved minerals. Combined with the requirements for strainers and filters on the infeed piping and screens on individual nozzles, these measures were viewed as sufficient safeguards against plugging of nozzles. The requirements for corrosion-resistant pipe were also intended to minimize the possibility of scale in the piping. For systems utilizing a pumped water supply from a continuous source, the screening and filtering measurements are probably sufficient to avoid plugging of nozzles.

Many preengineered water mist systems involve water stored in vessels or pressure cylinders. It is possible that bacteria present in the stored water could result in algae growth in the tank. Filtering out the particulates during infill would not necessarily prevent bacterial activity in the stored water. Diligent maintenance is required to ensure the quality of stored water for water mist systems. Where there is a risk of *Legionella* bacteria in stored water, continuous ultraviolet treatment of the water should be provided. Equipment to achieve this is available.

Mandating the quality of the water supply is not sufficient to prevent plugging of nozzles. Cleaning of pipe and tubing and system flushing following installation are extremely important. High-pressure systems involving welded stainless steel piping have "purge paper" or "rice paper" inside the pipe after a weld is complete. The purge paper is used to provide a backing for argon gas used to minimize oxidation during the welding process. After the weld is complete, the purge paper remains inside the piping. For standard petroleum industry conditions, the purge paper is soluble in hydrocarbons and is usually flushed through the system. For water mist systems the purge paper becomes a jelly, and if it is not completely flushed from the piping it can stick to the inside of the pipe and plug the nozzles over an extended period of time. Extensive flushing of all branches of the piping system is essential to minimize future problems.

Plastic thread sealant tape such as Teflon tape should not be used on piping for water mist systems. Even with the greatest care in following good workmanship practices during installation, bits of Teflon tape appear on nozzle screens and will plug small orifices.

The important requirements with respect to water quality are as follows:

- Draw from a source with quality equivalent to potable water.
- Strain or filter water going into the system, including into storage reservoirs.
- Provide treatment for stored water to minimize possibility of algae or bacterial growth. (Do not use chlorination or bromination of water in systems with stainless steel pipe.)
- If necessary due to evidence of poor quality of stored water, provide screens or strainers on the outlet of stored water containers, sized to pass the design flow without excessive head losses even with partial blockage.
- Monitor water quality at regular intervals.

Atomizing Media

Twin-fluid systems require a supply of atomizing medium in addition to a reliable water supply. Air and nitrogen are the most commonly used compressed gases for water mist systems. The source of compressed gas must have the same level of reliability as the water supply. Two options are the use of dedicated compressed gas cylinders manifolded in banks and the use of plant air supplies in facilities that have the necessary capacity. If used, plant air supplies must be available on a continuous basis, not only while the plant is operating. Also, NFPA 750 limits moisture content to 25 ppm: plant air supplies may not always meet this quality standard. An air compressor that is listed for fire protection service may also be used as an acceptable supply of compressed gas. The unit should be connected to a backup power supply.

Compressed gas supplies must be monitored for high and low pressure and protected against physical or mechanical damage. Some of the supervisory functions expected on fire protection systems are difficult to achieve with gas cylinders. For example, the control valves on standard commercial gas cylinders are not of the indicating type. It is impossible to be certain that the valve has been opened without handling it. Vigilant system maintenance by qualified personnel is very important for the long-term reliability of water mist systems.

SYSTEM MAINTENANCE CONSIDERATIONS

A number of acceptance and commissioning tests must be performed once the installation of a system is completed. NFPA 750 specifies measures involved in the acceptance testing. These

include a review of the design documentation, hydraulic calculations, working drawings, and the as-built installation. System piping is flushed and hydrostatically tested. All mechanical and electrical components are to be examined for correct installation and for functionality. Pumps are flow tested and, where possible, a system discharge test is carried out. Pumps are tested to confirm that they deliver the specified flow rate and pressure and that control features operate reliably. The acceptance tests are intended to identify the problems, which then must be corrected before the system is considered complete. The results of the acceptance tests must be recorded and kept with the system documentation. This basic documentation of all components of the system and acceptance test performance data is the basis on which the success of future maintenance practices rests.

After the acceptance testing, maintaining the reliability of the system depends on carrying out regular maintenance inspections. The owner or the tenant using the system is responsible for ongoing maintenance. NFPA 750 provides a table of recommended maintenance tasks to be carried out weekly, monthly, semiannually, or annually. The table in NFPA 750 was developed from common practices for similar fire protection systems involving pumps, compressed gas cylinders, water storage tanks, and detection and activation systems. Experience with installed water mist systems has increased since the time the table was drafted. A number of concerns specific to water mist systems have been discovered. The following list includes the most important concerns:

1. Water storage vessels must be equipped with a means of checking the level of water inside during a weekly or monthly inspection. Some high-pressure water storage cylinders do not have a means to confirm water levels. Some end users have installed weight scales to monitor the weight of the cylinders. If such cylinders are present in a system, extra measures to confirm water level should be implemented.
2. The quality of water in storage vessels should be checked for algae growth monthly or quarterly for the first year. A means of taking water samples should be provided. The vessels should be drained, flushed, and refilled at least quarterly or more frequently if water quality problems are identified by the monthly check.
3. Water mist systems make use of a variety of valves, some of which are not of the indicating type. It is not always possible to determine whether a critical valve is open or closed from external appearance. Key control valves that must be normally open should be of the indicating type.
4. Some valves on water mist systems are electrically activated. A manual means of operating the valve should be provided.
5. Systems involving the use of banks of compressed gas cylinders connected in parallel use a combination of pneumatic master and slave valves. Operation of the master valve triggers the release of all connected slave valves. Important differences between valves may not be evident to an inexpert maintenance person. Means of checking the readiness and functionality of pneumatic valves should be established. Valves should be marked to indicate whether they are the master or slave status.
6. An annual trip test should be conducted in all cases. If it is not possible to discharge water mist through the system nozzles, the discharge should be conducted through a test connection. The test connection should be designed to have the same K-factor as the actual piping system.
7. Confirmation of the adequacy of compressed gas supplies is best obtained by recording measurements of nozzle pressure throughout the discharge test. The minimum nozzle pressure must be sustained for the specified duration.

Table 16.8.10 is a modified version of the table in NFPA 750 specifying inspection frequencies. More complete discussion of maintenance requirements specific to the different types of water mist systems is provided in the NFPA handbook on inspection and maintenance of fire protection systems.[92]

SUMMARY

This chapter presents an overview of the history of development of water mist fire protection systems since 1990. Water mist fire suppression systems discharge less water, use smaller-diameter piping, and have lower overall weight than conventional water spray or sprinkler systems. Water mist can be used as a replacement for ozone-depleting substances such as halons and can be used in applications where water was not previously considered practical. Water mist fire suppression systems are used in a wide variety of marine-based and land-based applications, including machinery spaces on ships as well as land facilities, turbine enclosures in offshore drilling platforms, marine accommodation areas, electrical equipment rooms, tunnels, hotels, heritage buildings, and art galleries. The last five years have seen an intense effort to develop water mist systems for electrical cable, highway, and rail tunnels.

The objectives and characteristics of water mist systems are described for Class B fires in machinery spaces and turbine enclosures and for Class A fires in accommodation spaces, hotels, and heritage buildings. Use of water mist in electrical equipment rooms and computer rooms is discussed. The mechanisms by which water mist controls or extinguishes fire are described in detail, including flame cooling, evaporation of small droplets, enclosure effects, radiation attenuation, and others. Pressure fluctuations due to rapid cooling of a hot gas layer are described. The concept is established that water sprays must be described in terms of the range of drop sizes contained in the spray, not a single representative diameter. The chapter explains the role of spray momentum in allowing water mist to penetrate a strong fire plume or to penetrate a field of obstructions. The different types of nozzles, including impingement, pressure jet, and twin-fluid types, are described. Nozzles may be of the automatic type (thermally activated like sprinklers) or of the nonautomatic type (open nozzles). New technology involving ultra-fine mist (Nano-Mist) is referenced.

A section on hydraulic calculations for single-fluid and twin-fluid systems is presented. The chapter describes how positive displacement pumps are matched to variable-demand fire protection systems. The role of the unloader valve, which sends unused flow from the pump to a bypass, is explained. Acceptance testing of positive displacement pumps or pump assemblies must allow for variance in unloader valve settings.

TABLE 16.8.10 Recommended Inspection and Testing Frequencies for Water Mist Systems

Item	*Activity*	*Frequency*
Ambient conditions, temperature +4°C to 54°C in water tank/valve area	Check	Daily during extreme weather
Water tank (unsupervised)	Check water level	Weekly
Air receiver (unsupervised)	Check air pressure	Weekly
Dedicated air compressor (unsupervised)	Check air pressure	Weekly
Water tank (supervised)	Check water level	Monthly
Water tank	Check water quality	Monthly
Water tank	Drain, flush, refill	Quarterly first year
System strainer and filters	Inspect	Annually and whenever water has passed through it (after each refill)
Air receiver (supervised)	Check air pressure	Monthly
Dedicated air compressor (supervised)	Check air pressure	Monthly
Air pressure cylinders (unsupervised)	Check air pressure and indicator disk	Monthly
System operating components, including control valves (locked/unsupervised)	Inspect	Monthly
Air pressure cylinders (supervised)	Check air pressure and indicator disk	Quarterly
System operating components, including control valves	Inspect	Quarterly
Waterflow alarm and supervisory devices	Inspect	Quarterly
Initiating devices and detectors	Inspect	Semiannually
Batteries, control panel, interface equipment	Inspect	Semiannually
System strainers and filters	Inspect	Annually
Control equipment, fiber-optic cable connections	Inspect	Annually
Piping, fittings, hangers, nozzles, flexible tubing	Inspect	Annually

The chapter reviews the NFPA 750 classification of water mist systems as wet pipe, dry pipe, or preaction type; total compartment flooding, local application or zoned systems. The respective merits of low-, intermediate-, and high-pressure options are discussed; the concept of constant pressure water mist systems as opposed to declining pressure systems is introduced. Gas-driven systems are generally of the declining pressure type, but a water mist system utilizing assemblies of PD pumps may have a high-pressure mode and a lower-pressure design condition.

The importance of ensuring water quality to avoid potential plugging of small-orifice nozzles is highlighted. Issues relating to the supervision of certain equipment unique to water mist systems are raised. The chapter concludes with an overview of considerations pertaining to inspection testing and maintenance of water mist systems.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on water mist fire suppression systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 72®, National Fire Alarm Code®
NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways*
NFPA 750, *Standard on Water Mist Fire Protection Systems*

Chapter 9

Water Spray Protection

Revised by
Kerry M. Bell

Chapter Contents

Uses for Water Spray Protection
Spray System Description and Applications
Spray System Nozzles and Piping
Water Demand and Supplies
Other Considerations and Maintenance

Key Terms

fixed water spray system, spray nozzle, water mist, water spray system, water supply

The term *water spray* refers to water that is discharged from specially designed nozzles or devices to produce a predetermined pattern, particle size, velocity, and density. The use of these designations cannot be taken as an indication of any specific discharge pattern or spray characteristics of the nozzles. NFPA 750, *Standard on Water Mist Fire Protection Systems,* has been developed to address the use of very fine water droplets from spray nozzles (see Section 16, Chapter 8, "Water Mist Fire Suppression Systems"). The primary distinction between a water spray and a sprinkler system is that of specific coverage versus general area coverage. Water spray systems have typically been provided to protect a specific piece of equipment with surface coverage. Water spray for fire protection has been called by various trade-name designations.

The discharge from water spray nozzles differs, generally, from the discharge from sprinklers. The pattern of the water spray discharged from spray nozzles onto a surface may be elliptical or circular, and the cross section of the projected discharge is conical. The water spray is forcefully directed onto the object or surface being protected. The pattern of spray nozzle discharge must carry water spray over the distance between the nozzle and the target, compensate for wind and draft conditions, and effectively hit the surface to be protected. The required discharge density in gpm/ft^2 (L/min/m^2) and complete coverage of the area to be protected are also essential elements.

Unlike most automatic sprinkler systems, water spray systems are usually of the deluge type. Generally, spray nozzles are not equipped with fusible operating elements. Spray nozzles may be equipped with internal pilot-pressure-controlled valves or with frangible or removable plugs or caps that will be displaced when the water spray deluge system is actuated. Pilot-pressure-controlled valves, plugs, or caps prevent corrosive atmospheres from entering the piping system. They may be used to retain water in the piping system for the purpose of speeding its delivery from the spray nozzles.

NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection,* is the standard applicable to water spray systems and should be consulted on details of system design and installation not covered in NFPA 13, *Standard for the Installation of Sprinkler Systems.*

This chapter covers the uses and applications of water spray systems for fire suppression, control, and extinguishment and describes the components of spray systems and the specialized uses of the systems. Because of the similarities between sprinkler systems and water spray systems, their water supply requirements, some of the equipment used in the systems, and the hydraulic calculations for determining water supplies, the chapters listed below should be consulted. The list includes chapters on releasing devices that can be used with water spray systems as well as protection of conveyor openings: Section 14, Chapter 2, "Automatic Fire Detectors"; "Section 15, Chapter 4, "Water Supplies for Sprinkler Systems"; Section 16, Chapter 3, "Automatic Sprinkler Systems"; Section 16, Chapter 7, "Ultra-High-Speed Water Spray Systems"; Section 16, Chapter 8, "Water Mist Fire Suppression Systems"; and Section 17, Chapter 3, "Characteristics and Hazards of Water and Water Additives for Fire Suppression."

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USES FOR WATER SPRAY PROTECTION

Generally, water spray can be used effectively to extinguish a fire, control a fire, protect exposures, and/or prevent a fire.

Extinguishment

Water spray extinguishes a fire by cooling it, smothering it with the steam produced, emulsifying or diluting some flammable liquids, or by a combination of these factors.

Controlled Burning

With its consequent limitation of fire spread, controlled burning may be applied if the burning combustibles cannot be extinguished by water spray or if extinguishment is not desirable.

Exposure Protection

Exposures are protected by applying water spray directly to the exposed structures or equipment to remove or reduce the heat transferred to them from the exposing fire. Water spray curtains mounted at a distance from the exposed surface are less effective than direct application.

Prevention of Fire

It is sometimes possible to use water spray to dissolve, dilute, disperse, or cool flammable or combustible materials before they are ignited by an exposing ignition source.

SPRAY SYSTEM DESCRIPTION AND APPLICATIONS

Fixed Water Spray Systems

A water spray system is a special fixed pipe system connected to a reliable supply of fire protection water and equipped with water spray nozzles for specific water discharge and distribution over the surface or area to be protected. The piping system is connected to a water supply through a deluge valve that can be actuated both automatically and manually to initiate the flow of water.

Automatic system actuation valves for spray systems can be actuated electrically by the operation of automatic detection equipment, such as heat detectors, relay circuits, and gas detectors, or mechanically by hydraulic or pneumatic systems, depending on the operating mode of the individual valves. Generally, each manufacturer of system actuation valves, most of which can do dual service in deluge systems, provides its own particular combination of system actuation valve, releasing mechanism, detection system, and supervisory service.

Water Spray Applications

Water spray can be used to protect the following types of materials or equipment:

- Ordinary combustible materials, such as paper, wood, and textiles, particularly to extinguish fires in such materials rather than control them
- Electrical equipment installations, such as transformers, oil switches, and rotating electrical machinery
- Flammable gases and liquids, particularly to control fires in these materials and to extinguish types of fires involving combustible liquids
- Flammable liquid and gas tanks, processing equipment, and structures, as protection against exposure fires
- Open cable trays and runs containing electrical cables or tubing

The nature of the equipment to be protected, the physical and chemical properties of the material involved, and the environment of the hazard should be considered when determining the design and effectiveness of the water spray system.

Examples of Systems

Fixed water spray systems are most commonly used to protect equipment from exposure fires in flammable liquid and gas tankage, piping, and equipment; in electrical equipment, such as transformers, oil switches, rotating machinery, and cable trays; in structural supports; and in conveyor systems and the openings in firewalls and floors through which they pass. The type of water spray required for any particular hazard will depend on the nature of the hazard and the purpose for which the protection is provided.

A water spray installation being tested at a group of liquefied petroleum gas tanks is shown in Figure 16.9.1. The spray keeps the tanks cool in case of fire, prevents the liquid contents from boiling away, and protects the tank shells against rupture due to localized high-temperature flame impingement. The spray system shown in Figure 16.9.1 is designed to give complete surface wetting with a specified water density, taking into consideration nozzle types, sizes, and spacing; the influence of wind and drafts; the probability of water rundown; the prevention of the formation of difficult-to-wet deposits of soot or carbon on surfaces; the overlap of water discharge patterns onto the surfaces; and the ability of the water supply to furnish adequate pressure to all of the nozzles. Ordinarily, it is neither

FIGURE 16.9.1 Water Spray Protection for LP-Gas Tanks

desired nor expected that water spray extinguish escaping liquefied petroleum gas. However, the cooling effect of the water on the tanks may reduce and control the rate of burning and reduce the severity of the exposure until the gas supply to the fire is exhausted or can be shut off.

Water spray protection for a group of oil-filled electric transformers is shown under test in Figure 16.9.2. A thick layer of crushed stone and subsurface drainage is provided around the base of the transformer installation to prevent the possibility of burning oil flowing beyond the ground area protected by the spray.

Due to the relatively high flashpoint and boiling point of transformer oil, transformer fires can be extinguished quickly by properly designed water spray systems. However, the metal surfaces of the transformer case and its structural supports must be protected from radiant heat while the burning transformer oil is being extinguished. Care must be taken to locate nozzles, piping, and supports the prescribed distances from electrically charged parts of the transformer installation, and direct application of water spray to electrically charged terminals or insulating bushings should be avoided. Electricity to the transformer should be shut off automatically before water spray is applied.

Water spray systems are also used to provide protection from fire damage for equipment and structures for the petroleum industry. API RP 2030, *Application of Fixed Water Spray Systems for Fire Protection in the Petroleum and Petrochemical Industries,* provides guidance for the petroleum and petrochemical industries in determining where these systems might be used.[1]

SPRAY SYSTEM NOZZLES AND PIPING

General Design Information

The practical location of the piping and nozzles with respect to the surface to which the spray is to be applied or to the zone in which the spray is to be effective is determined largely by the physical arrangement and protection needs of the installation requiring protection. Once the criteria are established, the size of the nozzles to be used, the angle of the nozzle discharge cone, and the water pressure needed can be determined.

The first factor to determine is the water density required to extinguish the fire or to absorb the expected heat from exposure or combustion. When this has been determined, a nozzle may be selected that will provide that density at a velocity adequate to overcome air currents and to carry the spray to the equipment to be protected. Each nozzle must have the proper angle of discharge to cover the area to be protected by the nozzle.

Determining the proper density needed for extinguishment requires considerable engineering judgment and, in the case of flammable or combustible liquids, depends on such characteristics of the fuel as vapor pressure, flashpoint, viscosity, water solubility, and specific gravity. The density varies between 0.2 and 0.5 gpm/ft^2 (8.1 to 20.4 L/min/m^2) of protected surface.

For exposure protection of vessels, a density of 0.25 gpm/ft^2 (10.2 L/min/m^2) should provide sufficient cooling to limit an exposure fire's heat input through the vessel walls to 6000 Btu/hr/ft^2 (18,930 W/m^2). The water density required for exposure protection of structural supports and miscellaneous equipment, such as cable trays and runs, pipe racks, transformers, and belt conveyors, varies from 0.1 to 0.3 gpm/ft^2 (4.1 to 12.2 L/min/m^2) of exposed surface area. NFPA 15 should be consulted for more details on required distribution densities.

When water spray is to be used to protect oil-filled electrical equipment, such as transformers and large switch gear, special care must be taken to provide safe electrical clearances. Special fixed water spray nozzles have been developed to provide adequate spray density and range to accommodate wind, along with a simplified piping arrangement that is spaced safely from energized electrical parts.

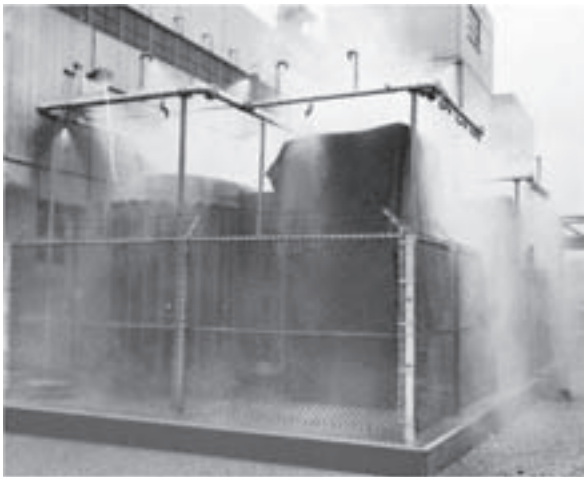

FIGURE 16.9.2 Water Spray System for Oil-Filled Electric Power Transformers

Selection and Use of Spray Nozzles

The selection of spray nozzles should take into consideration such factors as the character of the hazard to be protected, the purpose of the system, and the possibility of severe winds or drafts. In addition to different spray angles, droplet sizes, and velocities, spray nozzles are available in a variety of discharge patterns such as hollow cone, full cone, and flat discharge characteristics.

Nozzles of one type cannot be substituted for nozzles of another type when a water spray system is being repaired or nozzles are being replaced without taking into account the possibility of seriously compromising the effectiveness of the system. In general, the velocity, distribution, and size of water droplets affect the "reach" and coverage of the water spray pattern.

Some spray nozzles produce spray by giving the water streams a rotary motion in spiral passages inside the nozzles. These rotating streams are mixed internally with a center stream to project a solid cone of water spray from the nozzle. These nozzles are known as the internally impinging type (Figure 16.9.3). Another type of water spray nozzle uses the deflector principle of a sprinkler. The water-discharge orifice projects a solid, cylindrical stream of water onto a deflector that alters the stream into a conical distribution of water spray (Figure 16.9.4).

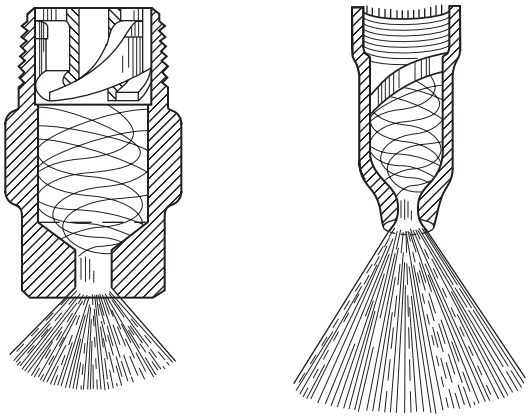

FIGURE 16.9.3 Water Spray Nozzles with Internal Spiral Water Passages

FIGURE 16.9.4 Water Spray Nozzle Using the Deflector Principles of the Standard Automatic Sprinkler

A characteristically different type of water spray nozzle discharges water along the axis of a spiral of diminishing inside diameter. This spiral continuously peels off a thin layer of water from the surface of the cone, and this thin layer of water breaks into spray as it leaves the spiral (Figure 16.9.5). Another unique type of water spray nozzle discharges water in a flat or sheet-type pattern. A flat spray nozzle has a deflector that diverts the discharged water from the axis of the inlet pipe connection (Figure 16.9.6). This discharge characteristic can be useful in developing an overlapping, flat spray between adjacent nozzles. These nozzles are commonly used to protect windows and structures from exposure fires.

Pipe Sizes

Once the type of nozzle has been selected and the location and spacing to give the desired area coverage have been determined, hydraulic calculations are made to establish the appropriate pipe sizes and water supply requirements. Pipe sizes must be calculated hydraulically for each system so that the water at the spray nozzles will have adequate pressure to provide the necessary flow and spray pattern. A procedure for making the hydraulic calculations for a fixed pipe water spray system is given in the Appendix to NFPA 15.

FIGURE 16.9.5 Spiral-Type Water Spray Nozzle

FIGURE 16.9.6 Flat-Spray-Type Water Spray Nozzle (Tyco Issue A) (Courtesy of Tyco Fire and Building Products)

Hydraulic calculations of water spray systems need to take into consideration the velocity head pressure in the calculations where the velocity pressure exceeds 5 percent of the total pressure at any junction point. When velocity pressures are high at a junction, the hydraulic principle in the tie fitting will not allow sufficient water to flow from the side outlet (acting much like a siphon). Ignoring the velocity pressure under these conditions can introduce a significant error, resulting in an actual nozzle pressure that is less than required. The 5 percent value used to determine whether velocity pressure needs to be considered can also be expressed in terms of velocity and total pressure. If $V \leq 2.7\ (P_T)^{1/2}$ then the velocity pressure does not need to be calculated, where V is the velocity (ft/sec) and P_T is the total pressure (psi).

Figure 16.9.7 shows a typical example of where the velocity head pressure needs to be included in the calculation as demonstrated by comparing calculations of the example configuration with (Figure 16.9.8) and without (Figure 16.9.9) veloc-

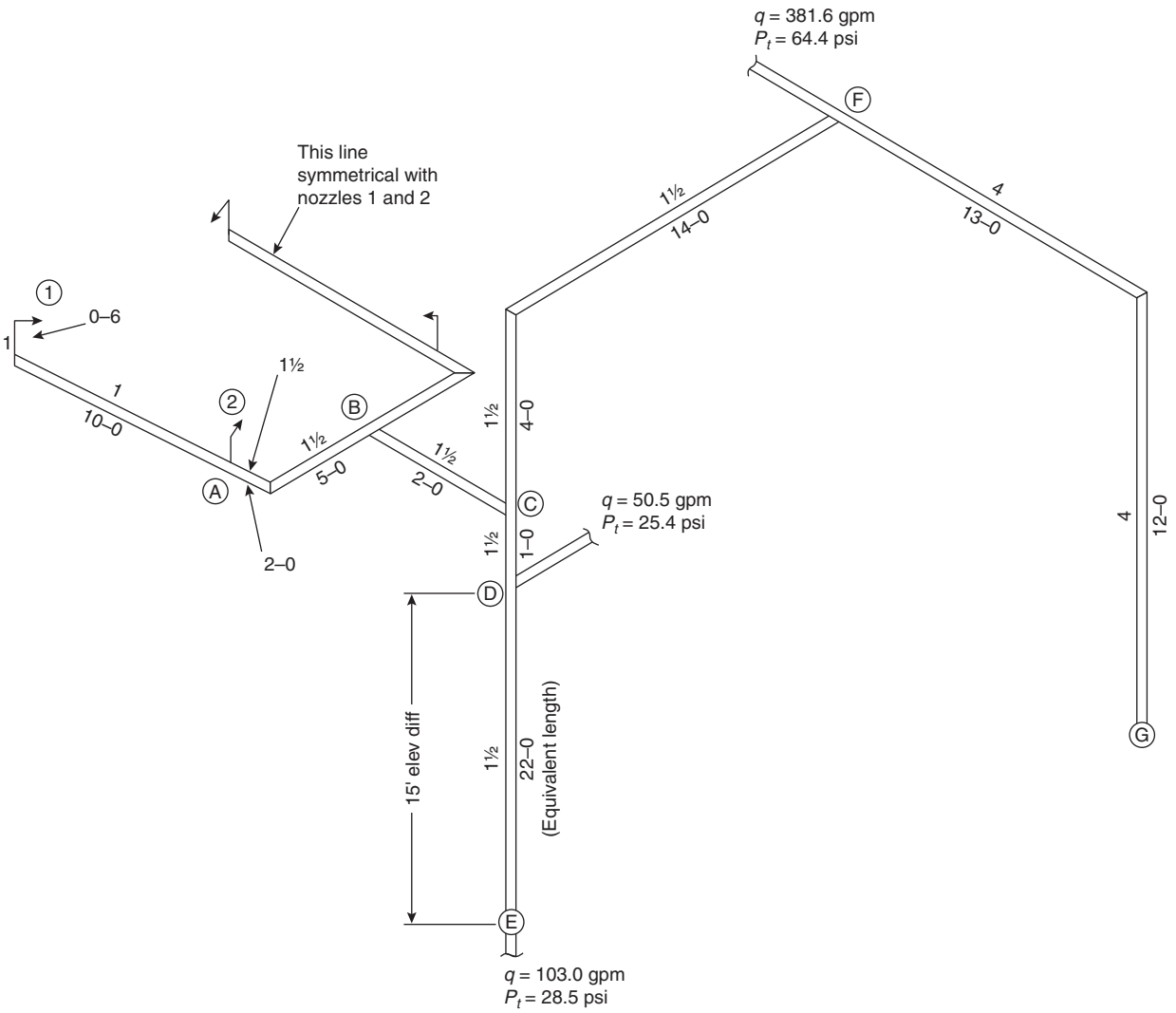

FIGURE 16.9.7 Water Spray System Used for Sample Calculation Shown in Figures 16.9.8 and 16.9.9

ity head pressures used in the calculations. Two methods exist to connect the system to a more balanced configuration, which include (1) increasing the pipe size upstream to reduce the effects of velocity pressure and (2) converting the side outlet tee fitting to a bullhead tee fitting (Figure 16.9.10).

WATER DEMAND AND SUPPLIES

Many factors govern the size of a water spray system, including the nature of the hazard or combustibles involved, the amount and type of equipment to be protected, the adequacy of other protection, and the size of the area that could be involved in a single fire. The size of the system needed may be minimized by taking advantage of possible subdivision by firewalls; by limiting the potential spread of flammable liquids with dikes, curbs, or special drainage; by installing water curtains or heat curtains; or by using a combination of these features.

The water demand will be heavy because water spray systems must perform as deluge-type systems with all nozzles open and because high densities of water are needed. Each hazard should be protected by its own water spray system to limit the cumulative demand on the water supply.

NFPA 15 advises that the size of a single water spray system be limited only by the available water supply so that the designed discharge rate will be calculated at the minimum pressures for which the nozzles are effective. Experience has shown that, in most installations, a single system should not exceed a design discharge rate of 3000 gpm (11,356 L/min). Separate hazard areas should be protected by separate systems.

Water Demand Rate

The water supply must be adequate to supply the operating water spray system(s) with the required gpm (L/min) at effective pressure. Water spray systems adjacent to the hazard initially protected may require additional water. The water supply

For all nozzles shown, K = 5.56; each nozzle covers 100.8 ft^2 at 0.25 gpm/ft^2 = 25.2 gpm minimum (Schedule 40 pipe used in example)

Nozzle I.D. and Location	*Flow in gpm*	*Pipe Size*	*Pipe Fittings and Devices*	*Equivalent Pipe Length*	*Friction Loss psi/ft*	*Pressure Summary*	*Normal Pressure*	*Notes*
1	q	1"	1-E	L 10.5	0.200	P_t 20.5	P_t	C = 120
				F 2.0		P_e +0.2	P_v	$P_t = (25.2/5.56)^2$
	Q 25.2			T 12.5		P_f 2.5	P_n	= 20.5 psi
				L		P_t 23.2	P_t	at A
	q			F		P_e	P_v	
	Q			T		P_f	P_n	
2	q	1"	1-T	L 0.5	0.200	P_t 20.5	P_t	K = 25.2/ $\sqrt{21.7}$
				F 5.0		P_e +0.2	P_v	= 5.41
	Q 25.2			T 5.5		P_f 1.1	P_n	
				L		P_t 21.7	P_t	
	q			F		P_e	P_v	
	Q			T		P_f	P_n	
A	26.1 q 25.2	1½"	1-E 1-T	L 7.0 F 12.0	0.092	P_t 23.2 P_e —	P_t P_v ~0.4	$q_2 = 5.41\sqrt{23.2}$ P_v < 5% of Pt, no
	Q 51.3			T 19.0		P_f 1.7	P_n	correction required
B	q 51.3	1½"	1-T	L 2.0 F 8.0	0.333	P_t 24.9 P_e —	P_t P_v	
	Q 102.6			T 10.0		P_f 3.3	P_n	
				L		P_t 28.2	P_t	at C
	q			F		P_e	P_v	
	Q			T		P_f	P_n	
E	q	1½"		L 22.0 F	0.335	P_t 28.5 P_e –6.5	P_t P_v	
	Q 103.0			T 22.0		P_f 7.4	P_n	
D	q 50.6	1½"		L 1.0 F —	0.702	P_t 29.4 P_e –0.4	P_t 29.4 P_v 3.9	$q = 50.5(25.5/25.4)^{1/2}$ P_v in to D from the
	Q 153.6			T 1.0		P_f 0.7	P_n 25.5	side assumed negligible
				L		P_t 29.7	P_t	
	q			F		P_e	P_v	
	Q			T		P_f	P_n	
C	185.7 q 102.6	1½"	1-T 1-E	L 18.0 F 12.0	2.250	P_t 43.4 P_e –1.7	P_t 43.4 P_v 15.2	q from D = 153.6(43.4/29.7)$^{1/2}$
	Q 288.3			T 30.0		P_f 67.5	P_n 28.2	= 185.7 (see NFPA 15)
F	q 496.9	4"	1-E	L 25.0 F 10.0	0.165	P_t 109.2 P_e +5.2	P_t P_v ~2.9	$q = 381.6(109.2/64.4)^{1/2}$ P_v < 5% of Pt, no
	Q 785.2			T 35.0		P_f 5.8	P_n	correction required
				L		P_t 120.2	P_t	at G
	q			F		P_e	P_v	
	Q			T		P_f	P_n	
						P_t		

FIGURE 16.9.8 Hydraulic Calculation Worksheet of System Shown in Figure 16.9.7 with Velocity Pressure Included

For all nozzles shown, K = 5.56; each nozzle covers 100.8 ft^2 at 0.25 gpm/ft^2 = 25.2 gpm minimum

Nozzle I.D. and Location	*Flow in gpm*	*Pipe Size*	*Pipe Fittings and Devices*	*Equivalent Pipe Length*	*Friction Loss psi/ft*	*Pressure Summary*	*Normal Pressure*	*Notes*
1	q	1"	1-E	L 10.5	0.200	P_t 20.5	P_t	C = 120
				F 2.0		P_e +0.2	P_v	$P_t = (25.2/5.56)^2$
	Q 25.2			T 12.5		P_f 2.5	P_n	= 20.5 psi
	q			L		P_t 23.2	P_t	at A
				F		P_e	P_v	
	Q			T		P_f	P_n	
2	q	1"	1-T	L 0.5	0.200	P_t 20.5	P_t	K = 25.2/$\sqrt{21.7}$
				F 5.0		P_e +0.2	P_v	= 5.41
	Q 25.2			T 5.5		P_f 1.1	P_n	
	q			L		P_t 21.7	P_t	
				F		P_e	P_v	
	Q			T		P_f	P_n	
A	26.1 q 25.2	1½"	1-E 1-T	L 7.0 F 12.0	0.092	P_t 23.2 P_e —	P_t P_v	$q_2 = 5.41\sqrt{23.2}$
	Q 51.3			T 19.0		P_f 1.7	P_n	
B	q 51.3	1½"	1-T	L 2.0 F 8.0	0.333	P_t 24.9 P_e —	P_t P_v	
	Q 102.6			T 10.0		P_f 3.3	P_n	
	q			L		P_t 28.2	P_t	at C
				F		P_e	P_v	
	Q			T		P_f	P_n	
E	q	1½"		L 22.0 F	0.335	P_t 28.5 P_e –6.5	P_t P_v	
	Q 103.0			T 22.0		P_f 7.4	P_n	
D	q 54.3	1½"		L 1.0 F —	0.734	P_t 29.4 P_e –0.4	P_t P_v	$q = 50.5(29.4/25.4)^{1/2}$ = 54.3
	Q 157.3			T 1.0		P_f 0.7	P_n	
C	q 105.3	1½"	1-T 1-E	L 18.0 F 12.0	1.893	P_t 29.7 P_e –1.7	P_t P_v	q from B = $102.6(29.7/28.2)^{1/2}$
	Q 262.6			T 30.0		P_f 56.8	P_n	= 105.1
F	q 437.9	4"	1-E	L 25.0 F 10.0	0.134	P_t 84.8 P_e +5.2	P_t P_v	$q = 381.6(84.82/64.4)^{1/2}$ = 437.9
	Q 700.5			T 35.0		P_f 4.7	P_n	
	q			L		P_t 94.7	P_t	at G
				F		P_e	P_v	
	Q			T		P_f	P_n	
	q			L F		P_t P_e	P_t P_v	
	Q			T		P_f	P_n	
						P_t		

FIGURE 16.9.9 Hydraulic Calculation Worksheet of System Shown in Figure 16.9.7 with Velocity Pressure Not Included

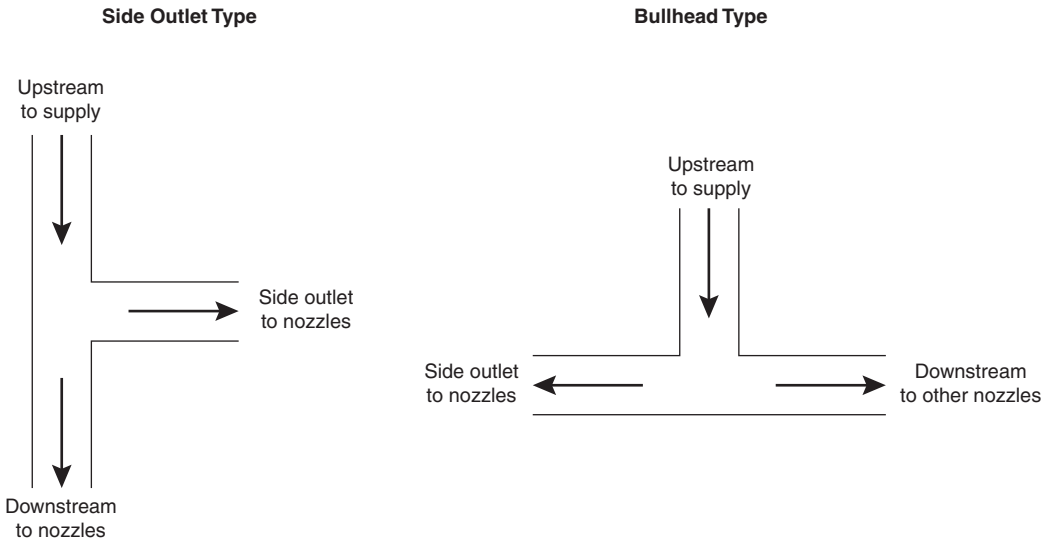

FIGURE 16.9.10 Tee Fittings—Side Outlet and Bullhead Types

should be able to supply hose streams simultaneously. The total required water supply pressure and flow rates should be considered when the system is designed. The duration of the discharge required varies according to the nature of the hazard, the purpose for which the system is designed, and other factors that can be evaluated only for each installation.

Waterflow demand is specified in terms of the density of a uniformly distributed spray measured in gpm/ft^2 (L/min/m^2) of area protected. The discharge rate per unit of area depends on whether the spray system is installed to extinguish a fire, to control a fire, or to protect an exposure, and on the characteristics of the materials involved.

Water Supplies

Fixed spray systems usually are supplied from one or more of the following:

- Connections from a reliable waterworks system of adequate capacity and pressure
- Automatic fire pumps with reliable power and a water supply of adequate capacity and reliability
- An elevated gravity tank of adequate capacity and elevation

The capacity of pressure tanks generally is not adequate to supply water spray systems. However, they may be acceptable as water supplies to small systems whose water and pressure requirements do not exceed the tank's capabilities.

OTHER CONSIDERATIONS AND MAINTENANCE

Strainers

Strainers are required in the supply lines of fixed piping spray systems to keep the nozzles from clogging where the waterways of nozzles are less than ⅜ in. (9.5 mm) or for systems in which the water is likely to contain obstructive material. The baskets of those selected should have a mesh small enough to protect the smallest water passages in the nozzles used. Figure 16.9.11 shows a Grinnell Model A strainer with a basket-type screen of corrosion-resistant metal. This particular strainer is available in 3 in., 4 in., 6 in., 8 in., and 10 in. sizes (1 in. = 25.4 mm). Water spray nozzles with very small water passages may have their own internal strainer, as well as a supply-line strainer to remove larger foreign material.

Drainage

Fixed water spray systems discharge large quantities of water. Special drainage and disposal facilities are important to control the spread of flammable or hazardous liquids to areas adjacent to the fire. Pitched floors, curbs, trenches, dikes, and sumps should be provided to direct the mixture of flammable or hazardous liquids and water runoff. These should be connected to a facility that separates flammable and hazardous liquids from the water. These liquids should be impounded in controlled areas until they can be disposed of safely.

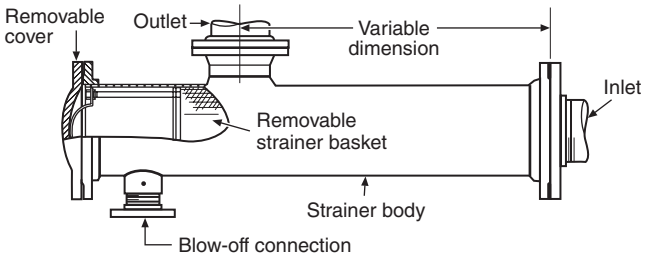

FIGURE 16.9.11 Grinnell Model A Strainer

Maintenance

It is important that fixed water spray systems be inspected and maintained on a regular basis. NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems,* provides specific requirements for periodic inspection, testing, and maintenance of water spray systems. Included in a scheduled inspection program are such items as strainers, piping, control valves, system actuation valves, heat-actuated devices, and spray nozzles, particularly those equipped with strainers. Flow tests are conducted frequently to ensure satisfactory operation. After the tests have been completed, it is necessary to clean all strainers and to check all valves to be sure the system is in normal operating condition.

Nozzles with blow-off caps or plugs are provided to protect the interior of the piping and the nozzles located in areas containing paint vapor, corrosive vapors, dusts, or other foreign matter. Other blow-off caps or plugs are attached to the nozzles to allow them to retain water in the piping system and, thus, reduce the time between the operation of the deluge valve and the discharge of water spray from the nozzles (Figure 16.9.12). Regular inspection and maintenance should confirm that caps and plugs are in place.

Specialized Systems Using Water

Specialized systems using water spray have been developed to fill particular fire control needs in the explosives industry. These systems are referred to as ultra-high-speed water deluge spray systems. (See Section 16, Chapter 7, "Ultra-High-Speed Water Spray Systems," for additional information on these systems.)

SUMMARY

Water spray systems primarily provide fire protection for specific hazards; that is, they are designed to protect specific hazards and equipment with surface coverage. This chapter addresses the applications of water spray systems in terms of fire suppression, control, and extinguishment and describes the components and specialized uses of water spray systems.

FIGURE 16.9.12 Grinnell Mulsifyre Nozzle with Blow-Off Cap

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on water spray protection discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 18, *Standard on Wetting Agents*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 22, *Standard for Water Tanks for Private Fire Protection*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 72®, *National Fire Alarm Code®*
NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*
NFPA 750, *Standard on Water Mist Fire Protection Systems*

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Chapter 10

Standpipe and Hose Systems

Revised by
David R. Hague

Chapter Contents

Standpipe System Design Considerations
Standpipe System Installation Considerations
Commissioning of Standpipe Systems
Fire Department Operations Using Standpipe Systems
Outside Hose Systems

Key Terms

automatic-dry standpipe system, automatic-wet standpipe system, fire department connection, manual-dry standpipe system, manual-wet standpipe system, semiautomatic-dry standpipe system, standpipe system, stationary fire pump, system demand

Standpipe systems are fixed piping systems with associated equipment that transports water from a reliable water supply to designated areas of buildings where hoses can be deployed for fire fighting. Such systems are typically provided in tall and large-area buildings.

Standpipe systems can significantly improve the efficiency of manual fire-fighting operations by eliminating the need for long and cumbersome hose lays from fire apparatus to a fire. Even in buildings that are protected by automatic sprinklers, standpipe systems can play an important role in building fire safety by serving as a backup for, and complement to, sprinklers.

The NFPA standard regulating the design, installation, and testing of standpipe systems is NFPA 14, *Standard for the Installation of Standpipe and Hose Systems* (references to NFPA 14 are based on the 2007 edition). Note that NFPA 14 does not cover where standpipe systems are required. Required installations are set forth in code documents, such as NFPA *101*®, *Life Safety Code*®; NFPA 1, *Uniform Fire Code*™; and model building codes, or they may be established by insurance regulations.

NFPA 13, *Standard for the Installation of Sprinkler Systems,* is a useful reference when considering hydraulically designed systems or combined sprinkler and standpipe systems. Other NFPA standards and recommended practices that may be helpful when dealing with standpipe systems are included in the bibliography at the end of this chapter.

For other information relevant to standpipe systems, see Section 15, Chapter 1, "Fixed Water Storage Facilities for Fire Protection"; Section 15, Chapter 6, "Water Distribution"; and Section 16, Chapter 11, "Care and Maintenance of Water-Based Extinguishing Systems."

STANDPIPE SYSTEM DESIGN CONSIDERATIONS

All standpipe systems share a common purpose of delivering water for manual fire fighting. However, system designs used to accomplish this purpose will vary. Whereas one system may involve a simple pipe network for conveying water from fire department apparatus to hose connections in a building, another may involve a fully automatic water supply and preconnected hoses.

Standpipe system designs are generally dictated by NFPA 14, but local, state, and model building codes and insurance standards may also have an influence. The requirements among these codes and standards vary, so it is essential for system designers to determine which codes and standards have been adopted by the regulating entity.

Because NFPA 14 is often recognized as the design standard for standpipe systems, the following discussion on design considerations focuses on the regulatory requirements in NFPA 14. In addition, model building code requirements and engineering and historical perspectives are also discussed.

The Design Process

The process of designing a standpipe system begins with determining the intended use, that is, whether it is for (1) full-scale fire fighting, (2) first-aid fire fighting, or (3) both. These three uses

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correspond with the three classes of standpipe systems—Class I, Class II, and Class III. Most aspects of system design, such as the required water supply, layout, and system components, are affected or dictated by the class of system.

Classes of Systems

Standpipe systems are designated as Class I, Class II, and Class III. Some sources refer to a fourth class of system called a "combined" system; however, combined systems are simply Class I or Class III standpipe systems that also supply water to a sprinkler system. Note that sprinkler systems with hose connections are not necessarily considered to be standpipe systems. Such systems are often regarded simply as sprinkler systems. The design of a combined system is similar to any other Class I or Class III system, except that the water supply and pipe sizes may be larger to accommodate the added sprinkler system demand.

Class I Systems. A Class I system provides 2½ in. (65 mm) hose connections at designated locations in a building for use by the fire department.

A Class I system is typically required in buildings that have more than three stories above or below grade because of the time and difficulty involved in laying hose from fire apparatus directly to remote floors. Class I systems are also sometimes required in malls because these occupancies contain areas that are difficult to access directly with hose from fire apparatus.

Class II Systems. A Class II system provides 1½ in. (40 mm) hose connections at designated locations in a building for first-aid fire fighting. These systems are generally intended for use by trained fire brigades before the fire department arrives, but they are occasionally provided for use by fire departments, as well. With Class II systems, a hose, a nozzle, and a hose rack are typically installed on each hose connection.

Class II systems are often required in large unsprinklered buildings. They may also be required to protect special hazard areas, such as exhibit halls and stages.

With respect to Class II standpipe systems, members of the fire protection community disagree about the desirability of having standpipe systems available for occupant use. Concerns focus on the ability of untrained occupants to safely use a 100-ft (30.5-m) long hose flowing up to 100 gpm (378 L/min) and on the wisdom of encouraging occupants to fight a fire instead of evacuating. These concerns have led to a trend of reducing the requirements for, or eliminating the installation of, standpipe systems with preconnected hoses. Consequently, the use of Class II systems is declining. The 2007 edition of NFPA 14 no longer recognizes "Building Occupant Use" of standpipes but refers to "Trained Industrial Fire Brigades."

Class III Systems. Class III systems combine the features of Class I and Class II systems. They are provided for both full-scale and first-aid fire fighting. These systems are generally intended for use by fire departments and fire brigades. Because of their multiple uses, Class III systems are provided with both Class I and Class II hose connections. This is sometimes accomplished by using 2½ in. (65 mm) hose valves with easily removable 2½- to 1½-in. (65- to 40-mm) adapters that are permanently chained to hose connections. Where Class III systems are required by code, the system may be provided with a 2½ in. (65 mm) hose value, a 2½ in. × 1½ in. (65 mm × 40 mm) reducer, and a cap and chain in lieu of providing hose.

Class III systems are sometimes used when both Class I and Class II systems are required and no useful purpose would be served by installing separate systems. Like Class II systems, the use of Class III systems is declining because of concerns about the safety and effectiveness of untrained occupants fighting fires.

Types of Systems

In addition to being subdivided into classes that delineate the intended use of a system (i.e., fire department use or industrial fire brigade use), standpipe systems are also classified by "type." These types delineate the basic characteristics of systems; that is, whether the piping will be filled with water or not (wet versus dry), and whether the water supply for fire fighting will be automatically available or not (automatic, semiautomatic, or manual).

Beginning with the 1993 edition of NFPA 14, standpipe system types were completely redefined. The result was the creation of five categories, as follows:

1. *Automatic-wet systems* have piping that is filled with water at all times and have an automatically available water supply capable of supplying the water demand necessary for fire fighting.

2. *Automatic-dry systems* have piping that is normally filled with pressurized air. These systems are arranged, through the use of devices such as a dry-pipe valve, to automatically admit water into system piping when a hose valve is opened, and they are connected to an automatically available water supply that is capable of supplying the water demand necessary for fire fighting.

3. *Semiautomatic-dry systems* have piping that is normally filled with air that may or may not be pressurized. These systems are arranged through the use of devices, such as a deluge valve, to admit water into system piping when a remote actuation device located at a hose station, such as a pull station, is operated. They also have a preconnected water supply that is capable of supplying the water demand necessary for fire fighting.

4. *Manual-dry systems* have piping that is normally filled with air, and these systems do not have a preconnected water supply. A fire department connection must be used to manually supply water for fire fighting.

5. *Manual-wet systems* have piping that is normally filled with water for the purpose of keeping the system full of water, thus avoiding "fill time" when the system is used. The water supply for these systems is typically provided by a small connection to domestic water piping, and it is not capable of supplying fire-fighting water demands. A fire department connection must be used to manually supply water for fire fighting.

In summary, wet systems have water-filled piping and dry systems do not. Automatic systems provide a water supply for

fire fighting simply by opening a hose valve. Semiautomatic systems are connected to a water supply for fire fighting but require activation of a device at a hose valve in addition to opening the valve to get water. Manual systems do not have a preconnected water supply for fire fighting, and these systems must be manually supplied by connecting hoses from a fire department pumper truck to a fire department connection.

Design Restrictions Based on System Class and Type

NFPA 14 specifies several design limitations based on the type of system to be used.

Manual standpipe systems are not allowed to be used in high-rise buildings. This is partly to provide an increased level of safety in such buildings and partly in recognition of the fact that a sprinkler system will be required by building codes for high-rise buildings, almost surely necessitating a fire pump. In such applications, the standpipe and sprinkler systems are "combined" using common feed main piping precluding the use of dry systems. Once a pump is called for, it is considered reasonable to require that the pump be capable of supplying the standpipe system demand, given the marginal additional cost.

Manual systems are also prohibited for Class II and Class III systems, because systems with preconnected hose obviously need an available water supply to be of benefit in fighting incipient fires.

Dry systems are not allowed for most Class II or Class III systems because of the risk to untrained users that would be created by delaying the availability of water. Also, dry systems are allowed only in areas subject to freezing, because wet systems are considered more reliable. Dry standpipes have been known to perform unsatisfactorily in the past because open valves or severe leaks went undetected until the system was charged with water. The NFPA 14 committee considered this risk of failure avoidable for most cases by simply requiring system piping to be filled with water unless a risk of freezing is present.

System Layout

Number and Location of Hose Connections. The required number of hose connections is primarily based on a building's design. Codes and standards employ two approaches to determining hose connection locations. The first method, termed the "actual length" method, is used only for 1½ in. (40 mm) hose connections on Class II and Class III systems. This method locates 1½ in. (40 mm) hose connections such that enough are provided to reach all portions of the area served with a 100 ft (30.5 m) hose that has a nozzle with a 20- to 30-ft (6- to 9-m) reach. The 100 ft (30.5 m) length limit is required for ease of handling. Distances should be measured around partitions and obstructions for hose length and along unobstructed straight-line paths for nozzle reach.

Because standpipe systems with preconnected hose are usually intended for extinguishing incipient fires before the fire department arrives, 1½ in. (40 mm) hose stations should be located in central areas, such as corridors, where they are clearly visible and readily accessible. Figure 16.10.1 illustrates the actual length method for locating hose stations. In the actual length method (as illustrated on a partial floor plan), a maximum distance of 130 ft (39.5 m), consisting of 100 ft (30.5 m) of flexible hose-lay distance and 30 ft (9 m) of straight-line nozzle trajectory is the basis for locating the 1½ in. (40 mm) hose stations.

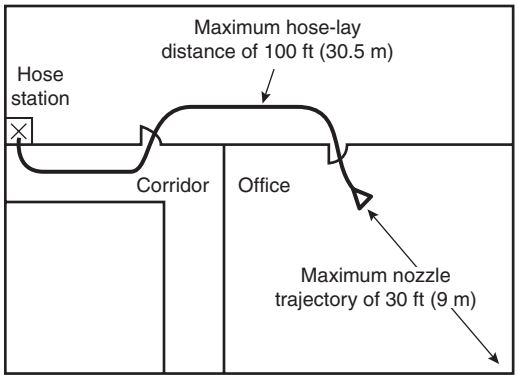

FIGURE 16.10.1 Actual Length Method for Locating Hose Connections

The second method, termed the "exit location method," is used for 2½ in. (65 mm) hose connections on Class I and Class III systems. This method locates connections based on a building's exiting system. Using this method, 2½ in. (65 mm) hose connections are located in exit stairs, at horizontal exits, and in exit passageways, as required by the building code. Because exits must be reasonably distributed within buildings to provide adequate egress, hose connections are considered to be adequately distributed when located at the points of egress from areas served. Figure 16.10.2 illustrates the exit location method for locating hose connections. In the exit location method, maximum travel distance to an exit (door), as established by the applicable building code, is the basis for locating required 2½ in. (65 mm) hose connections. Enclosed exit stairways are also

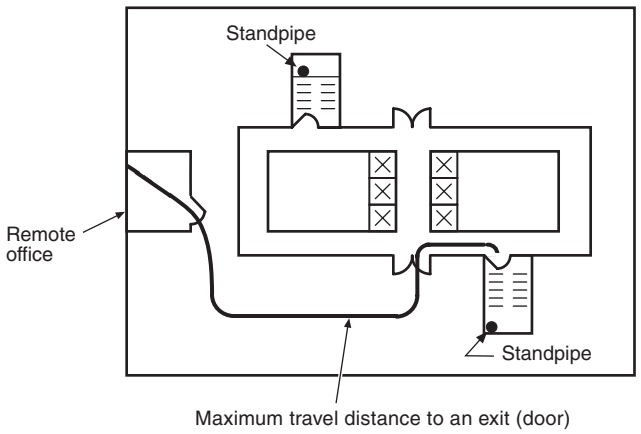

FIGURE 16.10.2 Exit Location Method for Locating Hose Connections

considered to be protected spaces and afford fire fighters an area to stage fire-fighting operations.

In early editions of NFPA 14, Class I hose connections were required to be located using the actual length method. In the 1993 and subsequent editions, the method specified is the exit location method. This switch was made because the actual length method encouraged locating hose connections in open-floor areas to meet distance requirements. Such locations are not advantageous to fire fighters because they may be obstructed by smoke or exposed to fire, preventing their use. NFPA 14 now recognizes that it is preferable to locate 2½ in. (65 mm) hose connections where they will be protected from a fire, such as within protected stair enclosures or on opposite sides of horizontal exits. This location allows fire fighters to connect to a system in relative safety and to have a charged hose available before entering a fire area.

Some have argued that extending hose from the inside of an exit enclosure compromises enclosure integrity and places occupants at risk during evacuation. However, NFPA 14 recognizes that the alternative is an unreasonable expectation of fire fighters to enter an area filled with smoke and heated gases to search for a hose connection, placing them in extreme danger. In addition, time lost while searching for a hose connection would prolong an uncontrolled fire, potentially posing a much greater threat to occupants.

It should be noted that NFPA 14 does permit additional 2½ in. (65 mm) hose connections to be required by local authorities when exit travel distances exceed 150 ft (46 m) in non-sprinklered buildings and 200 ft (61 m) in sprinklered buildings. This special option is provided because exit travel distance for occupants going out effectively equates to the maximum hose-lay distance for fire fighters going in, and deploying more than 200 ft (61 m) of charged hose is recognizably difficult. If additional connections outside of exit enclosures are considered necessary, they should be located only in areas protected by fire-resistive construction so that fire fighters will have a protected environment in which they can connect hoses.

For the purpose of locating standpipe outlets, the roof should be treated as an additional floor. Thus, for buildings with two or more standpipes, the building roof should be provided with two or more outlets. Beginning with the 2007 edition of NFPA 14, roof outlets can be omitted where the roof pitch is greater than 3 in 12. An additional outlet must be provided at the top of the standpipe for testing purposes. This outlet will permit flowing 500 gpm (1893 L/min).

Positioning of Hose Connections at Landings. One other aspect of locating 2½ in. (65 mm) hose connections that is worthy of discussion is the positioning of hose connections within stair enclosures. In earlier editions of NFPA 14, hose connections were required at floor levels within stair enclosures, positioning that actually hampered fire-fighting efforts.

The prior standards failed to recognize that fire departments typically use connections at the floor below the fire floor to leave the doorway to the fire floor uncongested and to give the fire fighters a safer location for connecting hoses. However, connecting hoses an entire story below the fire floor uses up valuable hose length, and connecting at a floor-level landing obstructs the adjacent doorway. The solution now included in NFPA 14 is to place connections at intermediate floor landings. This placement allows hoses to be connected somewhat below the fire floor while minimizing the additional hose length required to do so. It also avoids congestion problems associated with having hose connections located adjacent to exit doors and areas of wheelchair refuge within stairwells. Locating hose connections in this manner also prevents kinking hose, as it bends around doorways.

Interconnection of Piping. One last item to remember when laying out a system is that standpipes must be interconnected as close as possible to the source of supply, or at the top when gravity tanks are used. Interconnection of standpipes ensures that water supplies can service all portions of a system.

Water Supply and Piping Requirements

The class and type of system to be installed will dictate the required water supply. There are three aspects of water supplies that must be taken into account: (1) the minimum flow rate required, (2) the minimum pressure required, and (3) the type of supply to be used. In addition, the maximum pressure available may also be of concern.

Minimum Flow Rate and Minimum Pressure (System Demand). The minimum required flow and minimum required pressure are together referred to as the "system demand." The system demand for a standpipe system is a function of several variables:

1. The required flow rate and pressure at the hydraulically most remote hose connections
2. Required flow rates for additional standpipes
3. The water supply requirements for automatic sprinklers sharing common piping
4. Pressure losses from friction and changes in elevation between the water supply and the hydraulically most remote hose connection

Minimum flow rate and pressure requirements for standpipe systems are determined based on the class of system. According to NFPA 14, Class I and Class III systems are typically required to deliver 500 gpm (1893 L/min) for the first standpipe, plus 250 gpm (946 L/min) for each additional standpipe, up to a maximum of 1250 gpm (4731 L/min). The maximum flow is reduced to 1000 gpm (3785 L/min) for combined systems in recognition of the assistance provided by sprinklers even when sprinklers alone have been unable to control a fire. NFPA 14 also requires the water supply to be capable of providing the minimum flow rate for 30 minutes. This duration is intended to apply to automatic and semiautomatic supplies, and it assumes the fire department runs on a separate water source to supply the system using pumper trucks within 30 minutes. Figure 16.10.3 illustrates these design flow rate requirements for Class I and Class III systems.

With respect to pressure, NFPA 14 requires that a water supply for Class I and Class III systems be able to deliver a residual pressure of 100 psi (690 kPa) at the outlet of the topmost hose

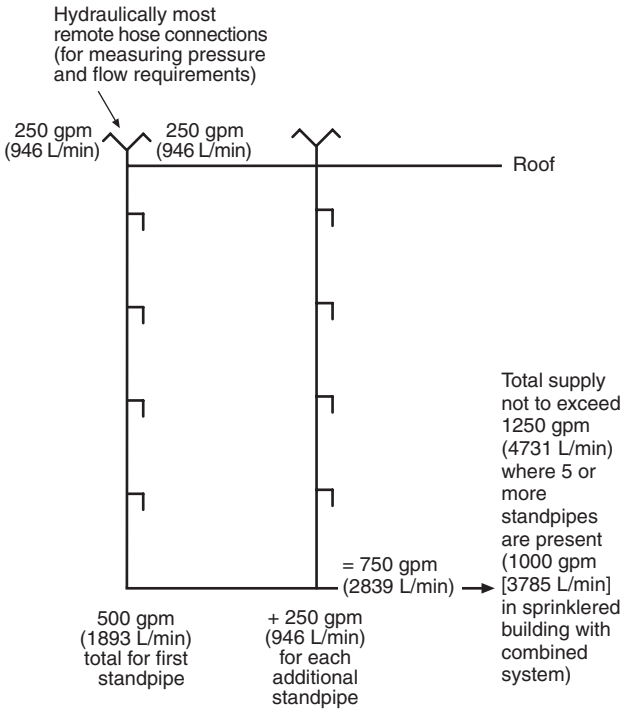

FIGURE 16.10.3 Basic Flow Rate Requirements for Class I and Class III Systems

TABLE 16.10.1 Pressure Limits for Standpipe System Outlets

Outlet Use	*Minimum Residual Pressure*	*Pressure-Regulating Device Required When Pressure Exceeds*[b]
1½ in. (40 mm) hose connection with preconnected hose	65 psi[a] (448 kPa)	100 psi (690 kPa)[c]
1½–2½ in. (40–65 mm) hose connection without preconnected hose	100 psi[a] (690 kPa)	175 psi (1207 kPa)[d]
Sprinkler system connection	per NFPA 13	175 psi (1207 kPa)[d]

[a]Measured at the hydraulically most remote hose connection while flowing at a rate specified by NFPA 14.
[b]Pressures in system piping should never exceed the rating of any system component.
[c]This is a residual pressure limit. Static pressure cannot exceed 175 psi (1207 kPa) before a pressure-regulating device is required.
[d]A setting of 165 psi (1138 kPa) can be used on a combined sprinkler/hose connection on combined systems while achieving acceptable flows and nozzles pressure. Set pressure-regulating device at 165 psi (1138 kPa) because NFPA 13 will require a relief valve set at 175 psi (1207 kPa).

connection on each standpipe. This pressure must be available while flowing 250 gpm (946 L/min) from each of the two topmost hose connections of the hydraulically most remote standpipe, plus 250 gpm (946 L/min) from each additional standpipe, up to the required maximum. Note that NFPA 14 no longer allows a reduction in the minimum pressure requirement.

For Class II systems, NFPA 14 requires that the water supply be capable of delivering 100 gpm (379 L/min) for 30 minutes. It must also be strong enough to maintain a residual pressure of 65 psi (448 kPa) at the outlet of the hydraulically most remote hose connection with 100 gpm (379 L/min) flowing.

In addition to minimum pressure and flow requirements, there are maximum pressure limits for hose connections as well. For a discussion on maximum pressure limits, see the subsection "Maximum Pressure and Zoning in Tall Buildings" later in this chapter.

See Table 16.10.1 for a summary of requirements.

Supplying System Demand for Standpipe Systems. For manual systems (described previously) the system demand must be supplied exclusively through the fire department connection. An automatic water supply is not required on such systems, and even where a manual-wet standpipe is combined with a sprinkler system, the standpipe demand does not have to be available via the preconnected water supply serving sprinklers.

History of Outlet Pressures and Fire-Fighting Nozzles. NFPA 14 was modified in the 1993 edition to increase the minimum outlet pressure for Class I and Class III outlets from 65 psi (448 kPa) to 100 psi (690 kPa) because of questions raised regarding the adequacy of a 65 psi (448 kPa) minimum design pressure on automatic and semiautomatic standpipes. From a performance perspective, the NFPA Committee on Standpipe and Hose Systems (NFPA 14 committee) agreed that the minimum pressure at any hose connection should be adequate to properly operate a fire nozzle while overcoming friction loss in a hose. From a design perspective, the establishment of a minimum design pressure for hose connections has proven difficult because nozzle operating pressures and friction losses in hoses vary, depending on the equipment used by each local fire department.

The concern over nozzle pressure originally became an issue when fog nozzles were introduced for fire fighting in the mid-1900s. Before fog nozzles, fire fighters used solid stream nozzles, which operated well at fairly low inlet pressures. As the use of fog nozzles became common, the fire protection community moved to increase the minimum pressure required at the hydraulically most remote hose connections on standpipe systems to accommodate the greater nozzle pressure required by fog nozzles. The NFPA 14 committee originally recommended a pressure of 65 psi (448 kPa), which was widely implemented. In establishing this pressure, the committee had tried to minimize the pressure required for standpipe system water supplies and assumed that nozzle designers and testing laboratories would establish criteria to ensure that fog nozzles would operate satisfactorily with a 65 psi (448 kPa) pressure at hose connections. Unfortunately, this assumption never materialized, and many later questioned the pre-1993 65 psi (448 kPa) minimum pressure requirement.

In reevaluating the minimum pressure requirement for the 1993 edition, the NFPA 14 committee decided that the minimum pressure required at standpipe hose connections must be chosen conservatively. This is because fog nozzle performance, unlike that of solid stream nozzles, varies significantly with respect to the minimum inlet pressure required to achieve satisfactory streams. Though some fire service fog nozzles operate satisfactorily with as little as 70 psi (483 kPa), others have discharge patterns that quickly deteriorate as the nozzle pressure drops below 100 psi (690 kPa). As a result of this inconsistency, the only pressure that will reasonably ensure satisfactory nozzle performance in all cases is the pressure at which nozzles are tested and rated, 100 psi (690 kPa). This is the residual test pressure for fog nozzles established by NFPA 1964, *Standard for Spray Nozzles.*

To deliver a pressure of 100 psi (690 kPa) at the nozzle, the pressure at the standpipe hose connection must exceed 100 psi (690 kPa) by a value great enough to offset friction loss in the hose connecting the nozzle to the outlet. Ideally, a design should provide an additional 25 psi (172 kPa) for this purpose. This is adequate to compensate for friction loss in (1) 200 ft (61 m) of 2½ in. (65 mm) rubber-lined hose flowing about 250 gpm (946 L/min), (2) 200 ft (61 m) of 2 in. (50 mm) rubber-lined hose flowing about 125 gpm (473 L/min), or (3) 150 ft (46 m) of 1¾ in. (45 mm) rubber-lined hose flowing about 100 gpm (379 L/min).

Based on the foregoing reasoning, the NFPA 14 committee contemplated requiring a 125 psi (862 kPa) minimum pressure at the most remote hose connection but eventually decided on 100 psi (690 kPa). At first glance, this figure appears inadequate for satisfactory streams, and an explanation of the committee's action is warranted. The basis of this figure is an assumption that a fire pump will typically be installed to supply an automatic standpipe and that a pump designed to deliver 100 psi (690 kPa) at the most remote outlet at full system demand will actually deliver 120 psi (827 kPa) or more at lower flows. This takes advantage of excess pressure at the low-flow end of a fire pump curve. (See NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection.*)

The 120-plus psi (827 kPa) initial pressure was considered reasonably adequate to satisfy a 100 psi (690 kPa) nozzle inlet pressure plus friction loss in the connecting hose for the first one or two hose lines deployed, and it was assumed that if fire-fighting operations grew beyond this level, fire apparatus would be available to supply additional pressure to meet fire nozzle demands. Alternatively, smooth-bore nozzles could be deployed. If these assumptions are not valid for a particular installation, consideration should be given to exceeding the minimum pressure specified by NFPA 14 to accommodate fire-fighting needs.

Although the 100 psi (690 kPa) minimum design pressure now specified by NFPA 14 may seem excessive when compared to the 65 psi (448 kPa) pressure specified in the past, it is consistent with established fire-fighting practices. Fire departments for decades have used 100 psi (690 kPa) as the target nozzle pressure when pumping hoses supplying fog nozzles, and fire hoses supplying fog nozzles are routinely pumped by fire apparatus at 150 psi (1034 kPa) or more when such hoses are connected directly to such apparatus.

For hose connections on Class II or Class III systems with preconnected hoses installed, nozzles with operating pressures in the 50 psi (345 kPa) range should be specified. By purchasing low-pressure nozzles, the minimum pressure required at the hydraulically most remote hose connection with preconnected hoses can be limited to 65 psi (448 kPa).

For additional information regarding selection of fire nozzles for use with standpipe systems, see "Fire Department Operations Using Standpipe Systems" later in this chapter.

Type and Number of Water Supplies. Manual standpipe systems may be supplied exclusively by a fire department connection (FDC) with a reliable and adequate water source accessible nearby.

Automatic and semiautomatic standpipe systems require a minimum of one preconnected water supply that is capable of supplying the standpipe system's hydraulic demand for the minimum required duration. Several types of water supplies may be acceptable. These include:

1. Public waterworks systems, supplemented by a booster pump when higher pressures are required
2. Fire pumps connected to a reliable fixed water source
3. Pressure tanks
4. Gravity tanks

In addition to the primary water supply on an automatic or semiautomatic standpipe system, one or more FDCs with a reliable water source accessible nearby are required.

Special Water Supply Requirements. In some cases, special water supply requirements may be applicable. For example, buildings in active seismic areas are often required by local regulations to use in-house tanks and pumps to supply standpipe systems rather than relying on public water supplies, which are susceptible to earthquake-induced failure.

Water Supply for High-Rise Buildings. For high-rise buildings, two remotely located FDCs are required for each zone within the pumping range of fire apparatus in addition to the automatic water supply. Two FDCs reduce the possibility of having falling glass cut all supply hoses and interrupt the secondary water supply during a fire.

Very tall buildings with floors located above the pumping range of fire department apparatus require a permanent secondary water source instead of FDCs because failure of the primary supply would otherwise render a building completely unprotected. If the primary water supply uses a pump, the backup arrangement could consist of a second pump, driver, and controller, or, perhaps, high-level water storage with additional pumping capability. The point at which a system is beyond the capability of fire department apparatus depends on the apparatus's pump and the residual pressure available from the water source. A permanent secondary water source is needed, if the following is "true":

$$AP + RP \leq SD$$

where

AP = Apparatus pressure boost available from a fire department pumper measured at the system demand flow rate

RP = Residual pressure available from the public or private water supply measured at the system demand flow rate

SD = System demand pressure at the system demand flow rate, measured at the pumper truck outlet supplying the hose to the FDC

If the system demand exceeds the sum of the fire apparatus pressure boost and the residual supply pressure (or the rated service pressure of the fire hose that will supply the FDC), fire apparatus will not be able to adequately supply upper portions of the standpipe system, and a secondary water supply is necessary. As a rule of thumb, buildings exceeding 300 ft (91.5 m) in height should be evaluated to determine whether the pumping range of the fire department apparatus has been exceeded.

Water Supply and Fire Pumps for Sprinklered Mid-Rise Buildings. An issue that is often raised in the design of standpipe systems for sprinklered mid-rise buildings is whether the sprinkler demand, the standpipe demand, or both, must be supplied by the automatic water supply serving the sprinkler system. The issue can have a major cost impact on mid-rise buildings, because the sprinkler demand can often be supplied by the public water supply without the use of a pump, whereas the standpipe demand almost always requires a pump.

In the 1993 edition of NFPA 14, an effort was made to provide further guidance on this issue. Although the solution is not clearly stated in the document, the intent is clear.

NFPA 14 allows a Class I standpipe system to be a manual system in buildings that are not high-rise buildings (defined as buildings having the floor level of an occupied floor located 75 ft [23 m] or more above the lowest level of fire department access). By allowing such standpipe systems to be manual systems, NFPA 14 does not require an automatic water supply to meet the standpipe demand. Therefore, where such standpipes also serve sprinklers in a combined system, only the sprinkler system demand must be automatically supplied. The combined system, from a standpipe perspective, is merely a Class I manual-wet standpipe system.

Sizing Pipe. Two methods of sizing standpipe system piping are (1) the pipe schedule method and (2) the hydraulic method.

With the pipe schedule method, pipe sizes are prescribed by a schedule, in NFPA 14, based on the class of system and the height of the standpipe. However, pipe schedule systems are no longer common, because buildings with standpipe systems typically require sprinkler protection as well. Such buildings also make use of combined systems, which must be hydraulically designed.

With the hydraulic design method, pipe sizes are calculated so that a system will deliver the minimum required pressure and flow. Pipe sizes must be large enough to allow each water supply, including fire department apparatus, to deliver the required flow at the hydraulically most remote hose connection.

When performing a hydraulic design, the hydraulic characteristics of each water supply must be known. The procedure for determining the hydraulic characteristics of permanent water supplies such as pumps is fairly straightforward and is described in NFPA 20 and in other chapters of this handbook. The procedure for determining the hydraulic characteristics of fire apparatus supplying a standpipe system is similar. Lacking better information about local fire apparatus, a conservative design would accommodate a 1000 gpm (3785 L/min) fire department pumper performing at the level of design specifications set forth in NFPA 1901, *Standard for Automotive Fire Apparatus*. NFPA 1901 specifies that fire department pumpers must be able to achieve three pressure/flow combinations. These are 100 percent of rated capacity at 150 psi (1034 kPa) net pump pressure, 70 percent of rated capacity at 200 psi (1379 kPa) net pump pressure, and 50 percent of rated capacity at 250 psi (1724 kPa) net pump pressure. Therefore, a 1000 gpm (3785 L/min) pumper can be expected to deliver no less than 1000 gpm (3785 L/min) at 150 psi (1034 kPa), 700 gpm (2650 L/min) at 200 psi (1379 kPa), and 500 gpm (1893 L/min) at 250 psi (1724 kPa). Residual supply pressure on the suction side of a pump from a municipal or other pressurized water supply can also be added.

To perform a hydraulic design, one should determine the minimum required pressure and flow at the hydraulically most remote hose connection and calculate this demand back through system piping to each water supply, accumulating losses for friction and elevation changes and adding flows for additional standpipes and sprinklers at each point where such standpipes or sprinklers connect to the hydraulic design path. When considering fire apparatus as a water supply, flows must be calculated from system piping through the fire department connection and back through connecting hoses to the apparatus. If the pressure available at each supply source exceeds a standpipe system's pressure demand at the designated flow, the design is acceptable. Otherwise, the piping design or the water supply must be adjusted. For more information, see Section 15, Chapter 3, "Hydraulics for Fire Protection."

Maximum Pressure and Zoning in Tall Buildings. In tall buildings, standpipe systems are often divided into subsystems to limit system pressure by controlling the maximum height of a water column. These subsystems are called zones. The goal of zoning is to limit the pressure that can be developed in system piping and at hose connections to reduce the need for high-pressure fittings and pressure-reducing valves.

In the 1993 edition of NFPA 14, the previous height limitation was replaced by a pressure limitation of 350 psi (24.1 bar). Beginning with the 2007 edition, the pressure limitation was eliminated in favor of a performance requirement that limits pressure based solely on the pressure rating of the system components. This revision also introduced the concept of a master pressure-reducing valve (PRV) to control pressures at lower elevations on a standpipe system. Traditionally NFPA 14 required a separate pump for each zone of a standpipe system. The 2007 edition of NFPA 14 permits the use of a single high-pressure pump to serve all areas of a building and employing a master PRV to control pressures for the lower floors. See Figure 16.10.4 for master PRV applications. When a master PRV is used, certain restrictions on its use apply. They are as follows:

- A method to isolate the PRV must be provided to allow maintenance and repair.

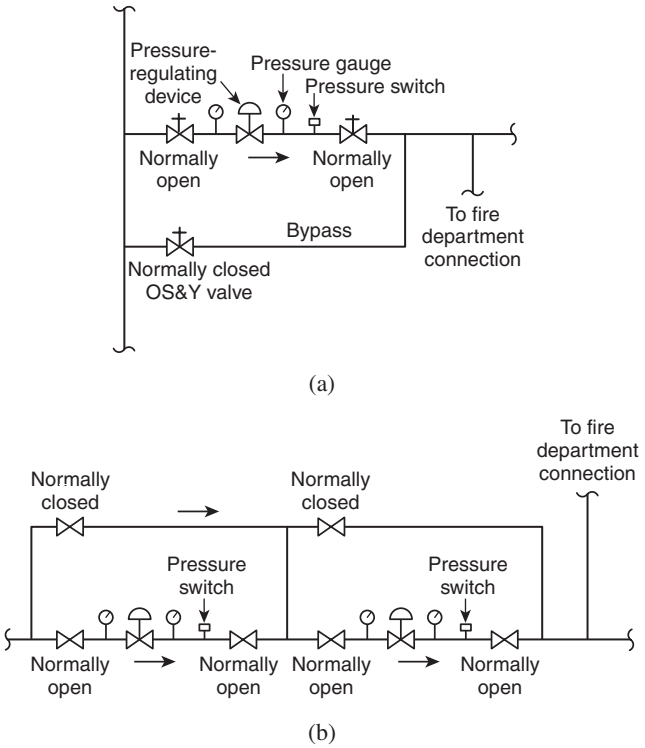

FIGURE 16.10.4 Two Examples of Master PRV Stations

- PRVs must be arranged so that failure of the device does not allow more than 175 psi (12.1 bar) to more than two hose connections.
- An equally sized bypass with a normally closed gate valve must be installed.
- The device must not be located more than 7 ft 6 in. (2.3 m) above the floor.
- Inlet and outlet pressure gauges must be provided.
- FDCs must be connected on the system side of the outlet isolation valve.
- A pressure relief valve must be provided in accordance with the manufacturer's recommendations.
- Remote monitoring for detecting failure of the PRV must be provided.

The maximum pressure in a standpipe system must always be limited based on the pressure ratings of system components. Fittings, valves, and pressure-regulating devices are usually the weakest links among system components with respect to pressure limits. Fittings often have a maximum pressure rating of 175 psi (1207 kPa); however, listed fittings are commonly available with pressure ratings of up to 350 psi (2413 kPa) or more. Listed valves and pressure regulating devices are also available with 350 psi (2413 kPa) or higher ratings. However, zone heights must be further limited if equipment with pressure ratings less than 350 psi (2413 kPa) is used.

Although the maximum zone height corresponding to a particular maximum system pressure can be calculated, zone height limits will be determined by trial and error in most cases. To determine whether a single zone can be used, a designer can lay out a system with one zone and calculate the required pressures and flows from hydraulic demand points back through system piping to the supply to determine the system demand. Assuming that the supply will be a pump, a single zone can be justified if a pump is available that would satisfy the hydraulic demand of the system without exceeding the system component pressure rating at churn, including residual supply pressure. If a pump cannot be found to meet these criteria, adjustments to the design or subdivision into zones can be made or a variable speed pump can be used.

Standpipe system pressures in the 350 psi (2413 kPa) range pose a danger to users and a risk of failure of sprinkler system components on combined systems. Therefore, pressure control devices are required when system pressure could exceed safety limits at hose or sprinkler connections.

The safety limits at hose connections are based on two criteria: (1) hose burst pressure and (2) handling. Hoses for fire department use are required to be tested periodically to 250 psi (1724 kPa) or more, according to NFPA 1962, *Standard for the Inspection, Care, and Use of Fire Hose, Couplings, and Nozzles and the Service Testing of Fire Hose*. NFPA 1962 requires preconnected standpipe hoses to be tested periodically to 150 psi (1034 kPa) or more.

Though a hose may not fail up to these pressures, experience indicates that 175 psi (1207 kPa) is about the maximum pressure on a hose that can be satisfactorily maneuvered by fire fighters and that 100 psi (690 kPa) is the maximum pressure that an untrained user should be expected to handle. Therefore, pressure-regulating devices are required to limit static and residual pressures to 175 psi (1207 kPa) at hose connections without preconnected hoses and to limit residual pressure to 100 psi (690 kPa) at hose connections with preconnected hoses.

The established pressure limit for sprinkler connections is also 175 psi (1207 kPa). This limit is the maximum pressure for which sprinklers are typically listed, and it provides a safety factor to prevent leakage. When higher pressure is expected at a sprinkler connection, both pressure-regulating and pressure relief valves are required. To allow a buffer between the pressure settings for the valves, regulating valves should be set at 165 psi (1138 kPa) and relief valves should be set at 175 psi (1207 kPa).

Table 16.10.1 summarizes the pressure for connections to a standpipe. Figures 16.10.5 and 16.10.6 illustrate sample multiple-zone systems. Note that, on multiple-zone systems, fire pumps may be used in series. In addition, two separate supply risers are always required for high zones supplied by pumps at lower levels so that a water supply can be maintained when one riser is out of service. Separate fire department connections are also required for each zone.

System Components

The selection of standpipe system components is determined largely by the class of system and the system layout. Particular attention should be given to ensuring that components are rated for pressures to which they may be subjected.

Piping and Fittings. Steel pipes assembled with welded joints, screwed fittings, flanged fittings, rubber-gasketed fittings, or a

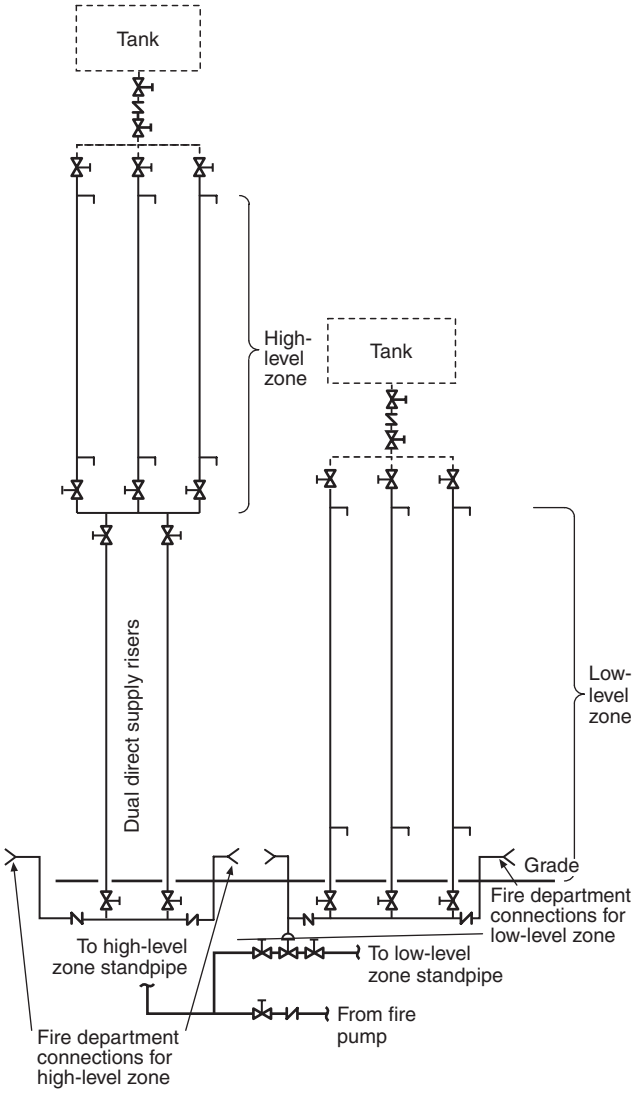

FIGURE 16.10.5 Major Components in a Multizone System with a Low-Level Pump

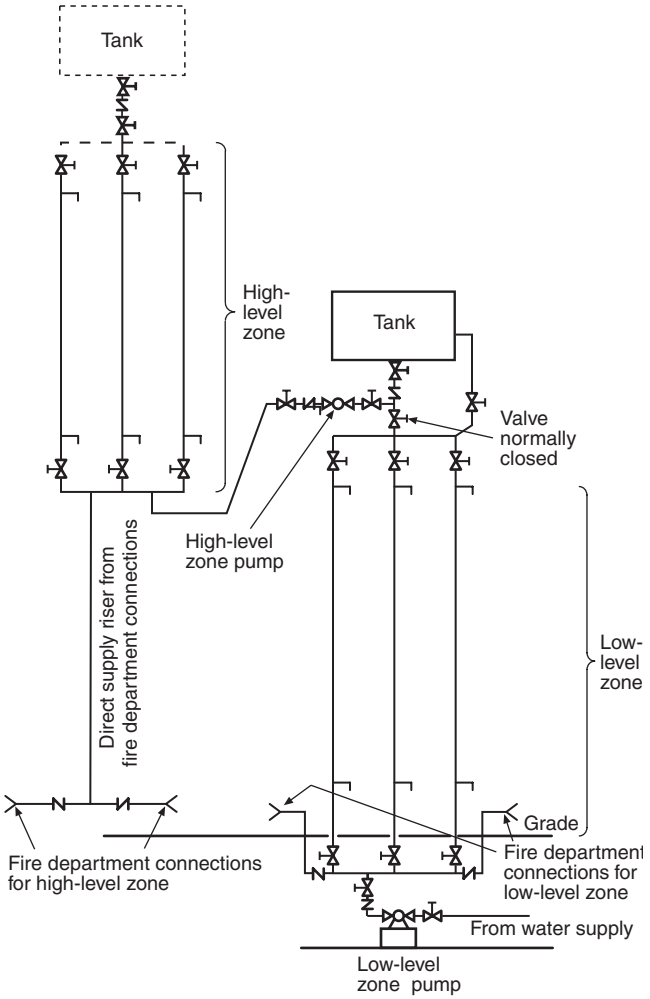

FIGURE 16.10.6 Schematic Diagram of Major Components in a Multizone System with a High-Level Pump

combination of these are the most common configurations of materials used for standpipe system piping and fittings. Piping should be capable of withstanding the maximum pressures that can be developed in a system.

Fittings are required to be rated to withstand either 175 psi (1207 kPa) or maximum system pressures, whichever is greater. When pressures are expected to exceed 175 psi (1207 kPa), extra-heavy fittings or fittings listed for greater pressures should be used for pressures up to 300 psi (2069 kPa), and specially designed fittings should be used for pressures exceeding 300 psi (2069 kPa).

Hose, Hose Racks, Nozzles, and Hose Cabinets. When preconnected hoses are required to be installed on Class II or Class III systems, lined hose must be used. Unlined linen hose has been phased out, because it is subject to rapid deterioration under moist or wet conditions. Usually, the size of choice is 1½-in. (40-mm) hose. However, the use of listed hoses smaller than 1½ in. (40 mm) is permitted by NFPA 14, in light-hazard occupancies when approved by the authority having jurisdiction. The allowance for smaller hose mounted on a reel recognizes that an untrained person might be more capable of using such equipment in the event of a fire. Similar equipment has been used in Europe for many years.

Preconnected hoses on Class II and Class III standpipes are generally limited to 100 ft (30.5 m) in length to minimize the difficulty that untrained users may have advancing a hose and to minimize kinking. Hoses are always required to be kept on compatible racks and should always be positioned in a readily accessible location within convenient reach of a person standing on the floor. Hoses should also be clearly visible and located in a place not likely to be obstructed. Where hoses are kept in cabinets or closets, the doors should have a glass panel or some other means to allow easy identification.

Preconnected hoses are required to be equipped with approved ⅜- or ½-in. (10- or 13-mm) open nozzles or combination spray/solid pattern nozzles. It is preferable to use nozzles that

have operating pressures in the 50 psi (345 kPa) range. This range minimizes the pressure demand on the system and helps to ensure that hoses can be handled by industrial fire brigade members. Because nozzle shutoff valves complicate the operation of a hose, they are considered undesirable unless the users are trained.

For typical hose rack and valve connections, see Figure 16.10.7. A typical hose cabinet is shown in Figure 16.10.8.

Valves. Several different types of valves may be used as components of standpipe systems. These include gate valves, check valves, pressure-regulating valves, and hose valves. Like piping and fittings, valves must be capable of withstanding the maximum pressure that can be developed in a system. The following discussion highlights the most common valves and pressure control devices encountered.

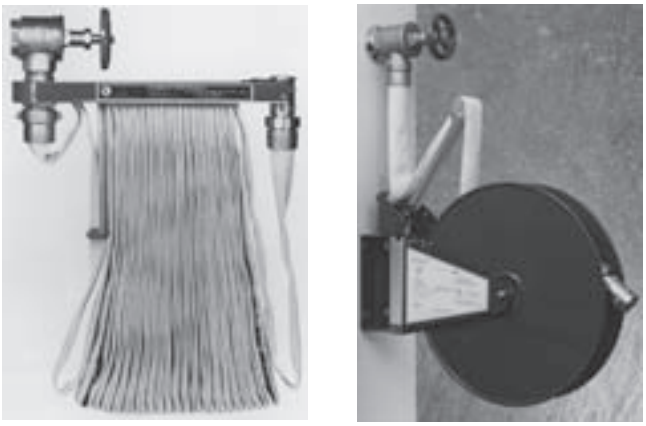

FIGURE 16.10.7 Typical Hose Racks and Valve Connections (Source: Potter-Roemer, Inc.)

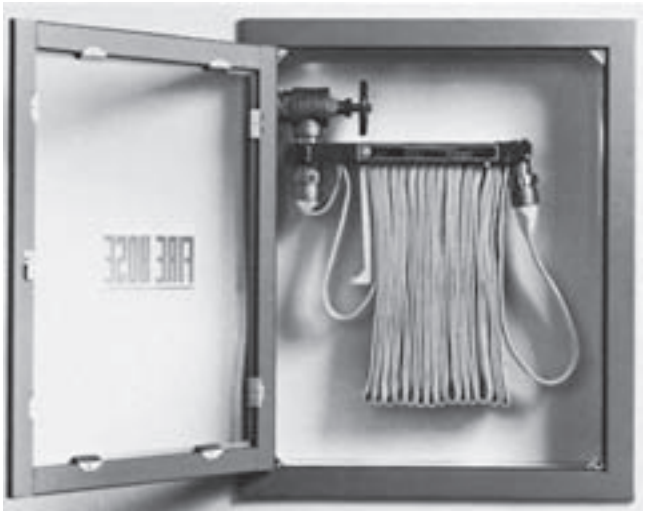

FIGURE 16.10.8 Typical Hose Cabinet

Starting at a permanent water supply, an indicating gate valve is required at each water source to allow isolation of any water source for servicing. Note that a gate valve is not permitted to be installed between a fire department connection and the standpipe system that it serves. This ensures the fire department's ability to pump into a system.

Next, each permanent water source should be protected by a check valve to prevent backflow. Check valves should also be installed between fire department connections and wet standpipe systems that they serve. These valves allow piping that is connected to fire department connections to normally be kept dry, when provided with automatic drain valves at low points. Keeping the FDC dry protects it from freezing and prevents the possibility of having FDC caps "thread-lock" if the internal clapper valves leak water back to the caps.

Moving farther into a system, gate valves should be installed at feed main connections to each standpipe to allow standpipes to be serviced independently without impairing protection to an entire building.

Drain valves also should be provided to allow individual standpipes, as well as an entire system, to be drained for servicing. Finally, each outlet from a standpipe system must terminate at a hose valve or at a sprinkler control valve on combined systems. When excessive pressures are expected at outlets, pressure-regulating devices are required.

Pressure-Regulating Devices. Pressure-regulating devices are used to limit system outlet pressures. Pressure-regulating devices used in standpipe systems can be categorized into three basic types: (1) pressure restricting, (2) pressure reducing, and (3) pressure control. Pressure-restricting devices reduce pressures in flowing conditions only. They do not compensate for changes in input pressure to maintain a constant discharge pressure, and they do not control pressure in static conditions. For these reasons, their use is limited to 1½ in. (40 mm) hose connections for limiting residual pressure to 100 psi (690 kPa) where the static pressure does not exceed 175 psi (1207 kPa). One example of a pressure-restricting device is an orifice plate. An orifice plate is a metal disk with a restricting orifice. Orifice plates may be inserted into connections to standpipe systems to reduce residual pressure on the downstream side. Though relatively inexpensive, orifice plates are generally undesirable because they do not maintain a steady discharge pressure, and because they can damage hoses if the pressure jet from an orifice strikes the inner wall of a hose. If used, orifice plates should always be installed at hose couplings to allow for easy removal.

The preferred devices for regulating excessive pressures are pressure control and pressure-reducing valves. These valves are designed to actively regulate outlet pressures in both static and flowing conditions, and they are required for outlets of systems where static pressure could exceed 175 psi (1207 kPa). Pressure control and pressure-reducing valves are preferred over pressure-restricting devices because hoses and sprinkler systems connected to standpipes are exposed to both static and flowing conditions; and uncontrolled static pressures can cause equipment failure and pose a danger to users.

Pressure control and pressure-reducing valves employ a mechanism that compensates for variations in inlet pressures by

balancing water pressure in an internal chamber or chambers, typically against a spring. Pressure control valves, which are a type of pressure-reducing valve that is pilot operated, are considered by many to be the most reliable method of controlling pressure. Figure 16.10.9 illustrates one example of a pressure control valve. In the example shown, the outlet pressure is a function of the setting on the regulating spring. Often the outlet pressure is not field adjustable, and valves are preset at the factory for use at a specific floor level in a building. In such cases, it is critical to ensure that valves are installed at the intended location.

Standpipe systems with pressure-regulating devices are required to be designed such that each device may be tested, and routine testing must be conducted. To accommodate the need for testing pressure-regulating devices, standpipe systems using such devices must have a dedicated drainage system with connections at every other floor and a central means for measuring flow. Figure 16.10.10 shows one possible design of a floor valve assembly for such an arrangement. The case shown assumes a standpipe pressure in excess of 175 psi (1207 kPa) and a combined sprinkler and standpipe system with a directly connected drainage riser for pressure-regulating device testing. As an option, the drainage riser may simply have a hose connection at every other floor where a short piece of hose can be connected to the two closest pressure-regulating devices for testing.

Where system pressures are extreme, pressure relief valves, which reduce pressure by flowing water into a drain, may be provided as a backup to pressure-regulating valves. Pressure relief valves are commonly available in two types: (1) spring operated and (2) pilot operated. Pilot-operated valves are preferred because they respond more accurately to changes in system pressures; however, these valves may require increased maintenance to prevent excessive accumulation of debris in strainers.

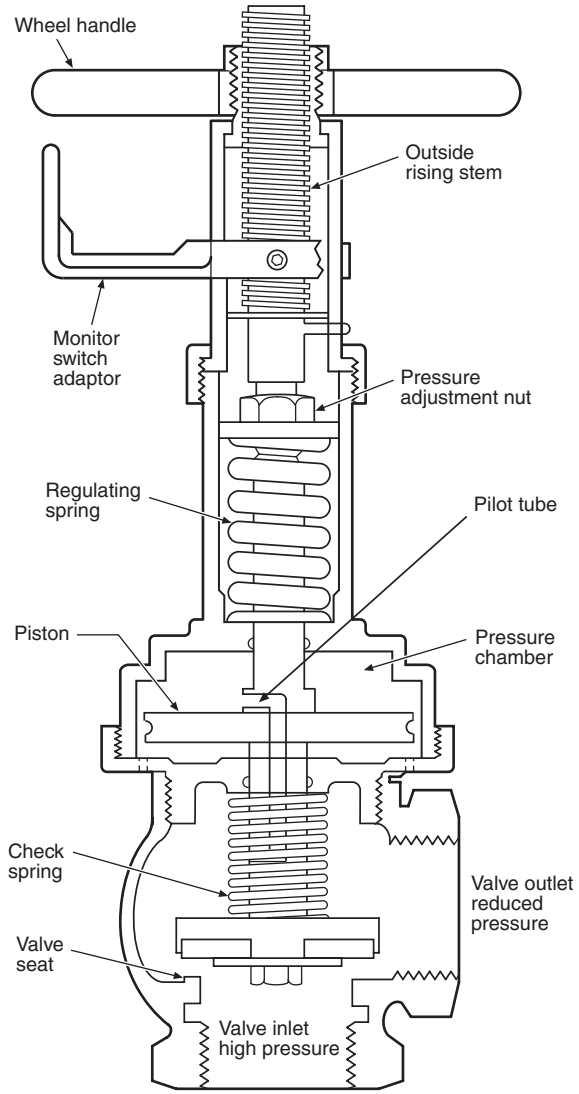

FIGURE 16.10.9 Cutaway of a Typical Pressure Control Valve

Fire Department Connections. (See the additional discussion under "Type and Number of Water Supplies" earlier in this chapter.) Fire department connections (FDCs) are required for all Class I and Class III systems. On manual standpipe systems, FDCs serve as the only water supply. On automatic and semiautomatic standpipe systems, they serve as an auxiliary water supply.

Fire department connections should be located where they are accessible to fire department vehicles and not more than 100 ft (30.5 m) from the nearest fire hydrant. They should not be obstructed by shrubbery, vehicles, or fences that limit visibility or access. For high-rise buildings, two or more connections, located remotely from each other, are required for each zone. This redundancy helps to ensure the fire department's ability to provide an uninterrupted water supply during a major fire. The concern is that falling glass from broken windows can cut supply hoses and prevent personnel from connecting new hoses to the affected FDC, and redundancy improves the chance of gaining access to at least one FDC in such cases.

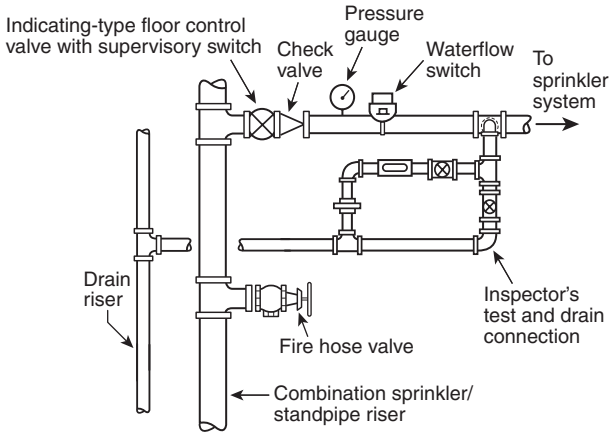

FIGURE 16.10.10 One Possible Arrangement for Valving at a Floor Connection for a Combined System (Not to Scale)

As a rule, most fire department connections are provided with one 2½ in. (65 mm) inlet for each 250 gpm (946 L/min) of design flow rate. Some fire departments require large-diameter inlets that are designed to connect to special high-pressure, large-diameter hoses. Even when large-diameter hoses are used, a second inlet is needed to allow for a backup hose that could be charged if the primary hose ruptures or separates from a coupling.

Another important issue that should not be overlooked is the size of the pipe connecting a fire department connection to system mains. This pipe should be sized to deliver the system demand, as discussed previously under "Sizing Pipe." It is preferable to use 4 in. (100 mm) or larger piping in all cases to avoid obstruction by debris.

Figure 16.10.11 illustrates a typical arrangement for a fire department connection on a wet standpipe system.

System Monitoring and Supervision Devices. To ensure the reliability and performance of standpipe systems, provisions must be made for monitoring system pressure and supervising control valves. Gauges should be provided at each water supply and at the top of each standpipe so that system pressure can be monitored.

Valve supervision can be accomplished by electrical or mechanical means. Supervision is generally required for water supply isolation valves, standpipe isolation valves, and similar valves that are capable of interrupting the water supply to large portions of a system. Supervision is necessary to ensure that the valves remain open at all times.

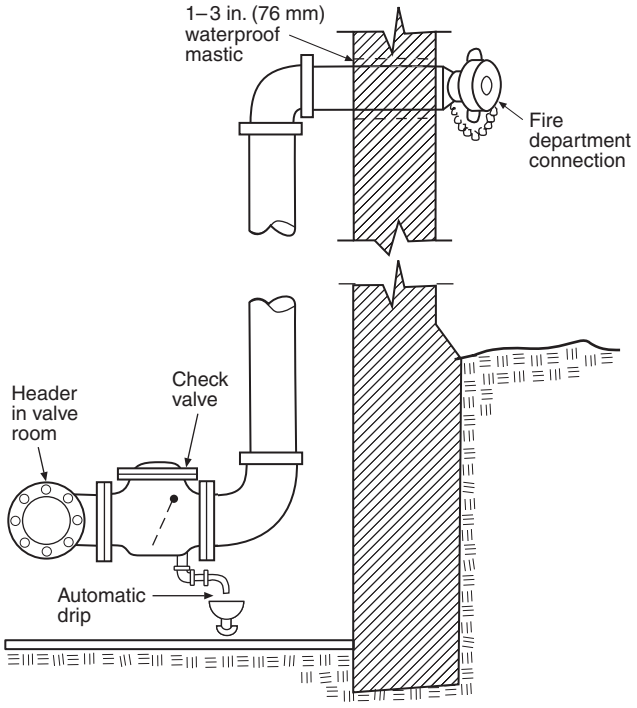

FIGURE 16.10.11 Typical Fire Department Connection for a Standpipe with Water-Filled Piping

Frequently, waterflow alarms are also specified for monitoring a system. This is usually limited to systems having preconnected hoses where immediate notification of waterflow is desired. Also, electronic supervision of hose cabinet doors may be provided where vandalism is a concern.

STANDPIPE SYSTEM INSTALLATION CONSIDERATIONS

Although a proper design establishes the groundwork for a reliable and usable standpipe system, the installation ultimately determines how well a system will perform. A few key considerations are discussed next.

Because most standpipe systems are hydraulically designed, it is essential that the installation conform to design drawings. This is especially true for combined standpipe and sprinkler systems that are based on hydraulically calculated designs. Because the installation of additional pipe or fittings has an adverse effect on hydraulic calculations, as will reductions in pipe sizes, plans should indicate that all such changes should be reported to the designer for approval. Plans should also caution installers of systems with preset pressure-regulating valves to ensure that the valves are installed at the proper floor levels.

To ensure operability and maintainability, it is preferable to label piping and indicate the direction of waterflow. Valve locations must also be clearly identified and accessible. Particular attention should be given to providing access space around hose connections, recognizing that fire fighters will be using large gloves when connecting hoses and operating valves. Twelve inches (0.3 m) of clear space from the valve handles and hose outlets to walls or other obstructions is desirable. Consideration should be given to installing hose valves at a 45 degree angle to prevent kinking the hose.

The key concerns for locating fire department connections are accessibility and visibility. Fire department connections should be clear of shrubbery, parking for vehicles, and other obstructions that could hinder their use. In addition, signs should be provided, preferably reflective, to indicate whether a connection serves standpipes, sprinklers, or both, and to indicate the area served by the connection.

During construction of a building that will have a standpipe system, it is important that the system be made operable before work progresses to a point where deployment of hoses from fire apparatus no longer provides an efficient means of fire fighting. Fire codes usually dictate the point at which standpipes must be made operable during construction.

Noncombustible structures often represent extreme fire hazards during construction because combustible shoring and a variety of ignition sources may be present. To provide protection during construction, the permanent system piping is typically used, along with a temporary fire department connection. At least one hose connection should be provided at each floor level, and all hose connections should be kept capped with an easily removable cap and protected from mechanical injury. Systems should be extended to keep pace with construction progress, and routine inspections should be scheduled to ensure that systems are kept operable.

COMMISSIONING OF STANDPIPE SYSTEMS

Because standpipe systems are essential fire safety systems, they must be routinely tested and inspected to verify that they perform to the original installation requirements and to ensure operational readiness. Testing should be conducted before system acceptance and at intervals adequate to verify reliability. Once accepted, inspection, testing, and maintenance of standpipe systems are regulated by NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems.* See Section 16, Chapter 11, for care and maintenance of water-based extinguishing systems.

Preinspection

Prior to conducting a performance test, the system should be inspected to verify that the installation is complete. This preliminary inspection should include the following:

- Location of control valves
- Method of valve supervision
- Verification of component type
- Valve identification/hydraulic data nameplate installed

Acceptance Tests

On completion of the inspection, the following tests should be conducted:

- Hydrostatic test
- Main drain test
- Pressure-regulating device test
- Alarm test
- Trip test for dry system (including water transit time)
- Trip test for semiautomatic system

The results of these tests are recorded on a form from NFPA 14 titled "Contractor's Material and Test Certificate for Above Ground Piping." The building owner should keep the form on file for the life of the system.

When standpipes are flow tested by flowing water at the roof level, a flow diffuser with a screen is recommended at the point of discharge to control the water stream and intercept any debris that may be ejected. Particular attention should be paid to the adequacy of the drainage route for water to avoid flooding the roof or other areas.

FIRE DEPARTMENT OPERATIONS USING STANDPIPE SYSTEMS

Preplanning

For standpipe systems to be effective, fire fighters must be trained in standpipe operations, and they should preplan to become familiar with systems that they will use. As part of the preplan, fire fighters should identify the locations of fire hydrants, fire department connections, water supply valves, pumps, tanks, and hose connections. The presence of orifice plates in hose connections or pressure-reducing or pressure control valves also should be noted. Fire departments also should develop standard operating procedures that assign personnel and apparatus responsibilities when using standpipe systems.

Equipment

To facilitate the use of standpipe systems, "standpipe packs" should be carried on responding fire apparatus. The packs should contain the equipment necessary to use standpipe system hose connections. Standpipe packs are typically carried on carts or in bags and contain between 100 and 200 ft (30.5 and 61 m) of hose, a nozzle, and miscellaneous tools and wrenches. A gated wye may also be carried to allow a second hose to be connected to a single hose connection. The length of hose carried should be based on local practices regarding which hose connections are expected to be used (at the fire floor or the landing below) and local building code requirements for locating hose connections. Probably the most versatile hose arrangement is one that includes 1¾- or 2-in. (45- or 50-mm) hose and a high-volume nozzle capable of flowing 200 gpm (757 L/min) or more. Such an arrangement can provide a flow capability comparable to a 2½ in. (65 mm) hose with a standard selectable flow fog nozzle when adequate pressure is available, but it is significantly easier to handle.

A fog nozzle that produces an effective pattern at operating pressures less than 100 psi (690 kPa) should be used to take maximum advantage of the pressure available. Use of piston-type automatic nozzles is not advised for standpipe systems because such nozzles may require high pressures to produce satisfactory steams. Some automatic nozzles require pressures in excess of 90 psi (621 kPa) to produce a reasonable fog pattern, and delivering this amount of pressure to the nozzle may prove difficult in some cases, particularly on older standpipe systems designed to provide only 65 psi (448 kPa) and to limit pressures to a maximum of 100 psi (690 kPa). Although low-pressure automatic nozzles designed to operate with inlet pressure in the 70 psi (483 kPa) range are available, the most reliable fog nozzle for use with standpipe systems is a selectable flow nozzle without an automatic piston.

In addition to standpipe packs, fire apparatus should also carry coiled or packed sections of 2½ in. (65 mm) hose for cases where large volumes of water are needed and the pressure available from a standpipe is limited. Such cases may occur in very tall buildings that have floor levels beyond the range of fire apparatus or where pressure regulating valves on a standpipe system have been improperly adjusted.

Operations

It is reasonable to expect the first fire-fighting crew on the scene of an incident in a building with a standpipe system to take a standpipe pack into the building when investigating the call. Meanwhile, an engine should connect to a fire department connection to supply the system. More than one supply hose should be connected to a system if a fire is discovered to prevent the water supply from being interrupted if a supply hose breaks. It is also preferable for additional apparatus to connect to a second

FDC, during major fires when more than one FDC is present. This connection reduces the risk of interruption of the water supply if glass breakage on upper floors makes conditions at some parts of a building's perimeter unsafe, perhaps cutting supply hoses.

When fire fighters determine that hoses are needed, they should select a hose connection located in a protected stairway enclosure, as opposed to a connection located in a corridor or open area (when such connections are present) because it is desirable to have a charged hose before entering a floor if smoke or flame is detected. In multiple-story buildings, a hose connection located at the intermediate landing below or one floor below a fire floor is often preferred over a connection at a fire floor because it provides additional space to spread a hose before charging it, and minimizes congestion at the fire floor entrance. It should be noted that using a hose connection on a lower level will create a need for additional hose to reach all areas on a fire floor, and by providing a gated wye preconnected in a standpipe hose line, fire fighters can add hose without having to shut off and disconnect an attack line. Fire fighters should also be aware that, depending on desired flows, they may have to remove pressure-restricting devices or adjust pressure-regulating valves if they are field adjustable.

The pressure to which a standpipe system should be charged varies from one fire department to another based on local preferences. Some departments use recommendations previously published in NFPA 13E, *Recommended Practice for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems,* which suggested that the pressure at the FDC should be initiated at 100 psi (690 kPa) when smoothbore nozzles will be used at elevations of 100 ft (30.5 m) or less, and at 150 psi (1034 kPa) when fog nozzles will be used at elevations of 100 ft (30.5 m) or less. For elevations above 100 ft (30.5 m), 5 psi (34.5 kPa) should be added for each floor level above 100 ft (30.5 m). Other departments simply pump 150 psi (1034 kPa) plus 5 psi (34.5 kPa) for each floor level above grade. The latter method is more commonly used and should deliver adequate pressure for fog nozzles in most cases.

OUTSIDE HOSE SYSTEMS

Outside hose systems are not standpipe systems. Rather, they are appendages to a water supply. However, outside hose systems and standpipe systems have similar purposes. They both provide an efficient means for manually applying water to fires. Though not mandated by model building or fire codes, outside hose systems may be requested by insurance authorities or by owners as an additional safety measure to minimize potential fire losses. For a discussion of outside hose systems, see Section 15, Chapter 4, "Water Supplies for Sprinkler Systems."

SUMMARY

Standpipe systems deliver water for manual fire fighting. This chapter provided an overview of standpipe system design and installation considerations. The chapter also included a discussion of the testing and inspection of standpipe systems and fire department operations using standpipe systems. The chapter concluded with a brief description of the design and equipment considerations of outside hose systems.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on standpipe and hose systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13E, *Recommended Practice for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 22, *Standard for Water Tanks for Private Fire Protection*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 72®, National Fire Alarm Code®
NFPA *101®, Life Safety Code®*
NFPA 1901, *Standard for Automotive Fire Apparatus*
NFPA 1961, *Standard on Fire Hose*
NFPA 1962, *Standard for the Inspection, Care, and Use of Fire Hose, Couplings, and Nozzles and the Service Testing of Fire Hose*
NFPA 1963, *Standard for Fire Hose Connections*
NFPA 1964, *Standard for Spray Nozzles*

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Chapter 11

Care and Maintenance of Water-Based Extinguishing Systems

David R. Hague

Chapter Contents

System Maintenance Basics
Types of Sprinkler System Inspections
General Maintenance of Sprinklers and Sprinkler Piping
Care and Maintenance of Specific Components
Obstructions in Piping
Other Sources of Obstruction
Extent of Cleaning Required
Cleaning Methods
Sprinkler Leakage
Reducing Water Damage
Water Spray Systems
Water Supplies
System Impairment

Key Terms

automatic sprinkler system, central station, fire pump, microbiologically influenced corrosion (MIC), standpipe, unintended discharge, water-based fire protection, waterflow alarm, waterflow detector, water spray fixed system, water supply (private), water supply (public), zebra mussel

Sprinkler systems are exceptionally reliable, such that the chance of dying in a fire is reduced by one-half to three-fourths when sprinklers are present. Statistics also indicate that property damage is reduced by one-half to two-thirds when sprinklers are present. This, of course, is only true for systems that have been designed, installed, and maintained properly. Maintenance procedures are critical, such as those required by NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems.*

This chapter covers the care and maintenance of sprinkler and water spray systems. It discusses the agencies involved in inspecting and testing these systems and the techniques they use. The chapter also covers sources of obstruction in sprinkler system pipes and methods for flushing and cleaning them, as well as sprinkler leakage and water damage.

For related topics, see Section 15, Chapter 1, "Fixed Water Storage Supplies for Fire Protection"; Section 15, Chapter 2, "Water Supply Requirements for Public Supply Systems"; Section 15, Chapter 5, "Microbiologically Influenced Corrosion in Fire Sprinkler Systems"; Section 16, Chapter 4, "Hanging and Bracing of Water-Based Systems"; Section 16, Chapter 8, "Water Mist Fire Suppression Systems"; and Section 16, Chapter 9, "Water Spray Protection."

SYSTEM MAINTENANCE BASICS

Importance of System Maintenance

Care and maintenance includes more than the inspection and testing of system components. For effective protection, an evaluation of the factors that affect system performance should be made. These factors include such items as the following:

- Occupancy changes
- Process or material changes
- Building modifications such as relocated partitions or ceilings or the addition of mezzanines
- Modifications to the heating system exposing systems to potential freezing

To maintain the proper level of protection for a water-based extinguishing system, there are four areas of concern:

1. Adherence to a regular inspection schedule as determined by the needs of the system
2. Execution of any special investigations or tests that can assess the performance of the devices and equipment
3. Exercise of due diligence in the repair of devices and equipment
4. Assurance that all personnel involved in maintenance are properly trained to correctly execute the procedures for inspection, testing, and maintenance of equipment

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Responsibility for Inspection, Testing, and Maintenance

Ultimately, the building owner is responsible for inspection, testing, and maintenance of fire protection systems. In the case of an absentee owner or where the complexity of the system is such that the building owner lacks the appropriate training and experience, that responsibility can be transferred to another qualified person or firm.

TYPES OF SPRINKLER SYSTEM INSPECTIONS

In addition to the indispensable inspection procedures followed by the property owner, other inspection services are available.

Insurance Company

In insured properties, extinguishing systems may be given special attention by the insurance carrier. Routine testing of sprinkler systems and devices at regular intervals is a service extended by some insurance companies. This service can benefit both the insurance carrier and the property owner. By these routine tests, the equipment can be shown to be in good operating condition or in need of repair or replacement. The purpose of these tests is also to verify reliability of the system to establish an insurance rate for the protected property.

Fire Department

Inspections are made of extinguishing system equipment by many fire departments at varying intervals. This type of inspection is principally done to make sure that valves are fully open for preplanning purposes and may not include the level of detail prescribed by NFPA 25. Inspections are customarily made by the fire department in the district where the property is located.

Sprinkler Contractor

Inspection and maintenance services are offered by sprinkler manufacturers, sprinkler contractors, and inspection service companies. This service provides periodic examinations and reports and is valuable to the property owner not only for a regular checkup of the sprinkler system and components but also for the valuable instruction that can be given to employees in the process. The inspection contract should include all components and systems needed for the proper protection of the property.

Central Station Supervision

Central station supervision of sprinkler alarm and control devices provided under contract is a valuable aid to any maintenance program. Reporting each incident involving waterflow or valve closure or other supervised events keeps a constant check on the condition of the equipment and encourages care on the part of the plant fire organization as well as the building owner.

All of the foregoing inspection procedures should follow the prescribed guidelines in NFPA 25 and *NFPA 72®, National Fire Alarm Code®*. For prescribed frequencies and sample report forms, see NFPA 25.

GENERAL MAINTENANCE OF SPRINKLERS AND SPRINKLER PIPING

Frequently, sprinklers are installed in areas that will subject them to harsh environments, causing loading (contamination), corrosion, exposure to high temperatures, and mechanical damage.

Frequency and Timing of Testing and Inspection

Testing Criteria. If sprinklers have generally performed satisfactorily through their service life, NFPA 25 requires testing of representative samples of installed sprinklers periodically to verify continued performance. The testing criteria for sprinklers are as follows:

- Sprinklers installed for 50 years must be tested, and tests must be repeated every 10 years thereafter.
- Sprinklers manufactured prior to 1920 must be replaced.
- Fast-response sprinklers must be tested after 20 years, with tests repeated every 10 years thereafter.
- High-temperature sprinklers (temperature ratings of 325°F [163°C] or greater) must be tested every 5 years.
- Dry-type sprinklers must be tested every 10 years.

The test sample should comprise 1 percent of the total number of sprinklers installed in the facility and should never be less than four sprinklers. Any sprinkler that shows signs of contamination (loading), corrosion, or paint (other than the paint applied by the manufacturer) should be replaced because the testing laboratory will not evaluate such sprinklers. See Figure 16.11.1 for an example of a loaded sprinkler. The test results will provide an indication of the service conditions that all sprinklers represented by the test sample are exposed to. Any sprinkler that fails the test requires that all sprinklers represented by the test sample be replaced. When removing or installing sprinklers, the manufacturer's instructions should be followed to minimize damage to the sprinkler.

Inspection procedures may be affected by their frequency as well as seasonal changes. The following are examples of inspections governed by seasonal effects.

Spring Inspection. When the danger of freezing temperatures (32°F [0°C]) has passed, spring inspections may be performed. Pertinent operations are as follows:

1. Open cold weather valves (it should be noted that these are prohibited for use on new systems).
2. Inspect, test, and reset dry-pipe valves.
3. Test water motor gongs.
4. Conduct waterflow tests.
5. Test fire pump.

Fall Inspection. At the approach of freezing weather, the system inspector(s) must perform the following functions:

FIGURE 16.11.1 Loaded Sprinkler

1. Close cold-weather valves and drain pipes exposed to freezing temperatures (drain valves on the exposed piping are left slightly open), and test the specific gravity of the solution in an antifreeze sprinkler system.
2. Check dry-pipe valves to make sure that the systems are holding air properly and that the pressure switches and water motor alarms are in order, check drains at the low points of the dry piping to ensure that they are properly clear of water, and check heating provisions for the dry-pipe valve enclosures.
3. Examine gravity tanks to verify that they are protected against freezing, and check that the employed heating system is in operating condition.
4. Check the condition of fire pump reservoirs and suction intakes from other water sources.
5. Carefully inspect buildings to make sure that cold air will not enter or unduly expose sprinkler piping to freezing.

Accumulation of Foreign Materials on Sprinklers

In many classes of properties, conditions exist that cause an accumulation of foreign material on automatic sprinklers. This accumulation is commonly known as loading. The operation of the sprinkler may be delayed or prevented by the loading effect.

Deposits on sprinklers tend to retard their operation as a result of the insulating effect of the loading material. If the deposit is hard, it may physically delay or prevent the sprinkler from operating. The best practice is to replace loaded sprinklers with new sprinklers rather than to attempt to clean the sprinkler. Attempts at cleaning, particularly in instances where deposits are hard, are likely to damage the sprinkler, thus rendering it inoperative or possibly causing leakage.

Deposits of light dust on sprinklers, such as may be found in woodworking plants and grain elevators, are less serious than hard deposits. Dust may be expected to partially delay the operation of sprinklers but ordinarily will not prevent the eventual discharge of water. Dust deposits can be blown or brushed off. Blowing by compressed air should not be undertaken where it can create a dust explosion or ignition hazard. When using a brush, make sure that it is soft to avoid possible injury to sprinkler parts. If these two methods prove unsatisfactory, then a damp, soft cloth may be used to clean the sprinkler. Water-solution cleaning liquids of caustic or acid type are likely to be destructive to sprinklers and should not be used for cleaning. Hot solutions of any kind should not be used.

Sprinklers are sometimes protected when ceilings or sprinkler piping are being painted by temporarily placing small, lightweight paper bags, plastic bags, or aluminum foil over them and securing them with rubber bands. Any such covering is likely to delay the operation of the sprinklers and should be removed immediately after the painting is completed. Should paint cover one of the sprinklers, the sprinkler should be replaced. There is no known method of adequately removing paint under the water cap or on the fusible link. Sprinklers that have been painted by anyone other than the manufacturer must be replaced with new sprinklers.

Sprinklers in spray booths present a special problem. To help minimize this problem, one acceptable solution is to conduct the spray process in a downward manner to avoid contaminating the sprinkler. Cleaning will be necessary; therefore, sprinklers must be installed in an easily accessible location. To facilitate the washing or wiping off of deposits, a light coating of a mild, soft soap should be used. Unless cleaning is done very carefully, deposits are likely to accumulate to such an extent as to interfere seriously with sprinkler operation. The use of paper, polyethylene, or cellophane bags to protect sprinklers in spray booths is fairly common and is permitted by NFPA 25 when the thickness of such bags does not exceed 0.0003 in. (0.008 mm).

Corrosion of Automatic Sprinklers

Corrosive conditions can make automatic sprinklers inoperative or delay the speed of operation. They can also seriously impede the waterways of spray nozzles, affecting the spray patterns of sprinklers. Corrosive vapors may seriously affect not only the heat-actuated element and the water-retaining mechanism of an automatic sprinkler but also may be severe enough to weaken or destroy other portions of the sprinkler. In most instances, such corrosive action is slow and chronic. Thus, the process must be monitored vigilantly. Illustrations of some typical corroded sprinklers are shown in Figure 16.11.2.

Some types of sprinklers are less susceptible than others to corrosive conditions. Nonferrous metal is used for some sprinkler parts, but special protective coatings are still necessary for sprinklers that are exposed to extreme corrosive conditions. Approved corrosion-resistant or special coated sprinklers

FIGURE 16.11.2 Examples of Corroded Automatic Sprinklers

are needed in locations where chemicals, excessive moisture, or corrosive vapors exist.

Protection of Pipe against External Corrosion

Under some conditions, corrosive vapors may cause rapid deterioration of steel pipe and hangers. Proper protection can prevent the frequent replacement of these components. Cast-iron fittings are generally not affected by corrosive vapors.

In severe corrosive conditions where protective methods are not wholly satisfactory, copper or special alloy, noncorrosive pipe will yield the best results. Galvanized steel may offer the most economical method of obtaining a reasonably long life for the piping system. Galvanized piping systems have met with success in chemical plants, saltworks, or similar properties where severe corrosion exists. Stainless steel and copper piping have also been used in some cases.

Corrosion of existing equipment becomes a maintenance problem. The options available are replacement of the components or corrective measures, such as an application of a recognized protective coating.

Advance Preparations Before Shutoff

When maintenance or testing requires systems to be shut off, the work should be planned for a time when the least amount of hazard exists and when there is the least disruption. Both considerations lead to impairment during idle periods rather than during normal business operations. Therefore, work that requires system shutoff should be performed during weekends or other idle periods. A fire watch may be required to aid in the detection of any fire that might develop while the systems are shut down.

Sectional valves, rather than main valves, should be used to reduce to a minimum the number of systems removed from service and to take advantage of multiple water supplies. All personnel, materials, and tools should be on hand before the system is impaired.

If underground mains are involved, a tapping machine should be used when possible to avoid shutting off the water. If mains are to be opened, wood or other plugs or caps and clamps to close the ends of pipes should be available and ready to install. Emergency measures should be taken to maintain the maximum possible water supply. One possibility is to make a temporary hose connection from a hydrant that is still in service to the system riser(s) (Figure 16.11.3). Other options include the use of a domestic or industrial supply to the riser(s) (Figure 16.11.4). These connections are usually made to the nominal 2 in. (50 mm) drain with the drain valve and hydrant valve left open. Adapters for connecting 2½ in. (65 mm) hose to sprinkler systems should be kept on hand.

FIGURE 16.11.3 Temporary Hose Connection from Hydrant

A formal procedure should be established and followed for closing valves, notifying the fire department and insurance companies, and making waterflow tests after the work is completed. Such impairment procedures will help to ensure that systems are out of service for a minimal period of time and that complete system protection is restored.

Emergency Measures for Maintaining Protection During Repairs or Alterations

The seriousness of having extinguishing systems shut off when a fire starts has been well documented. There is a danger if the water supply is shut off for extensions or alterations to piping, repairs due to accidental damage to sprinklers and spray nozzles, replacement of sprinklers after a fire, or maintenance or replace-

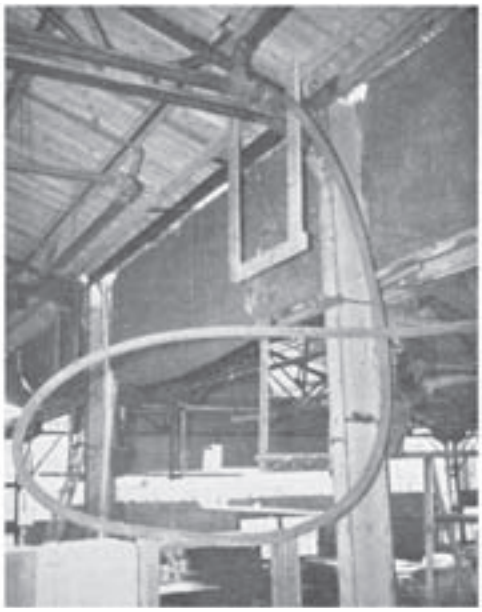

FIGURE 16.11.4 Temporary Hose Connection with Hose Connected to Sprinkler System Flushing Connection

ment of sprinklers and other system devices. When protection is interrupted, every effort must be made to limit the extent and duration of the interruption. A cardinal rule is to notify the fire department whenever an impairment exists so they will not place false reliance on the systems. Insurance companies also may request that building owners advise them when there is an interruption in protection, so that alternate means of protection can be arranged if necessary.

CARE AND MAINTENANCE OF SPECIFIC COMPONENTS

The following components are treated in relation to routine inspection, test, and maintenance programs. They are, however, independent of the organization performing the inspection and maintenance functions. These are in-house responsibilities and should be left in the care of trained and competent individuals.

Public and Private Water Supply Equipment

The inspection and testing of public water supplies and of private water-supply equipment, such as tanks and fire pumps, is covered elsewhere in Section 16. See NFPA 25 for a summary of valve and fire department connection inspection, testing, and maintenance.

Control Valves and Meters

Inspection and supervision of valves in fire protection systems is necessary because closed valves are the leading cause of unsatisfactory performance. The following paragraphs summarize some of the more salient points of valve inspection and supervision.

Service Valves. Service valves at private fire system connections to public systems are usually under the control of the water department and are seldom operated. Their condition is usually indicated adequately by waterflow tests made from the private protection system, as covered later in this chapter.

Meters. Meters in public water system connections are also generally under the control of the water department but are sometimes located in pits on the protected property.

Check Valves. Check valves in public water connections, where needed to prevent backflow into the public systems, are usually a part of the protection system for which the property owner is responsible. Tightness of check valves should be determined periodically by proper tests, depending on water supplies.

Check valves and any corresponding control valves should be properly arranged and located in accordance with the appropriate NFPA standards for sprinkler systems, water spray protection, or standpipe and hose systems.

Control Valves. All control valves should be readily accessible and unobstructed so they can be operated promptly and examined to see that they are open and in good operative condition, turn easily, and do not leak.

Pits for gate valves and check valves should be kept reasonably dry and clean, so that valves can be tested, examined, and maintained in good condition. Manhole covers should be kept clear of snow and ice. See Section 15, Chapter 2, "Water Supply Requirements for Public Supply Systems," for an example of a well-arranged check valve pit with access for inspection.

Each control valve should be numbered or otherwise identified at the valve and cataloged, giving location, use, or portions of the system controlled, on a plant fire inspection form or value chart. A plan showing valve locations should be posted at a central point known to plant and public fire officials.

Each valve should have a sign showing what it controls, with the legend "Must Be Open at All Times," or other proper wording. Underground valve sites should be shown by location and by distance markings on nearby buildings and on accurate plans of the property.

All control valves should be sealed or locked open, unless there is a central station supervisory service. Wrenches should be kept at post indicator valves or at locations where they are readily accessible.

For larger facilities or plants, there should be someone on premises at all times who knows the use and location of all the control and drain valves. This includes the person on watch or any others who may be on duty at night.

Sprinklers and Sprinkler Piping

In the inspection of the sprinkler system, the following eight categories should be considered.

Absence of Sprinklers. Observe whether there is any room or building from which sprinklers have been omitted. The following should be used as a basic checklist:

- Basement
- Lofts
- Show windows
- Concealed spaces
- Towers
- Under stairwells
- Under skylights
- Inside elevator shafts
- Vertical shafts
- Small enclosures, such as those for drying and heating
- Closets, unless open on top

Observe whether there are sprinklers under the following:

- Air ducts over 4 ft (1.3 m) in width
- Shelves
- Benches and tables
- Overhead storage racks
- Platforms or similar obstructions

Proper Clearance for Sprinklers. There are a few areas to review for clearance of sprinklers:

- Sprinklers cannot be obstructed by high-piled stock, walls, or partitions that might prevent free and proper water distribution.

- There must be a clear space of 18 in. (457 mm) below the deflectors of the sprinklers. This value is 36 in. (914 mm) for large-drop and ESFR sprinklers.
- Installation guidelines of special sprinklers have not been violated. This may include installation under certain construction types.
- Refer to NFPA 13, *Standard for the Installation of Sprinkler Systems,* for spacing recommendations for various occupancy classes, types of sprinklers, and construction factors.

Proper Position of Deflectors. The distance of deflectors from the ceiling or the bottom of beams or joists should conform to NFPA 13.

Proper Pitch of Dry-Pipe Systems. Note whether all pipes in a dry-pipe system have the proper pitch. This feature is of special importance, because water remaining in pockets or low points is likely to freeze and disable the system.

Proper Support of Piping. Are any hangers loose or pipes not properly supported? Observe whether sprinkler piping is used for any purpose unrelated to its function, such as hanging clothing. Sprinkler piping and hangers should never be used for such purposes.

Proper Sprinkler Installation. There are five areas to check for the proper installation of sprinklers:

- Sprinklers must be installed in the positions for which they are intended, in compliance with the rules for special application, whether they be pendent, upright, or sidewall types.
- Note the type and design of the sprinklers, the year of their manufacture, and the date of their installation.
- Are all sprinklers of the proper temperature rating? Ordinary-degree sprinklers should be substituted for high-degree sprinklers when the latter are unnecessary. Wherever the temperature around the sprinkler exceeds 100°F (37.8°C), substitute those sprinklers with intermediate-degree sprinklers.
- Are any sprinklers loaded or corroded? If so, remove immediately and replace with sprinklers of equal performance characteristics. In areas where corrosion is common, use sprinklers with the proper coating to decrease the likelihood of future corrosion.
- Sprinklers with coatings of paint, whitewashing, bronzing, or excessive deposits should be replaced immediately with new sprinklers.

A supply of extra sprinklers should be kept in a spare sprinkler cabinet so that any sprinklers that have operated or been damaged in any way can be replaced promptly. These sprinklers should correspond in type, style, and in temperature ratings to the sprinklers in the property. The cabinet should be situated in a cool, easily accessible location. The number of sprinklers stocked for replacement purposes is governed by the size and number of systems. Other considerations include the location of the protected property relative to the source of supply for replacement sprinklers and the number of sprinklers likely to be opened in the event of a fire.

The stock of spare sprinklers, under normal conditions, should be as follows:

System Size	*Number of Spares*
Up to 300 sprinklers	6 sprinklers
From 300 to 1000 sprinklers	12 sprinklers
More than 1000 sprinklers	24 sprinklers

For systems aboard vessels or in isolated locations, a greater number of sprinklers should be carried to permit restoring equipment to service promptly after a fire.

A sprinkler wrench should be kept in the sprinkler cabinet to be used for the removal and installation of sprinklers. This wrench should always be used for installing new sprinklers in order to minimize the chance of damaging the sprinkler.

System Waterflow Tests

NFPA 13 requires a water supply test of pipe and pressure gauges to be provided at locations that will permit flowing tests to be made to determine whether water supplies and connections are in order. A 2 in. (50 mm) drain at the sprinkler riser may suffice as a water supply test pipe. The valve of the water supply test pipe must be installed so that the valve may be opened wide for a sufficient time to ensure a proper test, without causing water damage. A similar main drain valve in a water spray system can serve the same purpose.

There should be provision for checking the system's gauge and its pressure recordings with an inspector's test gauge.

The pressure on the sprinkler system side of the alarm or check valves may be higher than that of the water supply, because any momentary high pressure on the supply will be transmitted to the system and retained by the check valves. This excess pressure is relieved when a waterflow test on the system side of such valves is made.

The drop in pressure below the normal static pressure with the 2 in. (50 mm) main drain pipe wide open should be noted, and general flow conditions evaluated. For instance, if the normal pressure is 50 psi (345 kPa), and if previous tests have shown a pressure drop to 45 psi (310 kPa) when the main drain valve is opened, it will be apparent that, if during a subsequent inspection the pressure drops to 35 psi (241 kPa) or lower, there is some obstruction to the flow, which should be investigated. Such a pressure drop could indicate a defect that should be located and remedied.

At each inspection, an individual flow test should be made for each water supply and each connection from a supply. This can be accomplished by closing all water supplies temporarily, except the one under test. Too much emphasis cannot be placed on the value of flow tests to determine whether there is any obstruction to full flow. It is mandatory that all water supplies be returned to service immediately after testing.

If there is a waterflow supervisory service, tests should not be made without first notifying the fire department, central station, or other alarm receiving facilities.

There should be a 1 in. (25 mm) test pipe having a test orifice of a size to simulate the flow of a single sprinkler at the remote point of each sprinkler system. This should be operated at least twice each year to make sure that there is free flow at good pressure and to test the waterflow alarm. In dry-pipe systems, this test pipe can also be used to trip the dry-pipe valve and determine water delivery time.

Dry-Pipe Sprinkler Systems

The best practice is to keep dry-pipe systems in the dry condition throughout the year. When water flows into sprinkler piping, rust scaling and other foreign materials tend to be carried into the smaller pipes. Accumulation and obstruction can occur due to the waterflow. Annual tripping of the dry-pipe valve to make the system wet may accelerate this condition.

When systems are wet, with the dry-pipe valve tripped, the waterflow alarm feature of the dry valve would have to be taken out of service.

Any old, obsolete, unapproved dry-pipe, or mechanically damaged valves should be replaced with the proper approved listed device. Instruction charts are provided for the maintenance of dry-pipe valves by the sprinkler manufacturing company and should be posted at or near the valves. All dry-pipe valves should be numbered and listed on inspection report forms.

The air pressure on each dry-pipe system should be checked at least once a week. A daily check is recommended for the first week after a dry-pipe valve is reset. If pressure is lost rapidly, requiring frequent replenishment of the air pressure, the piping system should be repaired and made tight. Air pressure higher than that called for by the valve manufacturer's instructions should be avoided as this may damage the gasketing on the valve or severely delay the operation of the valves.

Make sure that the priming water is maintained at the proper level above the dry-pipe valve.

Freezing of a dry-pipe valve may cause it to be inoperative. It is extremely important to make sure that adequate provisions are made for heating the valve enclosure or the room in which it is located, and that the heating equipment is safe and in proper working order.

Dry-pipe system piping should be thoroughly drained at all drum drips or low-point drains before freezing weather and kept clear of water during the winter. The freezing of a small amount of water in the piping may cause rupture of the piping or sprinklers and valve malfunction. Make sure that all low-point drains of the system are kept free of water and that the automatic drip or drain is clear and free to operate.

Dry-pipe valves should be examined externally at frequent intervals to detect evidence of deterioration. Thoroughly clean and reset each dry-pipe valve yearly during the warm weather. On such occasions, the valve body should be thoroughly washed out with warm water. Make sure that all small ports and piping leading to the alarm connections are free from obstructions.

Operating tests of dry-pipe valves and their quick-opening devices should be conducted annually. Such tests may be combined with the annual cleaning and resetting. Operating tests should also be conducted when any repairs, such as renewal of rubber gaskets, or the adjustment of gauges, alarm devices, connecting piping, and quick-opening devices, are performed.

When dry-pipe valves are tripped for testing purposes, the procedure should be such that only the minimum flow of water needed to trip the valve is admitted into the sprinkler riser. This can usually be done by opening the control valve only two to six turns and by closing it immediately after the dry-pipe valve trips.

Operating tests and servicing of dry-pipe valves, including quick-opening devices, should be conducted only by fully qualified personnel.

No grease or other sealing material should be used on seats of dry-pipe valves in an effort to stop leaks. Force should not be used to make dry-pipe valves tight.

Dry-pipe valves should carry a tag or card showing the date on which the valve was last tripped and the name of the organization making the test. Such tags are usually available from the installing company or the insurance company.

Quick-Opening Devices

The operation of quick-opening devices usually can be tested either with or without operating the dry-pipe valve. The manufacturer's instructions for testing and resetting the valve must be followed. If the device does not operate properly during a test, it can, if necessary, be removed and the sprinkler system kept in operation. The device can also be sent to the manufacturer for repair, adjustment, or replacement.

Pressure Gauges

Water and air pressure gauges should be tested for accuracy whenever the system valve is repaired or reset but not less frequently than every five years. Comparison with a calibrated gauge is considered sufficient for this test, or the gauge should be replaced if a calibrated gauge is not available.

Waterflow Alarm Devices

Vane-type waterflow alarm devices should be tested semiannually and pressure switches tested quarterly. Consideration should be given to the proper disposal of test water, particularly where freezing conditions exist. Water motor gongs in particular should never be tested in freezing weather.

Deluge and Preaction Systems

Complete charts are furnished by the installing contractor showing in detail the proper method of operating and testing thermostatically controlled systems. Only qualified persons, fully instructed with respect to the details and operation of such systems, should be employed in their repair and adjustment. It is highly advisable for the owner to arrange with the installing contractor to provide periodic inspection, testing, and maintenance of the equipment.

The automatic valves controlling the flow of water into these systems operate through the effect of fire temperatures on actuating devices. Ordinarily, when it is necessary to repair the actuating system of a preaction system, as distinguished from

the piping system itself, the piping system can be temporarily converted to a wet system, and automatic sprinkler protection is, thus, maintained on a preaction system, provided there is no danger of freezing.

Sprinkler System Supervisory Systems

Central station, proprietary, remote station, fire alarm, and supervisory services for sprinkler systems interpret sprinkler system waterflow signals as fire alarms and immediately initiate occupant notification and fire department response. Signals of other types, such as valve supervision and pressure or temperature supervision, do not serve as fire alarms but initiate appropriate courses of action as prearranged between the supervisory service and the property owner. It is extremely important that these services be notified and any special arrangements made in advance of any inspection or tests of equipment that will cause a signal to be transmitted.

Fire Department Connections

Inspect each fire department connection regularly to make sure caps are in place, threads are in good condition, the ball drip or drain is in order, and the check valve is not leaking. A hydrostatic test should be conducted periodically on old fire department connection piping to ensure that it will withstand the required pressure.

Open Sprinkler Equipment

Outside or open sprinkler equipment should be tested once each year during warm weather. These tests should be coordinated with the authority having jurisdiction and, if desired, the fire department.

Before making operational tests, care should be exercised to make sure that all windows and doors through which water might enter are tightly closed. Proper precautions must be taken to prevent damage from obstruction or accumulation of water to sidewalks, streets, pedestrian ways, or adjoining buildings.

Determine by test whether the sprinklers and system piping are in good condition and free from obstruction. Any piping or sprinklers found clogged should be removed, cleaned, and replaced at once.

OBSTRUCTIONS IN PIPING

Obstructions in system piping or yard mains reduce or cut off the flow of water from all or part of the system, compromising the expected performance of the protection. Obstructed piping is a well-recognized cause of unsatisfactory sprinkler performance. One source of obstruction is foreign material in the water supply. Another is foreign material originating from the interior of the pipe itself. Figure 16.11.5 graphically illustrates an example of obstructions removed from the sprinkler system water supply piping.

Foreign material, such as sand, gravel, stones, and pieces of wood, may enter the underground mains as a result of the carelessness of workers when laying or repairing the mains.

FIGURE 16.11.5 Work Gloves and Pipe Scale Recovered from Sprinkler System Water Supply Pipe

Sand, silt, or wood chips may also enter the mains through inadequately protected fire pump suction inlets. Sometimes when gravity tanks are cleaned, foreign material enters the discharge pipes unless preventive care measures are taken.

Keeping foreign material out of piping for water-spray systems is particularly critical. If the waterways in discharge nozzles are less than ⅜ in. (9 mm) in size or if it is suspected that the water is likely to contain obstructive material, then a strainer is required in the pipeline supplying the system. Small nozzles are prone to clogging if waterborne debris reaches them. Thus, it is imperative that strainers are maintained in good condition. Strainers used in fire protection systems should be approved and listed by a recognized testing laboratory for fire protection service. Strainers must be flushed through the flushing connection periodically, or in cases in which there is a substantial amount of obstructing material, the strainer basket must be removed and cleaned.

Scale and corrosion can form inside system piping. Dry sprinkler systems in particular are subject to the formation of scale because the condensation of moisture in the air supply reacts with the inner surface of the steel pipe. In many cases, dry systems are installed with galvanized pipe to prevent scaling. Untreated water from natural sources such as wells may contain salts that accelerate corrosion. Scale and corrosion can also affect wet-pipe systems.

Obstructing material can be distributed throughout a system when systems operate, during tests, or when systems are filled. The material may obstruct one or more fittings or a number of sprinklers, usually at the end of the branch line. The effective

pipe diameter can also be reduced by pipe tuberculation when the water contains dissolved calcium and magnesium salts.

If the water is badly discolored during waterflow tests, or if gravel or stones are discharged with the water, foreign material is probably present in the piping. Finding foreign material in a fire pump suggests that there may be similar material downstream in the system piping. Finding foreign material when resetting dry-pipe valves or examining check valves indicates a possible serious impairment of the entire fire protection system.

Obstruction to the flow of water from sprinklers usually comprises concentrations of the lighter materials, such as silt, sand, and small pebbles, piling up in the ends of the cross mains and in the nearby branch lines, with the heaviest solids collecting near the system risers (Figure 16.11.6). There are some cases where the foreign material deposits extend so far back into the system from the ends of the cross mains that complete cleaning of the entire system is necessary. More often, however, a preliminary investigation will disclose that, although foreign material may cause complete obstruction of waterflow from sprinklers on branch lines connected to the ends of cross mains, there may be no obstruction at any point on branch lines farther back in the system.

OTHER SOURCES OF OBSTRUCTION

Microbiologically Influenced Corrosion (MIC)

Although generally considered to be a source of corrosion and pitting of pipe, microorganisms can colonize inside of piping systems to the extent that the effective diameter of the pipe is substantially reduced (Figures 16.11.7 and 16.11.8). This can have the same effect as other types of obstructing material by reducing the amount of waterflow through the system and plugging sprinklers.

MIC is caused basically by two types of microbes—aerobic, those requiring the presence of oxygen, and anaerobic, those not requiring the presence of oxygen. MIC can be recognized by the presence of orange or black tubercules and/or mud-like slime in steel pipe. MIC also affects copper systems and can be recognized by green or blue discoloration.

The most effective method to determine the presence of MIC is laboratory analysis of a water sample. Once the presence of MIC is confirmed, several treatment strategies can be employed, such as altering the residual chlorine, pH (acidity), temperature, and oxygen concentration of the water. It is important to note that altering the oxygen concentration of the water only affects aerobic microbes. The most common method of treatment is a permanently attached chlorine injection system, which automatically introduces chlorine into the sprinkler system any time waterflow occurs. Excessive flushing and flow testing of systems should be avoided to reduce the introduction of new microbes and renewed oxygen supplies to the piping system. (Section 15, Chapter 5, "Microbiologically Influenced Corrosion in Fire Sprinkler Systems," provides additional information on MIC.)

FIGURE 16.11.6 Silt Built Up in Feed Main Piping Obstructing the Waterway

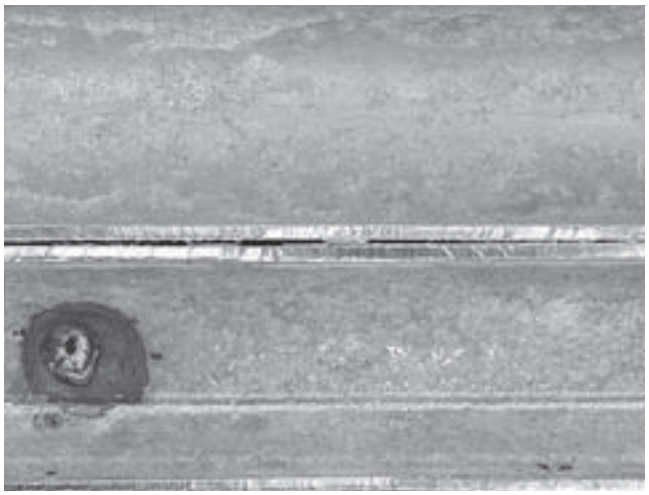

FIGURE 16.11.7 Typical Pinhole Formed by MIC

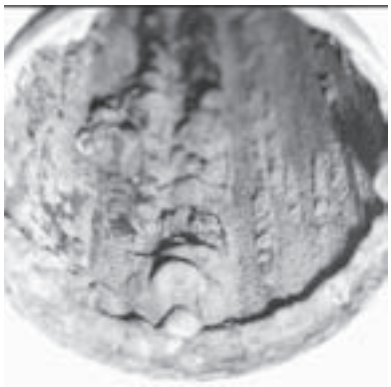

FIGURE 16.11.8 Substantial Obstruction of Pipe by MIC Colony

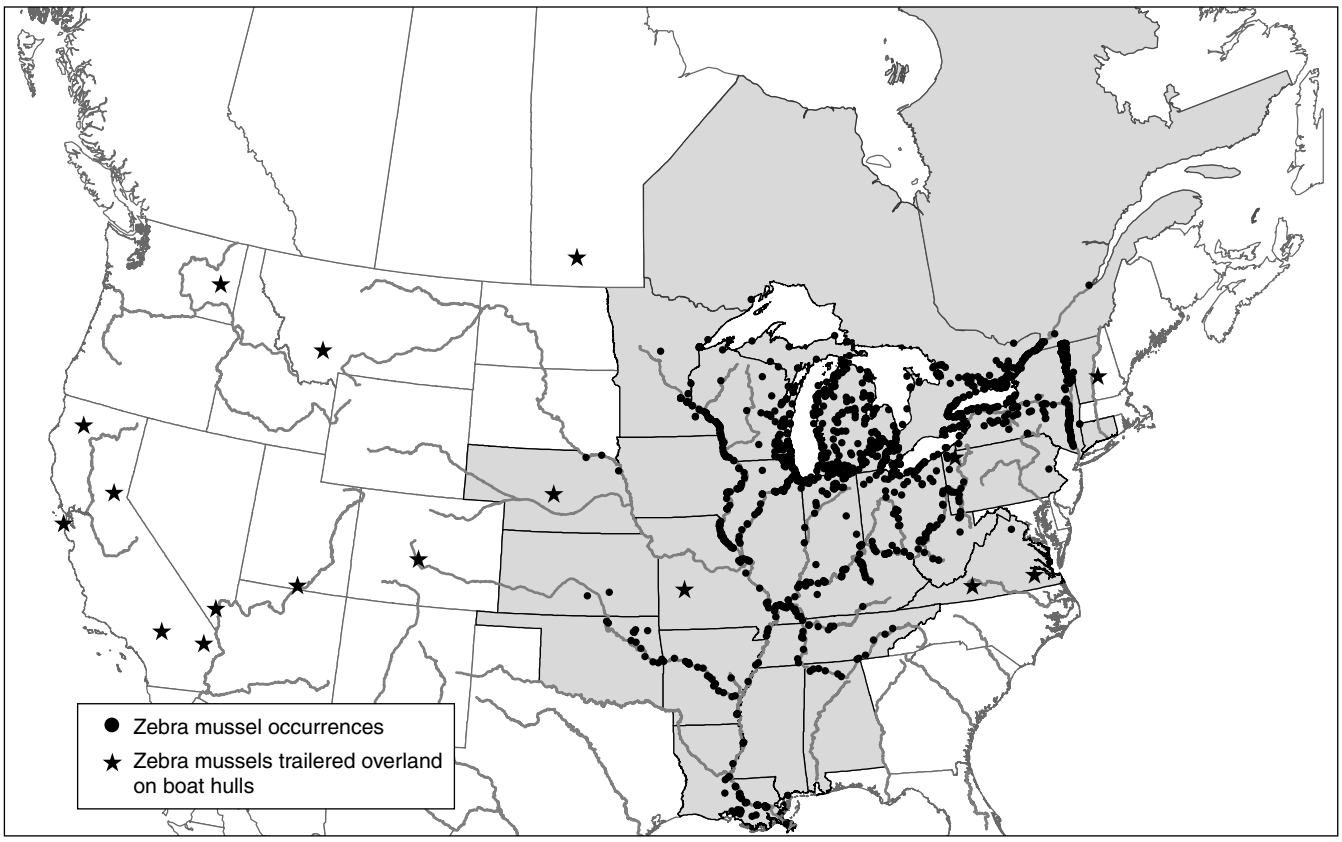

FIGURE 16.11.9 Zebra Mussel Sightings Distribution (*Dreissena polymorpha*) (Source: U.S. Geological Survey, Gainesville, Florida, June 13, 2005, http://www.unl.edu/nac/atlas/Map_Html/Ecosystem_Health/National/Current_zm_map/Current_zm_map.htm)

Zebra Mussels

Largely concentrated around the Great Lakes and Mississippi River areas (Figure 16.11.9), zebra mussels enter a sprinkler system through the water supply, particularly those systems that take their water from a natural body of water such as a lake or river. The mussels enter the pipe as larvae or young adults and colonize inside the piping, feeding from nutrients and oxygen in the water (Figures 16.11.10 and 16.11.11). As they continue to grow, they begin to obstruct waterflow to the system. The presence of zebra mussels is evidenced through the discharge of shells or live mussels during flow tests. An adult zebra mussel measures about ⅝ in. (16 mm) across the shell. Its name is derived from the distinct stripes on the shell resembling that of a zebra.

Treatment strategies for zebra mussels are similar to that for MIC, in other words, chlorination of water entering the system. Treatment with potassium in the range of 100 mg/L has shown promise; however, there are no commercially available systems at present.

Conditions Indicating Possible Obstructions in Piping

Evidence of possible obstruction in piping is given by any one of the following:

1. Plugging of test connections or discharge of dirty or colored water
2. Discharge of foreign material during routine water tests
3. Foreign material in dry-pipe valves, check valves, or fire pumps

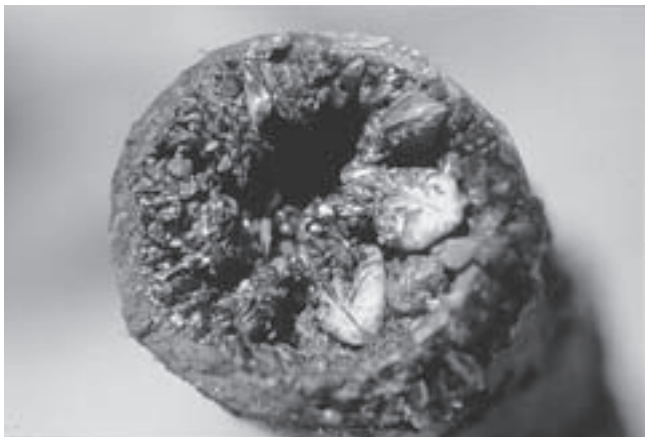

FIGURE 16.11.10 One Inch Pipe Completely Obstructed by Zebra Mussels

FIGURE 16.11.11 Two Inch Pipe Sample with Zebra Mussel Infestation

4. Obstructing material found in piping that is dismantled for building alterations
5. Defects found in fire pump suction screens when the water supply source is from open bodies of water
6. Repairs made to public water mains in vicinity
7. Underground piping not flushed before connection to systems
8. Plugged sprinklers or spray nozzles at time of fire
9. Old equipment, especially in dry-pipe systems

Investigation of Severity and Extent of Obstruction

An investigation of conditions must be made when evidence of foreign materials in systems is found or when obstructions are suspected. Where needed, cleaning or flushing procedures subsequently must be carried out to remove obstructing materials. Inspection and flushing methods outlined in this chapter are treated more completely in NFPA 25.

Flushing Feed Mains

Existing yard piping suspected of containing obstructing material should be thoroughly flushed through hydrants at dead ends of the system, blow-off valves, or groups of riser drains, by opening simultaneously as many outlets as possible and allowing the water to run until clean. If the water is supplied from more than one direction or through a looped system, divisional valves should be closed to produce a high-velocity flow through each single line.

It is usually desirable to learn the nature and extent of foreign material that may be in the piping. This can best be done by fastening burlap bags to the flowing outlets and examining the effluent remaining in the bag.

The connections to system risers should next be flushed through drain valves. If the foreign material is too large to pass through a main drain valve, some ingenuity must be used to procure a larger opening. Fire department connections can be used by removing the check valve. Flanged check valves or check valve covers or flanged fittings can be removed and a Siamese fitting can be substituted to facilitate such flushing.

Flushing System Piping

In choosing the critical points for examination, consideration should be given to the arrangement of the piping and the probable pattern of the flow of water when a system is rapidly filled (as in a dry-pipe system), or when a large flow of water from the system occurs due to operation of many sprinklers on a wet-pipe system.

After selection of the area in which the heaviest deposit of foreign material ordinarily would be expected, the investigation should take into consideration how much of the system's equipment in that area might be made ineffective by the obstructing material at the time of a fire. It is important that the preliminary investigation sufficiently indicates the extent of cleaning that may be required.

Flow Tests

Flow tests at critical points in a sprinkler system provide a positive means of determining the presence of foreign material in the system that may cause obstruction of flow from any of the sprinklers and also of indicating how much of the system is affected. To achieve this, valved hose connections are installed at the ends of two, three, or four branch lines on one side of and at the end of the affected cross main in the selected area. Flows are then taken simultaneously from these points and examined.

If obstruction occurs at any of the branch lines tested, additional tests may be necessary at points upstream on the system toward the system riser. Tests may next be extended to other floors to help make a judgment on the extent of cleaning operations that may be necessary for removing all foreign material that might cause obstructions.

Foreign deposits in sprinkler systems tend to be accumulated toward the ends of the cross mains and in the ends of branch lines. Of course, there will be exceptions to this general rule. For example, where highly corrosive material has been introduced into the system, severe corrosion and scaling of the interior surfaces of the piping will be evident uniformly throughout the system.

Visual Examination

The visual inspection of a system is a critical starting point of any flushing program. This first step will not tell the entire story of the condition of the piping; however, it can aid the trained person in an accurate determination of the piping condition. The visual examination encompasses the inspection of the interior and exterior of the piping, as well as the condition of and tuberculation in said piping.

The initial inspection should start by removing the end sprinklers at the upper- and lowermost portion of the system. Take extra care when removing any pendent sprinklers to check for sediment clogging the orifice.

The removal of the flushing connection is a simple method to determine the condition of the cross main.

Should these steps reveal the presence of obstructing material, and an internal inspection becomes necessary, the following should be used as a guideline:

1. Approximately 10 percent of the system should be examined when an internal inspection is recommended.
2. Remove
   a. Three to four endlines
   b. Riser nipples
   c. Elbows and tee feed for the cross main
3. Examine any areas where the water velocity decreases rapidly when draining the system piping.

If the internal inspection reveals substantial tuberculation and piping deterioration, a determination must be made by cost-efficiency analysis. The options available are flushing, whether it be by the hydropneumatic method or just with water, or the partial to total replacement of the affected area of the system.

The expense of flushing can be high when labor costs and materials are considered. Even though the system is flushed and back on line, the piping may have a shorter life expectancy than a new system.

EXTENT OF CLEANING REQUIRED

When preliminary tests show evidence of obstruction in sprinkler system piping, the next step is to undertake a cleaning program to remove the obstructing material. There are three levels of cleaning: (1) complete cleaning, (2) limited cleaning, and (3) flushing extremities only.

Generally, when obstruction occurs only in the branch lines at extremities of the system, only these areas of the system require flushing. If obstruction occurs at several test points, but indications are that free flows are available on the other lines back toward the riser, a limited cleaning procedure may be followed. If the obstruction is more extensive, then a complete cleaning procedure should be undertaken.

Before any cleaning efforts begin, written specifications or a flushing procedure covering the entire operation should be understood by all concerned. After completion of work, the sprinkler contractor or other party performing the cleaning operations should furnish a written report to those concerned indicating that all work has been completed in accordance with the approved procedure, that the specified examinations and tests have been made, and that the system has been left in normal condition.

Complete Cleaning

There are some cases where the foreign material is of such nature and extends so far back into the system from the ends of the cross mains that complete cleaning of the entire system will be necessary. In such cases, it is of prime importance that a plan of the piping system be prepared and be marked numerically to show the proper sequence of the cleaning operations, the size and length of hose to be used, the points where the hose is attached, and the number of flows to be made at each point.

Limited Cleaning

Where points of impairment can be identified as occurring within restricted areas rather than throughout the system, the limited cleaning procedure can be used. If these points exist in any appreciable amount but only in the ends of cross mains and in the branch lines connected at or near those points, not all branch lines need to be cleaned. The cleaning procedure may be limited to the branch lines at or near these points and to the cross mains on each floor.

Limited cleaning operations serve to minimize the time during which the sprinkler system is impaired. They lessen the interruption to normal activities within the premises where the cleaning operations are underway. Limited cleaning lowers the cost of the work as compared to more extensive cleaning. Because only a fraction of the total number of branch lines are being cleaned directly under the limited procedure, periodic flow tests should be made as the cleaning progresses in order to determine the effectiveness of the work.

Cleaning System Extremities Only

This method should be used only in cases in which obstruction of dry-pipe sprinkler system piping has been found to occur solely at the system extremities, and it relates to every floor protected, regardless of the number of floors. Extreme care should be exercised before this method is employed. Adequate examinations and flow tests are made to make certain that only the sprinklers located at the extremities of the system are subject to plugging. It should not be used where the deposits extend back into the cross main beyond the second branch line from the end of the cross main.

CLEANING METHODS

Generally, there are two methods used for cleaning sprinkler systems: (1) water flushing and (2) hydropneumatic. Convenience is a key factor that may make the hydropneumatic system preferable to the water flushing method. With the former, there is no open discharge of water outside the building, there is less interruption of plant operations, frequent filling and draining of the sprinkler system are unnecessary, there is considerably less pipe work, and a complete operation is performed at a single flush point.

Both methods are appropriate for complete cleaning and limited cleaning procedures. Good practice is to flush the underground piping and then to clean all private sources of water supply that might cause silting in the underground main. Both of these methods are thoroughly discussed in NFPA 25.

If it is anticipated that a sprinkler system may need periodic testing for obstruction or repeated flushing, a branch line tester may be installed permanently at the end of each branch line or between the last sprinkler and the end fitting on each branch line. The tester has a normally closed and capped outlet connection for hose. Turning a wrench fitting opens a passage to the outlet which has a 1 in. (25 mm) hose coupling thread. It is not necessary to remove the sprinkler when this type of device is used.

SPRINKLER LEAKAGE

The term *unintended discharge* is ordinarily used to describe leaks due to system component failure or damage, excluding fire conditions. Leaks, although infrequent, can occur in practically any portion of the system that has been damaged.

Unintended discharge from a properly designed, manufactured, and installed system should be very low because a sprinkler has undergone pressure testing during the commissioning process. Sprinkler pipe, fittings, and other components, including the sprinklers themselves, are rated for pressures far greater than are met with in practice. The supports are also designed to carry five times the weight of the pipe and water with a safety factor of 250 lb (113 kg). In some systems, the pipe supports are also intended to deal with the stress encountered during a seismic event. (See Section 16, Chapter 4, "Hanging and Bracing of Water-Based Systems.")

Automatic sprinkler systems protecting hazards vulnerable to water damage, such as computer equipment, works of art, valuable books, or important records, require an extra degree of attention due to the unusually severe consequences of any unintended discharge, which could occur, for example, if reasonable precautions are not taken against freezing, overheating, and mechanical damage. The use of single- or double-interlock preaction systems should be considered for these applications.

Mechanical Damage

Automatic sprinklers are designed to withstand at least 500 psi (3448 kPa) pressure without injury or leakage. If properly installed, there is little danger of the sprinkler breaking apart, unless it is physically damaged in some way. All of the listed sprinklers are very durable and will withstand considerable abuse. The frames can be bent somewhat, without opening the sprinkler.

When sprinklers are located in areas where they may suffer mechanical damage, they can be protected by commercially available metal guards (Figure 16.11.12).

The use of lift trucks or tractors in handling materials indoors must be carefully planned and supervised to avoid damaging sprinklers and sprinkler piping. Precautions should be taken where fast-response sprinklers are installed to reduce the chances of mechanical and environmental damage.

FIGURE 16.11.12 Metal Guard Protection Against Mechanical Injury

Freezing

The freezing of water in pipes is a common cause of trouble and the remedy in most cases is self-evident. Water expands slightly when it freezes, causing sprinklers to fail. When the ice melts, water is discharged. In other cases, the pipe or fittings may burst, causing more serious damage and more costly repairs. In some types of sprinklers, a moderate amount of freezing may not break the sprinkler open, but may cause it to leak at the seat after the ice has melted.

Some of the conditions that cause systems to freeze include the following:

1. Insufficient heat for severe weather conditions in certain portions, such as concealed spaces under roofs or blind attics, large open doorways for trucks or railway cars, entryways, or space under buildings
2. Windows left open during severely cold weather
3. Insufficient heat due to a shortage of heating fuel or power failure
4. Branch lines of dry-pipe systems not correctly pitched to drain
5. Feed mains or piping in unheated areas properly protected to prevent freezing
6. Freezing of tank risers due to lack of heat or lack of adequate protection; or obstructed circulating pipes of heating systems
7. Freezing of water in underground mains not buried deep enough

Overheating

"Overheating" is another potential cause of accidental discharge from sprinklers and is the term used when an automatic sprinkler operates as a result of abnormally high temperatures, without the presence of fire. This condition is usually caused by hot manufacturing processes, artificial heating, or lack of ventilation. It may result from a sudden increase in temperature that operates the thermal response element of the sprinkler, or from longer exposure to temperatures sufficiently high to cause gradual weakening of the element. In solder-type sprinklers, the latter condition, sometimes termed "cold flow" or "cold soldering," is indicated by partial separation of the soldered members.

In practice, there are a number of conditions that cause unsafe temperatures, such as the following:

1. Climatic conditions exceeding 100°F (41.3°C).
2. Ordinary temperature sprinklers located in close proximity to steam mains, unit heaters, or heating ducts. Temperatures higher than anticipated may occur after installation of sprinklers. Changes in heating methods, installation of unit heaters, or changes in manufacturing processes or equipment after sprinklers are installed can occur.
3. Changes in temperatures due to an occupancy change or processes that cause higher temperatures than contemplated.

These changes may be general or in isolated portions of a building.

4. In some cases, a fire that opens a number of sprinklers may weaken other sprinklers in that vicinity. This may not be apparent. Change all sprinklers in an area of fire influence and not just those that have opened.
5. Low-mass fusible linkage of quick-response sprinklers will enhance the negative influence as mentioned earlier. The installation and maintenance of this device requires great care.

NFPA 13 and NFPA 25 provide some information on sprinkler temperature ratings near unit heaters. Unit heaters should never be used without a careful study of conditions, and, in most cases, sprinklers near unit heaters must be replaced with a higher temperature rating in order to avoid unintended operation.

When conditions occur that require sprinklers higher than ordinary-degree rating, the maximum temperature at the sprinkler level must be determined and sprinklers of the correct temperature rating installed to avoid accidental discharge.

REDUCING WATER DAMAGE

It is evident that, if unintended waterflow occurs when there is no one in the building and no proper means of alarm notification to outsiders exists, the waterflow may continue for a considerable amount of time. This can result in serious damage to property, even with a small amount of water from just one leaking or flowing sprinkler.

Although security guard service is of value, it may not be adequate unless there is a sprinkler alarm device, which will notify the guard if water is flowing. Every sprinkler system should have a waterflow alarm device and properly located water motor gong to notify the proper personnel in case of fire or discharge of water due to inadvertent system discharge.

Large losses from sprinkler leakage or flow can result from lack of, or failure of, isolated sprinkler devices or the lack of waterflow alarms. Losses can also be attributed to the failure to promptly notify authorized person(s) who can investigate immediately and shut off the water if there is no fire. In some cases, water may run for many hours undetected.

Sprinkler supervisory service is of great value in the prompt discovery of system operation from a fire event. In addition, it is also useful to detect leakage from the system and in securing appropriate action to minimize the water loss.

WATER SPRAY SYSTEMS

Water spray systems are similar to sprinkler systems in that they contain a water supply, control valves, piping, hangers, and discharge devices. As such, these systems also require the same inspection, testing, and maintenance as sprinkler systems. However, water spray systems can have, in addition to these items, a detection system that is hydraulic, pneumatic, or electronic, other devices such as pipeline strainers (not normally found on sprinkler systems), and directional water spray nozzles. Each of these systems or devices requires special attention in order to maintain the operational status of the water spray system.

Strainers are usually present due to the small size of the orifice of the spray nozzles. They must be periodically flushed and/or cleaned to ensure that the perforations in the strainer basket are free of obstructing material. A small flushing connection, usually 2 to 2½ in. (50 to 65 mm) in diameter, is provided for this purpose. The strainer basket can be removed and cleaned when flushing is not sufficient for proper cleaning.

Water spray systems should be subject to a discharge test annually to verify automatic operation (if provided) of the systems and components and to verify proper orientation of spray nozzles (Figure 16.11.13). The nozzles used on these systems are directional type and are intended to directly impinge on the protected surface.

Some nozzles may be equipped with a protective cover, commonly referred to as a blow-off cap. It is important to ensure that the caps are in place before the test and that they are reinstalled following the discharge test. The cap prevents obstructing material, such as dirt or dust, from entering the system through the orifice of the nozzle (Figure 16.11.14).

FIGURE 16.11.13 Directional Spray Nozzle Testing (Source: NFPA 25 Handbook, 2002, Exhibit 10.3)

FIGURE 16.11.14 Nozzle with Blow-Off Cap (Source: NFPA 25 Handbook, 2002, Exhibit 10.6)

Pneumatic or hydraulic detection systems (pilot systems) also require some attention. Usually, a sprinkler with a fusible link is used as a thermal detector. These pilot sprinklers must be subject to the same inspection, testing, and maintenance as sprinklers installed in a common wet-pipe sprinkler system. They should be inspected to ensure that they are free of corrosion or contaminant loading.

Pneumatic systems rely on a source of compressed air. This can take the form of an air compressor, nitrogen cylinder, or plant air. In any case, the air supply should be inspected to determine its condition and operation, and any damaged or corroded parts should be replaced immediately.

Foam-Water Sprinkler and Foam-Water Spray Systems

In addition to the requirements for sprinkler and water spray systems, foam-water sprinkler and foam-water spray systems require special attention. These systems are equipped with a foam-proportioning system. The common types of proportioning systems are standard pressure, bladder tank, line, standard balanced pressure, and in-line balanced pressure type. Regardless of the proportioning system type, each component should be inspected quarterly for signs of corrosion or damage and to ensure that it is in good operating condition. In addition to inspection, at least every 10 years, the foam concentrate storage tank should be pressure tested to its working pressure. All components that are in contact with foam concentrate must be flushed and cleaned annually.

Foam-water sprinkler and foam-water spray systems are subject to an annual discharge test. During this test, a foam sample is taken and the proper concentration of foam is measured by refractometric or other methods to verify concentration of the foam-water solution. The results should be within 10 percent of the acceptance test results but not less than 10 percent below the minimum design standard. Foams are usually designed and listed for concentrations of 1, 3, and 6 percent. Following the discharge test, the foam concentrate tank must be refilled to capacity with adequate space remaining for expansion.

Standpipe Systems

Standpipe systems consist of pipe, fittings, valves, and sometimes hose intended to supply water for manual fire fighting in all areas of a building. A standpipe system eliminates the need to stretch long lengths of hose vertically and horizontally through a building to deliver water to a fire. There are three classes of standpipe systems—Class I provides a 2½ in. (65 mm) hose valve specifically for fire department use, Class II provides a 1½ in. (40 mm) hose valve, complete with hose and nozzles for building occupant use, and Class III is a combination of Classes I and II and may or may not include hose and nozzles. Standpipe systems may be automatic, providing a permanent water supply that is capable of supplying the required pressure and flow, or manual, relying on a fire department pumper to supply pressure and flow. Standpipe systems may also be wet or dry in cases in which the system may be subject to freezing temperatures.

Inspection of standpipe systems should begin at the water supply and continue throughout the entire system on a quarterly basis. This inspection, as for that of a sprinkler system, should reveal signs of damage, leaks, corrosion, or any condition that may impair system operation. Where building occupant hose is present, the hose should be removed from the rack or reel annually and inspected for evidence of vandalism. The hose should be free of obstruction and not damaged by mildew or abrasion of any kind. The hose should be reracked or rereeled in such a way that folds do not occur in the same position on the hose. Standpipe hose should be removed from the system for hydrostatic testing at five years and every three years thereafter.

Hose valves should be inspected quarterly to ensure that the handwheel is not missing or broken, the threads are not damaged, the valve is not leaking, and the cap is in place. In cases in which high pressures are present, the valve should be of the pressure-regulating type. Pressure-regulating hose valves are generally of two types—pressure reducing, which controls both static (nonflowing) and residual (flowing) conditions, and pressure restricting, which controls residual conditions only. Pressure-regulating devices should be flow tested every five years to verify that the pressure-reduction setting is correct. Valves that are not set properly should be reset; valves that are not adjustable should be replaced.

During commissioning, all standpipe systems must be hydrostatically tested at 200 psi (1379 kPa) for 2 hours, or 50 psi (345 kPa) in excess of the maximum anticipated static pressure, whichever is greater. Unless modifications to the piping system are made, no further hydrostatic testing is necessary. In the case of a manual dry-standpipe system, however, a hydrostatic test at five-year intervals is necessary to verify the piping system integrity. As defined in NFPA 14, *Standard for the Installation of Standpipe and Hose Systems,* a manual dry-standpipe system has no permanently attached water supply; the fire department is expected to supply waterflow and pressure through the fire department connection. Therefore, these systems must be hydrostatically tested periodically to confirm that they do not leak.

Standpipe systems of all types should be flow tested every five years at the most remote connection to reverify that the system can supply the required flow and pressure. Care should be exercised due to the potential high pressures involved and the proper disposal of test water should be considered.

WATER SUPPLIES

Private Fire Service Mains and Appurtenances

Since inspection of private fire service mains is not practical, flow tests should be conducted at least every five years. Flow test results should be compared to previous tests to reveal any sign of deterioration of the flow and pressure in the system. Should any deterioration be discovered, a complete investigation to determine the cause should be conducted.

Hydrants should be flushed annually by allowing full flow for at least one minute. Dry barrel hydrants should drain thoroughly in less than one hour. During this procedure, hydrants should be inspected for accessibility and operation, and hydrants should be lubricated.

Fire Pumps

A fire pump (when present) is a significant component of the system water supply. Therefore, it is imperative that fire pump equipment operates when needed. The lack of an inspection, testing, and maintenance program for a fire pump can result in costly repairs and system impairment.

Fire pumps should be inspected and tested on a weekly basis. The test is accomplished without flowing water. To begin the test, a pressure drop should be simulated by opening a valve on the fire pump sensing line. The pressure drop will cause the pressure switch in the pressure maintenance pump controller to start that pump. As system pressure continues to drop, the fire pump will start.

An electric pump should be run for a period of 10 minutes. During this time, several observations can be made. Of utmost importance, the casing relief valve should open, allowing a small discharge of water. This will cause an introduction of cool water into the fire pump casing, preventing overheating of the fire pump. The pump packing glands should be adjusted to provide a slight discharge of water. During the operation of the pump, other observations should be made such as unusual noise or vibrations and evidence of overheating. Suction and discharge pressures should be recorded and an inspection/operation test report filed (Figure 16.11.15).

A diesel pump should run for a period of 30 minutes. During operation, the following observations should be made and recorded: engine oil pressure, speed, water and oil temperature, and a check of the heat exchanger for cooling waterflow. Observations should be recorded and an inspection/operation report filed.

A diesel pump is operated for 30 minutes to allow the engine and cooling system to reach operating temperature. Another reason for the 30 minute operation time is to slowly consume fuel, since diesel fuel can become contaminated over time. By operating the engine weekly, diesel fuel will need to be replaced, thus avoiding problems with stale diesel fuel (Figure 16.11.16).

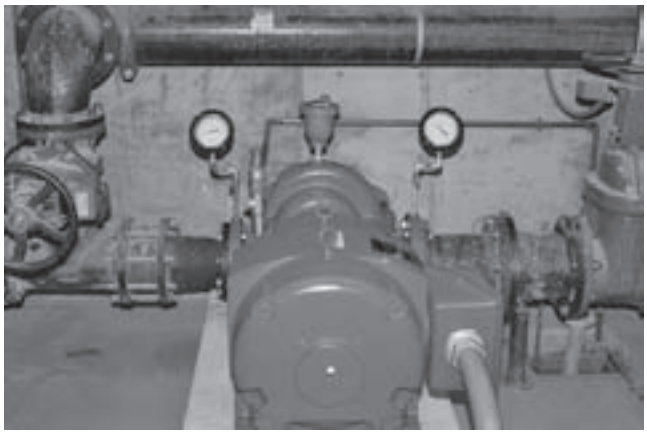

FIGURE 16.11.15 Electrically Driven Fire Pump

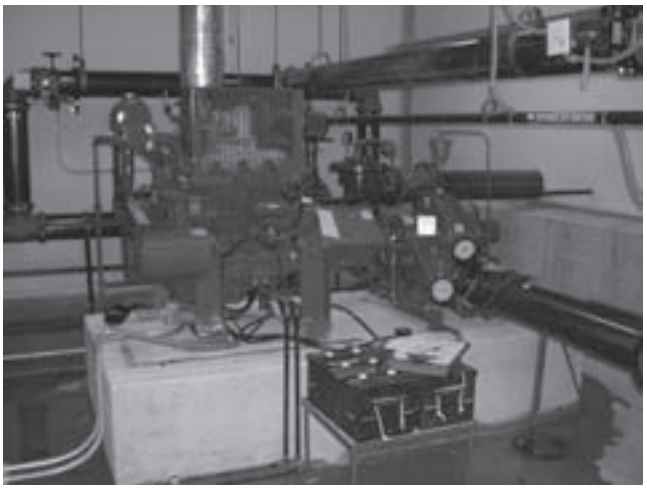

FIGURE 16.11.16 Diesel-Driven Fire Pump (Source: Mechanical Designs, Ltd.)

Fire pumps should be flow tested annually to verify that the pump is functioning properly. This test, identical to the initial commissioning test, is intended to discharge water through the pump at minimum, rated, and peak flows. The preferred test method is to discharge water through the fire pump test header and measure flow by means of a Pitot tube. The use of a flowmeter via a bypass is acceptable; however, once every three years, a test through the test header is necessary.

The results of the annual pump test should be recorded and compared to previous results. It is not the intent to reverify the fire pump curve each year; however, deterioration of performance should be recorded. The intent of the test is to verify that the pump is capable of supplying the maximum system demand.

Water Storage Tanks

Water can be stored in tanks for fire protection purposes, where no other source is available. The types of tanks used are described in Section 15, Chapter 1, "Fixed Water Storage Supplies for Fire Protection." Regardless of the type of tank in use, water tanks require inspection to ensure that they are in good condition.

All tanks should be inspected monthly to verify the correct water level and condition of the water. When installed in areas subject to freezing, tanks should be equipped with a heating system to maintain a minimum water temperature of 42°F (5.6°C). The heating system must be kept in operating condition to avoid the formation of ice that can cause an obstruction to the discharge pipe or cause tank walls to buckle. High and low water temperature alarms may be installed and should be kept in operating condition.

Steel tanks should be inspected for corrosion, including painting systems and cathodic protection where provided. Interior inspections should be done every five years by either a certified diver or by draining the tank completely and following confined space entry procedures.

SYSTEM IMPAIRMENT

When repair or modifications are necessary, a fire protection system may need to be taken out of service. To minimize this downtime, the building owner should appoint an impairment coordinator. The impairment coordinator should be familiar with the operation of the system, the tools and equipment necessary to make repairs, the operations affected by the repairs, and be thoroughly knowledgeable of the organizations that must be notified whenever a system is taken out of service. The impairment coordinator is responsible for supervising the impairment activity from system shutdown to restoration of service.

During any equipment shutdown, a lockout and/or tagout procedure should be in place. A tag should be posted on any valve that is closed (Figure 16.11.17). The tag should indicate that the system has been removed from service, the date, and person responsible for the procedure. Any electrical equipment, such as a fire pump, should be locked in the off position to avoid accidental start-up while the equipment is being serviced. Each tag or lock should be documented in the procedure and retrieved during restoration to service.

If systems must be taken out of service for extended periods of time, that is, four hours or more in a 24 hour period, additional safety procedures should be arranged. Consideration should be given to complete evacuation of the building, establishment of a temporary water supply, a fire watch, or an approved fire prevention program. In such cases, the building owner and the authority having jurisdiction should be consulted prior to system impairment.

Emergency impairments, such as replacement of sprinklers following a fire, leaks, or other service interruptions, should be supervised by the impairment coordinator following the same procedures for a preplanned impairment.

Restoration to service should include a complete inspection of the system to verify the following:

- Repairs are completed.
- All valves are returned to their normal operating position.
- Valve tags are retrieved and documented.
- The authority having jurisdiction, insurance and alarm companies, and all other interested parties are notified.

Closeout of the lockout/tagout program should be documented and filed.

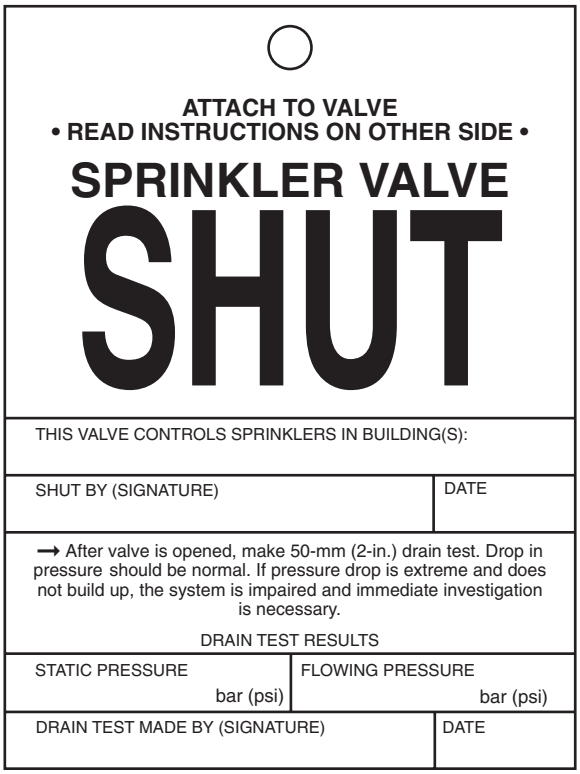
ATTACH TO VALVE
• READ INSTRUCTIONS ON OTHER SIDE •
SPRINKLER VALVE
SHUT
THIS VALVE CONTROLS SPRINKLERS IN BUILDING(S):
SHUT BY (SIGNATURE)
DATE
→ After valve is opened, make 50-mm (2-in.) drain test. Drop in pressure should be normal. If pressure drop is extreme and does not build up, the system is impaired and immediate investigation is necessary.
DRAIN TEST RESULTS
STATIC PRESSURE bar (psi)
FLOWING PRESSURE bar (psi)
DRAIN TEST MADE BY (SIGNATURE)
DATE

FIGURE 16.11.17 Sample Impairment Tag (Source: NFPA 25, 2008, Figure A.15.3.1)

SUMMARY

Of the leading causes of sprinkler system failures, 55 percent of those reported can be directly attributed to improper or lack of maintenance. NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems,* establishes a maintenance program that will improve sprinkler system performance. The standard devotes an entire chapter to valves, as water control valves account for 35.4 percent of unsatisfactory performance and defective dry-pipe valves account for 1.7 percent. Obstruction to water distribution accounts for 8.2 percent. A frozen system is responsible for 1.7 percent of unsatisfactory performance and, in general, 8.4 percent of sprinkler system failure is related to inadequate maintenance. (See *U.S. Experience with Sprinklers: Who Has Them? How Well Do They Work?* by Rohr.) By following the requirements of NFPA 25 and this chapter, the already excellent performance of fire protection systems can be improved.

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NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 72®, National Fire Alarm Code®

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SECTION 17

Fire Suppression Systems and Portable Fire Extinguishers

Mark T. Conroy

17.1 Carbon Dioxide and Application Systems
17.2 Chemical Extinguishing Agents and Application Systems
17.3 Characteristics and Hazards of Water and Water Additives for Fire Suppression
17.4 Foam Extinguishing Agents and Systems
17.5 Fire Extinguisher Use and Maintenance
17.6 Halon and Halon Replacement Agents and Systems
17.7 Application of Gaseous Agents to Special Hazards Fire Protection
17.8 Explosion Prevention and Protection

Fire suppression systems and portable fire extinguishers are the subjects of Section 17 of the *Fire Protection Handbook*®. For this edition, two earlier chapters on halogenated agents and systems and direct halon replacement agents and systems have been combined to form one chapter entitled "Halon and Halon Replacement Agents and Systems." A new chapter on the application of gaseous agents for special hazards is also included.

Chapter 1, "Carbon Dioxide and Application Systems," presents the properties and extinguishing characteristics and limitations of carbon dioxide and its methods of application, as well as components, design considerations, and testing and maintenance of carbon dioxide systems.

Chapter 2, "Chemical Extinguishing Agents and Application Systems," contains information on the properties of both dry and wet chemicals that contribute to their use as extinguishing agents. The limitations; methods of application; system design; and the inspection, testing, and maintenance associated with these systems are addressed.

Water is the most widely used and most readily available extinguishing agent. Chapter 3, "Characteristics and Hazards of Water and Water Additives for Fire Suppression," discusses the properties of water as an extinguishing agent, including its advantages and limitations.

Foam is generated by proportioning foam concentrate with water; the resulting foam solution is used in fixed and portable fire extinguishing systems. Chapter 4, "Foam Extinguishing Agents and Systems," describes those agents and systems, along with their uses and limitations. Specialized foam fire-fighting vehicles are described.

Chapter 5, "Fire Extinguisher Use and Maintenance," provides basic information on matching extinguishers to hazards, types of extinguishers, and health and safety considerations.

Chapter 6, "Halon and Halon Replacement Agents and Systems," describes extinguishing mechanisms, flame suppression effectiveness, toxicity and environmental factors, thermophysical properties, and similar fundamental information.

Chapter 7, "Application of Gaseous Agents to Special Hazards Fire Protection," examines the key characteristics of special hazards that are particularly relevant to the use of gaseous fire extinguishing agents. This chapter also provides information aimed at evaluating a given fire hazard and selecting an appropriate gaseous extinguishing agent system to protect it.

The section concludes with Chapter 8, "Explosion Prevention and Protection." The contents of this chapter include a description of events leading to an explosion, explosion hazard analysis, explosion protection, deflagration prevention and suppression, and enclosure integrity and strength.

Mark T. Conroy is a senior fire protection engineer for Brooks Equipment Company of Charlotte, North Carolina.

Chapter 1

Carbon Dioxide and Application Systems

Thomas J. Wysocki

Carbon dioxide (CO_2) has been used in fire extinguishing systems for nearly 100 years. The first systems were installed between 1910 and 1915 in Europe. CO_2 has no doubt safely extinguished more fires than any other gaseous fire-extinguishing agent. In the process, carbon dioxide systems have saved lives, maintained livelihoods, and prevented property damage. The benefits of carbon dioxide systems, properly applied, are enormous.

To gain the benefits of carbon dioxide extinguishing systems while minimizing risk to people, serious attention must be given to personnel safety in the design, installation, and maintenance of carbon dioxide systems. Training of personnel is essential.

This chapter will discuss the properties of carbon dioxide and its proper use in fixed fire-extinguishing systems; its limitations as a fire-extinguishing agent; life safety considerations; methods of application; system components; design considerations; and requirements for testing, maintenance, and training. NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems,* provides guidance to those responsible for the purchase, design, installation, testing, inspection, operation, and maintenance of carbon dioxide systems.

Other chapters in the handbook that reference carbon dioxide systems include Section 9, Chapter 8, "Protection of Records"; Section 16, Chapter 7, "Ultra-High-Speed Water Spray Systems"; and Section 21, Chapter 10, "Marine Vessels."

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Properties of Carbon Dioxide
Extinguishing Properties of Carbon Dioxide
Limitations of Carbon Dioxide as an Extinguishing Agent
Methods of Application
Life Safety Considerations
Components of Carbon Dioxide Systems
Carbon Dioxide System Design Considerations
Testing and Maintaining Carbon Dioxide Systems

Key Terms

carbon dioxide, carbon dioxide hand hose line, electrical control panel, gas standpipe system, inerting, local application discharge nozzle, lockout, odorizer, total flooding system

USAGE

Carbon dioxide has been used for nearly a century to extinguish flammable liquid fires, gas fires, fires involving electrically energized equipment, and, to a lesser extent, fires in ordinary combustibles, such as paper, cloth, and other cellulosic materials. Carbon dioxide will suppress fire effectively in most combustible material. Exceptions are a few active metals and metal hydrides and materials, such as cellulose nitrate, that contain available oxygen. Furthermore, practical limitations of carbon dioxide are related to the physiological effects of carbon dioxide and to restrictions imposed by the hazard itself.

PROPERTIES OF CARBON DIOXIDE

Carbon dioxide has a number of properties that make it a desirable fire-extinguishing agent. It is noncombustible, it does not react with most substances, and it provides its own pressure for discharge from the storage container. Since carbon dioxide is a gas, it can penetrate and spread to all parts of a fire area. As a gas or as a finely divided solid called "snow" or "dry ice," it will not conduct electricity and, therefore, can be used on energized electrical equipment. It leaves no residue, thus eliminating cleanup of the agent itself.

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Thermodynamic Properties

At room temperature and pressure, carbon dioxide is a gas. It is easily liquefied by compressing and cooling, and, with further compressing and cooling, it can be converted to a solid. The effect of temperature changes on compressed carbon dioxide in a closed container is shown in Figure 17.1.1. Above the critical temperature of 87.8°F (31°C), irrespective of pressure, it is entirely gas. Between 87.8°F (31°C) and the temperature of the triple point, which is –69.9°F (–57°C), in a closed container, it is part liquid and part gas. Below the triple point, it is either a solid or a gas, depending on the pressure and temperature.

On the part of the curve between –69.9°F (–57°C) and the critical temperature of 87.8°F (31°C), carbon dioxide in a closed container may be a gas or a liquid. The pressure is related to the temperature, as long as both vapor (gaseous) and liquid states are present. As the temperature and pressure increase, the density of the vapor phase increases while the density of the liquid phase decreases. At 87.8°F (31°C), the density of the vapor becomes equal to the density of the liquid, and the clear demarcation between the two phases disappears. Above the critical temperature, high-pressure carbon dioxide exists only in a gaseous form.

When the temperature is reduced to –69.9°F (–57°C) at 75 psia (517 kPa), carbon dioxide may be present in vapor, liquid, and solid forms in equilibrium with each other. Hence, the term "triple point" to describe this condition. Below the triple point, only vapor and solid phases can exist. Thus, when liquid carbon dioxide is discharged to atmospheric pressure, a portion instantly flashes to vapor while the remainder is cooled by evaporation and converted to finely divided snow, or dry ice, at a temperature near –110°F (–79°C). The proportion of carbon dioxide converted to dry ice depends on the temperature of the stored liquid. Approximately 46 percent of the liquid stored at 0°F (–18°C) will be converted to dry ice, compared to approximately 25 percent for liquid stored at 70°F (21°C).

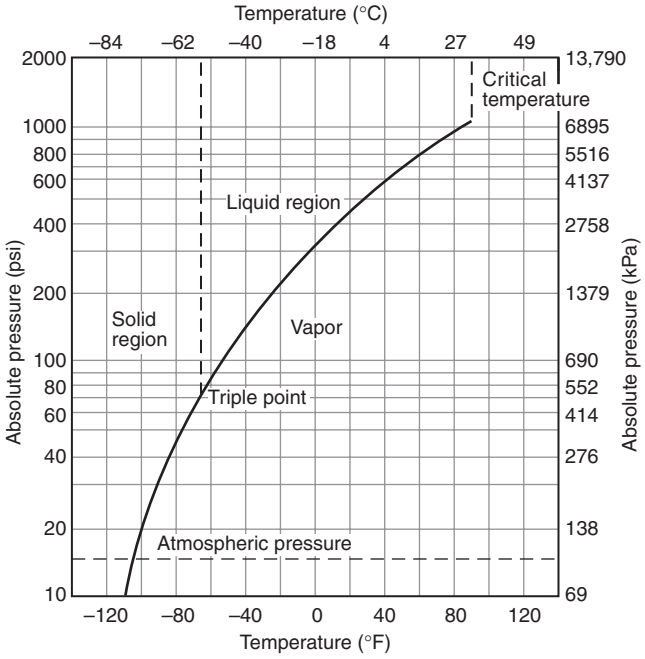

FIGURE 17.1.1 Effect of Pressure and Temperature Change on the Physical State of Carbon Dioxide

Storage

Liquid carbon dioxide may be stored in high-pressure cylinders with storage temperature varying with ambient temperature or in low-pressure refrigerated containers designed to maintain a storage temperature near 0°F (–18°C). Freezing (solidifying) in storage is not a problem. However, any substantial reduction in storage temperature—and corresponding storage pressure—could reduce the discharge flow rate below acceptable design limits. High-pressure systems normally are designed to operate properly with storage temperatures ranging from 32 to 120°F (0 to 49°C). Low-pressure systems, which normally operate at 0°F (–18°C), would not be affected unless the ambient temperature surrounding the storage container dropped to –10°F (–23°C) or lower for a prolonged time. Extreme climatic environments may require special design considerations to ensure proper operation. For low storage temperatures, high-pressure cylinders may require special "winterization" treatment, while low-pressure storage units may require heaters with circulation pumps.

Discharge Properties

A typical discharge of liquid carbon dioxide has a white, cloudy appearance due to finely divided dry ice particles carried along with the flash vapor. Because of the low temperature, some water vapor from the atmosphere will condense, creating additional fog that will persist for a time after the dry ice particles have settled out or sublimed.

Static Electricity

The dry ice particles produced during a discharge of carbon dioxide can carry a charge of static electricity. Static charge can also build up on ungrounded discharge nozzles. To prevent shock hazard to personnel or unwanted static discharge in a potentially explosive atmosphere, all discharge nozzles must be grounded. This is particularly important in the case of nozzles and playpipes used in hand hose line systems.

Vapor Density

Carbon dioxide gas has a density of one and one-half times the density of air at the same temperature. The cold discharge has a much greater density, which accounts for its ability to replace air above burning surfaces and maintain a smothering atmosphere when used in local application systems. When carbon dioxide is used for total flooding, the resulting mixture of carbon dioxide and air will be more dense than the ambient atmosphere.

Physiological Effects

Carbon dioxide is normally present in the atmosphere at a concentration of approximately 0.038 percent. It is present in humans and animals as a normal by-product of cellular respiration.

In the human body, carbon dioxide acts as a regulator of breathing, thus ensuring an adequate supply of oxygen to the system. Up to a point, an increase in carbon dioxide in the blood causes an increase in breathing rate. The maximum increase in respiration occurs when breathing 6 to 7 percent carbon dioxide in air. Higher concentrations of carbon dioxide slow down breathing. Finally, with 17 to 30 percent carbon dioxide in air, a narcotic effect takes over and stops breathing almost immediately—even with a sufficient supply of oxygen in the air. Death can result in a matter of minutes if prompt remedial action is not taken. Reduced oxygen supplies will cause a very much lower concentration of carbon dioxide to suppress breathing and cause death from asphyxiation. The exact concentration of carbon dioxide in air that will cause a decrease in respiration varies from person to person and is not constant even in the same person from time to time.

Six to 7 percent carbon dioxide is considered the threshold level at which harmful effects become noticeable in human beings. At concentrations above 9 percent, most people lose consciousness within a short time. Since the minimum concentrations of carbon dioxide in air used to extinguish fire far exceed 6 percent, adequate safety precautions must be designed into every carbon dioxide fire-extinguishing system.

The dry ice that is produced during a discharge can produce "burns," due to the extreme low temperature. Personnel should be warned not to handle any residual snow after a discharge.

EXTINGUISHING PROPERTIES OF CARBON DIOXIDE

The primary mechanism by which carbon dioxide extinguishes fire is oxygen reduction (smothering). The cooling effect of carbon dioxide is relatively small but does make some contribution to fire extinguishment, particularly when carbon dioxide is applied directly to the burning material.

Extinguishment by Smothering

In any fire, heat is generated by rapid oxidation of a combustible material. Some of this heat raises the unburned fuel to its ignition temperature, whereas a large part of the heat is lost by radiation and convection, especially in the case of surface burning materials. If the atmosphere that supplies oxygen to the fire is diluted with carbon dioxide vapor, the rate of heat generation is reduced until it is below the rate of heat loss. When the fuel is cooled below its ignition temperature, the fire dies out and is extinguished completely.

The minimum concentration of carbon dioxide needed to extinguish surface burning materials, such as liquid fuels, can be determined accurately, since the rate of heat loss by radiation and convection is reasonably constant. Table 17.1.1 lists the minimum concentrations of carbon dioxide for some common liquid and gaseous fuels as determined by the U.S. Bureau of Mines.[1] Minimum CO_2 concentrations for flammable liquid and gas hazards are based on inerting the air/fuel mixture. The theoretical minimum carbon dioxide concentration is the actual concentration of carbon dioxide required to extinguish and prevent fire in a given fuel. The minimum design concentration is

TABLE 17.1.1 Minimum Carbon Dioxide Concentrations for Extinguishment

Material	*Theoretical Minimum CO_2 Concentration (%)*	*Minimum Design CO_2 Concentration (%)*
Acetylene	55	66
Acetone	27*	34
Aviation gas grades 115/145	30	36
Benzol, benzene	31	37
Butadiene	34	41
Butane	28	34
Butane-I	31	37
Carbon disulfide	60	72
Carbon monoxide	53	64
Coal gas or natural gas	31*	37
Cyclopropane	31	37
Diethyl ether	33	40
Dimethyl ether	33	40
Dowtherm	38*	46
Ethane	33	40
Ethyl alcohol	36	43
Ethyl ether	38*	46
Ethylene	41	49
Ethylene dichloride	21	34
Ethylene oxide	44	53
Gasoline	28	34
Hexane	29	35
Higher paraffin hydrocarbons $C_nH_{2m} + 2m - 5$	28	34
Hydrogen	62	75
Hydrogen sulfide	30	36
Isobutane	30*	36
Isobutylene	26	34
Isobutyl formate	26	34
JP-4	30	36
Kerosene	28	34
Methane	25	34
Methyl acetate	29	35
Methyl alcohol	33	40
Methyl butene-I	30	36
Methyl ethyl ketone	32	40
Methyl formate	32	39
Pentane	29	35
Propane	30	36
Propylene	30	36
Quench, lubricating oils	28	34

Note: The theoretical minimum extinguishing concentrations in-air for the above materials were obtained from a compilation of Bureau of Mines Limits of Flammability of Gases and Vapors (*Bulletins* 503 and 627). Those marked with * were calculated from accepted residual oxygen values.

20 percent more than the theoretical minimum carbon dioxide concentration but is never less than 34 percent (per NFPA 12). It is difficult to obtain similar data for solid materials because the rate of heat loss by radiation and convection can vary widely, depending on shielding effects caused by the physical arrangement of the burning material. Design concentrations for hazards containing solid fuels have been determined from testing and experience. NFPA 12 gives design concentrations for a number of such hazards.

Extinguishment by Cooling

Although the temperatures involved in a carbon dioxide discharge may approach –110°F (–79°C), the cooling capacity of the carbon dioxide is quite small compared to an equal weight of water. The latent heat of 1 lb (0.4536 kg) of liquid carbon dioxide is about 120 Btu (126 kJ) from low-pressure storage and 64 Btu (67.5 kJ) from storage at 70°F (21°C). The cooling effect is most apparent when the agent is discharged directly on the burning material by "local application." A massive application quickly covering the entire surface area smothers the fire and helps cool the fuel.

LIMITATIONS OF CARBON DIOXIDE AS AN EXTINGUISHING AGENT

The use of carbon dioxide on general Class A fires is limited by its relatively low cooling capacity, compared to that of water, and by enclosures incapable of retaining an extinguishing atmosphere. True surface burning fires are extinguished easily because natural cooling takes place quickly. On the other hand, if the fire penetrates below the surface of the fuel and the mass of fuel provides a layer of thermal insulation that slows down the rate of heat loss (generally referred to as "deep-seated burning"), a higher concentration of carbon dioxide and a much longer holding time are needed for complete extinguishment. Some deep-seated fires may not be extinguished by carbon dioxide even after a long holding time. In such cases, carbon dioxide can be used to suppress open flaming and slow the propagation of the fire. This holding action should be maintained long enough to permit response by a properly equipped and trained fire brigade.

Carbon dioxide is not an effective extinguishing agent for fires involving chemicals that contain their own oxygen supply, such as cellulose nitrate. Fires involving reactive metals, such as sodium, potassium, magnesium, titanium, zirconium, and the metal hydrides, cannot be extinguished by carbon dioxide because the metals and hydrides decompose carbon dioxide.

METHODS OF APPLICATION

Two basic methods are used to apply carbon dioxide in extinguishing fires. One method is to discharge a sufficient amount of the agent into an enclosure to create an extinguishing atmosphere throughout the enclosed area. This is called "total flooding." The second method is to discharge the agent directly onto the burning material without relying on an enclosure to retain the carbon dioxide. This is called "local application." Other methods include hand hose lines, standpipe systems and mobile supply, extended discharge, and special applications.

Total Flooding

In total flooding systems, carbon dioxide is applied through nozzles designed and located to develop a uniform concentration of CO_2 in all parts of an enclosure (Figure 17.1.2). Calculation of the quantity of carbon dioxide required to achieve an extinguishing atmosphere is based on the volume of the room and the concentration of carbon dioxide required for the combustible materials in it.

The integrity of the enclosure is a very important part of total flooding, particularly if deep-seated fire potential exists in the hazard. If the room is tight, especially on the sides and bottom, the CO_2 extinguishing atmosphere can be retained for a long time to ensure complete control of the fire. If there are openings on the sides and bottom, however, the heavier mixture of carbon dioxide and air may leak out of the room rapidly. If the extinguishing atmosphere is lost too rapidly, glowing embers may remain and cause reignition when air reaches the fire zone. Therefore, it is important to close all openings to minimize leakage or to compensate for the openings by an extended discharge. Because of the relative weight of carbon dioxide, an opening in the ceiling helps to relieve internal air pressure during the discharge, with very little effect on leakage rate after the discharge.

Local Application

In local application systems, carbon dioxide is discharged directly on the burning surfaces through nozzles designed for this

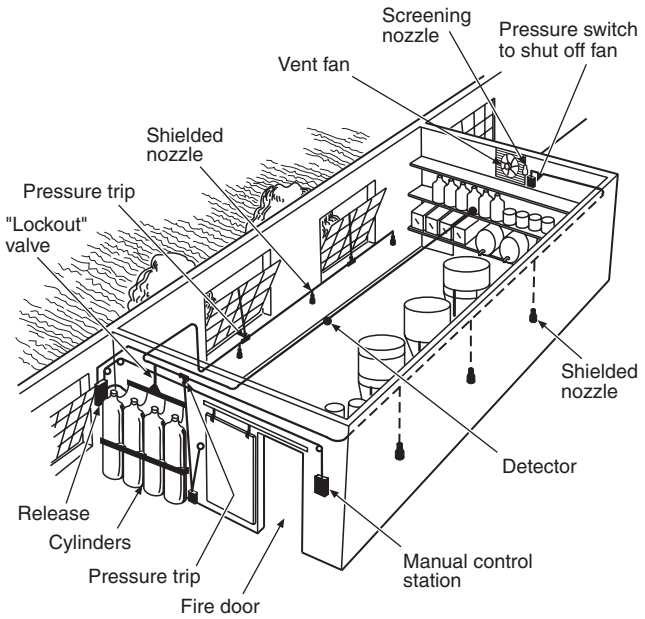

FIGURE 17.1.2 High-Pressure Carbon Dioxide System for Total Flooding

purpose. The intent is to cover all combustible areas with nozzles located so they will extinguish all flames as quickly as possible. Any adjacent area to which fuel or fire may spread also must be covered, because any residual fire could cause reignition after the carbon dioxide discharge ends (Figure 17.1.3).

Local application discharge nozzles usually are designed for relatively low velocity to avoid splashing and air entrainment. Automatic detection is a necessity to provide fast response and minimize heat buildup. Although not essential, an enclosure would help retain carbon dioxide in the fire area. Local application of carbon dioxide can also be used for fast fire knockdown in an enclosure where final total flooding can provide extinguishment.

Hand Hose Lines

Carbon dioxide systems can consist of hand hose lines permanently connected by means of fixed piping to a fixed supply of carbon dioxide. Such systems frequently are provided for manual protection of small localized hazards. Although not a substitute for a system with fixed nozzles, a hose line may be used to supplement a fixed system where the hazard is accessible for manual fire fighting, as well as to supplement portable equipment. There must be a sufficient carbon dioxide supply to permit the use of the hand hose line nozzle for at least 1 minute. Nozzles should be connected to a good electrical ground to permit static electrical charges produced by the carbon dioxide discharge to drain off. A wire-braided hose properly coupled to the discharge piping can provide a path to ground. Figure 17.1.4 shows a hand hose line system that offers flexibility for attacking fires.

FIGURE 17.1.3 Discharge of a Local Application Carbon Dioxide Extinguishing System (Source: Ansul Incorporated)

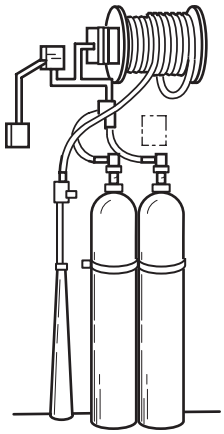

FIGURE 17.1.4 Carbon Dioxide Hand Hose Extinguishing System with Hose Mounted on a Reel

Standpipe Systems and Mobile Supply

Total flooding, local application, and hand hose line systems without a permanently connected carbon dioxide supply are known as gas standpipe systems. They are supplied by containers of carbon dioxide mounted on mobile units that can be moved and quickly coupled to a standpipe in case of fire.

Gas standpipe systems can be used as a supplement to complete fixed fire protection systems or as the only protection of hazards under certain circumstances. Mobile supplies may be equipped with hand hose lines for the protection of scattered hazards. If the possible fire damage that might occur while the mobile supply is moved to the scene and deployed is unacceptable, a fixed automatic system should be used.

Extended Discharge

An extended discharge of carbon dioxide is used when an enclosure is not tight enough to retain an extinguishing concentration as long as is needed. The extended discharge normally is at a reduced rate, following a high initial rate used to develop the extinguishing concentration in a reasonably short time. The reduced rate of discharge should be a function of the leakage rate, which can be calculated on the basis of leakage area, or of the flow rate through ventilating ducts that cannot be shut down.

Extended discharge is particularly applicable to enclosed rotating electrical equipment, such as generators, where it is difficult to prevent leakage until rotation stops. Extended discharge can be applied to ordinary total flooding systems, as well as to local application systems where a small hot spot may require prolonged cooling.

Special Applications

Carbon dioxide systems are sometimes used for inerting or purging to prevent fire or explosion. Carbon dioxide vapor is typically used in these applications. NFPA 69*, Standard on Explosion Prevention Systems,* gives guidance on these applications. Fire suppression in coal storage silos also can use carbon

dioxide vapor. Low-pressure storage with an in-line vaporizer can conveniently supply the large quantities of carbon dioxide vapor typically required for these applications.

LIFE SAFETY CONSIDERATIONS

To gain the benefits of carbon dioxide extinguishing systems while minimizing risk to people, serious attention must be given to personnel safety. Personnel safety must be considered in the design, installation, maintenance, and use of carbon dioxide systems. NFPA 12 discusses personnel safety at length.

General Safety Considerations

The minimum design concentration for total flooding systems is 34 percent. This is well above the acceptable exposure threshold for personnel. Breathing such a concentration of CO_2 will cause almost immediate unconciousness followed by death in a matter of minutes if appropriate emergency rescue action is not begun immediately. All total flooding systems will produce lethal concentrations of carbon dioxide in the protected space. For such systems, predischarge evacuation is always required.

Local application systems produce high concentrations of carbon dioxide in the immediate vicinity of the fire hazard. Each local application system must be evaluated to determine if evacuation of personnel is necessary prior to the start of the discharge.

If the local application hazard is located in a large open space, the initial discharge of carbon dioxide generally presents little risk to personnel. Indeed if personnel are in the immediate vicinity of the fire, they are likely at risk from exposure to the fire itself. On the other hand, if the local application hazard occupies a large portion of the space, dangerous concentrations of carbon dioxide can build up quickly throughout the space, particularly at lower elevations within the space. Again the risk of exposure to uncontrolled fire must be weighed against the risk that the carbon dioxide discharge will endanger personnel before they can leave the area.

In all cases, both local application and total flood, migration of CO_2 from a discharge to adjacent low-lying spaces can produce dangerous concentrations of carbon dioxide, and if personnel are present in such spaces, such migration of CO_2 can present a danger to life. Suitable warning devices must be incorporated into the system.

Safety Guidance

NFPA 12 prohibits the use of total flooding carbon dioxide systems in normally occupied spaces with certain specific exceptions. NFPA 12 contains guidance as to the circumstances where the use of carbon dioxide total flooding systems in a normally occupied space could be permitted. Where a gaseous extinguishing agent is desired for a normally occupied space, the "clean agents" covered in NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems,* are generally recommended.

Arrangements to ensure evacuation before discharge must be made for all spaces protected by total flooding systems, including those that are not normally occupied but in which personnel might be present for maintenance or other purposes. If evacuation cannot be assured, the system should be locked out while personnel are within the space. Local application systems must be evaluated on a case-by-case basis, giving consideration to potential for hazardous concentrations within the enclosure containing the fire risk as well as potential for migration of CO_2 to adjacent low-lying areas.

Lockouts

NFPA 12 requires system "lockouts" to be provided for all systems except those where the dimensional characteristics of the space will prevent personnel from entering the space. The system must be locked out to prevent accidental or deliberate discharge when persons unfamiliar with the system and its operation are present in the protected space. Lockouts are also needed when personnel egress from a space is hampered (e.g., when persons are climbing ladders, working on scaffolds, or entering confined spaces).

NFPA 12 defines a system lockout as "a manually operated valve in the discharge pipe between the nozzles and the (carbon dioxide) supply which can be locked in the closed position to prevent flow of carbon dioxide to the protected area." Such a lockout will prevent both automatic and manual discharge. The emergency manual release required by NFPA 12 should *not* override the lockout. The lockout should be supervised to give an indication to those responsible for the system when the system is locked out. An adequate fire watch should be established to deal with any fire that might occur during a system lockout.

Alarms

NFPA 12 gives detailed guidance on the requirements for alarms that must be installed as part of a carbon dioxide system. In general, audible and visual predischarge alarms are required for all systems except hand hose lines. Personnel who will enter an area that could be made hazardous by discharged carbon dioxide must be trained as to the correct response to these alarms. For total flooding systems, every precaution must be taken to ensure that personnel in a protected area are evacuated before the area is flooded with carbon dioxide. This is the primary purpose of a predischarge alarm, which must provide a suitable time delay before the carbon dioxide discharge.

NFPA 12 requires that all total flood systems protecting enclosures which personnel could possibly enter be equipped with pneumatic predischarge time delays and pneumatic predischarge alarms. Both the time delays and alarms are typically powered by carbon dioxide from the system storage; neither the pneumatic time delay nor the pneumatic alarms depend on electrical power. Such pneumatic time delays and alarms are likewise required for local application systems, if the discharge will expose personnel to hazardous concentrations of carbon dioxide. The NFPA 12 standard gives details as well as specific exceptions for the pneumatic time delay and alarm requirement.

For systems that will produce a hazardous concentration of carbon dioxide throughout an enclosure, warning signs and discharge alarms must likewise be located outside each entryway to the enclosure. The purpose of these devices is to warn persons

against entering the space containing a dangerous concentration of carbon dioxide.

Consideration should be given to any possibility that substantial volumes of carbon dioxide vapor could leak or flow into adjacent low-level areas, such as cellars, pits, or narrow hallways (i.e., spaces not included in the protected area). If this potential exists, alarms and warning signs should be extended to include these areas. Arrangements for safely ventilating all carbon dioxide–flooded spaces following a discharge must be made.

Odorizers, such as oil of wintergreen, are sometimes added to the carbon dioxide discharge to provide an olfactory indication of the presence of carbon dioxide. Odorizers are particularly useful to indicate that carbon dioxide has leaked from the protected area to adjoining areas.

Other Safety Features/Considerations

Manual controls for the system must be located to avoid confusion, and they must be clearly labeled with safe operating procedures. Avoid grouping manual controls for more than one hazard in order to avoid confusion. Self-contained breathing apparatus (SCBA) should be provided. This apparatus should be used by trained personnel to effect rescue of anyone who might be trapped in a carbon dioxide discharge.

Periodic maintenance is required to ensure proper function of these systems. Those doing maintenance must be thoroughly trained in the functions of the system. Whenever maintenance involves work on system controls, discharge valves, or other devices that could possibly initiate carbon dioxide discharge, personnel must be evacuated from areas where a discharge from the system could produce a dangerous concentration of carbon dioxide.

COMPONENTS OF CARBON DIOXIDE SYSTEMS

Components of a carbon dioxide system include the carbon dioxide supply, the piping system, the discharge nozzles, alarms, and control devices.

Carbon Dioxide Storage

The carbon dioxide supply may be stored in high- or low-pressure containers. Because of the differences in pressure, system design is influenced by the storage method.

High-Pressure Storage. High-pressure containers, usually cylinders, are designed to store liquid carbon dioxide at atmospheric temperature. Since the maximum pressure in the cylinder or other container is affected by the ambient temperature, it is important that the container be designed to withstand the maximum expected pressure. Figure 17.1.5 shows the change in gauge pressure with temperature.

Storage cylinders are designed, tested, and filled to applicable national codes and standards. In the United States the U.S. Department of Transportation (DOT) specifications apply. The maximum filling density permitted is equal to 68 percent of

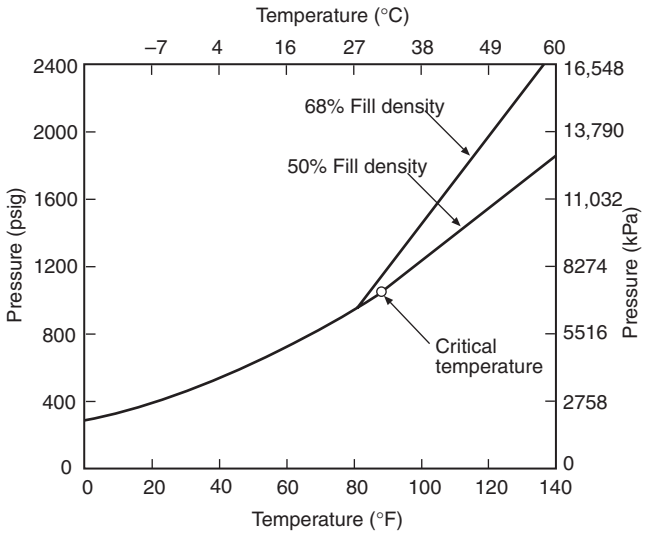

FIGURE 17.1.5 Variation in Pressure of Carbon Dioxide with Change in Temperature, Showing the Effect of Filling Density in High-Pressure Storage

the weight of water that the container can hold at 60°F (16°C). Standard cylinder capacities are 5, 10, 15, 20, 25, 35, 50, 75, 100, and 120 lb (2.3, 4.5, 6.8, 9.1, 11.3, 15.9, 22.7, 34, 45.4, and 54.4 kg) of carbon dioxide. Fire-extinguishing cylinders are fitted with an internal dip tube so that liquid will be discharged from the bottom when the cylinder is upright and the valve is opened.

Abnormally low storage temperatures adversely affect the rate of discharge. For this reason, NFPA 12 does not permit storage temperatures below 0°F (–18°C) for total flooding systems or below 32°F (0°C) for local application systems. Lower storage temperatures may be permitted only if the design includes special features to compensate for the reduced pressure. Techniques for "winterizing" cylinders are also available. Proper use of winterizing techniques can permit use of high-pressure storage at temperatures as low as –60°F (–51°C).

Low-Pressure Storage. Low-pressure storage containers are pressure vessels with a design working pressure of at least 325 psi (2240 kPa). These containers are maintained at a temperature of approximately 0°F (–18°C) by use of insulation and mechanical refrigeration. At this temperature, the pressure is approximately 300 psi (2069 kPa). A compressor, controlled by a pressure switch in the tank, circulates refrigerant through coils near the tank top. Tank pressure is controlled by condensation of carbon dioxide vapor by the coils. In the event of refrigeration failure, pressure-relief valves bleed off some of the vapor to keep the pressure within safe limits. This permits some of the liquid to evaporate, creating a self-refrigerating effect that reduces the pressure in the tank. Figure 17.1.6 shows a typical low-pressure container. Heaters with recirculating pumps are required if ambient temperatures will cool the tank contents below approximately –10°F (–23°C) (250 psi [1724 kPa] pressure level).

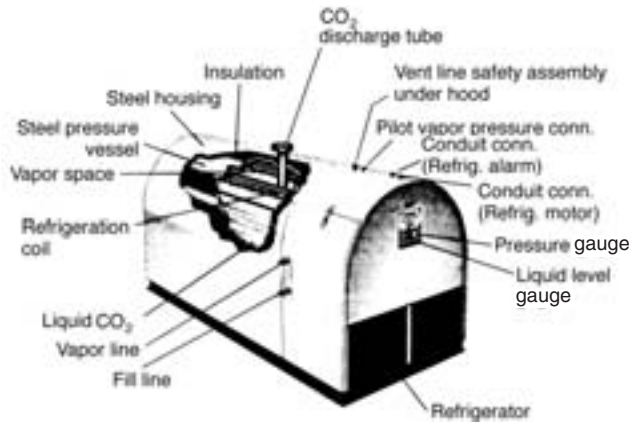

FIGURE 17.1.6 Low-Pressure Storage Unit—Carbon Dioxide Maintained at 0°F (–18°C) by Refrigeration; Pressure Is 300 psi (2069 kPa)

With low-pressure storage, it is common practice to protect multiple hazards from one central storage unit. The quantity of carbon dioxide discharged on a particular hazard is controlled by opening and closing the discharge valves in a preset timed sequence. Central low-pressure CO_2 storage units may have capacities ranging from less than 1 ton to 100 tons or more (1 ton is approximately 907 kg). For large hazards, the distance between hazard and storage may be several hundred feet (100 ft is approximately 30.5 m).

Piping System

Piping systems, normally empty, convey carbon dioxide from the storage container to open nozzles where there is a fire. Since the proper rate of flow is a critical requirement for fire extinguishment, it is important that the piping be designed and installed accurately. Minimum pressure in the pipeline must be kept well above the triple point pressure of 75 psia (5.2 bars). If the pressure of the flowing carbon dioxide falls below the triple point pressure, dry ice will form in the pipe and block orifices in the discharge nozzles, thus stopping the flow of carbon dioxide. NFPA 12 limits design nozzle pressures to a minimum of 300 psia (20.7 bars) for high-pressure storage and a minimum of 150 psia (10.3 bars) for low-pressure storage.

Carbon dioxide drawn from the bottom of the storage container enters the piping as a liquid. Friction causes loss in pressure. As pressure drops, the liquid boils, resulting in a mixture of liquid and vapor in the piping. The vapor increases in volume as the mixture passes through the piping, with a further drop in pressure. Thus, the flow is two-phase, a mixture of liquid and gas, a fact that pressure drop calculations must take into account.

NFPA 12 covers the calculation of carbon dioxide flow in some detail and provides pertinent equations and data tables. Although charts and tables are available for manual calculation of system piping, the use of available computer programs speeds and simplifies the design of piping systems.

The piping must be adequately supported to prevent movement during the discharge, and provision must be made for its contraction and expansion. Because liquid carbon dioxide is a refrigerant, it will substantially reduce the pipe temperature during discharge. Low-pressure liquid, in particular, starts at 0°F (–18°C) and may reach temperatures as low as –50°F (–46°C) in the piping before the discharge ends.

Valves and Operating Devices

Valves for controlling the discharge of carbon dioxide must withstand the maximum operating pressure, be absolutely bubbletight when closed, and be capable of both manual and automatic operation. Valves and allied devices, such as timers and pressure switches, must be listed or approved for use in carbon dioxide systems.

Discharge Nozzles

Many nozzle types are available for fire extinguishment applications. Nozzles used in total flooding simply may be orifices producing high-velocity jet streams, or they may be partially shielded to achieve reduced velocity or a specific discharge pattern. High-velocity types provide substantial mixing to ensure uniform concentration of carbon dioxide throughout an enclosure. Low-velocity types have a tendency to create high concentrations in the lower levels, which may be desirable under certain conditions.

Nozzle types used in local application systems normally are designed for relatively low discharge velocity. This helps to avoid splashing of liquid fuels and minimizes turbulence and air entrainment. All such nozzles must be tested for fire-extinguishing characteristics and listed or approved by a testing laboratory on the basis of test performance.

Figure 17.1.7 shows a typical performance curve for a nozzle designed for overhead mounting. The rate of discharge

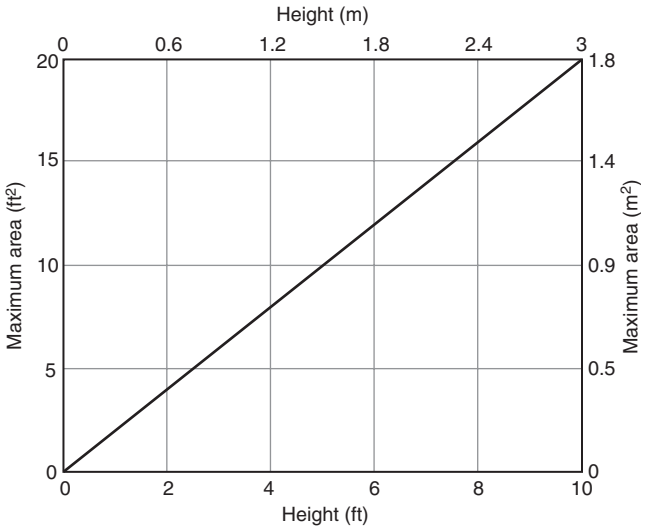

FIGURE 17.1.7 Listing or Approval Curve of a Typical Carbon Dioxide Nozzle Showing Maximum Area Versus Height or Distance from Liquid Surface

used is based on the height of the nozzle above the hazard or the fuel surface and is given in listing cards or approvals. (Testing is based on the maximum rate that will not splash liquid fuels.) The maximum fire area that the nozzle will extinguish also is based on the height above the hazard surface, using the design flow rate.

Performance information enables the system designer to select and properly locate the number of nozzles necessary to cover the entire fire area of the hazard. It also establishes the design flow rate that must be used on the hazard. The effective design flow rate must continue for a minimum of 30 seconds.

Figures 17.1.8 and 17.1.9 show typical performance curves for nozzles designed for mounting on the sides of open tanks containing flammable liquids. In such cases, the design flow rates are based on the area of coverage for the tankside nozzles or on the width of the hazard for linear nozzles mounted to extend the full length of one side. In each case, the design flow rate must be in the shaded area of the curves.

System Controls

Most carbon dioxide systems incorporate three methods of actuation: automatic, normal manual operation, and emergency manual operation.

Automatic Actuation. Automatic actuation is an operation that does not require any human action. Generally, fire detectors that sense abnormal heat, smoke, or flame initiate automatic actuation. The detector, on sensing a fire condition, initiates a signal at an electrical control panel.

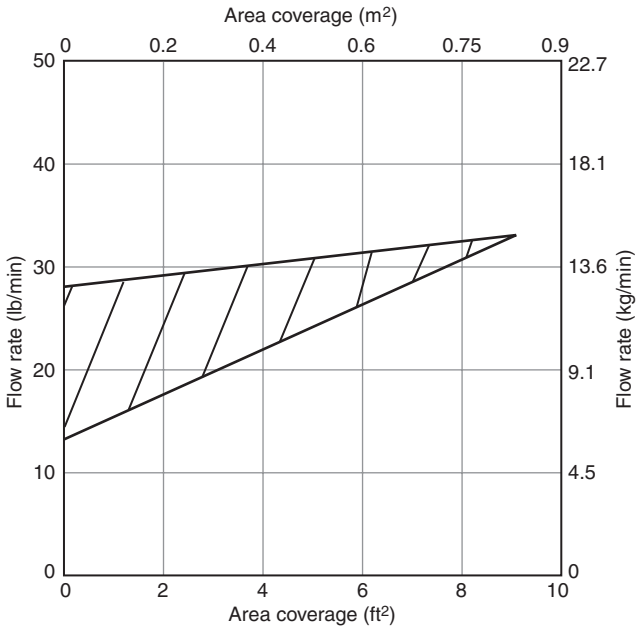

FIGURE 17.1.8 Typical Listing or Approval Curve of a Tankside Carbon Dioxide Nozzle Showing the Flow Rate Versus Area Coverage

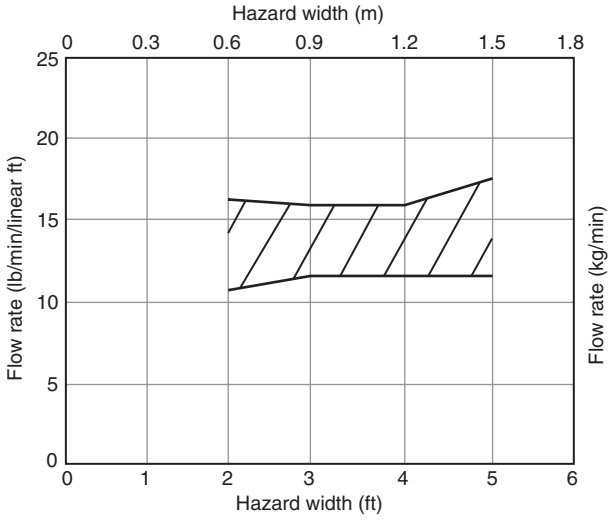

FIGURE 17.1.9 Typical Listing or Approval Curve of a Linear Carbon Dioxide Nozzle Showing Flow Rate Versus Hazard Width

Normal Manual Operation. Normal manual operation is actuation of the system requiring human action to initiate the operation. In modern carbon dioxide systems, normal manual operation is typically by a manual pull station connected to an electrical control panel.

Emergency Manual Operation. In emergency manual operation, the emergency manual release must function independently of electrical power and must be fully mechanical in nature. It can incorporate use of system carbon dioxide pressure to cause discharge. Emergency manual operation is intended for use only if both the automatic and normal manual operations have failed to cause a required discharge. Because most emergency manual operations cause immediate discharge of carbon dioxide without any alarm, it is essential that anyone who operates an emergency manual release be certain that the hazard area is evacuated and secured against entry of personnel prior to operation.

Control Panels

In modern carbon dioxide systems, fire detectors and manual electrical control stations (pull stations) are connected to an electrical control panel. Operation of a fire detector or pull station puts the control panel into an "alarm" condition. The control panel will cause a sequence of events leading to a discharge of carbon dioxide.

A relatively recent change to NFPA 12 requires pneumatic predischarge time delays and pneumatic predischarge alarms to be incorporated into most carbon dioxide systems. This is a retroactive requirement. Normally carbon dioxide from the system storage containers is used to power both the pneumatic time delays and the pneumatic audible alarms.

As part of the discharge sequence, the control panel opens a control valve to initiate carbon dioxide flow to the pneumatic predischarge time delay and pneumatic alarms. The control

panel will also provide power to electrically operated alarm devices. After the pneumatic time delay has expired, the discharge of carbon dioxide begins. If the system uses high-pressure storage containers, the discharge will continue until the containers are emptied. If the system uses a low-pressure storage container, the discharge is continued for a predetermined length of time after which a control valve is shut, ending the discharge.

The control panel may also cause required equipment shutdown and fuel line shutoffs, control dampers and fans, and send alarm signals to personnel responsible for response to fire situations. It is essential that electrical control panels that are intended to control carbon dioxide systems be designed such that a system discharge will not occur without the required predischarge time delay and alarms. The sequence of operation for the carbon dioxide system must be documented in writing and maintained in a protective enclosure with the system.

When the system is in "standby" condition, the control panel supervises the interconnections between all electrically powered components necessary for control of the systems and life safety. Connections between the control panel and detectors, manual electrical release stations, system valve actuators, and alarms should be supervised. The control panel also monitors the condition of system lockout valves and electrical power sources.

Some older carbon dioxide systems used timer-driven cams to operate switches that controlled the various discharge functions. Totally pneumatic systems using pneumatic detection and control were also common. Many of these systems are still in service.

Alarms

Both audible and visual predischarge alarms are generally required for carbon dioxide systems. Various types of sirens or horns are used for audible alarm. NFPA 12 requires that most total flood systems and some local application systems be equipped with pneumatically powered predischarge time delays and pneumatically driven predischarge audible alarms. Existing systems which lack such pneumatic alarms are required by NFPA 12 to be retrofitted with them. Whatever type of audible device is used, its sound should be distinctive and capable of being heard above background noises. Strobe lights or rotating beacons are often used as visual alarms. It is essential that the alarms function to warn people against entry into all areas made hazardous by a carbon dioxide discharge for as long as the hazard exists or until the areas are secured against entry by personnel.

CARBON DIOXIDE SYSTEM DESIGN CONSIDERATIONS

To organize basic components into a carbon dioxide fire protection system, a number of factors must be considered. These include the quantity of stored carbon dioxide, the method of actuation, the location of predischarge alarms, ventilation shutdown, pressure venting, and anything else involved in ensuring safe, prompt, and effective fire extinguishment and personnel safety.

Quantity Requirements

The quantity of carbon dioxide required for extinguishment depends on the type of fire, the type of extinguishing system, and conditions in the fire area. Where continuous protection is required, the quantity of carbon dioxide on hand should be at least twice that needed for extinguishment. Detailed methods of determining the quantity required for extinguishment are covered in NFPA 12.

Total Flooding Systems. The design concentration for a given enclosure should be sufficient to extinguish fires in all the fuels that are present in the hazard. The minimum concentration used in total flooding systems is 34 percent carbon dioxide by volume. Minimum design concentrations for various liquids and gases are given in Table 17.1.1. NFPA 12 requires a 50 percent concentration for electrical wiring hazards, including small electrical machines; 65 percent for bulk paper and fur storage vaults; and 75 percent for dust collectors. These are specific hazards for which there is a background of test experience. Other materials should be tested to determine minimum carbon dioxide concentrations and holding time.

The quantity of carbon dioxide must be sufficient to achieve a minimum design concentration and to maintain it until the fire is extinguished or a trained and suitably equipped fire brigade responds to complete the extinguishment. A series of specific flooding factors has been established for surface fire hazards. These factors include an allowance for distributed leakage due to cracks around doors, porosity of the walls, and other small openings based on room size. The factors are greater for smaller rooms, because the anticipated leakage would be greater relative to volume (Table 17.1.2 and Figure 17.1.10).

Note: If a hazard requires a design concentration greater than 34 percent, the basic quantity of carbon dioxide needed would be calculated by multiplying the appropriate flooding factor from Table 17.1.2 by the conversion factor determined from Figure 17.1.10.

If the enclosure has obvious openings that cannot be closed, or ventilating systems that cannot be shut off in the event of a

TABLE 17.1.2 Flooding Factors to Achieve 34 Percent Design Concentration

Volume of Space (ft^3)	Volume Factor		*Calculated Quantity Not Less Than (lb)*
	(ft^3/lb CO_2)	*(lb CO_2/ft^3)*	
Up to 140	14	0.072	—
141–500	15	0.067	10
501–1,600	16	0.063	35
1,601–4,500	18	0.056	100
4,501–50,000	20	0.050	250
Over 50,000	22	0.046	2500

For SI units: 1 ft^3 = 0.0283 m^3; 1 lb = 0.454 kg.

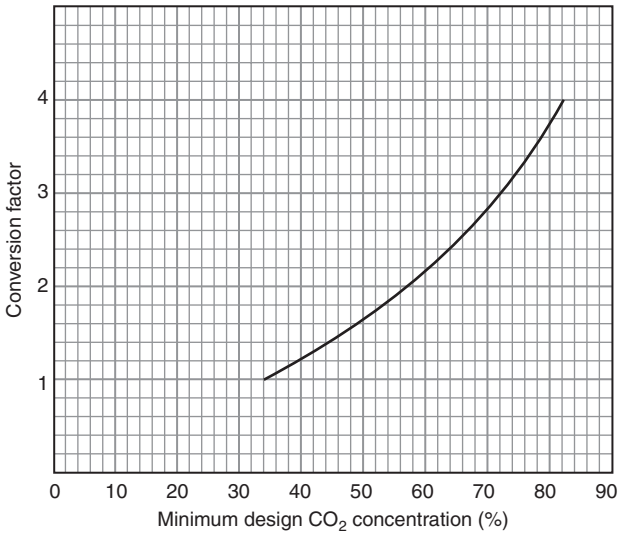

FIGURE 17.1.10 Minimum Design Carbon Dioxide Concentration Conversion Factors

fire, additional carbon dioxide must be added to the "basic quantity" calculated using the flooding factor and material conversion factor.

Surface burning fires, such as flammable liquid fires, are normally extinguished during a 1-minute carbon dioxide discharge. Leakage compensation must be in addition to the basic quantity.

Deep-seated fires require higher concentrations and much longer holding times. The rate of discharge must be high enough to develop a concentration of 30 percent in not more than 2 minutes, and the final design concentration must be achieved in not more than 7 minutes. Enclosures for deep-seated fires should be relatively tight, or it may be uneconomical to maintain the carbon dioxide design concentration. The basic quantity of carbon dioxide needed for deep-seated fire hazards is calculated using flooding factors given in NFPA 12. Some deep-seated fires can smolder for very long periods of time, even in the presence of a high carbon dioxide concentration. An example is fire in baled cotton stored in the cargo hold of a ship. For these fires, carbon dioxide may be used to suppress the open flaming and reduce the rate of fire spread. Complete extinguishment must be done by trained fire fighters using manual fire-fighting techniques. For such hazards, the carbon dioxide concentration should be maintained for sufficient time to permit response by a properly equipped and trained fire brigade.

Extended Discharge Systems. The most efficient way to compensate for leakage where the concentration must be maintained for a substantial time is to use an extended discharge at a reduced rate equal to the rate of leakage. The quantity of carbon dioxide required is based on the rate of discharge multiplied by the time that the concentration must be maintained. This is in addition to the quantity required to develop the design concentration.

Local Application Systems. These systems may be designed using either "rate-by-area" or "rate-by-volume" methods. When rate-by-area is used, the hazard is considered as a number of equivalent surface areas, each protected by a single nozzle. The rate of discharge from each nozzle is determined from listing information, and the total discharge rate for the system is the sum of the design rates required for each nozzle.

Where the hazard consists of three-dimensional irregular objects that cannot be reduced easily to equivalent surface areas, the rate-by-volume method may be used. In this case, the discharge rate of the system is based on the volume of an assumed enclosure entirely surrounding the hazard. Because this method is not as precise as the rate-by-area procedure, it usually results in more carbon dioxide discharge, unless the hazard is nearly enclosed with walls.

A discharge of vapor is not considered effective for local application. The liquid portion of the discharge should be continued for a minimum of 30 seconds, or longer if required for cooling. If a liquid fuel has an autoignition temperature lower than its boiling point (e.g., paraffin wax and some cooking oils), the mass of liquid can become "superheated" above its autoignition temperature. For such fuels, a minimum local application time of 3 minutes is required to permit the mass of liquid fuel to cool.

Additional carbon dioxide must be added to storage to compensate for any initial vapor discharge produced in cooling the piping. In high-pressure systems, only about 70 percent of the stored quantity will leave the storage cylinder as liquid. Therefore, the quantity calculated by rate and time must be increased by a factor of 1.4 to help ensure a 30 second liquid discharge.

Hand Hose Line Systems. The carbon dioxide supply depends upon the type and size of the hazard to be protected. As a practical matter, however, sufficient carbon dioxide should be available to counteract possible waste by inexperienced users. In any case, there should be sufficient carbon dioxide to permit operation of the system for at least 1 minute. The possible use of these hoselines by inexperienced personnel should be considered and enough carbon dioxide should be provided to permit extinguishment of a fire by such personnel. When more than one hose reel may possibly be used on a single hazard, sufficient carbon dioxide should be available to support the maximum number of hose reels that are likely to be used simultaneously for 1 minute.

Venting Requirements

When liquid carbon dioxide is discharged into a closed room, the atmosphere may shrink initially due to the sudden refrigerating effect. At a later flooding stage, the combined volume of the carbon dioxide and air may become greater than the initial room volume. Thus, although the first result may be to create a vacuum, or draw in air, the final result will be to increase the pressure or to exhaust the excess volume through vent openings. Actual air temperatures are greatly reduced during the discharge, but they soon return to normal as heat is absorbed from solid surfaces in the room.

Most ordinary rooms have sufficient leakage through cracks around doors and windows and through general porosity to prevent noticeable vacuum or pressure buildup. From the viewpoint of efficient total flooding, it is better to have major vent openings in or near the ceiling rather than near the floor.

In rooms that may be tightly sealed, a safe vent area can be estimated on the basis of calculated discharge flow rate and the strength of the enclosure:

$$X = \frac{Q}{1.3\sqrt{p}}$$

where

X = Vent area in in.^{2}

Q = Flow rate in lb/min

p = Allowable strength of the enclosure in lb/ft^2

For SI units:

$$X_m = \frac{239 Q_m}{\sqrt{p_m}}$$

where

X_m = Vent area in mm^2

Q_m = Flow rate in kg/min

p_m = Allowable strength of the enclosure in kg/m^2

More information on room venting can be found in NFPA 12.

System Control

Total flooding and local-application carbon dioxide systems normally should be designed to operate automatically. The detection device may be any of the listed or approved devices that are actuated by heat, smoke, flame, flammable vapors, or other abnormal process conditions that could lead to a fire or explosion. Automatically operated systems are required to have an independent means of manual actuation (emergency manual operator).

It is essential that electrical control panels intended to control carbon dioxide systems be designed such that a system discharge will not occur without the required predischarge time delay and alarms. NFPA 12 requires pneumatically powered predischarge time delays for most total flood systems and some local application systems. Existing systems must be retrofitted with pneumatic time delays to meet the NFPA 12 requirements. If a control panel fails to discharge the carbon dioxide system, the emergency manual operator is available to cause a discharge independently of the control panel. An unwanted discharge without proper predischarge alarms may endanger life.

Whether supplemental to automatic actuation or the sole means of placing a system in operation, manual controls must be easy to operate, accessible in case of fire, and located close to the valves they control. Remote manual controls usually are located near an exit for a total flooding installation or near a hazardous area for local application installations. Instructions for safe operation of the manual controls must be prominently displayed at the control.

Marine Systems

Systems used on offshore platforms and marine vessels are subject to different regulations and design procedures. Quantity calculations, piping design, nozzle sizing, and system control requirements can vary from those discussed in this chapter. The guidance of the authority having jurisdiction over the vessel must be followed for such systems.

TESTING AND MAINTAINING CARBON DIOXIDE SYSTEMS

An elaborate fire protection system could be ineffective or even dangerous unless it is properly tested to demonstrate adequate performance and maintained in good working condition.

Acceptance Testing

No newly installed system should be accepted until it has been inspected properly and tested to prove performance in accordance with design specifications. The inspection should ascertain whether the system is installed in accordance with approved plans. The piping is particularly important, because any changes might affect the flow rates that were calculated on the basis of the pipe sizes shown on the plans.

NFPA 12 requires a "full discharge test" of all newly installed systems. The final proof of performance is to discharge the system and, for total flooding hazards, to measure the concentrations of carbon dioxide and the holding time in the fire zone. Local application systems cannot be subjected to concentration testing. Their effectiveness is judged by observation during the test discharge. NFPA 12 gives the minimum requirements for approval of new installations.

Figure 17.1.11 shows a local application discharge test on a printing press. The effectiveness of the local application discharge is judged by observation during the discharge test. It is helpful to videotape the discharge of large local application systems. This photo taken from such a videotape reveals that carbon dioxide coverage on the front press stations was inadequate. Post-test inspection showed that the left nozzle for the station was plugged.

FIGURE 17.1.11 Local Application Discharge Test on Printing Press (Source: Photo Courtesy of Guardian Services, Inc.)

Inspections

To maintain a system in proper operating condition, it is essential to conduct periodic inspections. At least once a month, the system must be inspected to verify its operational status. The status of the carbon dioxide supply should be checked at least weekly for low-pressure supplies, at 6 month intervals for high-pressure cylinders, and immediately after the system has operated. The entire system should be inspected annually. In particular, inspectors should look for changes in the scope of the hazard, changes in the condition of any enclosure, and other changes that could affect the adequacy of the fire protection system.

Maintenance

All operating devices should be tested annually. Although much of this testing can be accomplished without discharging the system, a partial discharge may be necessary in some cases. Any required maintenance found by testing should be performed without delay.

Training

Personnel must be made aware of the importance of the fire protection as well as the potential effects of exposure to high concentrations of carbon dioxide. Training should include how the system extinguishes fire, physiological effects of exposure to carbon dioxide, how the system is actuated, proper response to alarms (including a detailed evacuation plan), and proper safety precautions that are to be observed before manually actuating the system. New personnel should be trained before they are permitted to enter spaces that could be affected by a carbon dioxide discharge or areas where carbon dioxide system controls are located. Periodic "refresher" training courses should be mandatory.

Persons who are not normally associated with the protected hazard and adjoining spaces, but who are given temporary assignment there, must also be briefed on the safety issues related to the fire protection system, including proper response to alarms and evacuation procedures. This applies likewise to outsiders, such as construction and maintenance people.

SUMMARY

Carbon dioxide is a widely used fire-extinguishing agent that is especially effective on flammable liquid fires, gas fires, and fires involving electrically energized equipment. It can also be used on ordinary combustibles such as cloth and paper. Carbon dioxide has several properties that make it a desirable fire-extinguishing agent; for example, it is noncombustible, does not conduct electricity, and is easily spread in its gaseous form. Total flooding systems may not be effective in enclosures incapable of retaining an extinguishing concentration. The CO_2 should not be used on fires involving chemicals that contain their own oxygen supply or on fires involving reactive metals. A variety of methods can be used to apply carbon dioxide, including total flooding and local application systems. Because concentrations resulting from the discharge of a carbon dioxide system can endanger life, it is essential that safety features be installed and kept in operating condition and that personnel be properly trained with respect to system safety. These systems must be properly designed, tested, and maintained by trained personnel in order to ensure that the systems work effectively and safely.

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Reference to the following NFPA codes, standards, and recommended practices will provide further information on carbon dioxide and application systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*

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Chapter 2

Chemical Extinguishing Agents and Application Systems

James D. Lake

Chapter Contents

Overview of Dry Chemical Extinguishing Agents
Uses and Limitations of Dry Chemical Systems
Wet Chemical Extinguishing Agents
Uses and Limitations of Wet Chemical Extinguishing Systems
Inspection, Testing, and Maintenance Procedures for Chemical Systems

Key Terms

dry chemical, dry chemical extinguishing system, fixed extinguishing system, flammable liquid fire, portable fire extinguisher, saponification, total flooding, wet chemical, wet chemical extinguishing system

Although water is the most common fire extinguishing agent available, it is understood that for many types of fires water may not be the most effective, efficient, or even the safest agent to use. Flammable liquids, combustible metals, and various machining processes present special hazards that may best be protected by chemical extinguishing agents.

For the purposes of this chapter, chemical extinguishing agents are divided into two categories: dry and wet. Dry chemical fire extinguishing systems first appeared on the market in the mid-1950s, and wet chemical fire extinguishing systems began receiving listings for the protection of commercial cooking operations in the late 1960s. Both types of systems are addressed by the NFPA Technical Committee on Dry and Wet Chemical Extinguishing Systems, which outlines the two standards that address these systems: NFPA 17, *Standard for Dry Chemical Extinguishing Systems,* and NFPA 17A, *Standard for Wet Chemical Extinguishing Systems*.

This chapter contains information on the properties of both dry and wet chemicals that contribute to their use as extinguishing agents. The limitations, methods of application, system design, and the inspection, testing, and maintenance associated with these systems will also be addressed in this chapter.

Portable dry and wet chemical fire extinguishers are discussed in Section 17, Chapter 5, "Fire Extinguisher Use and Maintenance." For other related topics, see Section 9, Chapter 5, "Metalworking Processes."

OVERVIEW OF DRY CHEMICAL EXTINGUISHING AGENTS

Dry chemical is defined as a powder composed of very small particles, usually sodium bicarbonate–, potassium bicarbonate–, or ammonium phosphate–based with added particulate material supplemented by special treatment to provide resistance to packing and moisture absorption (caking) and to provide the proper flow capabilities. It is intended for application by means of portable extinguishers, hand hose line systems, or fixed systems.

Dry chemical extinguishing agents are commonly listed for use on Class B and Class C fires. However, ammonium phosphate–based agents may also be referred to as *multipurpose dry chemical* because they are listed for use on Class A, B, and C fires. Dry chemical extinguishing agents are not effective on Class D fires as the heat developed by combustible metals consumes the agent prior to extinguishment. Furthermore, application of multipurpose dry chemical may result in a violent reaction with some types of combustible metals. Therefore, the terms *dry chemical* and *multipurpose dry chemical* should not be confused with *dry powder* and *dry compound,* which identify powdered extinguishing agents developed primarily for use on Class D fires. See Section 9, Chapter 5, "Metalworking Processes," for a discussion on combustible metal fires.

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The first dry chemical agents were borax- and sodium bicarbonate–based dry chemicals. Sodium bicarbonate eventually became the standard because of its greater effectiveness as a fire-extinguishing agent and was even modified to make it compatible with protein-based low-expansion foams for a dual agent attack in the 1960s. The mid-1960s saw the development of the monoammonium phosphate–based *multipurpose dry chemical;* the potassium bicarbonate–based *Purple K*, originally developed to be used with aqueous film forming foam (AFFF) in a dual system but is commonly used on its own for flammable liquid fires; and the potassium chloride–based *Super K*, which has extinguishing properties that are roughly equivalent to potassium bicarbonate but was developed as a dry chemical that would be compatible with protein-type foams.

As a group, dry chemical agents are noted for their efficiency in extinguishing fires in flammable liquids. They can also be used on fires involving some types of electrical equipment. Sodium bicarbonate– and potassium bicarbonate–based agents have certain limited applications in extinguishment of flash surface fires with ordinary combustibles, but the chemical requires water to put out deep-seated smoldering fires. Multipurpose dry chemical can be used on fires in flammable liquids, fires involving energized electrical equipment, and fires in ordinary combustible materials and seldom needs the help of water to completely extinguish fires in Class A materials.

In the late 1960s a urea-potassium bicarbonate–based dry chemical was developed in Great Britain but is not as widely used as the other agents.

Physical Properties

The principal base chemicals used in the production of currently available dry chemical extinguishing agents are sodium bicarbonate, potassium bicarbonate, potassium chloride, urea-potassium bicarbonate, and monoammonium phosphate. Various additives are mixed with these base materials to improve their storage, flow, and water repellency characteristics. The most commonly used additives are metallic stearates, tricalcium phosphate, or silicones, which coat the particles of dry chemical to make them free-flowing and resistant to the caking effects of moisture and vibration.

Because some of the additives in dry chemical agents may melt and cause sticking at higher temperatures, an upper storage temperature limit of 120°F (49°C) is recommended for dry chemical. (Temperatures up to 150°F [66°C] may be acceptable for very short durations.)

Most dry chemicals are alkaline (sodium bicarbonate, potassium bicarbonate, and potassium carbonate), one is neutral (potassium chloride), and the multipurpose type (monoammonium phosphate) is acidic. Inadvertent mixing of different base dry chemicals can initiate undesirable reactions, generating carbon dioxide gas and resulting in equipment failure or loss of discharge capability.

- *Sodium bicarbonate* is an odorless white crystalline powder that decomposes at 140°F (60°C), has a pH ranging from 8.3 to 8.6, is partly soluble in water, and is the mildest of all sodium alkalis. As an extinguishing agent, it commonly has a white or blue appearance. It is the original dry chemical extinguishing agent and may also be referred to as regular dry chemical. The production of sodium bicarbonate is more economical than any of the other dry chemicals, resulting in its being the most widely used of the group.
- *Potassium bicarbonate* is an odorless white powder that decomposes at 248°F (120°C), has a pH in the range of 8.4, and is not soluble in water. Purple K is given its characteristic hue by the addition of violet pigments during production.
- *Potassium chloride* is an odorless white crystal with a melting point of 1422°F (772°C), has a pH of 7, and is completely soluble in water. It was developed as a dry chemical that would be compatible with protein-type foams. Its extinguishing properties are about equal to those of potassium bicarbonate. One drawback is its tendency to cause corrosion after it has extinguished a fire.
- *Monoammonium phosphate* is a white crystal solid with a slight odor of ammonia. It has a melting point of 350°F (190°C) and is slightly soluble in water (0.04 oz/0.08 oz [1g/2.5mL]). As an extinguishing agent, it may have an off-white or yellow color.

Monoammonium phosphate is called a multipurpose dry chemical because it can be effective on Class A, B, and C fires. Ammonium salts interrupt the chain reaction of flaming combustion. The phosphate changes into metaphosphoric acid, a glassy fusible material, at fire temperatures. The acid covers solid surfaces with a fire-retardant coating. Therefore, this agent can be used on fires involving ordinary combustible materials such as wood and paper, as well as on fires involving flammable oils, gases, and electrical equipment. However, it may only control, but not fully extinguish, a deep-seated fire.

Toxicity. Dry extinguishing chemical agents are stable at both low and normal temperatures and are considered to be nontoxic and noncarcinogenic. However, other physiological conditions such as minor skin and respiratory irritations may occur on exposure to the agents. No chronic medical conditions have been reported from long-term exposure. The acute effects of exposure are irritation to mucous membranes, with the possibility of chemical burns of the skin, eyes, and mucous membranes lining the respiratory system. Moist skin may enhance this effect. In all cases, self-contained breathing apparatus (SCBA) should be worn to protect against smoke, fumes, and the dust created by fixed system discharge. Consult the appropriate material safety data sheets (MSDSs) for detailed information, instructions, and special precautions.[1]

Particle Size. Particles of dry chemical range in size from less than 10 microns up to 75 microns (1 micron = 0.000029 in.). Particle size has a definite effect on extinguishing efficiency, and careful quality control is necessary to prevent particles from exceeding upper and lower limits of this performance range. Each dry chemical has a unique size limiting factor, below which the particles completely decompose and vaporize, and above which the particles do not completely decompose or vaporize.[2] The best results are obtained by a heterogeneous mixture with a median particle size of 20 to 25 microns. Particle size also has an effect on the flow characteristics of dry chemical. Solid particles suspended in a gas stream present higher pressure losses than

does gas alone. Coarse powders cause excessive surging, low flow rates, and will require larger expellant gas quantities. Fine powder will produce similar results but not to the same degree. Particle size is also responsible for the aerodynamic drag phenomenon (ADP). The momentum gained by larger particles will transport smaller particles to penetrate the updraft of a flame. Ordinarily, smaller particles would decompose or vaporize prior to penetration.[3] Underwriters Laboratories Inc. (UL) and Factory Mutual Research Corporation listings and ratings are based on the specified use of the particular type of dry chemical set forth by the equipment manufacturer.

Extinguishing Properties

When introduced directly to the fire area, dry chemical causes extinguishment almost at once. Fire tests on flammable liquids have shown potassium bicarbonate–based dry chemical to be more effective than sodium bicarbonate–based dry chemical in extinguishment. Similarly, monoammonium phosphate has been found equal to or better than sodium bicarbonate in extinguishment effectiveness.[4] The effectiveness of potassium chloride is about equivalent to that of potassium bicarbonate, and urea-potassium bicarbonate exhibits the greatest effectiveness of all the dry chemicals tested.

Smothering, cooling, and radiation shielding contribute to the extinguishing efficiency of dry chemical, but studies suggest that a chain-breaking reaction in the flame is the principal cause of extinguishment.[5]

Cooling Action. It cannot be substantiated that the cooling action of dry chemical is an important reason for its ability to promptly extinguish fires. The heat energy required to decompose dry chemicals plays an undeniable role in contributing toward their individual extinguishing abilities, but the effect, per se, is minor. To be effective, any dry chemical must be heat sensitive and, as such, absorb heat in order to become chemically active.[6]

Radiation Shielding. Discharge of dry chemical produces a cloud of powder between the flame and the fuel; this cloud shields the fuel from some of the heat radiated by the flame. Tests to evaluate this factor concluded that the shielding factor is of some significance.[6]

Smothering Action. For special applications, such as kitchen range, hood, duct, and fryer fire protection, the extinguishing mechanism for dry chemical is based on the process of saponification. Saponification is the process of chemically converting the fatty acid contained in the cooking medium to soap, or foam, and it accomplishes extinguishment by forming a surface coating that smothers the fire.[7]

The soap produced by saponification is readily broken down by exposure to heat. As a result, because dry chemicals do not offer a substantial cooling effect, the cooking medium may reflash after a brief period of time. It is due to this lack of cooling and the resultant potential for reflashing of the cooking medium that dry chemical extinguishing agents are no longer listed for the protection of commercial cooking operations. Wet chemical extinguishing agents are currently the only agents listed for the protection of this hazard.

For many years it was widely held that regular dry chemical extinguishing properties relied primarily on the smothering action of the carbon dioxide released when sodium bicarbonate was heated by fire. The carbon dioxide does undoubtedly contribute to the effectiveness of dry chemical, as does the like volume of water vapor released when dry chemical is heated. However, tests have not supported the belief that these gases are a major factor in extinguishment.

Chain-Breaking Reaction. The preceding extinguishing actions, when combined, exert a minimal effect. The rapidity of extinguishment is due to the interference of the dry chemical particles with the propagation of the combustion chain reaction, which reduces the concentration of "free" radicals present within the flames. To accomplish this, the dry chemical must become thermally decomposed.

The discharge of dry chemical into the flames prevents reactive particles from coming together and continuing the combustion chain reaction. The explanation is referred to as the chain-breaking mechanism of extinguishment.[8,9]

When multipurpose dry chemical is discharged into burning ordinary combustibles, the decomposed monoammonium phosphate leaves a sticky residue (metaphosphoric acid) on the burning material. This residue seals glowing material from oxygen, thus helping to extinguish the fire and prevent reignition.

USES AND LIMITATIONS OF DRY CHEMICAL SYSTEMS

Dry chemical is primarily used to extinguish flammable liquid fires. Because it is electrically nonconductive, it can also be used on flammable liquid fires involving live electrical equipment. Regular dry chemical extinguishers have been tested and found suitable for use on flammable liquid and electrical fires (Class B and C fires) by fire equipment testing laboratories.

Due to the rapidity with which dry chemical extinguishes flame, dry chemical is used on surface fires involving ordinary combustible materials (Class A fires). There are several areas in the textile industry, notably opener-picker rooms and carding rooms in cotton mills, where regular dry chemical has been used effectively. However, wherever regular dry chemical is provided for use on surface-type Class A fires, it should be supplemented by water spray for extinguishing smoldering embers or in case the fire gets beneath the surface. In some baled cotton storage areas, the tops of bales can be covered with regular dry chemical to prevent surface spread should fire break out. This preventive measure does not eliminate the need for automatic sprinkler protection in such areas. Because multipurpose dry chemical becomes sticky when heated, it is not recommended for textile card rooms or other locations where removal of the residue from fine machine parts may be difficult.

Dry chemical does not produce a lasting inert atmosphere above the surface of a flammable liquid; consequently, its

use will not result in permanent extinguishment if reignition sources, such as hot metal surfaces or persistent electrical arcing, are present.

Dry chemical should not be used in installations where relays and delicate electrical contacts are located (e.g., in telephone exchanges and computer equipment rooms), as the insulating properties of dry chemical might render such equipment inoperative. Because some dry chemicals are slightly corrosive, they should be removed from all undamaged surfaces as soon as possible after fire extinguishment.

Specifications have been established by fire equipment testing laboratories to ensure the positive and consistent performance of dry chemical as an extinguishing agent. These specifications control moisture content, water repellency, electrical resistivity, storage at elevated temperatures, flow capability, caking resistivity, and abrasive action. The discharge characteristics of the device in which the dry chemical is to be used are also evaluated. Extinguishing effectiveness is determined by performance tests of the application to standard fires under conditions recommended by the manufacturer.

Dry chemical extinguishing systems can be used in those situations where quick extinguishment is desired and where reignition sources are not present. Dry chemical systems are used primarily for flammable liquid fire hazards, such as dip tanks, flammable liquid storage rooms, and areas where flammable liquid spills may occur. Systems have been designed for kitchen range hoods, ducts, and associated rangetop hazards, such as deep-fat fryers. However, due to its limited ability to prevent reflashing of a fire, no dry chemical agents or system has been able to meet the new listing criteria for the protection from these hazards. Where it is necessary to extinguish a flammable liquid or gas fire being fed by fuel under pressure, dry chemical hand hose line systems can be used, followed by closure of fuel shutoff valves.

Because dry chemical is electrically nonconductive, extinguishing systems using this agent can be used on electrical equipment that is subject to flammable liquid fires, such as oil-filled transformers and oil-filled circuit breakers. Dry chemical system protection is not recommended, however, for delicate electrical equipment, such as telephone switchboards and electronic computers. Such equipment is subject to damage by dry chemical deposit and, because of the insulating properties of the dry chemical, may require excessive cleaning to restore operation.

Regular dry chemical will not extinguish fires that penetrate beneath the surface or fires in materials that supply their own oxygen for combustion. Dry chemical may be incompatible with mechanical (air) foam unless the dry chemical has been specially prepared to be reasonably foam compatible.

Method of Application

Fixed systems are of two types: (1) total flooding and (2) hand hose line/local application. In total flooding applications, a predetermined amount of dry chemical is discharged through fixed piping and nozzles into an enclosed space or enclosure around the hazard (Figure 17.2.1). On actuation of the system by a heat detector, nitrogen is discharged into the 150 lb (68 kg) storage container and dry chemical is expelled through eight nozzles in the roof. Total flooding systems are applicable only when the hazard is totally enclosed or when all openings surrounding a hazard can be closed automatically, before or simultaneously when the system is discharged. In some instances, additional dry chemical can be included in the system design to compensate for unclosable openings. Total flooding can be used only where no reignition is anticipated, because the extinguishing action is transient.

FIGURE 17.2.1 A 15 ft by 24 ft (4.6 m by 7.3 m) Flammable Liquids Storage Building Protected by a Total Flooding Dry Chemical System

Hand hose line systems containing regular or ordinary dry chemical have been used to a limited extent for quick-spreading surface fires on ordinary combustible material. In such applications, the dry chemical system only stops or prevents a rapid surface spread, and must be supplemented by a water-type extinguishing device to put out deep-seated smoldering fires. Fixed systems containing multipurpose dry chemical are available and are suitable for the protection of ordinary combustibles, provided the dry chemical can reach all burning surfaces.

Hand hose line systems consist of a supply of dry chemical and expellant gas with one or more hand hose lines to deliver the dry chemical to the fire (Figure 17.2.2). Dry chemical systems of this type range from 125 to 3000 lb (57 to 1361 kg); the 3000 lb (1361 kg) system shown has six nitrogen cylinders and two 1 in. by 100 ft (25 mm by 30.5 m) hoses with shutoff nozzles. The hose stations are connected to the dry chemical container either directly or indirectly by means of intermediate piping. They can provide a large quantity of extinguishing agent for quick knockdown and extinguishment of relatively large fires, such as might be experienced at gasoline loading racks, flammable liquid storage areas, diesel and gas turbine locomotives, and aircraft hangars.

Figure 17.2.3 illustrates methods of dry chemical application.

System Design

Dry chemical systems are called either engineered or preengineered, depending on how the quantity of chemical, rate of flow, size and length of piping, and number and size of fit-

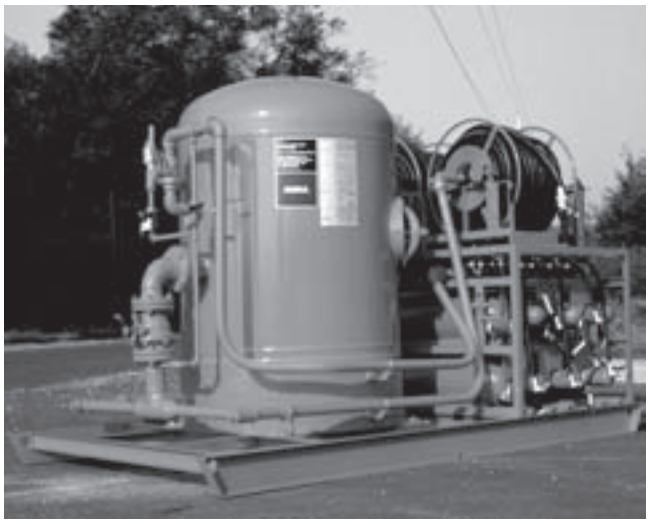

FIGURE 17.2.2 Dry Chemical Hand Hose Line System Consisting of an Expellant Gas Assembly, a Dry Chemical Storage Tank Assembly, and a Discharge Assembly (Source: Ansul Incorporated)

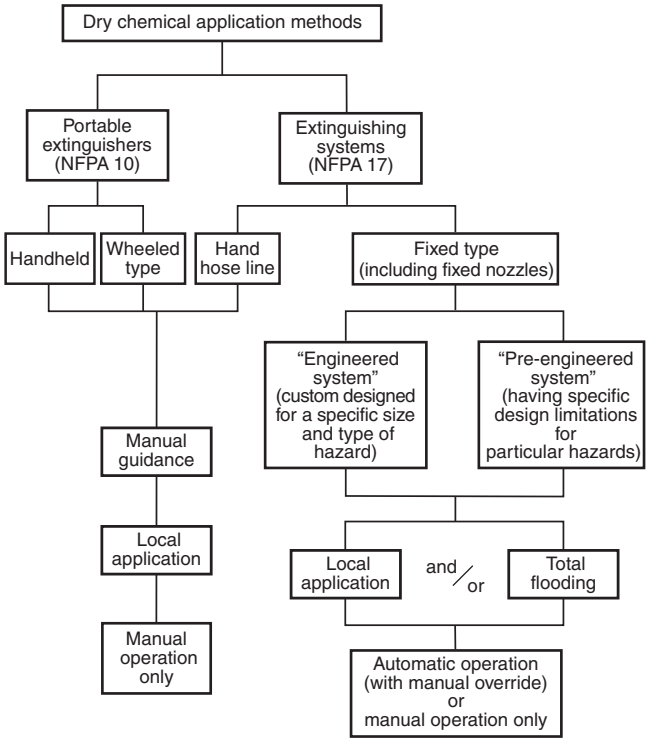

FIGURE 17.2.3 Methods of Dry Chemical Application

tings are determined. An engineered system is one in which individual calculation and design is needed to determine the flow rate, nozzle pressures, pipe sizes, quantity of chemical, and the number, types, and placement of nozzles for the hazard being protected. A pre-engineered system, sometimes called a package system, is one in which the size of the system (i.e., the quantity of chemical, pipe sizes, maximum and minimum pipe lengths, number of fittings, and number and types of nozzles) is predetermined by fire tests for specific sizes and types of hazards. Installation within these limits of hazard and system design ensures adequate flow rate, nozzle pressure, and pattern coverage without individual calculation (Figure 17.2.4).

In the past, pre-engineered systems were frequently used for kitchen range and hood fire protection, including deep-fat fryers. However, only alkaline dry chemicals (sodium bicarbonate, potassium bicarbonate, etc.) were used; multipurpose dry chemical was never used. It is important to note that dry chemical systems can remain in use provided the cooking equipment and the cooking medium have not changed from the time of the initial installation. Any changes in the system necessitate a change to a wet chemical system that has been listed in accordance with UL 300, *Standard for Fire Testing of Fire Extinguishing Systems for Protection of Restaurant Cooking Areas.*

Storage of Chemical and Expellant

Chemical agents are stored in pressure containers, usually of welded steel construction, either under atmospheric pressure until the system is actuated or under the pressure of the internally stored expellant gas.

Containers in which dry chemical is stored separately under atmospheric pressure are equipped with an expellant gas inlet, a moisture-sealed fill opening, and a dry chemical outlet. The gas inlet leads to an internal gas tube arrangement constructed so that, when it flows into the tank, it agitates and permeates the

FIGURE 17.2.4 A Double 30 lb (13.6 kg) Stored-Pressure Dry Chemical System with Pneumatic Release for Automatic Actuation. Each cylinder contains 30 lb (13.6 kg) of dry chemical pressurized to 350 psi (2413 kPa) with nitrogen.

powder, making it fluidlike. The dry chemical outlet is provided with a rupture disc or valve to permit buildup of proper operating pressure in the tank before the dry chemical can start to flow. The expellant gas assembly consists of a pressure storage vessel together with necessary valves, pressure regulators, and piping to deliver the expellant gas to the dry chemical storage tank at the correct pressure and rate of flow (see Figure 17.2.1). The expellant gas is usually dry nitrogen; however, dry air or other gases may be used. The volume and storage pressure of the expellant are dictated by the gas used and the requirements of the system. Containers in which dry chemical and the expellant gas are stored together are equipped with a moisture-sealed fill opening, a valve with integral discharge outlet and expellant gas charging inlet, and a pressure gauge.

It is desirable to locate the chemical expellant gas assemblies as near as practicable to the hazard to be protected. An area in which temperatures stay between –40 and +120°F (–40 and +49°C) is desirable to maintain the quality of the dry chemical.

System Actuation

Actuation of fixed systems is initiated by automatic mechanisms that incorporate sensing devices located in the hazard area and automatic, mechanical, or electrical releases that initiate the flow of the chemical, actuate alarms, and shut down process equipment. In systems with separate chemical and expellant gas containers, the flow of chemical is started by releasing the expellant gas, which pressurizes the chemical chamber to the point where the rupture disc in the container outlet operates. The chemical is then carried by the expellant gas through the distribution system to the hazard. In stored-pressure systems, however, the flow of chemical is started by merely opening the valve on the chemical chamber. If the expellant gas is used to pneumatically operate these devices, the gas shall be taken prior to its entry into the wet chemical tank.

Dry chemical systems have both automatic and manual methods of actuation. At least one manual actuator shall be provided for each system. It is important that the operating devices be designed, located, installed, or protected so that they are not subject to mechanical, environmental, or other conditions that could render them inoperative or cause inadvertent operation of the system. The automatic and manual means of system actuation must be separate and independent of each other so that a failure of one will not impair the operation of the other. Operation of any manual actuator is all that is required to operate the system. An easily accessible device for manual operation is required for all automatically operated systems.

A local signal is provided to indicate that the system has operated and is in need of recharging. The extinguishing system is also connected to the building fire alarm system, if one is provided, so that the actuation of the extinguishing system will sound the fire alarm throughout the building as well as provide the function of the extinguishing system.

System actuators are commonly mechanical and do not rely on electrical power for operation. However, it is permitted to have electrical actuators if there is a reserve power supply or the normal power supply is supervised. The means for mechanical actuator(s) shall be mechanical and shall not rely on electrical power for actuation.

When automatically actuated systems are used, consideration should be given to the reduced visibility and temporary breathing difficulty sometimes caused by quick discharge of large amounts of dry chemical in a restricted space. In all cases where there is a possibility that personnel may be stationed in such locations, suitable alarms and safeguards should be incorporated in the system to ensure adequate warning and prompt evacuation.

Operation of a hand hose line system requires two or, at the most, three steps. *Step one:* pressurizing the dry chemical chamber by opening the expellant gas valve (if the dry chemical and expellant gas containers are separate), or opening the main discharge valve if dry chemical is under stored pressure. *Step two:* operating the nozzle at the end of the hose line. *Step three:* if multiple hose stations are supplied by the same dry chemical supply, a distribution valve must be opened to direct the flow to the particular hose station to be used. It is extremely important to play out the hose fully (without kinks) to ensure the proper chemical discharge rate.

Fixed piping systems normally blow themselves clear. However, in hand hose line systems where the operator exercises control over the amount of dry chemical discharged, it is vital that all pipes and hose be independently blown clear before recharging to prevent blockage.

Distribution System

For fixed systems, the provisions for conveying the chemical to the hazard area and discharging it properly consist of piping or, for hand hose line systems, piping and hose lines or hose lines alone. Nozzles designed to emit wide, flat, or round streams in desired patterns are available to meet specific hazard requirements. Adjustable nozzles permitting an operator to vary the range and shape of the discharge are also available for use with hand hose line systems.

The piping and valving for dry chemical systems are of special design because dry chemical, while tending to behave as a fluid, has distinct flow characteristics.

Control of chemical flow starts at the chemical storage tank. In systems of separate dry chemical and expellant gas containers, expellant gas must be admitted to the tank in such a way as to properly fluidize the dry chemical while the pressure builds up equally throughout the entire volume of the tank before the dry chemical is released from the tank. Should the pressure increase too rapidly above the dry chemical, the powder will not be properly fluidized and, on release, the pressure drop in the piping or hose line will be excessive and result in a rate of dry chemical flow too low for proper extinguishing effectiveness.

If the expellant gas is permitted to channel to the outlet before the top of the dry chemical storage tank is properly pressurized, insufficient dry chemical will be carried by the flowing stream of gas, and the fire extinguishing effectiveness of the system again will be greatly reduced.

Pipe, Hose, and Fittings. After release from the storage tank, dry chemical is carried through the piping at high velocities by the expellant gas and is thrown to the wall of the piping by centrifugal force whenever the direction of flow is sharply altered, as by an elbow. Should an elbow be directly connected to a tee and lie in the same plane as the tee, it is obvious that the two branches of the tee will carry appreciably different proportions of gas and dry chemical. This condition is overcome by installing all tees in planes perpendicular to the planes of adjacent elbows, by allowing sufficient length of straight pipe between tees and elbows, or by inserting special venturi devices between tees and elbows to ensure proper redistribution of dry chemical in the stream of gas before the mixture enters the tee.

Another critical factor in dry chemical distribution system design is the pressure drop through various lengths of pipe, hose, or fittings. Consequently, the length and size of piping and hose, and the number and size of fittings, must be selected to provide the required rate of discharge and nozzle distribution. In pre-engineered systems, this is already ensured by virtue of the limitations established for piping and fittings. In engineered systems, this selection must be made on the basis of actual calculation of pressure drop and subsequent flow rate.

For engineered systems, pressure drop data have been obtained at various rates of flow for various sizes of pipe and fittings. In one manufacturer's system, the pressure drop through a standard elbow is equivalent to the pressure drop through 20 ft (6 m) of straight pipe of the same size.[10] Pressure drop through a tee is equivalent to that of 45 ft (14 m) of straight pipe of the same size.

Consideration must be given to the overall volume of the distribution piping. Excessive volume could result in agent remaining in the pipe due to insufficient pressure to move it through the system. Because these chemicals behave similarly to water in pipe, there is also a concern regarding hydraulic friction loss. Long runs and excessive numbers of elbow serve to reduce the velocity of the fluid as it travels through the pipe. Again, excessive pressure loss could result in agent being left in the piping and possibly resulting in an insufficient amount of agent being delivered to the fire.

Nozzles. Dry chemical agent is distributed through nozzles at predetermined flow rates and patterns depending on the hazard. Discharge nozzles are made of corrosion-resistant materials such as brass or stainless steel.

The selection of the proper types and sizes of nozzles for fixed systems is crucial to obtaining the proper coverage of the hazard. For example, total-flooding dry chemical agent nozzles are designed for a broadcast of turbulent agent flow. This is to achieve the fire-extinguishment mechanisms of smothering and shielding.[8] On the other hand, nozzles for local application, such as over deep fat fryers, are designed to get the liquid surface covered with agent while limiting the splashing effects, which could result in fire spread beyond the protected area. Consult the individual listing of the discharge nozzles to determine their intended use.

Due to the nature of the hazards protected and the extinguishing chemicals, it is necessary to protect the openings of discharge nozzles. Protection is provided against internal clogging by installing strainers in the distribution piping prior to the nozzles. Grease vapors, moisture, and other particles in the effluent from the processes may cause clogging at the nozzle or in the piping. For this reason, nozzles must have protective caps. These caps provide this protection and blow off or open when the system is discharged.

Nozzles for hand hose line systems may be of either a one- or two-position type. One-position nozzles provide a modified straight stream, whereas two-position nozzles provide a straight stream or a fan. Because the straight stream has a longer reach than the fan discharge, it is considered better for initial attack. The shorter, wider fan-shaped stream is usually preferred for a close-range attack to complete the extinguishment. However, the present state of the art seems to prefer the use of the modified straight stream only. It is more effective and less confusing in the hands of an experienced operator.

Quantity and Rate of Application of Dry Chemical

The quantity of chemical and rate of flow must be sufficient to create a fire-extinguishing concentration throughout all parts of the enclosure protected in a total flooding system, or over the specific fire area protected by a local application system. It must be realized that the fire-extinguishing concentration accomplished throughout an enclosure (total flooding) can occur only during discharge. Following discharge, dry chemical rapidly settles out and diminishes. This is in contrast to gaseous diffusion, where concentrations persist following discharge, such as in carbon dioxide and halon systems. Minimum rate of flow is critical because dry chemical will not extinguish a fire if applied too slowly. In local application systems, application at too high a rate may result in uneven discharge or complete discharge of chemical before extinguishment is accomplished.

Optimum quantities of chemical and application rates have been determined by experiment for engineered total flooding and local application systems. For pre-engineered systems, the maximum sizes of hazards that can be protected by the various sizes of systems within specific piping limitations have been determined.

The minimum flow rate in lb per second (kg/sec) is determined by multiplying the net volume in ft^3 (m^3) by 0.00125 (in SI units 0.020). These volume factors apply only to this manufacturer's equipment and are cited merely to illustrate a procedure used.[10] Quantities and flow rates determined in this manner are contingent on a nozzle arrangement that provides even distribution throughout the volume. The rates also assume that devices will be installed to close automatically all doors, windows, ventilators, or other openings through which dry chemical could escape from the enclosure.

In one manufacturer's pre-engineered total flooding system, a 1000 ft^3 (28 m^3) space not longer than 20 ft (6 m) can be protected by a 30 lb (14 kg) system with four nozzles and no more than 90 ft of ¾ in. pipe (27 m of 19 mm pipe), 13 elbows, three tees, and three venturi devices.[10] As with engineered systems, successful extinguishment is contingent on proper nozzle

location, shutdown of ventilation, and the closing of all openings, such as doors and windows, in addition to closure of fuel valves.

Although simultaneous shutdown of ventilation with the actuation of a total flooding system is the normal procedure, one exception exists. This exception is the special case of kitchen range hood and duct protection wherein pre-engineered systems are specifically designed to provide extinguishment, regardless of whether the ventilation is operating. Actually, this latter type of system is a combination of both total flooding and local application.

Quantities of dry chemical and flow rates for engineered local application systems are obtained from graphs plotted from tests using different flammable liquid surface areas, weights of dry chemical, and rates of application. These graphs are available from the manufacturer. For pre-engineered local application systems, the limitations of hazard size, system size, and piping arrangement are established by test and used in the same manner as for total flooding systems. The minimum recommended quantity of dry chemical for hand hose line systems is sufficient to permit use of the system for 30 seconds. Capacities of hand hose line systems range from 125 to 2000 lb (57 to 907 kg), and as many as four hose lines can be operated from a single system. As with fixed systems, a minimum flow rate must be maintained to prevent surging or interruption of flow. Minimum rates are determined by the equipment manufacturer and depend on the equipment used.

WET CHEMICAL EXTINGUISHING AGENTS

Wet chemical fire extinguishing agents consist of organic or inorganic salts mixed with water to form an alkaline solution that is capable of being discharged through piping or tubing when under expellant gas pressure. They are extremely effective and are currently the only agents listed for suppression of fires in commercial cooking equipment (Figure 17.2.5), such as deep-fat fryers, griddles, range tops, and broilers, because of their ability to retain the separation of the oil from air for a sufficient time to allow complete cooling.

Physical Properties

Wet chemical extinguishing agents are typically a proprietary mixture consisting of potassium carbonate, potassium acetate, potassium citrate, or a combination, mixed in water and other additives such as phenolphthalein, phosphoric acid, and/or dyes. As they are already liquid in character, wet chemical agents do not require additives to enhance flow. Wet chemicals range in other physical properties depending on the mixture used. Table 17.2.1 shows the ranges of values in the common properties associated with wet chemicals.

Compatibility. Wet chemicals are incompatible with any reactive metals, electrically energized equipment, lime dust (CaO), chlorine trifluoride (ClF_3), and any other material that is reactive with water. When in storage, it is also important that the containers be kept tightly closed and separated from acids.

Toxicity. Wet chemical extinguishing agents are stable at both low and normal temperatures and are considered to be nontoxic and noncarcinogenic. However, other physiological conditions such as minor skin and respiratory irritations may occur on exposure to the agents. No chronic medical conditions have been reported from long-term exposure. The acute effects of exposure are irritation to mucous membranes, with the possibility of chemical burns of the skin, eyes, and mucous membranes lining the respiratory system. Moist skin may enhance this effect. In all cases, self-contained breathing apparatus (SCBA) should be worn to protect against smoke, fumes created by fixed system discharge. Consult the appropriate material safety data sheets (MSDSs) for detailed information, instructions, and special precautions.[1]

Extinguishing Properties

When wet chemical extinguishing agents are sprayed on a grease fire, they interact immediately with the grease and saponify, forming a blanket of foam over the surface on which they are sprayed. This blanket extinguishes the fire by a combination of two primary methods: smothering and cooling.

(a)

(b)

FIGURE 17.2.5 Examples of Commercial Kitchen Cooking Equipment Protected by a Nozzle

TABLE 17.2.1 Characteristics of Wet Chemical Extinguishing Agents

Agent Property	*Value Range*
Storage life	12 years
Freeze point	10°F to –40°F –12°C to –40°C
Boiling point	215°F–230°F 102°C–110°C
Specific gravity	1.19–1.445
pH	7.8–13

Smothering Action. When wet chemical agent is applied to flammable liquid surfaces, the result is a rapid knockdown of flame and a spreading of foam on the fuel surface. This vapor-suppressing foam barrier extinguishes the flame by separating the liquid fuel and oxygen. The result is the inability of the flammable vapors from the fuel source to escape the surface and ignite. Because the primary use of wet chemical systems is for protection of commercial cooking equipment and this is a very localized protection area, it is critical that the fire be contained within the equipment involved. To achieve this end, wet chemical systems are specifically tested to determine that during the discharge process they do not splash burning grease.

Cooling Action. The effect of water vaporization by wet agents provides a cooling effect on the fuel. Furthermore, the application of the wet chemical solution and the resulting formation of foam on the surface of the fuel also provides a cooling effect, lowering the temperature of the flammable fuel, further decreasing flammable vapor release. Some wet chemical systems are designed to continue with an application of water through the nozzles after the wet chemical has been completely discharged. This serves to further cool the surrounding surfaces, thereby preventing reflash.

USES AND LIMITATIONS OF WET CHEMICAL EXTINGUISHING SYSTEMS

Commercial cooking operations have undergone major changes in recent years in two areas that have produced an increased challenge to chemical fire extinguishing systems.

First, there has been a change in the cooking medium from animal fats to vegetable oils. These newer cooking oils change their makeup after ignition. This change results in an ignition temperature that is considerably lower (50°F, or 28°C) than that of the original oil. Therefore, to prevent reflash of the oil, the entire volume of the oil must be cooled below the autoignition temperature. Vegetable oils also have less fatty acids than do animal fats. It is the fatty acids that interact with the alkaline solution of the chemical agent that produces the saponification that eventually smothers the fire. Because of the amount of fatty acids in animal fats, dry chemical agents were capable of producing a sufficient foam blanket to smother the fire. Vegetable oils, with their lower fatty acid content, do not provide as much of this catalyst and, therefore, the foam blanket is not as well developed. This results in the compromise of the smothering foam blanket and the potential for reflash of the fuel involved.

Second, new, energy-efficient cooking equipment allows the oils to retain their heat for greater lengths of time. The autoignition temperature of the majority of vegetable oils is 685°F (363°C), which is as much as 135°F (57°C) higher than that of animal fats. This temperature, combined with the ability of new cooking equipment to retain the heat, produces a fire that dry chemical agents cannot effectively suppress. Because heat breaks down the foam that is produced through saponification, it is also necessary to provide a sufficient cooling effect on the fuel. Dry chemical has limited saponification and cooling capabilities, and, as a result, is ineffective on present-day commercial cooking equipment fires. Wet chemical, because of the added cooling effect of its water base, is far more effective on these types of fire. As a result, only wet chemicals can be used to protect new commercial cooking systems in order to sufficiently saponify fats and oils. It is still possible for dry chemical systems to protect kitchen equipment that has not been changed since the original installation of the system.

Commercial cooking equipment is typically stainless steel, aluminum, or galvanized metal. As such, it is resistive to the corrosive effect of wet chemical agents. Caution must be exercised in the installation of other equipment near the cooking equipment as wet chemical extinguishing agents are not acceptable for use in areas where fires involve energized electrical equipment. However, wet chemical extinguishing agents may be used to protect other equipment within the commercial cooking exhaust system. The manufacturer's listed installation and maintenance manual should be consulted for the appropriate applications and limitations for which the specific wet chemical extinguishing system is considered satisfactory protection.

Methods of Application

Wet chemical is applied through fixed systems, but also may be applied in portable fire extinguishers that are used to provide additional support to the extinguishing system. The hardware components are similar to dry chemical systems insofar as there is an agent supply and expellant gas and an actuating method. The agent is delivered through piping to specially designed nozzles that atomize the solution and distribute the agent over the hazard area.

Wet chemical systems are local application systems. Local application systems are practical in those situations where the hazard can be isolated from other hazards so that fire will not spread beyond the area protected, and where the entire hazard can be protected. In this type of system, the nozzles are arranged to discharge directly onto the fire or burning surface such as

deep-fat fryers, griddles, and stoves. It is especially critical in commercial cooking operations that the cooking equipment not be rearranged after the installation of the extinguishing system. Most wet chemical systems apply the agent through nozzles that are specifically designed to protect the equipment under them. It is therefore critical to note that any rearrangement of the cooking equipment after installation of the extinguishing system could result in unprotected surfaces. That being said, there are wet chemical systems available that are designed with overlapping spray patterns. The overlapping spray allows coverage of the entire space below exhaust hood, permitting greater flexibility in the location and relocation of equipment, provided it is always located under the hood.

System Design

Wet chemical systems are proprietary, pre-engineered systems. Pre-engineered systems are defined by predetermined flow rates, nozzle pressures, and quantities of agent required. They have specific pipe sizes and maximum and minimum pipe lengths. Further specifications are provided in the manufacturer's installation manual for flexible hose, the number of fittings, and the number and types of nozzles to be used. An important point is that pre-engineered systems are limited to the protection of hazards for which they have been specifically listed.

Part of the listing process requires the system to perform satisfactorily any one or number of types of commercial cooking equipment. UL 300 contains testing protocols deep-fat fryers, griddles, range tops, charbroilers, including gas radiant, electric charbroilers, lava, pumice or synthetic rock, natural charcoal, mesquite wood, upright and chain broilers and woks. The standard tests also include splash tests specifically for deep-fat fryers, range tops, and woks.

The objectives of these tests are to prove that the agent is effective in complete extinguishment. For deep-fat fryers, woks, and ranges, there is an additional objective that the agent prevents reignition for 20 minutes or until the temperature of the grease decreases at least 60°F (33°C) below its autoignition temperature, whichever takes longer. For other types of equipment, the agent must prevent reignition for 5 minutes.

Storage of Chemical and Expellant

Wet chemical extinguishing agents are typically stored in plastic containers up to 5 gal (19 L) in capacity. Attention should be given to the freeze point of the particular agent. The agent storage life is approximately 12 years. System tanks containing wet chemical range in size between 1.5 and 3 gal (5.7 and 11.4 L), depending on the manufacturer's design. To expel that agent, most systems use pressurized cartridges of nitrogen or carbon dioxide. To ensure proper operation, the temperature ranges for wet chemical systems are between 32 and 130°F (0 and 54°C). This range is not normally a problem as wet chemical systems are primarily used in indoors.

System Actuation

Wet chemical systems are actuated by either automatic or manual means. Automatic actuation is provided by fusible link or heat detector operation (Figure 17.2.6). It is critical that the detector devices be placed in the proper locations. To ensure this, NFPA 17A requires detectors above each appliance or group of appliances protected by a single nozzle. Detectors must also be installed in the duct entrance and another above the electrostatic precipitator if one is installed near the base of the duct.

Manual actuation occurs by the use of a listed manual pull station located adjacent to the means of egress from the room. Manual pull stations provide a backup source of system operation and must be clearly identified (Figure 17.2.7).

Part of the listing for these manual actuators states that they not require a force of more than 40 lb (178 N) or a movement of more than 14 in. (35.6 cm) to secure operation. All remote manual operating devices must be identified as to the hazard they protect.

Actuation of the system punctures the seal on the expellant gas cartridge, and the gas flows to the agent cylinder and expels the liquid through the discharge piping and nozzles. Wet chemical systems that use a secondary water application also have a pneumatically controlled waterflow valve that allows water to flow into the system after the wet chemical is totally expelled. This assists in the overall cooling effect of the wet chemical agent.

NFPA 17A requires that all sources of fuel and power to equipment that produces heat be shut down on activation of the system. Other sources of electrical power that may be exposed to the spray pattern of the system must also be shut down so as not to react with the wet chemical agent. To achieve this, actuation of the system also trips gas valves and electrical switches that interrupt fuel and power to any heat-producing appliances under the hood (Figure 17.2.8).

Distribution

Piping and fittings must be of noncombustible materials and compatible with the characteristics of wet chemical. Distribu-

FIGURE 17.2.6 Typical Heat Detector Located in Exhaust Hood

FIGURE 17.2.7 Clearly Identified Manual Pull Station

FIGURE 17.2.8 Typical Gas Shut-Off Valve That Closes on Actuation of the Extinguishing System

tion piping should be either Schedule 40 black iron, chrome plated, or stainless steel. Galvanized piping is not used for the distribution piping. It is not necessary to calculate the flow rate, pressure drop, or nozzle pressure as the system has been pre-engineered for the specific protection and confirmed by testing by a listing laboratory. The manufacturer provides the necessary information on minimum and maximum piping limitations in the listing information and installation manual.

Nozzles

Discharge nozzles must be specifically listed for their intended use, and there may be many different nozzles manufactured for a given system (Figure 17.2.9). Each nozzle is designed to distribute the extinguishing agent in a specific pattern. It may not be possible to determine the type of nozzle from a cursory glance. Many of the nozzles appear to be identical; the differences are primarily in the tips of the nozzles that create the unique coverage characteristic. Nozzles carry permanent stampings that can be used to identify the type and spray pattern. This is very important when determining whether the system provides complete coverage. It is also critical that the nozzle be aimed in the

FIGURE 17.2.9 Wet Chemical Nozzles with Required Caps Protecting Against Clogging from Grease-Laden Vapors

proper direction. A specialized nozzle-aiming device is used for this purpose. This device clamps on the nozzle and uses a laser light that indicates the spray direction of the nozzles on the surface below. The nozzle can then be adjusted and tightened to hold the appropriate location.

Nozzles are typically chrome plated; however, they may constructed of any corrosion-resistant material such as brass or stainless steel. To prevent clogging, internal strainers or separate listed strainers are required to be located immediately upstream of the nozzle. Blow-off caps (either metal or rubber) are provided to protect the interior of the nozzle from clogging due to grease vapors, moisture, or other foreign materials.

Quantity and Rate of Application

The quantity and rate of application has been determined in the pre-engineering design process. Manufacturer's guidelines provide specific and detailed diagrams indicating the proper protection and coverage necessary for any component of the cooking operations, from the individual stove, wok, or broiler, to the hood and plenum areas, to the duct work. The quantity of extinguishing agent required is based on the number of flow outlets in the system. The number of nozzles in the system is then matched to the tank and cartridge requirements provided in the manufacturer's installation manual.

INSPECTION, TESTING, AND MAINTENANCE PROCEDURES FOR CHEMICAL SYSTEMS

Owners of chemical extinguishing systems should conduct monthly inspections to determine whether the system is in proper operating condition. This inspection is not intended to be detailed, but is rather a visual check of the system and should include determination of the following items:

- The extinguishing system is in its proper location.
- The manual actuators are unobstructed.
- The tamper indicators and seals are intact.
- The maintenance tag or certificate is in place.

- There is no obvious physical damage or condition that might prevent operation.
- There is no damage to, or obstruction of, fusible links or actuating devices.
- The pressure gauge(s), if provided, are in operable range.
- The nozzle blow-off caps are intact and undamaged.
- The hood, duct, and protected cooking appliances have not been replaced, modified, or relocated.

Systems subjected to process deposits (such as paint, dust, and grease) and corrosive conditions may require more frequent inspection of components. This inspection should be recorded in a report form and made available for review by the local authority having jurisdiction. Any deficiencies should be corrected immediately. For example, grease buildup on a link can severely delay the actuation of the system (Figure 17.2.10). Obstructed pull stations must be cleared to allow manual operation (Figure 17.2.11).

On a semiannual basis, routine maintenance, in addition to a more detailed inspection, should be performed. During this inspection, the hazard should be reviewed to determine whether it has been expanded or otherwise modified to extend beyond the capabilities of the system. A thorough examination of all system components is necessary. Each component should be inspected for wear, contaminant loading, corrosion, or any other condition that may render the component or system inoperable. The dry chemical agent is normally inspected at this time for evidence of caking. If caking is present, the dry chemical must be discarded and the system recharged in accordance with the manufacturer's instructions. In stored-pressure systems, the dry chemical must be checked every 6 years.

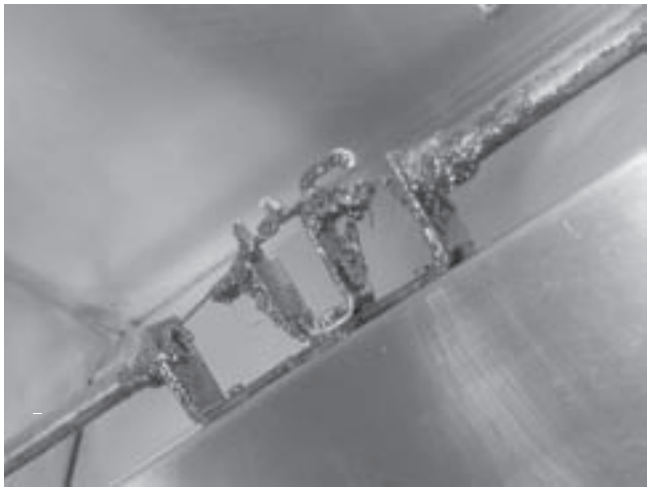

FIGURE 17.2.10 Grease Buildup on Link

FIGURE 17.2.11 Obstructed Pull Station

The distribution piping should be checked for obstructions during this procedure. This inspection can be accomplished by several means. If the system is small and accessible, the piping can be dismantled and inspected visually. If this is not practical, then purging with nitrogen or compressed air may be done. A full or partial discharge test may also be performed to verify the condition of the piping; however, all of the agent must be removed from the piping following the test to prevent caking and subsequent blockage of the pipe.

Periodically, a discharge test may be required during the performance of routine maintenance procedures. In this case, a "bag" test may be performed. During a bag test, the discharge nozzles are covered with a collection bag (a burlap bag or pillowcase) to retain discharged dry chemical. Following discharge of the system, the chemical should be weighed to determine the quantity of chemical contained. This can be compared to the amount required by the manufacturer's listed maintenance manual. Insufficient amounts may indicate possible piping obstructions.

Testing of wet chemical systems includes the operation of the detection system signals and releasing devices, including manual stations and other associated equipment. However, a discharge of the wet chemical normally is not part of this test.

The amount of expellant gas should be checked semiannually to ensure that there is sufficient gas to provide an effective discharge, and to automatically clean out the piping after the dry chemical has dissipated. In systems with separate expellant gas containers, this testing is accomplished by checking the pressure (if nitrogen) or weight (if carbon dioxide) against the manufacturer's recommended minimums. In stored-pressure systems, the pressure gauge is checked to see that it is in the operable range.

The inspection and maintenance of hand hose line systems will vary with the location and climate conditions. Equipment located in extremely hot or humid areas will require more frequent checking because the heat can cause cylinder pressure to increase and possibly cause leakage. Inspection of hand hose line systems consists primarily of checking the pressure of the expelling gas container, or the pressure of the unit itself (if it is of the pressurized type). It is also advisable to inspect all hose lines and nozzles to be sure that they are unobstructed and in good operating condition.

At least semiannually, maintenance should be conducted in accordance with the manufacturer's listed installation and maintenance manual. A trained person who has undergone the instructions necessary to perform the maintenance and

recharge service should conduct maintenance of the system. This can be determined by requiring proof of training by the manufacturer.

As a minimum, maintenance should include a check to see that the hazard has not changed, and an examination of all detectors, the expellant gas containers, the agent containers, releasing devices, piping, hose assemblies, nozzles, signals, all auxiliary equipment, and the liquid level of all nonpressurized wet chemical containers.

It is also important to verify that the agent distribution piping is not obstructed. This verification will require the disassembly of all piping and conducting at least a partial discharge test in accordance with the instructions from the manufacturer. Other obstructions may occur in the conduit carrying the cable that activates the system. Grease can cause plugging and moisture can cause corrosion that will inhibit proper operation.

Special attention is given to the fixed temperature-sensing elements. NFPA 17 and NFPA 17A both require these components to be replaced at least annually from the date of installation.

After maintenance and testing occurs, the system should tagged or labeled, indicating the month and year the maintenance and testing has been performed and identifying the person performing the service.

Chemical containers, auxiliary pressure containers, valve assemblies, hoses, fittings (not including field piping), check valves, directional valves, manifolds, and hose nozzles, in addition to the dry chemical chambers and hose assemblies of both dry and wet chemical systems, must be hydrostatically tested every 12 years. The dry or wet chemical removed from the chambers should be discarded. Care must be exercised to ensure that all equipment tested is thoroughly dried prior to recharging. If there is no automatic, connected reserve supply, alternative fire protection should be provided.

SUMMARY

Both dry and wet chemicals are used to extinguish fires. Multipurpose dry chemical is used on fires in flammable liquids, fires involving energized electrical equipment, and fires in ordinary combustible materials. Dry chemical causes extinguishment primarily through the chain-breaking reaction and also through smothering, cooling, and radiation shielding. Wet chemical extinguishing agents are used for suppression of fires in commercial cooking equipment, such as deep-fat fryers, griddles, range tops, and broilers. Wet chemical causes extinguishment because of its ability to retain the separation of the oil from the air for a sufficient time to allow complete cooling.

The installation of a complete chemical extinguishing system requires that various factors be determined, including the method of application, storage of chemicals, system actuation, distribution system, and quantity and rate of application. The system must undergo a regimen of periodic inspection, testing, and maintenance to ensure proper operating condition.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on chemical extinguishing agents and application systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
NFPA 17A, *Standard for Wet Chemical Extinguishing Systems*

Reference

UL 300, *Standard for Fire Testing of Extinguishing Systems for Protection of Restaurant Cooking Areas*

Chapter 3

Characteristics and Hazards of Water and Water Additives for Fire Suppression

John A. Frank

Chapter Contents

Introduction to Water
Properties of Water
Extinguishing Properties
Manual Application Rates
Opacity and Reflectivity
Water as an Extinguishing Agent
Water and Flammable and Combustible Liquids—Class B Fires
Water and Live Electrical Equipment—Class C Fires
Water and Combustible Metals—Class D Fires
Use of Water on Special Hazards
Water Additives for Specialized Uses
Care in Use of Water as an Extinguishing Agent

Key Terms

actual delivered density (ADD), Class A fire, Class A foam, Class B fire, Class C fire, Class D fire, extinguishing agent, fixed water spray system, fog stream, Iowa Flow Formula, ISO Flow Formula, NFA Flow Formula, ordinary combustible, required delivered density (RDD), water additive, water mist system, wetting agents

Water is the most widely used and most readily available extinguishing agent. Water is readily available and inexpensive. Water also possesses many advantages over other liquids in fire-fighting characteristics. However, it is not the proper extinguishing agent for all types of fires. It has some disadvantages; for example, it freezes at 32°F (0°C). This chapter discusses the properties of water as an extinguishing agent, including its advantages and limitations.

The principles of fire extinguishment are discussed in Section 2, Chapter 1, "Physics and Chemistry of Fire"; Section 2, Chapter 7, "Theory of Fire Extinguishment"; and in Section 17, Chapter 8, "Explosion Prevention and Protection." The systems and devices used for the transportation and application of water as a fire-extinguishing agent are addressed in other chapters in this section of the handbook. For the use of water as a suitable extinguishing agent on specific materials, such as chemicals, flammable liquids, gases, and metals, see Section 6, Chapter 9, "Metals"; and Section 6, Chapter 12, "Flammable and Combustible Liquids." For related topics, see Section 9, Chapter 16, "Mining and Mineral Processing"; Section 15, Chapter 2, "Water Supply Requirements for Public Supply Systems"; Section 16, Chapter 8, "Water Mist Fire Suppression Systems"; Section 16, Chapter 9, "Water Spray Protection"; and Section 17, Chapter 4, "Foam Extinguishing Agents and Systems."

INTRODUCTION TO WATER

Water is the most widely used and most readily available fire-extinguishing agent. Water is inexpensive, abundant, and effective in fire suppression. Water is transportable and can be pumped from a source to the fire. Water is available from domestic water distribution systems (fire hydrants), streams and rivers, wells, ponds, lakes, swimming pools, and in some cases is taken from the ocean.

Water is a very effective agent for controlling and extinguishing combustion. Water is the most abundant and available substance on the earth's surface and exists in three states: (1) liquid (water), (2) vapor (steam), and (3) solid (ice).

Life safety considerations must be weighed when choosing an effective fire-extinguishing agent. Water as an agent is safe, nontoxic, relatively noncorrosive, and stable. Water (H_2O) remains stable when applied to a fire and does not, except in very special circumstances, break down into its basic elements of hydrogen (H) and oxygen (O), both of which would encourage fire growth. Water can be applied as an extinguishing agent with building occupants in compartments, unlike some

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gaseous extinguishing agents, which could cause asphyxiation or adverse side effects.

PROPERTIES OF WATER

The physical properties that allow water to be an effective extinguishing agent are as follows:

1. At ordinary temperatures, water exists as a stable liquid. Water's viscosity in the temperature range of 34 to 210°F (1 to 99°C) remains consistent, which allows it to be transported and pumped.
2. Water has a high density, which allows it to be discharged from and projected from nozzles. Water's surface tension allows it to exist from small droplets to a solid stream.
3. The latent heat of fusion is the amount of energy required to change the state of water from solid (ice) at 32°F (0°C) to a liquid. Water absorbs 143.4 Btu per lb (333.2 kJ/kg) in this process.
4. The specific heat of water is 1.0 Btu per lb(°F) (4.186 kJ/kg(°C)). For example, raising the temperature of 1 lb (0.45 kg) of water 180°F (100°C) from 32°F (0°C) to 212°F (100°C) requires 180 Btu. Raising 1 kg of water from 0°C to 100°C requires 418.6 kJ.
5. Water is effective as a cooling agent because of its high latent heat of evaporation (changing water from a liquid to vapor), which is 970.3 Btu per lb (2260 kJ/kg) as described in Section 2, Chapter 1, "Physics and Chemistry of Fire." Some authors are giving "credit" to additional heat absorption from the steam as it is heated beyond the boiling point of water when water is applied in small droplets. The specific heat of steam is 2.01 kJ/kg(°C).[1]
6. Water expands in its conversion from a liquid state to a vapor state to 1600 to 1700 times the liquid volume. One gallon (3.8 L) of liquid (which occupies 0.1337 ft^2 [0.004 m^3]) produces over 223 ft^3 (6.3 m^3) of steam. Therefore, it follows that 1 gal (3.8 L) of water at room temperature applied to a fire and converted to steam (complete conversion) will absorb heat both in rising to the temperature at which it becomes a vapor and in the phase change from liquid to vapor. (For SI units: °F = °C × ⅘ + 32; 1 Btu = 1.055 kJ; 1 lb = 0.45 kg; 1 gal = 3.785 L; 1 ft^3 = 0.0283 m^3.)

   Heat required to raise temperature of water to boiling:

   - 212°F – 68°F (room temperature) = 144°F
   - 144Δ°F × 1 Btu/lb × 8.33 lb (weight of 1 gal) = 1200 Btu

   Heat required to change water from a liquid to a vapor:

   - 970.3 Btu/lb × 8.33 lb (weight of 1 gal) = 8083 Btu
   - Total heat absorbed is 1200 + 8083 = 9283 Btu/gal of water

Using SI units in the preceding example, the total heat absorbed by 1 kg of water raised from 20°C (room temperature) to its boiling point is 2594.9 kJ/kg of water. A figure of 2600 kJ/liter is commonly used.

Therefore, a fire department hose stream discharging at 100 gpm will absorb 928,300 Btu per minute in a complete conversion. The same fire department hose stream will create 22,300 ft^3 per minute of steam in a complete conversion. In SI units (using 2600 kJ/liter), this same hose stream (discharging 378.5 L/min) will absorb 984,100 kJ/min or 16,402 kJ/sec or 16.4 MW. Likewise, 631 cubic meters of steam will be created.

When reviewing the international literature recommended in this chapter, the reader is cautioned to carefully note the units being used. Minor differences may be noted due to unit conversions. Also note that the preceding example does not give credit to heat absorbed by the heating of steam above the boiling point of water. Some international authors are giving this credit in their suppression models if small water drops (e.g., smaller than 1 mm) are used. Some models also give credit to the observation that it is not necessary to absorb all of the heat released by diffusion flames. After these credits are applied, the models may then assign another factor that accounts for less than optimum performance, as discussed later in this chapter. As is the case with all models, it is essential that the user understand the model's inputs and outputs to make appropriate decisions.

EXTINGUISHING PROPERTIES

Water is a very effective extinguishing agent because of its ability to cool the fuel, remove or displace the oxygen supply, and separate/dilute the fuel source. See the discussion on the principles of fire in Section 2, Chapter 1, "Physics and Chemistry of Fire," and Section 2, Chapter 7, "Theory of Fire Extinguishment."

The dominant mechanism of extinguishment, or combination of mechanisms of extinguishment, depends on several interrelated factors, including the fuel's physical and chemical properties, the geometry of the compartment (if one exists), ventilation, ambient conditions, the form of the water applied (e.g., fog versus solid stream), and the application technique.

Knowledge of the influence of these factors and the interaction of the mechanisms of extinguishment vary widely with the extent of scientific research conducted on a given application method. Section 16, Chapter 8, "Water Mist Fire Suppression Systems," provides a good example of the extent of the body of knowledge that exists regarding the interactivity of these mechanisms for fixed water mist systems. For manually applied hose streams, see Grimwood et al.[2]

Extinguishing by Cooling

Water principally extinguishes solid fuel fires by cooling the fuel surface. In addition to the cooling of a solid fuel itself, water is effective as a cooling agent because of its high latent heat of evaporation (item 5 under properties). Water introduced to a fire promotes heat loss via the heat transfer from the fire to the water. When the heat loss exceeds the fire heat gain, the fuel surface will begin to cool until the flame can no longer exist at the surface. Water is an effective coolant for solid fuel surfaces.

Besides the direct cooling of a solid fuel, water can cool solid fuels indirectly by the reduction of the radiant heat flux from the flame, and from the hot upper gas layer (if present), to the fuel surface. This action reduces the rate of pyrolysis of the fuel, which reduces the heat release rate of the fire. This cooling results from the cooling effects of the water droplets and steam.

Conceptually, when the heat absorption rate of water approaches the total heat release rate of the fire, fire control begins. When the heat absorption rate of water exceeds the heat release rate of the fire, fire suppression and, ultimately, fire extinguishment are achieved. Other factors to consider in fire control and extinguishment include heat losses through openings and heat losses to walls, ceilings, and floors.

As discussed in Section 2, Chapter 7, "Theory of Fire Extinguishment," it is theoretically not necessary to absorb all of the heat being released, but only enough to effect the combustion reaction. Because of the difficulty of applying water in the manner described in Section 2, Chapter 7, the actual application needed for extinguishment may be 10 to 100 times the critical application rate. Mawhinney indicates that absorbing 30 to 60 percent of the heat released from a fire may be enough to extinguish the fire.[3] Some manual suppression models now account for this observation.

The amount of water required to extinguish a fire depends on the heat release rate [Btu/sec (kW)] of the fire. How quickly a fire is extinguished depends on how the water is applied, how much is applied, and in what form water is applied.

As shown in water mist applications, the smaller the droplet, the higher the rate at which water extracts heat from the fire and fire gases, resulting in using a lower volume of water. Grimwood[4] reports on the findings of Rasbash that a 2 mm droplet moving at 0.07 m/sec will extract heat at a rate of 167 kW/m^2 of droplet surface area. Decreasing the droplet size to 50 microns (0.05 mm) and increasing the velocity to 0.5 m/sec increased the heat transfer rate to 2500 kW/m^2 of droplet surface area. Calculations show that for many applications, the optimum diameter of a water droplet is in the range of 0.01 to 0.04 in. (0.3 to 1.0 mm), and that the best results are obtained when the droplets are fairly uniform in size. However, a water droplet approaching the fire can evaporate in the fire plume, thus only cooling the fire plume but not effectively cooling the fuel surface, which, as shown in Section 2, Chapter 7, "Theory of Fire Extinguishment," can be critical. The need for direct fuel surface cooling varies with the application. Actual delivered density (ADD) is the actual water application rate to a fire at the surface of the burning fuel. Research facilities at Underwriters Laboratories and FM Global are capable of measuring the ADD in warehouse applications. This figure is then compared to the required delivered density (RDD) for suppression. Fire suppression is achieved when the ADD > RDD.

The amount of water reaching a fire is affected by the fire's burning rate and associated upward plume velocity. The water droplets must overcome the effects of the upward momentum of the fire plume and air currents in order to reach the burning fuel and provide effective fuel cooling. For example, droplets, once produced at a sprinkler, are subject to high temperatures that evaporate the small droplets at the ceiling. If the small droplets survive the ceiling temperature, they may not have the mass or momentum to be able to penetrate the fire plume. Yao and Williams reported that 1 mm drops can penetrate a 20 ft/sec (6.1 m/sec) fire plume, 1.5 mm drops can penetrate a 30 ft/sec (9.1 m/sec) plume, and 2 mm drops can penetrate a 40 ft/sec (12.2 m/sec) plume, which occurs in high-challenge fires.[5] Drops smaller than 0.3 mm are found in some water mist applications. See Isman[6] for a complete discussion. For manual application from hose streams, see Clark[7,8] and Grimwood et al.[2]

As the preceding discussion indicates, the high heat absorption of a fine mist must be balanced against the need for water to reach the fuel surface to cool the fuel. The relative importance of these competing characteristics depends on several factors. These factors can be specifically accounted for in engineered systems. For example, engineered water mist systems emphasize general cooling whereas large drop sprinklers emphasize penetration of the fire plume to directly cool the pyrolyzing fuel.

For manual application from hose streams, the literature reports successful extinguishment from techniques that emphasize general cooling (as from a fog stream), from techniques that emphasize direct cooling of the fuel (as from a solid stream), and from various combinations of these techniques. As is the case with engineered systems, the high heat absorption characteristics of a fog stream must be balanced against the penetrating characteristics of a solid stream. Major texts discussing the advantages of solid stream applications are by Clark[7] and by Fornell.[9] A major text on fog streams entitled *The Safe and Effective Use of Fog Nozzles* was published in 2003.[10]

An application method known as fog attack or gas phase cooling has gained widespread acceptance in Europe and is gaining acceptance in Australia and the United States. A major text on this subject entitled *3D Fire Fighting, Training, Techniques, and Tactics* was published in 2005.[4] This text also gives a historical overview of all methods of manual application as well as where each is most effectively used. The limits of the fog attack technique are explained as well. See Grimwood[11,12] or http://www.firetactics.com.

Extinguishing by Smothering

When water is applied to a fire or a hot compartment surface, steam is formed. The dilution of the air (oxygen) supply around the fuel sources provides suppression by a smothering action. Suppression by this method is more effective if the steam and water droplets are confined around the fuel source. The steam and water droplets also continue to extinguish a fire by cooling as the water droplets continue to evaporate around the heated area of a fire.

Fires in ordinary combustibles are normally extinguished by the cooling effect of water—not by the smothering effect created by steam. Water mist systems, which may be used as an alternative to sprinkler systems or certain gaseous extinguishing systems, have been found to be effective in controlling *and* extinguishing fires by cooling and by smothering, as discussed in Section 16, Chapter 8, "Water Mist Fire Suppression Systems." The advantages and disadvantages of steam generation from manually applied water streams have been fiercely debated for many years.

Water may be used to smother a burning liquid when the liquid has a flashpoint above 100°F (37.8°C), a specific gravity greater than 1.0, and is not water soluble. To achieve this most effectively, a foam concentrate is added to the water to form a foam-water solution. The foam-water solution must then be applied gently to the surface of the flammable liquid. Water

mist systems have been used to extinguish fires in liquids with a flashpoint below 100°F (37.8°C). Heptane is a common test liquid. In cases where oxygen is produced while a burning material decomposes, smothering by any agent is not possible.

Systems based on the use of industrial process steam are sometimes used in industrial ovens. Design applications are discussed in NFPA 86, *Standard for Ovens and Furnaces*, and in insurance company guidelines.

Extinguishing by Emulsification

An emulsion is formed when immiscible liquids are agitated together and one of the liquids is dispersed throughout the others. Extinguishment by this process can be achieved by applying water to certain viscous flammable liquids, since the effect of cooling the surfaces of such liquids prevents the release of flammable vapors. With some viscous liquids (such as No. 6 fuel oil), the emulsification is a froth that retards the release of flammable vapors. Care must be used on liquids of appreciable depth, however, because frothing may spread the burning liquids over the sides of the container. A relatively strong, coarse water spray is normally used for emulsification. A solid stream of water should be avoided, as it will cause violent frothing. These techniques are rarely used. Additives that promote emulsification are discussed later in this chapter.

Extinguishing by Dilution

Fires in water-soluble, flammable materials may, in some instances, be controlled or extinguished by dilution. The percentage of dilution necessary varies greatly, as does the volume of water and the time necessary for extinguishment. For example, dilution can be used successfully in a fire involving an ethyl or methyl alcohol spill if it is possible to get an adequate mixture of water and alcohol and if the mixture can be contained while it is being diluted. Details for ethyl alcohol can be found in FM Global Data Sheet 7–74 *Distilleries*.

Dilution is not a common practice when tanks are involved. The danger of overflow because of the amount of water required and the danger of frothing should the mixture become heated to the boiling point of water seldom make this form of extinguishment practical.

MANUAL APPLICATION RATES

In the United States, three methods are widely used to determine the manual water application rate needed to extinguish a fire. These are the Iowa Flow Formula, the National Fire Academy (NFA) Formula, and the Insurance Services Office (ISO) method. A fourth method—the Illinois Institute of Technology method—is not as widely used. (See Section 15, Chapter 2, "Water Supply Requirements for Public Supply Systems," for detailed information on the Illinois Institute method.) Although useful for fire service preplanning and for municipal water supply planning, none are readily adapted for fire protection engineering applications and performance-based design. The Iowa Flow Formula and the ISO formula are more fully discussed in Section 15, Chapter 2, "Water Supply Requirements for Public Supply Systems." See Burns and Phelps[13] for further information on the NFA formula. Grimwood et al.[14] introduced a tactical flow rate based on extensive analysis of international research as well as extensive practical experience in London. A detailed comparison of the tactical flow rate to the Iowa and NFA methods is also provided.

The Iowa State Method has scientific research behind it that emphasizes both the cooling effect of water and the smothering effect of steam. Measurements focused on the reduction of ceiling and compartment temperature. Fire protection engineering calculations are driven by heat release rates or their constituent components of the mass loss rate of the fuel and the heat of combustion of the fuel. The effect of the rate of cooling and steam smothering on these engineering parameters was not measured, which limits the usefulness of the method. Further, the formula is meant to be applied to the largest open area in a structure, not to partially involved areas. The amount of water needed for adjacent areas and for exposures is not addressed. For additional information see Clark,[7,8] Fornell,[9] and Royer.[15] Wiesman and Iowa State University Bulletin No. 18 should be read in their entirety.

The NFA formula was developed from the experience of structural incident scene commanders. The formula can be applied to partially involved structures; however, there is no method for fire protection engineers to determine a footprint of a fire that can be substituted into the percent involvement portion of the formula.

The ISO formula is based primarily on how much water (in increments of 250 or 500 gpm [946.25 to 1892.5 L/min]) is needed to contain a fully involved structure (or a predefined portion of a multistory facility) and to prevent fire spread to adjacent structures. It is not suitable to determine the manual application rate needed to extinguish a growing fire within a structure. For further information see Hickey.[16]

It may seem desirable to use knowledge of the heat absorption rate of water and knowledge of the heat release rate of a fire to determine if the flow rate is adequate. This is being discussed more and more in the international literature. As previously discussed, a 100 gpm (378.5 L/min) stream will absorb 928,300 Btu per min (16.4 MW) in a complete conversion. The same 100 gpm (378.5 L/min) hose stream will create 22,300 ft^3/min (631 m^3/min) of steam in a complete conversion. The difficulty in applying this knowledge to fire protection engineering problems is based on the compound effect of the following unknowns:

- The amount of water that is converted to steam
- The amount of water that reaches the flame
- The amount of water that actually reaches the fuel surface
- The combined effect of steam's smothering and cooling
- The criticality of water reaching and cooling the fuel surface versus general area cooling for the given fire
- The amount of heat that must be removed to cause a collapse of the combustion reactions

Kimball observed that two to four times the flow rate suggested by the Iowa State study tends to be used.[17] Recently, factors have been introduced to account for the unknowns listed previously. When reviewing such factors, it is important not to mix the reduction factors with the theoretical heat absorption in

other models. This is because, as discussed earlier in this chapter, some heat absorption models give additional credits for heat absorption as the steam is heated beyond the boiling point of water and for the observation that it is not theoretically necessary to absorb 100 percent of the heat that is being released. Table 17.3.1 gives some of the values used in the international literature.

OPACITY AND REFLECTIVITY

Tests conducted at Underwriters Laboratories Inc. (UL), using water spray to provide exposure protection to a sheet metal surface from a gasoline fire, indicate that when the spray is applied as a thin film of water over the sheet metal, the temperature of the metal was contained within limits that protected the metal from significant damage. This did not occur, however, when the water spray was adjusted so that it did not touch the sheet metal, but it did provide a water curtain between the metal and the fire. In this latter case, the temperature of the metal was three to four times greater than when the water flowed over the metal. These tests indicate that, because of its lack of opacity, water does not prevent the passage of radiant heat very well. The principal value of water used to protect exposures is from the cooling obtained by evaporation of a water film on the exposed surfaces.

NFPA 13, *Standard for the Installation of Sprinkler Systems,* calls for outside sprinklers for protection against exposure fires to be positioned so that the water will thoroughly wet exposed glass windows and run down over the window sash

TABLE 17.3.1 Literature Values for Heat Absorption Efficiency of Water Applied by Fire Fighters

Researcher	*Reference*	*Efficiency (%)*	*Theoretical Heat Absorption Used (MW per kg/sec) (Same as L/sec)*[a]	*Conditions/Comments*
Barnett[b]	Draft SFPE *Engineers Guide to Fire Department Intervention* citing New Zealand Fire Engineering Guide and National Research Council of Canada	33	2.6	Based on first principles of heat absorption. The 33% factor includes an increase over heat absorption efficiencies alone to account for the effect of steam
Grimwood et al.[c]	*3D Fire Fighting, Training, Techniques, and Tactics*	32	2.6	Heat absorption a rounded conversion from 9.8 MW/gal/sec. Applies to direct attack
Särdqvist[d]	*An Engineering Approach to Fire-Fighting Tactics,* Sweden	40	2.6	Standard smooth bore nozzle (7 mm or 14 mm) at short range and well placed
Särdqvist	*An Engineering Approach to Fire-Fighting Tactics,* Sweden	30	2.6	Standard smooth bore nozzle (22 mm) or large-capacity nozzle at long range and well placed
Särdqvist	*An Engineering Approach to Fire-Fighting Tactics,* Sweden	20	2.6	Monitor nozzle at long range and well placed
Särdqvist	*An Engineering Approach to Fire-Fighting Tactics,* Sweden	20	10.8	Interior use of Swedish design fog nozzles producing droplets smaller than 1 mm
Zhao, Beck, and Kurban[e]	*Fire Brigade Intervention Model for Residential Buildings in Australia*	5	10.5	Exterior stream
Zhao, Beck, and Kurban	*Fire Brigade Intervention Model for Residential Buildings in Australia*	15	10.5	Interior stream

[a]Note: The 10+ MW values are extinction capacity based on not removing 100% of the heat. Steam heat absorption also credited.

[b]*Engineers Guide to Fire Department Intervention*, Society of Fire Protection Engineers, Bethesda, MD, 2005 draft, pp. 45–46, 50. This information will likely be more accessible in this guide once it is published than in the original sources.

[c]Grimwood, P., Hartin, E., McDonough, J., and Raffel, S., *3D Fire Fighting, Training, Techniques, and Tactics*, Fire Protection Publications, Stillwater, OK, 2005, p. 89.

[d]Särdqvist, S. *An Engineering Approach to Fire-Fighting Tactics*, Lund Institute of Technology, Lund, Sweden, 1996, pp. 52–55.

[e]Zhao, L., Beck, V., and Kurban, N., *Fire Brigade Intervention Model for Residential Buildings in Australia*, Victoria University of Technology, Melbourne, Australia. No date, appears to have been published in 1998 or 1999, pp. 8–9.

and the glass, wetting the entire window as much as possible. Similar recommendations require that as much of the cornice as possible be wetted when cornice sprinklers are installed. These recommendations reflect the experimental evidence.

In England, tests measured the transmission of radiant heat through water sprays from two types of nozzles.[18] The tests proved that the transmission of this kind of heat depends mostly on nozzle design, and that, with certain nozzles, a water curtain of low transmission could be produced for waterflows comparable to those of sprinkler installations. Fire fighters have, of course, used water curtains in situations where it was too hot or dangerous for them to remain exposed to flames and heat.

WATER AS AN EXTINGUISHING AGENT

It is recognized that fires involving various fuels and materials react differently to various extinguishing agents and that water is *not* the best agent for all types of fuels.

Water is not suitable for all types of fires. There are four typical classifications of fire: (1) Class A—ordinary combustibles, (2) Class B—flammable and combustible liquids, (3) Class C—electrical, and (4) Class D—combustible metals. A fifth class, Class K, has been added for cooking oils. Water is most effective and most commonly used for Class A fires. Water is not appropriate or the most desirable agent of choice for Class B, Class D, or Class K fires. (Water mist systems have been successful on tests of some Class B and Class K fires.) Using water for Class C fires must be considered carefully before the water is applied. Water may not be an acceptable agent where collateral water damage is deemed unacceptable.

A good reference to consult for recommendations on use of water on specific materials where problems could be encountered is the NFPA *Fire Protection Guide to Hazardous Materials.*[19]

Water applied to fires by certain types of water mist fire suppression systems has been found to be effective with fires involving flammable liquids and live electrical equipment. Water mist systems can be used to protect shipboard engine enclosures, valuable artwork, and computer room subfloors. Water mist is especially effective in confined spaces when a detection system operates the water mist fire suppression system. Water mist systems are also an attractive option for applications where the storage or discharge of water is to be minimized. Direction on the use of water mist as a suppression system is given in NFPA 750, *Standard on Water Mist Fire Protection Systems.* More information can be found in Section 16, Chapter 8, "Water Mist Fire Suppression Systems."

Water can be used in some instances for fires involving chemicals and combustible metals, where the quantity of water can overcome some adverse chemical reactions and extinguish the fire.

The following possible personnel hazards must be considered when choosing water as the extinguishing agent: (1) exposure and/or inhalation of steam in all fires, (2) electrocution or shock injury in electrical fires, and (3) adverse or explosive reactions in chemical and combustible metal fires.

Wetting Agents

Information in this section is based on NFPA 18, *Standard on Wetting Agents*. Wetting agents are compounds that are added to water to change some or all of the water's characteristics, for example, surface tension or viscosity. Experience as well as testing indicates that the addition of a proper wetting agent to water will, when properly applied, increase the extinguishing efficiency of that water with respect to quantity used and time to achieve fire control or suppression. The value of such a factor may well become important, especially in rural areas where adequate quantities of water are not always available for fire fighting.

Certain types of fires, such as those in baled cotton, stacked hay, some rubber compounds, and some flammable liquids that do not ordinarily respond to treatment with water may be extinguished when a proper wetting agent is used. This may be attributed to an increase in the penetrating, spreading, and emulsifying capability of water due to lowered surface tension. This decrease in surface tension can be described as a disruption of the forces holding the surface film of water together, permitting it to flow and spread uniformly over solid surfaces. The treated water possesses the ability to penetrate into small openings and recesses that nontreated water would flow over by the simple bridging action of the surface film. The treated water exhibits not only penetrating and spreading qualities but also increased absorptive speed and superior adhesion to solid surfaces.

Some wetting agents have foaming characteristics when mixed with water and air. The foam retains the wetting and penetrating characteristics of the wetting agent and provides an efficient smothering action for the extinguishment of Class A and some Class B fires. It also provides a fluid insulation for protection against fire exposure. The foam produced in this manner has the additional advantage of breakdown at approximately 175°F (79.4°C), then returns to its original liquid state and retains the penetrating and wetting qualities.

Although wetting agents can be used on some Class B fires, they do not perform as well as foam and in many cases the performance of a wetting agent on Class B fires may be unsatisfactory with respect to extinguishment or burnback resistance. A wetting agent that has been listed for Class B fires by UL has not undergone testing as rigorous as the testing required to be listed as a foam under UL 162, *Foam Equipment and Liquid Concentrates.*

There are numerous chemicals that fulfill the primary function of a wetting agent, which is to lower the surface tension of water. However, very few of these chemicals are suited to fire protection because their application is complicated by hazard considerations, such as toxicity, corrosive action on equipment, and stability in water.

Wet water is water plus a wetting agent. Wet water has the same limitations as water on fires in chemicals that react with water. The use of wet water on flammable and combustible liquid fires is not common. Wet water should not be used on flammable or combustible liquid fires if the liquids are water soluble, such as the alcohols, glycols, and some ketones.

Because of its conductivity, the application of wet water solutions on live electrical equipment requires the same precau-

tions as application of water on Class C (electrical) fires. Wet water applied by spray or fog might be used with caution due to its penetrating characteristics. Wet water may have more harmful effects on motors, transformers, and similar equipment than plain water. Any electrical equipment that has been penetrated by wet water should be thoroughly flushed and cleansed before it is returned to service.

A specific use of wet water is to penetrate combustible materials. One objective is to use less agent than if plain water were used, especially in Class A fuels with the potential for a deep-seated fire. This increased water absorption can increase the potential for structural or commodity collapse if too much agent is absorbed, thereby increasing the weight of the commodity.

Wetting agents may be either premixed with water or added to the water through suitable proportioning equipment at the time the water is being used. Mixing wetting agents from different manufacturers, or mixing a wetting agent with mechanical or chemical foam concentrates, is not recommended. Distinction must be made between wetting agents and wetting-agent foams and other detergent-type foams (high-expansion foam) and film-forming foam agents. Guidance for the use of wetting agents is given in NFPA 18, *Standard on Wetting Agents.*

Class A Foam

Water additives known as Class A foams have become extremely popular in recent years. Fornell describes seven advantages of Class A foam over water alone.[20] Colletti and Liebson should be read in their entirety. Also see NFPA 1150, *Standard on Foam Chemicals for Fires in Class A Fuels,* and NFPA 1145, *Guide for the Use of Class A Foams in Manual Structural Fire Fighting.*

Modern Water Additives

Manufacturers have developed water additives that appear to be much more effective on Class A and Class B fires than traditional wetting agents. These manufacturers often promote the environmental benefits of their agents as well. As of this writing, the Technical Committee on Water Additives for Fire Suppression and Vapor Mitigation is working on a new document, NFPA 18A, *Standard on Water Additives for Fire Control and Vapor Mitigation.* The challenge before the committee was how to quantify the improvements that these agents purport to offer. The proposed standard will provide quantifiable performance requirements. These requirements can be compared to other agents for the intended use.

For example, an agent meeting the minimum requirements of NFPA 18A is required to be applied at a greater density than a UL-listed Aqueous Film Forming Foam (AFFF) to extinguish a Class B fire. But the NFPA 18A agent may have additional listings and capabilities that AFFF does not have. Specifically, NFPA 18A requires that agents demonstrate improved performance over water on Class A fires.

Agents listed under NFPA 18A have the option of being listed for long-term vapor mitigation and for use on three-dimensional (flowing) fuel fires. AFFF is not listed for these applications. Agents listed under NFPA 18A must meet the requirements of UL 162 if they are intended to be used on Class B fuels in extreme depth such as tank fires. Some agents that would be covered under the NFPA 18A agent have found a niche market in the protection of Powder River Basin coal at power plants and have become the standard in that industry. Powder River Basin (PRB) coal refers to low-sulfur coal. Its name comes from the region along the Montana-Wyoming border where it is mined. Powder River Basin coal is a greater fire protection challenge than more traditional coals and warrants extra fire protection precautions. For more information visit the Powder River Basin coal users group at http://www.prbcoals.com. For related topics, see Section 9, Chapter 16, "Mining and Mineral Processing."

Additional information on the differences between agents covered under NFPA 18A and traditional Class B foams can be found in the annex of NFPA 18A. It is up to the user to carefully evaluate the intended application(s), the cost and amount of agent needed to meet those needs, and potential environmental impact before selecting the agent that best meets those needs.

Two additives, along with two types of aqueous film-forming foam and a film-forming fluoroprotein foam, were tested in sprinkler and water mist systems by the UK Royal Navy. Liu and Kim reported that "test results showed that all five types of additives improved the performance of both sprinklers and water mist but such improvement was much more significant for water mist."[21]

WATER AND FLAMMABLE AND COMBUSTIBLE LIQUIDS—CLASS B FIRES

Care must be exercised when using water as an extinguishing agent with Class B (flammable and combustible liquid) fires. Water density can create problems with flammable and combustible liquids. When the liquid is lighter (specific gravity less than 1.0) than water, the water can submerge beneath the liquid and can cause the flammable or combustible liquid to flow from its containment, spreading the fire. With crude oil, water can submerge to the bottom of the container and cause the crude oil to "boil over." Other hazards are slopover and frothover. (See Section 6, Chapter 12, "Flammable and Combustible Liquids.") Water is immiscible with hydrocarbon fuels, does not provide an effective coating of the fuel surface, and does not dilute the flammable or combustible mixture below the flammable limits. However, when properly mixed with certain types of foam concentrate, water is an effective fire-suppressing agent for certain types of flammable and combustible liquids.

Heavy fuel oil, lubricating oil, asphalt, and other high-flashpoint liquids do not produce flammable vapors unless heated. Once ignited, the heat of the fire will cause pyrolysis for continued burning. If water in spray form is applied to the surface of such high-flashpoint burning liquids, cooling will slow down the rate of pyrolysis enough that it may extinguish the fire. If water is applied to high-flashpoint burning liquids by means of a coarse spray, extinguishment may be obtained by emulsification.

Foam concentrate used for flammable and combustible liquids are commonly called Class B foams to distinguish themselves from the previously discussed Class A foams. Fire

department pumpers are now commonly equipped with one tank for Class A foam and another for Class B foam.

Fire-fighting foam for Class B liquids is (1) an aggregate of air-filled bubbles forming from aqueous solutions (water and foam concentrate) and (2) lower in density than flammable liquids. It is used principally to form a cohesive floating blanket on flammable and combustible liquids and prevents or extinguishes fire by limiting the amount of air and cooling the fuel. It also prevents reignition by suppressing formation of flammable vapors. (See Section 17, Chapter 4, "Foam Extinguishing Agents and Systems.")

Fire-fighting foams for Class B liquids consist of a combination of water, foam concentrate, and air. Low-expansion-type foams typically utilize a ratio of 1, 3, or 6 percent concentrate to 99, 97, or 94 percent water, respectively, to make a foam-water solution. Water remains the principal component in fire-fighting foams.

The ability of water without additives (foaming agents) to extinguish a fire is limited on low-flashpoint flammable liquids, such as Class I flammable liquids (flashpoints below 100°F [37.8°C]), as defined in NFPA 30, *Flammable and Combustible Liquids Code.* Sprinklers and water spray are usually effective in extinguishing fires in combustible liquids with flashpoints of 200°F (93.3°C) and higher, in flammable liquids with a specific gravity greater than 1.0, and in water-soluble liquids. Water can be effective with high-flashpoint hydrocarbon fires when introduced as a high-velocity spray causing penetration of the droplets and cooling of the surface layer.[22] If water does not evaporate and cool the fuel surface, it can accumulate and submerge and can displace the hydrocarbon. Control of fire, but not extinguishment, is possible in low-flashpoint (under 200°F [93.3°C]) flammable liquids. Any water that reaches the surface of a burning, low-flashpoint flammable liquid in a tank may sink and cause the tank to overflow. In the case of a spill fire, the water may cause the fire to spread. Special handling of certain types of water spray nozzles can result in extinguishment of fires in these liquids or, at a minimum, effective fire control.

Water can be used as an effective cooling agent in Class B fires; it can also (1) protect against flame-exposure of the storage container and (2) protect exposures as a cooling agent.

See Section 6, Chapter 12, "Flammable and Combustible Liquids," for characteristics and fire preventive methods for Class B fires.

WATER AND LIVE ELECTRICAL EQUIPMENT—CLASS C FIRES

Water in its natural state contains impurities that make it conductive. If water is applied to fires involving live electrical equipment, a continuous circuit might be formed that would conduct electricity back to the user and cause a shock, especially if there are high voltages or potentials. Foam-type extinguishing agents are also conductive. The amount of current, rather than the voltage, determines the extent of the shock. Conductivity of water when used on live electrical equipment depends on several variables:

1. The voltage and amount of current flowing
2. The "breakup" of the stream as a result of the nozzle design, the pressures used, and the wind conditions. This breakup influences the conductivity of the stream because the air spaces formed between the droplets interrupt the electrical path to ground. Water spray nozzles and combination straight-stream spray nozzles (in the spray position) provide for effective dispersion of the water droplets. The hazards of these are less than those of solid streams of water.
3. The purity of the water and the relative resistivity of the water
4. The length and cross-sectional area of the water stream
5. The resistance to ground through a person's body as influenced by location (whether on wet ground or not), skin moisture, the amount of current the body can endure, the length of exposure to the current, and other factors, such as protective clothing.
6. The resistance to ground through the hose

Conductivity and Hazard of Shock

There is some danger to fire fighters directing streams of water onto wires of less than 600 V to ground from a distance likely to be encountered under ordinary fire-fighting conditions. It is more dangerous if fire fighters, standing either in puddles of water or on moist surfaces, come into contact with live electrical equipment. In such cases, the fire fighters' bodies complete an electrical circuit, and the current from the electrical equipment relayed through their bodies is more readily grounded than if it were conveyed through dry, nonconductive surfaces. Rubber boots often contain enough carbon black to permit the passage of current through the body and do not provide reliable protection.

Research conducted by UL on electric fences indicates that there are differences in the electric current to which individuals may be safely subjected and that the maximum continuous (uninterrupted) current to which an individual may be safely subjected is 5 mA (milliamperes) AC applied on the surface of the body.[23]

Impurities in water (mostly the mineral content) also affect its conductivity. Tests of the resistivity of public water supplies in Indiana showed results ranging from 710 to 5400 ohms per cm^3; the lowest values were found in supplies from deep wells. The resistivity of deep well supplies ranged from 1000 to 2000 ohms per cm^3; and the resistivity of river waters was about 4000 ohms per cm^3. In tests conducted by the Commonwealth Edison Company in cooperation with the Chicago Fire Department, the resistivity of Chicago River water ranged from 1671 to 2393 ohms per cm^3.[24] At the time the tests were made, the normal hydrant water in the Chicago area had a resistivity of about 3800 ohms per cm^3.

Safe Distances from Live Equipment

From time to time, authorities have tried to determine safe distances between nozzles and live electrical equipment. The bibliography at the end of this chapter cites more papers on this subject.

The conductivity of water streams varies according to the type of equipment from which they are expelled, such as

(1) handheld or manually supported solid-stream nozzles, (2) handheld water spray (water fog) nozzles, (3) fixed water spray systems for fire protection services, and (4) plain water and water-solution portable fire extinguishers.

Data available on the minimum safe distances between manually supported solid-stream hose lines and live electrical equipment carrying voltages higher than 600 V are not entirely consistent because the results of different tests vary. These variations may be attributed to the different testing methods used, the variances in the purposes of the tests, the limitations of the tests caused by the physical circumstances and available equipment, and the fact that the same voltages were not used in all of the tests.

Data from the American Insurance Services Group (AISG), a unit of Insurance Services Offices, Inc. (formerly AIA), was published in the 18th and earlier editions of this handbook. At AISG's request, this information was removed from the 19th edition of this handbook because the data are based on an AIA bulletin that is no longer in print and is considered obsolete. AISG does not recommend the information published in Table 6-1A in the 18th edition of this handbook. Some limited tests made in 1958 by the Hydroelectric Power Commission of Ontario, in cooperation with the Office of the Fire Marshal of Ontario, Canada,[25] resulted in recommendations for minimum safe distances from live electrical equipment for a ⅝ in. (16 mm) solid-stream nozzle (Table 17.3.2). The report recommends that solid streams greater than ⅝ in. (16 mm) should not be used near live electrical equipment, but the tests were limited to a maximum stream distance of 30 ft (9.1 m). Larger nozzles might produce sufficient stream dispersion over longer distances, which would permit their use.

TABLE 17.3.2 Limit of Safe Approach to Live Electrical Equipment

Voltage to Ground	*Voltage Between Conductors*	⅝ in. (16 mm) Solid-Stream Nozzle:[a] Minimum Safe Distance	
		ft	*m*
2,400	4,160	15	4.6
4,800	8,320	20	6.1
7,200	12,500	20	6.1
8,000	13,800	20	6.1
14,400	24,900	25	7.6
16,000	27,600	25	7.6
25,000	44,000	30	9.1
66,000	115,000	30	9.1
130,000	230,000	30	9.1

[a]Nozzle pressure 100 psi (690 kPa) water resistance 600 ohms per in.[3].

Source: Fitzgerald, G. W. N., "Fire Fighting Near Live Electrical Apparatus," Research Division Report No. 58160, Hydro-Electric Power Commission of Ontario, Canada, 1958.

The results of tests made in 1934 for the Fire Brigade of Paris, France, present perhaps the most comprehensive guide[26] (Table 17.3.3). The distances are based on preventing the transmission of a 1 mA current to a fire fighter in contact with a nozzle or hose. The tests covered only voltages to ground ranging from 115 to 150,000 V, and the groupings of the voltages do not correspond to current standard U.S. voltages. The maximum size of the nozzle used is also nonstandard in the United States.

The preceding information indicates that definite shock hazards exist unless adequate distances are maintained, and these distances can only be estimated from the available data. It is difficult for fire fighters in the field to know precisely what electrical potentials exist in any given situation. For this reason, and those given next, it is best, whenever possible, to use water spray streams rather than solid streams.

As noted previously, water spray reduces the conductivity hazard. The design of the nozzle and the characteristics of the spray determine the amount of leakage current that can actually flow in the stream, and each nozzle should be tested to determine precisely the characteristics it possesses. Tests on various commercial water spray nozzles indicate that a minimum

TABLE 17.3.3 Minimum Safe Distances Between Hose Nozzles and Live Electrical Equipment Recommended for the Paris, France, Fire Brigade

Voltage to Ground	*Voltage Between Conductors*	Diameter of Nozzle Orifice: ¼ in. (6 mm) Safe Distance		¾ in. (19 mm) Safe Distance		1¼ in. (32 mm) Safe Distance	
		ft	*m*	*ft*	*m*	*ft*	*m*
115	230	1.6	0.50	3.3	1.00	6.6	2.00
460	480	2.5	0.75	9.8	3.00	16.4	5.00
3,000	5,195	6.6	2.00	16.4	5.00	32.8	10.00
6,000	10,395	8.2	2.50	19.7	6.00	39.4	12.00
12,000	20,785	9.8	3.00	21.4	6.50	49.2	15.00
60,000	103,820	14.8	4.50	39.4	12.00	72.2	22.00
150,000	259,800	19.7	6.00	49.2	15.00	82.0	25.00

Source: Buffet, "Peut-on Employer les Lances d'Incendie sur des Conducteurs Electriques?" 1934.

distance of 4 ft (1.2 m) should be maintained for voltages to ground up to about 10 kV. This distance is actually no greater than is sensible to prevent personnel from getting dangerously close to live electrical equipment. Distances should be increased when attacking fires involving live electrical equipment operating above this voltage. Figure 17.3.1 shows the results of four researchers, as analyzed by the U.K. Fire Offices' Committee, Joint Fire Research Organization.[27]

The Toledo Edison Company conducted tests in which water was discharged onto a screen at a potential to ground of 80,500 V (equivalent to a system or line voltage of 138 kV phase-to-phase). As a consequence, the Edison Electric Institute in 1967 adopted the following safety rules. (The distances in these rules will limit leakage currents to less than 1 mA):

1. Using all handheld water spray nozzles, the minimum approach distance is 10 ft (3 m).
2. Using handheld, 1½-in. (38-mm) straight (solid) stream nozzles, the minimum approach distance is 20 ft (6 m).
3. Using handheld, 2½-in. (64-mm) straight (solid) stream nozzles, the minimum approach distance is 30 ft (9 m).

When combination straight-stream spray nozzles are used on live electrical equipment, fire fighters should be sure they have the desired spray pattern before applying the stream. The use of spray nozzles on "applicators" increases the possibility of accidental contact between the nozzle and live electrical equipment, and most authorities recommend that they not be used.

Clearance from Fixed Water Spray Systems

Fixed water spray systems are used extensively to protect high-value and/or critical electrical equipment, such as transformers, oil switches, and motors. These systems are designed to provide effective fire control, extinguishment, prevention, or exposure protection. NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection,* gives installation recommendations for such systems and includes a table of recommended clearances between water spray equipment and unenclosed or uninsulated live electrical components at other-than-ground potential (Table 17.3.4). Modern practice is to coordinate the required clearance with the electrical design. The basic insulation level (BIL) values of the equipment are used as the basis, although the clearance between uninsulated live parts of the equipment and any portion of the water spray system should not be less than the minimum clearances provided elsewhere for electrical system insulation on any individual component (the minimum unshielded straight-line distance from the exposed electrical parts to nearby grounded objects). The BIL (expressed in kilovolts [kV]) is the crest value of the full wave impulse test. (See Section 16, Chapter 9, "Water Spray Protection.")

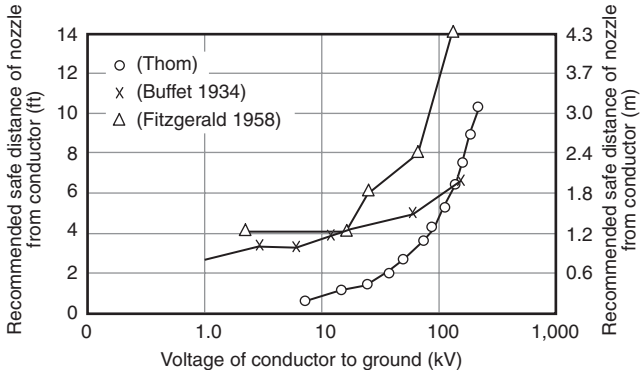

FIGURE 17.3.1 Variation of Safe Distance with Conductor Voltage for Spray Nozzles

TABLE 17.3.4 Clearance from Water Spray Equipment to Live Uninsulated Electrical Components

Nominal System Voltage (kV)	*Maximum System Voltage (kV)*	*Design BIL (kV)*	Minimum* Clearance	
			in.	*mm*
To 13.8	14.5	110	7	178
23.0	24.3	150	10	254
34.5	36.5	200	13	330
46.0	48.3	250	17	432
69.0	72.5	350	25	635
115.0	121.0	550	42	1067
138.0	145.0	650	50	1270
161.0	169.0	750	58	1473
230.0	242.0	900	76	1930
		1050	84	2134
345.0	362.0	1050	84	2134
		1300	104	2642
500.0	550.0	1500	124	3150
		1800	144	3658
765.0	800.0	2050	167	4242

Note: BIL values are expressed as kilovolts (kV), the number being the crest value of the full wave impulse test that the electrical equipment is designed to withstand. For BIL values that are not listed in the table, clearances can be found by interpolation.

*For voltages up to 161 kV, the clearances are taken from NFPA 70, *National Electrical Code.* For voltages 230 kV and above, the clearances are taken from Table 124 of ANSI C2, *National Electric Safety Code.*

Source: NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*, Table 6.1.2.2, 2007, p. 15-13.

Portable Extinguishers and Hazard of Shock

Water-based or water-solution portable fire extinguishers are not recommended for use on live electrical equipment, that is, Class C fires. NFPA 10, *Standard for Portable Fire Extinguishers,* recommends that extinguishers specifically tested for use on Class C fires be used for such fires. When electrical equipment is de-energized, water-based extinguishing agents and extinguishers for Class A or B fires may be used safely. Conductivity tests of portable fire extinguishers containing water indicate that soda-acid (now discontinued), loaded-stream (now discontinued), foam, and antifreeze solution extinguishers, all of which produce solid streams and have a short range, are particularly hazardous. One test involving an antifreeze solution extinguisher

showed a current of 157 mA for a potential of 1 kV with a 3/32 in. (2.4 mm) stream at a distance of 1 ft (0.3 m). To reduce the current to below 1 mA, it would be necessary to use the device from a distance at which the stream is dispersed; it is generally agreed that for such extinguishers the minimum distance should be 4 ft (1.2 m) for voltages up to 1 kV. Extinguishers containing plain water might, in theory, be used at shorter distances, but it is best to maintain a 4 ft (1.2 m) distance if it is necessary to use this kind of extinguisher.

Water on Electrical, Electronic, and Computer Equipment

Automatic sprinkler protection and water spray fixed systems are valuable for fire control, even where electrical, electronic, or computer equipment may be present. There should be little concern about the possibility of shock or of the water causing excessive damage to the equipment. Experience has proved that, if a fire activates sprinklers, the sprinklers, if properly installed and maintained, provide effective protection, with regard to electrical shock, with no measurable increase in damage to the equipment, as compared with the damage done by heat, flame, smoke, and the manual hose streams.[28]

NFPA 75, *Standard for the Protection of Information Technology Equipment,* recognizes the importance of automatic sprinkler protection in computer rooms. It recommends that, where sprinklers are installed to protect electronic computer equipment, the power to the equipment should be disconnected prior to the application of water.

WATER AND COMBUSTIBLE METALS—CLASS D FIRES

The reaction between water and combustible metals ranges widely from minor reactions to an explosive reaction. In some instances, water can be used to overcome some adverse chemical reactions if a large quantity is applied. As a rule, water should not be used on fires involving combustible metals, for example, magnesium, titanium, metallic sodium, and hafnium, or on metals that are combustible under certain conditions, for example, calcium, zinc, and aluminum. However, water can be utilized to protect exposures as a cooling agent. NFPA 484, *Standard for Combustible Metals*, specifies when sprinklers may and may not be used when magnesium is present.

USE OF WATER ON SPECIAL HAZARDS

Although water is generally a universal extinguishing agent, there are certain prohibitions and precautions that must be observed when it is applied manually on some burning materials that either react chemically or explosively on contact with water. In other instances, the mechanical action of applying water must be carefully monitored to avoid creating conditions that intensify the hazard rather than controlling it.

The following paragraphs give guidance on using water on different materials that can present problems if water is used arbitrarily as an extinguishing agent. See Section 6, "Characteristics of Materials and Products," for specific information on chemicals and gases.

Chemical Hazards

As a general rule, water should not be used on materials that react with water and may release oxygen, flammable gases, and heat. Examples include alkalies, anhydrides, carbides, hydrides, nitrates, and peroxides (organic and inorganic) to list a few. When wet, certain materials, such as unslaked lime, will heat spontaneously over a period of time if heat cannot be dissipated due to storage conditions.

Radioactive Metals

Water should not be used continuously on radioactive metals. The requirements for fire protection for radioactive metals are generally consistent with their nonradioactive counterparts (for all practical purposes, radioactivity does not influence, nor is it influenced by, the fire properties of a metal). Control of contaminated runoff water is a complicating factor in using water on radioactive metals.

Flammable Gases

In gas-fire emergencies, water is generally used for the control of heat from the fire while efforts are made to shut off, or stop, the flow of escaping gas. Water in the form of spray applied from hose lines or monitor nozzles, or by fixed water spray systems, is commonly used for dispersement or dilution of concentrations of flammable gases.

WATER ADDITIVES FOR SPECIALIZED USES

Freezing Temperatures and Antifreeze Additives

Because water freezes at 32°F (0°C), its use as an extinguishing agent is limited in climates or situations where freezing temperatures are encountered. There are several methods commonly used to prevent problems of freezing. These include using dry-pipe sprinkler systems instead of wet-pipe systems, circulation or heating tank water supplies held for fire protection purposes, adding freezing-point depressants to the water, or a combination of these.

The water-soluble freezing-point depressant most widely used in fire equipment is calcium chloride with a corrosion-inhibitor additive. Calcium chloride solutions are not used when fire protection systems are supplied by public water connections. Sodium chloride (common salt) is unsatisfactory because of its limited ability to depress the freezing point of water and its highly corrosive attribute.

Antifreeze Additives for Sprinkler Systems

Chemically pure glycerine (U.S. Pharmacopoeia 96.5 percent grade) or pure propylene glycol can be used to depress the

freezing point of water in portions of water suppression systems connected to public water supplies, if authorized by local health or water authorities. Diethylene glycol, ethylene glycol, or calcium chloride, as well as glycerine or propylene glycol, can be used for the same purposes where public water is not connected to the system. Both ethylene and diethylene glycol are poisonous and cannot be permitted to contaminate drinking water.

Antifreeze Additives for Water-Type Extinguishers

Alkali-metal salt solutions provide protection against freezing temperatures as low as –40°F (–40°C). Only the antifreeze solutions specified by the manufacturers should be used. Glycol solutions should not be used in extinguishers because the amount required to protect against freezing would be high; a 52.5 percent solution of ethylene glycol would be needed to depress the freezing point to –40°F (–40°C). Such amounts will alter the effectiveness of the extinguisher and may also lead to complications if the water should "boil off" and leave a strong concentration of the glycol, which, under certain conditions, could be ignited.

Efforts have been made to develop other additives that can be mixed with water to lower the freezing point to –65°F (–54°C). This work has been largely stimulated by increased activity in extremely low-temperature areas, with most of the research being done by the U.S. armed forces. To date, formulas of lithium chloride, lithium chloride–calcium chloride, and lithium chloride–anhydrous sodium chromate have been used successfully. No commercial use of these solutions is known; however, the U.S. Naval Research Laboratory has developed a lithium chloride solution for fire extinguishers exposed to low temperatures of –65°F (–54°C).

Additives to Modify Flow Characteristics

Friction loss in fire hose is always an obstacle for fire fighters. The longer the hose or the more water pumped through it, the greater the pressure loss. With a smooth fire hose lining, most of the pressure loss is the result of friction between particles of water generated by the turbulence in the flowing stream. When flow is either smooth or laminar, the friction loss tends to be very low with a slow stream of water. However, the amount of water delivered under laminar flow is generally too low for fire fighting. Fire fighting requires high-velocity streams that generate turbulence, which, in turn, results in friction between water particles. This friction accounts for about 90 percent of the pressure loss in fire hose. The friction between the flowing water and the interior hose wall accounts for only 5 to 10 percent of the loss.

Until 1948 it was generally believed that not much could be done to reduce friction loss. At the time, trace quantities of certain polymers were found to reduce friction loss of turbulent streams. Most researchers report that linear polymers (i.e., polymers that form a single straight-line chemical chain with no branches) are the most effective in reducing turbulent frictional losses. Of these, the poly-chain (polyethylene oxide) is the most effective. Friction-reducing efficiency is a direct function of polymer linearity.

Poly-chain synthetics are nontoxic, have no effects on plants or marine life, and will degrade in sunlight. A poly-chain synthetic is a long linear chain, high-molecular-weight polymer, and is two to three times more effective as a friction-reduction agent than other materials tested to date. It is an odorless, opaque, white slurry that weighs 9.1 lb per gal (1.1 kg/L) and must be kept within 0 to 120°F (–17 to 49°C). When it is injected into the hose stream, it dissolves completely and does not separate. It is compatible with all fire-fighting equipment and is useful in both fresh and salt water. One gallon (2.6 L) of additive treats 6000 gal (22,710 L) of water and achieves at least a 40 percent greater water delivery.

Tests conducted by the New York City Fire Department and Union Carbide Corporation found that a 1½ in. (38 mm) hose with an additive delivered 250 gpm (946 L/min), or as much as a 2½ in. (64 mm) hose without the additive. With the additive, a 2½ in. (64 mm) hose was able to deliver more water than a 3 in. (76 mm) hose, and nearly as much water as a 3½ in. (89 mm) hose. These tests also showed that the additive nearly doubled the nozzle pressure. The stream's reach was increased by nearly 30 percent, and the stream was more coherent.

The author is unaware of any fire departments that are currently using these additives. Certainly, they are not in widespread use.

Additives to Increase Water's Viscosity

The relatively low viscosity of water makes it tend to run off solid fuel surfaces quickly and limits the ability to blanket a fire by forming a barrier at the surface. Additives make the use of water more effective on certain types of fires. Most applications of viscous water have been directed at fighting forest fires.

Viscous water has had several thickening agents added to it. In proper proportions, viscous water has the following advantages over nontreated water: ability to cling and adhere to the fuel surface; provide a continuous coating over the fuel surface; provide a layer thicker than water; absorb heat proportional to the amount of water present; project farther when discharged from a nozzle; and resist movement due to wind and air currents.

Viscous water has the following disadvantages over water: it does not penetrate the fuel as well as water, it creates a higher friction loss in fire hose or piping, increases the water droplet size, makes surfaces slippery and difficult to walk on, and requires mixing prior to use.

The author is unaware of any systems currently using this additive. Certainly, they are not in widespread use.

CARE IN USE OF WATER AS AN EXTINGUISHING AGENT

There are numerous factors that must be considered before using water as an extinguishing agent, as this chapter has already discussed. It must be considered if the use of water will cause the fire to grow or spread, whether there will be a chemical reaction causing harm, or if live electrical equipment can endanger personnel.

Fire fighters must also consider water runoff when using water-based fire extinguishing agents. Water can carry pollut-

ants from a fire to a water supply or cause groundwater contamination. When using water to extinguish hazardous materials fires, such as pesticides and flammable liquids, some of the fuel will be carried off by the water vapor (steam), some of the water may be absorbed by the fuel, and some fuel may be carried by the runoff water.

SUMMARY

Water is the most widely used extinguishing agent because it is readily available and because of its ability to cool, to remove and displace the oxygen supply, and to separate/displace the fuel source. Although water is highly effective on Class A fuels, it is not usually the agent of choice on Class B, C, D, or K fires.

Several additives are available to improve water's performance. The most common are Class A and B foams, and an emerging class of additives collectively known as water additives for fire control and vapor mitigation.

Care must be exercised before using water on fires involving energized electrical apparatus, hazardous materials (including flammable and combustible liquids), and combustible metal fires. The effect of contaminated runoff on the environment should always be considered.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on water and water additives for fire suppression discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems*
NFPA 18, *Standard on Wetting Agents*
NFPA 18A, *Standard on Water Additives for Fire Control and Vapor Mitigation*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 70, *National Electrical Code®*
NFPA 75, *Standard for the Protection of Information Technology Equipment*
NFPA 86, *Standard for Ovens and Furnaces*
NFPA 484, *Standard for Combustible Metals*
NFPA 750, *Standard on Water Mist Fire Protection Systems*
NFPA 1145, *Guide for the Use of Class A Foams in Manual Structural Fire Fighting*
NFPA 1150, *Standard on Foam Chemicals for Fires in Class A Fuels*

Chapter 4

Foam Extinguishing Agents and Systems

Joseph L. Scheffey

Chapter Contents

Uses and Limitations of Fire-Fighting Foams
Types of Foam
Guidelines for Fire Protection with Foams
Foam-Generating Methods
Delivering Foam from Vehicles
Combined Agent or "Twinned" Equipment
Medium- and High-Expansion Foam-Generating Equipment and Systems
Foam Equipment Testing and Surveillance
Environmental Issues

Key Terms

alcohol-type foaming agent, aqueous film-forming foam, chemical foam, crash-rescue vehicle, film-forming fluoroprotein (FFFP) agent, fire-fighting foam, foam extinguishing agent, high-expansion foaming agent, low-temperature foaming agent, protein foaming agent

Fire-fighting foams are used in fixed and portable fire extinguishing systems. They are used primarily to combat flammable and combustible liquid fuel fires. Aqueous foam solutions, created using foam concentrate mixed with water, are expanded with air to create foam. Foam is used to suppress liquid fuel vapors and cool the liquid surface. There are many NFPA standards and guidelines that address foam application for tank/dike protection, aviation spill hazards, aircraft hangar protection, and liquid warehousing applications.

Foams vary in terms of their chemical makeup, which affects the required rate of application and appropriateness for use on particular liquid fuel hazards. For example, protection of polar solvent hazards requires specially formulated alcohol-type concentrate (AR). High-expansion foams can, in some cases, be used to protect both Class A and Class B fire hazards; they are particularly suited as a flooding agent for large spaces. Foams may be tailored for combined use with dry chemical agents. This provides for both two-dimensional pool and three-dimensional spilling fuel fire scenarios.

Foam is generated by proportioning foam concentrate with water. Various fixed and portable proportioning devices are used. Discharge devices include nozzles, foam monitors, and sprinklers. Tank protection requires special nozzle and distribution systems. Specialized foam fire-fighting vehicles are described.

For related topics, see Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 13, Chapter 7, "Aircraft Rescue and Fire Fighting (ARFF)"; and Section 16, Chapter 1, "Principles of Automatic Sprinkler System Performance."

USES AND LIMITATIONS OF FIRE-FIGHTING FOAMS

Low-expansion foam is used principally to extinguish burning flammable or combustible liquid spill or tank fires by application to develop a cooling, coherent blanket. Foam is the only permanent extinguishing agent used for fires of this type. Its application allows fire fighters to extinguish fires progressively. A foam blanket covering a tank's liquid surface can prevent vapor transmission for some time, depending on the stability and depth of the foam. Fuel spills are quickly rendered safe by foam blanketing. The blanket may be removed after a suitable period of time; typically it has no detrimental effect on the product with which it comes into contact.

Foams can be used to diminish or halt the generation of flammable vapors from nonburning liquids or solids and may be used to fill cavities or enclosures where toxic or flammable gases may collect.

Foam is of great importance where aircrafts are fueled and operated. Sudden, large fuel spills resulting from aircraft accidents or malfunction require rapid foam application. Hangar fire protection is best accomplished by properly designed foam systems.

Increasingly, warehouses and buildings storing large quantities of combustible and flammable liquids are protected by foam-water sprinkler systems. The protection required is a function of the

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type and quantity of liquid stored, building height, and storage configuration.

Foams of the medium- or high-expansion type (20 to 1000 times) may be used to fill enclosures such as basement room areas or holds of ships where fires are difficult or impossible to reach. Here foams act to halt convection and access to air for combustion. Their water content also cools and diminishes oxygen by steam displacement. Foams of this type (with expansion ratios of 400 to 500) may be used to control liquefied natural gas (LNG) spill fires and help disperse the resulting vapor cloud.

Many foams are generated from solutions with very low surface tension and penetration characteristics. Foams of this type are useful where Class A combustible materials are present. In such instances, the water solution draining from the foam cools and wets the solid combustible.

Foam breaks down and vaporizes its water content under attack by heat and flame. It therefore must be applied to a burning liquid surface in sufficient volume and rate to compensate for this loss, with an additional amount applied to guarantee a residual foam layer over the extinguished liquid. Foam is unstable and may be broken down easily by a physical or mechanical force, such as a water hose stream. Certain chemical vapors or fluids may also destroy foam quickly. When certain other extinguishing agents are used in conjunction with foam, severe breakdown of the foam may occur. Turbulent air or violently uprising combustion gases from fires may divert foam from the burning area.

The mechanisms of foam fire extinguishment on two-dimensional hydrocarbon fuel fires have not been fully developed. Recent theoretical and preliminary experimental work has attempted to correlate foam extinguishment with fundamental fluid spread mechanisms. More research is required to develop foam suppression theory.

Foam solutions are conductive and therefore not recommended for use on electrical fires. If foam is used, a spray is less conductive than a straight stream. However, because foam is cohesive and contains materials that allow water to conduct electricity, foam spray is more conductive than water spray.

Engineering design requirements and recommended application methods must be followed for successful use of foams. These requirements can be found in NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam;* NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems*; and NFPA 403, *Standard for Aircraft Rescue and Fire-Fighting Services at Airports*. Additionally, NFPA codes and standards, such as NFPA 30, *Flammable and Combustible Liquids Code*, and NFPA 409, *Standard on Aircraft Hangars*, provide application rate and installation details on special hazard systems.

In general, the following criteria for the hazardous liquid must be met for a foam to be fully effective:

1. The liquid must be below its boiling point at the ambient conditions of temperature and pressure.
2. Care must be taken in application of foam to liquids with a bulk temperature higher than 212°F (100°C). At these fuel temperatures and above, foam forms an emulsion of steam, air, and fuel. This may produce a fourfold increase in volume when applied to a tank fire, with dangerous frothing or slopover of the burning liquid.
3. The liquid must not be unduly destructive to the foam used, or the foam must not be highly soluble in the liquid to be protected.
4. The liquid must not be water reactive.
5. The fire must be a horizontal surface fire. Three-dimensional (falling fuel) or pressure fires cannot be extinguished by foam unless the hazard has a relatively high flashpoint and can be cooled to extinguishment by the water in the foam.

TYPES OF FOAM

A number of types of foaming agents are available, known as foam concentrates, some of which are designed for specific applications. Some are suitable for extinguishing all types of flammable liquids, including water-soluble and foam-destructive liquids. Descriptions of the common types of foam follow.

Aqueous Film-Forming Foam Agents (AFFF)

Aqueous film-forming foam agents are composed of synthetically produced materials that form air-foams similar to those produced by the protein-based materials. In addition, these foaming agents are capable of forming water solution films on the surface of flammable hydrocarbon liquids, hence the term *aqueous film-forming foam* (*AFFF*). AFFF concentrates are available for proportioning to a final concentration of 1 percent, 3 percent, or 6 percent by volume, with either fresh water or seawater.

The air-foams generated from AFFF solutions possess low viscosity, have fast spreading and leveling characteristics, and, like other foams, act as surface barriers to exclude air and halt fuel vaporization. These foams also develop a continuous aqueous layer of solution under the foam, maintaining a floating film on hydrocarbon fuel surfaces to help suppress combustible vapors and cool the fuel substrate. This film, which can also spread over fuel surfaces not fully covered with foam, is self-healing following mechanical disruption and continues to spread as long as there remains a reservoir of nearby foam. Film effectiveness may be reduced on hot surfaces and aromatic hydrocarbons. To ensure fire extinction, an AFFF blanket should cover the fuel surface entirely, as with other types of foam.

AFFF fluidity and film strength on kerosene makes it particularly suitable for jet aircraft fuel spill fire fighting.

AFFF concentrates contain fluorinated, long-chain synthetic hydrocarbons with particular surface-active properties.

Because of the extremely low surface tension of the solutions draining from AFFF, these foams may be useful under mixed-class fire situations (Classes A and B), where deep penetration of water is needed in addition to the surface-spreading action of foam itself.

Foam-generating devices yielding stable, homogeneous foams are not necessarily needed in the employment of AFFF. Less sophisticated foaming devices, such as water spray nozzles and sprinklers (unlike with most other foaming agents), may be used because of the inherent rapid and easy foaming capability of AFFF solutions. However, such foams drain relatively rapidly, and they may provide less burnback resistance com-

pared to protein-based foams. AFFF also may be used, without compatibility problems, in conjunction with dry chemical agents. Although AFFF concentrates must not be mixed with other types of foam concentrates, foams made from them do not break down other types of foams in fire-fighting operations. The normal-use temperature range for these agents is 35 to 120°F (1.7 to 49°C).

Fluoroprotein (FP) Foaming Agents

The concentrates used for generating fluoroprotein foams are similar in composition to protein foam concentrates, but, in addition to protein polymers, they contain fluorinated surface active agents that confer a "fuel shedding" property to the foam generated. This makes them particularly effective for fire-fighting conditions where the foam becomes coated with fuel, such as in the method of subsurface injection of foam for tank fire fighting, and nozzle or monitor foam applications where the foam may often be plunged into the fuel. Fluoroprotein foams are very effective for in-depth crude petroleum or other hydrocarbon fuel fires because of this fuel shedding property. In addition, these foams demonstrate better compatibility with dry chemical agents than do the regular protein-type foams. They also possess superior vapor securing and burnback resistance characteristics. Fluoroprotein-type concentrates are available for proportioning to a final concentration of either 3 percent or 6 percent by volume, using either fresh water or seawater. They are nontoxic and biodegradable after dilution. The normal-use temperature range for these agents is 20 to 120°F (–7 to 49°C).

Film-Forming Fluoroprotein (FFFP) Agents

Film-forming fluoroprotein (FFFP) agents are composed of protein together with film-forming fluorinated surface-active agents, which make them capable of forming water solution films on the surface of most flammable hydrocarbons and conferring a fuel-shedding property to the foam generated.

Air-foams generated from FFFP solutions have fast-spreading and leveling characteristics and, just as other foams, act as surface barriers to exclude air and prevent vaporization. Like AFFF, they generate a self-healing, continuous floating film on hydrocarbon fuel surfaces that helps suppress combustible vapors. However, to ensure fire extinction, an FFFP blanket, as with other types of foam, should cover the entire fuel surface.

Because of the rapid and easy foaming capability of FFFP solutions, water spray devices may be used in many situations. However, the foams produced drain rapidly and may have less burnback resistance compared to protein-based foams.

Film-forming fluoroprotein-type concentrates are available for proportioning to a final concentration of either 3 or 6 percent by volume, using either freshwater or seawater. They may be used in conjunction with dry chemical agents without compatibility problems.

Protein (P) Foaming Agents

Protein-type air-foams use aqueous liquid concentrates proportioned with water for their generation. These concentrates contain high-molecular-weight natural proteinaceous polymers derived from a chemical digestion and hydrolysis of natural protein solids. The polymers give elasticity, mechanical strength, and water retention capability to foams generated from them. The concentrates also contain dissolved polyvalent metallic salts, which aid the protein polymers in their bubble-strengthening capability when the foam is exposed to heat and flame. Protein-type concentrates are available for proportioning to a final concentration of either 3 or 6 percent by volume, using either freshwater or seawater. In general, these concentrates produce dense, viscous foams of high stability, high heat resistance, and good resistance to burnback, but they are less resistant to breakdown by fuel saturation than are AFFF and fluoroprotein foams. They are nontoxic and biodegradable after dilution. The normal-use ambient temperature range for these concentrates is 20 to 120°F (–7 to 49°C).

Low-Temperature Foaming Agents

This type of foam concentrate is protected for storage and use at low temperature by the inclusion of freezing-point depressants. Low-temperature foaming agents may be used at ambient temperatures as low as –20°F (–29°C). They are available for use at either 3 or 6 percent by volume concentration in either freshwater or seawater, and may be of the AFFF or protein-based type.

Alcohol-Type Foaming Agents (AR)

Air-foams generated from ordinary agents are subject to rapid breakdown and loss of effectiveness when they are used on fires that involve fuels that are water soluble, water miscible, or of a "polar solvent" type. Examples of this type of fuel are alcohols, enamel and lacquer thinners, methyl ethyl ketone, acetone, isopropyl ether, acrylonitrile, ethyl and butyl acetate, and the amines and anhydrides. Even small amounts of these substances mixed with common hydrocarbon fuels, such as gasohol, may cause rapid breakdown of ordinary fire-fighting foams.

Therefore, certain special foaming agents, called alcohol-type concentrates, have been developed. These alcohol-resistant (AR) concentrates are proprietary compositions of several types, some containing a protein, fluoroprotein, or an aqueous film-forming foam concentrate base. The most common are usually described as polymeric alcohol-resistant AFFF concentrates which produce foams suitable for application to spill or in-depth fires of either hydrocarbon or water-miscible flammable liquids by any foam-generating device. They exhibit AFFF characteristics on hydrocarbons and produce a floating gel-like mass for foam buildup on water-miscible fuels. Agents of this type have no transit time limitations. Normal-use temperatures for any of the alcohol-type agents are 35 to 120°F (1.7 to 49°C).

Medium- and High-Expansion Foaming Agents

Medium- and high-expansion foams are agents for control and extinguishment of Class A and some Class B fires, and are particularly suited as a flooding agent for use in confined spaces. The foam is an aggregation of bubbles, mechanically generated by aspiration or a blower-fan, which forces air or some other gas through a net or screen that is wetted by an aqueous solution of

surface-active foaming agents. Under proper conditions, fire-fighting foams of expansions from 20:1 up to 1000:1 can be generated.

Medium- or high-expansion foam is a unique vehicle for transporting wet foam masses to inaccessible places, for total flooding of confined spaces, and for volumetric displacement of vapor, heat, and smoke. Tests have shown that when used under certain circumstances in conjunction with water from automatic sprinklers, the foam will provide more positive control and extinguishment than either extinguishing agent by itself. Optimum efficiency in any one type of hazard is dependent on the rate of application and the foam expansion and stability.

Liquid concentrates for producing medium- and high-expansion foams consist of synthetic hydrocarbon surfactants of a type that will foam copiously with a small input of turbulent action. They are generally used in approximately 2 percent proportion in water solution. Medium-expansion foam may also be generated from solutions of fluoroprotein, protein, or AFFF concentrates at 3 or 6 percent proportion.

Medium- or high-expansion foams are particularly suited for indoor fires in confined spaces. Their use outdoors may be limited because of the effects of weather. These foams have several effects on fires:

1. When generated in sufficient volume, they can prevent the air necessary for continued combustion from reaching the fire.
2. When forced into the heat of a fire, the water in the foam is converted to steam, which reduces the oxygen concentration by diluting the air.
3. The conversion of the water to steam absorbs heat from the burning fuel. Any hot object exposed to the foam will continue breaking down the foam, converting the water to steam, and being further cooled.
4. Because of its relatively low surface tension, foam solution not converted to steam will tend to penetrate Class A materials. However, deep-seated fires may require overhaul.
5. When accumulated in depth, high-expansion foam can provide an insulating barrier for protection of exposed materials or structures not involved in a fire, thereby preventing fire spread.

Research has shown that using air from inside a burning building to generate high-expansion foam has an adverse effect on the volume and stability of the foam produced. Combustion and pyrolysis products, when they react chemically with the foaming agent, can reduce the volume of foam produced and increase the drainage rate. The high temperature of the air breaks down the foam as it is generated. Physical disruption also takes place, apparently caused by vapor and solid particles from the combustion process. These factors that cause foam breakdown may be compensated for by higher rates of foam generation.

Entry to a foam-filled passage must not be attempted without use of self-contained breathing apparatus. The foam mass also reduces vision and hearing, and lifelines must be used for personnel entering the foam.

Foam of approximately 500:1 expansion can be successfully used for control of fires and reduction of vaporization from LNG spills. As water slowly drains from the foam in small amounts, it forms a thin ice layer which floats on the LNG and supports the high-expansion foam blanket. Fixed and portable high-expansion foam facilities of this type have been provided for LNG storage and manufacturing plants.

Other Synthetic Hydrocarbon Surfactant Foaming Agents

There are many synthetically produced surface active compounds that foam copiously in water solution. When these are formulated properly, they may be used as wetting agents or as fire-fighting foams and employed in much the same manner as other types of foam (see NFPA 18, *Standard on Wetting Agents*).

Hydrocarbon surfactant foam liquid concentrates are employed in 1 to 6 percent proportions in water. When these solutions are used in conventional foam-making devices, the resulting air-foam possesses low viscosity and spreads quickly over liquid surfaces. Its fire-fighting characteristics depend on (1) the volume of the foam layer on the burning surface, which halts access to air and controls combustible vapor production; and (2) the minor cooling effect of the water in the foam, which becomes available due to a relatively rapid breakdown of the foam mass. This water solution does not possess film-forming characteristics on the flammable liquid surface although, under some conditions, it may produce a temporary water emulsion due to its wetting agent or "detergent-type" properties. Because of the low surface tension and wetting properties of the water solutions of these foams, they also may be used as extinguishing agents for Class A fires, although they were primarily developed with medium- or high-expansion foam in mind.

Synthetic hydrocarbon surfactant foams are generally less stable than other fire-fighting foams. Their water solution content drains away rapidly, leaving a bubble mass which is highly vulnerable to fuel heat or mechanical disruption. Usually these foams must be applied at higher rates than other fire-fighting foams to achieve extinction. Many formulations of this type of foam concentrate break down other foams if used simultaneously or sequentially.

Caution should be used when using wetting agents described in NFPA 18 for Class B situations. The test criteria used to classify the wetting agent for use on Class B fires may be significantly different than that used to classify AFFF, fluoroprotein, and protein foams. Fire suppression of Class A, B, and D fires using wetting agents is the subject of ongoing investigation.

Foams for Vapor Suppression

Fire-fighting foams may be used to suppress vapors from unignited flammable liquids for which the foams are proven extinguishing agents. To ensure good vapor suppression, the foam must be applied gently, so as to not mix fuel with the foam, and must cover the entire fuel surface. Care should be taken not to agitate the fuel during foam application, because static spark ignition of volatile hydrocarbons can result from plunging and turbulence from a foam or water stream.

There are flammable, toxic, or otherwise hazardous liquids on which fire-fighting foams are unstable and are therefore

unsuitable for use either for fire fighting or vapor suppression. Special vapor-mitigating foams have been developed that are relatively stable on many hazardous liquids; one type is an alcohol-resistant fire-fighting foam of the low-expansion type, which can be additionally stabilized to enhance its effective foam life and stability on toxic, flammable, or corrosive liquids. Other types are medium-expansion foams especially formulated to be stable on either acidic or alkaline hazards. These medium-expansion foams are not effective fire-fighting foams.

In general, vapor-mitigating foams should be applied to spills of toxic liquids only by trained personnel wearing suitable protective gear. These foams require special engineering consideration, and, to date, no standards have been developed for their use. The manufacturers should be consulted for use, limitations, and application data.

Chemical Foam Agents and Powders

These foam-producing materials have become obsolete because of the superior economics and ease of handling of the liquid foam-forming concentrates previously discussed. Chemical foam is formed from the chemical reaction in aqueous solution between aluminum sulfate ("A," acidic) and sodium bicarbonate ("B," basic) which also contains proteinaceous foam stabilizers. Foam is formed by the generation of carbon dioxide gas trapped in the bubbles of the foaming solution.

GUIDELINES FOR FIRE PROTECTION WITH FOAMS

The following general rules apply to the application and use of ordinary air-foams:

1. The more gently the foam is applied, the more rapid the extinguishment and the lower the total amount of agent required.

2. Successful use of foam is also dependent on the rate at which it is applied. Application rates are described in terms of the amount by volume of foam solution reaching the fuel surface (in terms of total area) every minute. If the foam has an expansion rate of 8:1, an application rate of 0.1 gpm/ft^2 (4.1 Lpm/m^2) will provide 0.8 gal/ft^2 (32.8 L/m^2) of finished foam every minute. Increasing the foam application rate over the recommended minimum will generally reduce the time required for extinguishment. However, little time advantage is gained if application rates are increased more than three times the minimum recommended. If application rates are less than the minimum, extinguishment time will be prolonged or may not be accomplished at all. If application rates are so low that the rate of foam loss by heat or fuel attack equals or exceeds the rate of foam application, the fire will not be controlled or extinguished.

3. The minimum recommended application rate is the rate found by test to be the most practical in terms of speed of control and amount of agent required. The general curve in Figure 17.4.1 illustrates the rate-time relationship for foam application to a hazard. The curve may be displaced right or left depending on fuel, method of application, and type of foam concentrate; hence, the need for carefully engineered systems based on the appropriate standard and actual test information.

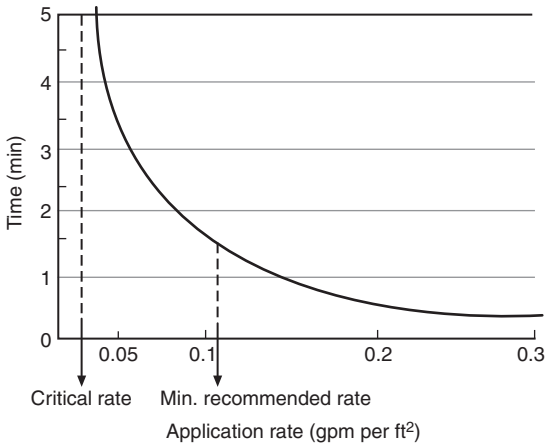

FIGURE 17.4.1 General Relationship of Foam Application Rate to Time of Application Necessary for Extinction (1.0 gpm/ft^2 equals 40.7 Lpm/m^2)

4. In general, air-foams will be more stable when they are generated with water at ambient temperature. Preferred water temperatures range from 35 to 80°F (1.7 to 27°C). Either freshwater or seawater may be used. Water containing known foam contaminants, such as detergents, oil residues, or certain corrosion inhibitors, may adversely affect foam quality.

5. Foams are adversely affected by air containing certain combustion products. Although the effect is minor with ordinary air-foam and ordinary hydrocarbon fuels, it is desirable to locate fixed foam-makers on the sides of, rather than directly over, the hazard.

6. Recommended pressure ranges should be observed for all foam-making devices. Foam quality will deteriorate if these limits (high and low) are exceeded.

7. Many air-foams are adversely affected by contact with vaporizing liquid extinguishing agents, their vapors, and by some dry chemical agents.

FOAM-GENERATING METHODS

The process of producing and applying fire-fighting air-foams to hazards requires three separate operations, each of which consumes energy. They are (1) the proportioning process, (2) the foam generation phase, and (3) the distribution method. A flow diagram illustrating the relationship of the three operations is given in Figure 17.4.2.

In general practice, air-foam generation and distribution occur nearly simultaneously within the same device. There are also many types of proportioning. In certain portable devices, all three functions are combined into a single device. The design and performance requirements of foam systems dictate the choice of types of proportioning, generating, and distributing equipment for the protection of specific hazards.

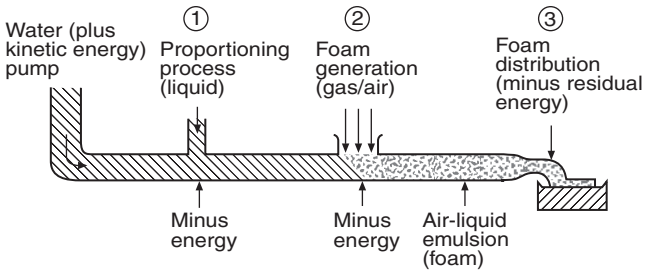

FIGURE 17.4.2 Steps in Air-Foam Generation

Foam Concentrate Proportioners

It is very important that foam concentrate be proportioned accurately into the water stream. Proportioning equipment, foam concentrate, and discharge equipment must be matched to produce the proper solution concentration at system design operating pressures. If proportioning is low, the foam will be relatively weak and unstable; if too high, the foam may be stiff and concentrate will be wasted, thus reducing effective system operating time.

So that a predetermined volume of liquid foam concentrate may be mixed with a water stream to form a foam solution of fixed concentration, the following two general methods are used:

1. Methods that use the pressure energy of the water stream by venturi action and orifices to induct concentrate
2. Methods that use external pumps or pressure heads to inject concentrate into the water stream at a fixed ratio to flow

Figures 17.4.3 and 17.4.4 illustrate the general principles of the two different proportioning methods. Figure 17.4.5 shows a section view of a proportioner. Specific system designs of proportioning equipment are given below.

The Nozzle Eductor. This type of foam concentrate proportioner is of simple design and is widely used in portable foam-making nozzles where foam concentrate is available in 5 gal (19 L) pails or drums as shown in Figure 17.4.6. Incorporating a modified venturi within the foam-making nozzle section, the nozzle eductor drafts concentrate from a portable container through a pickup tube. By using a properly sized orifice or pipe section at the low-pressure cavity, the concentrate is mixed in proper proportion to the fixed flow and operating pressure of the nozzle and foam generation proceeds.

In-Line Eductor. This type of proportioner educts or drafts foam concentrate from a container or tank by venturi action, using the operating pressure of the hose water stream on which it is installed, and injecting concentrate into that flow of water. Its correct operation is very sensitive to waterflow and pressure. Changes in either of these factors from those for which the eductor was designed will result in incorrect proportioning. Distances of more than 6 ft (1.8 m) elevation from the eductor to the lowest liquid level of the foam concentrate container also may result in incorrect proportioning. Foam-generation devices and

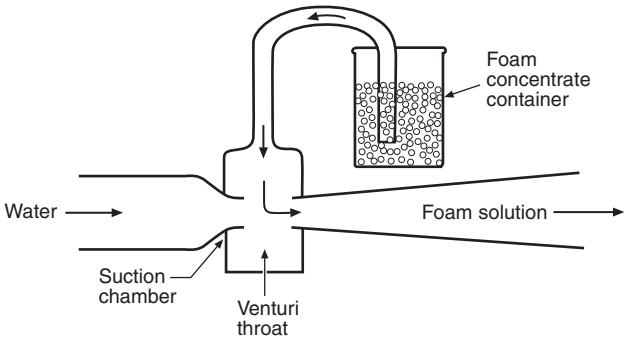

FIGURE 17.4.3 Venturi Induction (In-Line) Proportioner

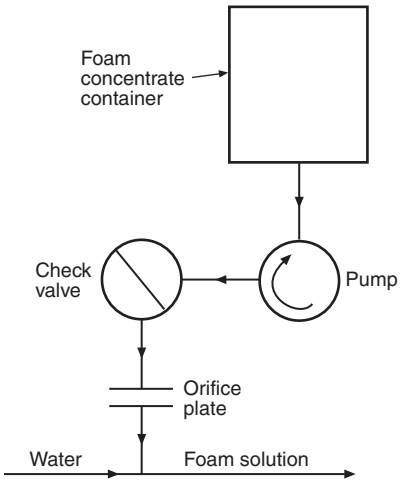

FIGURE 17.4.4 Foam Concentrate Pump Proportioner

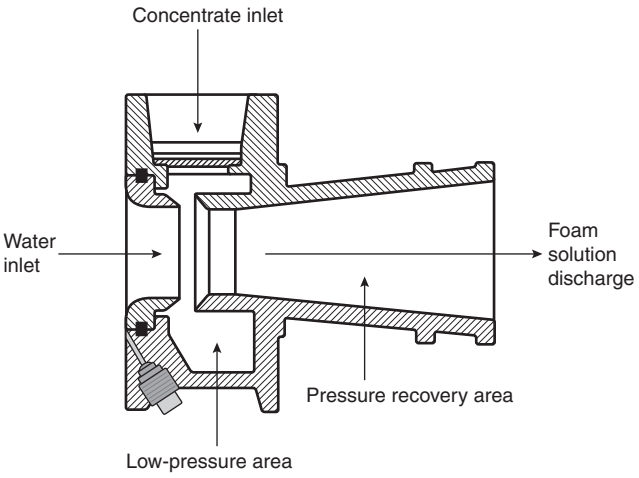

FIGURE 17.4.5 Section of Proportioner (Source: Ansul Incorporated)

FIGURE 17.4.6 Air-Foam Nozzle with Built-In Eductor

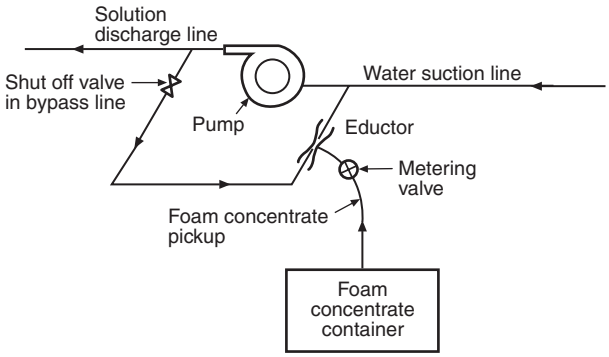

FIGURE 17.4.7 Around-the-Pump Proportioner

maximum downstream lengths of hose recommended for each eductor must be carefully adhered to. This proportioning device may be used in the hose line leading to the foam-generation device. An eductor of this type may also be installed at the foam concentrate tank in a fixed system or at the pump discharge of a mobile pumper.

Some designs of this proportioning device incorporate metering valves in the foam concentrate intake line so various volume percentages of concentrate in the water stream may be obtained. A check valve is usually placed in this intake so that water cannot flow back into the foam concentrate container if a blockage occurs or a valve is closed in the downstream hose. The use of this eductor requires an allowance for a pressure loss of approximately 30 percent in the system or layout.

Around-the-Pump Proportioner. This type of proportioner also operates on the venturi principle, except that this proportioner must be situated at the pump and connected to both suction and pressure sides. Its advantage is that pressure recovery of the venturi action is attained, and pump delivery pressures to the foam-making device or devices downstream require no compensation for pressure loss except for that in the layout hose length. The net delivery volume of the pump will be decreased by 10 to 40 gpm (38 to 150 Lpm) in this method of proportioning (Figure 17.4.7). The small portion of the pump discharge flows through a bypass line to the suction side of the pump. A venturi eductor in this line produces a negative pressure on the foam concentrate pickup line from the foam concentrate container. Foam concentrate is led to the eductor, where it mixes with water and is delivered to the suction side of the pump.

Multiple foam-makers may be supplied with foam solution by this type of proportioner when it is supplied with a multiported metering valve designed for the required flows.

Pressure Proportioning Tank. This type of proportioner may consist of one tank or of two tanks separately connected to the water and foam solution lines. The tank or tanks in the system may each be fitted with a flexible diaphragm or bladder to separate the "driving" water from foam concentrate. Tanks may rely simply on differences in density of the two liquids to retard mixing during operation (without diaphragm or bladder) when proportioning protein or fluoroprotein concentrate.

The principle of this device is simple. A small amount of the flowing water volumetrically displaces foam concentrate into the main water stream. The design pressure of the vessel must be above the maximum static water pressure encountered in the system.

Water is allowed to enter the foam tank from the main stream with as little friction loss as possible. An orifice meters liquid in the tank into the low-pressure area. Advantages of this system are its low-pressure drop, automatic proportioning over range of flows and pressures, and its freedom from external power. Its disadvantages are a long refill time (since it is a "batch" method, the tank must be drained of its driving water and the tank or the bladder refilled with concentrate) and an economic limit on size.

Coupled Water Motor-Pump Proportioner. This proportioner consists of two positive displacement rotary pumps mounted on a common shaft. Water delivered to the larger pump (motor) causes it to drive the smaller pump, which is used to draft concentrate from a container and deliver it (at line pressure) to the water discharge line from the larger pump. By proportioning the sizes of the two pumps, the correct volume of concentrate is delivered to the water stream.

This proportioner is manufactured in only two sizes for water throughputs of 60 to 180 gpm (227 to 680 Lpm) and 200 to 1000 gpm (757 to 3800 Lpm). Both sizes are designed for proportioning foam concentrates recommended for use at 6 percent concentration. A pressure drop of 25 to 30 percent in the water stream supplied to the device is required for its operation.

Balanced Pressure Proportioner. Foam proportioning into the water line supplying a foam suppression system can be accomplished by using a balanced pressure or positive-pressure injection-type proportioning system. These two methods provide the widest variations for operating flows, pressures, and operating ranges for systems having single and multiple supplies

to protected areas. Although these systems are widely used for fixed systems, they may also be used in mobile apparatus as shown in Figure 17.4.8. The following sections describe installations for fixed systems. Figure 17.4.9 shows a representative skid-mounted balanced pressure proportioner unit.

Balanced Pressure System Utilizing a Foam Concentrate Pump for a Single Injection Point. This method, illustrated in Figure 17.4.10, uses a separate pump for supplying foam concentrate that is delivered in the correct proportions into the flowing water. Foam concentrate to water percentage equals 1 percent (1:99), 3 percent (3:97), or 6 percent (4:96) for Class B foams protecting flammable liquids. Usually a modified venturi type proportioner that includes a fixed metering orifice is used at the injection point of foam concentrate into the water stream. A pressure-balancing valve senses the water and foam pressures entering the modified venturi during flowing conditions. The balancing valve maintains equal water and foam pressures entering the venturi device by sensing the water pressure and relieving the higher-pressure foam concentrate supply back to the foam tank reservoir. The foam pressure at the entry point to the metering orifice is maintained equal to the water pressure at all flowing conditions of the system. The modified venturi creates a low-pressure point. This metering pressure drop at the foam concentration entry point allows the concentrate to enter the water stream and mix as a solution, supplying the discharge devices in the protected area. As waterflow increases to system, the metering pressure drop increases, thereby maintaining proper proportions of foam concentrate to water.

Balanced Pressure System Using Diaphragm Bladder Tank for Single Injection Point. This simple system, illustrated in Figure 17.4.11, uses water power to operate. The system consists of a pressure vessel-type steel tank that includes a reinforced rubber bladder inside that is shaped to fit the inside geometry of the tank vessel. Foam concentrate is contained inside the bladder, and water is supplied to the outer shell of the bladder. As the water compresses the bladder, foam concentrate is forced out of the tank and supplied to the modified venturi proportioner and metering orifice in the same manner as used for the foam concentrate pump system described previously. As the waterflow increases through the venturi, a metering pressure loss is created. When this pressure loss reaches a point equal to the pressure loss in the supply and discharge piping of the foam concentrate tank, the proper foam concentrate flow will occur. This provides the proper solution mixture of foam water required to extinguish the fire at 1 percent (1:99), 3 percent (3:97), or 6 percent (6:94). The height of proportioner above the tank top must be considered in the friction loss calculations, as it will directly affect the foam concentrate percentage accuracy. This type of system proportions lean (lower foam concentrate than needed) below the approved or listed minimum flow rates. Consideration should be used before applying this system below these flow rates: the listed minimum flow rates should fall within the operating limits of the application. AFFF or nonviscous foam concentrates are generally acceptable considering the initial operation of the system discharge device. Most alcohol-resistant foam concentrates are very viscous and create much higher friction loss in foam concentrate piping. The higher friction loss results in a much higher minimum flow rate where the desired percentage of foam to water is developed. This is critical in closed sprinkler systems where initial operation of sprinklers will not result in enough flow to produce proper foam water so-

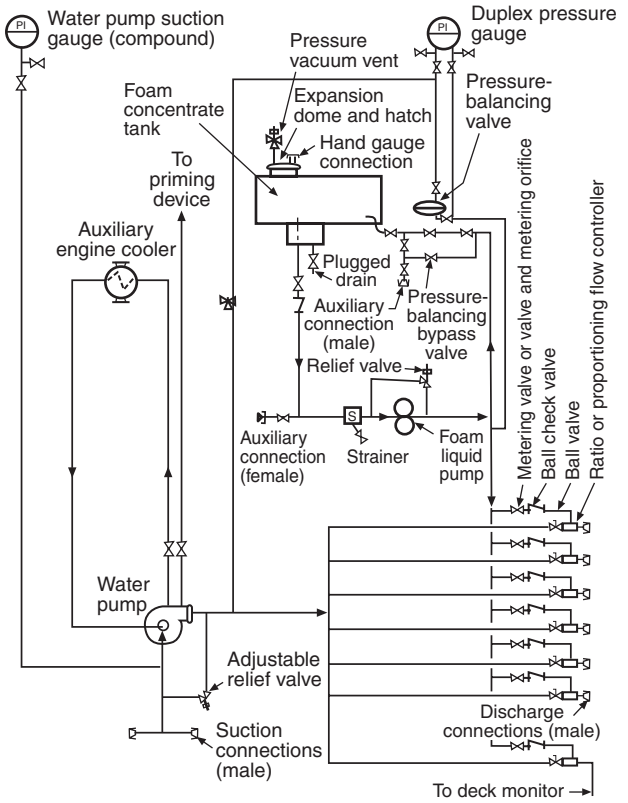

FIGURE 17.4.8 Balanced Pressure Proportioning for Mobile Equipment

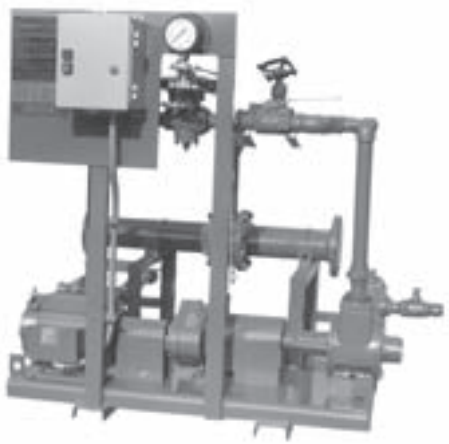

FIGURE 17.4.9 Skid-Mounted Balanced Pressure Proportioner (Source: Ansul Incorporated)

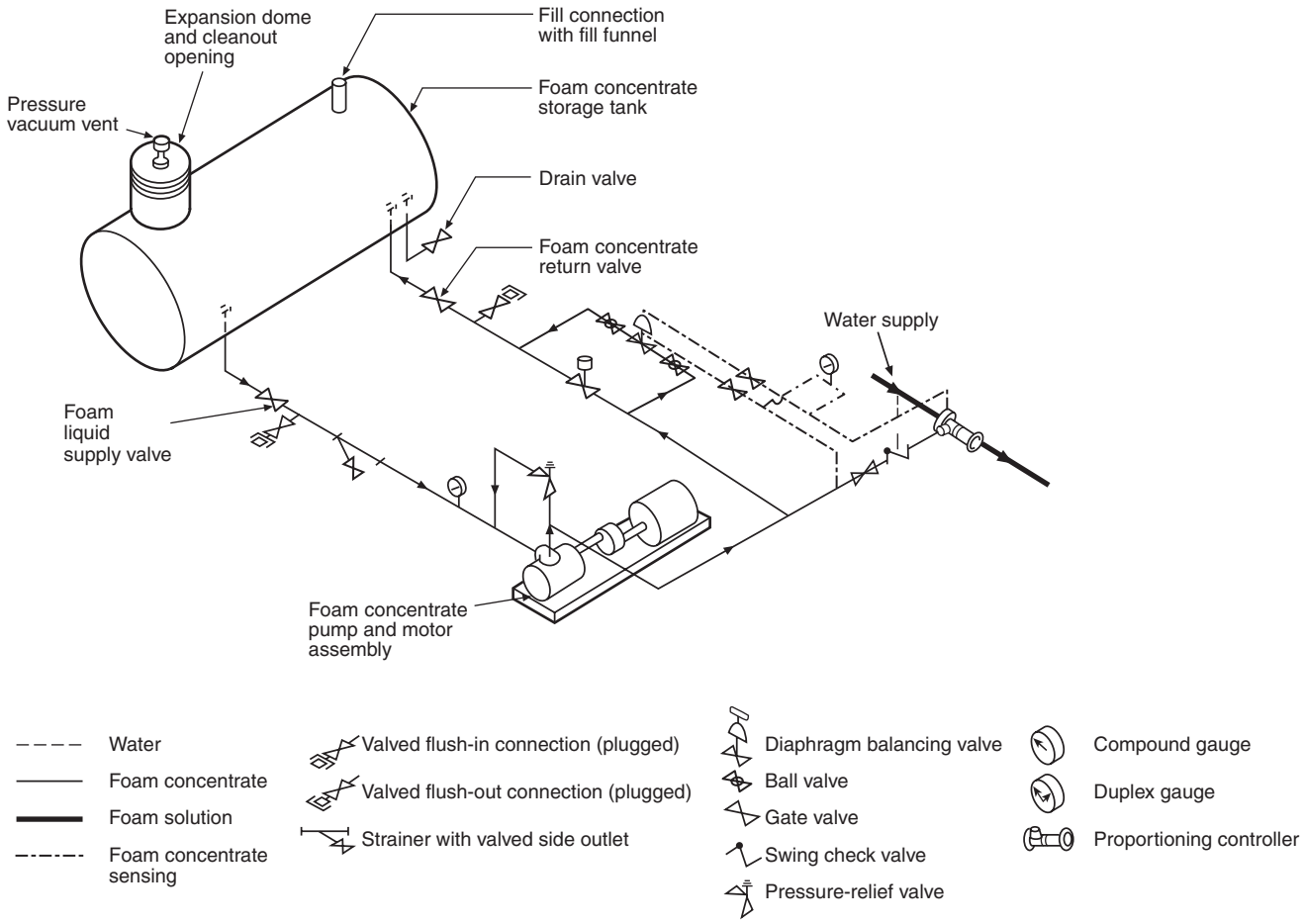

FIGURE 17.4.10 Balanced Pressure Proportioning with Single Injection Point

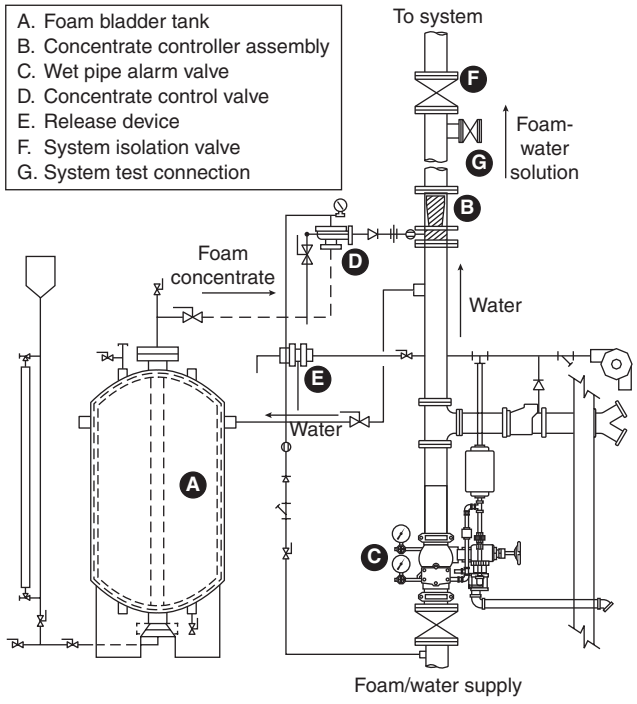

FIGURE 17.4.11 Wet Pipe Bladder Tank Balanced Pressure System (Source: The Viking Corp.)

lution to extinguish a flammable liquid fire. In a deluge system, the proportioner should be sized to meet the desired hydraulic characteristics of the application.

Balanced Pressure System Using Positive Pressure Foam Injection and In-Line Balanced Pressure Proportioners (ILBP). Balanced pressure proportioning systems using positive-pressure foam injection and an ILBP device use two basic methods of foam concentrate supply (Figures 17.4.12, 17.4.13, 17.4.14, and 17.4.15). Foam concentrate can be supplied from a bladder tank or a foam concentrate pump as long as it is being supplied at a higher pressure than the water supply at the point of foam injection to the system.

In a bladder tank system, concentrate proportioning is accomplished by installing a pilot-operated pressure control valve (POPCV) upstream of the ILBP assembly (see Figures 17.4.12 and 17.4.13). The POPCV is adjusted to a lower outlet pressure differential that meets the required difference to operate the ILBP balancing valve (note: this differential is manufacturer dependent). The water supply to the bladder tank is taken upstream of the POPCV, which provides a higher outlet pressure of foam concentrate being supplied to the ILBP proportioner assembly (Figure 17.4.16). The ILBP balancing valve senses the water supply pressure entering the modified venturi proportioner device and lowers the foam concentrate pressure entering the metering orifice to that equal to the water pressure entering

the venturi proportioner. When the water pressure equals the foam concentrate pressure and the waterflow is such that the proper metering pressure drop is created across the venturi, the proper percentage of foam concentrate is injected into the water supply, thereby delivering the proper foam solution to the protected area.

Since this is a positive injection system, foam solution percentage will be rich (i.e., higher foam concentrate than needed) at lower flow rates. For example, this phenomemon will occur in a closed sprinkler system during the initial operation of several sprinklers. Also, the minimum listed flow rates for this type of system, compared to the balanced pressure bladder tank system, are typically much lower when alcohol-resistant foam concentrates are used.

In some installations, the total water supply pressure available is not adequate to create the proper pressure differential to allow the system to proportion within its operating limits. A foam concentrate pump can be used to supply the foam concentrate at a higher pressure than the water supply pressure at the point of foam injection to the system. Positive displacement foam pumps are generally used to supply the higher foam concentrate pressure. Accurate supply is maintained by using a pressure-relief-type valve in the foam supply line. The relief is piped back to the foam supply tank and is set to supply adequate pressure at the full range of system operating conditions (Figure 17.4.17).

A positive-pressure foam system using a bladder tank with POPCV or foam concentrate pump can supply multiple system proportioning points from a single foam supply source. Also, a longer distance from the foam concentrate supply is feasible. Large variations in system pressure are tolerable with the same accuracy of foam proportioning throughout the system. Multiple discharge devices and system sizes are adaptable to a single foam concentrate supply source.

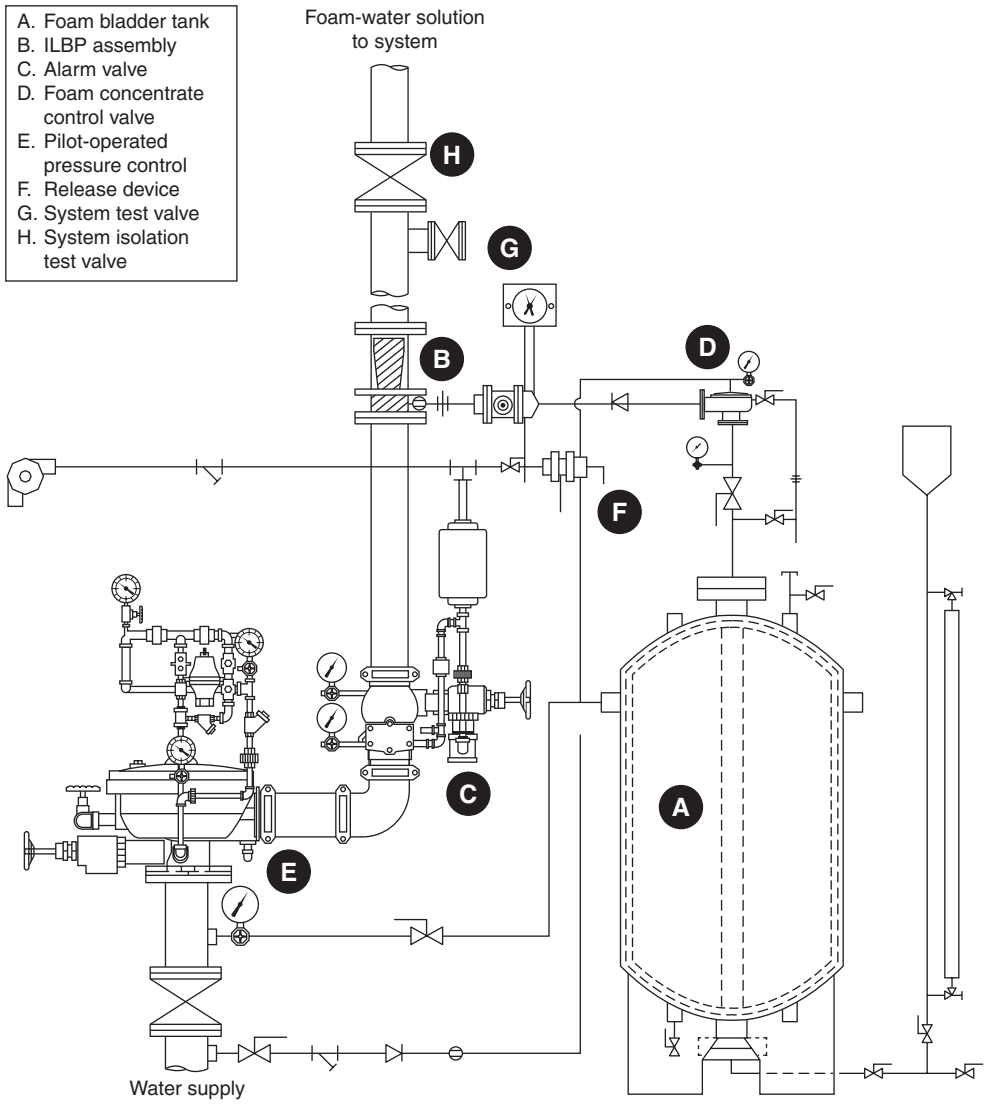

FIGURE 17.4.12 Wet Pipe Low-Flow Foam Proportioning System Bladder Tank Foam Supply (Source: The Viking Corp.)

Advantages and Disadvantages of Various Balanced Pressure Proportioning Systems. The different balanced pressure proportioning systems have advantages and disadvantages, depending on the particular design. The balanced pressure system with foam concentrate pump for single injection point has the following advantages and disadvantages:

Advantages

1. Foam concentrate can be pumped longer distances and the balancing valve can be kept adjacent to proportioner.
2. Foam supply can be replenished on the run by adding to the atmospheric tank.
3. The system will proportion at the correct percentage at lower flow rates due to less effect by friction loss.

Disadvantages

1. Maintenance and reliability requirements are relatively greater.
2. The cost is relatively high.
3. A backup power supply is required for electric systems.

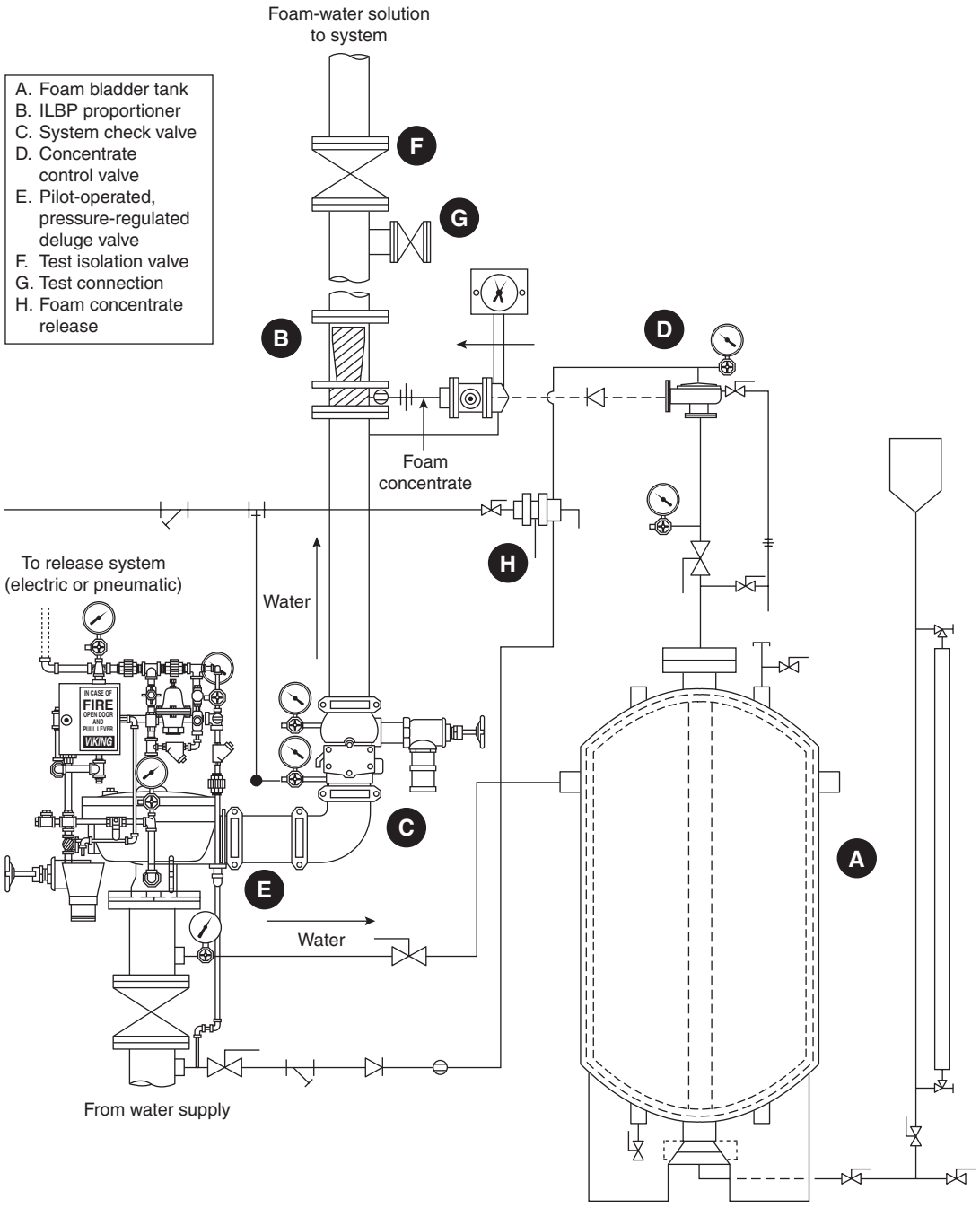

FIGURE 17.4.13 Low-Flow Preaction System with Bladder Tank (Source: The Viking Corp.)

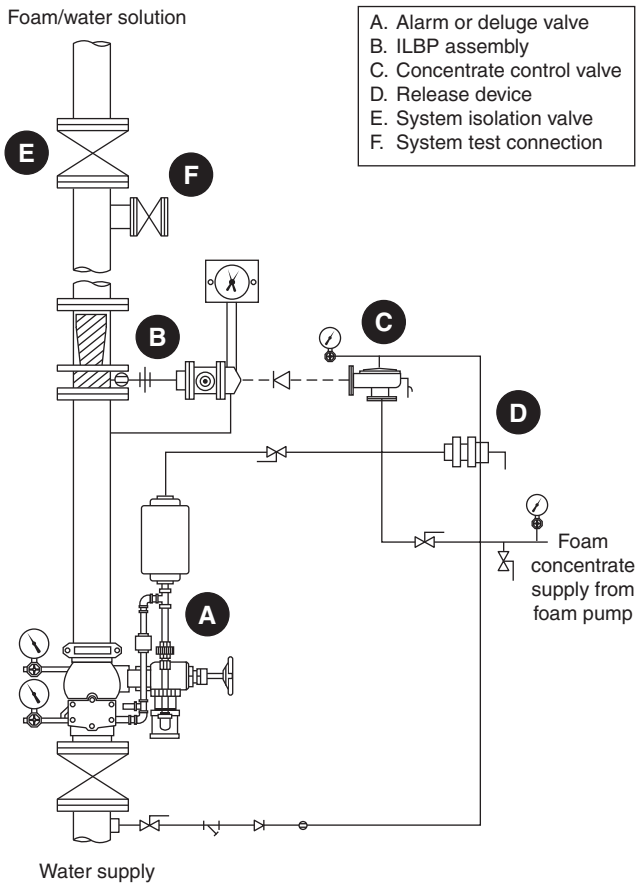

FIGURE 17.4.14 Wet Pipe Low-Flow System, Foam Supply from Foam Pump (Source: The Viking Corp.)

4. The balanced pressure proportioning systems require more space than other systems.
5. The system is limited to a single point of foam injection.

The balanced pressure system with bladder tank has the following advantages and disadvantages:

Advantages

1. No electrical power is required for the water-powered design.
2. Costs are lower for smaller systems and deluge applications.
3. Pre-engineered systems and foam storage are available.
4. Retrofitting into an existing system is relatively easy.
5. Maintenance costs are relatively low.

Disadvantages

1. Refill during a fire condition is not easy.
2. The bladder tank must be installed adjacent to proportioning equipment.
3. Proportioning of foam at low flows is lean, that is, has a lower concentrate percentage than needed or below listed rates.
4. The application is limited to a single proportioning source. (It is difficult to balance various flows that may be required in a multi-injection point system.)

The balanced pressure system with positive foam injection bladder or foam pump has the following advantages and disadvantages:

Advantages

1. The system can handle variable-pressure applications with the bladder tank design discharging a constant supply.
2. Multiple proportioning points and sizes can be accommodated from a single foam supply source.
3. Foam concentrate can be supplied a long distance to multiple points.
4. A wide flow range is available.
5. In closed head sprinkler systems, foam is supplied at the first sprinkler operation.
6. Multiple discharge devices and multiple areas of protection can be supplied.
7. Pressures and proportioning can be adjusted at the point of application.

Disadvantages

1. Refill during a fire condition is not easy.
2. Higher relative cost proportioning assembly compared to the system with only an injection pump or bladder.

Variable Orifice, Variable Flow Demand Proportioner. This type of balanced pressure system uses a specially designed, flow-sensitive, moveable piston section in the water supply that controls a variable orifice in the foam concentrate line. A pump supplies concentrate at monitored pressures to the metering orifice, which changes in size proportionally to the system demand for foam solution. The device is especially designed for large-capacity systems. Its design provides accurate proportioning over ranges of flow of water of approximately 2.3 to 1.

Premixed Foam Solution. This method of proportioning is a batch type of mixing of concentrate with water, usually in a container that can be pressurized. The measured volume of concentrate is poured into a measured volume of water to yield a foam solution of the recommended strength; for example, for a 3 percent solution in a container that holds 100 gal (378.5 L) of liquid, 97 gal (367 L) of water are poured into it and 3 gal (11.5 L) of foam concentrate are mixed with it to give a solution of 3 percent by volume. The final solution mixture is then educted from a tank to a pump or placed in a pressurizing vessel.

Some foam concentrates are not suitable for storage in premixed solution. Even those that are formulated for this use may show gradual loss of effectiveness. Manufacturers' recommendations should be followed carefully.

Portable Aspirating Equipment and Systems

Because of the difficulties associated with pumping or transporting generated foam in pipes or hoses and the familiarity of fire fighters with nozzles, the earliest designs of air-foam generators were devised to be used in much the same manner as water nozzles. They incorporated a crude venturi design whereby a jet or jets of foam solution enter an open contracted portion of a large-diameter foam tube. This action lowers the atmospheric

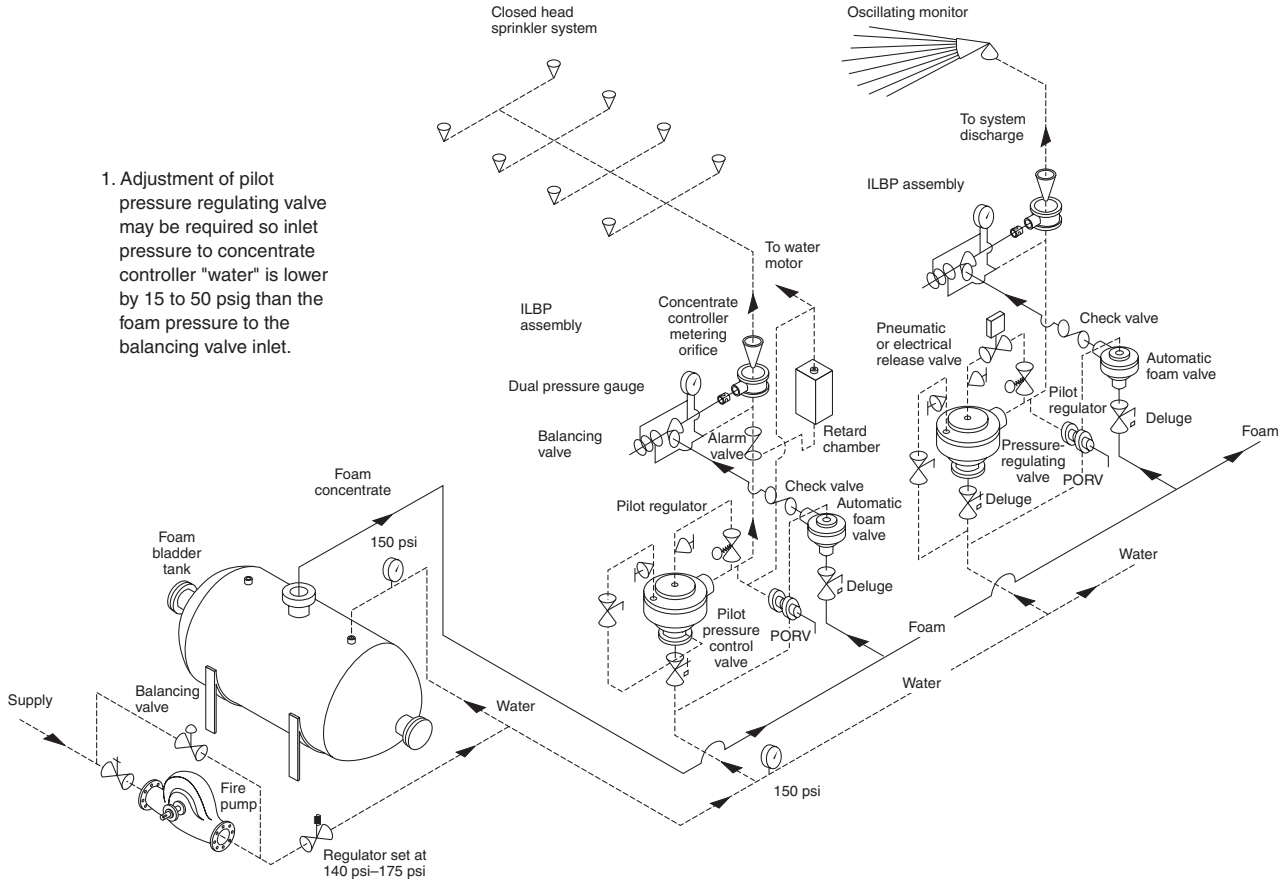

FIGURE 17.4.15 Low-Flow Foam System Schematic with Multiple Discharge Areas (Source: The Viking Corp.)

FIGURE 17.4.16 ILBP Assembly (Source: The Viking Corp.)

pressure surrounding the jets, and air is drawn or aspirated into the throat of the tube. Downstream of the contracted portion of the tube, a high turbulence and mixing of air and foam solution occurs. This turbulence may be increased by internal turbulence-accelerating devices, such as screens or baffles. The kinetic energy of the fluid contributes to this mixing action so that a useful, stable foam exits the tube at a relatively low pressure (Figure 17.4.18).

The basic design principles of this method of producing air-foam have been changed in many ways to yield, for many purposes, foams with greatly differing characteristics. However, all types of nozzles incorporating foam solution jets leading into free air-mixing cavities, followed by discharge apertures of one kind or another, use the aspirating action for making foam.

Hose Line Foam Nozzle. This is the most widely used portable, air-aspirating foam device for flammable liquid fire fighting. It is manufactured in a variety of capacities up to approximately 350 gpm (1325 Lpm) (Figure 17.4.19). Supplied with foam solution from a proportioner or by means of a pickup tube, it is used for combating fires resulting from spills of flammable liquid, or fires in tanks or fuel pits. To provide a variety of foam stream patterns that may be needed for the extinguishment operation, these nozzles often contain built-in devices that allow continuous foam pattern variation from a solid, straight stream to an inverted, filled umbrella shape (Figure 17.4.20). As with water streams, foam is employed in a solid, straight stream for range or reach. A flat or wide "bushy" shape is used for gentle

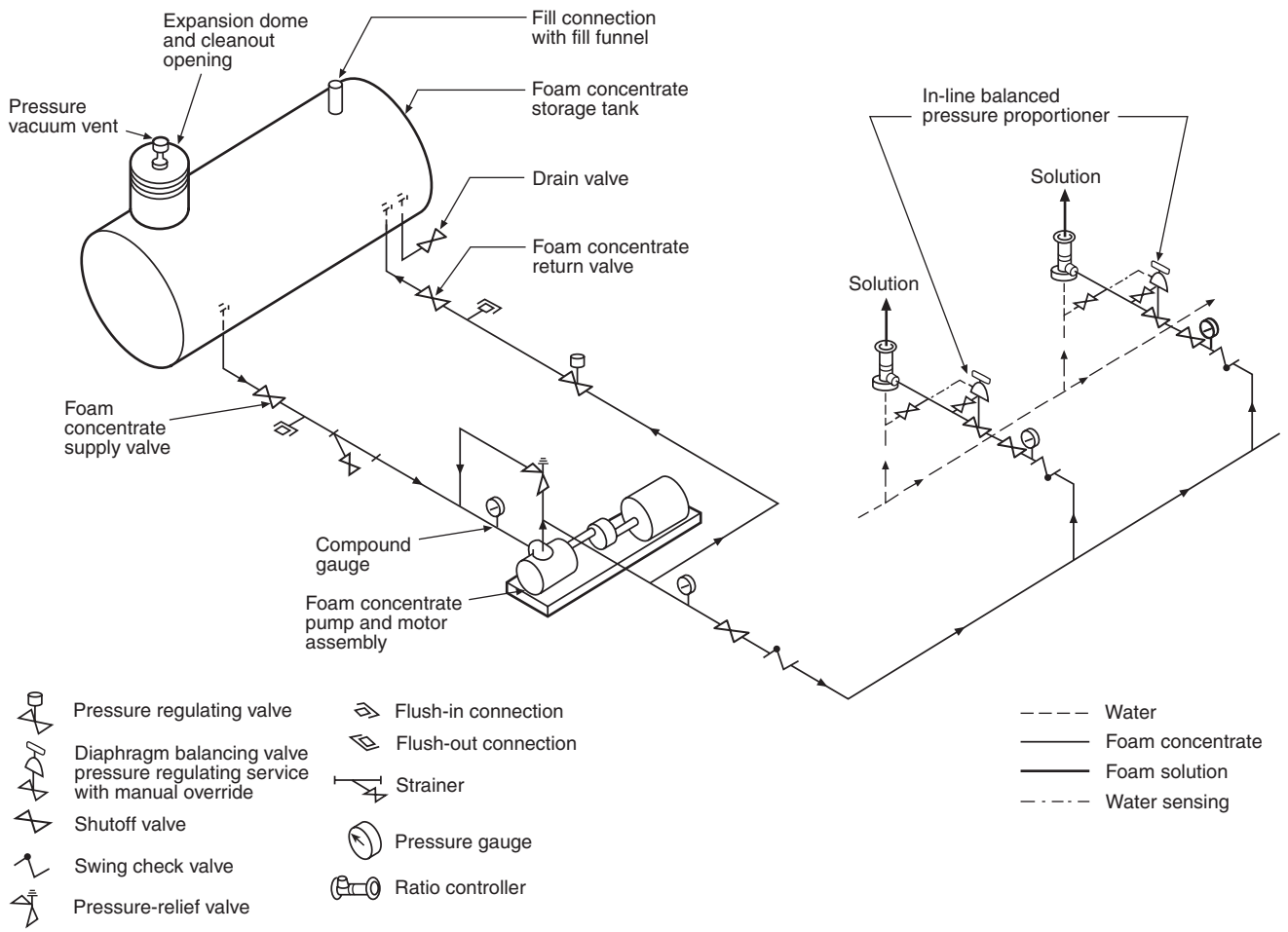

FIGURE 17.4.17 Balanced Pressure Proportioning with Multiple Injection Points

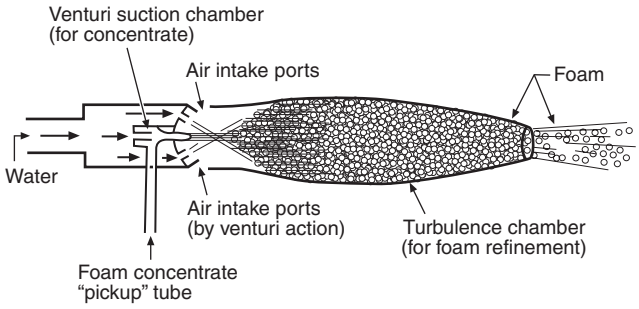

FIGURE 17.4.18 Aspirating Foam-Maker with a Concentrate Pickup Tube

FIGURE 17.4.19 Hose Line Foam Nozzle

FIGURE 17.4.20 Adjustable Hose Line Foam Nozzle (Source: Kidde Fire Fighting)

"snowstorm" application on the burning fuel surface, and a very wide, circular "bushy" shape is used for radiance shielding of the operator during fire extinguishment or penetration into the fire area.

Another type of hose line foam nozzle is especially designed for quick, portable, one-person use during emergency operations from airport crash-rescue vehicles. Customarily

called a handline foam nozzle, it is equipped with a foam pattern changing device, and some types are supplied with a valve control for converting the water or solution stream into a water spray for cooling purposes.

Foam and Foam-Water Monitors. In large-scale fuel-fire fire-fighting operations, it may become necessary to position a foam-making nozzle with a high discharge rate at an advantageous position for continuous application of foam to one point or over an area. Devices for this purpose are available in a variety of types, for example, as part of mobile truck apparatus, on a trailer, wheeled, or permanently mounted. The foam pattern change is accomplished by moving a deflector into the foam stream or by opening or closing the "jaws" at the exit end of the large tube.

This equipment has largely been replaced with non-air-aspirating monitor nozzles. Non-air-aspirating monitors are effective devices for extinguishing hydrocarbon pool fires.

High Back-Pressure Foam-Maker. Certain circumstances necessitate that foam be generated and supplied under pressure for transmission in pipes under a definite pressure head. The subsurface foam injection method for fuel tank fire extinguishment requires this type of foam-maker. The high back-pressure foam-maker, or "forcing foam-maker," is a venturi device that is carefully designed to make foam by air aspiration and to supply it under pressure at a carefully selected ratio (from 2:1 to 4:1) of air-to-foam solution. Approximately 20 to 40 percent of the inlet pressure is recoverable. In use, this foam device is usually brought to the fixed piping foam inlet, installed, and then supplied with foam solution by a portable or mobile pumper, or it may be permanently installed as part of a fixed system (Figure 17.4.21).

Medium- and High-Expansion Foam-Generating Devices. There are two principal methods used for the generation of these types of fire-fighting foams. One method uses a modified venturi action with air aspiration flow, whereas the other requires use of a blower and screen to form the finished foam. The latter system produces high-expansion foam containing sufficient residual kinetic energy to enable it to be forced through large tubes and passageways.

Figure 17.4.22 illustrates the operating principles of high-expansion foam-generating devices.

Water Fog or Spray Nozzles and Monitors. Several types of adjustable water fog or spray nozzles for portable use provide an acceptable fire-fighting foam of adequate characteristics when supplied with certain foam concentrates. The most universal design of these is shown in Figure 17.4.23. An adjustable water spray monitor nozzle designed for this purpose is shown in Figure 17.4.24.

These portable water spray nozzles are used with aqueous film-forming foam (AFFF) solutions for combating flammable liquid tank and spill fires and are used in this manner on crash-rescue vehicles. The foam resulting from the discharge of AFFF solution devices that do not aspirate air is generally fast draining and may not impart the same degree of burnback resistance as the foam produced from AFFF agents when foam-generating devices of an air-aspirating type are used.

Foam monitors using AFFF can be either air-aspirating or non-air-aspirating. Non-air-aspirating monitor nozzles have the advantage of increased stream reach compared to air-aspirated devices. Combined with the rapid-fire knockdown characteristics of AFFF, these monitors are very effective for large hydrocarbon pool fire suppression. In particular, foam monitors are effective in aviation fire protection, both as turrets on aircraft rescue and fire-fighting vehicles and in fixed systems protecting aircraft hangars (Figure 17.4.25).

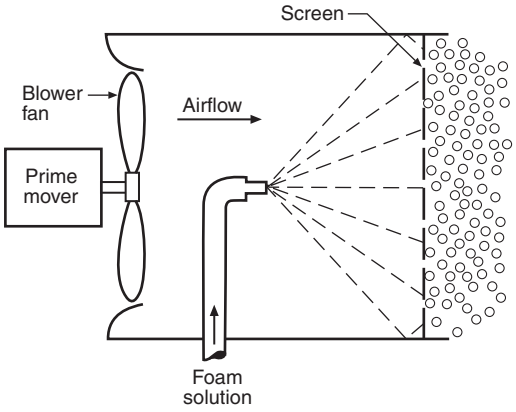

FIGURE 17.4.22 Fan-Blower-Type High-Expansion Foam-Generator

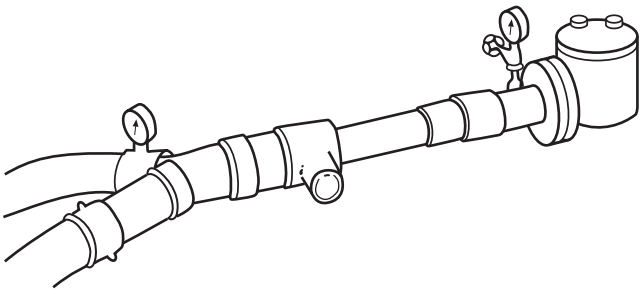

FIGURE 17.4.21 High Back-Pressure-Type (or Forcing-Type) Foam-Maker

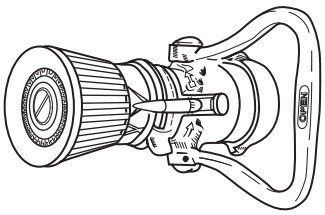

FIGURE 17.4.23 Variable-Pattern Water Fog Nozzle Foam-Maker for Use with AFFF

FIGURE 17.4.24 Adjustable 350 to 500 gpm (1325 to 1893 Lpm) Water Spray Foam Monitor Nozzle (Source: Elkhart Brass Mfg. Co.)

FIGURE 17.4.25 Foam Monitor (Source: Ansul Incorporated)

Foam-Generating Equipment

Where flammable liquid fire protection is required for permanently installed hazards, such as fuel storage tanks or dip tanks containing flammable or combustible liquids, air-foam-generating and distributing devices are installed integrally with the hazard. These fixed devices, which are piped to a source of foam solution, may be arranged for manual control or automatic activation by fire detectors in the event of fire.

Open Dip Tank, Quench Tank System. This system consists of a small, aspirating foam-maker supplied by a water line and foam concentrate educted to the foam-maker. Foam discharges into a mixing box, which also acts as a surface distributor for gentle foam application.

Foam Chambers for Large Fuel Storage Tanks. Fire protection of large outdoor fuel storage tanks requires that several foam chambers with foam-makers be installed at equally spaced positions slightly below the curb angle on the top periphery of the tanks. These chambers are connected to lines on the ground that supply foam solution to each foam-maker simultaneously in case of ignition of the flammable contents of the tank. Frangible seals at the discharge outlet of the foam chamber prevent vapor from entering the foam piping. These seals are designed to burst when foam pressure is applied. A screen for the air inlet to the aspirating foam-maker prevents clogging from foreign matter, such as bird nesting material. A universal or swing pipe joint is installed at ground level in the foam solution inlet pipe to prevent fracturing of the supply piping if an explosion precedes a tank fire (Figure 17.4.26).

Internal Tank Foam Distributing Devices. A prime requirement for efficient fuel tank extinguishment by topside foam devices has always been that the foam must be applied to the burning surface without undue plunging into the fuel or allowing the foam to become coated with burning fuel. This gentle application of foam must be accomplished at any level of the contents of the tank. Many devices have been developed to gently apply foam from one point, regardless of burning fuel level. These devices are required for some alcohol-type foams. Alternatively, foam discharge into a tank may be deflected to run down the inside tank shell to the burning fuel surface.

Central "Foam House" Distributing Systems. These systems, as shown in Figure 17.4.27, consist of an enclosure housing a foam concentrate supply tank and a proportioning device of an automatic or balanced pressure type. Foam solution is supplied under adequate pressure from this foam house to the piping system and controlled by appropriate valves so that the foam chambers with foam-makers on the burning tank receive foam solution.

Semifixed systems of similar design are more frequently used with mobile foam concentrate supply from foam trucks. The truck proportions and pumps foam solution to the pipe laterals feeding the foam-makers from a safe location outside the dike.

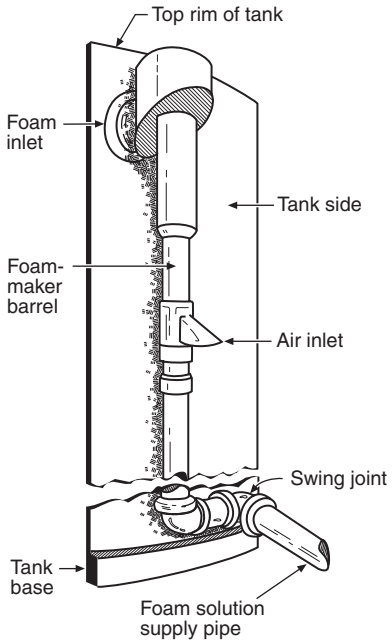

FIGURE 17.4.26 Air-Foam Chamber at Top of Storage Tank

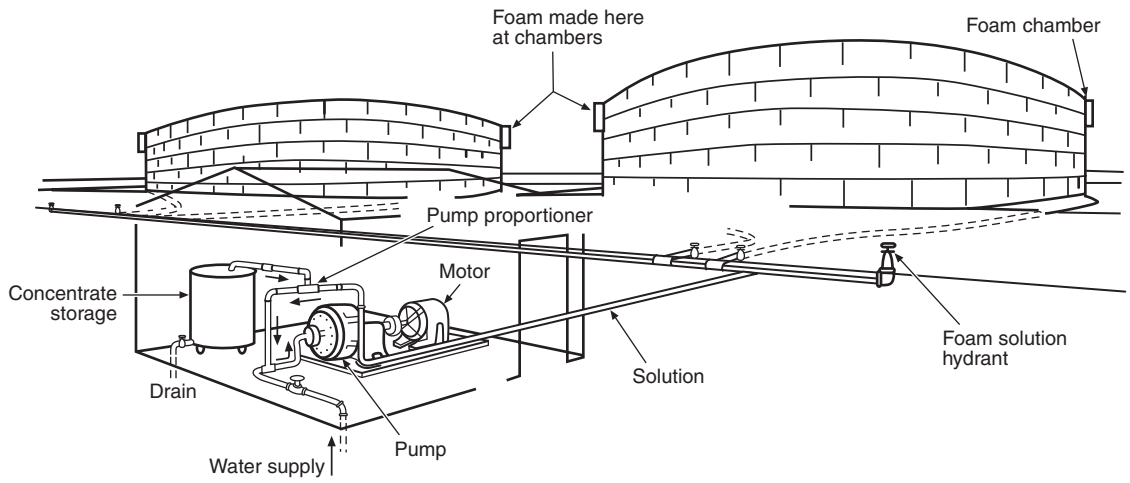

FIGURE 17.4.27 Schematic Arrangement of Foam Protection for Storage Tanks

Intermediate Back-Pressure System. Although this system of tank protection is similar to the preceding central foam house distributing systems, it utilizes strong and well-braced foam-delivery pipes on the side of the tank, which act as supports to prevent buckling of the tank from heat. This system also uses a foam truck to proportion and pump foam solution to the piping outside the dike or firewall of the burning tank.

Subsurface Foam-Injection Systems. The problems inherent with the application of foam from above the burning surface (topside) are sometimes difficult to combat. Problems may consist of explosion or fire damage to the foam-makers or tankside piping, forceful upward fire-drafted air currents that prevent the falling foam from reaching the burning surface, hazard to workers attempting to erect portable foam distributing devices near the burning tank, or inability of foam applied from the periphery of a large tank (greater than about 200 ft [61 m] in diameter) to flow and form a complete center seal during fire attack.

The obvious solution to these problems is to apply foam from the underside of the fire, causing it to come up through the contents of the tank. The subsurface foam-injection system accomplishes this by injecting foam under the pressure of the head of fuel in the tank, using the high back-pressure foam-maker referred to previously in this chapter.

Entry of foam may be provided at several points at the base of the tank (base injection), or it may be accomplished by means of the product line. Where large tanks are involved, a branched pipe foam distributor may be installed on or slightly above the floor of the tank above any expected water level and connected to a central foam-injection point outside the tank.

Mobile foam concentrate proportioning equipment is used with these systems, pumping from a protected position outside the tank dike (Figure 17.4.28).

Subsurface application of foam is recommended only for protection of cone-roof tanks containing hydrocarbon fuels. It is not recommended for use on floating-roof tanks or for protection of polar or water-miscible fuels.

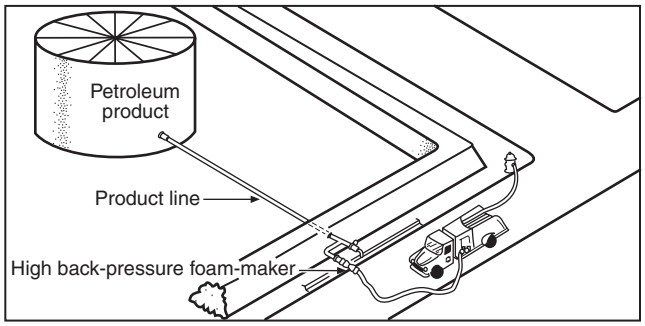

FIGURE 17.4.28 Semifixed Subsurface Foam Installation

These topside and subsurface injection systems require careful design. Their minimum installation requirements are found in NFPA 11.

Portable Foam Devices for Tank Protection. Mobile foam monitors of high-capacity discharge (foam cannon) may be used to direct a stream of foam over the open top rim of a burning tank so foam will fall into the burning area. These devices waste foam because of crosswinds, fire updrafts, and inability to place the equipment in an advantageous position. A foam-application rate 60 percent higher, therefore, must be included in the design; details are contained in NFPA 11. Nozzles of this type also are used to extinguish fires in the overflow space inside the dike surrounding the tank. Care is needed in directing the foam stream from such devices, as shown in Figure 17.4.29.

In recent years, mobile foam monitors with capacities up to 4000 gpm (15,144 Lpm) have been developed and used successfully for extinguishment of hydrocarbon fires in tanks up to 195 ft (60 m) in diameter.[1] Careful planning is required to ensure availability of adequate waterflow and pressure, foam concentrate, proportioning equipment, trained personnel, and safe accessibility to the hazard when relying on such devices.

FIGURE 17.4.29 Portable (Trailer) Foam Monitor (Cannon) (Source: Kidde Fire Fighting)

Other Considerations for Fuel Storage Tanks. The floating-roof storage tank has a good chance of freedom from fire; consequently, fixed foam systems are usually not required for their protection. Under certain circumstances, however, there may be a need for a foam-flooding system to flood the rim area.

As indicated by its name, the "covered" floating-roof tank is totally enclosed above the floating roof with a properly vented steel roof. Usually Class IB flammable liquids, such as gasolines and crudes, are stored in "open top" or covered floating-roof tanks. During storage operations, there is no vapor space between the bottom of the floating roof and the stored product surface. However, during periods of initial fill, a flammable vapor space will exist until the floating roof is buoyant. In the case of covered floating-roof tanks, the space between the fixed and the floating roof will be within the flammable range during periods of initial fill and longer, depending on atmospheric temperatures, wind, and vapor pressure of the stored product. Class II and III combustible liquids are usually stored in fixed-roof tanks.

In an open-top floating-roof tank, a rim of fire is all that can be expected. Rim fires may be caused by atmospheric disturbances, such as lightning, but usually do not occur if the floating roof is bonded properly to the shell as specified in NFPA 780, *Standard for the Installation of Lightning Protection Systems.* Rim fires due to atmospheric disturbances do not occur in covered floating-roof tanks because of the "Faraday effect" of the fixed roof. Rim fires may occur in either type of floating-roof tank due to a serious exposure fire.

Fixed foam fire protection for the open top floating-roof consists of aspirating-type foam-makers installed in such a way that when supplied with foam solution, their foam discharge floods the annular area covered by the seal around the tank periphery. A metal foam dam may be needed to restrict the foam to this area. Further details of such construction are contained in the Appendix to NFPA 11.

When foam protection is desired for covered floating-roof tanks, a foam system similar to those described for fixed-roof tanks may be provided. Subsurface injection systems are not recommended for open top or covered floating-roof tanks because of the possibility of tilted or sunken roofs resulting in improper foam distribution.

Fixed foam systems employing foam spray nozzles or monitors are used to protect large oil-water separators, pump areas, and oil piping manifolds. Fixed foam systems are not generally used to protect tank diked areas. Large wheeled monitors or trailer-mounted foam cannons, as shown in Figure 17.4.29, are used for this purpose.

Other Hazards. Certain hazardous areas, for example, aircraft hangars, may require additional foam-making and distributing devices, such as foam monitors mounted near floor level. Often these devices are provided with an automatic oscillator so that foam is continually distributed over the floor to extinguish burning spilled fuel under obstacles, such as aircraft wings. These are typically combined with air-aspirating or non-air-aspirating sprinklers installed at the roof of the hangar. Application rates for non-air-aspirating AFFF sprinklers are lower than air-aspirating sprinklers, in recognition of the fire plume penetration capability of AFFF discharged from ordinary sprinklers. NFPA 409 provides design details for overhead and low-level foam systems.

NFPA 409 also recognizes low-level AFFF application, combined with water-only sprinklers at the ceiling. A recently developed low-level AFFF nozzle can be installed in the floor

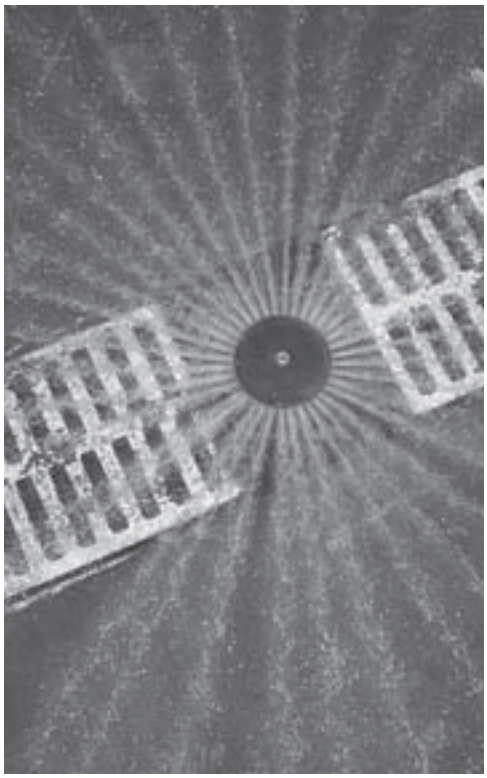

FIGURE 17.4.30 Low-Level AFFF Nozzle Installed in Aircraft Hangar Floor (Source: The Viking Corp.)

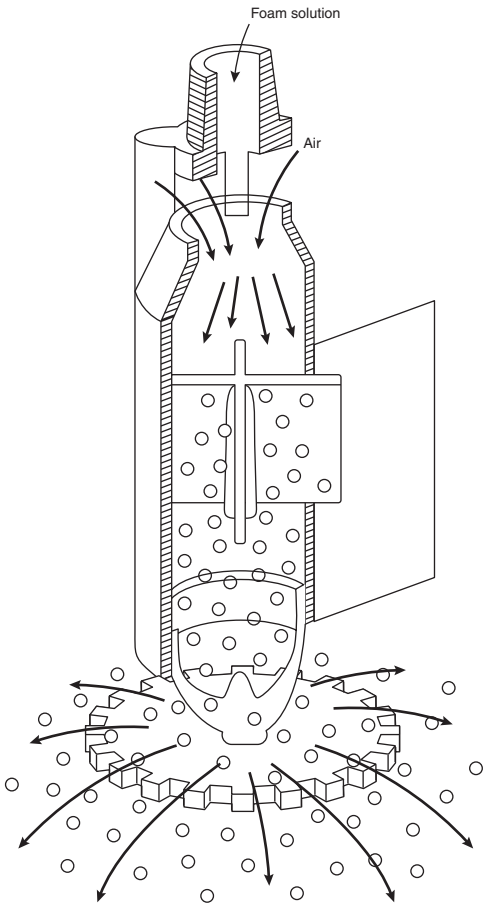

FIGURE 17.4.31 Air-Aspirating Foam Sprinkler (Source: Ansul Incorporated)

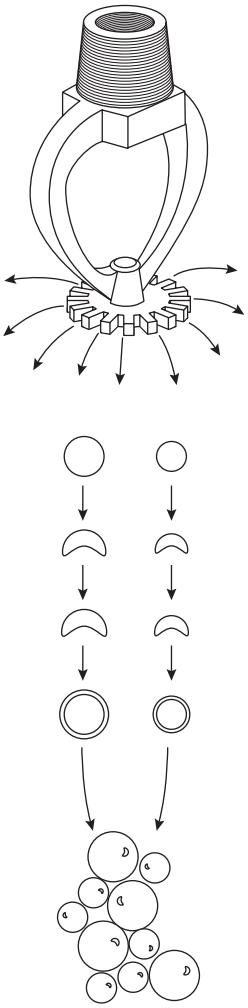

FIGURE 17.4.32 Non-Air-Aspirating Sprinkler (Source: Ansul Incorporated)

of a hangar (Figure 17.4.30). This design reduces AFFF spray to aircraft in the event of a false discharge.

Fixed foam systems are used to protect petroleum piers and wharves where products and petroleum crude are handled. Foam monitors of 1000 gpm (3800 Lpm) and greater capacity are mounted on towers and remotely operated to cover both the pier and the tanker deck in the pipe manifold area. Below deck, foam spray systems or oscillating monitors are installed to keep the pier tenable in the event of a spill fire floating on the water surface under the pier.

Fixed systems consisting of automatically operated combinations of foam spray systems and foam monitors are often installed to protect chemical processing plants. Alcohol-resistant foams are usually required. In these designs, where there may be a high risk, process vessels, pumps, and piping often are all included within the foam distribution pattern for overall protection. The system can be automatically activated by heat or fire detectors. See NFPA 11 for design of foam spray systems.

Foam-Water Sprinkler Systems. In areas where flammable and combustible liquids are processed, stored, or handled, water discharge may have limited effectiveness for controlling or extinguishing large spill fires. The effectiveness of water in these applications is a function of many variables, including fuel type, storage container, fuel configuration and geometry, height of the facility, and the level of acceptable risk. NFPA 30 recognizes both water and AFFF protection for indoor storage of liquids.

Sprinklers or nozzles used to protect liquid hazards may be air-aspirating or non-air-aspirating devices. Figures 17.4.31 and 17.4.32 show examples of both types of sprinklers. Air-aspirating sprinklers, such as that shown in Figure 17.4.31, were developed for use with protein-based foam in deluge sprinkler applications. Foam solution is discharged through the device, aerated, and applied through the open sprinkler or nozzle to the hazard. Detection systems are often provided to actuate the system automatically. The design area is the entire area of the deluge system.

Although AFFF can be effectively applied using air aspirating deluge sprinklers, it can also be discharged through traditional water sprinklers. Research was performed by the Factory Mutual Research Corporation related to aircraft hangar fire protection.[2] This research demonstrated that AFFF discharged through non-air-aspirating standard sprinklers was at least as

effective in extinguishing large spill fires as AFFF discharge from air-aspirating sprinklers. The effectiveness of the standard sprinklers was attributed to more effective plume penetration by higher-density foam particles. Figure 17.4.32 shows an example of a non-air-aspirated sprinkler.

Standard sprinklers used with AFFF may be open for use in a deluge system, or closed where the use is similar to a standard closed sprinkler system. For example, NFPA 409 recognizes the use of open standard sprinkler AFFF systems installed at the ceiling of aircraft hangars. NFPA 30 requires the use of closed sprinklers where AFFF is used. The sprinkler temperature rating, response characteristics, and application rate are specified based on test data for a specific hazard.

Air-aspirating foam sprinklers and standard sprinklers used to discharge AFFF are tested in accordance with UL 162.[3] Systems are listed for use by the combination of foam concentrate, proportioning system, and discharge device. For example, a vendor's foam sprinkler design may consist of 3 percent AFFF concentrate using a balanced pressure proportioner discharging through a standard sprinkler. Additionally, foam sprinkler or spray nozzles must have essentially the same discharge pattern when water is discharged. This dual capability affords the system Class A and B extinguishing capability.

Fundamental design requirements can be found in NFPA 16. Listing of system components is required in accordance with UL 162. Listing requirements vary as a function of discharge device (air-aspirating and non-air-aspirating sprinkler), type of fuel (miscible and nonmiscible hydrocarbons), extinguishment time, and burnback resistance. Only AFFF and FFFP can be used through standard orifice sprinkler and spray systems. These agents must extinguish test fires at an application rate of 0.10 gpm/ft^2 (4.1 Lpm/m^2). Standard orifice (½ in. [12.7 mm]) and large orifice ($^{17}/_{32}$ in. [13.5 mm]) sprinklers are recognized. Air-aspirated foam-water sprinklers using protein or flouroprotein foam are tested at 0.16 gpm/ft^2 (6.6 Lpm/m^2). It should be recognized that NFPA 16 requires a minimum design application rate of 0.16 gpm/ft^2 (6.6 Lpm/m^2) for all foam agents. Other standards, such as NFPA 409 and NFPA 30, provide specific requirements for the particular hazards.

Application rates required to protect polar solvents using alcohol-type foams are generally greater than those required for nonmiscible hydrocarbons. The sprinkler design must meet the minimum application rate in the UL listing for the polar solvent being protected. Where polar solvents in containers are protected in warehouses, other factors may impact minimum design application rates. For example, the lowest design application rate currently permitted in NFPA 30 for indoor storage is 0.30 gpm/ft^2 (12.3 Lpm/m^2).

Fixed systems using foam-water or standard sprinklers require associated foam concentrate tanks, proportioners, and suitable pumps to supply the system with foam solution. NFPA 16 is the installation standard that provides fundamental design requirements. Other standards may require specific additional features. For example, NFPA 30 requires that foam solution be discharged when four closed AFFF sprinklers have operated. This requires a system that can proportion at the low end of the flow range, such as the positive pressure ILBP system discussed earlier.

DELIVERING FOAM FROM VEHICLES

The majority of the mobile fire protection vehicles using foam consist of airport crash-rescue trucks and industrial foam trucks used at oil refineries and petrochemical plants. Many of these vehicles are also equipped to discharge dry chemical in combination with foam. These have combined, or "twinned," agent equipment and are described later in this chapter.

Crash-Rescue Trucks

Mobile foam trucks, developed by military and municipal authorities in the United States and other countries, are large, custom-designed vehicles with oversize running gear that allows them to travel over all types of terrain. The trucks carry their own water supply as well as foam concentrate. Automatic balanced pressure proportioning is usually provided, although in some designs an around-the-pump proportioning system is used. The trucks are equipped with separate engine-driven water pumps and foam concentrate pumps so that the turret monitor nozzles and roadway foam nozzles can be discharged while the truck is in motion. Recent designs accomplish this using one or two engines for all necessary power requirements. Crash-rescue trucks are equipped with large-capacity, adjustable foam monitors of 500- to 1500-gpm (1900- to 5700-Lpm) discharge, depending on truck size. The foam monitors are usually installed on top of the cab with remotely operated controls. The trucks are also equipped with portable handlines. Although limited, their supply of foam concentrate and water is sufficient for fire fighters to form a passageway for access to a burning aircraft for rescue. Their primary purpose is rescue of people and not necessarily a total extinguishment of fire. Aircraft crash-rescue foam vehicles are specially designed and require special attention to detail in their fabrication and performance requirements. NFPA 414, *Standard for Aircraft Rescue and Fire-Fighting Vehicles,* provides standards for such vehicles.

Industrial Foam Truck Design

Foam trucks are manufactured by vendors who make a specialty of this design and by some vendors of fire department pumpers. Generally, using NFPA 1901, *Standard for Automotive Fire Apparatus,* as a design basis, these trucks are fabricated on a suitable commercial or custom truck chassis. In the United States, they are available with water pumps in sizes from 750 to 2000 gpm (2839 to 7570 Lpm), using gasoline or diesel engine drives.

Balanced pressure proportioning is provided for maximum flexibility and simplification. A positive-displacement-type foam concentrate pump takes suction from a 500- to 1000-gal (1900- to 3800-L) foam concentrate storage tank. The foam concentrate pump is driven by a power takeoff or hydraulic motor. The water pump is driven by a transfer gear from the main drive shaft behind the transmission. A metering valve at each truck outlet can vary foam proportioning from 3 to 6 percent.

In addition to the foam concentrate, each foam truck usually is equipped with a 500- to 1000-gpm (1900- to 3800-Lpm) monitor and carries fire hose, foam nozzles and adjustable water spray nozzles, hose adapters, and other accessories. The maxi-

mum truck height is limited to permit passage beneath overhead obstructions. When the truck is equipped with a large-capacity nozzle on a telescopic or articulated boom, a second power take-off is used to power the boom hydraulic system.

Foam trucks for special hazard application, instead of fixed foam systems, are popular for refinery and petrochemical plant use. Their advantages are as follows:

1. Capability of discharging their maximum capacity at any hazard in the plant rather than only to the limited areas covered by a fixed system.
2. Improved reliability because their equipment is easily maintained; thus, operating procedures can be simplified and fire fighters can be trained more easily to use the equipment.

Industrial foam trucks are used to extinguish spill fires in process areas, piping runs, and tank diked areas, as well as in fighting tank fires. Their 500- to 1000-gpm (1900- to 3800-Lpm) foam-water monitors and 1½ in. (38 mm) and 2½ in. (64 mm) handlines are used for fighting major spill fires. Designs that are equipped with monitor nozzles on articulated or telescopic booms enable the operator to discharge foam at various elevations in and around process equipment. In some cases, a tank fire can be extinguished with this equipment. Figure 17.4.33 illustrates a typical industrial foam truck. Figure 17.4.34 illustrates a typical foam truck with a telescopic boom, ladder, and basket. The foam trucks with booms may or may not be equipped with a ladder and/or basket.

COMBINED AGENT OR "TWINNED" EQUIPMENT

The capability of dry chemical agent (especially potassium-salt-types) for very fast flame control and three-dimensional flowing fuel extinguishment is well documented. However, dry chemicals have no cooling or vapor-suppressing capability, and reflash can occur. With dry-chemical-compatible foam concentrates, it is possible to apply a coating of vapor-securing foam to a burning fuel surface that has been freshly extinguished by the chemical action of dry chemical discharges.

FIGURE 17.4.33 A Typical Industrial Foam Truck (Source: Motiva Enterprises LLC)

FIGURE 17.4.34 Foam Truck with Telescopic Boom and Nozzle with Ladder and Basket (Source: Kidde Fire Fighting)

The logical extension of these developments has been incorporated into portable and mobile devices with dual-trigger valve nozzles and monitor nozzles discharging AFFF and dry chemical. Figure 17.4.35 illustrates a type of twinned agent nozzle where dry chemical is entrained in the foam stream. Figure 17.4.36 shows a twin agent unit consisting of a dry chemical agent tank and an AFFF solution tank for dual agent application. The use of this combined agent attack allows three-dimensional as well as spill fire extinguishment of flammable liquid with both speed and freedom from reignition. The fire-fighting vehicle shown in Figure 17.4.37 is for aircraft crash-rescue purposes and for extinguishment on freeways or in plants, using combined agents.

In use, the twinned hose from the hose reel supplies dry chemical and AFFF to a dual nozzle for one-person operation. Similarly, the turret nozzles at the front of the vehicle discharge dry chemical from the upper nozzle and AFFF from the lower. With a sweeping motion, the flames are controlled with the dry chemical, quickly followed by a vapor-securing, cooling layer of foam to prevent reflash. This rapid action halts

FIGURE 17.4.35 Twinned Agent Nozzle (Source: Crash Rescue Equipment Service)

FIGURE 17.4.36 Twin Agent Unit Consisting of One Dry Chemical Agent Tank and One AFFF Solution Tank for Dual Agent Application (Source: Ansul Incorporated)

FIGURE 17.4.37 A Combined-Agent Vehicle (Source: Emergency One, Inc., and Kidde Fire Fighting)

flame radiation and makes advancement over the fire area safe and cool.

A design especially for petroleum refinery plant protection involves the combined agent concept in a triple-use arrangement consisting of a 2000 lb (908 kg) dry chemical tank, a 200 gal (757 L) AFFF premixed solution tank, nitrogen bottles for pressurization of both tanks, a 500 gal (1900 L) foam concentrate tank, a 1500 gpm (5700 Lpm) water pump, and balanced pressure proportioning up to 2000 gpm (7600 Lpm). Two monitors mounted behind the truck cab are twinned for operation as a unit and consist of a 50 lb/sec (23 kg/sec) dry chemical turret nozzle and a 500 gpm (1900 Lpm) AFFF or foam nozzle as shown in Figure 17.4.38. A different configuration uses three monitors mounted behind the truck cab—twinned 50 lb/sec (23 kg/sec)

FIGURE 17.4.38 Triple-Agent Truck (Source: Kidde Fire Fighting)

dry chemical and 180 gpm (680 Lpm) AFFF nozzles, and one adjacent 1000 gpm (3800 Lpm) adjustable foam monitor. In addition, the truck carries two hose reels, each with 100 ft (30.5 m) of twinned hose, and hose nozzles for dry chemical and AFFF arranged for twinned operation. The hose reels are equipped with an electric motor rewind. Foam nozzles, adjustable water fog nozzles, fire hose, and other accessories are carried on the truck.

The dry chemical turret nozzle will extinguish three-dimensional or pressure fires at a distance of 100 ft (30.5 m) and spill fires at a distance of approximately 150 ft (46 m). In addition, for long-range operation with lengthy duration, the 1000 gpm (3800 Lpm) foam-water monitor has a range of more than 200 ft (61 m). The truck is capable of fighting fires in fixed-roof oil storage tanks with a maximum diameter of 160 ft (49 m). The proportioning system is designed to permit an external tank, such as a tank truck or trailer, to be used for foam concentrate supply without interrupting foam solution proportioning.

Twinned agent hose reels are often used on offshore oil platforms for equipment protection and in naval shipboard engine rooms. These systems have suitably sized potassium bicarbonate (Purple K) dry chemical containers that are pressurized by nitrogen when put into operation and AFFF central pumped systems using balanced pressure proportioning. Similar twinned agent skid-mounted systems are used in refineries and petrochemical plants.

MEDIUM- AND HIGH-EXPANSION FOAM-GENERATING EQUIPMENT AND SYSTEMS

Medium- or high-expansion foam is an aggregation of bubbles resulting from the mechanical expansion of a foam solution by air or by other gases, with expansion ratios in the range of from 20:1 to approximately 1000:1. There are three types of systems: (1) total flooding, (2) local application, and (3) portable.

The foam generators for these systems are of two types: (1) aspirator and (2) blower. The portable or fixed aspirator-type device utilizes jet streams of water-foam solution, entraining suitable amounts of air to produce foam. With the blower-type device, foam solution is discharged onto a screen through which an air stream, developed by a fan or blower, is passing. As the

air passes through the screens wetted with the foam solution, large masses of bubbles or foam are formed. The blower may be powered by a hydraulic or water motor, compressed air or gas, an electric motor, or an internal combustion engine.

System Design and Use

Detailed design information on medium- and high-expansion foam systems can be found in NFPA 11.

Basically, medium- and high-expansion foam systems are used to control or extinguish fires involving surface fires in flammable and combustible liquids and solids, and deep-seated fires involving solid materials subject to smoldering. Three-dimensional fires in flammable liquids (falling or flowing under pressure) with flashpoints below 100°F (38°C) generally cannot be extinguished with this technique, although they may be kept under control. The following are key factors to consider in determining the design adequacy of medium- and high-expansion foam systems:

1. The quality and adequacy of water supply, the adequacy of supply of foam liquid concentrate, and the source of the air supply
2. Suitability of the generator and foam delivery system (piping, fittings, valves, ducts)
3. Needed submergence volume and time as influenced by the space being protected, the nature of the hazards involved, leakage of the foam, and similar factors
4. If outdoors, the effect of wind, because some of the foam may be dissipated by air currents

High-expansion foam may be useful in controlling LNG fires and unignited spills by forming an ice layer on the liquid and by helping disperse the vapor cloud.

Total Flooding Systems

A total flooding system may be used where there is an enclosure surrounding the hazard being protected that will permit the required amount of medium- or high-expansion foam to be built up to extinguish or control the fire. Examples of such enclosures are rooms, vaults, pits, and basement areas. Even an entire building may be so protected where the foam generators are of sufficient capacity and steps are taken to ensure effective distribution and retention of the foam. Since the efficiency of the system depends on the development and maintenance of a suitable quantity of foam within the particular enclosure, leakage of the foam from the enclosure must be avoided. Thus, it is important that doorways or windows be designed to close automatically, with consideration being given to the evacuation of personnel. High-level venting is required for the air that is displaced by the foam.

For adequate protection, sufficient high-expansion foam must be discharged at a rate to fill the space to an effective depth above the hazard before an unacceptable degree of damage occurs. The depth of the foam above the hazard will vary, depending on the type of materials creating the hazard. Generally, the minimum depth above the hazard should be 2 ft (0.6 m). The time allowed to cover the hazard will likewise vary depending on the type of material involved, construction features, and whether the enclosure also has an automatic sprinkler system or similar protection. Consideration has to be given to the disintegration of the foam by the heat of the fire, by normal foam shrinkage, by leakage around doors and windows and through unclosable openings, and by the effects of sprinkler discharge where sprinkler protection is provided.

Local Application Systems

Local application systems can be used where total flooding systems may be impractical or unnecessary. Such hazards may be indoors or outdoors, where air currents are not likely to be severe. These systems are best adapted to the protection of flammable or combustible liquids in dip tanks and associated drainboards, and for pits and trenches. Medium- or high-expansion foam may be used for extinguishing spill fires where it is feasible to apply the foam from fixed or portable nozzles at adequate rates of discharge to develop a foam blanket to achieve complete extinguishment.

Compressed Air Foam Systems

Unlike traditional foam systems in which air aspiration occurs at or near the discharge device, compressed-air foam (CAF) systems inject air prior to the discharge device. Foam is generated by injecting air under pressure into a foam solution stream. As solution moves through a hose or piping system, foam is produced by the combined momentum of the foam solution and the injected-air stream in the hose or pipe.

CAFs for mobile fire fighting have been used primarily as Class A fire-fighting agents. There are mobile systems that are designed for use on Class B fire hazards; sometimes these Class B CAFs are combined with a secondary agent such as Purple K. AFFF foam concentrate is generally used in these systems.

CAF in fixed-pipe systems is a recent development. As with the mobile systems, AFFF is used as the foam concentrate. In one listed/approved system, the AFFF is proportioned at 2 percent compared to 3 percent for traditional foam sprinkler systems. Also, the effective application rate (foam solution, gpm/ft^2 [Lpm/m^2]) is lower than similarly listed low-expansion foam sprinkler systems. NFPA 11 recognizes this system and provides design and installation requirements. The primary advantage of CAF systems is for situations in which there is an extremely limited water supply.

Precautions to Be Observed with Medium- or High-Expansion Foam

Medium- or high-expansion foam is normally nontoxic to persons who may be trapped in a space filled with it, since the air entrained in the foam is generally not contaminated. However, because of the foam bubbles, some difficulty may be experienced in breathing, and breathing discomfort will increase with reduction of foam expansion. Air is usually taken from a clean source, but where products of combustion are introduced, the foam quality may be substandard because of the contaminants present and the temperature of the heated air. Entering a foam-filled space should be avoided unless adequate precautions are taken because loss of vision and disorientation introduce life

and injury hazards. A coarse water spray may be used to "cut" a path in the foam. Personnel should wear self-contained breathing apparatus and employ a lifeline when entering an area filled with high-expansion foam.

FOAM EQUIPMENT TESTING AND SURVEILLANCE

The continued effective emergency performance of foam equipment depends entirely on fully adequate maintenance procedures, with periodic testing where possible. The many variations in system design and equipment applications for hazards requiring foam make it impossible to establish anything other than general procedures for periodic inspection. Because air-foam concentrates, foam equipment, and fire protection systems are subject to change, variation, and even malfunction over long unattended spans of time, they must be kept adequate for the purpose for which they are designed.

Foam Concentrate Surveillance

Because all air-foam concentrates are water solutions of organic and inorganic chemicals of one sort or another, they must be carefully observed for changes in constitution and characteristics. They must be stored in shipping containers and in storage tanks according to the manufacturer's recommendations. Exposure to extreme heat, cold, or contamination, or mixing with other materials must be avoided. Sedimentation or precipitate formation in containers or tanks of concentrate should be carefully checked periodically. The manufacturer or the manufacturer's representative is best qualified to test and determine the extent of reliability of foam concentrates under questionable conditions of deterioration. Foam concentrates should be tested at least annually.

Equipment Testing

The performance of all foam equipment under emergency conditions is best guaranteed by the initial acceptance test and periodic inspection of the equipment. Original design specifications of fixed installations should include provision for periodic testing of proportioners, pumps, and other ancillary equipment, without the trial distribution of foam to the hazard being protected.

Problems of corrosion, clogged orifices, sticky valves, and electric circuitry malfunction may be detected by suitable means without full system activation.

In the absence of an actual fire, and without full system activation, the complete testing of foam equipment performance for fire protection adequacy may be accomplished by various means. In the absence of an actual fire, complete testing may be accomplished by several physical test methods. However, because these tests are similar in nature to "fingerprint" tests, their results can only be interpreted by comparison with similar tests conducted at the installation acceptance of the equipment or as provided for under the performance guarantee of the manufacturer.

Foam equipment performance can be tested for the following physical characteristics of foam:

1. The dimensions of the discharge pattern or patterns of the device or system
2. The percent concentration of foam concentrate in the finished foam solution
3. The degree of expansion of the finished foam
4. The rate at which water drains from the foam, for example, 25 percent drainage time. This correlates with its viscosity or rate of spreading over fuel surfaces
5. Film-forming capacity of the foam concentrate

The preceding tests require specially designed test equipment and standardized techniques. They require qualified operators and may or may not be carried out easily in the field. Detailed information concerning the equipment required, methods used, and some interpretations of the test results can be found in the Appendices of NFPA 11 and NFPA 412, *Standard for Evaluating Aircraft Rescue and Fire-Fighting Foam Equipment,* which includes tests for foam discharge patterns, AFFF-type foams, and protein-based foams.

The test for the concentration of the foam concentrate is very important because it indicates the efficiency of operation of the concentrate proportioning device in the system. It is performed easily in the field with a hand refractometer and volume-measuring device or portable electrical conductivity meter.

ENVIRONMENTAL ISSUES

The use of fire-fighting foams is essential for the control of flammable liquid fire threats. The ability of foam to rapidly extinguish flammable liquid fires has contributed to life safety and property conservation. However, with the increasing global environmental awareness, fire-fighting foams are being scrutinized for their potential environmental impact. The primary concerns are toxicity, biodegradability, persistence, treatability in wastewater treatment plants, and nutrient loading.

Discharge Scenarios

In order to assess the impact of foam on the environment, likely discharge scenarios should be considered. These scenarios include the following:

1. Uncontrolled fire situations
2. Potential hazardous situations (e.g., unignited fuel spills)
3. Fire-fighting training evolutions
4. Fixed or mobile vehicle suppression system discharge
   - Intentional system test
   - Inadvertent discharge

Under many fire-fighting situations, control of foam and water/fuel effluent will be difficult. Control and extinguishment are usually of paramount importance, and rapid control by foam can substantially reduce the potential total effluent from an incident. Where possible, blocking of sewer drains, along with the use of portable dikes or booms, can be used to implement mitigation strategies.

Training scenarios provide greater opportunities to control foam flow, particularly by means of collection. New training

techniques, using simulated pool fires and simulated foams, are available.

System tests can also be performed, to a certain extent, with the use of simulants. Alternatively, small amounts of foam can be flowed and contained for proper disposal in accordance with local regulations and manufacturer's recommendations. Inadvertent system discharges may be handled by preplanned, engineered containment strategies or by portable containment devices, where containment is deemed appropriate.

Environmental Properties and Concerns

Fluorochemical surfactants in film-forming foams can exhibit characteristics having undesirable environmental impact. Of particular concern to the U.S. Environmental Protection Agency (EPA) are chemicals that are persistent, bioaccumulative, and potentially toxic (PBT). A major producer of AFFF, which was produced using the electrochemical fluorination process, has an agreement with the EPA to no longer manufacture a range of products that uses perfluoroctanyl sulfonate (PFOS) chemistry. This decision was based on data that suggest that these chemicals can exhibit a degree of toxicity and bioaccumulation not previously identified in addition to their known persistence to resist biodegradation. Other manufacturers of AFFF use a different process (e.g., telemerization) to produce fluorosurfactants used in their AFFF. Environmental characteristics of these agents have been under study by the industry and the EPA. Telmer-based agents have been found to be persistent but are not generally considered to be significant environmental toxins. Although there was concern that telemer-based AFFF could break down in the environment to perfluoroctanoic acid (PFOA) and would eventually be regulated by the EPA, the EPA decided that AFFF is not likely to be a source of PFOA. There are currently no restrictions on the production or sale of telemer-based AFFF in the United States. Users of AFFF should monitor these regulatory activities to determine the potential impact of regulations that may restrict the future use of AFFF and FFFP.

Foam solutions generally have a high biological oxygen demand (BOD); that is, they extract high levels of oxygen to break down. This is an issue both in the natural environment and where foam is discharged to wastewater treatment plants.

Foaming can occur in natural waterways and in treatment plants. In wastewater plants, foaming can cause bubbles to trap activated sludge, upsetting the normal operation of the plant. Before discharge of foam to a wastewater treatment plant, the plant operator should be contacted to discuss the type of foam, estimated BOD, total volume, and time over which the foam may be discharged to the plant. This should be done, where possible, as part of the emergency planning process.

In sufficient concentrations, foam may affect aquatic life. Where sufficiently diluted, foam solutions may not have an impact on aquatic life; however, localized concentrations in streams or ponds may create levels that are toxic to fish. Under emergency conditions, attempts should be made to prevent discharge to waterways (recognizing the primary concern of controlling the fire). Under controlled discharge conditions, prevention of foam discharge to natural waterways is appropriate.

The U.S. EPA requires reporting of certain releases of chemicals in broadly defined categories. The glycol ether category of chemicals was placed on the list of hazardous air pollutants under the 1990 Clean Air Act Amendments. These chemicals are used as solvents in certain fire-fighting foams. Although the EPA had originally assigned no reportable quantity for any glycol ethers, these chemicals still were designated as hazardous substances under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA). In a 1995 clarification, the EPA decided not to assign reportable quantities to several broad categories of glycol ethers, including the commonly used butyl carbitol. As a result, fire-fighting foams containing solvents within the glycol ethers category no longer require reporting under CERCLA when discharged. Several manufacturers have replaced glycol ether solvents with alternative solvents that have less environmental impact. Manufacturers should be consulted regarding environmental aspects in general and for responsible use guidance.

Disposal Alternatives

The uncontrolled release of foam solutions to the environment should be avoided. Alternative disposal options include the following:

1. Discharge to a wastewater treatment plant with or without pretreatment
2. Discharge to the environment after pretreatment
3. Solar evaporation
4. Transportation to a wastewater treatment plant or hazardous waste facility

When foam is collected, any fuel from a fire should be separated. Dilution with water may be required before discharging foam to a wastewater treatment plant. Defoamers or other pretreatments may also be required. Any discharge to a wastewater treatment plant should be coordinated in advance with the treatment facility personnel. Foam manufacturers can advise on proper disposal techniques for specific circumstances.

SUMMARY

Fire-fighting foam is an effective agent for combating flammable and combustible liquid fuel fires. Various types of foam are applied in different manners, but all act to suppress flammable vapors and cool fuel surfaces to extinguish fires. Foam may have low- or high-expansion ratios. Foam may be proportioned using various methods in both fixed and mobile systems. Foam agents are used to combat fires in various hazards, including tank farms, airfields, aircraft hangars, and flammable liquid hazards. Foam may be discharged through fixed nozzles, sprinklers, hose line nozzles, and monitors.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on foam extinguishing agents and systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems*
NFPA 18, *Standard on Wetting Agents*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 403, *Standard for Aircraft Rescue and Fire-Fighting Services at Airports*
NFPA 409, *Standard on Aircraft Hangars*
NFPA 412, *Standard for Evaluating Aircraft Rescue and Fire-Fighting Foam Equipment*
NFPA 414, *Standard for Aircraft Rescue and Fire-Fighting Vehicles*
NFPA 780, *Standard for the Installation of Lightning Protection Systems*
NFPA 1901, *Standard for Automotive Fire Apparatus*

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Chapter 5

Fire Extinguisher Use and Maintenance

Mark T. Conroy

Chapter Contents

Matching Extinguishers to Hazards
Available Personnel—Ease of Use
Physical Environment
Health and Operational Safety Considerations
Operation and Use
Obsolete Extinguishers
Distribution of Fire Extinguishers
Inspection and Maintenance of Fire Extinguishers

Key Terms

AFFF fire extinguisher, carbon dioxide fire extinguisher, Class A fire, Class B fire, Class C fire, Class D fire, Class K fire, Classification of Hazards for Portable Fire Extinguishers, dry chemical fire extinguisher, dry powder fire extinguisher, halogenated agent fire extinguisher, portable fire extinguisher, water-based fire extinguisher

Before choosing an extinguisher, it is important to know the nature of the fuels present, who will use the extinguisher, the physical environment in which the extinguisher will be placed, and whether any chemicals present in the area will react adversely with an extinguishing agent. When choosing from among various extinguishers, one should consider whether it is effective on the specific hazards present, whether it is easy to operate, and what maintenance and upkeep it requires.

Related information can be found in the following chapters in this section: Section 17, Chapter 1, "Carbon Dioxide and Application Systems"; Section 17, Chapter 2, "Chemical Extinguishing Agents and Application Systems"; Section 17, Chapter 3, "Characteristics and Hazards of Water and Water Additives for Fire Suppression"; and Section 17, Chapter 4, "Foam Extinguishing Agents and Systems." See also Section 6, Chapter 9, "Metals."

MATCHING EXTINGUISHERS TO HAZARDS

By far the most important consideration when selecting extinguishers is the nature of the area to be protected. NFPA 10, *Standard for Portable Fire Extinguishers,* classifies fires as either Class A, Class B, Class C, Class D, or Class K, according to the fuel involved:

- Class A fires are fires in ordinary combustible mateirals, such as wood, cloth, paper, rubber, and many plastics.
- Class B fires are fires in flammable liquids, combustible liquids, petroleum greases, tars, oils, oil-based paints, solvents, lacquers, alcohols, and flammable gases.
- Class C fires are fires that involve energized electrical equipment.
- Class D fires are fires in combustible metals, such as magnesium, titanium, zirconium, sodium, lithium, and potassium.
- Class K fires are fires in cooking applicances that involve combustible cooking media (vegetable or animal oils and fats).

Extinguishers are classified for use on one or more of these types of fires.

In addition, the relative hazard in a building varies according to its fire load, or the amount of combustibles it contains. NFPA 10 establishes three types of hazards. A light, or low, hazard exists when there are few combustibles. Light-hazard occupancies include offices, churches, schoolrooms, assembly halls, and so on. An ordinary, or moderate, hazard exists when the combustibles present are substantial but ordinary in nature or where there are small quantities of combustibles capable of rapid fire growth. Examples of ordinary-hazard occupancies are mercantile storage and display areas, auto showrooms, and parking garages. Some offices, schools, and so on can contain a sufficient amount of combustible materials to be classified as ordinary hazard. An extra, or high, hazard exists in areas where there are substantial quantities of on-site combustibles whose nature or configuration could readily support rapid fire growth and large fire size, such as woodworking areas, aircraft servicing areas, and warehouses with high-piled combustibles.

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Hazard type is an important factor when selecting extinguishers. For example, a 2½ gal (9.5 L) water extinguisher with a 2-A rating is only suitable in low- and moderate-hazard areas. In a high-hazard area, an extinguisher with a minimum rating of 4-A is needed.

Class-A-rated extinguishers are used most often for ordinary building protection. Among the agents classified for Class A use are water, loaded stream, aqueous film-forming foam (AFFF), film-forming fluoroprotein foam (FFFP), multipurpose (ammonium-phosphate-base) dry chemical, and halogenated agent types. Due to the environmental problems associated with halons, however, they are no longer being produced and their use is being discouraged except in specific circumstances. Extinguishers containing halogenated agents called halocarbons have been introduced to replace halon extinguishers.

Class-A-rated extinguishers are sometimes not the only type needed for building protection. In most areas of a restaurant, for example, the principal combustibles are wood, paper, and fabrics. In the kitchen, however, the hazard of greatest concern is cooking media (vegetable oils and fats), which requires a Class-K-rated extinguisher. In hospitals, there is a general need for Class-A-rated extinguishers in rooms, corridors, and offices, but Class-B:C-rated extinguishers should be placed in laboratories, generator rooms, and areas where anesthetics are stored or used. In short, the extinguishers in any one area should correspond to the hazards of that area.

Class B fires are fires in flammable liquids. Class-B-rated extinguishing agents include carbon dioxide, dry chemicals, AFFF, FFFP, and halogenated agent types. There are three general types of flammable liquids fires: (1) fires in liquids of appreciable depth (deeper than ¼ in. [6.4 mm]), such as those in industrial dip tanks and quench tanks; (2) spill fires or running fires in liquids of a depth of ¼ in. (6.4 mm) or less; and (3) pressurized flammable liquid or gas fires from damaged vessels or product lines. Portable fire extinguishers should not be relied on when the surface area of an indoor open tank is in excess of 10 ft^2 (1 m^2); fires in such areas can give off so much heat and smoke that it is dangerous for anyone to remain in the area.

Pressurized flammable liquids and pressurized gas fires present special hazards. Only dry chemical type extinguishers have proved to be effective. In addition, special nozzles and higher rates of agent application are often required. Extinguishers for these types of fires should therefore be selected on the basis of manufacturers' recommendations. *No* attempt should be made to extinguish these fires unless there is reasonable certainty that the source of fuel can be shut off promptly.

Class-C-rated extinguishers contain extinguishing agents that are considered electrically nonconductive to the extinguisher operator while being discharged and are therefore preferred for fires in charged electrical equipment. They should be chosen based on the materials used in constructing the electrical equipment, the degree of agent contamination that can be tolerated, and the types of other combustibles in the area. Of these, the first is particularly important. For example, a power panel will contain more Class A insulating materials than an oil-filled transformer will, which will contain mostly Class B material. The agents classified for Class C use include carbon dioxide, dry chemicals, and the halogenated agent types.

Class D fires are fires in combustible metals. These require special extinguishing agents, known as dry powder.

Once an area has been analyzed for hazards, appropriate extinguishers can be chosen. For the Class A fire, three basic types of extinguishers can be used: water-based extinguishers, multipurpose (ammonium-phosphate-base) dry chemical extinguishers, or halogenated agent extinguishers. For Class B fires, there are carbon dioxide, dry chemical, halogenated agent, and AFFF and FFFP extinguishers. (Some small extinguishers are rated less than 5-B and, as indicated by their omission from Table 17.5.1, are not permitted as a required extinguisher.) For Class C fires there are carbon dioxide, dry chemical, or halogenated agent extinguishers. Water mist extinguishers have recently been reconsidered for use in the vicinity of live electrical equipment. The various types of extinguishing agents for Class D combustible metal fires are discussed separately. (See Section 6, Chapter 9, "Metals.")

AVAILABLE PERSONNEL—EASE OF USE

Before extinguishers are selected, consideration should be given to who will use them. Evaluation should include the potential user's physical abilities, reactions under stress, and previous training. Many firms have standardized their extinguishers so that employees need only learn one set of instructions. In companies employing trained fire brigades, there may be more variation.

An individual's emotional reaction to a fire will be greatly influenced by his or her familiarity with the extinguisher, experience in using it or observing its use, and self-confidence. Training is, therefore, very important. Many companies have employees practice with extinguishers when the units are scheduled for recharging. Employees should be adequately trained so they will not jeopardize their own safety and safety of others.

Sometimes, the size or weight of an extinguisher is important. Some extinguisher models have lightweight shells or use agents with more extinguishing capacity per unit of weight. A very common fire extinguisher holds 2½ gal (9.5 L) of water and weighs about 30 lb (13.6 kg). The weight of many extinguishers varies. For example, one manufacturer offers two dry chemical extinguishers with a rating of 40-B:C. The sodium-bicarbonate-based model has a 20 lb (9.1 kg) capacity and weighs 27 lb (12.3 kg), but the potassium-bicarbonate-based model has a 9 lb (4.1 kg) capacity and weighs only 14 lb (6.4 kg).

PHYSICAL ENVIRONMENT

Still another factor that influences extinguisher selection is the area in which the extinguishers will be placed. Is the extinguisher affected by extreme temperatures, for example? ANSI standards require evaluation of water-based extinguishers at temperatures between 40 and 120°F (4 and 49°C) and all other types between –40 and 120°F (–40 and 49°C).

Performance Standards for Fire Extinguishers:[1]

(a) Carbon Dioxide Types. ANSI/UL 154, *Standard for Carbon Dioxide Fire Extinguishers;* CAN/ULC-S503-M90, *Standard for Carbon Dioxide Hand and Wheeled Fire Extinguishers*

(b) Dry Chemical Types. ANSI/UL 299, *Standard for Dry Chemical Fire Extinguishers;* CAN/ULC-S504-M86, *Standard for Dry Chemical and Dry Powder Hand and Wheeled Fire Extinguishers*

TABLE 17.5.1 Characteristics of Extinguishers

Extinguishing Agent	*Method of Operation*	*Capacity*	*Horizontal Range of Stream*	*Approximate Time of Discharge*	*Protection Required below 40°F (4°C)*	*UL or ULC Classifications*[a]
Water	Stored-pressure	6 L	30 to 40 ft	40 sec	Yes	1-A
	Stored-pressure or pump	2½ gal	30 to 40 ft	1 min	Yes	2-A
	Pump	4 gal	30 to 40 ft	2 min	Yes	3-A
	Pump	5 gal	30 to 40 ft	2 to 3 min	Yes	4-A
Water (wetting agent)	Stored-pressure	1½ gal	20 ft	30 sec	Yes	2-A
	Stored-pressure	25 gal (wheeled)	35 ft	1½ min	Yes	10-A
	Stored-pressure	45 gal (wheeled)	35 ft	2 min	Yes	30-A
	Stored-pressure	60 gal (wheeled)	35 ft	2½ min	Yes	40-A
Loaded stream	Stored-pressure	2½ gal	30 to 40 ft	1 min	No	2-A
	Stored-pressure	33 gal (wheeled)	50 ft	3 min	No	20-A
Water mist	Stored-pressure	6 L	NA	60 to 70 sec	Yes	2-A:C
	Stored-pressure	2½ gal	NA	70 to 80 sec	Yes	2-A:C
AFFF, FFFP	Stored-pressure	2½ gal	20 to 25 ft	50 sec	Yes	3-A:20 to 40-B
	Stored-pressure	6 L	20 to 25 ft	50 sec	Yes	2-A:10-B
	Nitrogen cylinder	33 gal	30 ft	1 min	Yes	20-A:160-B
Carbon dioxide[b]	Self-expelling	2½ to 5 lb	3 to 8 ft	8 to 30 sec	No	1 to 5-B:C
	Self-expelling	10 to 15 lb	3 to 8 ft	8 to 30 sec	No	2 to 10-B:C
	Self-expelling	20 lb	3 to 8 ft	10 to 30 sec	No	10-B:C
	Self-expelling	50 to 100 lb (wheeled)	3 to 10 ft	10 to 30 sec	No	10 to 20-B:C
Regular dry chemical (sodium bicarbonate)	Stored-pressure	1 to 2½ lb	5 to 8 ft	8 to 12 sec	No	2 to 10-B:C
	Cartridge or stored-pressure	2¾ to 5 lb	5 to 20 ft	8 to 25 sec	No	5 to 20-B:C
	Cartridge or stored-pressure	6 to 30 lb	5 to 20 ft	10 to 25 sec	No	10 to 160-B:C
	Stored-pressure	50 lb (wheeled)	20 ft	35 sec	No	160-B:C
	Nitrogen cylinder or stored-pressure	75 to 350 lb (wheeled)	15 to 45 ft	20 to 105 sec	No	40 to 320-B:C
Purple K dry chemical (potassium bicarbonate)	Cartridge or stored-pressure	2 to 5 lb	5 to 12 ft	8 to 10 sec	No	5 to 30-B:C
	Cartridge or stored-pressure	5½ to 10 lb	5 to 20 ft	8 to 20 sec	No	10 to 80-B:C
	Cartridge or stored-pressure	16 to 30 lb	10 to 20 ft	8 to 25 sec	No	40 to 120-B:C
	Cartridge or stored-pressure	48 to 50 lb (wheeled)	20 ft	30 to 35 sec	No	120 to 160-B:C
	Nitrogen cylinder or stored-pressure	125 to 315 lb (wheeled)	15 to 45 ft	30 to 80 sec	No	80 to 640-B:C
Super K dry chemical (potassium chloride)	Cartridge or stored-pressure	2 to 5 lb	5 to 8 ft	8 to 10 sec	No	5 to 10-B:C
	Cartridge or stored-pressure	5 to 9 lb	8 to 12 ft	10 to 15 sec	No	20 to 40-B:C
	Cartridge or stored-pressure	9½ to 20 lb	10 to 15 ft	15 to 20 sec	No	40 to 60-B:C
	Cartridge or stored-pressure	19½ to 30 lb	5 to 20 ft	10 to 25 sec	No	60 to 80-B:C
	Cartridge or stored-pressure	125 to 200 lb (wheeled)	15 to 45 ft	30 to 40 sec	No	160-B:C
Multipurpose/ABC dry chemical (ammonium phosphate)	Stored-pressure	1 to 5 lb	5 to 12 ft	8 to 10 sec	No	1 to 3-A[c] and 2 to 10-B:C
	Stored-pressure or cartridge	2½ to 9 lb	5 to 12 ft	8 to 15 sec	No	1 to 4-A and 10 to 40-B:C
	Stored-pressure or cartridge	9 to 17 lb	5 to 20 ft	10 to 25 sec	No	2 to 20-A and 10 to 80-B:C

(continued)

TABLE 17.5.1 Continued

Extinguishing Agent	*Method of Operation*	*Capacity*	*Horizontal Range of Stream*	*Approximate Time of Discharge*	*Protection Required below 40°F (4°C)*	*UL or ULC Classifications*[a]
Multipurpose/ABC dry chemical (ammonium phosphate) *(continued)*	Stored-pressure or cartridge	17 to 30 lb	5 to 20 ft	10 to 25 sec	No	3 to 20-A and 30 to 120-B:C
	Stored-pressure or cartridge	45 to 50 lb (wheeled)	20 ft	25 to 35 sec	No	20 to 30-A and 80 to 160-B:C
	Nitrogen cylinder or stored-pressure	110 to 315 lb (wheeled)	15 to 45 ft	30 to 60 sec	No	20 to 40-A and 60 to 320-B:C
Dry chemical (foam-compatible)	Cartridge or stored-pressure	4¾ to 9 lb	5 to 20 ft	8 to 10 sec	No	10 to 20-B:C
	Cartridge or stored-pressure	9 to 27 lb	5 to 20 ft	10 to 25 sec	No	20 to 30-B:C
	Cartridge or stored-pressure	18 to 30 lb	5 to 20 ft	10 to 25 sec	No	40 to 60-B:C
	Nitrogen cylinder or stored-pressure	150 to 350 lb (wheeled)	15 to 45 ft	20 to 150 sec	No	80 to 240-B:C
Dry chemical (potassium bicarbonate urea based)	Stored-pressure	5 to 11 lb	11 to 22 ft	18 sec	No	40 to 80-B:C
	Stored-pressure	9 to 23 lb	15 to 30 ft	17 to 33 sec	No	60 to 160-B:C
	Nitrogen cylinder or stored-pressure	175 lb (wheeled)	70 ft	62 sec	No	480-B:C
Wet chemical	Stored-pressure	3 L	8 to 12 ft	30 sec	No	K
	Stored-pressure	6 L	8 to 12 ft	35 to 45 sec	No	K
	Stored-pressure	2½ gal	8 to 12 ft	75 to 85 sec	No	K
Halon 1211 (bromochloro-difluoromethane)	Stored-pressure	0.9 to 2 lb	6 to 10 ft	8 to 10 sec	No	1 to 2-B:C
	Stored-pressure	2 to 3 lb	6 to 10 ft	8 to 10 sec	No	5-B:C
	Stored-pressure	5½ to 9 lb	9 to 15 ft	8 to 15 sec	No	1-A:10-B:C
	Stored-pressure	13 to 22 lb	14 to 16 ft	10 to 18 sec	No	2 to 4-A and 20 to 80-B:C
	Stored-pressure	50 lb	35 ft	30 sec	No	10-A:120-B:C
	Stored-pressure	150 lb (wheeled)	20 to 35 ft	30 to 44 sec	No	30-A:160 to 240-B:C
Halon 1211/1301 (bromochloro-difluoromethane bromotrifluoro-methane) mixtures	Stored-pressure or self-expelling	0.9 to 5 lb	3 to 12 ft	8 to 10 sec	No	1 to 10-B:C
	Stored-pressure	9 to 20 lb	10 to 18 ft	10 to 22 sec	No	1-A:10-B:C to 4-A:80-B:C
Halocarbon type	Stored-pressure	1.4 to 150 lb	6 to 35 ft	9 to 23 sec	No	1-B:C to 10-A:80-B:C

Note: Halon should be used only where its unique properties are deemed necessary.
[a]UL and ULC ratings checked as of July 24, 1987. Readers concerned with subsequent ratings should review the pertinent lists and supplements issued by these laboratories: Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062, or Underwriters Laboratories of Canada, 7 Crouse Road, Scarborough, Ontario, Canada M1R 3A9.
[b]Carbon dioxide extinguishers with metal horns do not carry a C classification.
[c]Some small extinguishers containing ammonium phosphate–based dry chemical do not carry an A classification.
NA = Not available.
Source: Modified from NFPA 10, *Standard for Portable Fire Extinguishers,* Table H.2, 2007, p. 10-50.

(c) Water Types. ANSI/UL 626, *Standard for 2½-Gallon Stored-Pressure, Water-Type Fire Extinguishers;* CAN/ULCS507-92, *Standard for 9 Litre Stored Pressure Water Type Fire Extinguishers*
(d) Halon Types. ANSI/UL 1093, *Standard for Halogenated Agent Fire Extinguishers;* CAN/ULC-S512-M87, *Standard for Halogenated Agent Hand and Wheeled Fire Extinguishers*
(e) Film-Forming Foam Types. ANSI/UL 8, *Standard for Foam Fire Extinguishers*
(f) Halocarbon Type. ANSI/UL 2129, *Standard for Halocarbon Agent Fire Extinguishers*

If extinguishers are installed in areas subject to higher or lower temperatures, they should be listed for those areas or put in an enclosure where the proper temperature is maintained. Some

stored-pressure extinguishers for Class B fires use nitrogen rather than carbon dioxide as the pressurizing force. For units that must perform in temperatures as low as –65°F (–54°C), nitrogen pressurization is used.

Other conditions that may affect extinguisher performance are direct sunlight, snow, rain, airborne debris, and corrosive fumes. If extinguishers must be placed outdoors, installing them in cabinets and sheltered areas or placing a protective cover over them will help prevent damage or premature deterioration (Figures 17.5.1 and 17.5.2).

Corrosives can cause extinguishers to fail, and extinguishers capable of withstanding corrosive conditions are listed separately. For example, extinguishers that may be used in salt-air atmospheres appear under the heading "Marine Type, USCG." Where corrosive fumes exist at industrial sites, special analysis should be made before extinguishers are chosen.

Extinguishers may also be affected by the vibration found in places such as a drop forge or hammer mill, trains, vehicles, and power boats. In such cases, they should be of rugged design, mounted securely, and inspected at frequent intervals.

FIGURE 17.5.1 Cover Used to Protect Extinguishers That Are Mounted Outside from Substances That Would Interfere with Operation (Source: Ansul Incorporated)

HEALTH AND OPERATIONAL SAFETY CONSIDERATIONS

Potential health hazards should always be considered when selecting extinguishers. Manufacturers normally provide prominent labels of caution on extinguishers that could produce toxic vapors or decomposition vapors. Sometimes, however, the danger resides not in the extinguisher but in the area in which it will be used. Useful safeguards include posting warning signs at the entries to confined areas, providing extinguishers with long-range nozzles, installing special ventilation, or supplying employees in the area with self-contained breathing apparatus.

Most water-based extinguishers are rated only for Class A fires. AFFF and FFFP models are also rated for Class B fires. Class K fire extinguishers have water additives intended for fires

FIGURE 17.5.2 Surface-Mounted Extinguisher Cabinet with a Hinged Door (Source: Larsen's Manufacturing Company)

in commercial fryers. If the nonfoam/water types are used on Class B fires, the fire may flare up, spread, or injure the operator in some way. If water-based extinguishers are used on fires in or near live electrical equipment, the water stream may transmit an electric shock to the operator.

Although carbon dioxide is not itself toxic, it will not support life when used in concentrations high enough to extinguish a fire. (See Section 17, Chapter 1, "Carbon Dioxide and Application Systems.") If a carbon dioxide extinguisher is used in an unventilated area, it dilutes the oxygen supply, and those remaining in the area may become unconscious or even die if they do not receive oxygen. In addition, the thick cloud of condensing water vapor that forms upon discharge may cause persons to become disoriented.

Older carbon dioxide extinguishers may have metal horns that transmit a shock to the user when the horns touch live electrical equipment. These metal horns should be replaced with nonmetallic horns. Occasionally, the operator may receive a shock even when no contact has been made; these result from built-up static electricity and are generally more annoying than hazardous.

Dry chemical extinguishers are not considered toxic, but their discharge can be irritating if breathed for a long time. Monoammonium phosphate is the most irritating, followed by potassium-based agents. Sodium bicarbonate is the least irritating. If dry chemicals are discharged in a confined area, they may reduce visibility and cause disorientation. Because dry chemical agents are nonconductors, deposits left on electrical contacts can reduce or negate the ability of the contacts to conduct. They may also clog air conditioning and air cleaning filters if discharged nearby.

Multipurpose dry chemical (ammonium-phosphate-base) is acidic and, if mixed with even a small amount of water, will corrode some metals unless all agent residues are removed promptly and thoroughly. Finally, the initial discharge of agent from an extinguisher has considerable force. If it is aimed at close range at a small flammable liquid or grease fire, it can cause the fire to spread extensively before it can be brought under control.

Extinguishers containing halogenated agents such as halons (Halon 1301 or Halon 1211 or a mixture of these) or halocarbons (halocarbon agents include hydrochlorofluorocarbon [HCFC], hydrofluorocarbon [HFC], perfluorocarbon [PFC], and fluoroiodocarbon [FIC]) present some degree of toxicity under normal operating conditions. However, the decomposition products of these agents can be hazardous. When using these extinguishers in unventilated places, such as small rooms, closets, motor vehicles, or other confined spaces, it is best to avoid breathing the vapors or the gases produced by thermal decomposition.

Class D fires involving burning metal chips can be scattered if the full force of a dry powder extinguisher is used at close range. To avoid spreading the fire, the discharge lever should be squeezed slowly, beginning at a safe distance.

Virtually every fire produces toxic products of combustion, and some burning materials create highly toxic gases. Until the fire has been extinguished and the area well ventilated, it is important either to stay out of the area or to wear protective breathing apparatus.

OPERATION AND USE

Whether an extinguisher is effective often depends on who is using it. One person may be able to extinguish a fire that someone else, using the same equipment, may not. Many extinguishers discharge their entire contents in 8 to 15 seconds, leaving little time for experimentation. Occasionally, improper use of an extinguisher injures the operator and delays extinguishment.

There are several kinds of extinguishers. Because differences exist among extinguishers, it is imperative that people be trained to use them properly. Ideally, this includes the general public. In any case, fire fighters and others responsible for fire protection, such as industrial fire brigades, should be trained thoroughly in the operation and use of extinguishers.

Currently, listed fire extinguishers are classified into six major groups, based on the extinguishing medium each contains. They are (1) water-type, (2) carbon dioxide, (3) halogenated agent, (4) dry chemical, (5) foam, and (6) wet chemical. Dry powder for Class D fires receives special testing and listing based on specific combustible metals. Additionally, special extinguishers containing wet chemical are tested and listed for cooking oil fires that could occur in commercial fryers. Information about each of these can be found in the following subsections and in Table 17.5.1.

In addition, extinguishers that are no longer manufactured may still be found in some areas. Some information on them is provided under the heading "Obsolete Extinguishers."

Water-Based Extinguishers

Water-based extinguishing agents include water, antifreeze, loaded stream, wetting agent, wet chemical, and foam. All except AFFF, FFFP, and wet chemical are for use on Class A fires only. Antifreeze, loaded stream, AFFF, wetting agent, and wet chemical all use water as a base to which chemicals are added to improve the extinguisher's performance. Both antifreeze and loaded stream models are specially treated to withstand low temperatures; the additive in loaded stream extinguishers is an alkali metal-salt solution. In wetting agents, a material is added to reduce the surface tension of the water so that it will spread and penetrate better. Wet chemicals include, but are not limited to, aqueous solutions of potassium acetate, potassium carbonate, potassium citrate, or combinations of these materials.

Originally, water-based extinguishers were of three basic designs: (1) stored-pressure, (2) pump tank, and (3) inverting. In 1969, however, the manufacture of all inverting extinguishers was discontinued. Consequently, the soda-acid and foam agents used exclusively in inverting extinguishers also became obsolete. The two designs that remain, stored-pressure and pump tank, are discussed later.

If ordinary, or nonfoam, water-based extinguishers are used on flammable liquids or electrical fires, they can spread the fire, injure the operator, or both. After activating an extinguisher, the operator should point the stream at the base of the flames and work from side to side or around the fire. When flames are high, the range of the stream (about 30 ft [9 m]) should be used to best advantage. As the flames diminish, it is possible to move closer and change the solid stream to a spray by holding a fingertip over the end of the nozzle. A spray stream is more effective on burning embers. Deep-seated smoldering or glowing areas should be wetted thoroughly. If necessary, a hand tool should be used to poke apart burning materials to do this.

Stored Pressure. For the capacities, ratings, discharge times, stream range, and temperature requirements of the various stored-pressure water-based extinguishers available, see Table 17.5.1. The most common stored-pressure water-based extinguisher contains 2½ gal (9.5 L) and weighs about 30 lb (13.6 kg). It can be operated intermittently, is rechargeable, and has a comparatively long stream range and discharge time. It consists of a single chamber that contains both the agent and expellant gas. The head assembly includes a siphon tube, a combination carrying handle/operating lever, a discharge valve, an air valve and pressure gauge, a discharge hose, and a nozzle (Figure 17.5.3). The extinguisher is pressurized with air or inert gas by means of an automobile-tire-type valve. Charging pressures range from 90 to 125 psi (620 to 862 kPa). A "fill mark" is stamped on many older stored-pressure water-based extinguishers about 6 in. (152.4 mm) from the top; when refilling, this level should never be exceeded. Some models use a special tube device to prevent overfilling.

In most models, the operating lever is locked by a ring pin that prevents accidental discharge. To activate the extinguisher, set it on the ground. Hold the combination handle loosely in one hand and pull out the ring pin or release a small latch with the other hand. Then grab the hose in one hand and squeeze the discharge lever with the other.

Pump Tanks. Two different types of pump tanks are available: one is cylindrical, and the other is made to be used as a backpack. The sizes, ratings, discharge times, stream ranges, and weather requirements of the various pump tanks are given in Table 17.5.1. The cylindrical model has carrying handles either attached to the container or built into the pump handle, and the water is discharged by a built-in, hand-operated vertical piston pump with an attached short rubber hose. The pump is double-acting and discharges water on both the up and the down strokes (Figure 17.5.4). The cylindrical models are available with copper, steel, or plastic shells.

To operate a cylindrical pump tank, place it on the ground and put one foot on the extension bracket at the base to steady the unit. To force water through the hose, pump the handle up and down. Cylindrical pump tanks have two characteristics that may be slight disadvantages: (1) to move the extinguisher, the operator must stop pumping, and (2) the force, range, and duration of the stream are dependent, in part, on the operator.

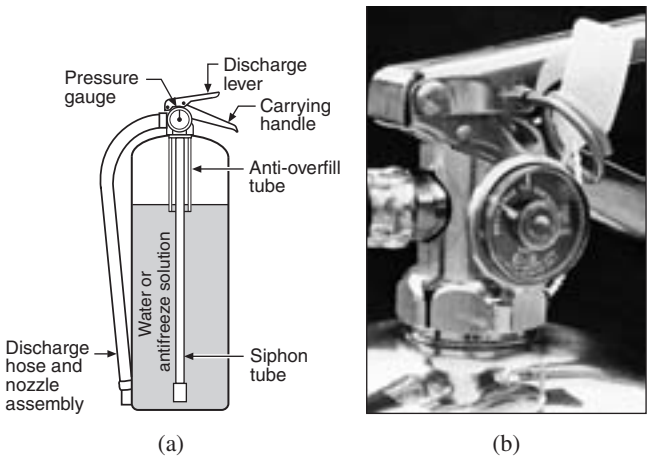


FIGURE 17.5.3 (a) Stored-Pressure Water Fire Extinguisher; (b) Close-Up of Head Assembly (Photo courtesy of Badger Fire Protection)

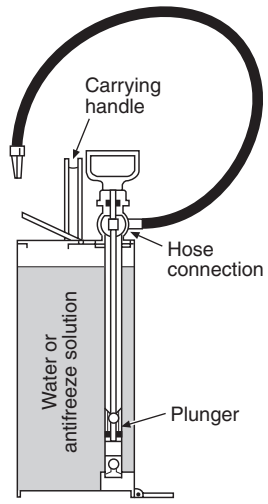


FIGURE 17.5.4 Cylindrical Pump Tank Fire Extinguisher

Cylindrical pump tanks can be filled with either plain water or antifreeze charges recommended by the manufacturer. Common salt or other freezing depressants might corrode the extinguisher or damage the pump assembly. Copper- or plastic-shell models do not corrode as easily as steel and are recommended for use with antifreeze.

Backpack pump tanks are used chiefly for fighting outdoor brush and wildland fires. As the name implies, they are carried on the operator's back. The most common backpack pump tank holds 5 gal (19 L) and weighs about 50 lb (23 kg) when full (Figures 17.5.5 and 17.5.6). Although listed, backpack pump tanks do not have a designated rating. Generally, the tank is filled with plain water, though antifreeze agents, wetting agents, and other special water-based agents may be used. The tank may be made of fiberglass, stainless steel, galvanized steel, or brass, or it may be a flexible water bag. Some models have a large opening with a tight-fitting filter that allows speedy refilling and prevents foreign matter from entering and clogging the pump.

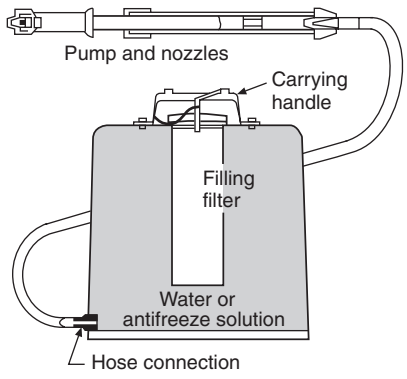


FIGURE 17.5.5 Backpack Pump Tank Fire Extinguisher

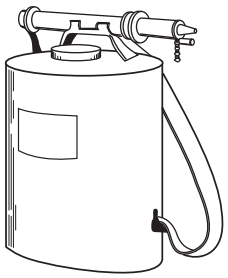


FIGURE 17.5.6 Backpack Pump Tank Fire Extinguisher with 5 gal (19 L) Tank Made of Fiberglass and with Trombone-Type Pump Action at Nozzle

This design also permits refilling from sources such as ponds, lakes, and streams.

The most common backpack pump tank has a trombone-type, double-acting piston pump connected to the tank by a short length of rubber hose. To discharge the device, the operator holds the pump in both hands and moves the piston back and forth. Other models have compression pumps mounted on the right side of the tank. In these, the expellant pressure is built up with about ten strokes of the handle and then maintained by slow, easy pumping. The left-hand controls discharge by means of a lever-operated shutoff nozzle at the end of the hose.

Water Mist. The water mist extinguisher is a fairly recent development. Currently it is available in the 2½ gal (9.5 L) size, and it is similar to the stored-pressure water extinguisher, but has a wand with a special nozzle, which disperses the water into a fine spray. The wand allows the operator to stand at a safe distance from the fire and deliver the low velocity water mist to the burning materials. The mist does not conduct electricity, but operators need to be cautious if pooling of the water occurs near energized electrical equipment, since pooled water will conduct electricity. Besides the advantage of being nonconductive while in a mist, the water can cool and soak the burning materials, helping to extinguish the fire and prevent reflash.

Carbon Dioxide Extinguishers

Carbon dioxide is a compressed gas agent and is commonly referred to as CO_2. Although rated for use on Class B and C fires, it is often effectively used on small Class A fires.

Carbon dioxide prevents combustion by displacing the oxygen in the air surrounding a fire and by cooling the fuel. Its principal advantage is that it does not leave a residue, a consideration that may be important in laboratories and in areas in which food is prepared or electronic equipment is present. The rapid expansion and pressure reduction of the pressurized liquid carbon dioxide in the cylinder results in the cooling and refrigeration effect. However, carbon dioxide extinguishers have a relatively short range because the agent is expelled in the form of a gas/snow cloud; they are also affected by wind or drafts. If a carbon dioxide extinguisher is used in a confined or unventilated area, precautions should be taken so that people are not overcome from lack of oxygen. For the various sizes, stream ranges, discharge times, temperature requirements, and ratings of carbon dioxide extinguishers available, see Table 17.5.1.

In all carbon dioxide extinguishers, the agent is retained as a liquid at 800 to 900 psi (5516 to 6205 kPa) at temperatures below 88°F (31°C), and is self-expelling. The extinguisher design consists of a pressure cylinder, or shell; a siphon tube and valve for releasing the agent; and a discharge horn or horn-hose combination. The siphon tube extends from the valve almost to the bottom of the shell, so that normally only liquid carbon dioxide reaches the discharge horn until about 80 percent of the content has been released. The remaining 20 percent enters the siphon tube as a gas. The rapid expansion from liquid to gas when most of the carbon dioxide is discharged converts about 30 percent of the liquid into a very cold "snow" or "dry ice," which then sublimes into a gas.

To operate a carbon dioxide extinguisher, hold it upright by its carrying handle, remove the locking pin, and squeeze the operating lever (Figure 17.5.7). In smaller portable models, the discharge horn often is connected to the valve assembly by a metal tube/swing joint connector, and the models may be operated with one hand. Larger portable models require two hands, and their discharge horns are attached to a length of hose. Wheeled extinguishers have a cylinder valve with a locking ring pin, a long hose of 15 to 40 ft (4 to 12 m), and a projector that consists of a horn, a long handle, and a control valve. Once the cylinder valve has been opened, the operator controls the discharge with the valve on the projector handle.

Care should be taken not to touch the discharge horn during operation, because it can become extremely cold. If carbon dioxide extinguishers are used in subzero temperatures, the valve must remain open at all times or the discharge may become blocked unless a special low-temperature charge has been added.

Because carbon dioxide extinguishers have a limited range and are affected by draft or wind, they should be applied as close to the base of a fire as possible. Agent should be applied even after the flames have been extinguished to allow time for cooling and to prevent reflash. Due to the relatively short discharge range, carbon dioxide extinguishers are of limited effectiveness on large Class B fires. For flammable liquid fires, the usual method is to begin at the near edge and sweep from side to side toward the back of the fire. However, there is another method called "overhead application." In this method, the discharge horn is pointed downward at an angle of about 45 degrees toward the center of the burning area. Usually, the horn is not moved, and the agent spreads out in all directions. The side-to-side sweeping method may give better results on spill fires, while the overhead method may be best for confined fires.

For fires involving electrical equipment, the discharge should be directed at the source of the flames. It is important to deenergize the equipment as soon as possible to prevent possible reignition.

Halogenated Agent Extinguishers

Halogenated agents fall into two categories. These categories are (1) halons, which include bromochlorodifluoromethane (Halon 1211), bromotrifluoromethane (Halon 1301), and mixtures of

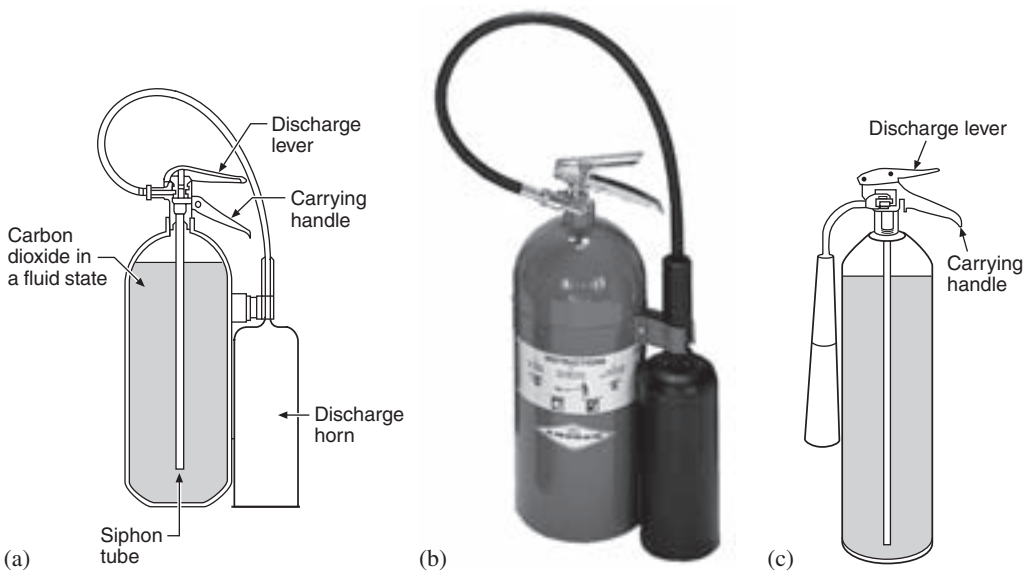


FIGURE 17.5.7 Carbon Dioxide Fire Extinguisher (Photo courtesy of Amerex)

Halon 1211 and Halon 1301; and (2) halocarbons, which include hydrochlorofluorocarbon (HCFC), hydrofluorocarbon (HFC), perfluorocarbon (PFC), and fluoroiodocarbon (FIC) (Figure 17.5.8). These extinguishing agents are often called "clean agents" because they leave no residue.

Halogenated agents not only leave no residue, but are virtually noncorrosive and nonabrasive, and are effective on Class A and B fires. With the exception of Halon 1301, these extinguishing agents are streaming agents because they discharge as a liquid stream from the extinguisher. Because of their physical properties, they need no cold weather protection. When halogenated agents are used on a fire, the decomposition products are a concern to the user and people in the area as the products are toxic. Normally, only small quantities of these chemicals are formed, and, as a warning of their presence, they give off an acrid odor. Using a halogenated agent extinguisher on a large intense fire such as a large flammable liquid spill fire will produce large quantities of decomposition products. Although halogenated agents are retained under pressure in a liquid, a booster charge of nitrogen or inert gas is added to ensure proper operation.

The most common application for halogenated agent extinguishers is for the protection of delicate electronic equipment such as in computer rooms. Since there are production restrictions on the chemical Halon 1211 due to environmental concerns, the halocarbon agent extinguishers have been installed where Halon 1211 was previously the preferred extinguishing agent. Due to these concerns, Halon 1211 use is being discouraged except in specific circumstances. Halon 1211 should never be inadvertently discharged into the atmosphere or used for training purposes.

Dry Chemical Extinguishers

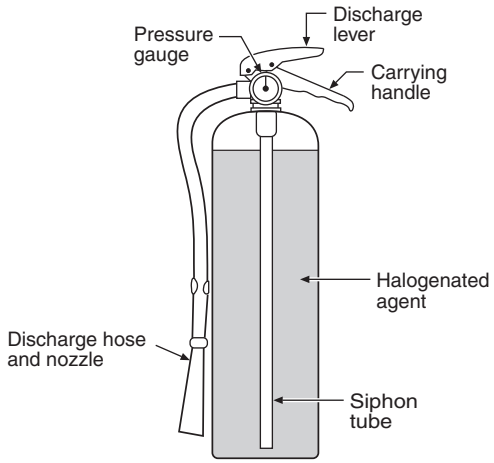
There are two basic kinds of dry chemical agents: (1) ordinary dry chemicals, which are rated B:C and include sodium bicarbonate, potassium bicarbonate (Purple K), urea-potassium-bicarbonate (Monnex®), and potassium-chloride-based agents; and (2) multipurpose dry chemical, ammonium-phosphate-based agent, which achieves the A:B:C rating. There are also two basic designs of dry chemical extinguishers: one uses a separate pressurized cartridge or cylinder of gas to expel the agent *(cartridge- or cylinder-operated extinguisher),* and the other pressurizes the agent chamber for the same purpose (stored pressure extinguisher). The stored-pressure is the most widely used. It is best suited to areas where infrequent use is anticipated and where skilled personnel with professional recharge equipment are available. By contrast, the cartridge-operated type can be refilled quickly in remote locations without special equipment.

The size, rating, and method of operation of any particular extinguisher depends both on its design and on the agent. Table 17.5.1 gives specific information on the capacities, ratings, discharge times, and stream ranges of the dry chemical extinguishers now available.

In areas where Class A:B:C protection is needed, water-based extinguishers may be omitted if multipurpose dry chemical extinguishers are installed. However, they are not replacements for water-based extinguishers under all conditions.

When choosing a dry chemical extinguisher for Class C protection, it is important to remember that potassium chloride and ammonium phosphate are more corrosive than the other dry chemicals.

The various dry chemical extinguishers possess certain common characteristics. Dry chemical extinguishers can be discharged while being carried, and all can be stopped from discharging momentarily to conserve the agent. Dry chemicals also can be used simultaneously with water, either straight stream or spray. Special long-range nozzles may be necessary for some very hazardous areas, such as those with pressurized gases and flammable liquids. Dry chemicals are dispersed less easily by wind than carbon dioxide, though dry chemicals can be more



(a)

(b)

FIGURE 17.5.8 Halogenated Agent Stored-Pressure Fire Extinguisher (Source: *NFPA Guide to Portable Fire Extinguishers,* NFPA, 2003, Figure 1-29. Reproduced courtesy of Jones and Bartlett Publishers.)

effective during windy conditions if the wind is at the operator's back.

If dry chemicals are used on wet, energized electrical equipment, such as rain-soaked utility poles, high-voltage switch gear, and transformers, electrical leakage problems may be aggravated. The combination of dry chemical with moisture provides an electrical path that can keep insulation from being effective. In such cases, all traces of dry chemical should be removed after the fire has been extinguished.

Although all dry chemicals are treated for water repellancy, they may harden if exposed to water. It is therefore important to avoid exposing them to any moisture during storage, handling, and recharging. Manufacturers' specifications must be followed carefully.

Ordinary dry chemicals are rated for use on Class B:C fires, but they may be used on Class A fires to knock down flames rapidly until something more suitable can be obtained. When used on flammable liquid fires, the stream should be directed at the base of the flame. Attack the fire near the edge, and move the discharge toward the back of the fire while sweeping the nozzle from side to side. Do not direct the initial discharge directly at the burning surface at close range (less than 5 to 8 ft [1.5 to 2.4 m]), because the high velocity of the stream may splash and spread the burning material.

Multipurpose dry chemical extinguishers should be used in exactly the same manner as ordinary dry chemical agents on Class B fires. On Class A fires, the multipurpose agent softens and sticks to hot surfaces. In this way, it forms a coating that smothers and isolates the fuel from the fire. The agent itself has little cooling effect and cannot penetrate below the burning surface. For this reason, it may be hard to extinguish deep-seated fires unless the agent is discharged below the surface or the material is broken apart and spread out.

Dry chemicals extinguish fires by interfering with the propagation of the combustion chain reaction, which reduces the concentration of "free" radicals present within the flames. The dry chemical thermally decomposes and prevents the flaming process from continuing. In other words, discharge of dry chemical into the flames prevents reactive particles from coming together and continuing the combustion chain reaction.

Cartridge-Operated Extinguishers. Cartridge-type dry chemical extinguishers have a chamber in which the agent is kept at atmospheric pressure; the chamber has a large opening at the top through which the extinguisher may be filled. Attached to the side of the extinguisher, on most models, is a small cartridge of propellant gas, either carbon dioxide or nitrogen, threaded into a puncture valve and gas tube assembly. The agent is discharged through a hose attached to the bottom edge of the shell, and the discharge is controlled by a squeeze-grip nozzle at the end of the hose (Figure 17.5.9). Cartridge-operated extinguishers should be recharged once they have been pressurized. Even if no agent has been released, the propellant gas can leak away in several hours.

To activate a cartridge-operated extinguisher, hold it upright or place it on the ground. Remove the nozzle from its holder, and hold it in one hand while first pushing down the puncture lever before squeezing the nozzle. Pushing the puncture lever releases the propellant from the cartridge and pressurizes the agent cylinder. On some models, it may be necessary to remove a locking pin before pushing the puncture lever. This operation requires two hands, one to hold the device and the other to release and direct the discharge. Do not stand directly over the extinguisher when pressurizing it.

Stored-Pressure Extinguishers. Dry chemical extinguishers with this expellant method are available in both rechargeable and disposable shell models. Most disposable models have a

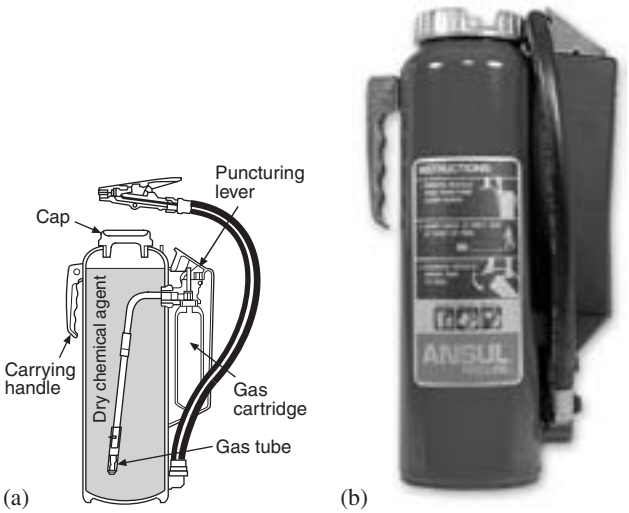


FIGURE 17.5.9 Cartridge-Operated Dry Chemical Fire Extinguisher (Photo courtesy of Ansul Incorporated)

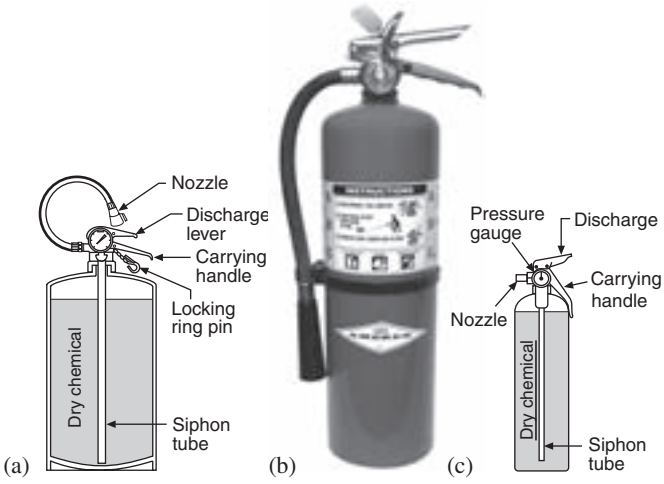


FIGURE 17.5.10 Stored-Pressure Dry Chemical Fire Extinguisher (Photo courtesy of Amerex)

disposable, factory-sealed cylinder containing agent and propellant gas that is threaded into the valve and nozzle assembly. Some small models are designed so that the entire device can be discarded after use. Once this type of device has been used, it should be replaced, even if only a small amount of agent has been discharged, because the propellant gas will leak, leaving no pressure to discharge to agent.

Rechargeable stored-pressure extinguishers come in two types. In both, the agent and the propellant gas are in the extinguisher shell. When the extinguisher is activated, the agent is forced up the siphon tube, where its release is controlled by the operator. One type of extinguisher has a threaded valve assembly and combination carrying handle/operating lever that screws into an opening on the top of the shell. To activate it, release the locking device and squeeze the operating lever (Figure 17.5.10). On smaller sizes of this extinguisher, only one hand is needed to operate the device because the nozzle is part of the valve assembly. Larger sizes require two hands for operation, one to squeeze the lever and carry the device, and the other to direct the agent discharge from the hose.

The other rechargeable stored-pressure dry chemical extinguisher (pre-1975) has a release lever and a hose attached to the cap assembly that covers the fill opening. The hose has a squeeze-grip nozzle for controlling the discharge. To activate it, pull the ring pin and push down the release lever. The agent will travel down the hose to the nozzle, where its discharge can be controlled by squeezing the nozzle. Two hands are needed to operate this extinguisher, one to carry the extinguisher, and the other to release and aim the discharge stream.

Dry Powder Extinguishers

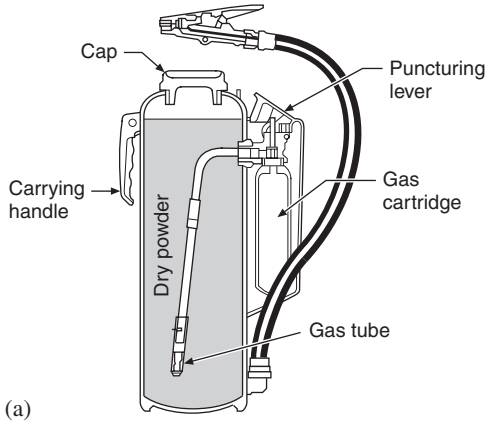
Dry powder extinguishers are intended for use on Class D fires, which involve combustible metals. The agent and method of application should be chosen according to manufacturers' recommendations. The agent may be applied to the fire from an extinguisher or with a scoop and shovel, depending on the type of both agent and metal. In any case, the agent should be applied so that it covers the fire and provides a smothering blanket. More agent may be necessary on hot spots. Care should be taken not to scatter the burning material, which should be left undisturbed until it has cooled.

If there is a fire in finely divided combustible metal or combustible metal alloy scrap that is wet, or if such a fire is wetted with water or water-soluble machine lubricants, the metal may burn rapidly and violently. Such fires may become so hot that it is impossible to get close enough to apply extinguishing agent. If burning metal is on a combustible surface, it should be covered with dry powder. Then a 1- or 2-in. (25- or 50-mm) layer of powder should be spread out nearby, and the burning metal shoveled into it.

One cartridge-operated portable (30 lb [13.6 kg]) dry powder extinguisher currently is available (Figure 17.5.11). Wheeled models are available in 150- and 350-lb (68- and 159-kg) sizes. The extinguishing agent is sodium chloride with additives that render it freeflowing. Thermoplastic material also is added to bind the sodium chloride particles into a solid crust when applied to a fire. With the nozzle fully open, the portable model has a range of 6 to 8 ft (1.8 to 2.4 m).

The method of agent application depends on the type, quantity, and physical form of the burning metal. If the fire is very hot, discharge should begin at the maximum range with the nozzle fully open. Once control is established, the nozzle should be partly closed to produce a soft, heavy flow so that complete coverage can be accomplished at close range. More complete details should be obtained from the manufacturer.

In bulk form, dry powder agents are available in 40- or 50-lb (18- or 23-kg) pails and 350 lb (159 kg) drums. The two most common agents are sodium chloride and G-1 powder. The latter consists of graded, granular graphite to which compounds containing phosphorous have been added. The sodium chloride can be used in an extinguisher or applied by hand. The G-1 agent must be applied by hand. When G-1 is applied to a metal fire, the heat of the fire causes the phosphorous compounds to generate vapors that blanket the fire and prevent air from reaching the



(a)

(b)

FIGURE 17.5.11 Dry Powder Extinguishers: (a) Cartridge-Operated Extinguisher; (b) Stored-Pressure Extinguisher (Photo source: *NFPA Guide to Portable Fire Extinguishers,* NFPA, 2003, Figure 1-39. Reproduced courtesy of Jones and Bartlett Publishers.)

burning metal. The graphite, being a good conductor of heat, cools the metal.

Aqueous Film-Forming Foam (AFFF) and Film-Forming Fluoroprotein Foam (FFFP) Extinguishers

AFFF and FFFP are extinguishing agents that contain an aqueous film-forming surfactant. When added to water, AFFF and FFFP form solutions that create a foam when discharged through an aspirating nozzle. On Class A fires, these agents both cool and penetrate to reduce temperatures below the ignition level. On Class B fires, they act as a barrier to exclude oxygen from the surface of the fuel.

AFFF and FFFP currently are available in 2½ gal (9.5 L) stored-pressure models rated at 3-A:20-B. They discharge their contents in approximately 50 seconds and have a range of 20 to 25 ft (6 to 8 m). They should be installed only in areas not subject to temperatures below 40°F (4°C). There is also a 33 gal (125.4 L) unit with 20-A:160-B ratings.

These types of extinguishers closely resemble the stored-pressure water extinguisher, except for their special aspirating nozzles (Figure 17.5.12). On flammable liquid fires of appreciable depth, the best results are obtained when the discharge is played against the inside of the back wall of the vat or tank just above the burning surface, which should permit the natural spread of the foam back over the burning liquid. If this is not possible, the operator should stand far enough away from the fire to allow the foam to fall lightly on the burning surface instead of splashing it into the burning liquid. Where possible, the operator should walk around the fire while directing the stream to get maximum coverage during discharge. For flammable liquid spill fires, the foam may be flowed over a burning surface by bouncing it off the floor just in front of the burning area. The operator should never turn his or her back on the fire, as unburned fuel may reignite. For fires in ordinary combustibles, the foam may be used to coat the burning surface directly. Foam is not effective on flammable liquids and gases escaping under pressure, nor is it suitable for fires involving ethers, alcohols, esters, acetone, lacquer thinners, carbon disulfide, and other flammable liquids that either break down or penetrate the foam blanket.

OBSOLETE EXTINGUISHERS

In 1969, the manufacture and testing of all inverting-type extinguishers—soda acid, chemical foam, and cartridge-operated water and loaded stream—was halted in the United States. It was not only the difficult and unorthodox "upside-down" method of actuation that brought about the discontinuance of these extinguishers. Of greater importance was the fact that, after 10 to 15 years, many inverting types tended to fail the minimum test pressure requirements of NFPA 10 (original factory test pressure). When pressurized, the failure record, including hydrostatic test failures, was alarmingly high. Since the inverting types are not normally pressurized, potential failures generally are not evident until the time of operation or hydrostatic testing.

When inverted, normal operating pressures are about 100 psi (690 kPa). Should the discharge elbow or hose become blocked, however, pressures in excess of 300 psi (2069 kPa) may occur. Container failures can injure the operator seriously.

NFPA 10 was revised in 1978, and stated that extinguishers with copper or brass shells joined by soft solder or rivets could no longer be hydrostatically tested, which would result in their removal from use within five years of the latest hydrostatic test date. Reliability and safety of this type of construction could not be determined by standard hydrostatic test procedures.

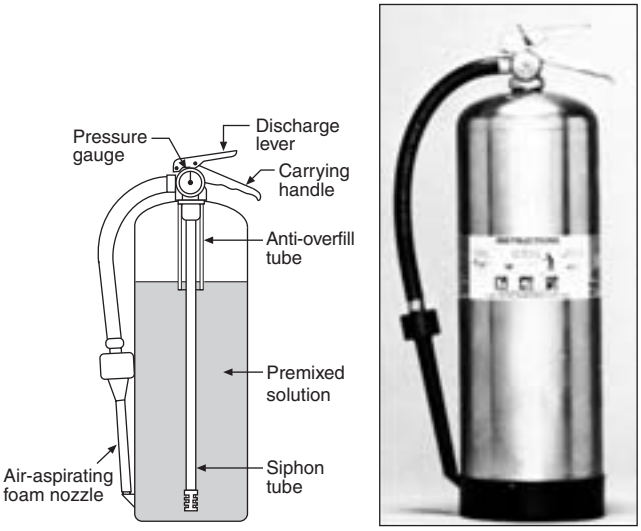


FIGURE 17.5.12 Aqueous Film-Forming Foam (AFFF) Extinguisher (Photo courtesy of Amerex)

In 1978, NFPA 10 called for the removal from service, by or before 1983, of all riveted and soft-solder copper and brass shell extinguishers of the inverting type. The one exception is stainless-steel shells and brass shells that are brazed, as opposed to soft-soldered. Also in 1978, stored-pressure water and/or antifreeze fiberglass shell types were required to be removed from service immediately because they had been recalled by the manufacturer. The following types of fire extinguishers are considered obsolete and should be removed from service:

- Soda acid
- Chemical foam (excluding film-forming agents)
- Vaporizing liquid (e.g., carbon tetrachloride)
- Cartridge-operated water
- Cartridge-operated loaded stream
- Copper or brass shell (excluding pump tanks) joined by soft solder or rivets
- Carbon dioxide extinguishers with metal horns
- Solid charge–type AFFF extinguishers (paper cartridge)
- Pressurized water fire extinguishers manufactured prior to 1971
- Any extinguisher that must be inverted to operate
- Any dry chemical extinguisher with a stainless steel shell
- Any stored pressure extinguisher manufactured prior to 1955
- Any extinguisher with a 4B, 6B, 8B, 12B, or 16B fire rating
- Stored-pressure water extinguishers with fiberglass shells (pre-1976)
- Any extinguisher that can no longer be serviced in accordance with the manufacturer's maintenance manual

Vaporizing liquid extinguishers with CCl_4 (carbon tetrachloride) and CBM (chlorobromomethane) became obsolete in the late 1960s. The toxic properties of these agents expose the operator to unwarranted health hazards, and their use was supplanted by safer, more effective extinguishers. In 2007, NFPA 10 called for the removal from service, at the next six-year maintenance interval or the next hydrostatic test interval, all dry chemical stored pressure extinguishers that were manufactured prior to October 1984.

DISTRIBUTION OF FIRE EXTINGUISHERS

No matter how carefully extinguishers are chosen to match the hazards of an area and the ability of the people who will use them, they will not be effective unless they are readily available. Sometimes extinguishers are kept at hand, as in welding operations, but, more often, one has to travel from the fire to the extinguisher and back before beginning to put out the fire. In such cases, travel distance to the nearest extinguisher is very important. Travel distance is the actual distance around partitions, through doorways and aisles, and so on that someone must walk to reach the extinguisher.

When placing extinguishers, select locations that provide uniform distribution, easily accessible and relatively free from temporary blockage, near normal paths of travel, near exits and entrances, free from the potential of physical damage, and readily available.

Mounting Extinguishers

If an extinguisher falls, it may injure someone or be so damaged that it must be replaced. Extinguishers should be mounted on walls or columns by securely fastened hangers so that they are supported adequately. Some extinguishers are mounted in cabinets or wall recesses. The operating instructions should always face outward, and the extinguisher should be placed so that it can be removed easily. Cabinets should be kept clean, dry, and ventilated if installed in outdoor locations.

Where extinguishers may become dislodged, brackets specifically designed to cope with this problem are available. In areas where they are subject to physical damage, such as warehouse aisles, protection from impact is important. In large open areas, such as aircraft hangars, extinguishers may be mounted on moveable pedestals or wheeled carts. To maintain some pattern of distribution and specify intended placement, locations should be marked on the floor.

NFPA 10 specifies floor clearance and mounting heights, based on extinguisher weight, as follows:

1. Extinguishers with a gross weight not exceeding 40 lb (18 kg) should be installed so that the top of the extinguisher is not more than 5 ft (1.5 m) above the floor.
2. Extinguishers with a gross weight greater than 40 lb (18 kg), except wheeled types, should be installed so that the top of the extinguisher is not more than 3½ ft (1 m) above the floor.
3. In no case can the clearance between the bottom of the extinguisher and the floor be less than 4 in. (100 mm).

When extinguishers are mounted on industrial trucks, vehicles, boats, aircraft, trains, and so on, special mounting brackets, available from the manufacturer, should be used. It is also important that the extinguisher be located at a safe distance from the hazard so that it will not become involved in the fire.

Extinguisher Distribution for Class A Combustibles

Table 17.5.2 is a guide to determining the minimum number and rating of extinguishers for Class A fires needed in any particular area. Sometimes extinguishers with ratings higher than those indicated in Table 17.5.2 may be necessary because of process hazards, building configuration, and so on, but in no case should the recommended maximum travel distance be exceeded.

The first step when calculating how many Class A extinguishers are needed is to determine whether an occupancy is light-, ordinary-, or extra-hazard, according to NFPA 10. Next, the extinguisher rating should be matched with occupancy hazard to determine the maximum area that an extinguisher can protect. The maximum travel distance, or actual walking distance, allowed for Class A extinguishers is 75 ft (23 m).

The figure of 11,250 ft^2 (1044 m^2) in Table 17.5.2 is used instead of 12,000 ft^2 (1115 m^2), which would appear to be a normal progressive increment. This is because the largest square inside a circle with a 75 ft (23 m) radius would be 106 ft × 106 ft (32 m × 32 m), or 11,250 ft^2 (1044 m^2). Because buildings are usually rectangular, this is the largest open area one can have and still comply with the 75-ft (23-m) travel distance rule (Figure 17.5.13).

The area that can be protected by one fire extinguisher with a given A rating is shown in Table 17.5.3. These values are determined by multiplying the maximum floor area per unit of A shown in Table 17.5.3 by the various A ratings until a value of 11,250 ft^2 (1044 m^2) is exceeded.

NFPA 10 also provides that up to half of the complement of extinguishers for Class A fires, as specified in Table 17.5.2, may be replaced by uniformly spaced small-hose (1½ in. [38 mm]) stations. However, the hose stations and extinguishers should be located so that the hose stations do not replace more than every other extinguisher.

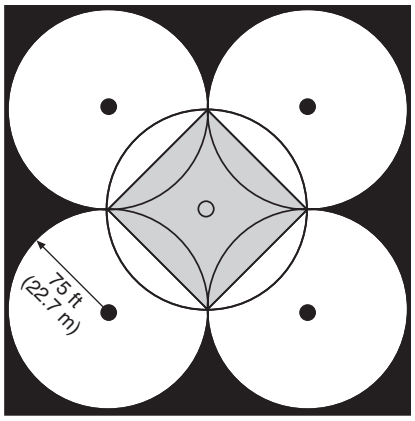


FIGURE 17.5.13 Maximum Extinguisher-Protected Area. The shaded square shows the maximum area (11,250 ft^2 [1044 m^2]) that an extinguisher can protect within the limits of a 75 ft (23 m) radius.

The following examples illustrate the number and placement of extinguishers according to occupancy hazard and extinguisher rating. The sample building is 150 ft by 450 ft (46 m by 137 m), which gives a floor area of 67,500 ft^2 (6270 m^2). Although several different ways of placing extinguishers are given, a number of other locations could have been used with similar results.

The first example demonstrates placement at the maximum protection area limits (11,250 ft^2 [1044 m^2]) allowed per extinguisher in NFPA 10 for each class of occupancy. Installing extinguishers with higher ratings will not affect distribution or placement.

TABLE 17.5.2 Fire Extinguisher Size and Placement for Class A Hazards

	Light (Low) Hazard Occupancy	*Ordinary (Moderate) Hazard Occupancy*	*Extra (High) Hazard Occupancy*
Minimum rated single extinguisher	2-A[a]	2-A[a]	4-A[b]
Maximum floor area per unit of A	3,000 ft^2	1,500 ft^2	1,000 ft^2
Maximum floor area for extinguisher	11,250 ft^2	11,250 ft^2	11,250 ft^2
Maximum travel distance to extinguisher	75 ft	75 ft	75 ft

[a]Up to two water-type extinguishers, each with 1-A rating, can be used to fulfill the requirements of one 2-A rated extinguisher.
[b]Two 2½ gal (9.46 L) water-type extinguishers can be used to fulfill the requirements of one 4-A rated extinguisher.
For SI units: 1 ft = 0.305 m; 1 ft^2 = 0.0929 m^2.

Source: NFPA 10, *Standard for Portable Fire Extinguishers,* Table 6.2.1.1., 2007, p. 10-11.

TABLE 17.5.3 Maximum Area in Square Feet to Be Protected per Extinguisher

Class A Rating Shown on Extinguisher	*Light (Low) Hazard Occupancy*	*Ordinary (Moderate) Hazard Occupancy*	*Extra (High) Hazard Occupancy*
1-A	—	—	—
2-A	6,000	3,000	—
3-A	9,000	4,500	—
4-A	11,250	6,000	4,000
6-A	11,250	9,000	6,000
10-A	11,250	11,250	10,000
20-A	11,250	11,250	11,250
30-A	11,250	11,250	11,250
40-A	11,250	11,250	11,250

Note: 11,250 ft^2 is considered a practical limit.
For SI units: 1 ft^2 = 0.0929 m^2.

Source: NFPA 10, *Standard for Portable Fire Extinguishers,* Table E.3.4, 2007, p. 10-43.

EXAMPLE 1:

$\frac{67{,}500}{11{,}250} = 6$

4-A Extinguishers for light-hazard occupancy

10-A Extinguishers for ordinary-hazard occupancy

20-A Extinguishers for extra-hazard occupancy

This placement along outside walls would not be acceptable because it clearly violates the travel distance rule (Figure 17.5.14). Instead, relocation and/or additional extinguishers are needed.

Example 2 is for fire extinguishers having ratings that correspond to protection areas of 6000 ft^2 (557 m^2). Example 3 is for extinguishers having the minimum ratings permitted by Table 17.5.2 with corresponding minimum protection areas. As the number of lower-rated extinguishers increases, meeting the travel distance requirement generally becomes less of a problem.

EXAMPLE 2:

$\frac{67{,}500}{6{,}000} = 12$

2-A Extinguishers for light-hazard occupancy

4-A Extinguishers for ordinary-hazard occupancy

6-A Extinguishers for extra-hazard occupancy

EXAMPLE 3:

$\frac{67{,}500}{6{,}000} = 12$ 2-A Extinguishers for light-hazard occupancy

$\frac{67{,}500}{3{,}000} = 23$ 2-A Extinguishers for ordinary-hazard occupancy

$\frac{67{,}500}{4{,}000} = 17$ 4-A Extinguishers for extra-hazard occupancy

Extinguishers could be mounted on exterior walls or, as shown in Figure 17.5.15, on building columns or interior walls, and conform to both distribution and travel distance rules.

The arrangement illustrated in Figure 17.5.16 shows extinguishers grouped together on building columns or interior walls in a manner that still conforms to distribution and travel distance rules.

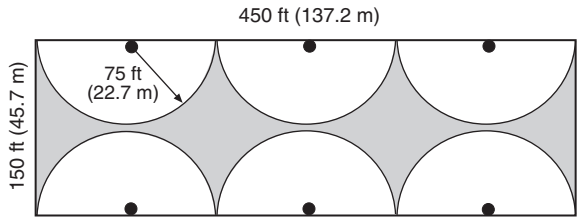


FIGURE 17.5.14 Diagrammatic Representation of Extinguishers Located Along Outside Walls of a 150 ft × 450 ft (46 m × 137 m) Building. The large dots represent extinguishers. The shaded areas indicate "voids" that are farther than 75 ft (23 m) from the nearest extinguisher.

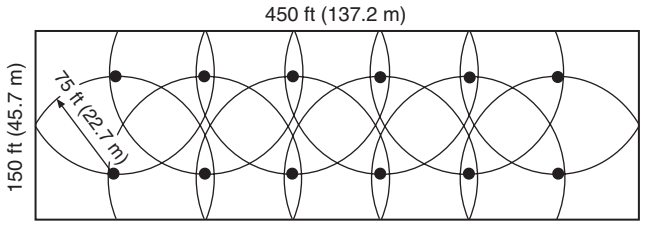


FIGURE 17.5.15 Configuration of 12 Extinguishers Mounted on Building Columns or Interior Walls, Meeting Requirements for Travel Distance and Extinguisher Distribution

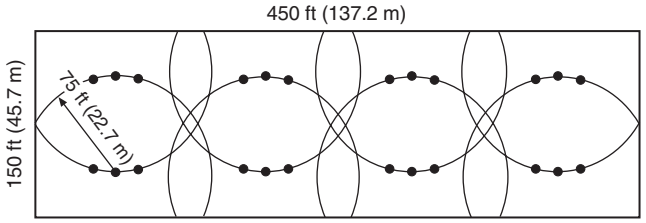


FIGURE 17.5.16 Extinguishers Grouped Together

Extinguisher Distribution for Class B Combustibles

Class B fire hazards fall into two distinct categories. The first includes liquids ¼ in. (6.4 mm) deep or less, and the other includes liquids deeper than ¼ in. (6.4 mm).

In areas where liquids do not reach an appreciable depth, extinguishers should be provided according to Table 17.5.4. The reason the basic maximum travel distance to Class B extinguishers is 50 ft (15 m), as opposed to 75 ft (23 m) for Class A extinguishers, is that flammable liquid fires reach their maximum intensity almost immediately, and thus the extinguisher must be nearer to hand. With lower-rated extinguishers, the travel distance is reduced to 30 ft (9 m).

Even though Table 17.5.4 specifies maximum travel distances to extinguishers for Class B fires, judgment should be used when actually placing the devices. The closer the extinguisher to the hazard, the better—up to the point at which a fire might damage or obstruct access to the device.

When flammable liquids reach an appreciable depth, the extinguisher's rating number, except for foam types, should be at least twice the number of square feet (m^2) of surface area of the largest tank in the area, assuming that other requirements are met. The travel distances specified by Table 17.5.4 should also be used to locate extinguishers for protection of spot hazards. Sometimes, one extinguisher can be installed to provide protection against several different hazards, provided that travel distances are not exceeded.

Where there are open process tanks of flammable liquids with surface areas greater than 10 ft^2 (1 m^2), complete dependence should not be placed on fire extinguishers. It is often advisable to consider installing fixed fire protection systems for

TABLE 17.5.4 Fire Extinguisher Size and Placement for Class B Hazard Excluding Protection of Deep-Layer Flammable Liquid Tanks

Type of Hazard	*Basic Minimum Extinguisher Rating*	Maximum Travel Distance to Extinguishers	
		ft	*m*
Low	5-B	30	9
	10-B	50	15
Moderate	10-B	30	9
	20-B	50	15
High	40-B	30	9
	80-B	50	15

these tanks because of the potential size and intensity of the fire which could occur. If a fixed protection system suitable for Class B fires is installed, then the extinguisher requirement may be waived for the hazard, or hazards, it protects, though not for the complete structure or any other special hazards in the area. Portable extinguishers can be useful even when fixed protection systems have been installed, in case a burning tank spills liquid outside the range of the fixed equipment or a fire begins adjacent to a tank rather than in it.

Pressurized flammable liquids and gases are not stored in open containers, and it is not possible to select extinguishers for them according to the square foot (m^2) requirements. Instead, extinguishers with special nozzles and rates of agent application should be chosen. The manufacturers of these specialized extinguishers usually recommend what equipment they are suited for. In general, however, no attempt to extinguish pressurized fuel fires should be made unless the source of fuel can be shut off promptly. As before, the travel distances to portable extinguishers should not exceed those specified by Table 17.5.4.

Because Class B fires can become so intense so quickly, the flow rate and the duration of discharge of an agent are very important. For these reasons, NFPA 10 does not permit substituting two or more extinguishers of lower rating for the minimum ratings given in Table 17.5.4, except for certain foam extinguishers. The exception permits the substitution because foam progressively "secures" a fire, and the foam from one extinguisher is effective during the time it takes to bring other units into operation. With carbon dioxide and dry chemical extinguishers, however, four extinguishers rated 5-B are not equal to one extinguisher rated 20-B; the larger extinguisher has a higher flow rate in pounds per second (kg/sec) and a longer continuous discharge time than the smaller models.

Wheeled extinguishers with ratings from 20-B to 480-B are available. They are designed chiefly for outdoor fire fighting and should be used only by trained employees. They should be distributed according to the 50 ft (15 m) travel distance rules of Table 17.5.4, though longer travel distances may be authorized by the authority having jurisdiction.

A sample problem from NFPA 10 for protection by portable extinguishers follows.

Sample Problem. A light-occupancy office building is to be protected by portable fire extinguishers. The floor area is 11,100 ft^2 (1031 m^2) and of unusual design (Figure 17.5.17).

The most common fire extinguisher selections would be 2½ gal (9.5 L) stored-pressure water models rated 2-A. According to Table 17.5.2 (Table E-3.4 from NFPA 10), two fire extinguishers are needed (11,100/6000 = 2). Travel distance requirements are 75 ft (23 m) maximum.

The two units are placed at points 1 and 2, and a check is make on the travel distance requirement. Because of the area's unusual shape, it is found that the shaded areas exceed the 75 ft (23 m) distance. Two additional fire extinguishers (at points 3 and 4) are needed. The additional fire extinguishers afford more flexibility in placement, and alternative locations are indicated. It is important to consider any partitions, walls, or other obstructions in determining the travel distance.

As an additional item, consider that Area A contains a small printing and duplicating department that uses flammable liquids. This area is judged to be an ordinary Class B hazard. A 10-B:C or 20-B:C fire extinguisher should be specified to protect this area.

There are now two alternatives to be considered. First, a fifth fire extinguisher, either carbon dioxide or ordinary dry chemical, with a rating of 10-B:C or 20-B:C could be specified. Second, the water fire extinguisher at point 2 could be replaced with a multipurpose dry chemical fire extinguisher that has a rating of at least 2-A:10-B:C. It should be located near point 2, keeping in mind the 75 ft (23 m) travel distance for the 2-A protection and the 30 ft or 50 ft (9.1 m or 15.25 m) travel distance required for the Class B protection that this fire extinguisher provides.

Extinguisher Distribution for Class C Fires

Extinguishers for Class C fires are required wherever there is live electrical equipment. This sort of extinguisher contains a nonconducting agent, usually carbon dioxide, dry chemical, or a halogenated agent.

Once the power to live electrical equipment is cut off, the fire becomes a Class A or Class B fire, depending on the nature of the burning electrical equipment and the burning material in

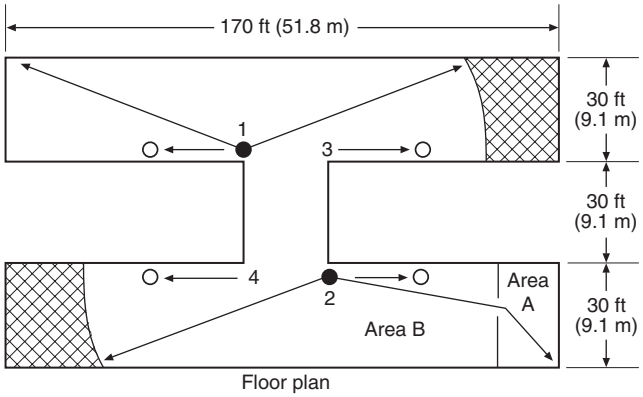


FIGURE 17.5.17 Floor Plan

the vicinity. Extinguishers for Class C fires should be selected according to the size of the electrical equipment; the configuration of the electrical equipment, particularly the enclosures of units, which influence agent distribution; and the range of the extinguisher's stream. At large installations of electrical equipment where continuity of power is critical, fixed fire protection is desirable. But even when fixed fire protection is present, it is recommended that some Class C extinguishers be provided to handle incipient fires.

Class D Extinguisher Distribution

It is particularly important that the proper extinguishers be available for Class D fires. Because the properties of combustible metals differ, even an agent for Class D fires may be hazardous if used on the wrong metal. Agents should be chosen carefully according to the manufacturers' recommendations. The amount of agent needed is normally figured according to the surface area of the metal, plus the shape and form of the metal, which could contribute to the severity of the fire and cause "bake-off" of the agent. For example, fires in magnesium filings are more difficult to put out than fires in magnesium scrap, and more agent is needed for magnesium filings. The maximum travel distance to all extinguishers for Class D fires is 75 ft (23 m).

INSPECTION AND MAINTENANCE OF FIRE EXTINGUISHERS

Once a fire extinguisher has been purchased, it becomes the responsibility of the purchaser or an assigned agent to maintain the device. Adequate maintenance consists of periodically inspecting each extinguisher, recharging each extinguisher following discharge, and performing periodic hydrostatic tests or as needed.

A fire equipment servicing agency is considered the most reliable way for the general public to maintain extinguishers, but large industries often train employees to handle this maintenance themselves. Many jurisdictions require service technicians to be licensed. Carson[2] provides checklists for periodic inspection and maintenance of fire extinguishers.

Inspection Considerations

An inspection is a quick check that visually determines whether the fire extinguisher is properly placed and will operate. The purpose of an inspection is to give reasonable assurance that the extinguisher is fully charged and will function effectively if needed. An inspection should determine that the extinguisher is in its designated place, is conspicuous, is not blocked in any way, has not been activated and partially or completely emptied, has not been tampered with, and has not sustained any obvious physical damage or been subjected to an environment that could interfere with its operation, such as corrosive fumes. If the extinguisher is equipped with a pressure gauge and/or tamper indicators, the inspection should show conditions to be satisfactory. In addition, the maintenance tag can be checked to determine the date of the last thorough maintenance check.

In order to be effective, inspections must be frequent, regular, and thorough. In a small building with few extinguishers, the manager, property owner, or some designated person could check extinguishers at the beginning of each workday. If a building is large enough to employ security guards or a surveillance service, extinguishers should be inspected at least once during each 8 hour shift. In industrial plants, the plant fire brigade or fire inspector often inspects extinguishers either daily, weekly, or monthly. The maximum time period between inspections is 30 days.

An individual evaluation must be made of each property to determine how frequently inspections should be made. If a particular operation is fire prone or is crucial to the use of the property, more frequent inspections should be made. For example, if all the products manufactured in a particular industrial plant had to be painted, a fire in the painting room could be disastrous, so inspections should be very frequent.

It is important to consider the nature of the hazards present that influence the potential use of the extinguisher: the exposure of the extinguisher to tampering, vandalism, and malicious mischief; extraordinary weather conditions; the likelihood of accidental damage to the extinguisher; and the possibility of visual or physical obstructions to the accessibility of extinguishers.

Manual Inspection Alternative

An alternative to a manual inspection of extinguishers is to have them electronically monitored. These extinguisher monitoring systems have gained acceptance and are now routinely used to check the condition of extinguishers. Typically, extinguishers are connected to a fire alarm system and are electronically monitored to ensure that they are in their designated places. Such electronic monitoring can also verify that there are no obstructions to accessing the extinguishers and that the pressure gauge is in its operable range. This alternative is desirable for locations where the extinguishers were previously neglected or where there is a problem of theft.

Maintenance Considerations

Maintenance, as distinguished from inspection, means a complete and thorough examination of each extinguisher. A maintenance check involves examining parts, cleaning and replacing any defective parts, and reassembling, recharging, and, where appropriate, pressurizing the extinguisher.

Maintenance checks sometimes reveal the need for special testing of extinguisher shells or other components. For example, they may reveal that the extinguisher container should be hydrostatically tested or even replaced.

Frequency. Maintenance should be performed periodically, but at least once every 12 months, after each use, or when an inspection shows that the need is obvious. If an inspection reveals evidence of serious damage by corrosion, for example, the extinguisher should be subjected to a thorough maintenance check, even though it may have undergone one recently. Similarly, if an inspection shows evidence of tampering, agent leakage, or physical damage, a complete maintenance check

should be initiated. NFPA 10 contains specific details related to maintenance.

Tags and Tamper Seals. For many years, extinguisher tags have been used as a convenient means for recording maintenance checks. For routine maintenance, a tied-on tag or pressure-sensitive label is used to record the date and the inspector's initials. Newer technology using bar code readers also can be used. Tamper seals also should be used. Lead and wire seals were used commonly until plastic seals were introduced in 1972. As long as the seal remains intact, one can be reasonably sure that the extinguisher has not been used. However, it is important to note that a stored-pressure extinguisher can develop a leak and lose its pressure even though the tamper indicator remains intact or the pressure gauge reads normal. During annual maintenance, the tamper seal is removed by operating the pull pin or locking device. This is done to ensure that they operate freely. A new tamper seal is then installed.

A neck ring collar is installed on an extinguisher following servicing, which necessitates the removal of the extinguisher valve assembly. This is used to verify if the extinguisher was depressurized and the valve was removed. The collar design also necessitates the removal of the valve before the collar can be attached to the extinguisher. The collar design permits the date to be recorded. The collar provides the authorities having jurisdiction with convenient visual proof that the extinguisher was disassembled. Figure 17.5.18 provides a guide to the design of a "Verification of Service" collar.

Maintenance Operations

In any operational test of a portable fire extinguisher, there are three basic items that need to be checked: (1) the mechanical parts of the device—that is, the extinguisher shell and other component parts; (2) the amount and condition of the extinguishing agent; and (3) the condition of the means for expelling the agent.

A record of the date of purchase, as well as maintenance dates, should be kept for each extinguisher. A separate record is also desirable and should include the maintenance date and the name of the person or agency performing the maintenance; the date last recharged and the name of the person or agency performing the recharge; the hydrostatic retest date and the name of the person or agency performing the hydrostatic test; description of dents remaining after passing a hydrostatic test; and the date of the six-year maintenance for certain stored-pressure dry chemical and halogenated agent extinguishers.

Individuals who own extinguishers might neglect them if there is no planned periodic follow-up program. It is recommended that owners become familiar with their extinguishers so that they can detect telltale signs which suggest the need for maintenance. An alternative is to have the dealer from whom the extinguisher was purchased establish an annual follow-up maintenance program.

On properties where extinguishers are maintained by the occupant, a supply of recharging materials should be kept on hand. When recharging extinguishers other than those with plain water, use only those recharging materials specified on the extinguisher's nameplate. Other recharging materials may impair the efficiency of the extinguisher or cause it to malfunction and injure the operator. Special precautions are necessary for certain types of extinguishers, and they are discussed elsewhere in this chapter.

NFPA 10 has an appendix with a checklist of items that require maintenance. The checklist is divided into two sections. One section of the checklist is arranged to pinpoint the mechanical parts common to most extinguishers. The other section addresses agent and expelling means.

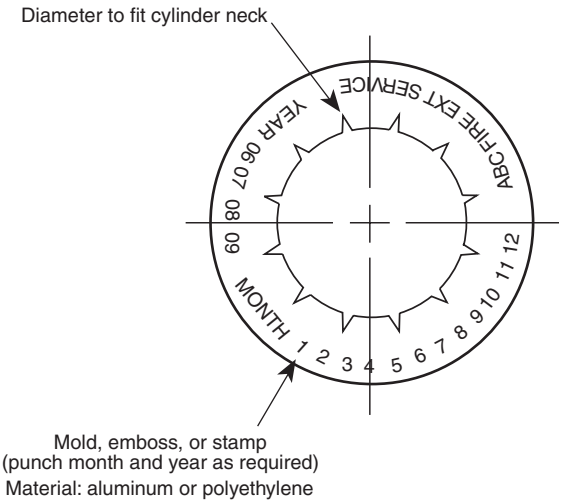


FIGURE 17.5.18 Design of a "Verification of Service" Collar

Inspection and Maintenance of Water-Type Extinguishers

Inspection and maintenance for stored-pressure models is too often thought of as quite simple. Unless the extinguisher has been used or a routine inspection reveals a defect, maintenance is sometimes left until the five-year hydrostatic test is performed. This practice can result in failures and malfunctions. The principal items that need to be checked during an inspection are a loose, worn, or damaged hose; a plugged nozzle; a dented shell; a damaged indicator gauge; and a damaged or jammed ring pin. Normal maintenance service, as specified in NFPA 10, should be performed annually.

Mechanical pump extinguishers, such as pump tanks and backpacks, are easy to inspect and maintain. The tanks containing the water or antifreeze solution must be checked to ensure they are in good condition, have not been weakened by corrosive action, and do not contain sediment that might block the stream during the pumping operation. If the device has not been used in the last 12 months, the liquid should be removed from the tank and the tank should be flushed and filled with new liquid. Pumps require lubrication from time to time. They should be checked annually to ensure that the plungers are in proper condition, that seals and washers have not deteriorated, and that

hoses are not clogged. Antifreeze solutions need to be checked to ensure that they are not contaminated and can withstand the temperatures in the area.

Inspection and Maintenance of Dry Chemical Extinguishers

Dry chemical extinguishers should be inspected monthly, and they should also undergo normal annual maintenance. The quantity of agent for a cartridge-operated model can be checked by weighing or by removing the fill cap and checking it visually. The gas cartridge also can be checked by weighing. On stored-pressure models, the pressure gauge will indicate if adequate pressure is maintained, and the agent quantity can be checked by weighing.

Dry chemical extinguishers should be refilled promptly after use, even if they have been discharged only partially. When refilling, extreme caution must be taken to ensure that no water, moisture, or foreign material enters the cylinder. Even though dry chemical agents are treated for moisture repellency, they can eventually harden if moisture is present. When these extinguishers are hydrostatically tested, they must be dried thoroughly so that no trace of water or moisture remains. Before new agent is added, all of the unused agent should be removed by dumping or vacuuming, and any residue should be removed from the hose.

An extinguisher containing a Class B:C dry chemical (bicarbonate-base or potassium chloride) should not be refilled with a Class A:B:C agent (monoammonium-phosphate-base). Mixing different dry chemical agents can result in malfunction, damage to the extinguisher, or both. The bicarbonate-based agent is chemically alkaline and will react with the acidic ammonium phosphate. This reaction is aggravated by exposure to heat or the presence of moisture in amounts as small as 0.1 percent. One result is caking of the agent; another possible result is the internal corrosion of the extinguisher. Under certain conditions, the reaction will cause excess pressure to build up within the shell, which may damage or rupture the extinguisher.

Substituting another manufacturer's dry chemical of the same type is not recommended unless it has the same chemical and physical characteristics, or has been tested and found to give equivalent performance. The problems involved in substitution include the following:

1. An altered flow rate of the dry chemical, which could influence extinguishing efficiency
2. The amount of agent that could be placed in the extinguisher, which could influence discharge time
3. Incompatibility of one dry chemical to another, including chemical reactions, caking, and jamming of hose or nozzles. The flow rate can change with the particle size and density of the agent. A discharge nozzle designed to dispense one dry chemical efficiently might well be less efficient for another. An extinguisher designed to hold a given weight of one formula may not hold the same amount of another. Dip tubes, hoses, or valves could become plugged.

Recharge operations for the cartridge-operated models are relatively easy. The rubber sleeves on the gas tube should be checked for cracking or overstretching, and the gasket and gasket seats on the shell and cap should be wiped clean. The cap should be screwed on handtight. When replacing the cartridge, care should be taken that the threads are not dirty, cross-threaded, or otherwise damaged. For stored-pressure models, the entire valve body, stem, and "O" ring should be carefully wiped clean and blown out with dry nitrogen to get rid of all traces of agent residue which might cause a pressure leak.

Nitrogen gas used for pressurizing should be of the standard industrial grade, with a dew point of –60°F (–51.1°C) or lower so that it is free of moisture. Once the extinguisher has been pressurized, it should be given a leak test or allowed to stand for about 12 hours and then checked for leaks before it is returned to service.

Some stored-pressure extinguishers are factory-sealed and are not rechargeable. No effort should be made to recharge these units in the field. Normally, the shell of the extinguisher is discarded following use; only the valve and nozzle assembly are retained. Refill units should be obtained from the manufacturer, and detailed instructions for replacement are included on the extinguisher nameplate.

The general inspection and maintenance procedures for dry powder (Class D) extinguishers are the same as for cartridge-operated dry chemical extinguishers.

Inspection and Maintenance of Carbon Dioxide Extinguishers

Weighing is the only way to determine whether carbon dioxide extinguishers are fully charged. They should be weighed at least semiannually for loss of weight and inspected for deterioration and/or physical damage. The full and empty weights are stamped on the valve assembly. Any carbon dioxide extinguisher that has a weight loss of 10 percent or more should be recharged and tested for leaks. Recharging is generally done by an extinguisher servicing company. Should on-site recharging be desirable, however, the manufacturer should be contacted for assistance in setting up a recharging station.

Recharging extinguishers with carbon dioxide from dry-ice converters is no longer permitted due to the high potential for moisture in the carbon dioxide. The vapor phase of carbon dioxide must not be less than 99.5 percent carbon dioxide. The water content of the liquid phase must not be more than 0.01 percent by weight (–30°F [–34.4°C] dew point). The oil content of the carbon dioxide must not exceed 10 ppm by weight.

Specific recommendations are given for such recharging in NFPA 10. The required source of carbon dioxide is a low-pressure carbon dioxide supply (300 psi at 0°F [206.8 kPa at –17.8°C]), either directly from the source or through dry cylinders used as intermediaries. It cannot be emphasized too strongly that internal moisture can seriously corrode an extinguisher, and that moisture is most easily introduced into a cylinder either during recharging or following a hydrostatic test.

Inspection and Maintenance of Halogenated Agent Extinguishers

The general inspection and maintenance procedures for halogenated agent extinguishers are similar to the requirements

for other extinguishers. They are physically similar to stored-pressure dry chemical extinguishers. The specific requirements of each manufacturer should be followed.

Hydrostatic Testing of Extinguishers

The purpose of hydrostatic testing of portable fire extinguishers that are subject to internal pressures is to protect against unexpected, in-service failure. Such a failure may be due to undetected internal corrosion caused by moisture in the extinguisher; external corrosion caused by atmospheric humidity or corrosive vapors; damage caused by rough handling, which may or may not be obvious by external inspection; repeated pressurizations; manufacturing flaws in the construction of the extinguisher; improper assembly of valves or safety relief discs; or exposure of the extinguisher to abnormal heat, as during a fire.

NFPA 10 requires that hydrostatic pressure tests be performed on extinguishers according to Table 17.5.5. The first hydrostatic retest may be conducted between the fifth and sixth year for those with a designated test interval of five years. However, carbon dioxide types require a strict five-year interval according to federal law. Hydrostatic tests also should be conducted immediately upon discovery of any mechanical injury or corrosion to the extinguisher shell.

In the United States, various U.S. Department of Transportation (DOT) rules apply to specific types of cylinders used for fire extinguishers. Title 49 of the *Code of Federal Regulations* calls, with some exceptions, for the hydrostatic retesting every five years of compressed-gas cylinders offered for interstate transportation in a charged condition. Paragraph 173.34(e) calls for periodic retesting of DOT compressed-gas cylinders whether or not the cylinders are shipped interstate.

Many different DOT specification cylinders are used for dry chemical extinguishers, including Types DOT-4B and DOT-4BA. The requirements for these types are peculiar to them.

The preferred method of hydrostatic testing of compressed-gas cylinders is the water-jacketed, volumetric expansion method recommended in NFPA 10. The guide to follow in conducting this type of test is Pamphlet C-1, "Methods for Hydrostatic Testing of Compressed Gas Cylinders," published by the Compressed Gas Association, Inc. (CGA).[3] For visually evaluating the condition of cylinders made to DOT specifications, CGA's Pamphlet C-6, "Standards for Visual Inspection of Steel Compressed Gas Cylinders,"[4] is helpful.

Procedures for testing extinguishers other than compressed-gas extinguishers or affixed compressed-gas cylinders are detailed in NFPA 10. Table 17.5.6 gives the basic data on the hydrostatic test pressure requirements. Figures 17.5.19 and 17.5.20 illustrate equipment used in hydrostatic testing work.

It is not necessary to hydrostatically test certain extinguishers, such as pump tanks, backpacks, and similar devices. Factory-sealed, nonrefillable, disposable fire extinguishers cannot be hydrostatically tested. When such extinguishers are damaged, they must be replaced.

Proper hydrostatic testing requires competent personnel and suitable testing equipment and facilities. The preparation for testing and the removal of all traces of water and moisture with special drying equipment after testing are very important and reinforce the recommendation that only those experienced in this type of work should undertake such servicing. The DOT requires that agencies testing carbon dioxide extinguishers hydrostatically be certified by the DOT.

Extinguisher hoses of certain types also need to be hydrostatically tested, and the details of these tests can be found in NFPA 10.

Because hydrostatic test results are of major importance, they must be recorded on the extinguisher. For high-pressure cylinders and cartridges passing a hydrostatic test, the month and year is stamped into the cylinder, in accordance with CGA Pamphlet C-1, or the Canadian Transport Commission regula-

TABLE 17.5.5 Hydrostatic Test Interval for Extinguishers

Extinguisher Type	*Test Interval (Years)*
Stored-pressure water loaded stream and/or antifreeze	5
Wetting agent	5
AFFF (aqueous film-forming foam)	5
FFFP (film-forming fluoroprotein foam)	5
Dry chemical with stainless-steel shells	5
Carbon dioxide	5
Wet chemical	5
Dry chemical, stored-pressure, with mild steel shells, brazed brass shells, or aluminum shells	12
Dry chemical, cartridge or cylinder operated, with mild steel shells	12
Halogenated agents	12
Dry powder, stored pressure, cartridge- or cylinder-operated, with mild steel shells	12

TABLE 17.5.6 Hydrostatic Test Pressure Requirements

Carbon dioxide extinguishers Carbon dioxide and nitrogen cylinders (used with wheeled extinguishers)	5/3 service pressure stamped on cylinder
Carbon dioxide extinguishers with cylinder specification ICC3	3000 psi (20,685 kPa)
All stored-pressure	Factory test pressure not to exceed 3 times the service pressure
Carbon dioxide hose assemblies	1250 psi (8619 kPa)
Dry chemical and dry powder, water, foam, halogenated agent hose assemblies	300 psi (2068 kPa) or at service pressure, whichever is higher

Note: The factory test pressure is the pressure at which the shell was tested at time of manufacture. This pressure is shown on the nameplate.
The service pressure is the normal operating pressure as indicated on the gauge and nameplate.

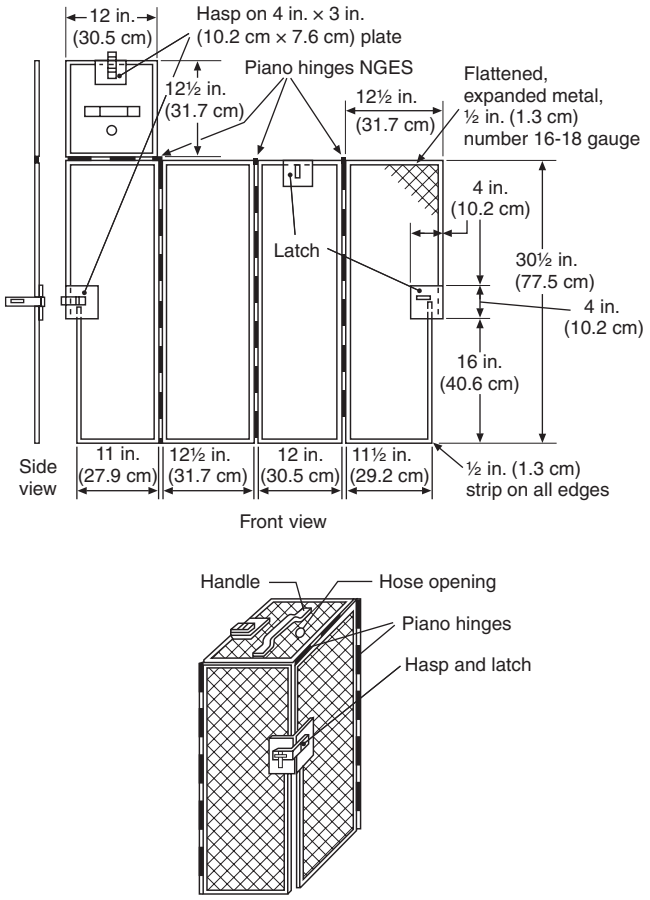


FIGURE 17.5.19 Low-Pressure Portable Hydrostatic Test Cage Used for Hydrostatic Tests of Low-Pressure Cylinders. Cage is not used for hydrostatic testing of high-pressure cylinders. Cage should not be anchored to floor during testing. Such cages can be made by any metal fabricator. For SI units: 1 in. = 25.4 mm.

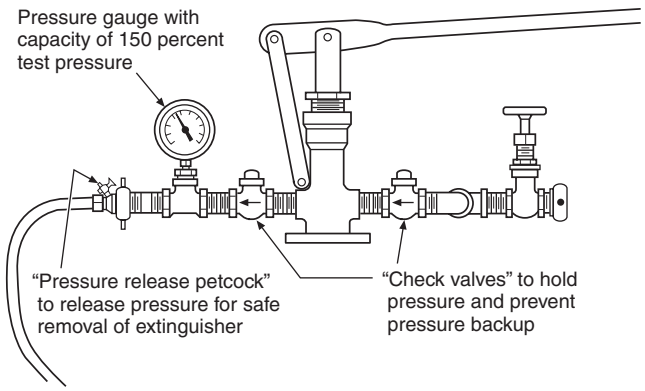


FIGURE 17.5.20 Hydrostatic Hand Pump

tions. It is important that the recording, or stamping, be placed only on the shoulder, top head, neck, or footing (when so provided) of the cylinder. For low-pressure cylinder extinguishers, the test information should be recorded on metal or some equally durable material. The label should be affixed by a heatless process to the shell and should be self-destructive if removal is attempted (Figure 17.5.21.) The label must include the following information:

1. The month and year the test was performed, indicated by a perforation, such as by a hand punch
2. The test pressure used
3. The name or initials of the person performing the test, and the name of the agency performing the test

Above all, remember the following: Allow only competent personnel with proper equipment and facilities to do the testing. Do not use air or gas for pressure testing because a violent rupture may occur in cases of failure. Place any extinguisher undergoing a test in a protective cage before applying the test pressures. Remove all traces of moisture from dry chemical, carbon dioxide, halogenated agent, and dry powder extinguishers before refilling after each test; a heated air stream not exceeding 150°F (65°C) is recommended for such drying. Destroy any extinguisher shell that fails a hydrostatic test—do not attempt to repair it.

Do not hydrostatically test any cylinder or shell if it has one or more of the following conditions:

1. Repairs by soldering, welding, brazing, or use of patching compounds; for welding or brazing on mild steel shells, consult the manufacturer of the extinguisher
2. Damaged cylinder or shell threads
3. Pitting caused by corrosion, even under the removable nameplate band assemblies
4. Burns from a fire
5. Calcium chloride agent in a stainless steel extinguisher

Destroy any such cylinder or shell.

Extinguisher Maintenance Services

Fire extinguisher maintenance, particularly hydrostatic testing, is a specialized activity and should be performed by competent, dependable people. Fire extinguishers are provided to protect life and property; this means that there should be no doubt as to

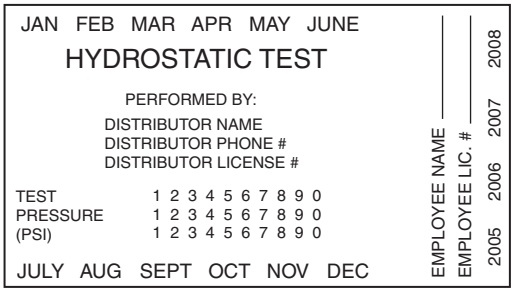


FIGURE 17.5.21 Typical Hydrostatic Test Label

their reliability or safe use in an emergency. Extinguisher owners are thus urged to seek out the services of reliable fire extinguisher maintenance firms. Such firms should be able to show proof that they are competent, that their facilities are adequate, and that they are licensed or registered in accordance with any local or federal law.

SUMMARY

Extinguishers are available in a number of different forms and use a variety of extinguishing agents, including water, carbon dioxide, halogenated agents, dry chemicals, dry powders, and foam. Extinguishers are classified for use on one or more types of fire, known as Class A, Class B, Class C, Class D, and Class K fires. In addition to the class of fire, the selection of the extinguisher should take into account the hazard level of the area being protected, the physical environment, the ease of operation and maintenance, and safety considerations. In order to provide effective fire protection, extinguishers must be distributed, mounted, maintained, and tested properly.

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2. Carson, W. G., and Klinker, R. L., *Fire Protection Systems, Inspection, Test, & Maintenance Manual,* 3rd ed., National Fire Protection Association, Quincy, MA, 2001.
3. *Methods for Hydrostatic Testing of Compressed Gas Cylinders,* Pamphlet C-1, Compressed Gas Association, Chantilly, VA, 1996.
4. *Standards for Visual Inspection of Steel Compressed Gas Cylinders,* Pamphlet C-6, Compressed Gas Association, Chantilly, VA, 2001.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire extinguisher use and maintenance discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following document.)*

NFPA 10, *Standard for Portable Fire Extinguishers*

Chapter 6

Halon and Halon Replacement Agents and Systems

Revised by
Philip J. DiNenno ■ Gary M. Taylor

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Explosion Inerting
Toxicity
Environmental Factors
Thermophysical Properties
Application Systems
Use Considerations for Clean Agent Systems
Clean Agent System Design

Key Terms

application fire extinguishing systems, carbon dioxide, clean fire extinguishing agents, clean fire suppression agents, explosion suppression, halogenated extinguishing agents, halon, safety factors, total flooding fire extinguishing systems

Clean fire-extinguishing agents include halogenated and inert gas fire suppressants. Halon and halon replacement clean agents including inert gases are used to provide total flooding fire-extinguishing systems that do not result in lethal conditions for any occupants of a protected space inadequately exposed when properly designed and installed. Although some clean agents cannot be used in occupied areas due to toxicity concerns, the primary distinction today between clean agents and carbon dioxide is the toxicity of the gases. Whereas carbon dioxide is used in fire-extinguishing concentrations far in excess of fatal limits, clean agents are generally used in occupied areas in fire-extinguishing concentrations below toxic thresholds.

Halogenated extinguishing agents are hydrocarbons in which one or more hydrogen atoms have been replaced by atoms from the halogen series: fluorine, chlorine, bromine, or iodine. This substitution confers not only nonflammability but also flame extinguishment properties to many of the resulting compounds. Halogenated agents are used both in portable fire extinguishers and in extinguishing systems. Streaming agents, such as Halon 1211 and 2402, have most often been used in manually applied fire equipment and local application-type fixed systems. Halon 1301 has most often been used in total flooding-type fixed systems.

Halons have been identified as stratospheric ozone-depleting substances. In fact, halons have been identified as the most potent of all ozone-depleting substances. The Montreal Protocol on Substances That Deplete Stratospheric Ozone is an international agreement to control the production and trade of ozone-depleting substances. The agreement has been signed by over 140 countries and is administered by the United Nations Environment Programme.

Production of Halons 1301, 1211, and 2402 ceased in developed countries on January 1, 1994, and is currently being phased out in the last developing country that produces halons. Many halon systems remain in use worldwide and, consequently, this chapter discusses Halons 1211, 1301, and 2402. The transition to other forms of fire protection for applications that historically used halons is well underway.

Recycled halons, recovered from less critical applications, now serve as a source of supply for those specialized applications such as mobile military equipment, aviation applications, and explosion prevention applications that remain dependent on halons.

See also Section 2, Chapter 7, "Theory of Fire Extinguishment"; Section 17, Chapter 1, "Carbon Dioxide and Application Systems"; Section 17, Chapter 7, "Application of Gaseous Agents to Special Hazards Fire Protection"; and Section 17, Chapter 8, "Explosion Prevention and Protection."

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BACKGROUND AND DEFINITIONS

Background

The use and development of halogenated fire-extinguishing agents have evolved over many years. The first member of this family of chemicals was carbon tetrachloride (Halon 104). Use as a fire extinguishant probably occurred before 1900, and by 1910 portable fire extinguishers, tested by independent agencies, had appeared. The growing popularity of the automobile and other uses of internal combustion engines signaled an increasing need for fire extinguishants suitable for use on flammable liquids fires.

By 1917, there were discussions regarding the possible effects that carbon tetrachloride could have on the human system. In 1919 the first known deaths due to carbon tetrachloride use occurred. Two men working on the construction of a submarine were killed. One man's clothing caught fire, and the other man extinguished the fire with a carbon tetrachloride agent fire extinguisher. Both were overcome by the fumes and later died. During the 1920s, the discussions regarding the toxicity of carbon tetrachloride continued with particular attention to the possibility that freezing point depressants and impurities were contributing factors.

Methyl bromide (Halon 1001) gained popularity after it was discovered in the late 1920s. Due to its high toxicity, it was never popular for use in portable extinguishers, although it was used in British and German aircraft and ships during World War II. During World War II, Germany developed bromochloro-methane (Halon 1011) to replace methyl bromide. In 1947 a report by Underwriters Laboratories Inc. (UL) showed that the toxicities of carbon tetrachloride (Halon 104) and bromochloro-methane (Halon 1011) were comparable, but bromochloro-methane was a more efficient fire-extinguishing agent.

In the post–World War II era, the addition of stearate to sodium bicarbonate–based dry chemicals provided improved flow and moisture repellency characteristics to sodium bicarbonate–based dry chemicals. This, in turn, encouraged the use of portable dry chemical fire extinguishers as an alternative to vaporizing liquid extinguishers that used early halons as extinguishants.

By the 1950s the era of the early halons (Halons 104, 1001, and 1011) was ending. Increased popularity of dry chemicals had decreased the need for widespread use of these early halons, and growing concerns with their toxic effects resulted in their "official" death by the 1960s.

In 1947, the Purdue Research Foundation conducted a systematic evaluation of more than 60 new candidate extinguishing agents. Simultaneously, the U.S. Army Corps of Engineers undertook toxicological studies of these same compounds. As a result, four halons were selected for further study: dibromodifluoromethane (Halon 1202), bromochlorodifluoromethane (Halon 1211), bromotrifluoromethane (Halon 1301), and dibromotetrafluoroethane (Halon 2402). Testing showed that Halon 1202 was the most effective fire extinguishant, but it was also the most toxic. Halon 1301 ranked second in fire-extinguishing effectiveness and least toxic. As a direct result of this program, a portable fire extinguisher employing Halon 1301 was developed by the U.S. Army, primarily for use inside armored personnel carriers and tanks. The U.S. Air Force selected Halon 1202 for military aircraft engine protection, and the U.S. Federal Aviation Administration approved the use of Halon 1301 for commercial aircraft engine fire protection.

In the 1960s attention began to focus on the use of Halon 1301 as a total flooding extinguishant for the protection of computer rooms. For the next 25 years, Halon 1301 grew in popularity as an agent for use in fixed fire protection systems, primarily for the protection of vital electronics facilities, such as computer rooms and communications equipment rooms. Other significant applications for Halon 1301 systems include protection for museums, shipboard machinery spaces, and pipeline pumping stations.

In 1966, NFPA organized a Technical Committee on Halogenated Fire Extinguishing Agent Systems to develop standards covering installation, maintenance, and use of such systems. NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems,* and NFPA 12B, *Standard on Halon 1211 Fire Extinguishing Systems* (discontinued), were approved in the early 1970s. NFPA 12CT was a tentative standard for Halon 2402; however, the standard was never adopted as a full standard due to lack of acceptance of this agent by users of NFPA standards. Halon 2402 has been employed extensively within the Russian federation as both a total flooding system agent and a streaming agent for use in portable fire equipment. There is limited experience with Halon 2402 in the United States; therefore, it cannot be treated as extensively as the other agents in this handbook.

In 1972, following extensive testing by several major companies on the effects of Halon 1301 decomposition products on electronic equipment, the NFPA Committee on Electronic Computer/Data Processing Equipment recognized Halon 1301 total flooding systems as suitable for protection of electronic computer/data processing equipment. With suitable precautions, such as time delays, Halon 1211 total flooding systems have been used in Europe.

The regulation of Halon 1301 under the Montreal Protocol on Substances That Deplete Stratospheric Ozone and its amendments culminated in the phaseout of production of halons in the developed countries on December 31, 1993. This regulation engendered tremendous research and development efforts across the world in a search for replacements and alternatives. There are currently over 12 commercialized total flooding, clean agent alternatives to Halon 1301, and development continues on others. In addition to clean agent total flooding gaseous alternatives, new technologies, for example, water mist and fine solid particulate, are being introduced. This chapter focuses on total flooding clean agent halon replacements.

The primary design and installation standard used in North America is NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems.* The first edition of the standard was published in 1994. The third and current edition was issued in February 2000. The first International Standards Organization (ISO) standard, ISO Standard 14520—Parts 1 through 15—was issued in 2000.[1]

Clean Agents Defined

Clean fire suppression agents are defined as fire extinguishants that vaporize readily and leave no residue.[1] Clean agent halon replacements fall into two broad categories: (1) compounds

and (2) inert gases and mixtures. Halogenated agents include compounds containing carbon, hydrogen, bromine, chlorine, fluorine, and iodine. They are grouped into seven categories, as displayed in Table 17.6.1.

Table 17.6.2 summarizes currently available clean fire suppression agents included in NFPA 2001.

Although the characteristics of halocarbon clean agents vary widely, they share several common attributes:

- All are electrically nonconductive.
- All are clean agents; they vaporize readily and leave no residue.
- All are liquefied gases or display analogous behavior (e.g., compressible liquid).
- All can be stored and discharged from typical Halon 1301 hardware (with the possible exception of HFC-23, which more closely resembles 600 psig [40 bar] superpressurized halon systems).
- All (except HFC-23) use nitrogen superpressurization in most applications for discharge purposes.
- All are less efficient fire extinguishants than Halon 1301 in terms of storage volume and agent weight; the use of most of these agents requires increased storage capacity.
- All are total flooding gases after discharge; many require additional care relative to nozzle design and operating pressure to ensure mixing.
- All produce more decomposition products than Halon 1301, given similar fire type, fire size, and discharge time.

TABLE 17.6.1 Categories of Clean Agent Fire Suppression Agents

Category	*Compounds*
Halon	Chlorine, bromine, or fluorine and hydrogen and carbon
Hydrofluorocarbons (HFC)	Fluorine, hydrogen, and carbon
Hydrochlorofluorocarbon (HCFC)	Fluorine, chlorine, carbon, and hydrogen
Perfluorocarbons	Carbon and fluorine
Fluoroiodocarbon (FIC)	Carbon, fluorine, and iodine
Fluoroketones (FK)	Carbon, fluorine, and oxygen
Hydrobromofluorocarbon (HBFC)	Bromine, fluorine, and carbon

Inert gas alternatives include nitrogen and argon, and blends of these. One inert gas replacement has a small fraction of carbon dioxide. Carbon dioxide is not an inert gas because it is physiologically active and fatal at low concentrations (approximately 9 percent). Inert gas clean agents are stored as pressurized gases and, hence, require substantially greater storage volume. They are electrically nonconductive, form stable mixtures in air, and leave no residue.

EXTINGUISHING MECHANISMS

Halocarbon clean agents extinguish fires by a combination of chemical and physical mechanisms, depending on the compound. Chemical suppression mechanisms of HBFC and HFIC compounds are similar to Halon 1301; that is, the Br and I species scavenge flame radicals, thereby interrupting the chemical

TABLE 17.6.2 Clean Fire Extinguishing Agents in NFPA 2001

FC-2-1-8	Perfluoropropane	C_3F_8
FC-3-1-10	Perfluorobutane	C_4F_{10}
FIC-13I1	Trifluoroiodide	CF_3I
FK-5-12mmy2	Dodecafluoro-2-methylpentan-3-one	$CF_3CF_2C(O)(CF(CF_3)_2)$
HCFC Blend A	Dichlorotrifluoroethane HCFC-123 (4.75%) Chlorodifluoromethane HCFC-122 (82%) Chlorotetrafluoroethane HCFC-124 (9.75%) Isopropeny-1-methylcyclohexene (3.75%)	$CHC_{12}CF_3$ $CHCIF_2$ $CHCIFCF_3$
HCFC-124	Chlorotetrafluoroethane	$CHCIFCF_3$
HFC-125	Pentafluoroethane	CHF_2CF_3
HFC-227ea	Heptafluoropropane	CF_3CHFCF_3
HFC-23	Trifluoromethane	CF_3CHFCF_3
HFC-236fa	Hexafluoropropane	$CF_3CH_2CF_3$
IG-01	Argon	Ar
IG-100	Nitrogen	N_2
IG-541	Nitrogen (52%) Argon (40%) Carbon dioxide (8%)	N_2 Ar CO_2
IG-55	Nitrogen (50%) Argon (50%)	N_2 Ar

chain reaction. Other replacement compounds suppress fires primarily by extracting heat from the flame reaction zone, reducing the flame temperature below that which is necessary to maintain sufficiently high reaction rates by a combination of heat of vaporization, heat capacity, and the energy absorbed by the decomposition of the agent.

Burgess et al.[2] performed kinetic simulations on a range of fluorinated compounds (CF_4, CF_3H, CF_2H_2, CF_3-CF_3, CF_3-CF_2H, and CF_3-CFH_2) for chemical kinetic fire suppression effects of fluorine compounds. Of the agents examined, only CF_3H was seen to have any chemical effect on flame suppression. They concluded that the differences in flame suppression properties can be explained by differences in heat capacity and relative amounts of heat release during agent combustion. Battin-LeClerc et al.[3] indicate that, while clearly some noncatalytic flame inhibition may occur with FC and HFC compounds, this effect is expected to be limited. Richter et al.[4] draw similar conclusions, owing to the inability of fluorine atoms to be continuously recycled in the flame, as occurs with bromine.

Oxygen depletion also plays an important role in reducing flame temperature. The energy absorbed in decomposing the agent by breaking fluorine and chlorine bonds is quite important, particularly with respect to decomposition production formation. There is undoubtedly some degree of "chemical" suppression action in flame radical combustion with halogens, but it is considered to be of minor importance because it is not catalytic.

The lack of significant chemical reaction inhibition in the flame zone by HCFC, HFC, and FC compounds results in higher extinguishing concentrations relative to Halon 1301. The importance of the energy sink, represented by breaking halogen species bonds, results in higher levels of agent decomposition relative to Halon 1301.

Inert gas agents suppress flames by reducing the flame temperature below the threshold necessary to maintain combustion reactions. This flame supression is done by reducing the oxygen concentration and by raising the heat capacity of the atmosphere supporting the flame. For example, the addition of a sufficient quantity of nitrogen to reduce the oxygen concentration below 12 percent (in air) will extinguish flaming fires. The agent concentration required (and, hence, the minimum oxygen level) is a function of the heat capacity of the inert gas added. Hence, there are differences in minimum extinguishing concentrations between inert gases.

The differences between argon and nitrogen are clearly shown in Table 17.6.2, with nitrogen extinguishing concentrations in the range of 30 percent (14.6 percent O_2) and argon extinguishing concentrations of 41 percent (12.3 percent O_2). Inert gas blends with more nitrogen than argon will have lower minimum extinguishing concentrations. When one considers nitrogen as the primary inert gas in examining oxygen concentrations at extinction in fire experiments, the minimum oxygen concentration at extinction can be as low as 12 percent, or a 42.5 percent "agent" concentration.[5,6]

FLAME SUPPRESSION EFFECTIVENESS

Flame suppression effectiveness of total flooding halon replacement agents has been evaluated in a number of ways. The predominant small-scale test method for establishing flame extinguishing concentrations for liquid and gaseous fuels is the cup burner.

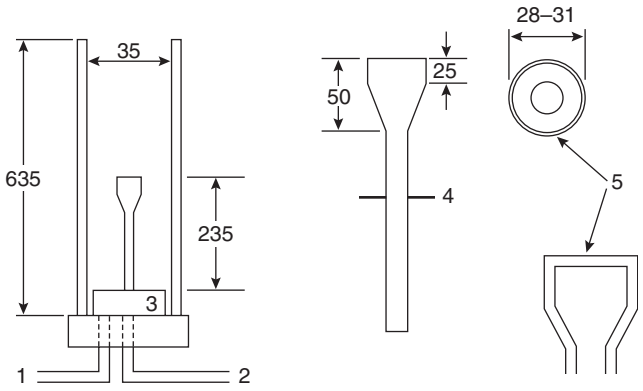

FIGURE 17.6.1 ISO Standard Cup Burner Apparatus (Source: ISO 14520-1, "Gaseous Fire Extinguishing Systems—Physical Properties and System Design, Part 1: General Requirements," International Organization for Standardization, Geneva, Switzerland, 2005. Copyright International Organization for Standardization.)

Figure 17.6.1 is a schematic of the standardized ISO cup burner.[1] A small laminar flame is established above a "cup" of fuel surrounded by a cylindrical chimney. An air/agent mixture flows up the chimney surrounding the flame. The minimum concentration of agent (in air) at which the flame is extinguished is the minimum extinguishing concentration (MEC). There are many variations of the basic device as used by different laboratories; these variations include cup and chimney diameter, different mixing and measuring methods, chimney height, and agent/air mixture velocity past the flame.[7]

Table 17.6.3 gives the most recent heptane cup burner values vetted on a consensus basis and contained in the ISO series of documents. These data are the best available consensus values for the MEC for heptane. There have been substantial differences between MEC values published in the past. These differences are largely due to the use of more standardized test devices, different test procedures, and operator error.

TABLE 17.6.3 Minimum Class B Extinguishing Concentration

Agent	*ISO Class B Extinguishing Concentration (%)*
HFC-227ea	6.9
HFC-125	9.3
HFC-23	12.6
FK-5-1-12	4.5
IG 541	31.7
IG 55	36.5
IG 01	39.5
IG 100	33.6

Minimum extinguishing concentrations for Class A fuels are determined as part of the third-party approval process. They are based on standardized tests of plastic sheet array. There are substantial differences between Class A extinguishing concentrations developed for use in NFPA 2001 versus those required in ISO 14520. The differences are largely based on the details of the test, such as ignition pan size and preburn, but are also substantially affected by the allowable extinguishment time. Both UL and FM and, therefore, NFPA 2001 allow a much longer extinguishment time (600 seconds) than the 180 seconds presented by ISO. This partially explains the substantially higher Class A extinguishing concentrations obtained under ISO 14520, as seen in Table 17.6.4.

Wickham[8] has provided comparative values for cost and footprint of halon and halon replacement systems for use in marine applications. These comparisons are given for weight, footprint, and cost in Tables 17.6.5, 17.6.6, and 17.6.7, respectively.

Note that all clean agent alternatives require at least 50 percent more agent by weight as a consequence of the elimination of bromine in the compounds and subsequent level of catalytic recombination of flame radicals. These data should be taken as representative values, as there are variations among hardware manufacturers. The storage volume equivalent does not translate directly to a required area or volume for storage cylinders. The relative "footprint" of these storage volume equivalents will vary with the volume of the space protected and the maximum storage cylinder size offered by a manufacturer for a particular gas.

EXPLOSION INERTING

One of the most important application areas of total flooding fire suppressants is explosion inertion. The inerting concentration of an agent is the concentration required to prevent unacceptable pressure increases in a premixed fuel/air/agent mixture subjected to an ignition source. Inertion concentrations are typically measured in small laboratory-scale spheres with an electric spark initiator.

The measured inerting concentration of an agent is dependent on the details of the test apparatus used, particularly the ignition source strength and "allowable" pressure rise. The "allowable" pressure rise is a surrogate measurement of the distance the flame front travels inside the constant volume sphere prior to suppression. Inerting concentrations are not appropriate for use in deflagration or detonation (explosion) suppression.

Small-scale sphere data are used to develop flammability diagrams for various fuel/oxidizer/agent concentrations. The chapter on flammability limits by Beyler in the *SFPE Handbook of Fire Protection Engineering* gives an excellent introduction to the subject.[9] A wealth of data on flammability limits for inert gases, such as nitrogen and argon, and for a variety of fuels is available in the combustion literature.

Table 17.6.8 provides inerting concentration data for several agents and fuels taken from small-scale inertion spheres. There are some substantial differences in results. Ignition source type and strength as important variables with differences of approximately 40 percent for Halon 1301 inerting concentrations are reported. Figure 17.6.2 shows flammability diagrams[10] derived from small-scale inertion data along with points taken from a large-scale 795 ft^3 (22.5 m^3) explosion vessel. Although the small- to large-scale agreement is reasonable, there are scale effects.

Explosion suppression systems employ rapid delivery of agent following very early detection of an ignition. Such systems employ significantly higher agent quantities (than flame suppression or inertion) delivered at higher rates. The total agent delivery time is on the order of 100 millisecond.

Explosion suppression systems must be specifically designed for a particular application. There are no generic design requirements or standards currently available for such systems.

Senecal et al.[11,12] report on explosion suppression testing for occupied armored fighting vehicles and aerosol filling rooms. Results were obtained on premixed fuel droplet sprays. In contrast to flame suppression or inerting, suppression or deflagration requires significantly more agent. The aerosol filling room tests employed 44.1 lb (20 kg) of HFC-227ea, FC-3-1-10, HFC-236fa, and 22 lb (10 kg) of water in a 2827 ft^3 (80 m^3) test room to suppress a 3.2 oz. (90 g) propane release in a simulated aerosol fill station. Suppression of the propane-air deflagration was achieved, and the maximum flame front extension was approximately 4 ft (1.22 m). Suppression tests of heated diesel fuel droplet cloud deflagrations were conducted in simulated armored fighting vehicle crew compartments.

Table 17.6.9 summarizes typical data for flame suppression, inertion, and deflagration suppression concentrations. Note that these values are for comparison purposes only. They should not be used in any way for design purposes.

Suppression of detonations requires substantially higher agent concentrations. An excellent discussion is given in "Review of the Use of Carbon Dioxide Total Flooding Fire Extinguishing Systems." [8]

TOXICITY[13]

Background

Toxicology tests are performed based on (1) the duration and frequency of the exposure and (2) determination of specific biological effects.[14] The studies examining duration and frequency are divided into four categories:[15]

1. Acute: less than 24 hour exposure
2. Subacute: 1 month or less of exposure
3. Subchronic: 1- to 3-month exposure
4. Chronic: more than 3 months of exposure

The specific biological effects examined are many, but for the purposes of halocarbon fire-fighting agents, the following are the most common:

1. Inhalation toxicity
2. Developmental toxicity
3. Reproductive toxicity
4. Genetic toxicity
5. Cardiotoxicity
6. Central nervous system (CNS) effects

TABLE17.6.4 Summary of the Class A and Class B Extinguishing Concentrations for Various Agents and Equipment Manufacturers

			UL				ISO						
			Class B		Class A		Class B		Class A			Plastic Sheet	
Agent	*Trade Name*	*Equipment Manufacturer*	*Test*	*Design*	*Test*	*Design*	*Test*	*Design*	*Min (95% of Class B)*	*Test*	*Design*	*Test*	*Design*
HFC-227ea	FM-200, FE-227	A	6.7	8.7	—	—	—	—	—	—	—	—	—
		B	6.7	8.7	—	—	—	—	—	—	—	—	—
		C	6.7	8.7	—	—	—	—	—	—	—	—	—
		D	6.7	8.7	5.2	6.2	—	—	—	—	—	—	—
		E	6.7	8.7	5.4	6.5	—	—	—	—	—	—	—
		F	6.6	8.6	—	—	6.9	9.0	8.5	6.1 (4.9 wood crib)	7.9	6.1	7.9
HFC-125	FE-25	A	—	—	6.7	8.0	—	—	—	—	—	—	—
		B	—	—	—	—	—	—	—	8.6 (6.7 wood crib)	11.2	8.6	11.2
		—	8.7	11.3	—	—	9.3	12.1	11.5	—	—	—	—
	NAF-S-125	C	8.7	11.3	6.7	8.0	—	—	—	6.7	8.7	6.7	8.7
HFC-23	FE-13	A	—	18	—	18	—	—	—	—	—	—	—
		B	12.9	16.8	—	—	12.6	16.4	15.6	12.5 (10.5 wood crib)	16.3	12.5	16.3
FK-5-1-12	Novec-1230	A	4.5	5.9	3.5	4.2	—	—	—	—	—	—	—
		B	4.5	5.9	—	—	4.5	5.9	5.6	4.1 (3.4 wood crib)	5.3	4.1	5.3
IG-541	Inergen	—	28.9	37.6	28.5	34.2	31.7	41.2	39.1	30.7 (28.2 wood crib)	36.5	30.7	39.9
IG-55	Argonite	—	—	—	—	—	36.5	47.5	45.1	31 (28.7 wood crib)	40.3	31.0	40.3
IG-01	Argon	—	—	—	—	—	39.2	51.0	48.4	32.2 (30.7 wood crib)	41.9	32.2	41.9
IG-100	Nitrogen	—	—	—	—	—	33.6	43.7	41.5	31.0 (30 wood crib)	40.3	31.0	40.3

TABLE 17.6.5 Percent Weight Comparisons of Systems in 500–5000 m^3 Range of Volumes

	Percentage Additional Weight When Compared to a Halon 1301 System			
Agent	*500 m^3*	*1000 m^3*	*3000 m^3*	*5000 m^3*
Halon 1301	0	0	0	0
Carbon dioxide	150	163	200	186
FE-13	200	188	219	211
FM-200	50	38	48	36
Novec 1230	50	50	71	58
Inergen	400	450	529	497
Water mist	625	613	671	522

TABLE 17.6.6 Percent Footprint Comparisons of Systems in 500–5000 m^3 Range of Volumes

	Percentage Additional Weight When Compared to a Halon 1301 System			
Agent	*500 m^3*	*1000 m^3*	*3000 m^3*	*5000 m^3*
Halon 1301	0	0	0	0
Carbon dioxide	84	82	118	99
FE-13	105	94	122	107
FM-200	20	20	19	6
Novec 1230	20	20	43	19
Inergen	327	365	459	404
Water mist	1119	889	1030	636

TABLE 17.6.7 Percent Cost Comparisons of Systems in 500–5000 m^3 Range of Volumes

	Percentage Additional Weight When Compared to a Halon 1301 System			
Agent	*500 m^3*	*1000 m^3*	*3000 m^3*	*5000 m^3*
Halon 1301	0	0	0	0
Carbon dioxide	108	140	200	204
FE-13	315	406	553	585
FM-200	202	267	351	361
Novec 1230	259	368	513	515
Inergen	277	330	449	460
Water mist	1032	723	478	376

The separation into categories is based on experience that acute exposure toxicity and chronic exposure toxicity can be significantly different. For example, the acute (single) exposure toxicity for organic solvents is typically central nervous system disturbances that are reversible once the exposure ends. Chronic (repeated, long-term exposure) toxicity for organic solvents can include liver damage and cancer, which are not considered reversible. Each chemical may cause different specific acute

TABLE 17.6.8 Inerting Concentrations for Various Agents

Fuel	*Agent*	*Volume Percent Inerting Concentration*
i-Butane	HFC-227ea	11.3
	HCFC Blend A	18.4
	IG-100	40.0
1-Chloro-1, 1-difluoro-ethane (HCFC-142b)	HFC-227ea	2.6
1.1-Difluoroethane (HFC-152a)	HFC-227ea	8.6
	HCFC Blend A	13.6
Difluoromethane (HFC-32)	HFC-227ea	3.5
	HCFC Blend A	8.6
Ethane	IF-100	44.0
Ethylene oxide	HFC-227ea	13.6
Hexane	IG-100	42.0
Methane	HFC-125	14.7
	HFC-227ea	8.0
	HFC-23	20.2
	HCFC Blend A	18.3
	IG-100	37.0
	IG-541	43.0
Pentane	HFC-227ea	11.6
	IG-100	42.0
Propane	FC-3-1-10	10.3
	FC-3-1-10	9.9
	FC-5-1-14	7.3
	FIC-1311	6.5
	HFC-125	15.7
	HFC-227ea	11.6
	HFC-23	20.2
	HFC-23	20.4
	HCFC Blend A	18.6
	IG-541	49.0
	IG-100	42.0

TABLE 17.6.9 Comparison of Concentrations for Flame Extinguishment, Inerting, and Deflagration Suppression

	Volume Percentage		
Agent	*Typical Value Flame Suppression*	*Inerting Concentration in Propane*	*Diesel Fuel Droplet Deflagration Suppression*
Halon 1301	3.0	6–7	12
FC-3-1-10	5.5	10.3	8
HFC-227ea	5.8	~12	11
HFC-23	12.0	20.2	—
IG-541	29.0	49.0	—

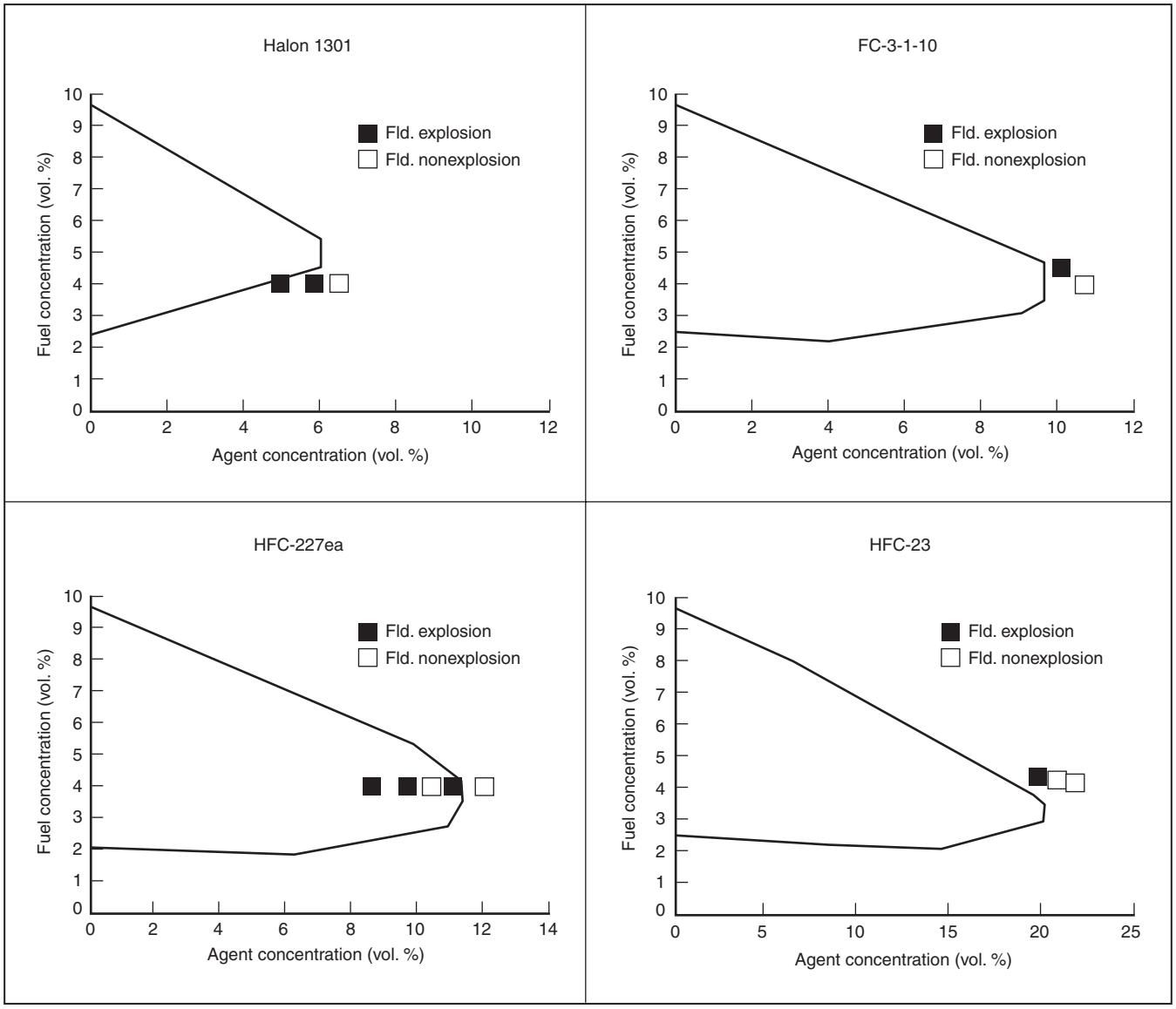

FIGURE 17.6.2 Small-Scale Flammability Diagrams for Propane and Several Replacement Agents. Squares denote explosion/no explosion points in large-scale 792 ft^3 (22.5 m^3) chamber. (Source: Moore, T. A., "Large-Scale Inertion Evaluation of NFPA 2001 Agents," *Proceedings* of the 1993 International CFC and Halon Alternatives Conference, Washington, DC, October 20–22, 1993)

and chronic toxicity problems that need to be addressed. These include cancer, birth defects, liver toxicity, heart toxicity, and so on.[15] Different chemicals within the same family may cause different effects or similar effects over a wide range of concentrations. Lastly, the route of exposure is examined. For gaseous fire-fighting agents, inhalation studies are required.

A series of tests is required, beginning with the acute studies. This is done to build on the results from previous shorter-term studies. One important reason is to establish the correct exposure concentrations for testing. An improper dosage could cause the invalidation of a long-term test halfway or more through the study; that is, too many test specimens may die from an excessive test dosage. An equally important reason is to preclude running expensive, longer-term chronic studies when the shorter-term studies do not suggest any need. The shorter-term studies can be used as screens to give indications, but not direct results, for the type of toxicity problems that longer-term tests may need to address. The toxicology series is not a "cookbook" process. Professional toxicologists must evaluate the results through each step of the process and make educated decisions on the next phase of testing.

A minimum set of tests required by the U.S. Environmental Protection Agency (EPA) under the Significant New Alternatives Policy (SNAP) program would likely include:[16]

1. Acute toxicity "range finder," for example, limit or LC_{50} test
2. Cardiac sensitization test

3. Developmental and reproductive toxicity
4. 4- or 13-week subchronic test
5. Genetic toxicity screening test (such as Ames test)
6. Thermal decomposition product test

As noted, acute toxicity studies are usually the first to be done. These tests provide information on acute lethality. For inhalation toxicity this is called the LC_{50} and is the concentration at which 50 percent of the animals die within 14 days of the exposure. This study is usually a single 4 hour exposure and generally performed with mice and rats.

Subacute studies are the lowest tier of the repeated exposure tests. They are used to (1) discover specific toxicity problems above the acute effects and (2) refine the proper doses for follow-up tests. Subacute studies generally run 14 days.

Subchronic studies are used to (1) establish final dosage data to be used in chronic studies and (2) identify further the specific toxicity concerns of long-term exposures. These studies are usually performed for 90 days on one or two species.

Chronic studies are generally performed in the same way as subchronic tests, except that the exposure is increased beyond 3 months and up to 2½ years. Often chronic studies incorporate carcinogenicity (cancer) tests to preclude running separate tests.

Developmental and reproductive toxicity studies are designed to look at the adverse effects on the reproductive system and on offspring. Developmental tests examine the effects on a developing organism any time during its life span as the result of repeated exposure by either parent before conception or during pregnancy and postnatally until puberty. Reproductive toxicology is a multigenerational study concerned with the adverse effects to the reproductive system that may be passed on to the first-generation and second-generation offspring by either parent. The specific study of defects caused between conception and birth is called teratology.

Genetic toxicity studies examine mutangenic potential, that is, the capability of a chemical to cause changes in the genes of a cell. These studies are also effective as screens and tests for the potential to cause cancer. Two of the most common tests used for halocarbon agents are (1) the Ames test and (2) the micronucleus test. The Ames test examines the ability of the chemical to cause changes or mutations in the genes of a cell. The micronucleus test studies look at chromosome aberrations. Both screens are used as indicators of the potential to cause cancer. Results of these screens are used to decide whether longer-term cancer studies, other genetic toxicity studies, or developmental and reproductive studies are required.

Beyond the preceding tests, specific toxicology concerns may warrant requiring other, less standard, toxicity studies. Such is the case for halocarbons where they have been found to depress the heart rate. In the presence of adrenaline, the heart can experience mild conditions of an irregular heartbeat to severe conditions of a full heart attack. This effect was first seen with chloroform when it was widely used as an anesthetic. The test developed to assess this type of cardiotoxicity is called "cardiac sensitization."

The data gathered from these tests on nonhuman species are only an indication of the toxicity for humans. Toxicologists use these studies to do risk assessments to predict the toxicity of a chemical or specific mixture of chemicals in a particular exposure scenario. The acute tests are used to establish limits for single or very infrequent exposures. For example, acute toxicity is used in determining the effects that can be expected when a fire suppression system is discharged. Subchronic and chronic studies are used to establish limits for repeated exposures for workers who are subjected to the halocarbon on a more frequent basis, such as production plant workers and maintenance personnel who fill/refill cylinders.

The EPA requires, as a minimum for halocarbon fire suppression agents, cardiac sensitization and developmental toxicology studies to set acute exposure limits. To set worker/manufacturer exposure limits, the EPA uses, as a minimum, genetic toxicology, 90-day subchronic and developmental toxicology studies.[16]

Although all halocarbon agents are tested for long-term health hazards, the primary end point is acute, or short-term, exposure. The primary acute toxicity effects of the halocarbon agents described in this chapter are anesthesia and cardiac sensitization. For inert gases, the primary physiological concern is reduced oxygen concentration.

Halocarbon Agents

Cardiac sensitization is the primary short-term "acute" toxicity problem for fire suppression applications. *Cardiac sensitization* is a term describing the sudden onset of cardiac arrhythmias in the presence of a concentration of an agent caused by sensitization of the heart to epinephrine. The presence of epinephrine is critical to the onset of arrhythmias. This is important in fire protection applications due to the increased production of epinephrine by the body under stress.

The toxicity end points used to describe cardiotoxicity and allowable exposure levels are no observed adverse effect level (NOAEL) and the lowest observed adverse effect level (LOAEL). The NOAEL is the highest concentration of an agent at which no "marked" or adverse effect occurred. The LOAEL is the lowest concentration at which an adverse effect was measured.

The procedures used to evaluate cardiac sensitization vary somewhat. The procedure involves intravenous dosing of male beagles with epinephrine for 5 minutes. Continuous inhalation exposure to the agent follows for 5 minutes. Following this inhalation exposure, the dog is dosed again with epinephrine and monitored for 5 minutes to determine the effect of the agent and epinephrine. The protocol is performed at higher doses until an effect occurs.

Effects are monitored by electrocardiograph (ECG) measurements. An adverse effect is generally considered to be the appearance of five or more arrhythmias or ventricular fibrillation. The data from these tests are evaluated by medical experts, and the appropriate NOAEL and LOAEL values are reported by the EPA under the SNAP program.

There is no direct correlation between the experimental results from dogs to humans. It is generally accepted due to the combination of the high doses of epinephrine in the tests and the similarity in cardiovascular function between dogs and humans that the results can be applied to humans. It is believed that the results of these tests are conservative with respect to direct

application of the results to humans in typical fire suppression applications.

In addition to the short-term chronic exposure limits of interest in fire suppression system design, the EPA evaluates longer-term inhalation data for these compounds. Table 17.6.10 summarizes NOAEL, LOAEL, and LC_{50} values. Note that the LC_{50} values greatly exceed the NOAEL.

The use of halocarbon agents in occupied areas is generally subject to the constraint that the design concentration must be less than the NOAEL. In the 1996 edition of NFPA 2001, an exception allows the use of total flooding gases up to LOAEL for Class B hazards where a predischarge alarm and time delay are provided and where acceptable to the authority having jurisdiction. The rationale for the exception is based on (1) the conservative nature of NOAEL/LOAEL, (2) consistency with EPA guidelines, and (3) positive benefit of higher agent concentrations in certain flammable/combustible liquid hazards. Although it is recommended that all systems employ predischarge alarms and that personnel evacuate prior to system actuation, it is understood that inadvertent discharges and short-term exposures will occur, hence the limitation. It is expected that emergency exposures for up to several minutes at or below the NOAEL and possibly the LOAEL are reasonably safe. In no case should systems be designed or installed where intentional exposure of any duration is anticipated.

In the 2000 edition of NFPA 2001, the exposure limits for halocarbon agents have been modified. Physiologically based pharmacokinetic modeling (PBPK) for evaluation of acute exposure to halocarbon agents has been used to establish alternative exposure limits for halogenated agents. PBPK modeling attempts to account for the time-dependent uptake rate of halocarbons in the body and establishes exposure limits based on the rate of uptake.[17–22] The limits are based on the concentration of agent and the time at which the concentration of agent in the blood equals that of the LOAEL. Typical PBPK results for safe exposure times for HFC-227ea and HFC-125 are given in Table 17.6.11. Note exposure above the NOAEL limits and up to the LOAEL is permitted.

These limits were derived and supported by the EPA, which has the primary regulatory authority for health and toxicity associated with halon replacements. The use of the PBPK approach partially accounts for the differences between laboratory animal tests and humans. The laboratory results form the basis of the end points (LOAEL) and are still conservative due to the nature of epinephrine dosage used during the animal tests.

TABLE 17.6.10 Toxicity Data for Halocarbon Clean Agent Fire Suppression

Designation	*Formula*	*NOAEL Percentage V/V$_a$*	*LOAEL Percentage V/V$_a$*	*LC_{50} or $ALC_{b,c}$ Percentage*
FC-3-1-10	C_4F_{10}	40	>40$_d$	>80
HFC-227ea	C_3F_7H	9.0	>10.5	>80
HFC-23	CHF_3	50	>50$_d$	>65
HCFC-124	C_2HClF_4	1	2.5	23–29
HFC-125	CH_2HF_5	7.5	10.0	>70
FK-5-1-12		10	>10	

TABLE 17.6.11 Exposure Limits Derived from PBPK Modeling for HFC-227ea and HFC-125

HFC-227ea Concentration			HFC-125 Concentration		
Percentage v/v	*ppm*	*Human Exposure Time (min)*	*Percentage v/v*	*ppm*	*Human Exposure Time (min)*
9.0	90,000	5.00	7.5	75,000	5.00
9.5	95,000	5.00	8.0	80,000	5.00
10.0	100,000	5.00	8.5	85,000	5.00
10.5	105,000	5.00	9.0	90,000	5.00
11.0	110,000	1.13	9.5	95,000	5.00
11.5	115,000	0.60	10.0	100,000	5.00
12.0	120,000	0.49	10.5	105,000	5.00
			11.0	110,000	5.00
			11.5	115,000	5.00
			12.0	120,000	1.67
			12.5	125,000	0.59
			13.0	130,000	0.54
			13.5	135,000	0.49

Inert Gas Agents

Inert gas agents are effectively physiologically inert. The primary physiological problem with these agents is the reduced oxygen concentration caused by the high agent design concentrations. One inert gas blend employs a low concentration of CO_2 (which is not physiologically inert) in order to counter the effects of the reduced oxygen concentration. The mechanism of this effect is discussed in "Research Basis for Improvement of Human Tolerance to Hypoxic Atmospheres in Fire Prevention and Extinguishment." [23]

The EPA had previously determined that inert gases can be used in concentrations up to 43 percent in normally occupied areas subject to similar limits placed on halocarbon agents when used at the NOAEL. This usage results in a residual oxygen concentration of 12 percent. The analog to the LOAEL is 52 percent agent concentration with a 10 percent residual oxygen concentration. NFPA 2001 requirements mirror the EPA limitations at 43 percent agent concentration with the exemption permitting use up to 52 percent concentration for Class B hazards. There appears to be a growing consensus among independent toxicologists that inert gases could be safely used up to 52 percent concentration for a 5-minute exposure time.

This consensus was further developed in the 2000 edition of NFPA 2001. The current limitations on exposure limits for inert gases are as follows:

> For gas concentrations up to 43 percent (a residual oxygen concentration of 12 percent), exposure time is limited to 5 min. For agent concentrations between 43 and 52 percent (12 and 10 percent residual oxygen concentration), the exposure time is limited to 3 min. For concentrations between 52 and 62 percent (10 and 8 percent residual oxygen concentration), exposure time is limited to 30 s. For concentrations above 62 percent (above 8 percent residual oxygen concentration) exposure must be avoided.

There is strong indication that small concentrations of CO_2 added to inert gases (such as IG-541) substantially reduce hypoxic effects and improve human performance at low oxygen levels. Regulatory authorities have not yet differentiated between such agents and other inert gases or blends.[23]

ENVIRONMENTAL FACTORS

Two main environmental impacts need to be considered with respect to halocarbon extinguishing agents: (1) ozone depletion and (2) global warming.[24] Another environmental factor, atmospheric lifetime, can be considered in the discussion of each of these environmental impacts. It is also a "stand-alone" environmental concern that needs to be addressed. International, national, state, and local governments currently regulate halocarbon fire-fighting agents based on their effect on ozone depletion. However, the U.S. EPA also takes into account atmospheric lifetimes and global warming potentials in the implementation of its SNAP program under Section 612 of the Clean Air Act, as amended in 1990. Although no specific national environmental regulations cover global warming and atmospheric lifetimes, the consideration of these issues in the EPA's implementation of existing regulations makes these issues of concern.

Ozone Depletion

Ozone (O_3) is a naturally occurring gas that is found in the atmosphere. Most naturally occurring ozone is created by the reaction of O_2 with ultraviolet (UV) light coming from the sun.

$$O_2 + UV \rightarrow O + O$$

$$O + O_2 \rightarrow O_3$$

The UV light causes this reaction to occur. Ozone is also created in nature when the high energy output from lightning initiates a similar reaction.

Ozone is also formed by a number of manufactured sources, mainly as a result of air pollution. When carbon monoxide, methane, and other hydrocarbons meet nitrogen oxide (e.g., from car exhaust) and ordinary sunlight, ozone is produced.[25] It is also produced by laser printers and electrical motors, and is responsible for the pungent odor often associated with the devices. Man-made ozone is often called "smog" and is a considerable health risk.

With respect to the environment, an important difference exists between naturally occurring and man-made sources of ozone. Man-made ozone is produced in the region of our atmosphere called the troposphere. This is the portion that starts at the earth's surface and extends 3.7 to 10.6 mi. (6 to 17 km) above the surface. (The thickness of this region is different at the poles versus the equator.) Naturally occurring ozone is produced primarily in the stratosphere. The stratosphere is the region directly above the troposphere and extends to approximately 31 mi (50 km) above the earth's surface.[26] The ozone produced in the stratosphere by the reaction described earlier is what is known as the "ozone layer" and serves a very important purpose. Ozone absorbs the UV-b portion of the total UV in sunlight and prevents it from entering further into the atmosphere. This absorption has two net effects: (1) it lowers the amount of harmful UV-b that plants and animals are exposed to and (2) it prevents more ozone from being created naturally in the troposphere.

Over about the last decade, the United States has begun to give "ozone alerts," typically as part of daily weather reports. The ozone referred to by these alerts is tropospheric ozone and does not refer in any way to stratospheric ozone or ozone depletion. There are, however, concerns with tropospheric ozone. These concerns will be addressed along with the discussion of global warming.

Halons, HCFCs, and other halocarbons containing chlorine or bromine have been shown to cause the destruction of stratospheric ozone. The characterization of stratosphere ozone destruction is not a measure of the exact amount of ozone destroyed. Instead, it is the relative amount of ozone destroyed as compared with an arbitrary standard. The standard chosen is CFC-11, which has been assigned an ozone depletion potential (ODP) of 1. ODP of all other halocarbons relates to their relative effect on the destruction of ozone as compared with CFC-11. Halon 1301 has an ODP of 13, meaning it will destroy 13 times

as much ozone as CFC-11 on a pound-for-pound (kilogram-for-kilogram) basis. A compound having an ODP of 0.1 would have 10 percent of the relative ozone-depleting effects of CFC-11. All ODP values are based on mass (weight) and not on moles (numbers of molecules).

Atmospheric Lifetimes

When one thinks of a chemical species lifetime, the term *half-life* is often used. This usage is most common in the nuclear field where calculations are made to determine how long it takes a species to decay to half its original concentration. Atmospheric lifetime values used in the determination of ozone depletion and global warming potentials are *not* half-lives. They are $1/e$ lifetimes, sometimes called *e*-folding lifetimes.

It has been determined that greenhouse gases break down in the atmosphere according to the following equation:

$$C = C_0 e^{-kt}$$

where

C = Concentration at time t

C_0 = Initial concentration at time

k = An experimentally determined rate constant (units = 1/time)

A mathematical manipulation can be made to express this equation as a function of more readily quantifiable terms and is accomplished by defining the atmospheric lifetime, *L,* as an *e*-folding lifetime, or the time it takes for the ratio of C:C_0 to be equal to $1/e$ (e is the base of the natural logarithm system and has a numerical value of approximately 2.718). The resulting equation is as follows:

$$C = C_0 e^{-t/L}$$

Although the term *half-life* is most commonly used when describing the decay of a species concentration, the use of the *e*-folding lifetime allows for quantification of concentration in terms of a compound's atmospheric lifetime, as previously shown. A half-life refers to the time it takes for half a given amount of compound to be broken down in the atmosphere; thus, the ratio C:C_0 is equal to $1/2$. Using an *e*-folding lifetime, the ratio is equal to $1/e$ or 0.368. After one lifetime, the concentration will be equal to 0.368 times its original value. After two lifetimes, the concentration will be 0.135 or $(0.368)^2$ its original value. After three lifetimes, the concentration will be 0.0498 or $(0.368)^3$ times its original value, and so on.

An important factor when using the preceding equation to solve for concentration as a function of time is that, no matter what value is used for time, the concentration never equals zero. Some portion will always exist in the atmosphere. When the atmospheric lifetime is small, the concentration over hundreds of years may become negligible. When the atmospheric lifetime is very large, on the order of tens of thousands of years, the concentration in the atmosphere may not be negligible.

The environmental concern is one of "what if" The halocarbons were believed to be "safe" for many years after their release into the atmosphere began. It was not until many years later that they were linked to ozone depletion. There is a concern that these other halocarbons, or other compounds, may cause other environmental impacts that yet are unknown. If the atmosphere is filled with these chemicals and they exist in appreciable amounts for hundreds, thousands, and millions of years, what then? Might the damage we do to our environment be more than humans can cope with? Nature can probably overcome this impact, but it may take tens of millions of years. This is a short time frame for nature but not for man. Current implementation of the EPA SNAP program places restrictions on perfluorocarbons that have very large or "outlying" atmospheric lifetimes as compared with the rest of the halocarbons. This restriction is not based on any known or anticipated environmental problem. It is a response to the "what if" concerns raised previously.

Global Warming Potential

A basic understanding about the earth's climate and atmosphere is needed to understand what global warming potential (GWP) is and how to attempt its measurement.

The atmospheric region closest to Earth, the troposphere, represents approximately 81 percent of the earth's atmosphere. It is made up mainly of nitrogen (N_2) and oxygen (O_2), representing 99 percent of its composition. The remaining 1 percent is made up of mostly argon, with smaller amounts of water, 0.2 percent; and CO_2, 0.03 percent (300 parts per million by volume [ppmv]). The atmosphere also contains several compounds in very small amounts known as "trace gases." These are methane, nitrous oxide, carbon monoxide, hydrogen, ozone, and halocarbons, which are so dilute that they are measured in parts per billion by volume (ppbv).

Weather and climate are not the same. Weather is the short-term, day-to-day conditions of temperature, humidity, rainfall, winds, and so on.[27] Climate is the long-term condition averaged over many years. Based on the climate of a region, particular weather is expected or predicted. Many factors determine a region's climate. These are a complex interaction of both natural and man-made activities. The biggest factor on the overall behavior of the earth's climate is the sun. The sun's energy hits Earth more at the tropics and equator than at the poles. Driven by diffusion principles, Earth distributes heat away from the tropics, which leads to the major wind and ocean currents.

Estimates of the average temperature of Earth's atmosphere have been made, assuming two theoretical conditions. The first assumes no atmosphere at all, and the second assumes an atmosphere made up solely of N_2 and O_2 (normally representing 99 percent of our atmosphere). In both cases, models have predicted that the earth's surface would be some 91°F (33°C) cooler than it is. The temperature difference is believed to be a direct result of the very small amounts of trace gases, water vapor, and CO_2. These act very much like the glass on a greenhouse that lets the sunlight in but helps to prevent the heat from escaping—hence, the terms *greenhouse effect* and *greenhouse gases.* A greenhouse gas is defined as any gas that absorbs infrared (IR) radiation.

It should not be surprising that certain constituents in the air can cause it to stay warmer. For example, it is common knowledge that the temperature on a hot, humid night does not

drop as much as on a less humid night. During the winter, a clear night will have a larger drop in temperature than a cloudy night. In both cases, the difference is due to the water vapor present in the air. In fact, water is the largest contributor to the natural greenhouse effect, followed by CO_2.

Climate change and global warming are not synonymous. Climate change includes cooling and warming of the atmosphere. Global warming only deals with the aspects of climate change that result in warming of the atmosphere.

It is estimated that about one-third of the total solar radiation is reflected off earth's atmosphere. Most of the remaining two-thirds passes through the atmosphere and is absorbed by the earth's surface, causing it to warm.[28] The earth cools itself by releasing heat, or IR. In order for a balance to be maintained, the solar radiation coming in must equal the radiation going out. If more radiation entered the atmosphere than left, the earth would be constantly getting warmer. The opposite would be true if more radiation left earth than came in; that is, the earth would be constantly getting cooler.

O_2 and N_2 are transparent to IR, meaning that these compounds easily let IR radiation or heat pass through. Greenhouse gases are not transparent to IR—they absorb it. Their ability to absorb IR is finite, however, and some of what they absorb is reradiated out of the atmosphere. The IR reradiated is what is important. For a given concentration of greenhouse gases, reradiation depends on two factors: (1) how much IR comes in and (2) the temperature of the gas. Given the premise that the atmosphere wants to establish an equilibrium, the IR from the earth's surface and the amount reradiated from these gases want to be equal. Because the IR coming from the earth's surface does not change, the only remaining variable to affect the equilibrium is temperature. The atmosphere will heat until the IR balance is achieved. As stated previously, this has been predicted as a 91°F (33°C) rise in the temperature of the atmosphere.

On a day-to-day basis, the premise that the solar radiation is equal to the sum of IR radiated from the earth's surface and the IR reradiated from the greenhouse gases is not necessarily true. Daily, weekly, monthly, and yearly changes in weather are always occurring. Nevertheless, over the years, the averages are very close to equal and have resulted in a stable climate. To understand the greenhouse effect, scientists studying the climate have developed the concept of *radiative forcing.* They define radiative forcing as anything that will cause the energy balance at the top of the troposphere to no longer be in balance. Put another way, it is when radiation in and the radiation out of the top of the troposphere are not equal. This unbalanced radiation forces the climate to adapt, hence the term *radiative forcing.* The theory is that the climate will change to equalize the incoming and outgoing radiation. Any condition that results in a positive radiative forcing will cause a rise in the average temperature and, therefore, is responsible for global warming. Any condition that results in a negative radiative forcing will cause a drop in the average temperature and, therefore, is responsible for global cooling.[28]

To estimate the amount of global warming expected from a release of a particular greenhouse gas, a scale was developed by the International Panel on Climate Change (IPCC), based on the idea of radiative forcing. This scale is called the global warming potential (GWP) and relates to positive radiative forcing that will cause the atmosphere to heat up. The GWP is the cumulative amount of radiative forcing between the present and some future time caused by a unit mass (weight) of a compound, as compared with the same unit mass (weight) of an arbitrary standard. CO_2 is the most common reference, and 20 year, 100 year, and 500 year time periods, or horizons, are the most common time references cited in the literature.[28] The choice of time horizons is a policy issue and not a technical one.[29]

Since the GWP is a cumulative effect, summed year by year over a given time horizon, the quantity present in the atmosphere must be known year by year over that horizon. The atmospheric lifetime is used to perform these calculations. GWPs are also affected by the specific IR-absorbing capabilities of the chemical. Analogous to ODPs, GWPs are not exact numbers showing the precise effect on global warming. A 100 year horizon GWP of 6200 for Halon 1301 means that 1 lb (0.454 kg) of Halon 1301 will cause as much global warming as 6200 lb (2812 kg) of CO_2. A 500 year horizon GWP for methylene chloride of 0.3 means that 1 lb (0.454 kg) of methylene chloride will cause the same warming as 0.3 lb (0.14 kg) of CO_2.

GWPs are used to determine the future global warming contribution of a substance *over a given time* by multiplying the weight of the greenhouse gas by a specific time-horizon-GWP. The resultant number can be compared with others to decide which will have the least (or greatest) impact *over that time horizon.* Emitting a large quantity of a small GWP greenhouse gas may cause less global warming than a small release of a very large GWP greenhouse gas over a certain time horizon. Different time horizons may lead to different results.

The choice of which time horizon to use is a policy issue and not a technical one. A standard measure to predict future global warming commitments was developed as a tool to help policy makers and regulators in making decisions of which greenhouse gases would provide the biggest "bang for the buck." Currently, there is no standard in choosing a time horizon. In the future, however, this may change. It is also possible that different time horizons will be used for different greenhouse gases.

Environmental Regulation of Halon Replacements

The evaluation of clean agent fire suppressants includes a consideration of environmental factors. International, national, and local government regulations control the use of any alternatives in this regard. The primary environmental consideration is ODP. This is a measure of a chemical's ability to deplete stratospheric ozone with CFC-11 as a basis with an ODP of 1. All chemicals with a nonzero ODP are subject to phaseout under the Montreal Protocol and its amendments. Table 17.6.12 summarizes environmental impact data for halocarbon alternatives. Note that FC and HFC compounds have zero ozone depletion potential. One relatively recent advance has been the development of the Fluoroketone FK-5-1-12, a halogenated agent with essentially zero GWP.[30] This agent pressures many of the advantages of a halogenated agent but with an environmental impact similar to inert gases.

In the United States, the EPA has the responsibility for regulating the use of halon replacements. Through the SNAP

TABLE 17.6.12 Environmental Factor for Clean Agents

Designation	*ODP*	*GWP (100 years)*	*Atmospheric Lifetime (years)*
Halon 1301	12.000	7,030	LS
HFC-227ea	0.000	2,900	34.2
HFC-23	0.000	14,310	270
HFC-125	0.000	3,450	29
FK-5-1-12	0.000	Extremely low	0.038
Inert gas	0.000	0	NA

program, the EPA may prohibit or restrict the use of halon replacements on the basis of certain environmental factors or toxicity. There are two basic types of restrictions given to date: (1) restrictions on use in occupied versus unoccupied areas and (2) use restrictions (e.g., HCFC-22, HCFC-124, CF_3I) related to high atmospheric lifetime (e.g., C_4F_{10}, C_3F_8). The EPA periodically updates this list as new agents are proposed or as new data become available. It is relatively common to have NOAEL/LOAEL values updated, usually increased, as additional data become available. Such updates may change the acceptability of an agent for use in occupied areas.

HFCs and PFCs are part of the basket of industrial gases (also including methane, sulfurhexafluoride, and nitrous oxide) included in the Kyoto Protocol and may therefore be subject to emission controls in signatory nations. Currently, HFCs and PFCs represent less than 2 percent of greenhouse gas emissions on a carbon equivalency basis. Some PFCs were briefly used as fire extinguishants.

THERMOPHYSICAL PROPERTIES

Tables 17.6.13 and 17.6.14 give thermophysical properties of clean agent replacement update from NFPA 2001, in U.S. custom and SI units, respectively.

Representative isometric diagrams for various clean agents are given in Figures 17.6.3, 17.6.4, and 17.6.5 for HFC-227ea, HFC-23, and IG-541, respectively. The features of a typical isometric diagram for a liquefied halocarbon, superpressurized to 360 psig, can be seen in Figure 17.6.3. The importance of an isometric diagram is that it determines the maximum fill density for an agent in a cylinder with a fixed pressure rating. The basic rule is that the cylinder must not become liquid full at 130°F (54°C) (for U.S. DOT) and/or the pressure developed at 130°F (54°C) must not exceed $^5/_4$ cylinder design pressure. The pressure developed is a function of the agent, the superpressurization level, and the temperature. For 360 psig (at 70°F) cylinders, pressure is limited to $^5/_4$ of the design working pressure of 500 psig at 130°F. For HFC-227ea, as seen in Figure 17.6.5, this yields a maximum fill density of 72 lb/ft^3. The 360 psig pressurization level is not based on characteristics of halon replacement halocarbons but is a vestige of standard Halon 1301 systems.

Figure 17.6.4 is an isometric diagram for HFC-23. HFC-23 is not pressurized with nitrogen. At a maximum fill density of 54 lb/ft^3, it has a vapor pressure of 609 psi at 70°F. Above its critical point of 78.6°F, there is no distinction between liquid

TABLE 17.6.13 Thermophysical Properties of Clean Halocarbon Agents (U.S. Customary Units)

	Units	*FK-5-1-12mmy2*	*HCFC Blend A*	*HFC-125*	*HFC-227ea*	*HFC-23*	*IG-541*	*IG-55*	*IG-01*
Molecular weight	NA	316.04	92.90	120.2	170.03	70.01	34.0	33.95	39.9
Boiling point at 760 mm Hg	°F	120.02	–37.0	–55.3	2.6	–115.7	–320	–310.2	–302.6
Freezing point	°F	–162.4	<–161.0	–153	–204	–247.4	–109	–327.5	–308.9
Critical temperature	°F	335.6	256.0	158.8	215.0	78.6	—	–210.5	–188
Critical pressure	psia	270.44	964	521	422	701	—	602	711
Critical volume	ft^3/lbm	0.0251	0.0280	0.0281	0.0258	0.0305	NA	NA	NA
Critical density	bm/ft^3	39.91	36.00	35.68	38.76	32.78	NA	NA	NA
Specific heat, liquid at 77°F	Btu/lb-°F	0.2634	0.30	0.301	0.2831	0.370	NA	NA	NA
Specific heat, vapor at constant pressure (1atm) and 77°F	Btu/lb-°F	0.2127	0.16	0.191	0.1932	0.176	0.195	0.187	0.125
Heat of vaporization at boiling point of 25°C	Btu/lb	40.1	97.0	70.8	57.0	103.0	94.7	77.8	70.1
Thermal conductivity of liquid at 77°F	Btu/h ft °F	0.033	0.052	0.0376	0.040	0.0450	NA	NA	NA
Viscosity, liquid at 77°F	lb/ft hr	1.27	0.508	0.351	0.443	0.201	NA	NA	NA
Relative dielectric strength at 1 atm at 734 mm Hg 77°F (N_2 = 1.0)	NA	2.8	1.32	0.995 at 70°F	2.00	1.04	1.03	1.01	1.01
Solubility of water in agent at 70°F	NA	<0.001	0.12% by weight	0.07% by weight at 77°F	0.06%	500 ppm at 50°F (10°C)	0.015%	0.006%	0.006%
Vapor pressure at 77°F	psi	—	1.37	199	66.4	686.0	2207	NA	NA

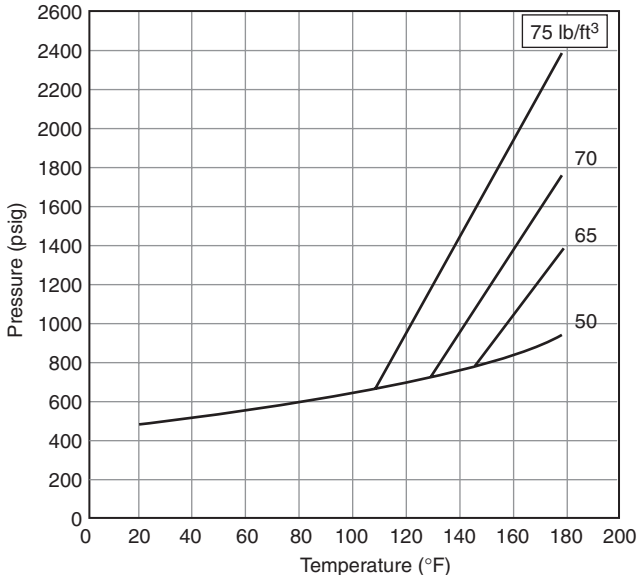

FIGURE 17.6.3 Isometric Diagram of HFC-227ea, Pressurized to 360 psig with N_2 at 70°F. For SI units: 1 lb per ft^3. (Source: Sheinson, R. S., et al., "Halon 1301 Replacement Total Flooding Fire Testing, Intermediate Scale," *Proceedings* of Halon Options Technical Working Conference 1994, Albuquerque, NM, May 3–5, 1994, pp. 43–53)

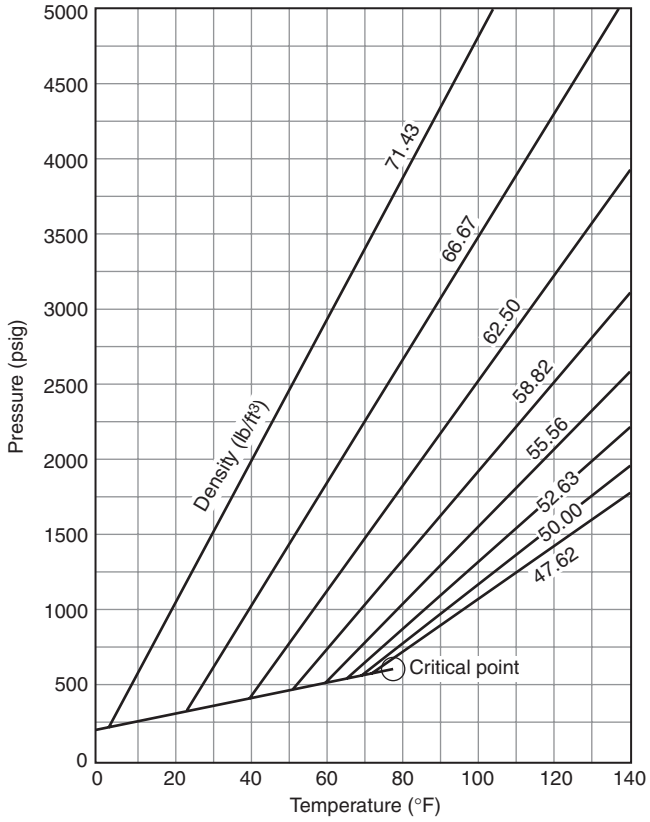

FIGURE 17.6.4 Isometric Diagram of HFC-23. For SI units: 1 lb per ft^3.

TABLE 17.6.14 Physical Properties of Clean Halocarbon Agents (SI Units)

	Units	*FK-5-1-12mmy2*	*HCFC Blend A*	*HFC-125*	*HFC-227ea*	*HFC-23*	*IG-541*	*IG-55*	*IG-01*
Molecular weight	NA	316.04	92.90	120.2	170.03	70.01	34.0	33.95	39
Boiling point at 760 mm Hg	°C	49	–38.3	–48.5	–16.4	–82.1	–196	—	—
Freezing point	°C	–108	<–107.2	–102.8	–131	–155.2	–78.5	—	—
Critical temperature	°C	168.66	124.4	66.0	101.7	25.9	—	—	—
Critical pressure	kPa	1865	6647	3595	2912	4836	—	—	—
Critical volume	cc/mole	494.5	162	210	274	133	NA	NA	NA
Critical density	kg/m^3	639.1	577	571	621	525	NA	NA	NA
Specific heat, liquid at 25°C	kj/kg °C	1.103	1.256	1.260	1.184	1.549	NA	NA	NA
Specific heat, vapor at constant pressure (1 atm) and 25°C	kj/kg °C	0.891	0.67	0.800	0.8082	0.737	0.574	—	—
Heat of vaporization at boiling point of 25°C	kj/kg °C	93.2	225.6	164.7	132.6	239.6	220	—	—
Thermal conductivity of liquid at 25°C	W/m °C	0.057*	0.900	0.0651	0.069	0.0779	NA	NA	NA
Viscosity, liquid at 25°C	Centipoises	0.524	0.21	0.145	0.184	0.083	NA	NA	NA
Relative dielectric strength at 1 atm at 734 mm Hg 25°C (N2=1.0)	NA	2.8	1.32	0.955 @ 70°F	2.00	1.04	1.03	1.01	1.0
Solubility of water in agent at 21°C	NA	<0.001	0.12% by weight	0.07% by weight at 77°C	0.06% by weight	500 ppm at 50°F (10°C)	0.015%	0.006%	0.0
Vapor pressure @ 25°C	kPa	—	948	1371	457.7	4730	15200	NA	NA

*3M estimated values.

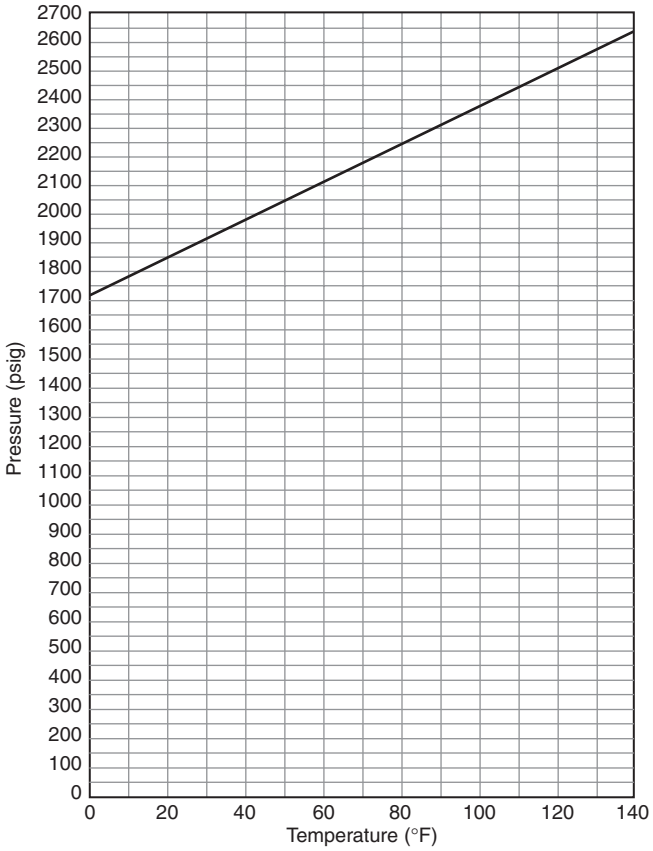

FIGURE 17.6.5 Isometric Diagram of Inert Gases and Blends Treated as Ideal Gases Pressurized to 2175 psig at 70°F

and gas with no liquid/gas separation in the cylinder. Further, compression does not result in formation of a liquid phase. Since it is not possible for the cylinder to be "liquid" full at 130°F, the pressure developed at a maximum fill density of 54 lb/ft^3 must be less than $^5/_4$ of the container design level working pressure of 1800 psi or 2250 psig, as shown in the graph. Below the critical temperature, the agent will exist as a liquid with a vapor or gas phase above it.

Figure 17.6.5 is a typical isometric diagram for inert gases exhibiting ideal gas law behavior at the pressures and temperatures of interest. Because these are compressed gases only, there is no fill density variation, only a linear relationship between temperature and pressure.

APPLICATION SYSTEMS

An application system consists of a supply of agent, a means for releasing or propelling the agent from its container, and one or more discharge nozzles to apply the agent into the hazard or directly onto the burning object. A system may also contain other elements, such as one or more detectors, remote and local alarms, a piping network, mechanical and electrical interlocks to close fire doors and to shut down ventilation, directional control valves, installed reserve agent supplies, and so on. The extent of the auxiliary functions of a system is usually dependent on the nature of the hazard in keeping with the desires and resources of the user.

A system is usually a fixed or stationary apparatus, but some portable or mobile systems have been designed. A portable or mobile system may be moved from one hazard to a similar one, but it is placed in a stationary position while it is in service. In this regard, all systems may be considered to be "fixed" but not necessarily permanently placed.

Halogenated clean agent systems are broadly classified by their method of applying agent to the hazard. The two main types are (1) total flooding and (2) local application systems. Another category, called "specialized systems," includes those systems that are designed to protect special or unique hazards and that have been tested and approved under these specific conditions. There are no NFPA design and installation standards for local application clean agent systems.

Total Flooding Systems

These systems protect enclosed, or at least partially enclosed, hazards. A sufficient quantity of extinguishing agent is discharged into the enclosure to provide a uniform fire-extinguishing concentration of agent throughout the entire enclosure. Examples of total flooding systems using halogenated agents are found in computer rooms, electrical switchgear rooms, magnetic tape storage vaults, and electronic control rooms; storage areas for artwork, books, and stamps; aerosol filling rooms; machinery spaces in ships; cargo areas in large transport aircraft; processing and storage areas for paints, solvents, and other flammable liquids; and so on.

Total flooding systems may be further distinguished by their method of design or installation. An engineered system is custom designed for a particular hazard, using components that are approved or listed only for their broad performance characteristics. Components may be arranged into an almost unlimited variety of configurations.

In preengineered systems, the number of components and configurations are determined in advance and included in the description of the system's approval or listing. Although the degree of preengineering can differ from one system to another, the following limits of components and configurations must be considered:

1. Maximum number of cylinders per manifold
2. Maximum and minimum size and length of piping
3. Maximum and minimum size and number of elbows, tees, and discharge nozzles
4. Container volume, fill density, and level of nitrogen superpressurization

Modular systems consist of single containers connected to discharge nozzles with minimal piping. A group of container-nozzle assemblies may be distributed throughout the protected area and interconnected electrically. Modular systems permit a more attractive and less expensive initial installation but often result in higher maintenance costs.

Central storage systems locate all agent containers in one centralized location. The agent can be stored in multiple tanks

connected by a manifold arrangement or in a single bulk storage tank. A piping network distributes the agent to the various discharge nozzles. Ease of maintenance is the primary advantage of central storage systems.

Local Application Systems

As the name implies, these systems discharge extinguishing agent in such a manner that the burning object is surrounded locally by a high concentration of agent to extinguish the fire. In local application systems, neither the quantity of agent nor the type or arrangement of discharge nozzles is sufficient to achieve total flooding of the enclosure containing the object. Often, too, a local application system is required because the enclosure itself may not be suitable to provide total flooding. Examples of areas protected by local application are printing presses, dip and quench tanks, spray booths, oil-filled electric transformers, vapor vents, and so on. The protected object is not enclosed; therefore, discharge nozzles and rate of application must be capable of enveloping the object. The agent supply must be sufficient to maintain flow for the required time of protection, usually several minutes. Nozzle design is critical and must be determined by extensive testing.

Because of its lower volatility, Halon 1211 is well suited for local application systems. The lower volatility, plus a high liquid density, permits the agent to be sprayed as a liquid and, thus, propelled into the fire zone to a greater extent than is possible with other gaseous agents. Halon 2402 also is well suited for local application systems.

The material relating to local application systems, in NFPA 12B, was largely theoretical and intended for use by equipment manufacturers and testing laboratories in designing and evaluating components for local application systems. The component of overriding importance was the discharge nozzle, and its performance characteristics must be known with a high degree of reliability.

USE CONSIDERATIONS FOR CLEAN AGENT SYSTEMS

Advantages and Disadvantages

The primary advantages of total flooding clean agent systems are (1) the ability to extinguish shielded, obstructed, or three-dimensional fires in complex geometries; (2) the ability, through the use of appropriate detector-based actuation, to extinguish fires at a very early stage, well before direct or indirect fire/smoke damage occurs; and (3) the ability to cause no collateral damage due to agent discharge. These three technical attributes drive much of the usage of these agents in both flammable and combustible liquid hazards (e.g., shipboard engine rooms, pump rooms, etc.) and electronics equipment areas.

There are, however, the following technical disadvantages with respect to the use of clean agents:

1. They require a reasonably intact enclosure with the doors closed and external ventilation secured prior to discharge.
2. These agents provide virtually no cooling. This is an important consideration for situations in which large fires with long preburn times are expected.
3. Electrical power to wire/cable and equipment must be secured, or sufficiently high agent concentrations and hold times must be provided to ensure extinguishment at the expected electrical power density in the cable.
4. All elements of the detection, control, actuation, release, and distribution system must perform as designed. This requirement places increased reliance on both acceptance testing and postinstallation maintenance and test.

Use Recommendations

The decision to use total flooding clean agents is a relatively complex risk management decision. There are several recommendations on the use of these systems in the context of an overall fire protection program. The following are some commonsense recommendations:

1. In general, it does not make sense to protect a hazard area with a total flooding gas system within a building in which all other areas are not protected. Consider the case of a sensitive electronics facility within an office building. The probability of a fire occurring outside the space is at least equal to, and probably greater than, a fire occurring inside the space. Given the cost of protecting the electronics space, the cost/benefit of providing alternative protection (for example, automatic sprinklers) in the remainder of the building is much lower. For a fixed investment, it makes more sense to protect areas outside the electronics area first. As a general rule, never protect an area with a clean agent total flooding system unless the remainder of the building is adequately protected. Notable exceptions to this rule are cases in which the only or predominant fire hazard is in the space to be protected with a clean agent.

2. In facilities where the room or enclosure geometry changes frequently, sufficient administrative control of such modifications is required to ensure a clean agent total flooding system is not rendered inoperable or useless by changes in partitioning, modifications to detection equipment, and so forth. Although the same can be said for other types of fire protection, total flooding gas systems are particularly vulnerable to enclosure volume changes, enclosure integrity, and the integrity of the originally designed and installed detection, actuation, and control system.

3. Wherever possible, individual fire suppression equipment item failures should be anticipated and accounted for in the design. Examples include the use of higher design concentration to account for floodable volume changes or leakage changes, the addition of an extra cylinder to account for valve actuation failure, and provision of very early warning sampling detectors to permit human intervention prior to discharge.

4. Given the cost of halon replacement clean agent systems, it is expected that one significant use area will be in critically important sensitive electronics facilities. Substantial additional risk reduction at very high benefit/cost ratios may be realized by protecting these facilities with *both* clean agent total flooding systems and, at a relatively low incremental cost,

standard wet-pipe automatic sprinklers. Because both systems are designed to perform at different levels, the provision of an additional wet-pipe sprinkler system can be viewed as a backup system to the total flooding gas system. Although one expects higher direct and indirect damage levels in sensitive electronics, due to the difference in actuation time of sprinklers, they are relatively inexpensive and a reliable means of preventing excessively large losses in the event of the primary system (i.e., clean agent system) failure. For a typical 8 ft (2.4 m) high compartment, the additional cost of providing a simple wet-pipe sprinkler system as a secondary system can be as low as 5 percent of the installed clean agent system cost.

Clean agent total flooding systems can offer unequaled performance for the very early extinguishment of fires, which is critical in certain electronics facilities and the suppression of three-dimensional flammable liquid fires. However, the system must function as designed through the life of the facility. In the case of these total flooding gases, the system includes not only the detection, alarm, and suppression system but also the hazard enclosure, doors, dampers, ventilation/fans, and electrical power isolation. A study of existing clean agent system installations undertaken by Taylor/Wagner, Inc., indicated that within 5 years of initial installation, over 50 percent of the systems no longer met design requirements due to changes in the configuration of the protected space. The consequences included inability to achieve design concentration or the possibility of achieving concentrations that would have exceeded human exposure limits. The need to control and maintain this "system" cannot be overstated. See also Section 17, Chapter 7, "Application of Gaseous Agents to Special Hazards Fire Protection."

CLEAN AGENT SYSTEM DESIGN

The basic process of designing a total flooding gaseous extinguishing system involves the following:

1. Determine the design concentration
2. Determine the total agent quantity
3. Establish the maximum discharge time
4. Select piping material and thickness consistent with pressure rating requirements
5. Design piping network and select nozzles to deliver required concentration at required discharge time to ensure mixing
6. Evaluate compartment over/underpressurization and provide venting if required
7. Establish minimum agent hold requirements and evaluate compartments for leakage

These attributes apply only to the mechanical design of the system.

The detection and actuation system is a critical and integral part of a clean agent system design. The detection system should be designed to actuate the system, with appropriate predischarge alarms, before unacceptable thermal or nonthermal damage occurs. This is particularly important relative to the thermal decomposition in which products of halocarbon clean agents are a concern. Section 14, Chapter 2, "Automatic Fire Detectors," provides engineering methods and calculation procedures for this purpose.

In addition to the detection, actuation, and alarm system, the enclosure itself is critical in the design of any total flooding gaseous suppression system. The most important considerations are that the enclosure's integrity is sufficient to prevent (1) preferential agent loss during discharge and (2) excessive agent/air mixture loss after discharge to ensure adequate hold time.

As a general rule, all openings, notably doors and ventilation fans and/or openings, must be secured prior to discharge in conjunction with the detection and alarm system. System installation in rooms with unenclosable openings should not be attempted with these agents unless sufficient test data are available to ensure adequate concentrations. Some enclosures, such as very tightly sealed low electromagnetic field (EMF) emission electronics spaces, require additional care to avoid compartment damage due to overpressurization or underpressurization during agent discharge.

Design Concentrations

Design concentrations for various agents and fuel combinations are generally determined by a combination of small-scale testing, large-scale testing, independent laboratory approval of hardware, and addition of design safety factors.

Historically, minimum design concentrations for Halon 1301 were set by the cup burner extinguishing concentration plus a 20 percent safety factor. A minimum Halon 1301 design concentration of 5 percent was also established for all applications. For *n*-heptane, the cup burner value was approximately 3 percent; with a 20 percent safety factor, a design concentration of 3.6 percent is obtained. At the minimum design concentration set by NFPA 12A of 5 percent, a 66 percent safety factor was achieved. For fuels with cup burner extinguishing concentrations greater than 4.2 percent, the safety factor remained at 20 percent.

The basic requirement for determining the design concentration of clean agents in NFPA 2001 is twofold. First, the minimum extinguishing concentration as determined by the cup burner must be established. After this minimum is established by the *system* manufacturer, full-scale third-party approval testing is conducted using the manufacturer's hardware on *n*-heptane, wood crib, and selected flammable liquids. These tests are performed at the cup burner minimum extinguishing concentration, not the design concentration. Further, they are conducted with flooding factors lower than utilized in design. Hence, the minimum set by the cup burner or equipment manufacturer, whichever is higher, is tested in full scale as part of the approval/listing process for the agent/system combination. Often hardware manufacturers will establish a minimum concentration greater than the cup burner value to account for nozzle efficiency.

Reliance on the cup burner to set a minimum value is supported by the observation that no full-scale test known to the author conducted at the cup burner concentration plus 80 percent safety factor has failed to extinguish a flammable liquid fire in an enclosure. It is critical to recognize that, in real system design, the agent and the hardware delivering it, particularly the nozzle, are not independent. They must be taken as a system

and designed and installed per the listing/approval guidelines and limitations.

There has been some full-scale test work that indicates that the 20 percent safety factor may be insufficient for certain applications, depending on the performance required of the system. Sheinson noted significant improvement in extinguishing time performance with a safety factor of 40 percent.[31] Brockway noted similar results with no performance improvement beyond a safety factor of 40 percent.[32]

It has also been noted by several investigators that higher safety factors result in lower thermal decomposition products.[31–33] None of the previously referenced investigations utilized listed or approved hardware for the specific agents tested; as in most cases, the tests were performed before such hardware was available.

There was an exception in the first edition of NFPA 2001 to the general rule that a minimum extinguishing concentration be established by the cup burner method. It was alleged that reliable cup burner data were not available for HCFC Blend A due to two facts: (1) the agent was a blend and (2) one of the blend components heats at a low vapor pressure. In the case of this agent, a minimum extinguishing concentration of 7.2 percent and, hence, a design concentration of 8.4 percent was established through limited full-scale testing. Since at the time insufficient data were available to evaluate the claim, the exception that requires full-scale testing at minimum extinguishing concentration consistent with UL 1058, *Halogenated Agent Extinguishing Systems Units,* was invoked. Since that time, reliable cup burner data were obtained for the blend from several laboratories. The data are consistent with MEC values for the blend components, primarily HCFC-22. Furthermore, some full-scale testing has indicated that the design concentration of 8.6 percent may be inadequate.[34] This exception was removed in the second edition of NFPA 2001. The current requirement for Class B fires is that the cup burner concentration for the worst-case fuel in the protected enclosure forms the MEC basis for that hazard.

It is important to recognize that the use of *n*-heptane cup burner values as a minimum for design concentration has no technical basis. With Halon 1301, *n*-heptane was a reasonable "worst case" fuel, but such is not the case with the replacements. It is important, therefore, that the design concentration be based on the "worst case" or fuel requiring the highest design concentration when designing systems for flammable or combustible liquid risks.

Extinguishing concentrations for Class A fuels were traditionally developed using wood cribs as part of the equipment listing/approval process. Further, the minimum Class A extinguishing concentration used for design purposes was required to be greater than or equal to the minimum extinguishing concentration for heptane. Recently, additional tests utilizing plastic sheet arrays of polymethylmethacrylate (PMMA), acrylonitrile-butadiene-sytrene (ABS), and polypropylene (PP) have been required.[35,36]

The test consists of an array of four sheets of polymer, 200 mm × 4000 mm × 10 mm thick, oriented vertically, forming three vertical channels. The array is enclosed on two sides and the top and surrounded by an additional baffle arrangement as shown in Figure 17.6.6. The array is tested in a minimum 100 m^3 compartment. The fuel is ignited by a small heptane pan, and the entire array is subjected to a 210-second preburn time.

Clean agent systems are widely used in electronic equipment areas where fires involving electrically energized cables and equipment are often encountered. Extinguishment tests involving PMMA heated externally with nichrome wire indicated

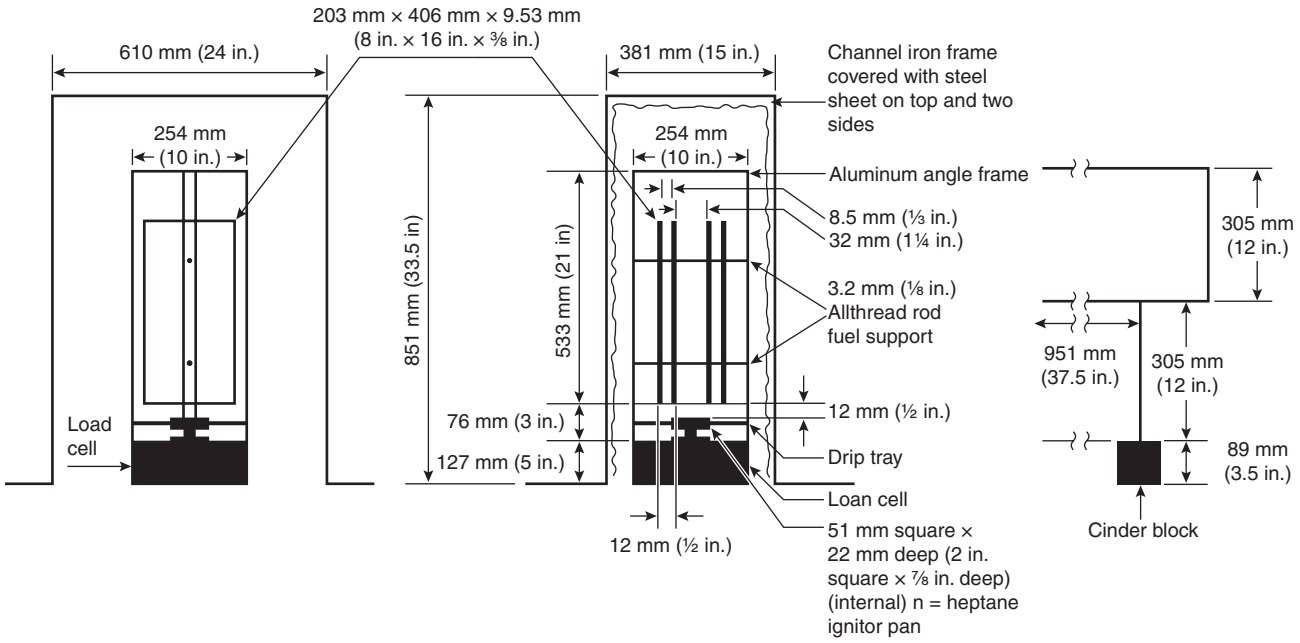

FIGURE 17.6.6 Four-Piece Modified Plastic Setup

that agent concentrations substantially higher than those typical for plastic fuels were required. For example, extinguishing concentrations of 9.5 percent, 9.0 percent, and 20 percent were required for FC-3-1-10, HFC-227ea, and HFC 23, respectively.

Extinguishment tests on actual wire and cable materials were reported by McKenna et al.[37] Three types of tests were conducted: ohmic heating, conductive heating, and printed wiring board arcing. The ohmic heating tests involved deliberate electrical overheating of the conductor. Under severe overcurrent conditions, all cable assemblies were extinguished at 5.8 percent, a typical Class A extinguishing concentration. The one exception was the 18 AWG polyethylene coaxial cable, which is generally not used in power applications. The striking difference between these results and those discussed earlier for PMMA probably lies in the fire-retardant nature of real electrical wire and cable assemblies. Results for cable assemblies heated at the ends by conduction, a situation simulating an overheated connection, showed results similar to the ohmic heating tests for Hypalon and PVC cables. There has, however, been no systematic evaluation of grouped electrical cables or high-voltage cables. Cable arrays with long preburn times have been demonstrated to require substantially higher agent concentration than for surface fires in the case of Halon 1301 and carbon dioxide.

Given the widespread use of clean agents in areas involving continuously energized equipment and recognizing the significant gaps in knowledge of required extinguishing concentration, the ISO standard[2] has required an extinguishing concentration no less than 95 percent of the heptane extinguishing concentration when any of the following conditions apply:

1. Cable bundles greater than 100 mm in diameter
2. Cable trays with a fill density greater than 20 percent of the tray cross section
3. Horizontal or vertical stacks of cable trays (closer than 250 mm)
4. Equipment energized during the extinguishment period in which the collective power consumption exceeds 5 kW

The issue of inadequate design concentration is exacerbated by the relatively recent decline in extinguishing concentration achieved in the Class A polymeric sheet tests. Additional uncertainty in the Class A extinguishing concentration was seen in Table 17.6.3, in which minimum required concentration is a function of system hardware. The extinguishing concentration for total flooding systems should be system and scale independent.

There has been no systematic evaluation of these agents under so-called "deep-seated" fire scenarios. However, the Underwriters Laboratories Inc. (UL) and FM Global Research listing procedures require testing on wood cribs subsequent to long preburn times (approximately 5 minutes). Under these tests, surface oxidation and char reactions do occur.

Design concentrations for fire scenarios involving long preburn times in thick arrays of cellulosic fuels may require additional testing. For most applications in which incidental quantities of cellulosic materials may be involved and preburn times have relatively short (5 minute) time frames (i.e., automatic actuation), the flame extinguishing concentrations for Class A fuels that are less than, or equal to, that of *n*-heptane can be used.

IG-541 is used at 37.5 percent minimum design concentration where Class A materials are involved. IG-55 may have slightly higher minimum design concentrations; IG-01 (argon) should have substantially higher MEC.

The minimum design concentration is a function of the fuel, the agent, and the delivery system. Design concentrations for specific hazards must be determined in accordance with the system manufacturer's approval or listing.

Safety Factors

The safety factor requirement in NFPA 2001 used for developing design concentrations should be considered a minimum. It can reasonably be expected to account for minor errors arising from the design and installation process, such as errors in room volume calculations, cylinder filling/agent weight, and cup burner MEC values.

The 20 percent minimum safety factor required in previous editions of NFPA 2001 has been increased under certain conditions. Systems protecting Class B or any system exclusively operated by manual means now requires a 30 percent safety factor. The ISO standard requires a minimum safety factor of 30 percent for all systems. The increase in safety factor resulted from a combination of theoretical analysis and fire testing. The ISO standard requires a 30 percent safety factor in all cases.

Analysis by Schlosser[38] indicated that the probability of failure of a system was reduced from approximately 15 percent to 10 percent when the safety factor increased from 20 percent to 30 percent. In addition to these data, the variation in cup burner values used as a basis for design concentration was significant due in part to a lack of standardization in the method. Some full-scale test results[39] also indicated a need for higher design concentrations.

The safety factor was also increased in response to increasing uncertainty concerning the determination of extinguishing concentrations for Class B fuels by the cup burner method. One concern was the observed increase in extinguishing concentration for inert gases as the cup burner flow rate was increased. VdS also reported a significant increase in extinguishing concentration for inert gases as the cup burner was increased in size.[40] The extinguishing concentration for all agents was observed to increase when the fuel pan was either thin-gauge metal or allowed to heat excessively. In addition to these small-scale test observations, difficulties were observed in full-scale tests in which long preburn times (for both Class A and Class B fuels) and compartment venting schemes may have resulted in higher than expected extinguishing concentrations.[41]

The increase in the safety factor was, therefore, judged prudent for application to future system installations. There is no evidence whether or not systems designed and installed prior to these changes are adequate. There have been no reported incidents in which an existing system failed to extinguish a fire using the 20 percent safety factor.

In addition to increased safety factors, the concept of design factors was introduced into the 2000 edition of NFPA 2001. A

design factor is used to increase the agent quantity for a specific installation or design that has attributes for which the minimum safety factor may not be sufficient. The only variable for which design factors have been quantified is for systems with multiple flow splits protecting more than four enclosures simultaneously. The motivation for a design factor in these very rare cases is the uncertainty in the split of agent mass flow at unbalanced tee junctions and the compounding of that error with more than four tees in series.

Table 17.6.15 gives the required additional design quantity or design factor for systems with a large number of unbalanced flow divisions at tee splits. Note that the inert gas factor is always less than the halocarbon agent factor, reflecting the higher calculation uncertainty due to the complex two-phase behavior at flow splits for the halocarbon agents.

Consideration should be given to increasing the safety factor and, hence, the minimum design concentration when any of the following conditions apply:

1. When the nozzle is installed at or near its maximum listed ceiling height or area coverage
2. For the protection of combustible or flammable liquid hazards when limiting the quantity of thermal decomposition products (for halocarbon agents) and/or rapid (less than 15 seconds) extinguishment times are required
3. When a large number of highly imbalanced flow splits occurs in a piping network protecting large and small enclosures simultaneously (use design factors approach)
4. When the floodable room volume is highly variable (e.g., record storage), unless the maximum floodable volume is used
5. Where unenclosable openings exist or pressure-relief vents are provided and located such that excessive agent loss during discharge will occur
6. When excessive postdischarge agent leakage is expected

TABLE 17.6.15 Design Factors for Piping Tees

Design Factor Tee Count	*Halocarbon Design Factor*	*Inert Gas Design Factor*
0–4	0.00	0.00
5	0.01	0.00
6	0.02	0.00
7	0.03	0.00
8	0.04	0.00
9	0.05	0.01
10	0.06	0.01
11	0.07	0.02
12	0.07	0.02
13	0.08	0.03
14	0.09	0.03
15	0.09	0.04
16	0.10	0.04
17	0.11	0.05
18	0.11	0.05
19	0.12	0.06

Increasing the safety factor or design concentration is not warranted in many applications and may not substantially improve the reliability or performance of the system. For example, increasing the safety factor will not improve system reliability if doors are not closed. The design safety factor is not a panacea and cannot be used in lieu of other system design requirements.

Agent Quantity

Once the design concentration is established, the quantity of agent necessary to achieve that concentration is determined. The quantity of halocarbon agent necessary is determined by the following equation:

$$w = \frac{V}{S}\left(\frac{C}{100 - C}\right) \tag{1}$$

where

w = Specific weight of agent required

V = Net volume of protected space

C = Design concentration (%)

S = Specific volume (ft^3/lb or m^3/kg), and is determined by

$$S = k_1 + k_2(T) \tag{2}$$

where

T = Minimum ambient temperature of the protected space

k_1 and k_2 are constants

Values for k_1 and k_2 used in Equation 2 are given in Table 17.6.16.

The flooding factor in Equation 1 implies that the agent/air mixture "lost" during discharge is well mixed and has an agent concentration of C. This formula makes no assumption regarding leakage of the enclosure. During UL/FMRC approval testing, the agent is evaluated with a flooding factor of (C/100), essentially assuming that losses during discharge are 100 percent air.

For inert gases, the following formula is used:

$$X = 2.303\,\frac{V}{S}\log\left(\frac{100}{100 - C}\right)V_s \tag{3}$$

where

X = Volume of inert gas required at 70°F (21°C)

V_s = Specific volume at 70°F (21°C)

V = Net protected hazard volume

S = Specific volume at ambient temperature in protected volume (from Equation 2)

The flooding factor used here is derived assuming that leakage from the compartment during discharge occurs with a varying concentration of agent from zero to C from beginning to end of discharge. It is identical to the expression used in CO_2 system

TABLE 17.6.16 Specific Volume Constants

Generic Name	*Trade Name*	k_1 *English Units*	k_2 *English Units*	k_1 *SI Units*	k_2 *SI Units*
Halocarbons					
Halon 1301	Halon 1301	2.206200	0.0050460	0.1478	0.0005700
HFC-23	FE-13	4.730200	0.0106990	0.3168	0.0011942
HFC-125	FE-25	2.722000	0.0063760	0.1828	0.0007085
HFC-227ea	FM 200	1.879775	0.0046625	0.1268	0.0005133
HFC-236fa	FE-36	2.097800	0.0051400	0.1413	0.0005800
FK-5-1-12	Novec-1230	0.985600	0.0024410	0.0664	0.0002743
Inert Gases					
IG-01	Argotec	8.40299	0.0182810	0.56120	0.0020540
IG-55	Argonite	9.88090	0.0214956	0.65979	0.0024134
IG-100	NN-100	11.97600	0.0260600	0.79970	0.0029270
IG-541	Inergen	9.85800	0.0214300	0.65900	0.0024100

design. It assumes that the displaced atmosphere is freely vented from the enclosure.

Discharge Time

The maximum discharge time permitted for halocarbon clean agent systems is 10 seconds. This discharge time is taken to be the point at which all liquid agent has cleared the nozzle. The total discharge time will be longer as agent vapor and nitrogen are expelled from the system.

The 10-second discharge time limitation for halocarbon agents is designed to aid the following four objectives:

1. Provide high flow rates through nozzles to ensure adequate mixing of agent with air inside the enclosure
2. Provide sufficient velocity through pipes to ensure homogeneous flow of liquid and vapor
3. Limit the formation of agent thermal decomposition products
4. Minimize direct and indirect fire damage, particularly in fast-developing fire scenarios

The most important of these objectives relative to discharge time is the minimization of agent thermal decomposition product formation. Items 1 and 2 alone are determined by the piping system design.

The discharge time requirement for inert gases is currently 60 seconds. Longer discharge times are typically used for these systems in Europe. The primary reasons to constrain the discharge time of inert gas agents that form no decomposition products are to limit the direct and indirect fire damage and to minimize the length of time that the fire burns in a depleted oxygen atmosphere. As more information is developed on the effect of discharge time on inert gas agent performance, this 60 second limit may be increased for certain applications.

In some applications, such as flammable liquid hazards and explosion inerting, it is necessary to discharge the agent quickly to minimize direct fire damage or to ensure that the agent concentration is achieved prior to the lower explosive limit (LEL) being reached.

Thermal Decomposition Products

All of the halocarbon replacement agents form higher levels of decomposition products than Halon 1301 under similar conditions. For a given fuel, the primary variables determining the level of decomposition products are (1) the size of the fire at the time of discharge, (2) the time required to reach an extinguishing concentration in the compartment, and (3) the agent design concentration.

The dependence of thermal decomposition product formation on discharge time and fire size has been extensively evaluated.[31–33,42–46] Figure 17.6.7 is a plot of peak HF concentration as a function of fire size to room volume ratio. The data encompass room scales of 1.2 to 972 m^3. The 526 m^3 results are from USCG testing; the 972 m^3 results are based on Naval Research Laboratory testing.

These fires include diesel and *n*-heptane pool and spray fires. The design concentrations in all cases, except HCFC Blend A (at 8.6 percent), are at least 20 percent above the cup burner value. For fires in which the extinguishment times were greater than 17 seconds, the extinguishment time is noted in braces. Note that excessively high extinguishment times (greater than 60 seconds), generally an indication of inadequate agent concentrations, yield qualitatively higher HF concentrations. In addition, Halon 1301 will yield bromine or bromine acids as well as HF. Likewise, HCFC Blend A will produce HCl in addition to HF.

The quantity of HF formed is approximately three to eight times higher for all halocarbon replacements relative to Halon 1301. There may be differences between the various HFC/HCFC compounds tested, but it is not clear from these data whether (1) such differences occur, (2) the differences are attributable to agent mixing and distribution, or (3) the differences are attributable to locally high velocities or concentrations of agent from the nozzle. In all of the data reported, the fire source, *n*-heptane pans of varying sizes, was baffled to prevent direct interaction with the agent jet.

Whereas these results are based on flammable and combustible liquid fires, solid polymeric fires of similar size will

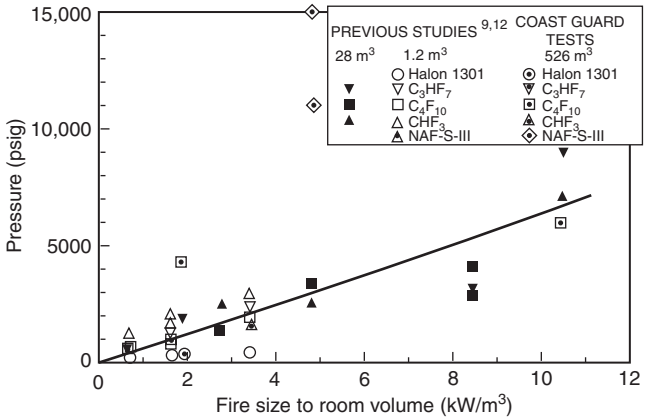

FIGURE 17.6.7 Maximum HF Concentration Resulting from Extinguishment of Test Fires with Nominal 10 sec Discharge Times with Data from U.S. Coast Guard Research and Development Testing and from Naval Research Laboratory Testing. For U.S. customary units: 1 ft^3 = 0.0283 m^3. (Sources: Back, G. G., et al., "Full-Scale Machinery Space Testing of Gaseous Halon Alternatives," USCG R&D Center, Groton, CT, Sept. 1994; Forssell, E. W., and DiNenno, P. J., "Evaluation of Alternative Agents for Use in Total Flooding Fire Protection Systems," Contract NAS 10-1181, National Aeronautics and Space Administration, John F. Kennedy Space Center, FL, Oct. 1994)

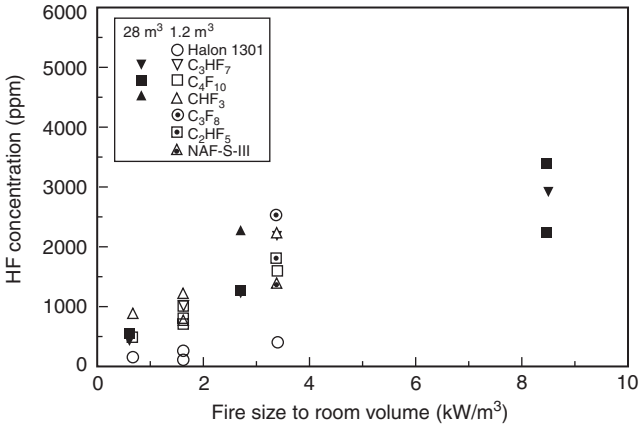

FIGURE 17.6.8 Average HF Concentration Resulting from Extinguishment of *n*-Heptane Fires with Nominal 15 sec Total Discharge Time. For U.S. customary units: 1 ft^3 = 0.0283 m^3. (Source: Forssell, E. W., and DiNenno, P. J., "Evaluation of Alternative Agents for Use in Total Flooding Fire Protection Systems," Contract NAS 10-1181, National Aeronautics and Space Administration, John F. Kennedy Space Center, FL, Oct. 1994)

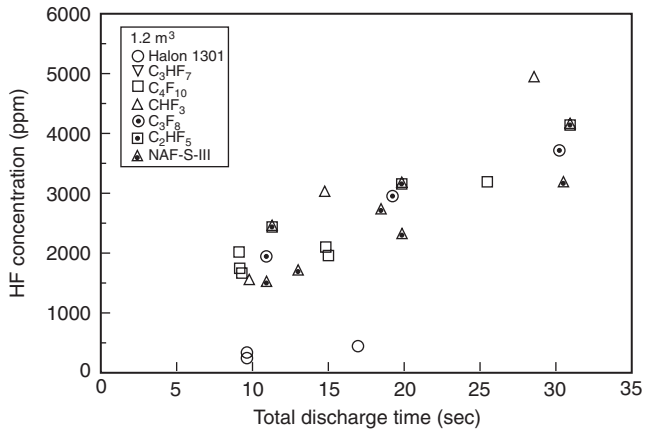

FIGURE 17.6.9 Maximum HF Concentration Resulting from Extinguishment of 4.0 kW *n*-Heptane Fires. For U.S. customary units: 1 ft^3 = 0.0283 m^3. (Source: Forssell, E. W., and DiNenno, P. J., "Evaluation of Alternative Agents for Use in Total Flooding Fire Protection Systems," Contract NAS 10-1181, National Aeronautics and Space Administration, John F. Kennedy Space Center, FL, Oct. 1994)

generally produce lower HF concentrations. Figure 17.6.8 reports 10-minute average HF concentration data for the 1.2 and 29 m^3 enclosures as opposed to the peak values shown in Figure 17.6.7. These 10 minute average values show HF concentrations 50 percent (or less) of the peak values.

Figure 17.6.9 shows the dependence of the quantity of decomposition products formed on the discharge time. Increased discharge time will also result in longer extinguishment times. The relationship is approximately linear with a doubling in discharge time resulting in a 100 percent increase in HF production. Clearly, increasing the amount of time the flame is exposed to a subextinguishing concentration of agent will increase the amount of agent decomposition expected.

Sheinson[47] has shown that increasing the design concentration of HFC-227ea from 8 percent (approximately 1.2 × cup burner) to 9.8 percent (1.8 × cup burner) results in a decrease in peak HF concentration from 8000 ppm to 2500 ppm for real-scale large combustible liquid fires. He also found HF concentrations 4 to 5.5 times higher than the peak HF concentration of Halon 1301 under similar conditions. He did not report HBr or bromine formation in these tests.

Although other thermal decomposition products have been identified in some cases, it appears that HF is the primary decomposition product of interest relative to human safety and equipment damage.

One of the characteristics of HF, like HCl, is that it is an irritant gas, detectable at very low concentrations; however, there is a very large difference between the human detection threshold, the severe sensory irritant threshold, and the ALC (approximately two and three orders of magnitude, respectively).

Fire sizes necessary to generate short-term lethal concentrations of HF in an enclosure (on the order of 1000 ppm) are large enough in some cases that the hazard posed to personnel in the protected space during a discharge in a fire incident is primarily from the fire and its effects rather than the secondary impact of agent decomposition products. This outcome,

however, should be verified for a particular application under a range of fire scenarios using engineering methods discussed by Hanauska et al.[48,49]

The impact of decomposition products on electronic equipment is another area of concern. There are not sufficient data at present to predict the effects of a given HF exposure scenario on all electronic equipment. Several evaluations of the impact of HF on electronic equipment have been performed relative to the decomposition of Halon 1301, where decomposition products include HF and HBr. One of the more notable evaluations was a NASA study where the space shuttle *Orbiter* electronics were exposed to 700, 7000, and 70,000 ppm HF and HBr. In these tests, exposures up to 700 ppm HF and HBr caused no failures. At 7000 ppm, severe corrosion was noted; there were some operating failures at this level.

Dumayas[50] exposed IBM-PC-compatible multifunction cards to environments produced by a range of fire sizes as part of an evaluation program on halon alternatives. He found no loss of function of these boards following a 15 minute exposure to a postfire extinguishment atmosphere up to 5000 ppm HF, with unconditioned samples stored at ambient humidity and temperature conditions for up to 30 days. Forssell et al.[51] exposed multifunction boards for 30 minutes in the postfire extinguishment environment; no failures were reported up to 90 days posttest. HF concentrations up to 550 ppm were evaluated.

Although no generic rule or statement can be made at this time, it appears that short-term damage resulting in electronic equipment malfunction is not likely for exposures of between 500 and 1000 ppm HF for up to 30 minutes. This outcome, however, is dependent on the characteristics of the equipment exposed, postexposure treatment, exposure to other combustion products, and relative humidity. Important equipment characteristics include its location in the space, existence of equipment enclosures, and the sensitivity of the equipment to damage.

All HCFC, PFC, and HFC clean agents form more decomposition products than Halon 1301, given similar fire sizes and discharge times. The primary variable controlling the quantity of decomposition products is the size of the fire at the time of agent discharge. Through evaluation of the fire size at the time of system actuation, the potential hazard posed can be adequately managed.

Hanauska et al. have indicated that the degree of decomposition products in electronic applications of agents can be safely managed when automatic detection and actuation are provided. Full-scale testing with typical Class A fuel packages in conjunction with typical detection system installation[51] has shown that the level of decomposition products is acceptable in typical computer/electronics spaces. For installation in hazard areas where very rapidly developing large fires are likely, the degree of thermal decomposition formation should be evaluated in the context of the hazard posed by the fire and the performance of alternative fire protection systems.

The production of HF and other agent decomposition products forms a potential hazard for occupants. Table 17.6.17, from *Toxicology of Substances in Relation to Major Hazards: Hydrogen Fluoride,*[52] summarizes potential health effects in healthy individuals. Note that exposure above 200 ppm may begin to impair escape particularly at exposure times exceeding 5 minutes.

Emergency Response Planning Guidelines (ERPG) values, developed by the American Industrial Hygiene Association, for 10 minute exposures are as follows: ERPG-2, a level at which mitigating steps such as evacuation should be taken is 50 ppm; and ERPG-3, the maximum nonlethal exposure concentration for 10 minutes is 170 ppm. The ERPG values are in contrast to an analysis by Melchrum, which indicates a dose of 12,000 ppm/

TABLE 17.6.17 Potential Human Health Effects of Hydrogen Fluoride in Healthy Individuals

Exposure Time (min)	*Hydrogen Fluoride (ppm)*	*Reaction*
2	<50	Slight eye and nasal irritation
	50–100	Mild eye and upper respiratory tract irritation
	100–200	Moderate eye and upper respiratory tract irritation; slight skin irritation
	>200	Moderate irritation of all body surfaces; increasing concentration may be escape impairing
5	<50	Mild eye and nasal irritation
	50–100	Increasing eye and nasal irritation; slight skin irritation
	100–200	Moderate irritation of skin, eyes, and respiratory tract
	>200	Definite irritation of tissue surfaces; will cause escape impairment at increased concentrations
10	<50	Definite eye, skin, and upper respiratory tract irritation
	50–100	Moderate irritation of all body surfaces
	100–200	Moderate irritation of all body surfaces; escape-impairing effects likely
	>200	Escape-impairing effects will occur; increasing concentrations can be lethal without medical intervention

Source: *Toxicology of Substances in Relation to Major Hazards: Hydrogen Fluoride,* Health and Safety Executive Information Centre, U.K., 1993.

min based on 1 percent lethality in exposed animals. Additional health effect and risk assessment data have been reported.[53–56]

For large flammable or combustible liquid fire hazards utilizing manual system operation, the concentration of thermal decomposition products may be high enough to preclude entry into the space without special precautions. The use of an inexpensive water spray, wash-down cooling system in conjunction with a gaseous suppressant will provide substantial cooling, a reduction in the total decomposition products generated, and a reduction in the postdischarge decomposition product concentration due to scrubbing. Although the enhanced cooling would benefit all total flooding gases, the reduced decomposition product potential applies only to halocarbons. The provision of such a system would permit more rapid reentry into the space and may be of particular benefit for shipboard engine room protection.

Hydraulic and System Discharge Characteristics

All of the halocarbon replacement agents will exhibit two-phase flow behavior. Since all, except HFC-23, are used in cylinders pressurized to 360 or 600 psig (2482 or 4137 kPa) with nitrogen, they are also multiple component flows. Inert gases and blends will be single-phase compressible fluid flow problems. Most of the following discussion will not apply to inert gas systems; the testing and approval of flow calculations are similar with emphasis placed on flow parameters relevant to compressible gas flow, ignoring phase separation issues such as the orientation. As in the case of engineered Halon 1301 systems, all flow calculation procedures used must be listed or approved by a third-party laboratory and within the limitations of the flow calculation method determined during the engineered system approval process.

The characteristics that differentiate two-phase pipe flow from incompressible fluid (e.g., water) pipe flow is the existence of gas and liquid phases simultaneously in the pipe network. This coupled with the relatively short flow times results in significant challenges to correctly predicting the flow. Among the important factors are the change in density of the fluid with pressure, the release of nitrogen in the cylinder and pipe as the fluid pressure and temperature change, differences in agent mass delivered caused by the flow time imbalances between nozzles, and preferential distribution of phases (and subsequently agent mass) at tee splits.

The need for accurate flow predictions is driven by the following three design requirements:

1. Control of agent discharge time
2. Maintenance of adequate nozzle flow and pressure to ensure agent distribution and mixing at the listed coverage area
3. Delivery of adequate, but not excessive, agent quantities to different rooms within the same protected area, when such rooms are flooded simultaneously

In addition, agent flow rate and thermodynamic state properties are necessary for estimating compartment pressurization levels during agent discharge.

For preengineered systems, limits on discharge time and nozzle pressure are built into the limits on piping system geometry. Agent distribution is handled by constraining preengineered systems to balanced flow conditions (i.e., the same agent mass is distributed from each nozzle). For adequate design of preengineered systems, accurate methods for predicting these elements are required.

Figure 17.6.10 is an idealized plot of cylinder and nozzle pressure during discharge.

Testing and Approval of Design Methods

The approval or listing of a clean agent flow calculation procedure including inert gases is part of the approval granted for engineered systems. Since some aspects of two-phase flow calculations are empirically based (e.g., flow regime, pressure drop, flow splits) and all calculation procedures have some bounds on their validity, testing is performed to verify the predictions and establish the limits of the calculation procedure. These limitations are crucial in helping to ensure that system designs do not exceed verified limits of calculation.

One of the most rigorous approval procedures used in verifying design methods is outlined by Underwriters Laboratories Inc. UL 1058, *Halogenated Agent Extinguishing Systems Units,* was used for evaluating engineered Halon 1301 systems, but the same approach is taken for all clean agent alternatives. Design method limitations are described by the following 10 parameters, and tests are required to verify the accuracy of the calculation procedure at all of these limits (some of these parameters will not apply to inert gas systems):[35,36]

1. Percent of agent in piping (maximum)
2. Minimum and maximum discharge times
3. Minimum pipeline flow rates
4. Variance of piping volume to each nozzle

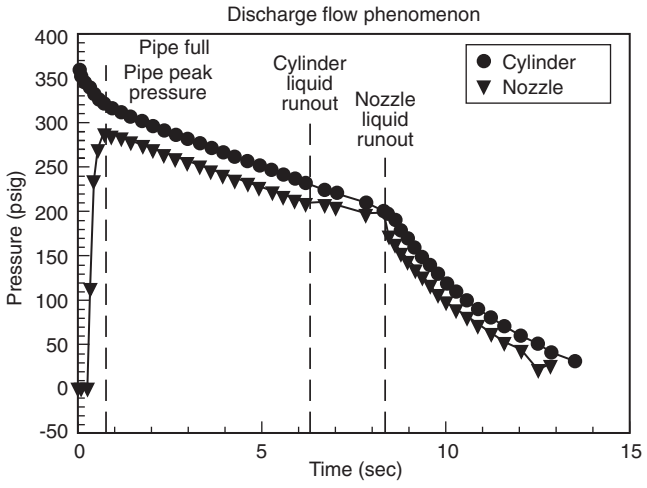

FIGURE 17.6.10 Idealized Cylinder and Nozzle Pressure Time Curves for Halocarbon Agents. For SI units: 1 psi = 6.895 kPa.

5. Maximum variance of nozzle pressures within a piping arrangement
6. Maximum ratio of nozzle diameter to inlet pipe diameter
7. Arrangement most likely to exhibit vapor time–imbalance condition at nozzle
8. All types of tee splits, including through tees, bullhead tees, and tee orientation (vertical versus horizontal)
9. Minimum and maximum container fill density
10. Minimum and maximum flow split for each type of tee

These parameters are related to the important attributes of the agent discharge process previously discussed. Full-scale testing is performed to evaluate the performance of the design method. The limits on flow calculation method performance are as follows:

1. Actual versus predicted discharge time (second)
2. Actual versus predicted nozzle pressure (percent)
3. Actual versus predicted mass flow through a nozzle (percent)

The accuracy limits required for mass flow rate through a nozzle, particularly the –5 percent allowable variation, are quite challenging given the complex nature of the problem. This allowable variation points to an area where increased agent quantity (or safety factor) may be appropriate. For networks in which a small fraction of the total agent flow is directed to a simultaneously protected but segregated enclosure *and* a large number of tees or flow splits are involved, the provision of additional agent to provide an allowance for the mass flow accuracy through greater than five or six tees should be considered. This is generally not a problem when all of the agent is discharged into the same enclosure.

Testing in conjunction with a particular manufacturer's hardware is important. Two critical hardware-dependent verifications are (1) ensuring that pressure drop through a particular valve assembly is calculated properly and (2) evaluating the nozzle orifice discharge coefficient.

In order to preserve a 10-second discharge time, the mass flow rate of these clean agents must be higher than Halon 1301. The increased density of some of the alternative agents in the piping, caused by lower vapor pressures and nitrogen solubility differences, may result in high enough mass flow rates to retrofit existing Halon 1301 systems. Although agent cylinders and nozzles will require changeout, it is often possible to preserve the existing Halon 1301 pipe network and often requires the use of lower fill density cylinders to increase the average system pressure throughout the discharge time. Any such retrofit using existing Halon 1301 piping must be carefully evaluated with respect to hydraulic performance with particular care given to preserving minimum required nozzle pressures and flow divisions at tees.

Nozzle Area Coverage and Height Limitations

One of the most important requirements of a gaseous total flooding fire suppression system is the ability of the system to deliver a uniform concentration of agent throughout the protected enclosure. The nozzle design and minimum nozzle pressure are critical in ensuring this distribution of agent. The performance of the nozzle is evaluated by full-scale approval testing.[57,58] The basic testing performed to evaluate nozzles is as follows:

1. Establish minimum nozzle pressure and maximum nozzle height by ensuring extinguishment of *n*-heptane fires located throughout a space with a height equal to the maximum allowable at the minimum allowable nozzle pressure.
2. Establish maximum nozzle coverage area by extinguishing tests in a plenum at the minimum height (generally less than 1.6 ft [0.5 m]) at the maximum nozzle coverage area (on the order of 1076 ft^2 [100 m^2]) and minimum nozzle operating pressure.

There are substantial differences among hardware manufacturers relative to minimum nozzle pressure, maximum ceiling height, and maximum average coverage. All nozzle orientations should be evaluated. In general, maximum nozzle heights are on the order of 13 to 16 ft (4 to 5 m), nozzle area coverage on the order of 97 to 108 ft^2 (9 to 10 m^2), and minimum nozzle pressures between 3 and 6 bar. It is critical to ensure that the nozzle spacing, height, and minimum pressure limits are not exceeded for a particular manufacturer's hardware in a specific design.

The flow, mixing, and distribution of an agent from a nozzle into an enclosure can be predicted theoretically for relatively simple nozzle designs by using sophisticated computer models.[59] Further development of such methods for complex nozzle designs and compartment geometries may eventually form the basis of a design procedure. At present, however, the primary means of ensuring adequate nozzle performance is the hardware approval process and real-scale testing.

Since many of the halocarbon replacements have lower vapor pressures than Halon 1301, there is often a much higher percentage of liquid at the nozzle. This makes the task of vaporizing and mixing the agent in the compartment more difficult. In general, nozzle designs used for Halon 1301 systems are not adequate for the halocarbon replacement agents. Due to the increased liquid fraction at the nozzle, it is critical to ensure that no unenclosed openings exist along the trajectory of the nozzle orifices. This may result in significant preferential loss of agent through these openings. This further emphasizes the need for third-party approval testing of nozzle performance. In any retrofit situation, the nozzles will need to be replaced even if the piping is adequately sized to deliver adequate agent flow rates.

Compartment Pressurization

The rapid discharge of agent into a compartment will cause rapid changes in the compartment pressure. Depending on the agent and rate of discharge, the initial pressure change may be negative. Figure 17.6.11 is a plot of compartment pressure versus time for the discharge of HFC-227ea into a 989 ft^3 (28 m^3) room with a 56 $in.^2$ (360 cm^2) leakage area.[44] Immediately after discharge, the pressure in the compartment drops below ambient to a minimum of –0.3 kPa; at approximately 1.5 seconds after discharge starts, the pressure begins to increase to a maximum of approximately 0.14 kPa after nozzle liquid runout. Similar results were obtained for FC-3-1-10. HFC-23 discharge exhibited much higher compartment overpressurization without the

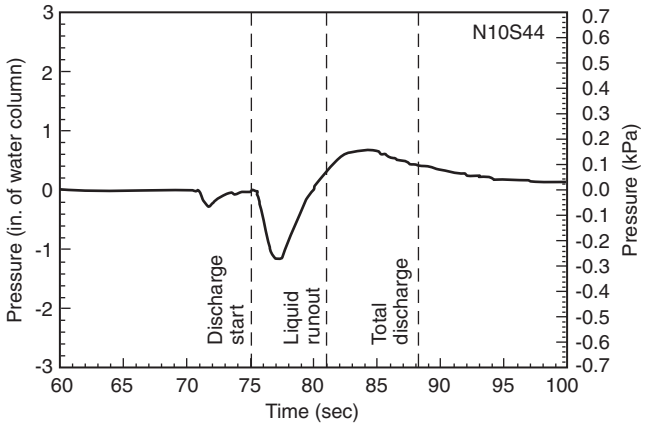

FIGURE 17.6.11 Pressure Measured in 989 ft^3 (28 m^3) Enclosure During HFC-227ea Discharge with Nominal 15 sec Discharge Time and 10 in. (254 mm) Pan of *n*-Heptane (Source: Forssell, E. W., and DiNenno, P. J., "Evaluation of Alternative Agents for Use in Total Flooding Fire Protection Systems," Contract NAS 10-1181, National Aeronautics and Space Administration, John F. Kennedy Space Center, FL, Oct. 1994)

marked initial negative pressure. The maximum overpressure for HFC-227ea and FC-3-1-10 discharge was similar to that of Halon 1301. Inert gas agents will, in general, result in positive pressure throughout the discharge.

As the halocarbon agent is discharged into the space, it vaporizes rapidly, cooling the compartment and lowering the pressure. As the agent/air mixture gains heat from the walls or other objects in the space, the pressure recovers and, as additional agent is added, the pressure increases over ambient as mass is added to the compartment.

The expected maximum and minimum compartment pressure during discharge will be a function of the following:

1. Thermodynamic state of the agent at the nozzle (determined by the agent and piping arrangement)
2. Nozzle design
3. Compartment volume and wall surface area
4. Size of fire
5. Initial conditions in space
6. Leakage area from compartment
7. Agent flow rate

For inert gases, significant compartment overpressurization can occur during discharge, unless adequate free vent area is provided. Calculation of required open area for venting is a part of the design manual for IG-541 systems.[60]

No generalized design procedure for calculating under/overpressurization has been established. Forssell and DiNenno[44] have developed a procedure for estimating the compartment pressure as a function of agent, agent flow rate, agent thermodynamic state at the nozzle, compartment volume, and surface area and leakage area. For inert gases utilizing relatively high agent concentrations, the required vent area calculation used for CO_2 systems is often used.

One area of concern with respect to vents is the possibility of preferential leakage of agent (as opposed to leakage of an agent/air mixture). This leakage can occur when an unenclosable opening or vent opening during discharge is located where a jet (from the nozzle) with a high agent concentration directly impinges on the opening. In this case, the possibility of higher than expected (in the flooding factor assumption) agent losses during discharge may occur. This outcome is particularly important for small rooms or areas with high wall area/room volume ratios and is probably more a problem for liquified halocarbon agents. Direct impingement by horizontal projection nozzles is most problematic where vents are located high on the walls.

Note that this preferential agent loss will not occur with the distributed leakage normally found in a room. A simple fix is to baffle any unenclosable opening or vent opening so that direct impingement by a nozzle jet on the opening is avoided. Ductwork attached to the relief vent discharge will also help prevent excessive agent loss.

Agent Hold Time and Leakage

Traditionally, total flooding gas systems were required to maintain a minimum concentration for a specified time period (10–20 minutes) after discharge. The minimum required hold time was a function of the following:

1. Soak time required for deep-seated Class A fuels
2. Response time of emergency personnel
3. Time required to prevent reflash due to presence of hot surfaces and other reignition sources, particularly in flammable and combustible liquid applications

Currently, there is no specified minimum hold or soak time for clean agents. The variables described earlier will vary among installations, and there is no significant database on the performance of these agents on "deep-seated" fires other than wood cribs. The designer will be required to specify the minimum soak time consistent with the requirements of the hazard being protected. A practical minimum of 10 minutes is generally recommended, with some applications requiring substantially longer hold times.

The ability of a compartment to maintain adequate agent concentration is a function of the leakage of the compartment. Historically, leakage testing was done with Halon 1301 through the use of discharge tests. Discharge testing for this purpose was rendered unnecessary by the introduction of door fan pressurization leakage tests. Annex B of NFPA 2001 describes a complete procedure for evaluating agent hold time as a function of compartment leakage measured by the door fan pressurization method.

The only difference between alternative agents and Halon 1301, in this regard, is the density of the agent/air mixture that is the driving force for leakage in quiescent environments. The mixture density can be estimated as follows:[1]

All agents, except inert gases, have higher mixture densities than Halon 1301 at 5 percent when used at their design concentrations. This will require slightly more leaktight enclosures to maintain the same hold time.

Note that IG-541 and IG-55 have densities very close to air. Such densities will result in excellent concentration retention or, conversely, relatively high allowable leakage areas, minimizing

problems associated with leak integrity testing and required hold time.

Based on actual room testing with halogenated agents, the allowable leakage area calculated from the enclosure integrity test procedure given in Annex B of NFPA 2001 will be conservative. The actual hold time can be expected to be quite longer than the calculated hold time. This conservatism arises from the necessary, conservative simplifying assumption that the total equivalent leakage area measured by the door fan is evenly distributed at the top and bottom of the enclosure being tested.

Recent work by Dewsbury and Whitely[61,62] and Klocke[63] indicates interface between the air and the agent/air mixture may result in shorter than expected agent retention times due to the development of a wide interface of a subextinguishing concentration mixture of the agent. This more conservative method as modified has been adapted by ISO.

SUMMARY

A wide range of inert gas and halocarbon total flooding clean agents has been introduced over the past several years. More will be commercialized in the near future. The use of an agent must be consistent with applicable environmental regulations. The selection of an agent is driven by its fire performance characteristics; agent and system space and weight concerns; toxicity, particularly for use in occupied areas; and the availability of approved system hardware.

The design of clean agent systems must be carefully done in accordance with third-party listing and approval limitations on both agent and hardware. Given the relative lack of experience with systems employing these new agents, particular care in design, installation, inspection, testing, and maintenance is warranted. Design and installation standards, such as NFPA 2001 and the associated hardware approval standards, form the minimum requirements for these new technologies.

As generalized design methods and more detailed requirements evolve, the ability to design and install systems on a performance basis will increase. A critical part of the installation process is postinstallation inspection and testing. NFPA 2001 contains requirements for the approval and postinstallation inspection and test of clean agent systems. Bearing in mind the relative complexity of these systems and the importance of the detection system and enclosure integrity, postinstallation inspection and testing should be rigorously performed.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on halon replacement discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*

Chapter 7

Application of Gaseous Agents to Special Hazards Fire Protection

Jeff L. Harrington

Chapter Contents

Fundamentals of Special Hazards
Characteristics of Special Hazards
Types of Gaseous Agents
Characteristics of Gaseous Agents
Performance-Based Analysis in Agent Selection

Key Terms

automatic sprinkler system, clean agent, design fire scenario, gaseous fire-extinguishing agent, halogenated agents, inert clean agent, performance-based design, special hazard

For purposes of this chapter, a *special hazard* is defined as a fuel array that for one or more reasons cannot be effectively protected by standard spray sprinklers.

Many alternatives to standard spray sprinklers have been developed to protect special hazards, each having certain characteristics uniquely suited to effectively protect the specific aspects of certain special hazards. Special hazard fire protection systems employ every known fire extinguishant, including water.

This chapter examines the key characteristics of special hazards that are particularly relevant to the use of gaseous fire-extinguishing agents (i.e., carbon dioxide, Halon 1301 and clean agents). *Gaseous fire-extinguishing agents* are chemicals or chemical compounds that are discharged on or about a fire hazard in their gaseous phase.

Until the late 1980s, there were two predominant gaseous agents to choose from to protect significant mission-critical hazards that required either a local application approach (carbon dioxide) or total flooding approach (Halon 1301 and carbon dioxide). However, since the advent of the Montreal Protocol and the U.S. Clean Air Act of 1990, production of new Halon 1301 has ceased. Chlorofluorocarbon (CFC) agents, including Halon 1301, have been identified as contributors to depletion of the ozone layer and targeted for phaseout. However, many new Halon 1301–like gaseous agents have been developed, and regulations have emerged aimed at safeguarding human health from exposure to gaseous fire extinguishants.

Halon 1301 is no longer manufactured in most industrialized nations and new fire-extinguishing systems that employ Halon 1301 are generally not allowed except for certain specific national defense applications. Halon 1301 is, however, still in use in existing systems and recycled Halon 1301 is readily available to refill them should they discharge for any reason.

NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems,* lists 13 gaseous extinguishing agents that have been developed with the hope of filling, at least in part, the market once held solely by Halon 1301. Nine of these agents are halocarbon chemical compounds or mixtures of them, and four are inert gases or mixtures of them.

For new systems, how does one choose the optimal gaseous agent for a particular fire hazard? Should it be carbon dioxide, one of the nine halocarbons, or one of the four inert agents? This chapter provides information aimed at helping to evaluate a given fire hazard and select one or more gaseous extinguishing agents that can provide an optimum fire protection solution for that hazard.

Also provided is information that will assist in effectively and safely maintaining existing Halon 1301 systems in service, so they will continue to provide effective fire protection that is safe for personnel in close proximity.

See also Section 2, Chapter 7, "Theory of Fire Extinguishment"; Section 3, Chapter 11, "Overview of Performance-Based Fire Protection Design"; Section 17, Chapter 1, "Carbon Dioxide and

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Application Systems"; and Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems."

FUNDAMENTALS OF SPECIAL HAZARDS

Fire and Fuel Classification

The performance objective of any special hazard fire-extinguishing system, of course, is to effectively extinguish the fire. It is critical, therefore, to select an extinguishing agent that is well suited to this task.

The nature of a potential fire is influenced by the type of fuel as classified in accordance with the definitions given in NFPA 10, *Standard for Portable Fire Extinguishers.* These definitions are summarized in Table 17.7.1 and are also discussed in Section 17, Chapter 5, "Fire Extinguisher Use and Maintenance."

Applicability of Sprinklers

In general practice, if standard spray sprinklers discharging plain water can adequately protect a fuel array using an occupancy hazard fire control approach, then that fuel array is not considered a special fire hazard. An occupancy hazard fire control approach, in general, utilizes standard spray sprinklers at the ceiling in a rectangular pattern, and is further detailed in NFPA 13, *Standard for the Installation of Sprinkler Systems.*

Class A fuel arrays are commonly protected by standard spray sprinklers discharging plain water, usually using the occupancy hazard fire control approach. An administrative office area is an example of this. This same approach is used to protect small Class B fuel arrays such as might be stored in a cleaning supply closet within the administrative office area. Certain Class C fuel arrays can also be protected using this approach. NFPA 13 requires sprinkler protection in electrical rooms, while allowing exemption from this requirement if certain conditions are satisfied.

If for any reason a fuel array is considered unsuitable for sprinkler protection using the occupancy hazard fire control approach and plain water, then it is often deemed to be a special hazard. In some instances, a water-based sprinkler system may be considered inappropriate for a particular fuel array because the water by itself may be ineffective or could cause unacceptable collateral damage. An example of the former is a flammable liquid pool array where plain water may not be an effective flame extinguishant. An example of the latter is a highly critical computer operations hub where water may result in significant collateral damage and extensive interruption of critical operations.

Standard spray sprinklers should never be used to protect Class D fuels because water is not an effective extinguishant and can cause violent reactions. Class K fuel arrays are normally protected by wet chemical extinguishants. Sprinklers can be used effectively, but a special design method is needed.

In summary, a special fire hazard might consist of a fuel array that meets the definition of any one, or a combination of, the standard classifications of Class A, B, C, D, or K. The hazard will need to be protected as a special fire hazard if it possesses one or more characteristics that make it unsuitable for protection by standard spray sprinklers using the occupancy hazard fire control approach and plain water.

Gaseous fire-extinguishing agents, among other options, are often considered and chosen as the primary fire extinguishant to protect certain special fire hazards where they can be effective, and where water is deemed inappropriate or used as a secondary protection method.

TABLE 17.7.1 Fire Classification and Fuel

Fire Classification	*Fuel*
Class A	Ordinary combustible materials, such as wood, cloth, paper, rubber, and many plastics
Class B	Flammable liquids, combustible liquids, petroleum greases, tars, oils, oil-based paints, solvents, lacquers, alcohols, and flammable gases
Class C	Energized electrical equipment
Class D	Combustible metals, such as magnesium, titanium, zirconium, sodium, lithium, and potassium
Class K	Combustible cooking media (vegetable or animal oils and fats)

Examples of Special Hazards Protected by Gaseous Agents

Examples of special hazards protected by gaseous agents include the following:

- Aircraft engine nacelles
- Cargo holds
- Computer data centers
- Dip tanks and coating machines
- Electrical equipment cabinets
- Electrical transformers and transformer vaults
- Engine rooms aboard ships
- Flammable liquid storage rooms
- Gas and oil processing facilities
- Hot oil industrial food fryers
- Industrial ovens
- Machine lube oil pits
- Offshore oil platforms
- Printing presses
- Process control room
- Steel rolling mills
- Telecommunications centers
- Turbine generator lube and seal oil systems
- Valuable electronic media storage vault
- Valuable paper records storage vault
- Wave soldering machines

Note that several of these examples are covered in more detail in relevant chapters of Section 8 ("Special Equipment") and Section 9 ("Processes and Facilities").

CHARACTERISTICS OF SPECIAL HAZARDS

The choice of the most appropriate fire-extinguishing agent for a special fire hazard depends on its specific characteristics. The most influential hazard characteristics commonly evaluated when making this choice include fuel properties, dimensional orientation, enclosure around the hazard, physical location, and occupancy.

Fuel Properties

Fuel properties that are particularly germane to special hazards fire protection include class and form of fuel and the presence of an oxidizer.

Classification of Fuel. Careful identification of the fuel related to the hazard being protected is a key first step in selecting an appropriate gaseous fire-extinguishing agent. One should collect as much information as possible, including the elemental materials involved, such as wood, paper, plastic, chemical, and so on. Then the fuel array should be classified using the system previously described (Class A, B, C, D, or K).

If the hazard involves electronic equipment, such as data processing or telecommunications equipment, determine whether power to the equipment will be interrupted prior to agent discharge, in which case the fuel classification might well be Class A (surface burning). Otherwise, the fuel classification would more accurately be Class C (energized electrical).

Class A—Surface Flame or Smoldering Combustion Tendency. Class A fuel arrays often burn with a predominant surface flame and negligible smoldering combustion. Materials made of plastic or rubber often produce this type of fire, which is often referred to as a Class A surface fire. A surface flame propagates in the gas phase in close proximity to the fuel surface, but not actually in contact with it.[1] Heat from the flame vaporizes the solid or liquid fuel just ahead of the flame front. The flame then ignites the vaporized fuel at the lower flammability range of the vapor mixture, and the flame advances, vaporizing more solid or liquid fuel in a continuing process. Surface-type flame spread can occur in solid, liquid, or gas fuels.

In Class A fuel arrays comprising cellulosic material in fibrous or particulate form, smoldering may be the predominant form of combustion, either in the absence of any surface flaming or after the surface flaming has subsided. Smoldering is a form of combustion without flame that occurs in fuel comprising finely divided fibers or particles that have a relatively large surface area to mass ratio.[2] Wood, pressed fiber insulation board, corrugated paper board, paper, and natural textile fabrics are examples of cellulosic materials or products that will produce significant smoldering combustion. The fuel aggregate must be permeable, allowing oxygen transport to the combustion reaction zone below the surface of the fuel. The fuel aggregate must also be dense enough to form an effective insulation layer that slows down heat losses from the reaction zone. Smoldering combustion can occur only in solid fuels.

Class C—Energized Electrical Equipment. Many special hazards protected by gaseous fire-extinguishing systems involve electrically energized equipment. Examples include telecommunication switches, satellite uplink transmitters, data processing equipment, and industrial process control rooms. When a fire in such hazards results in interruption of power to the equipment, the fuel is immediately converted from a Class C to a Class A–type hazard. The polymeric materials used in electric cable insulation and printed circuit boards are inherently Class A materials. When these materials burn, the flame is predominantly a surface burning phenomenon. Extinguishing a surface burning fire in Class A materials with gaseous agents is a relatively straightforward process.

These same materials are considered Class C fuel if the electrical power is not interrupted during the extinguishing process. One can easily conclude that fires in Class C fuels are more difficult to extinguish and prevent rekindling due to the presence of a persistent electrical energy input, which can add heat to the combustion zone. Various building and fire codes that may apply to a particular project could require electrical equipment to be de-energized prior to agent discharge, effectively converting the Class C fire into a Class A surface fire. Examples are found in NFPA 70, *National Electrical Code®*, and NFPA 75, *Standard for the Protection of Information Technology Equipment.*

Form of Fuel. For a given special fire hazard, the fuel array may be in solid, liquid, or gas form, or a combination of these forms. The fuel form plays a major role in determining the nature of the fire hazard. For example, solid cellulosic fuels can foster smoldering combustion that spreads very slowly with no visible flame. A flammable liquid pool, on the other hand, can produce a surface fire that spreads very rapidly with a high heat release rate. The fire characteristics, which are determined by the fuel characteristics, will influence the most appropriate choice of gaseous extinguishing agent.

Gaseous extinguishing agents are also suitable as inerting agents when a fuel exists in gaseous form. Such an atmosphere can be inerted by certain gaseous agents to prevent a fire or explosion.

Presence of Oxidizer. NFPA 430, *Code for the Storage of Liquid and Solid Oxidizers,* defines an oxidizer as any material that readily yields oxygen or other oxidizing gas, or that readily reacts to promote or initiate combustion of combustible materials and can undergo a vigorous self-sustained decomposition due to contamination or heat exposure. Generally, gaseous extinguishing agents are not suitable for use on hazards that contain oxidizers.

Dimensional Orientation

Gaseous extinguishing agents are particularly well suited to protect hazards that have three-dimensional fuel characteristics or where the fuel may be shielded. An example of this is a computer cabinet where the fuel is located inside a closed cabinet in the form of printed circuit boards and electric cable insulation. A gaseous extinguishing agent can flood the area surrounding the cabinet and permeate the cabinet interior through gaps and holes in concentrations sufficient to surround the fuel and extinguish a fire inside.

Enclosure Around the Hazard

Many fire hazards are surrounded partially or completely by an enclosure, such as a room. If the enclosure is complete, and any openings can be effectively closed, then the hazard may be protected by a total flooding gaseous extinguishing system. If the enclosure cannot be effectively sealed to accommodate total flooding, then partial flooding or local application systems using gaseous agents may be possible. Where no enclosure exists, and the hazard is not concealed or shielded, gaseous extinguishing agents might be applied as local applications or they simply may not be the most suitable choice.

Total Flooding Application. A total flooding configuration is one where the fire hazard being protected is surrounded completely by an enclosure, usually consisting of a floor, four walls and ceiling. A total flooding extinguishing system is designed to quickly fill the entire enclosure with a concentration of agent sufficient for fire extinguishment. The system should also be designed to maintain the concentration for a period of time to prevent rekindling and enable a manual emergency response.

Total Flooding Enclosure Integrity. When a total flooding gaseous extinguishing system discharges into an enclosure with no fire present, rapid pressure changes occur, that exert significant forces on the enclosure boundaries. With a fire present, the pressure forces produced will likely be even greater.[3] The enclosure construction elements must be capable of withstanding the peak pressures produced during agent discharge, or damage to the enclosure—and even catastrophic failure—could occur. This could in turn lead to failure of the fire protection system to extinguish the fire. Any failure of the enclosure's integrity could also endanger personnel in the immediate vicinity.

Evaluation of Peak Pressures During Agent Discharge. The discharge of halocarbon agents, both halocarbon clean agents and Halon 1301, causes an initial drop in pressure within the enclosure followed by a temporary rise in pressure. Shortly after the completion of agent discharge, the enclosure pressure reaches equilibrium, just slightly above the pressure value prior to discharge. The enclosure pressure changes during halocarbon agent discharge are shown schematically in Figure 17.7.1. (Note that the graphic does not, however, apply to HFC-23 [FE-13].)

The discharge of inert clean agents and carbon dioxide causes a positive pressure change within the enclosure. This pressure change can be quite large, exceeding the strength of most common enclosure elements. Thus, inert clean agent and carbon dioxide total flooding extinguishing systems will normally require the installation of enclosure pressure relief vents to protect the integrity of the enclosure during agent discharge. The enclosure pressure changes during inert agent discharge are shown graphically in Figure 17.7.2.

Evaluation of Enclosure Strength. During the development of heptafluoropropane (HFC 227ea), several studies evaluated various aspects of the enclosure pressure dynamics during agent discharge and the inherent strength of various construction elements to resist these pressure forces.[3] These studies found that the enclosure walls for the majority of total flooding applications using HFC 227ea are either gypsum wallboard on studs or masonry units such as concrete block and/or brick. Findings from these studies of particular interest follow:

- The peak pressures developed during agent discharge ranged from –8 psf (–383 Pa) to 8 psf (383 Pa).
- The peak pressures developed in an enclosure with gypsum wallboard on studs was less than that developed with walls of concrete block, because gypsum wallboard on studs flexes in response to pressure changes, which dampens peak pressure development. Concrete block walls do not flex, thus enabling peak pressure magnitudes to be greater.

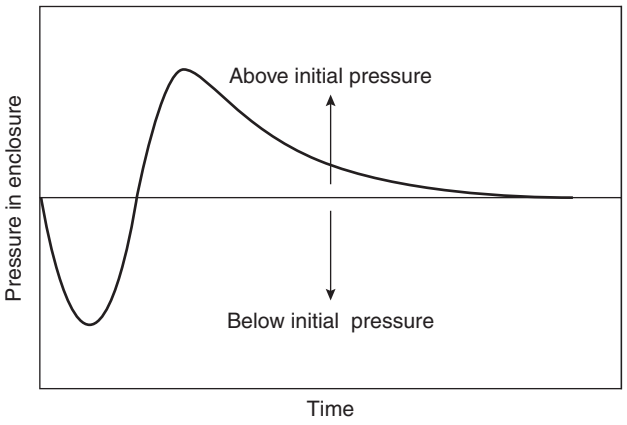

FIGURE 17.7.1 Variation in Room Pressure During Halocarbon Agent Discharge (Source: *Room Pressure Venting Guideline with FM-200®—Application Guide,* 93-1001, Fenwal Protection Systems, Ashland, MA, Dec. 2003)

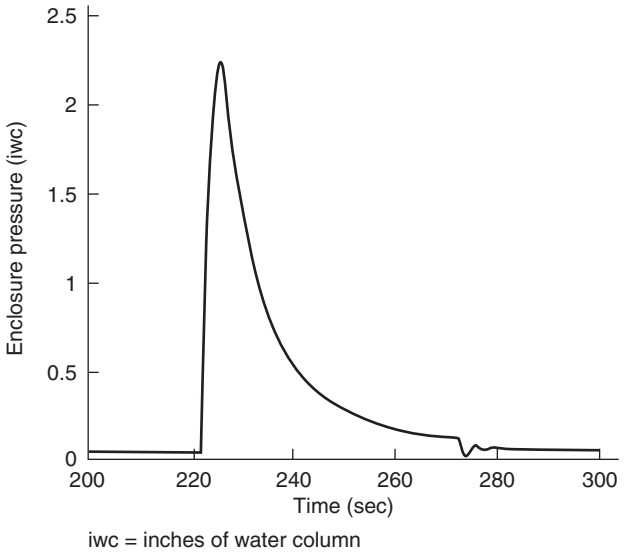

FIGURE 17.7.2 Variation in Room Pressure During Inert Agent Discharge (Source: Robin, M. L., Forssell, E. W., and Sharma, V., "Pressure Dynamics of Clean Agent Discharges," Halon Options Technical Working Conference, 2005)

- The metal studs most commonly used in gypsum wallboard construction can resist a peak pressure of over 25 psf (1197 Pa) before reaching their yield strength. This value can vary depending on such variables as wall height and stud spacing.
- The wood studs most commonly used in gypsum wallboard construction can resist a peak pressure of about 11 psf (527 Pa) before reaching their maximum tensile strength. This value can vary depending on such variables as wall height and stud spacing.
- Additional investigation is warranted on other construction materials and assemblies commonly used in protected enclosures, such as concrete, other masonry units, doors, and windows.
- For very tight enclosures, that is, those with predicted agent retention times significantly exceeding 10 minutes, and for enclosures significantly higher than 12 ft (3.7 m), the pressures developed during agent discharge could reach or exceed the maximum strength of the construction elements.

It is advisable to consult a qualified structural engineer for assistance with the determination of enclosure strength. Likewise, the gaseous extinguishing system manufacturer should be consulted to assist with the determination of peak discharge pressure values. Once the peak pressure load and enclosure strength values are determined, the need for enclosure relief venting or strengthening the enclosure should be evaluated.

Partial Flooding Application. A partial flooding configuration is one where the fire hazard being protected is surrounded only partially by an enclosure. An example of this is a flight simulator. Flight simulators are large boxes elevated above the floor on sophisticated hydraulically operated supports. The hydraulic oil system is usually located on the floor directly beneath the simulator box. Because a hydraulic oil fire could endanger the occupants of the box during simulation exercises, a partial height wall is constructed beneath the box, completely surrounding the hydraulic oil equipment and completely sealed to the floor, gastight. This partial enclosure is then equipped with an automatic gaseous extinguishing system that will flood the partial enclosure like filling a bathtub. The burning fuel will be submerged in an extinguishing concentration of gaseous agent and the fire will be extinguished.

Local Application. Where the fire hazard being protected is not surrounded by an enclosure, a local application extinguishing system is designed to discharge extinguishing agent in predominantly liquid form directly onto the burning fuel surfaces in sufficient quantity to extinguish the fire and very often cool the fuel. See "Carbon Dioxide" later in this chapter under the section "Local Application Capability" for more information. A printing station on a large commercial printing press is an example of a fire hazard that is commonly protected with a local application gaseous extinguishing system.

Physical Location

The physical location of a hazard to be protected has an influence on the most suitable fire-extinguishing system for the application. Gaseous clean agent systems have been employed in just about every location imaginable with great success. For example, gaseous agent systems protect engine and machinery spaces on cargo ships, gas compressor rooms at the North Slope in Alaska, telecommunication rooms at the top of air traffic control towers, and cargo compartments on commercial aircraft. Carbon dioxide systems have also been used in many of these same locations.

The physical location of the hazard should be carefully evaluated. Different variables associated with the hazard location may favor the use of one gaseous agent over another. For example, some locations may experience extreme low or high temperatures. Others may be relatively remote, providing a challenge to the process of refilling and restoring a system to full operation following a system discharge. These and other factors related to hazard location can favor one gaseous extinguishant over others.

Occupancy

One clear objective of the NFPA standards addressing gaseous extinguishing agents is to design and install systems in a manner that prevents human exposure to the extinguishing agent. This objective was emphasized with EPA involvement in the process to find safe new alternatives for fire protection halons such as Halon 1301 and Halon 1211 that were deemed harmful to the stratospheric ozone layer. All gaseous agents currently used, other than Halon 1301 and Halon 1211, are included in the Safe New Alternatives Policy Program (SNAP), EPA's program to evaluate and regulate substitutes for ozone-depleting chemicals being phased out under the stratospheric ozone protection provisions of the U.S. Clean Air Act.

EPA has stated, "The Administrator has determined a large number of alternatives that exist to reduce overall risk to human health and the environment. The purpose of the program is to allow a safe, smooth transition away from ozone-depleting compounds by identifying substitutes that offer lower overall risks to human health and the environment." It is clear that EPA intends not only to reduce environmental risk, but also human health risk.

NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems,* NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems,* and NFPA 2001 provide various requirements to reduce human health risks from potential exposure to the gaseous agents listed in these standards. Table 17.7.2 presents several definitions related to occupancy and human health exposure.

In general, requirements in the standards are designed to provide protection against human exposure to the gaseous agents in direct proportion to the likelihood of human occupancy in the protected room or space. The risk of human exposure to the agent is relatively high in a space that is "normally occupied" and relatively low in a space that is "unoccupiable."

TYPES OF GASEOUS AGENTS

Although there are many gaseous fire-extinguishing agents to choose from for a given application, the three main types of gaseous agents are clean agents, carbon dioxide, and Halon 1301. NFPA publishes design, installation and maintenance standards for each type in NFPA 2001, NFPA 12, and NFPA 12A respectively.

TABLE 17.7.2 Human Health Exposure Terms and Definitions Related to Occupancy

Term	*Definition*
Normally occupied area	An area that is intended for occupancy
Normally occupied	An enclosure where, under normal circumstances, persons are present
Normally unoccupied	An area or space not normally occupied by people that could be entered occasionally for brief periods
Unoccupiable	An enclosure that cannot be occupied due to dimensional or other physical constraints

Clean Agents

Clean agents are in the gaseous state in the vicinity of the fire hazard. As gases, they quickly surround the fuel and permeate the fire, even if physical barriers or complex fuel geometries exist. They are electrically nonconductive and leave no residue.

Clean agents were developed and commercialized in direct response to the phaseout of Halon 1301 initiated by the Montreal Protocol. The Montreal Protocol was adopted into U.S. law through the Clean Air Act of 1990. The aim of the Montreal Protocol was to reduce the emissions of chemicals that destroy stratospheric ozone. Compounds that contain bromine and, to a lesser extent, chlorine, were known to be especially detrimental to the ozone layer. Clean agents are addressed in NFPA 2001 as well as several other international standards.

Clean agents are categorized into two chemical groups, halocarbon and inert.

Halocarbon compounds are chemicals in which one or more carbon atoms are linked by covalent bonds with one or more halogen atoms: fluorine, chlorine, bromine, or iodine. Nine halocarbon agents are currently listed in NFPA 2001. None of these contain bromine, and only two contain chlorine. All contain fluorine and one contains iodine. See Table 17.7.3.

Inert clean agents consist of one of several naturally occurring inert chemicals, or mixtures of them. Four inert agents are currently listed in NFPA 2001 (see Table 17.7.4).

Carbon Dioxide

Carbon dioxide is a naturally occurring atmospheric gas. At normal room temperature and atmospheric pressure, carbon dioxide is a gas. Under certain conditions of temperature and pressure, carbon dioxide forms a liquid. For fire protection systems, it is stored as a liquid in steel containers, either by applying high pressure or by cooling the gas and applying a lower pressure.

Halon 1301

Halon 1301 is a halocarbon compound that contains bromine, and has, therefore, been deemed harmful to the stratospheric ozone layer. The Montreal Protocol targeted Halon 1301 for phaseout. Many countries have ceased production of Halon 1301 and prohibit its use in new fire-extinguishing systems. For example, the U.S. Clean Air Act of 1990 required that no new Halon 1301 be manufactured after January 1, 1994.

TABLE 17.7.3 Halocarbon Clean Agents Listed in NFPA 2001

Halocarbon Clean Agents	*Chemical Name*	*Chemical Formula*
FC-3-1-10	Perfluorobutane	C_4F_{10}
FK-5-1-12[a]	Dodecafluoro-2-methylpentan-3-one	$CF_2CF_2C(O)CF(CF_3)_2$
HCFC Blend A[b]	Dichlorotrifluoroethane HCFC-123 (4.75%)	$CHCl_2CF_3$
	Chlorodifluoromethane HCFC-22 (82%)	$CHClF_2$
	Chlorotetrafluoroethane HCFC-124 (9.5%)	$CHClFCF_3$
	Isopropenyl-1-methylcyclohexene (3.75%)	
HCFC-124	Chlorotetrafluoroethane	$CHClFCF_3$
HFC-125	Pentafluoroethane	CHF_2CF_3
HFC-227ea	Heptafluoropropane	CF_3CHFCF_3
HFC-23	Trifluoromethane	CHF_3
HFC-236fa	Hexafluoropropane	$CF_3CH_2CF_3$
FIC-13I1	Trifluoroiodide	CF_3I

Note: Other agents could become available at later dates.
[a]The full analogous ASHRAE nomenclature for FK-5-1-12 is FK-5-1-12mmy2.
[b]Composition of HCFC Blend A is given in percent by weight.

TABLE 17.7.4 Inert Clean Agents Listed in NFPA 2001

Inert Clean Agents	*Chemical Name*	*Chemical Formula*
IG-01	Argon	Ar
IG-100	Nitrogen	N_2
IG-541	Nitrogen (52%)	N_2
	Argon (40%)	Ar
	Carbon dioxide (8%)	CO_2
IG-55	Nitrogen (50%)	N_2
	Argon (50%)	Ar

Notes:
1. Other agents could become available at later dates.
2. Composition of inert gas agents are given in percent by volume.

CHARACTERISTICS OF GASEOUS AGENTS

Common Characteristics

All gaseous extinguishing agents share certain properties that are considered generally advantageous for special hazard fire-extinguishing applications. These include the following:

- They are applied to the hazard in gaseous form that is electrically nonconductive and leaves no residue.
- As a gas, these agents are able to extinguish fires even in the presence of physical barriers or obstructions.
- They are able to surround and penetrate three-dimensional fuel arrays.
- They are able to totally flood an enclosure about a hazard and be held at a design concentration to extinguish a fire.
- They are able to inert an enclosed volume for a period of time to prevent a fire or explosion from occurring.
- They do not cause direct collateral damage to equipment or materials in the protected area.

Specific Characteristics

It is important to carefully evaluate the specific characteristics of one or more gaseous extinguishing agents when looking for the optimal choice for a specific fire hazard. The characteristics most relevant to this task are the following:

- Fire extinguishing effectiveness
- Health and safety
- Environmental impact
- Cost
- Temperature range
- Collateral damage (direct or indirect)
- Availability for recharge
- Discharge pressure effects
- Local application capability

Table 17.7.5 summarizes these characteristics for each type of gaseous agent. The following sections discuss some of these characteristics in more detail.

Fire Extinguishing Effectiveness

For a given halocarbon clean agent, care must be taken to apply the minimum extinguishing concentration value for the actual Class A or B hazard to achieve the desired extinguishing effectiveness.

Class A Deep-Seated Fires. There are no standardized tests to determine the minimum extinguishing concentrations for Class A deep-seated fires. NFPA 2001 cautions that deep-seated Class A fires may require substantially higher design concentrations and longer holding times than for surface burning Class A fires. No quantified recommendations are provided by the standard. The designer should seek guidance from the system manufacturer where deep-seated Class A fires may be a concern.

Class C Fires. NFPA 2001 addresses Class C fire hazards only briefly by stating that the minimum design concentration for Class C fires should be no less than that for Class A surface-type fires. Additional guidance is provided in Annex A, which suggests that higher initial design concentrations and extended agent discharge be considered when electrical equipment cannot be de-energized. Testing of certain halocarbon clean agents on Class C fires has revealed the following:

- After initial flame extinguishment, the flame can rekindle due to the persistence of the heat energy source via the continuation of electrical energy to the fuel array.[4]
- Flame rekindling can be prevented by raising the design concentration above the minimum value required for Class A surface-burning type fires.[5,6]
- The minimum extinguishing concentration for a particular halocarbon agent is dependent on numerous variables, including the form of electrical heat energy (i.e., electric arc, ohmic, or conductive), the absence or presence of a pilot ignition source, the quantity of electric energy involved, and so forth.

Only a few of the many possible combinations of variables have been tested for some of the available halocarbon agents. Although these tests are not sufficient to be conclusive for all possible configurations of Class C hazards, two definitive recommendations are offered regarding Class C fires as follows:

- Make every possible effort to arrange for electric energy to be interrupted prior to or during agent discharge.
- If it is not possible to interrupt electric energy, consider increasing the quantity of agent for the hazard to compensate for the continuous energy being supplied to the hazard, seeking guidance from the system manufacturer.

Health and Safety

As seen in Table 17.7.5, the four types of agents vary in safety for use in normally occupied spaces. Clean agents are assigned several values used to help determine the relative health risk in the event of human exposure to a clean agent. One such value is termed "No Observed Adverse Effect Level" (NOAEL) and the other, "Lowest Observed Adverse Effect Level" (LOAEL). In the case of halocarbon clean agents, the LOAEL value is the

TABLE 17.7.5 Characteristics of Types of Gaseous Agents

	Halocarbon Clean Agents	*Inert Clean Agents*	*Carbon Dioxide*	*Halon 1301*
Fire Extinguishing Effectiveness				
For Class A and B fuels[a]	Excellent	Excellent	Excellent	Excellent
Additional agent needed for extinguishment for Class C fires	Sometimes[b]	Sometimes[b]	No	Sometimes[b]
For Class D and K fuels	May not be effective	May not be effective	May not be effective	May not be effective
Health and Safety[c]				
Primary health risk	Cardiac sensitization leading to heart arrhythmia and possibly death	Hypoxia	Death from asphyxiation	Cardiac sensitization leading to heart arrhythmia and possibly death
Considered safe for use in normally occupied spaces	Yes, when the design concentration is less than or equal to the agent's NOAEL value[d]	Yes, when the design concentration is less than or equal to the agent's NOAEL value	Only at low design concentrations	Yes, when the design concentration is 7% or less and human exposure can be limited to 15 minutes or less
Environmental Impact				
Approved for use by U.S. Environmental Protection Agency	Yes[e]	Yes[e]	Yes[e]	Generally, new systems are not allowed except in certain applications deemed essential to national defense[f]
Ozone depletion potential (ODP)	ODP = 0 for most systems and agents	ODP = 0 for all systems and agents	ODP = 0	Highest ODP of any man-made ozone-depleting substance
Global warming potential and atmospheric lifetime characteristics	Vary among agents; the impact of each agent should be evaluated individually	One agent contains a small percentage of CO_2 (see next column)	Regulated in some countries as a contributor to global warming	Has characteristics that can contribute to global warming
Cost				
Generalized system cost[g]	Agent = 25.0%; mechanical = 12.5%; electrical = 12.5%; labor = 50%	Agent = 5% mechanical = 22.5% electrical = 12.5% labor = 60%	System cost varies greatly and cannot be generalized	New systems are generally not allowed[h]
Cost of fire-resistant enclosure[i]	Can be substantial[i]	Can be substantial[j]	Can be substantial[k]	NA
Cost impact of proximity of hazard to agent refill supply	Consider a connected reserve supply of agent if the refill time from the closest supply sources is considered excessive or unacceptable	Consider a connected reserve supply of agent if the refill time from the closest supply sources is considered excessive or unacceptable	Consider a connected reserve supply of agent if the refill time from the closest supply sources is considered excessive or unacceptable	Consider a connected reserve supply of agent if the refill time from the closest supply sources is considered excessive or unacceptable
Cost impact of cylinder footprint size	Relatively small	Relatively large	Relatively large (for cylinders or tanks)	NA
Cost impact of distance between agent storage and protected hazard	Limited; increasing distance increases cost	Limited; increasing distance increases cost	Limited, but to a lesser degree than with clean agents	NA

TABLE 17.7.5 Continued

	Halocarbon Clean Agents	*Inert Clean Agents*	*Carbon Dioxide*	*Halon 1301*
Extra tall enclosure configuration may require additional levels of discharge nozzles.	Yes	Yes	Yes	NA
Temperature Range[l]				
Typical storage temperature range	32ºF (0ºC) to 130ºF (54.4ºC)	32ºF (0ºC) to 130ºF (54.4ºC)	0ºF (–17.8ºC) to 130ºF (54.4ºC) for total flooding systems[m] 32ºF (0ºC) to 120ºF (48.9ºC) for local application systems	32ºF (0ºC) to 130ºF (54.4ºC)
Temperature range for flow calculation programs	60ºF (15.6ºC) to 80ºF (26.7ºC)	60ºF (15.6ºC) to 80ºF (26.7ºC)	NA	60ºF (15.6ºC) and to 80ºF (26.7ºC)
Collateral Damage				
Contains fluorine or other substances which form potentially harmful acid gases upon breakdown.	Contain fluorine (F), which breaks down during the fire extinguishing process to form hydrogen fluoride (HF)	No	No	Contains bromine (Br) and fluorine (F), which break down during the fire extinguishing process to form hydrogen bromide (HBr) and hydrogen fluoride (HF)
Availability for Recharge[n]				
Worldwide availability of agent	Varies with agent	Varies with agent	Widely available throughout the world	Recycled Halon 1301 is readily available around the world and can be obtained at reasonable cost to recharge existing systems that have discharged
Discharge Pressure Effects in a Protected Enclosure[o]				
General guidance	Evaluate extremely tight or tall enclosures carefully	Evaluate all enclosures carefully	Evaluate all enclosures carefully	Evaluate extremely tight or tall enclosures carefully
Initial pressure effects	Momentary negative pressure spike followed by a momentary positive pressure spike	Momentary positive pressure spike	Momentary positive pressure spike	Momentary negative pressure spike followed by a momentary positive pressure spike (similar to halocarbon clean agents)
Enclosures generally strong enough to withstand pressure spikes without damage	Yes, in most cases	Usually not	No, in most cases	Yes, in most cases

(continued)

TABLE 17.7.5 Continued

	Halocarbon Clean Agents	*Inert Clean Agents*	*Carbon Dioxide*	*Halon 1301*
Considerations for extremely tight (low vent to volume ratio) or tall enclosures	Could be damaged, especially tall, brittle walls, such as those constructed of concrete block, brick, or clay tile. Evaluate carefully and provide pressure relief venting if necessary.	Must provide pressure relief venting	Must provide pressure relief venting	Could be damaged, especially tall, brittle walls, such as those constructed of concrete block, brick, or clay tile. Evaluate carefully and provide pressure relief venting if necessary.
Local Application Capability	Very limited	Very limited	Yes	Very limited

[a]Additional extinguishing agent needed for smoldering combustion (deep-seated fires) involving Class A fuels.
[b]Additional agent is needed in certain Class C fires (i.e., the required agent quantity generally increases as the electrical energy and related heat energy input to the fire increases).
[c]General guidance during system maintenance is to avoid human exposure.
[d]PBPK (physiologically based pharmacokinetic) modeling can be used to determine safe use in normally occupied spaces above the NOAEL value.
[e]Listed as acceptable alternative to Halon 1301 in EPA's SNAP program.
[f]Existing systems are allowed to remain in service in the United States; however, some countries have required that they be decommissioned.
[g]Cost of detection system increases as size of fire to be detected decreases.
[h]The costs associated with Halon 1301 systems are related to maintenance of existing systems.
[i]On rare occasions, may need to protect the enclosure from damage due to overpressure during agent discharge (total flooding systems).
[j]Usually need to protect the enclosure from damage due to overpressure during agent discharge (total flooding systems).
[k]Always need to protect the enclosure from damage due to overpressure during agent discharge (total flooding systems).
[l]For typical operating temperature range, see manufacturer's listing or approval documentation.
[m]When used outside of this temperature range, agent quantity must be adjusted.
[n]Each location needs to be evaluated for ability to recharge.
[o]Postdischarge pressure inside the enclosure reaches an equilibrium point just slightly higher than the original starting point.
NA = Not applicable.

lowest agent concentration by volume percent in air where adverse health effects were first noticed in animals being tested, which in these tests were beagle dogs. The adverse health effect observed is the onset of heart arrhythmia.

In the case of inert clean agents, the LOAEL value is the agent concentration by volume percent in air where adverse health effects are expected to occur in humans as determined by a panel of experts organized by the EPA. The panel reviewed pertinent literature regarding adverse health effects in humans exposed to hypoxic (low oxygen concentration) atmospheres and drew conclusions based on this existing body of knowledge. All inert agents are considered to be the same in relation to the determination of an appropriate LOAEL and NOAEL value.

Halocarbon Clean Agents. Table 17.7.6 provides the NOAEL and LOAEL values for the halocarbon clean agents.

Table 17.7.7 provides safe exposure limits in the unlikely event that halocarbon clean agent is discharged while one or more persons are still in the protected area.

The following example is presented to help illustrate the criteria in Tables 17.7.5 and 17.7.7 related to the use of PBPK data. Halocarbon clean agent X is proposed for use in a normally occupied space at a design concentration of 10 percent. The NOAEL value for this agent is 8 percent and the LOAEL value is 9.5 percent. Under the original human exposure rules, this proposed design could only be used for a space not normally occupied because the design concentration exceeds the LOAEL

TABLE 17.7.6 NOAEL and LOAEL Values for Halocarbon Clean Agents

Halocarbon Clean Agent	*NOAEL (Agent % by Volume)*	*LOAEL (Agent % by Volume)*
FC-3-1-10	40.0	>40.0
FK-5-1-12	10.0	>10.0
HCFC Blend A	10.0	>10.0
HFC Blend B	5.0	7.5
HCFC-124	1.0	2.5
HFC-125	7.5	10.0
HFC-227ea	9.0	>10.5
HFC-23	30.0	>30.0
HFC-236fa	10.0	15.0
FIC-13I1	0.2	0.4

TABLE 17.7.7 Safe Exposure Limits for Halocarbon Clean Agents

Agent Design %	*Occupancy*	*Exposure Time Limit*	*Comments*
≤ NOAEL	Normally occupied	Up to 5 minutes	No PBPK data needed
> NOAEL and LOAEL	Normally occupied	PBPK model limit corresponding to design concentration and 5 minute exposure	PBPK data needed
> NOAEL and LOAEL	Normally occupied	PBPK model limit corresponding to design concentration and *less than* 5 minute exposure	Conditions: 1. Authority having jurisdiction (AHJ) approval 2. Egress time calculations 3. Adhere to PBPK model exposure time limitation
> LOAEL	Not occupied	PBPK model limit corresponding to the design concentration	PBPK data needed
≤ LOAEL	Not occupied	Up to 60 seconds	No PBPK data available
> LOAEL	Not occupied	Up to 30 seconds	No PBPK data available

value. Furthermore, the design would have to ensure that occupants of the room would evacuate before agent discharge.

Application of the PBPK model allows additional flexibility. The PBPK model needs, as input, the arterial blood level measured in the beagle dog that experienced a heart arrhythmia at the LOAEL concentration of 9.5 percent. This value is loaded into the PBPK model, as is the desired design concentration of 10 percent. The PBPK model calculates the human exposure time that will allow the human arterial blood concentration of agent to reach the same level as the input value from the dog. The result is 6 minutes.

In this example, the PBPK model determines that a human being can be safely exposed to an agent concentration of 10 percent for up to 6 minutes. The second row of Table 17.7.6 applies to this case. This result indicates that the proposed design is safe for use in normally occupied spaces, and no special approvals are needed nor do any special conditions apply. The system design must limit human exposure to 5 minutes, even though the PBPK model predicts that 6 minutes is safe.

Altering this example slightly will illustrate other provisions in the safe exposure rules. Assume that the PBPK model determines that a human being can safely be exposed to an agent concentration of 10 percent for only 3 minutes. For this case, the third row of Table 17.7.7 applies. Special conditions must be satisfied to allow this proposed design to be used in a normally occupied space. Egress calculations must be performed to demonstrate that all occupants of the space can egress within 3 minutes corresponding to the PBPK model result. Widely accepted calculation methods are available and applicable for this purpose.[7–9] Furthermore, special approval from the authority having jurisdiction (AHJ) must be obtained.

Design concentrations greater than the NOAEL may be used in normally occupied spaces using PBPK modeling results corresponding to a minimum safe human exposure time of 5 minutes.

Halocarbon clean agents are considered conditionally safe for use in normally occupied spaces when design concentration exceeds the agent's NOAEL value using PBPK modeling results corresponding to a human exposure time of less than 5 minutes. This requires special approval by the AHJ. See Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems," for more information on PBPK modeling.

Inert Clean Agents. Table 17.7.8 provides the NOAEL and LOAEL values for the inert clean agents.

Table 17.7.9 provides safe exposure limits in the unlikely event that an inert clean agent is discharged while one or more persons are still in the protected area.

TABLE 17.7.8 NOAEL and LOAEL Values for Inert Clean Agents

Inert Clean Agent	*NOAEL (Agent % by Volume)*	*LOAEL (Agent % by Volume)*
IG-01	43.0	52.0
IG-100	43.0	52.0
IG-541	43.0	52.0
IG-55	43.0	52.0

TABLE 17.7.9 Safe Exposure Limits for Inert Clean Agents

Agent Design %	*Oxygen %*	*Occupancy*	*Exposure Time Limit*
≤ 43	≥ 12	Normally occupied	Up to 5 minutes
> 43 and ≤ 52	≥ 10 and < 12	Normally occupied	Up to 3 minutes
> 52 and ≤ 62	≥ 8 and < 10	Not occupied	Up to 30 seconds
> 62	< 8	Not occupied	No exposure allowed

Carbon Dioxide. At a concentration of about 9 percent, most humans will become unconscious. At 25 percent to 30 percent, respiration will suddenly stop and death will soon follow.

Collateral Damage

Halocarbon clean agents and Halon 1301 contain fluorine (F), which breaks down during flame extinguishment and forms hydrogen fluoride. Hydrogen fluoride (HF) is a weak acid that in small concentrations can cause mild irritation in exposed humans in the upper respiratory tract and eyes. HF in sufficiently high concentrations can be debilitating to humans and cause damage to exposed equipment.

Availability for Recharge

The many halocarbon clean agents and several inert clean agents differ in their availability for recharging a system after it has discharged. Some are widely available throughout the world. Some are not as widely available and may require a significant amount of time to accomplish a system recharge.

Discharge Pressure Effects in a Protected Enclosure

In the case of Halon 1301 systems with extremely tight or tall enclosures, enclosure damage due to pressure spikes during total flooding system discharge has been rare. This is due in large part to the fact that Halon 1301 enclosures have a relatively high vent to volume ratio. That is, they are much leakier than enclosures that are protected by halocarbon or inert clean agents.

Local Application Capability

Halocarbon Clean Agents. Historically, halocarbon clean agents have been used primarily in total flooding applications. NFPA 2001 applies only to total flooding systems. Local application systems are, therefore, excluded. One halocarbon agent has been developed for use in hazard-specific local application and partial-flooding applications. These systems are typically proven by individual test to the satisfaction of the purchaser or approval authority.

Inert Clean Agents. Inert clean agents discharge from the nozzles as a gas with no liquid component. It is very difficult to direct this gaseous discharge precisely for any distance from the nozzle. Inert clean agents, therefore, have not been developed for local application use.

Carbon Dioxide. Carbon dioxide is stored in liquefied form inside pressure containers. In high-pressure systems, carbon dioxide is stored at 70°F (21°C) at a pressure of 850 psi (5860 kPa). In low-pressure systems, the carbon dioxide is stored at a controlled low temperature of 0°F (–18°C). At this temperature the pressure in the container is 300 psi (2068 kPa). As carbon dioxide liquid flows from the storage containers to the discharge nozzles, it absorbs heat and begins to gasify. It does not fully gasify in the pipe network; therefore, a portion of the discharge from the nozzles is still in liquid form. This characteristic enables carbon dioxide to be configured in local applications systems and to protect hazards that are partially enclosed or completely unenclosed.

Halon 1301. Halon 1301 gasifies in very close proximity to the discharge nozzles; therefore, it is not well suited for use in local application systems. Local application systems using Halon 1301 have been very uncommon. Those that exist now, or existed in the past, most likely were protecting hazards with enclosures that had uncloseable openings making it impossible for the agent to be retained for at least 10 minutes, as was commonly required of total flooding applications. These systems are typically proven by individual test to the satisfaction of the purchaser or approval authority.

PERFORMANCE-BASED ANALYSIS IN AGENT SELECTION

Steps in Performance-Based Analysis and Design

The *SFPE Engineering Guide to Performance-Based Fire Protection: Analysis and Design*[10] offers an excellent performance-based engineering methodology that can easily be adapted to the process of selecting clean agents. The *Guide* defines performance-based design as follows:

> An engineering approach to fire protection design based on (1) agreed upon fire safety goals and objectives, (2) deterministic and/or probabilistic analysis of fire scenarios, and (3) quantitative assessment of design alternatives against the fire safety goals and objectives using accepted engineering tools, methodologies, and performance criteria.

Performance-based analysis and design offers a number of benefits over other design methods, including maximized value, reliability, and effectiveness. The process of performance-based analysis and design, as detailed in the guide, includes eight generic steps, preceded by a preliminary unnumbered step of identifying stakeholders. Table 17.7.10 lists those steps and presents the first two steps of an example related to gaseous agent selection for a generic corporate data center that incorporates sophisticated electronic data processing and telecommunications equipment. It also contains some limited administrative office space for occupants with responsibilities for the operations. The operations are contained within a single room on the first floor of a two-story building of noncombustible construction. The room is fully sprinklered using a double-interlock preaction configuration. The data center room is cut off from surrounding spaces by 1 hour fire rated, full-height walls, and contains an 18-in. (46-cm) raised access floor and a suspended acoustical ceiling at the 10 ft elevation. The room covers 20,000 feet^2 (1858 m^2) and is occupied by 18 persons during the day shift, 8 persons during the evening shift, and 3 persons during the night shift. All occupants are well-trained, full-time employees of the end user. All occupants are capable of self-preservation without assistance.

TABLE 17.7.10 Steps in Performance-Based Analysis and Initial Application to Gaseous Agent Selection

Step	*Activity*
1	Define the project scope. Select the optimum gaseous extinguishing agent for this corporate data center.
2	Identify the project goals and prioritize them. a. Minimize interruption of the company's business operations where such interruption would harm a customer's business, harm a customer's relationship with the company, harm the company's brands, or otherwise prevent accomplishment of the mission. b. Prevent loss of life or serious injury to building occupants and emergency responders. c. Minimize damage to the company's physical assets.
3	Define the project objectives.
4	Develop the performance criteria.
5	Develop design fire scenarios.
6	Develop trial designs.
7	Evaluate and modify the trial designs.
8	Select the final design.

Stakeholder Identification

The purpose of the preliminary step is to identify key stakeholders so that all primary system performance objectives can be identified and evaluated.

Step 1: Define the Project Scope

The project scope defines the boundaries of the performance-based analysis or design. If the scope of the project were more complex, it would be advisable to identify all of the stakeholders and solicit their input in defining project scope. Developing a consensus of the stakeholders relative to the project scope will improve the quality and overall acceptance of the results. The guide defines stakeholder as "one who has a share or interest in an enterprise. Specifically, an individual (or representative) interested in the successful completion of a project."

A list of stakeholders typical to a gaseous extinguishing system design project might include, but not necessarily be limited to, the following:

- Business owner (end user)
- Design team
- AHJs (building, fire, insurance)
- Construction team (construction manager, general contractor, subcontractors)
- Gaseous extinguishing agent and system manufacturers

Step 2: Identify and Prioritize the Project Goals

One or more of three general goals is commonly assigned to most fire protection analysis or design projects: (1) prevent loss of life or serious injury due to fire or its effects, (2) minimize loss of property due to fire or its effects, and (3) minimize interruption of business operations due to fire or its effects (also referred to as mission preservation).

All three of these general fire protection goals are applicable to most projects that consider the use of gaseous extinguishing agents. In the performance-based example that follows, the goal of minimizing business interruption is considered by the stakeholder group to be the biggest challenge (see Table 17.7.10). Therefore, this goal is listed first. Gaseous extinguishing agents, for example, are widely used to protect operations that utilize computerized electronic data processing, telecommunications, and broadcasting equipment. It is paramount to keep interruptions to such operations to an absolute minimum in the event of a fire. Preserving the mission is critical. Accomplishing this goal will usually also substantially achieve the second goal of preventing loss of life or serious injury. Protecting people is always important. For many gaseous extinguishing agent applications, such as those mentioned above, the expected fires are relatively low-energy fires that are not likely to threaten the occupants in the immediate surrounding areas before they are able to escape safely. However, gaseous extinguishing agents are also commonly employed to protect hazards involving flammable or combustible liquids, such as engine rooms on ships, where fast large fires are expected.

Step 3: Define the Project Objectives

This step involves identification of the stakeholder objectives to meet the project goals. The various stakeholders might define these objectives in different terms; however, they should be clear and agreed to by all stakeholders. In the example begun in Table 17.7.10, there are multiple goals. Table 17.7.11 presents hypothetical stakeholder and design objectives related to those multiple goals, as well as performance criteria.

Minimize Interruption of the Company's Business. For example, the company can establish an objective to limit interruption of telecommunication operations to no more than 4 hours. The insurance stakeholder may state an objective to limit interruption

TABLE 17.7.11 Hypothetical Objectives and Performance Criteria

Stakeholder Objective	*Design Objective*	*Performance Criteria*
Minimize interruption of the company's business operations where such interruption would harm a customer's business, harm a customer's relationship with the company, harm the company's brands, or otherwise prevent accomplishment of the mission.		
1. Limit interruption of all critical telecommunications operations to no more than 4 hours. 2. Limit interruption of all noncritical telecommunications operations to 48 hours. 3. Maintain power to all critical telecommunications equipment during a fire to minimize interruption of operations and customer services.	1. Limit damage to all critical equipment from a fire, fire effects, and suppression effects to one, or several, individual components that can be replaced or restored to full service in less than 4 hours. 2. Limit damage to all noncritical telecommunications equipment from a fire, fire effects, and suppression effects to equipment, or equipment components, that can be replaced or restored to full service in less than 48 hours. 3. Supply power to all critical telecommunications equipment independently from any manual or automatic emergency power off (EPO) systems. The gaseous extinguishing agent must be capable of extinguishing fires in energized electrical equipment.	1. Extinguish the fire at or below 2 kW (1.9 Btu/sec).* 2. Limit the production of halide acids to a concentration within the protected space of 200 ppm or less. 3. Extinguish a fire in energized electrical equipment and prevent re-ignition for the specified hold time or at least 10 minutes.
Prevent loss of life or serious injury to building occupants and emergency responders.		
1. No loss of life and no serious injuries to occupants of the protected enclosure from fire or products of combustion. 2. No loss of life and no serious injuries to occupants of the surrounding areas from fire or products of combustion. 3. No loss of life and no serious injuries to occupants of the protected enclosure from direct exposure to the gaseous extinguishing agent or its decomposition products. 4. No loss of life and no serious injuries to occupants of the surrounding areas from direct exposure to the gaseous extinguishing agent or its decomposition products. 5. Minimize short-term and long-term harm to the natural environment from the gaseous extinguishing agent or arising from the process of accomplishing final fire extinguishment.	1. The smoke layer and radiation heat flux from all feasible and reasonably conservative design fire scenarios must not cross thresholds harmful to the occupants of the protected space before they are able to exit the space. 2. The smoke layer, and radiation heat flux, from all feasible and reasonably conservative design fire scenarios must not cross thresholds harmful to the occupants of the areas surrounding the protected space before they are able to exit these areas to the building exterior. 3. The gaseous extinguishing agent selected must not be harmful to the occupants of the protected space in the required design concentration, and must not produce acidic decomposition products during the extinguishing process that could be harmful to an occupant inadvertently remaining in the protected space following gaseous extinguishing agent discharge. 4. The gaseous extinguishing agent selected must not be harmful in the required design concentration	1. The design concentration for the gaseous extinguishing agent for Class C fires (energized electrical equipment) must be at or below the level corresponding to a maximum 5-minute human exposure time as defined in NFPA 2001. 2. Extinguish the fire at or below 2 kW (1.9 Btu/sec). 3. Limit the production of halide acids to a concentration within the protected space of 200 ppm or less 4. The negative and positive pressure changes during the discharge of the gaseous extinguishing agent must be controllable to a magnitude of 5 psf (239 Pa) or less. 5. The gaseous extinguishing agent must have an ozone depletion factor (ODP) of 0, a relatively low atmospheric lifetime and global warming potential, and must not contain HFC compounds, or carbon dioxide.

TABLE 17.7.11 Continued

Stakeholder Objective	*Design Objective*	*Performance Criteria*
	to the occupants of the areas surrounding the protected space, and must not produce acidic decomposition products during the extinguishing process that could be harmful to occupants that remain in the building following gaseous extinguishing agent discharge. The integrity of the enclosure construction surrounding the protected area must remain during and following gaseous extinguishing agent discharge. 5. The selected gaseous extinguishing agent must be approved for use in normally occupied spaces by the U.S. EPA's SNAP program, and must not be targeted for reduction or phaseout in the Kyoto Protocol.	
Minimize damage to the company's physical assets.		
Minimize the loss of physical assets (real and personal property) to no more than $1,000,000.	Limit damage to all critical equipment from a fire, fire effects, and suppression effects to one, or several, individual components that can be replaced in less than 4 hours, or noncritical equipment components that can be replaced in less than 48 hours. Do not allow an entire piece of equipment, equipment cabinet, or equipment rack to be destroyed by a fire or fire effects.	1. Extinguish the fire at or below 2 kW (1.9 Btu/sec).* 2. Limit the production of halide acids to a concentration within the protected space of 200 ppm or less. 3. Extinguish a fire in energized electrical equipment and prevent reignition for the specified hold time or at least 10 minutes.

*For more information, see Meacham, B. J., "Factors Effecting the Early Detection of Fire in Electronic Equipment and Cable Installations," *Fire Technology,* first quarter 1993.

of telecommunication operations to no more than 24 hours. By selecting a final limit of 4 hours, both stakeholders are satisfied.

Once the consensus stakeholder objectives have been identified, the design engineer translates them into concise design objectives. Design objectives are stated in terms that can be subsequently quantified in fire protection engineering terms and used to develop specific performance criteria.

For the goal of minimizing business interruption, the third stakeholder objective of maintaining power usually does not find easy consensus among all stakeholders. Typically the end user and the insurance authority might be in agreement that electric power should not be interrupted to critical equipment. The building and fire code authorities might prefer automatically interrupting power to all equipment prior to application of the gaseous extinguishing agent. After negotiations, the building and fire code authorities may agree to allow power to remain uninterrupted. The design engineer may assist in reaching consensus on this objective by offering to select and design a gaseous extinguishing agent system such that it is capable of extinguishing fires in electrical equipment that remains continuously energized.

Prevent Loss of Life or Serious Injury. The fifth stakeholder objective for this goal is to minimize harm to the natural environment. Normally, only the end user stakeholder would identify an objective such as this. The other stakeholders might easily reach consensus to include this objective, since it likely will not conflict with their interests. Some end users have set such objectives to achieve harmony with their corporation's environmental policies. It is shown here to illustrate that environmental factors can be a strong determining factor in the selection process of a gaseous extinguishing agent and should always be considered in the performance-based analysis process.

Step 4: Define the Performance Criteria

Performance criteria for the gaseous extinguishing agent must be developed that will satisfy the design objectives (listed in

Step 3) and be used to evaluate the trial designs (candidate gaseous extinguishing agents). Table 17.7.11 presented sample performance criteria for the hypothetical example.

Step 5: Define the Design Fire Scenarios

The purpose of a gaseous extinguishing system is to extinguish a fire. It is therefore necessary for the design engineer to analyze the possible fire scenarios that are plausible for the protected space. These are then reduced to a reasonable number and called *design fire scenarios* that represent the boundaries of the conditions present. Only then is it possible for the design engineer to begin evaluating possible gaseous extinguishing agents for selection.

Possible fire scenarios should address the heat sources and fuel involved in fire ignition and growth. They should address the building construction, service equipment, and spatial relationships that might influence or be affected by the fire. They should address the human element, such as the number and distribution of occupants, their emergency response training and commitment, and their physical and psychological conditions related to self-preservation abilities.

Listed below are summaries of possible fire scenarios for the example of the corporate data center used to illustrate performance-based analysis and design, as summarized in Table 17.7.10.

Possible Fire Scenario 1. An electric drive motor in a high-speed data storage unit overheats due to an internal failure. Insulation on the internal windings ignites, leading to a fire that spreads to adjacent combustibles inside the equipment enclosure.

Possible Fire Scenario 2. A manufacturer's defect on a printed circuit board inside a telecommunications equipment module within an equipment rack leads to localized overheating and ignition of the board. The fire spreads to adjacent boards until it involves the entire module, and then spreads until it involves the entire rack.

Possible Fire Scenario 3. Two electrical extension cords are connected to a wall outlet and extended to a nearby work desk module where four workers share its power simultaneously. The two cords are draped over the top of an open box of paper forms. Their interconnection point is only partially engaged and is resting on top of the paper forms. The connection point overheats and ignites the box and the paper forms. Initially, this fire is a Class A surface fire but, if not extinguished early, has the potential to become a deep-seated Class A fire. The fire could then spread to involve the entire box of forms and begin heating adjacent racks of telecommunications components.

Possible Fire Scenario 4. An electrical fault in a power circuit within a data processing equipment enclosure results in sustained electrical arcing, which is not interrupted by the circuit fault protection device. The heat from the continuous arcing ignites cable insulation that spreads to other cables and combustible components within the equipment cabinet. If not extinguished early, this fire could spread to fully involve the original equipment cabinet and spread to adjacent equipment and other combustibles. Ultimately, the spreading fire would have enough energy to activate the sprinkler system in the room. This is a Class C fire. It would become a Class A surface fire on interruption of electrical power to the equipment involved.

The preceding fire scenarios are just a few representative examples of the relatively large number of those possible for such an operation. The full range of possible fire scenarios must be identified, then reduced to a smaller, more manageable number of design fire scenarios, which will be used to evaluate trial designs to select a final, optimized design. For this example, the four possible fire scenarios are narrowed down to a single design fire scenario, which will be used to evaluate the suitability of the trial designs. In this case the design fire scenario 5 is the same as possible fire scenario 4.

Step 6: Develop Trial Designs

Trial designs should be developed that have the potential to achieve the performance criteria. The design fire scenarios are used to test the effectiveness of each trial design, with the results being analyzed to help narrow the trial designs to one or two that are most effective. Applying this process to the task of selecting a gaseous extinguishing agent is relatively simple, since it involves only one of the several subsystems that are part of a complete gaseous extinguishing agent fire-extinguishing system. In the context of this example, a single agent is a trial design. Multiple trial designs (i.e., agents) should be considered. Each agent should be evaluated to ensure it meets the stated goals and objectives.

Step 7: Evaluate and Modify the Trial Designs

The trial designs should be evaluated to determine if they satisfy the performance criteria when challenged by the design fire scenarios. If a trial design is successful, the next trial design would be evaluated, and so on. If a trial design is not successful, it might be modified and retested or eliminated from consideration. In this manner, all trial designs are optimized (i.e., evaluated, modified, or eliminated) until one or more acceptable designs are developed.

Step 8: Select the Final Design

The acceptable designs should be further evaluated and one chosen as the final design. All performance criteria should be reviewed and compared to the capabilities of each acceptable design. Secondary criteria that are important to any stakeholder should also be evaluated in an effort to identify the design that is optimal for this particular project. Considerations include availability of agent, agent storage and space requirements, cost of system, complexity of system, and life cycle costs of the system.

SUMMARY

Until the late 1980s, there were predominantly two gaseous agents to choose from to protect significant mission-critical

hazards that required either a local application approach (carbon dioxide) or total flooding approach (Halon 1301 or carbon dioxide). Since the advent of the Montreal Protocol and the U.S. Clean Air Act of 1990, several new gaseous agents have been developed, and regulations have emerged aimed at safeguarding human health relative to exposure to gaseous fire extinguishants.

Fire hazards and gaseous fire extinguishants possess certain characteristics that make it possible to optimize the selection of one or more agents to protect a given fire hazard. A performance-based decision methodology was developed that can provide a consistent and repeatable framework for the selection of gaseous extinguishants and systems optimized for a particular hazard.

The performance-based analysis and design process illustrated in this chapter summarized the steps necessary to selecting a gaseous extinguishing agent that is best suited for the example project. The gaseous extinguishing agent must have the capability to enable all primary, and some secondary, performance criteria to be achieved, assuming that the remaining subsystems are properly designed and installed.

The examples used to illustrate the performance-based analysis and design process were greatly oversimplified. The reader is encouraged to review the *SFPE Engineering Guide to Performance-Based Fire Protection: Analysis and Design* in detail and study the many design variables that influence the performance of gaseous agent fire-extinguishing systems using each of the available gaseous extinguishing agents. Each of them have performance strengths and weaknesses that, when properly evaluated, would result in one or more agents being an acceptable candidate for each particular application.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the application of gaseous agents to special hazards, as discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 17, *Standard for Dry Chemical Extinguishing Systems*
NFPA 17A, *Standard for Wet Chemical Extinguishing Systems*
NFPA 72®, National Fire Alarm Code®
NFPA 75, *Standard for the Protection of Information Technology Equipment*
NFPA 430, *Code for the Storage of Liquid and Solid Oxidizers*
NFPA 2001, *Standard on Fire Clean Agent Extinguishing Systems*

Chapter 8

Explosion Prevention and Protection

Erdem A. Ural ■ Henry W. Garzia

Chapter Contents

Events Leading to an Explosion
Explosion Hazard Analysis
Deflagration Prevention
Enclosure Integrity and Strength
Explosion Protection

Key Terms

deflagration, dust explosion, explosibility, explosion, explosion control, flame arrester, flame front diverter, flammable limit, flammable mixture, fuel control, hazard analysis, ignition control, inert gas, limiting oxidant concentration (LOC), minimum ignition energy (MIE)

In literature, the word *explosion* is used to express a number of different chemical or physical processes. Some of these processes are outlined in Section 2, Chapter 8, "Explosions." This chapter focuses only on deflagrations where, by definition, the combustion reaction front propagates through a nearly premixed fuel-air mixture at a velocity less than the speed of sound in the unburnt mixture. The fuel may be in the form of a gas, vapor, dust, mist, or a combination. The definition provided in NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* and NFPA 69, *Standard on Explosion Prevention Systems,* further limit the meaning of the word *explosion* to "the bursting or rupture of an enclosure or a container due to the development of internal pressure from a deflagration."

For related topics, see Section 2, Chapter 8, "Explosions"; Section 6, Chapter 8, "Dusts"; Section 9, Chapter 7, "Storage and Handling of Grain Mill Products"; and Section 18, Chapter 6, "Deflagration (Explosion) Venting."

EVENTS LEADING TO AN EXPLOSION

Explosions often have catastrophic consequences. Fortunately, explosions occur only when a number of preceding events take place almost simultaneously. Table 17.8.1 lists a generic chain of events that can lead to an explosion. Examples of the hazard tests to characterize the material, equipment, or process, as well as the possible means of engineering intervention that can be used to break the chain are also listed in Table 17.8.1. It should be pointed out that the generic list provided in Table 17.8.1 might not cover all possible processes and that not all steps listed play a key role in each situation.

Unless dust is kept suspended in the air by design, most dust explosions start with a disturbance that raises dust into suspension. The disturbance could be as simple as the rupture of a compressed air line, a mechanical jolt to beams where dust layers have accumulated, or a small explosion somewhere else in the plant. Once subjected to the disturbance, the amount of dust removed from the deposit is a property of the dust and how the layer was formed.[1] These steps obviously do not play a role in gas or vapor explosions.

Once the fuel is released into an enclosure, it mixes with air and forms flammable volumes. The size of the flammable volume is controlled by the fuel supply rate and the ventilation/recirculation conditions inside the enclosure; it directly affects the severity of the explosion, if ignited. Therefore, control of the fuel supply rate and proper ventilation are frequently practiced methods of explosion prevention or protection.

A flammable fuel-air mixture can be ignited by a number of possible ignition sources. In critical applications, credible strength of ignition sources can be evaluated and compared to the

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TABLE 17.8.1 Generic Chain of Events That Can Lead to an Explosion

Steps of Explosion (Gas, Vapor, Dust, Mist)	*Material/Enclosure/Process Hazard Characterization*	*Possible Means of Engineering Intervention*
Disturbance	Maximum credible leak size	Avoid disturbances
	Maximum credible pressure	Redirect disturbances to a safe location
Entrainment of dust deposits	Particle size distribution	Eliminate/limit dust deposits (refer to p. 17-150, "Housekeeping")
	Critical shear stress	Spray dust deposits (with oil or water)
Fuel dispersion	Turbulence inside enclosure	Minimize fuel source
	Ventilation/recirculation	Improve ventilation
	Localization of flammable mixtures	
Mixture flammability	LFL and UFL for gases and vapors	Fuel control (refer to p. 17-149, "Fuel Control")
	MEC for dusts	Oxygen control
	Limiting oxygen concentration	
Credible ignition sources	Open flames	Eliminate ignition sources (refer to p. 17-150, "Ignition Source Control")
	Heated volumes or surfaces	
	Static electricity	
	Lightning	
	Stray currents	
	Mechanical sparks, friction, impact and vibration	
Material ignitability	Electrostatic ignition (MIE)	Material additives
	Hot surface ignition	Change particle size distribution
	Hot volume ignition temperature	
Material reactivity	Peak pressure	Material additives
	Peak rate of pressure rise	Change particle size distribution
	Burning velocity	
	Deflagration-to-detonation transition propensity	
Flame propagation	Turbulent flame speeds	Arrest flame propagation
	Flame accelerations induced by geometry	Explosion suppression (refer to p. 17-155, "Deflagration Suppression")
		Explosion isolation (refer to p. 17-157, "Deflagration Isolation")
Pressure development	Heat released by combustion	Pressure containment (refer to p. 17-154, "Pressure Containment")
		Explosion suppression (refer to p. 17-155, "Deflagration Suppression")
	Heat lost by radiation/convective cooling	Explosion venting
	Mass lost by venting	
Damage to	Mechanical damage due to overpressure	Improved mechanical design
People	Projectiles	Projectile control
Equipment	Thermal damage (people are vulnerable)	Thermal protection (passive or active)
Physical		
Plant	Chemical damage	
Environment	Environmental damage	

ignition requirement of the fuel-air mixtures. Such an exercise may reveal whether elimination of ignition sources is a viable prevention method for the particular application.

Once ignition takes place, the reaction front (flame) moves toward the unburnt fuel-air mixture with a well-defined velocity, called the burning velocity. If the enclosure is practically unvented, the maximum explosion pressure is related to the heat of combustion of the fuel-air mixture. Fully confined deflagrations commonly develop pressures in the range of seven to ten times the initial absolute pressure, or 100 to 140 psig (7 to 10 barg). If the enclosure has large openings, then the maximum explosion pressure is also related to the burning velocity and the maximum flame surface area. Pre-existing turbulence conditions inside the enclosure, turbulence induced by flame propagation, and the geometry of the enclosure can increase both the burning velocity and the maximum flame surface area.

Process enclosures are seldom designed for pressure containment. Pressures at which enclosure failure occurs can be quite low, particularly for enclosures of rectangular sheet metal construction. These can fail completely at internal pressures of a few pounds per in.^{2} (psi [1 psi = 6.895 kPa]). Typically, buildings can tolerate only a fraction of 1 psi pressure. Active and passive suppression and isolation methods can be used to limit the extent of flame propagation and magnitude of the pressure increase caused by an explosion.

If allowed to proceed uncontrollably, an explosion can cause harm to the physical plant, to people, and to the environment. In addition to the pressure damage considered in the NFPA 68/69 definition, an explosion can do the following:

- Hurt people (by skin burns,[2] eardrum rupture, lung collapse, body translation, toxic unburnt/burnt material)
- Create projectiles and fireballs that can lead to domino effects
- Pollute the environment
- Interrupt production
- Start fires

EXPLOSION HAZARD ANALYSIS

Conducting a thorough and competent process hazard analysis is perhaps the most important task of any explosion prevention or protection project. Such an analysis should consider the entire process chain, all the buildings, enclosures, and interconnections. The process analysis generally includes, but is not limited to, review of the general scope of work, process design criteria, process description, material flow diagrams, bases for fire and explosion protection methods and systems, basis for the physical and chemical properties of the process materials, equipment layouts, detailed mechanical drawings and specifications, supporting engineering calculations, and process and instrumentation diagrams. This analysis should consider startup, normal operation, normal shutdown, temporary operations, and emergency shutdowns. The analysis should also consider the hazards that can be created by the explosion prevention and protection systems. It is essential to update this analysis periodically, as well as each time changes are made to the process and to the protection systems. A detailed description of the explosion hazard analysis is beyond the scope of this chapter. Examples can be found in *Guidelines for Hazard Evaluation Procedures,* American Institute of Chemical Engineers, 1992.[3]

Figure 17.8.1 shows a simplified flowchart for dust explosion prevention and protection philosophy, adapted from material in R. K. Eckhoff's *Dust Explosions in the Process Industries.*[4] Within each appropriate box, the relevant ASTM E27 test method that can be used to characterize material hazard properties is listed. Standardized tests are often performed to characterize the hazard properties of materials. A comprehensive menu of such tests can be assembled from the standards of ASTM (American Society for Testing and Materials International), CEN (European Committee for Standardisation [Comité Européen de Normalisation]), CENELEC (European Committee for Electrotechnical Standardization [Comité Européen de Normalisation Electrotechnique]), DIN (German Institute for Standardization [Deutsches Institut für Normung]), VDI (Association of German Engineers [Verein Deutscher Ingenieure]), IEC (International Electrotechnical Commission), ISO (International Organization for Standardization), NFPA (National Fire Protection Association), and the UN (United Nations). Although a comprehensive review of the tests used to characterize material flammability, ignitability, and explosibility is beyond the scope of this chapter, a tabulation of the ASTM tests pertaining to explosion prevention and protection and simplified conceptual descriptions of key test methods are provided. A more detailed description can be found in "The Role of ASTM E27 Methods in Hazard Assessment."[5]

Fuel-Air Mixture Flammability

The classic notion of the "fire triangle" is that an ignition source must come together with both fuel and oxidant, the latter usually being atmospheric oxygen, in order to initiate and sustain a fire. This representation, although convenient, oversimplifies the more complex requirements needed to sustain a deflagration, particularly regarding fuel and oxygen concentration requirements. A flammability diagram can be used to illustrate, in composition space, the boundary that divides mixtures of fuel, oxygen, and inert components into flammable and nonflammable regions. Figure 17.8.2 is an example of one of the several types of such representations.

The three-component (ternary) diagram is plotted as a triangular graph, with each corner representing fuel, oxidant, or inert gas. Where appropriate, the oxidant may be taken as air, or other separately managed stream containing the oxidizing species, and the inert gas as only added inert components not associated with atmospheric air. Only two components are plotted in some diagrams, the concentration of the third being determined by the difference from 100 percent. The lower and upper flammable limits are two limiting points on such a diagram for compositions having no added inert component. (See Bodhurtha,[6] Lewis,[7] and Strehlow[8] for more detailed discussions on flammability.)

Dust-air mixtures also display a lower flammability limit (often called the minimum explosible concentration [MEC]), which is comparable in magnitude (on the order of 50 g/m^3) to that for gases and vapors. An extensive compilation of MEC data for generic dust samples can be found in Eckhoff.[4] Although

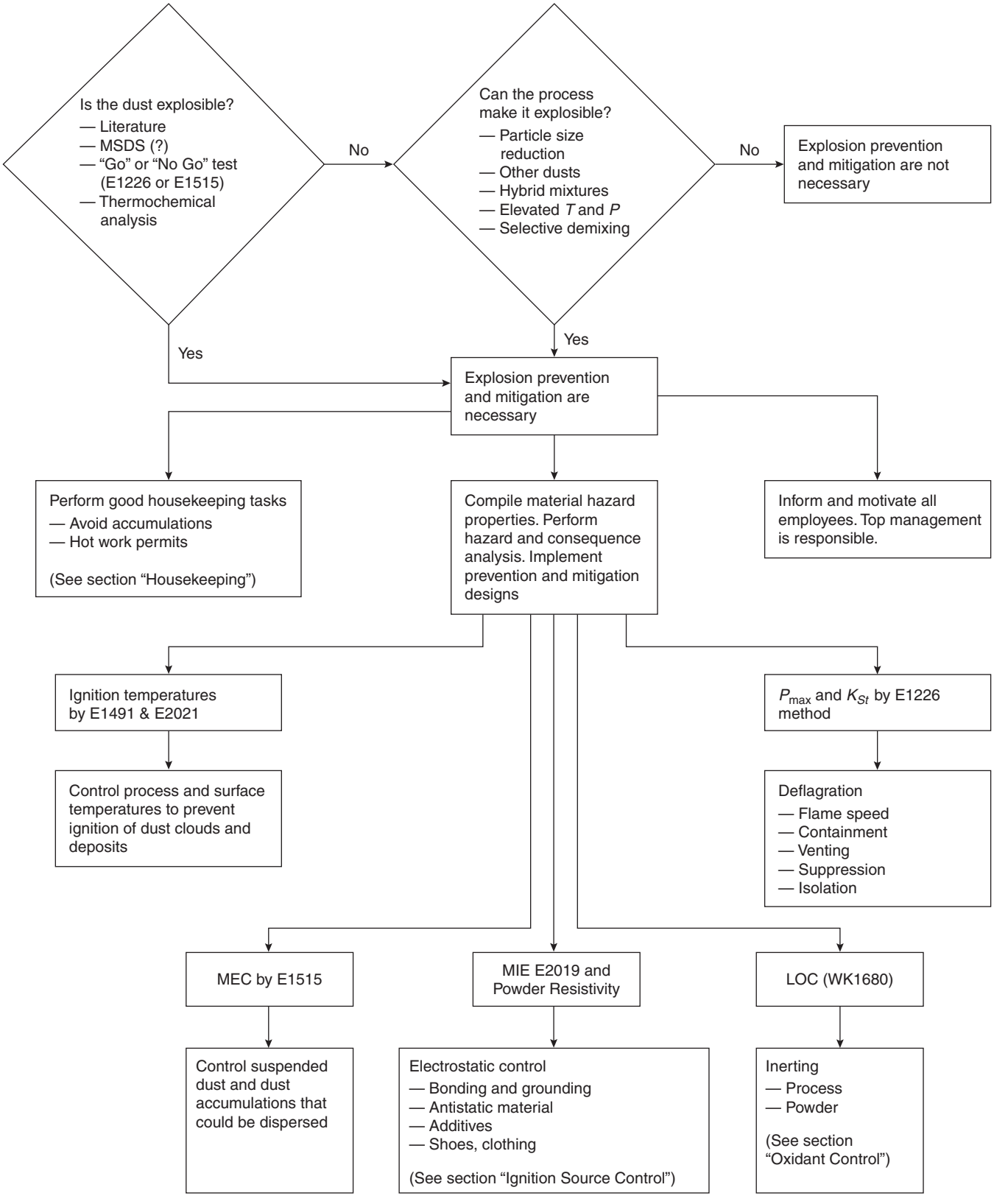


FIGURE 17.8.1 Dust Explosion Protection Philosophy. LOC = Limiting oxygen concentration. WK1680 = The ASTM draft standard for limiting oxidant concentration determination of dust samples. (Source: Adapted from Eckhoff, R. K., *Dust Explosions in the Process Industries,* Butterworth, Heinemann, Boston, 1991)

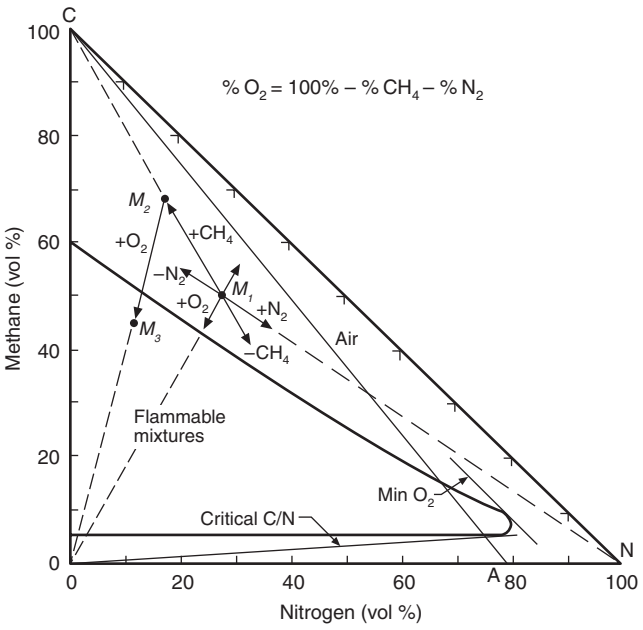


FIGURE 17.8.2 Flammability Diagram for Methane-Air-Oxygen System in Triangular Format (Source: Zabetakis, M. G., "Flammability Characteristics of Combustible Gases and Vapors," Bulletin 627, U.S. Bureau of Mines, Washington, DC, 1965)

sometimes academically debated, there is no practical upper flammability limit for dust-air mixtures because such high concentrations are difficult to produce and control.

An important part of deflagration prevention is maintaining atmospheres in process volumes that are nonflammable. This may be achieved by using any of several techniques, either singly or in combination. These include reduction of airborne concentrations of gaseous, dusty, or misted fuels. Alternatively, the concentration of the oxidant may be reduced. Finally, a nonflammable component, such as inert gas, may be added to the atmosphere. Thus, the composition of the atmosphere within a process volume that has the potential to be in the flammable range is controlled to prevent this condition.

Flammability properties of materials generally depend on temperature and pressure.[9] In the case of dusts, particle size distribution and moisture content can also play a significant role.

Fuel-Air Mixture Ignitability

Ignition of a flammable mixture occurs when a critical mass is heated to a temperature above the ignition temperature of the mixture. For example, all incandescent sparks (e.g., mechanical, electrical, electrostatic) have sufficiently high temperatures to cause ignition, but may lack sufficient energy to heat a minimal propagating mass to its ignition temperature.[10,11] A hot process surface may have a temperature below that required for prompt ignition, but may have large energy content. Dust deposits on such surfaces can be subject to accelerated self-heating and eventual ignition.

As illustrated in Table 17.8.2, there are a number of test methods to characterize the ignition propensity of gases, vapors, and dusts. It is important to note that the minimum ignition energy or minimum autoignition temperature depends not only on the material and the test sample, but also on the details of the test setup. Therefore, when using ignitability data for safety analysis, one should be careful to consider the relevance of the test setup and test conditions to the safety threats being considered.

Table 17.8.3 shows the minimum ignition energy (MIE) of selected gases and vapors in air at 1 atmosphere and 25°C. The MIE for gases and vapors is seen to vary from a fraction of a millijoule (mJ) to joules (J). In pure oxygen, MIE can be an order of magnitude or smaller than that in air.

Table 17.8.4 lists the MIE of dust clouds of selected materials. Since the dust cloud MIE is a strong function of the particle size distribution, particle size distribution as well as the median particle size of the samples are included in the table. A theoretical analysis included in Eckhoff[4] predicts MIE to be proportional to the cube of the median particle size. One of the authors' experience suggests that the relationship is more complex and probably involves additional parameters further characterizing the quantity of the fines. That is why the data in Table 17.8.4 do not seem to support a strong empirical correlation to the cube of the median particle size. In fact, the cubic relation becomes prominent when the data from samples with narrow particle size distributions are analyzed (Figure 17.8.3). A didactic composite diagram of ignition energies of various materials and types of ignition source that may ignite them has been reproduced in Figure 17.8.4.

Fuel-Air Mixture Explosibility

The most commonly used parameters are the maximum unvented explosion pressure, P_{max}, and volume scaled maximum rate of pressure rise, K. The latter parameter is defined as

$$K = V^{1/3}(dP/dt)_{max} \quad (1)$$

where V denotes the volume of the test vessel. K is often used with the subscript St (abbreviation of the German word *staub*)

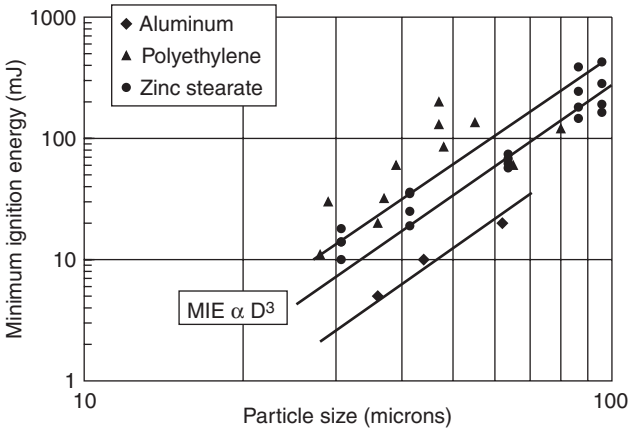


FIGURE 17.8.3 Round Robin MIE Data Showing the Effect of Particle Size

TABLE 17.8.2 ASTM Test Methods Characterizing Material Hazard Potential Pertaining to Explosion Prevention and Protection

ASTM Designation	*Title*
E476	Standard Test Method for Thermal Instability of Confined Condensed Phase Systems (Confinement Test)
E487	Standard Test Method for Constant-Temperature Stability of Chemical Materials
E502	Standard Test Method for Selection and Use of ASTM Standards for the Determination of Flashpoint of Chemicals by Closed Cup Methods
E537	Standard Test Method for Assessing the Thermal Stability of Chemicals by Methods of Thermal Analysis
E582	Standard Test Method for Minimum Ignition Energy and Quenching Distance in Gaseous Mixtures
E659	Standard Test Method for Autoignition Temperature of Liquid Chemicals
E680	Standard Test Method for Drop Weight Impact Sensitivity of Solid-Phase Hazardous Materials
E681	Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gases)
E771	Standard Test Method for Spontaneous Heating Tendency of Materials
E918	Standard Practice for Determining Limits of Flammability of Chemicals at Elevated Temperature and Pressure
E698	Standard Test Method for Arrhenius Kinetic Constants for Thermally Unstable Materials
E1226	Standard Test Method for Pressure and Rate of Pressure Rise for Combustible Dusts
E1231	Standard Practice for Calculation of Hazard Potential Figures-of-Merit for Thermally Unstable Materials
E1232	Standard Test Method for Temperature Limit of Flammability of Chemicals
E1491	Standard Test Method for Minimum Autoignition Temperature of Dust Clouds
E1515	Standard Test Method for Minimum Explosible Concentration of Combustible Dusts
E1981	Standard Guide for Assessing the Thermal Stability of Materials by Methods of Accelerating Rate Calorimetry
E2012	Standard Guide for Preparation of Binary Chemical Compatibility Chart
E2019	Standard Test Method for Minimum Ignition Energy of a Dust Cloud in Air
E2021	Standard Test Method for Hot-Surface Ignition Temperature of Dust Layers
E2046	Standard Test Method for Reaction Induction Time by Thermal Analysis
E2079	Standard Test Methods for Limiting Oxygen (Oxidant) Concentration in Gases and Vapors
D56 D92 D93 D1310 D3278 D3828 D3934 D3941 D4206	Miscellaneous open cup and close cup flashpoint tests
D323 D2879 E1194 E1719 E1782	Miscellaneous vapor pressure tests
WK1680	ASTM draft Standard for Limiting Oxygen Concentration Determination of Dust Samples

for dusts and G for gases and vapors. ASTM E1226[12] provides a standard test method for the determination of K_{St} and P_{max} values for dust-air mixtures. An extensive compilation of K_{St} and P_{max} data for generic dust samples can be found in Eckhoff.[4] The K_{St} value is theoretically (e.g., see Ural[13]) proportional to an equivalent turbulent burning velocity for dust-air mixtures.

Although the simple one-third power correction seen in the K definition (Eq. 1) adequately accounts for the effect of the test volume in dust explosions, the prediction of the volume dependence of the maximum rate of pressure rise is complicated by other flame acceleration mechanisms in gas explosions. Nevertheless, K_G values have long been used in explosion protection technology. Although a standard test method for K_G and burning

TABLE 17.8.3 Minimum Ignition Energy of Selected Gases and Vapors in Dry Air at 1 atm and 25°C

Fuel	*MIE (mJ)*
Hydrogen	0.016
Acetylene	0.017
Methanol	0.14
Methane	0.21
Ethane	0.24
Propane	0.24
n-Butane	0.25
n-Pentane	0.28
Acetaldehyde	0.37
Isopropyl alcohol	0.65
Acetone	1.15
Isooctane	1.35
Neopentane (2,2-dimethyl propane)	1.57
Ethylamine	2.40
Ammonia	680
Methylene chloride	>1000

Source: Adapted from Britton, L. G., *Avoiding Static Ignition Hazards in Chemical Operations, A CCPS Concept Book,* American Institute of Chemical Engineers, New York, 1999.

velocity is not yet available, Annex C of NFPA 68 (2007 edition) provides some data and guidance for testing.

DEFLAGRATION PREVENTION

Oxidant Control

The process of reducing the concentration of an oxidant beyond the flammable zone is also called inerting. Materials other than oxygen can act as oxidants. The selection of a gas for inerting a process atmosphere will be influenced by several factors such as inert gas effectiveness, availability, cost, process conditions, distribution requirements, and toxicity. The heat capacity of a gas is the most important inerting property. This is because a nonflammable condition is achieved when the heat capacity of a fuel-oxygen-inert gas mixture is elevated above about 250 J/mol-K of oxygen in the mixture. Thus, the higher the heat capacity of the inert gas, the lower the quantity required to achieve an inert mixture. Certain halogenated hydrocarbons used in total flooding fire protection systems have also been shown to be useful in inerting flammable atmospheres. Table 17.8.5 shows data on several inert gases.

Minimum inerting concentration for a specific fuel/oxidant/inert system can be determined by performing the limiting oxygen concentration (LOC) tests described by Frurip et al.[5] The LOC depends on the temperature, pressure, and fuel concentration as well as the type of diluent and should be determined at the worst case conditions.

LOC of dust samples can be determined using the ASTM standard draft WK1680. It is prudent to use a sufficiently strong chemical ignition source for dusts to avoid the ignitability effects on the LOC determination. Hence, some of the old LOC values, if they were obtained using spark ignition, may be considered suspect. Some references provide LOC data tabulations. These values should be used with care, since the LOC of dusts depends on the particle size distribution.

Where the fuel is gas or vapor, ASTM E2079 is the contemporary test method of choice. Unfortunately, most data listed in reference publications were obtained decades ago, using flammability tubes. Preliminary results of the ASTM E2079 round robin tests for gases and vapors revealed that the LOC data obtained using different test methods and listed in a majority of reference publications are nonconservative. The old Bureau of Mines data were obtained mostly in a 5 cm diameter flammability tube. This diameter may be too small to mitigate the flame quenching influence, thereby impeding accurate determination of the LOC of most fuels. The 4 L minimum volume specified in ASTM E2079 would correspond to a diameter of at least 20 cm. As a result, some LOC values determined using this standard are

TABLE 17.8.4 MIE Data for Selected Dust Samples in Air

	Particle Size Distribution						
	Weight % < Size (microns)						
Material	*500*	*125*	*71*	*32*	*20*	*Median (microns)*	*MIE (mJ)*
Sulfur			97	85	71	12	<1
Toner			100	96	48	21	<1
Dimethyl terepthalate				60		27	2
Ferrocene		71	33			95	5
Calcium stearate	100	43	25			145	12
Fructose (from filter)	99	39	17			150	<1
Fructose	92	15				200	180
Fructose	81					400	>4000
Silicon			99	98	97	<10	54
Wood dust	58	57	55	43	39	80	7
Wood dust			90	47	7	33	100

Source: Adapted from Eckhoff, R. K., *Dust Explosions in the Process Industries,* Butterworth, Heinemann, Boston, 1991.

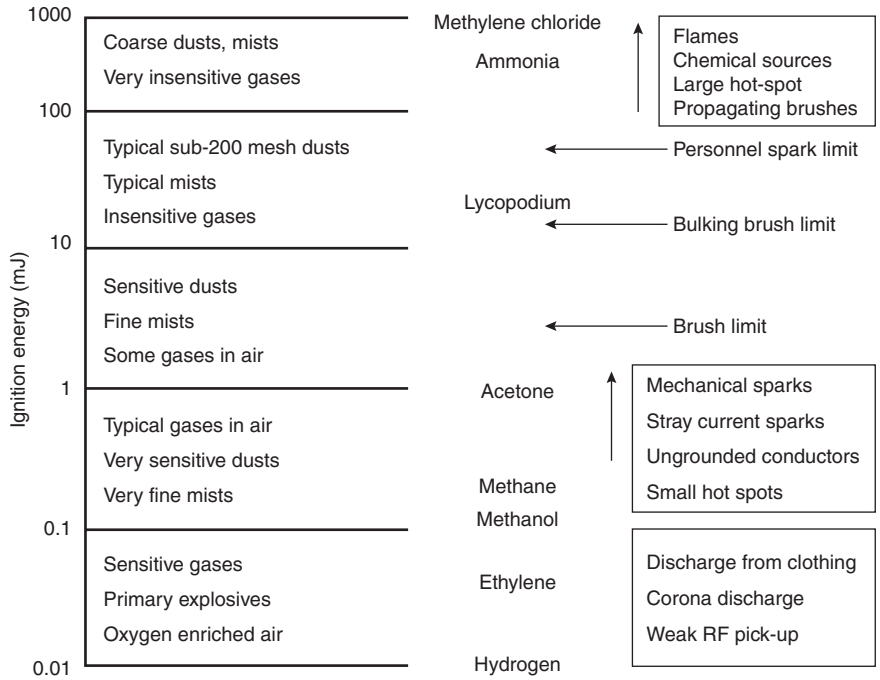


FIGURE 17.8.4 Ignition Energies of Various Materials and Types of Ignition (Source: Britton, L. G., *Avoiding Static Ignition Hazards in Chemical Operations, A CCPS Concept Book,* American Institute of Chemical Engineers, New York, 1999)

approximately 1 percent by volume oxygen lower than the previous values measured in the flammability tube, and a few are even up to 2 percent by volume lower. The lower LOC values obtained in larger chambers are more appropriate for use in fire and explosion hazard assessment studies. A data comparison can be found in Table 17.8.6.

If inerting is used as the primary means of explosion protection, several safety margins are applied to the LOC in order to arrive at the design inerting concentration. Such safety margins are selected to address factors such as mixture nonuniformities, temperature/pressure fluctuations, concentration measurement/alarm system accuracy, response time, and the consequences of false alarms. Where total inerting cannot be achieved due to technical or financial constraints, partial inerting may be considered in conjunction with other explosion prevention and protection methods. Even above the LOC, reduced oxygen concentration generally narrows the combustible range, reduces explosibility parameter *K,* and increases MIE.

TABLE 17.8.5 Heat Capacities of Inert Gases (Values at 25°C)

Gas	C_p *(J/mol-K)*
Argon	20.9
Nitrogen	28.4
Steam	35.4 at 100°C
Carbon dioxide	37.5
HFC 23 (CHF_3)	51.6
HFC 227ea (CF_3CHFCF_3)	137
FC 3-1-10 (C_4F_{10})	191

For U.S. units: 77°F = 25°C; 212°F = 100°C.

TABLE 17.8.6 Effect of Test Enclosure on LOC Values When Using Nitrogen as Diluent

	Flammability Tube, 5 cm Diameter	*120 L Sphere, 60 cm Diameter*
Hydrogen, H_2	5.0	4.6
Carbon monoxide, CO (at high humidity)	5.5	4.8
Methane, CH_4	12.0	11.0
Ethylene, C_2H_4	10.0	8.5
Propane, C_3H_8	11.5	10.6

Sources: Flammability tube data from J. M. Kuchta, "Investigation of Fire and Explosion Accidents in the Chemical, Mining, and Fuel-Related Industries," Bulletin 680, U.S. Bureau of Mines, 1985. 120 L chamber data from Isaac Zlochower, National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory, 2005, unpublished and not peer-reviewed. The data were obtained in accordance with ASTM test method E2079, at 1 atm and at 20 to 30°C on N2 air-fuel mixtures. Electric spark was created by the discharge of a 1300 μF capacitor, initially charged to 300 V, through 15 kV transformer. The standard criterion (i.e., minimum 1 psi or 7% absolute pressure rise) was used to detect ignition.

Nitrogen is commonly used as an inerting gas. It may be obtained from cryogenically stored liquefied gas. Catalytic combustion of ammonia in air followed by water condensation results in a relatively pure grade of nitrogen for process inerting. Carbon dioxide is somewhat more effective than nitrogen due to its higher heat capacity. It can be stored as a liquefied compressed gas in cylinders or kept in low-pressure refrigerated tanks for use on demand. Flue gas from a combustion system is a mixture of carbon dioxide and nitrogen, usually saturated with water vapor and having a low oxygen concentration. Flue gas is commonly used to inert storage tanks when offloading oil from ships. Carbon dioxide should not be used as an inerting gas for certain refractory metals. Examples are magnesium, silicon, and zirconium. In such cases, it may be necessary to use a noble gas, such as argon, for inerting. Examples of the LOC values for a variety of gases, metals, and carbonaceous dusts can be found in the 2008 edition of NFPA 69, *Standard on Explosion Prevention Systems.*

Since oxygen is essential to sustain life, inerting systems present an inherent risk to personnel safety. It is important to follow the OSHA regulations when entrance is required to the protected equipment. External leakage to other areas that are unventilated can present a hidden risk and must be kept in mind. Adverse health effects of selected gases used for inerting, as well as the corresponding inerting concentrations, can be found in NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems.*

Methods of Inert Gas Application. Inert gas can be applied in three ways: using batch methods, using the continuous methods described below, or using a combination of the two.

Batch Methods. In vacuum purging, the pressure in the process unit is reduced from its initial value, P_1, to a lower pressure, P_2. Inert gas is then added to return the vessel to P_1. If the gas within the process volume is assumed to be well-mixed, then the fraction of original gas remaining after one such purge cycle will be

$$X = \frac{P_2}{P_1} \tag{2}$$

In *pressure purging,* a volume is pressurized from P_1, to a higher pressure, P_2, by addition of purge gas and then vented back to the initial pressure, P_1. The fraction of original gas remaining after each such cycle will be

$$X = \frac{P_1}{P_1 + P_2} \tag{3}$$

The fraction of original gas remaining after n cycles by either batch purge method is

$$X(n) = X^n \tag{4}$$

Continuous Methods. Some enclosures, such as solvent storage tanks, are under continuous use or are not suited to batch purge methods due to structural considerations. Such tanks "breathe" on addition or removal of liquid contents or when their internal temperature changes due to climatic variations. In *fixed-rate* purging, inert gas is added continuously at the maximum anticipated demand rate. This method has the advantage of being simple to monitor and control but at the expense of purge gas consumption and, perhaps more important, results in carrying product vapors out of the enclosure.

Variable-rate purging may involve elements of both pressure demand and load demand gas addition. A small rate of continuous inert gas addition may be used together with pressure monitoring to determine when automatic addition of gas is required to make up for vapor space cooling. Addition of inert gas may also be increased on removal of liquid contents of a tank.

Purging enclosures of volatile liquids can be regulated under Title IV of the U.S. Clean Air Act Amendments of 1990. The capture and recovery, recycling, or incineration of process gas emissions has become common. Vapor recovery systems need consideration with respect to possible explosion risks that may be present. The U.S. Coast Guard has promulgated rules on operation of marine vapor recovery systems pertaining to explosion prevention and control.[14]

Fuel Control

Effective explosion prevention can be ensured if combustible materials are excluded from spaces to be protected. Four aspects of minimizing risks associated with combustibles are (1) containment, (2) ventilation, (3) purging, and (4) housekeeping.

(1) Containment. Special considerations are necessary for each class of combustible material. For example, cylinders and tanks of flammable compressed gases must be properly stored or located to ensure valves and other appurtenances are not subject to accidental damage. Containers and tanks of flammable and combustible liquids need periodic inspection to verify tightness of closures and the absence of damage or corrosion. Filter bags in dust collectors need periodic inspection to locate and replace damaged elements that can allow passage of combustible dusts. It is recommended that conformance be maintained with materials handling and storage requirements as outlined in NFPA codes (such as NFPA 30, *Flammable and Combustible Liquids Code,* NFPA 484*, Standard for Combustible Metals,* and NFPA 654*, Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*) and other codes and practices pertaining to specific flammable and combustible materials.

(2) Ventilation. Where the presence of flammable gases or combustible dusts may be possible as a result of normal operations or upset conditions their concentrations can be kept to a minimum or excluded altogether by general area or localized ventilation techniques. Continuous introduction of clean air to a room may be used to either continually sweep away contaminants or to maintain a room or process space under constant positive pressure to exclude entry of flammable materials. Appendix D of NFPA 69 contains guidance on the concentration control design of ventilation systems, and NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids,* provides guidance on the physical installation of such systems. An improperly designed

dusty operation ventilation system can create dust deposits in most unexpected locations and set the stage for devastating secondary explosions as in the West Pharmaceutical explosion on January 29, 2003.

(3) Purging. Purging is used to prevent development of ignitable atmospheres in enclosures or equipment. Specific methods are recommended for maintaining safe atmospheres inside electrical equipment enclosures. Type X, Type Y, and Type Z purging pertain to reducing the classifications within enclosures from Division 1 to nonhazardous, Division 1 to Division 2, and Division 2 to nonhazardous, respectively. The details of these purging methods can be found in NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment.*

(4) Housekeeping. This is the most obvious yet often the most difficult method of dust explosion prevention. Good practices adopted into NFPA 654 include minimizing dust emission from equipment, from operations, and from cleaning activities, and setting up regularly scheduled thorough cleaning procedures to reduce the probability of primary or secondary dust explosions fueled by dust accumulations. NFPA 654 also provides guidance on housekeeping requirements when they are employed in conjunction with the ignition control method described later in the next section and as shown in Table 17.8.7.

Ignition Source Control

Ignition control techniques can be used successfully to reduce the frequency of fires and explosions. However, ignition control must almost always be used in conjunction with another explosion prevention and protection method. This is because the means by which flammable atmospheres can become ignited are diverse and readily available in industrial settings. Although it is often true that the ignition source of a given event cannot be identified with certainty after the fact, due to the generalized destruction of the scene, a number of important mechanisms of deflagration initiation are recognized and should be carefully considered when conducting a hazard analysis.

Mechanical Sparks. A survey of 357 dust explosions between 1965 and 1980 revealed that, in 29 percent of the cases, the source of ignition was mechanically generated by sparks.[15] It has been shown[16] that sparks generated by grinding handheld steel can have sufficient energy to ignite organic dust clouds. This clearly points to the ignition energy potential when high-

TABLE 17.8.7 Guidance for Area Electrical Classification

Depth of Dust Accumulation (in.)	*Frequency*	*Housekeeping Requirement*	*Area Electrical Classification*
Negligible[a]	NA	NA	Unclassified (general purpose)
Negligible to < 1/32[b]	Infrequent[c]	Clean up during same shift.	Unclassified (general purpose)
Negligible to < 1/32[b]	Continuous/frequent[d]	Clean as necessary to maintain an average accumulation below 1/64 in.[e]	Unclassified; however, electrical enclosures should be dusttight[f,g]
1/32 to 1/8	Infrequent[c]	Clean up during same shift.	Unclassified; however, electrical enclosures should be dusttight[f,g]
1/32 to 1/8	Continuous/frequent[d]	Clean as necessary to maintain an average accumulation below 1/16 in.	Class II, Division 2
> 1/8	Infrequent[c]	Immediately shut down and clean.	Class II, Division 2
> 1/8	Continuous/frequent[d]	Clean at frequency appropriate to minimize accumulation.	Class II, Division 1

[a] Surface color just discernible under the dust layer.
[b] 1/32 in. is approximately the thickness of a typical paper clip.
[c] Episodic release of dust occurring not more than about two or three times per year.
[d] Episodic release of dust occurring more than about three times per year or continuous release resulting in stated accumulation occurring in approximately a 24 hour period.
[e] It has been observed that a thickness of about 1/64 in. of a low-density dust is sufficient to yield a small puffy cloud with each footstep.
[f] For example, National Electrical Manufacturers Association (NEMA) 12 or better. Note: Ordinary equipment that is not heat producing, such as junction boxes, can be significantly sealed against dust penetration by the use of silicone-type caulking. This can be considered in areas where fugitive dust is released at a slow rate and tends to accumulate over a long period of time.
[g] Guidance to be applied for existing facilities. For new facilities, it is recommended that the electrical classification be at least Class II, Division 2.
For SI units, 1 in. = 25.4 mm.
NA = Not available.
Source: NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids,* Table A.6.6.2, 2006, p. 654-24.

energy systems—for example, coal pulverizers or mills of the rolling, hammer, and pin type—cause grinding action on metal or other spark-inducing materials. Where tramp metal is a recognized hazard, the use of magnetic separators is recommended.

Fires. Unexpected open flaming due to ignition of accumulated dust can serve to ignite an ambient dust cloud. There are several mechanisms of causing such fires. Their risk of occurrence can be reduced by both understanding the ignition characteristics of the material being processed and by preventing the accumulation of materials susceptible to ignition by the given mechanism.

Hot Surfaces. Accumulated dust on a motor housing, transformer, high-pressure steam pipe, or other like hot surface can lead to slow pyrolysis of the solids, which can then ignite. The ignition probability is related to the surface temperature, dust layer thickness, and the thermal stability of the dust. A method of characterizing surface ignition temperature for dusts is available.[17] Approved equipment will be marked to indicate the operating temperature. The temperature of equipment operating in Class I or II (discussed later) environments must not exceed the ignition temperature of the gas or dust to which it is exposed. NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas,* provides ignition temperature data on vapors and gases, whereas NFPA 499, *Recommended Practice for the Classification of Combustible Dusts and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas* provides similar data for dusts.

Autoignition. Dusts layers exposed to continuous uniform elevated temperature, or even ambient temperatures, can also undergo self-heating and ignite.[9,10] The temperatures at which autoignition of bulk dusts occurs are much lower than for surface ignition, above, and are dependent on the volume of the heated dust. A small-scale method for characterizing the self-heating tendency of dusts was developed by the U.S. Bureau of Mines.[18] Another method is recommended by the United Nations (originally by the U.S. Department of Transportation) for determination of packaging classification of self-heating materials for purposes of road shipment.[19]

Mechanical Impact. Some materials may be subject to immediate ignition due to sudden mechanical impact. The ASTM E680 drop hammer test method can be used to characterize materials in this regard.[20]

Friction. Frictional heating of combustible materials is possible where moving components are found. Rotating drums and moving belts in bucket elevators are an example of a system that requires special consideration. Regular lubrication of bearings is essential. Use of belt-alignment devices is mandated in some cases.[21]

Embers. Wood-processing operations, such as grinding, sanding, and cutting, can produce glowing wood particles that can be conveyed to a dust collector. Such embers can lead to ignition of a wood–dust layer in which it becomes embedded. Spark detection and extinguishing systems, described in NFPA 69, may be appropriate in such operations.

Electrical Equipment. Electrical motors, switches, lights, heaters, and similar high-current devices may be powerful ignition sources. Such equipment can be constructed for use in hazardous atmospheres and is rated with respect to the type of atmosphere in which it is suited for use. A synopsis of one of the rating systems is given next:

Class I	*Groups*
Flammable gases	A (acetylene) B (hydrogen) C (ethylene) D (propane)
Class II	*Groups*
Combustible dusts	E (metal dusts) F (carbonaceous dusts, e.g., coal, charcoal, coke, etc.) G (flour, grain, wood, plastics, chemicals)
Class III	
Combustible fibers	
Division 1	Flammable gases or combustible dusts may be present at ignitable concentrations, under normal operating conditions.
Division 2	Where hazardous materials may be handled, processed, or used; ignitable atmospheres not normally present due to containment or ventilation of hazardous materials; areas adjacent to Division 1 locations.

The examples given in the preceding groups are representative only. Flammable gases are classified according to the maximum experimental safe gap (MESG), which prevents flame passage, and the minimum igniting current ratio, MIC. NFPA 70, *National Electrical Code®,* determines the group designations whereas NFPA 497 defines the MESG and MIC values for each group. MESG and MIC are determined by tests.[22] Thus, a motor rated as Class I, Division 1, Group D would be rated for use in an environment where a propane-like gas was likely to be present.

Unrated electrical equipment can be employed in hazardous areas, provided such equipment is contained in a pressurized or purged enclosure. The requirements for this approach are given in NFPA 496. Various purging methods are described that can render the classification within an enclosure from Division 1 to nonhazardous (Type X purging); from Division 1 to Division 2 (Type Y purging); and from Division 2 to nonhazardous (Type Z purging).

Electrostatic Ignition. Conveyance of liquids or dusts leads to electron transfer at the boundary of the moving material and a duct or pipe. The flow of electric charge in this manner is called a *streaming current,* I_s. The discharge of the moving material from the conduit to a receiving point (tank or drum for liquids; bin or pile for solids), of capacitance C, results in

charge separation and the development of an electric potential difference, V. The accumulated charge, Q, if not allowed to dissipate or *relax,* will have a stored energy of $E = QV/2 = CV^2/2$. Potentials exceeding 350 V and stored energies exceeding 0.1 mJ are considered hazardous in flammable gas areas. MIE of dust clouds vary widely, but can be less than 10 mJ. Most dusts of organic composition have MIEs in the range of 10 to 100 mJ. Charge potentials of several thousand volts and stored energies sufficient to ignite dust clouds are readily achieved in some solids transfer operations.

Ignition of flammable atmospheres by electrostatic discharges can be avoided by first recognizing process operations that can lead to charge separation. One can then provide conduction paths to maintain process components at low or zero electric potential. Resistance to ground should not exceed 100,000 Ω from any component. It is important to consider all components in a system. A section of pipe may be connected to a system by bolted flanges but electrically insulated by nonconductive gaskets. Such a component has the characteristics of a capacitor and can hold an electric charge. *Bonding* of electrically isolated process components is achieved by connecting a wire between them (see NFPA 70 for guidance). *Grounding* of the bonded components to an earth ground provides a conduction path that prevents charge accumulation. Britton,[11] Jones,[23] Glor,[24] Louvar,[25] and Pratt[26] should be consulted for a more complete discussion of electrostatic hazards. A consensus standard is not available for the control of electrostatic ignition sources. As a result, most companies develop their internal standards. Figure 17.8.5 and Table 17.8.8 show an approach used by Ciba Specialty Chemicals (see Hoppe et al.[10]) for this purpose.

Combined Mechanisms. In any given ignition scenario it is possible that multiple ignition mechanisms were involved. For example, an unlubricated bearing (*friction, hot surface*) in the tension roll in the boot (bottom) section of a bucket elevator conveying grain could generate a smoldering mass of grain dust (*ember*). The burning matter could become dislodged and fall into the general mass of moving grain and be conveyed in a bucket into an upper section of the elevator, during which time

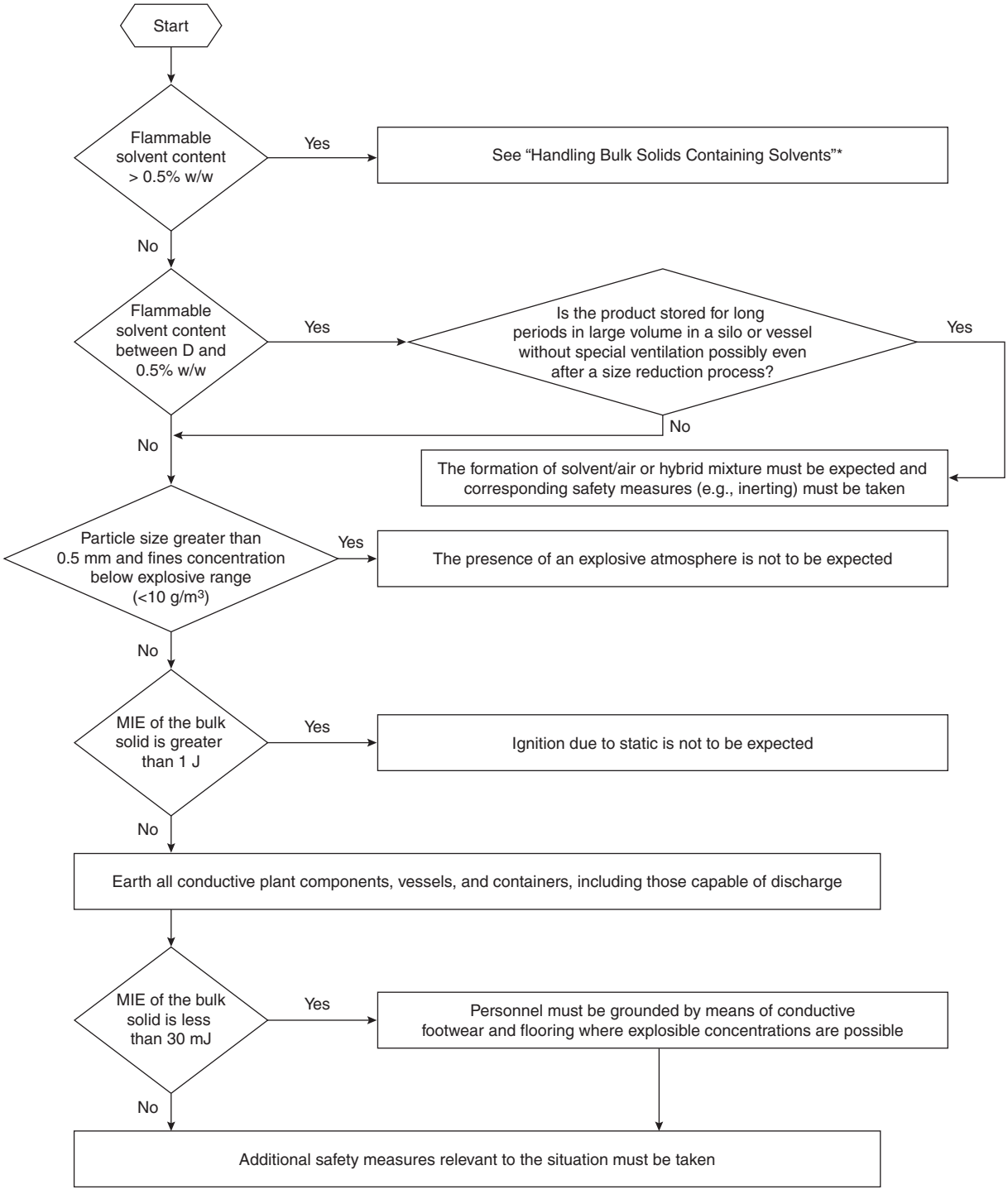
TABLE 17.8.8 Additional Safety Measures Required for Large Containers (Volume > 2 m^3) Where Combustible Powders Are Handled or Stored in the Absence of Flammable Gases or Vapors

Minimum Ignition Energy, MIE (mJ)	*Volume Resistivity (ρ_V) of Powder (MΩ-m)*	*Safety Measures*
MIE < 10 mJ	Any value	All parts of the installation must be conductive and grounded All containers must be conductive or dischargeable and grounded Apply additional explosion protection measures (e.g. inerting, venting, suppression) OR Seek expert advice
10 mJ < MIE < 1000 mJ	10,000 MΩ-m < ρ_V	Use only conductive or dischargeable containers which are grounded, AND Apply additional explosion protection measures (e.g. inerting, venting, suppression) OR Seek expert advice
	1 MΩ-m < ρ_V < 10,000 MΩ-m	Use only conductive or dischargeable containers which are grounded, OR Restrict the filling rate to 5 kg/sec OR Apply additional explosion protection measures (e.g. inerting, venting, suppression) OR Seek expert advice
	ρ_V < 1 MΩ-m	All parts of the installation must be conductive and grounded All containers must be conductive or dischargeable and grounded
1,000 mJ < MIE	Any value	Electrostatic ignition unlikely

Notes: Containers capable of discharge: The leakage resistance from any point to ground must be less than 100 MΩ.
Conductive containers: maximum leakage resistance less than 1 MΩ.

Source: CIBA methodology adapted from Hoppe, T., Jaeger, N., and Terry, J., "Safe Handling of Combustible Powders During Transportation, Charging, Discharging, and Storage," 8th International Colloquium on Dust Explosions, Schaumburg, IL, September 21–25, 1998.

its extent of burning increases. At some moment the ember becomes a flaming mass (*open flame*), and encounters a dust cloud with a concentration greater than its lower explosible limit, thus initiating a deflagration. The pressure developed by the primary deflagration could rupture the elevator leg enclosure. The escaping pressurized blast of gases could cause grain dust on nearby surfaces to become airborne and ignited (*flame jet ignition*). An ensuing secondary deflagration would likely involve



*See section in Hoppe et al.[10]

FIGURE 17.8.5 Decision Tree Used to Evaluate Electrostatic Ignition. (Source: Hoppe, T., Jaeger, N., and Terry, J, "Safe Handling of Combustible Powders During Transportation, Charging, Discharging, and Storage," 8th International Colloquium on Dust Explosions, Schaumburg, IL, September 21–25, 1998, pp. 253–263)

a much larger mass of fuel and air and lead to generalized pressure damage to the facility. Due to failure of a grease fitting, the plant could be substantially damaged. This example does not represent any particular event. Rather, it is a synthesis of many similar actual events that have occurred.

ENCLOSURE INTEGRITY AND STRENGTH

The explosion prevention methods discussed in the previous section and those that will be discussed in the next section rely on the premise that the enclosures will remain intact throughout the prevention and protection missions. This is achieved by determining the loads and by determining the strength of each enclosure and interconnecting piping.

Loads on the Enclosure

Explosion prevention techniques generally impose little or no additional loads on the enclosure, beyond the loads (such as weight, seismic loads, process fluctuations) considered in the conventional design. On the other hand, there are cases where such loads can be considerable. For example, batch methods of inerting create repeated overpressure or vacuum loads by design. A malfunction in an inerting system can conceivably exceed the design loads by a great margin.

The deflagration loads that a protected enclosure experiences are generally significant. For example, a 10 barg (150 psig) overpressure for an explosion containment application, and 0.3 barg (5 psig) overpressure for an explosion venting or explosion suppression application are not uncommon. These loads must be characterized as a part of the explosion protection system design.

Enclosure Strength

Explosion protection standards allow two separate approaches towards the enclosure strength determination. Calculations or design can be based on either of the following:

- Preventing rupture of the vessel enclosure (the ultimate strength of the vessel enclosure), but allowing permanent deformation (also called explosionproof/shock-resistant)
- Preventing permanent deformation (the yield strength of the vessel enclosure, which is also called explosion-pressure/shock-resistant) from internal positive overpressure

NFPA 69 allows loads up to two-thirds of yield or ultimate strength for containment design. If venting is chosen as the protection method, NFPA 68 also allows the same fraction, based on a dynamic loading factor. When enclosures are designed and constructed according to the ASME Boiler and Pressure Vessel Code or similar codes, NFPA 68 and 69 both allow deflagration loading to the same two-thirds fraction of yield or ultimate strength. Since pressure vessel codes include a larger inherent safety factor, this means that the anticipated deflagation loading (i.e., pressure) can be greater than the stamped maximum allowable working pressure (MAWP). The ASME Boiler and Pressure Vessel Code recognizes the NFPA methodology as acceptable for deflagration applications.

EXPLOSION PROTECTION

As used in this chapter, *explosion protection* means the measures adopted to control and mitigate the effects of ignition of the contents of a process volume that may be capable of propagating a deflagration. Thus, although appropriate explosion prevention measures may have been implemented, it is assumed at this point that these steps have only reduced the probability of initiating a deflagration and not eliminated such a possibility altogether. Whether the probability of the occurrence of a deflagration is now so small as to constitute a risk of acceptable magnitude is a matter for evaluation using the methods of risk and consequence analysis, which is beyond the scope of this chapter.

There are essentially only four strategies available as explosion protection options: (1) pressure containment, (2) deflagration venting, (3) deflagration suppression, and (4) deflagration isolation.

Pressure Containment

Equipment can be designed to contain the full brunt of the explosion load for pressure containment. This approach may be required if no emission of vessel contents is tolerable (for concerns relating to toxicity, environmental pollution, or public perception). In some cases, design for pressure containment (DPC) may be the most economical approach.

The use of pressure relief vents on vessels in some processes may be impractical. Where the safety strategy is to allow a possible deflagration to occur, but be contained, the process vessel must be constructed to be able to contain the pressurized gases with no equipment damage or with limited acceptable damage. No credit is taken for pressure relief devices on the vessel. The design pressure to which the vessel must be fabricated is determined by the maximum anticipated deflagration pressure, P_{Cont}, that may develop in the enclosure. This is the maximum deflagration pressure of the combustible material that is used. If the enclosure is operating at atmospheric temperature and pressure, P_{Cont} is equal to the P_{max} determined for standard initial temperature and pressure from either closed vessel test series (e.g., ASTM E1226) or from equilibrium calculations. When the operating temperatures and pressures are different from standard conditions, the pressure load to be contained, P_{Cont}, can be estimated using the following simple equation:

$$P_{Cont} = [(P_{max} + 1) \times (P_i + P_{std}) - P_{std}] \times \frac{298}{273 + T_i} \quad (5a)$$

where

P_i = Initial pressure (gauge in units consistent with other pressure values)

T_i = Initial temperature (°C)

P_{std} = 1 atm = 14.7 psia, standard pressure

T_{std} = 25°C = 298 K, standard temperature

Vessels designed and constructed for pressure containment must conform to the ASME *Boiler and Pressure Vessel Code,* Section VIII, Division I. The design pressure for deflagrations may be calculated, using Equation 5a, to result in a vessel of sufficient strength to either not deform at the maximum defla-

gration pressure or to deform but not rupture. Accordingly, the maximum allowable working pressure, P_{MAWP}, of the enclosure is selected using the following equations:

$$P_{MAWP} \geq \frac{3}{2}\left(\frac{P_{Cont}}{F_u}\right) \quad (5b)$$

or

$$P_{MAWP} \geq \frac{3}{2}\left(\frac{P_{Cont}}{F_y}\right)$$

where

F_u = Ratio of ultimate stress of the enclosure to the allowable stress of the materials of construction of the enclosure per the ASME Boiler and Pressure Vessel Code

F_y = Ratio of the yield stress of the enclosure to the allowable stress of the materials of construction of the enclosure per the ASME Boiler and Pressure Vessel Code

For vessels constructed of carbon steel or low-alloy stainless steel, F_u and F_y are approximately 3.5 and 1.75, respectively. See NFPA 69 for further details.

Design for pressure containment requires further consideration of the eventual release of the pressurized gases. If the vessel is truly leaktight, then pressure reduction will occur as the products of combustion cool, and vacuum may develop. Alternatively, pressurized gases will flow through process openings or pressure relief devices. The essential point here is that hot combustion gases should be prevented from passing to other process units where adverse consequences may occur due to initiation of a fire or another deflagration. Techniques for using deflagration isolation systems to prevent deflagration propagation to interconnecting piping and equipment are discussed later in this chapter.

Deflagration Venting

Deflagration venting is widely used to direct expanding gases and overpressure out of a vessel to a safe location. This protection option may be appropriate when material toxicity and environmental contamination are not a concern and when a safe vent discharge location is available. When appropriate, venting is often the low-cost protection option.

A simplified theory of explosion venting is provided by Ural.[13] The explosion pressure rise is created by the burnt gases heated by the combustion energy. Where vent openings are provided, developing explosion overpressure pushes both unburnt and burnt mixtures outside the enclosure, thereby reducing the maximum pressure.

The simplest postignition method of explosion protection is deflagration venting. Pressure development within a process enclosure in which a deflagration occurs is prevented from attaining damaging levels by allowing the enclosure contents to be ejected, in a controlled way, to a safe location. It is the control and safety aspects of a vented deflagration that differentiate it from an explosion.

A detailed discussion of the design and use of deflagration vents is given in Section 18, Chapter 6, "Deflagration (Explosion) Venting," and in NFPA 68. Venting reduces the maximum deflagration pressure in the protected enclosure to reduced pressure, P_{red}. Documents such as NFPA 68, VDI 3673, and European Standard EN 14491, provide correlations to calculate P_{red} for a given vent opening area and vice versa. These documents and the equations are publicly available and hence subject to thorough peer review and contribution. This approach also allows calculation and verification of proper vent size by any of the stakeholders, including vendors, owner/operators, and authorities having jurisdiction (AHJ).

Deflagration Suppression

Deflagration suppression may be the preferred approach when the consequences of employing other prevention and protection options are unacceptable. Process equipment may be too large to economically construct for DPC, venting may not be possible due to the location or contents of the vessel, or mechanical isolation of the process system may have unacceptable secondary consequences in a complex plant.

Deflagration suppression is the only one of the four explosion protection methods that terminates the combustion process before most of the fuel-air mixture is consumed. Because of this, explosive fuel-air mixture may still exist in the protected enclosure after the suppression system operates as intended, if the suppressant can settle out or condense after discharge. The utility of this approach is that it provides protection in special applications where other methods cannot meet the requirements imposed by the hazard. For example, venting may be inappropriate where toxic or noxious materials are concerned or where equipment vents cannot be discharged to a safe location. Isolation methods, on the other hand, are designed to protect adjacent process units, not the unit where ignition has occurred. Containment is applicable only where the vessel has sufficient pressure resistance.

Deflagration Suppression Defined. Deflagration suppression systems are active systems similar to fire protection systems. These systems typically comprise deflagration detectors (pressure or optical), a control/alarm panel, and suppressors containing the suppressant to be applied. Because a deflagration grows much more rapidly than a fire, the overall system response time is one of the key design parameters. Detection time, suppressor response time, suppressor discharge time, and suppressant travel time in the enclosure all contribute to the overall system response time. The principle of operation is that, once detection of ignition has occurred, the extinguishing agent is delivered to and distributed within the protected volume more rapidly than the rise in demand for the agent (to achieve extinguishment) by the growing flame ball. Deflagration suppression systems reduce the pressure in the protected enclosure to P_{red}, which comprises the sum of the two contributors: pressure rise due to partial burning of the contents prior to total extinguishment and pressure rise created by the agent injection. Using proprietary calculation procedures, a suppression system designer tries to control the suppressant delivery time, nominal concentration, and dispersion uniformity in the protected enclosure by specifying the number of suppressors, their volumes, and discharge cross-sections to achieve desired P_{red}. Increasing the number of suppressors effectively increases the suppressant discharge area, hence decreasing the delivery time and the reduced

pressure. Increasing the number of suppressors also improves the suppressant uniformity in the protected enclosure. If the total rise in pressure that occurs in a vessel during suppression, P_{red} (reduced pressure), is less than the pressure strength of the equipment, then the suppression is considered successful.

Explosibility. Combustion of a flammable mixture in a closed vessel results in a rapid rise in pressure (Figure 17.8.6). Key characteristics of closed-vessel combustion are the maximum pressure attained, P_{max}, and the maximum rate of pressure rise, that is, the $(dP/dt)_{max}$ developed during the event.

The principal quantitative measure of the explosibility of a combustible material is characterized with parameter K_G for gases and K_{St} for dusts as shown previously in Equation 1.

A typical set of data points obtained in evaluating the explosibility of a dust is illustrated in Figure 17.8.7. The term *index of explosibility* is sometimes applied to K_{St}. Explosibility is dependent on chemical composition and, for dusts, physical parameters such as moisture content, particle size, and shape. The K_{St} value of a dust has been found to be nearly invariant with $V^{1/3}$ for vessels 20 L or larger in size. For this reason, it is important that K_{St} values be determined according to an approved standard that employs a vessel of at least 20 L volume.[12]

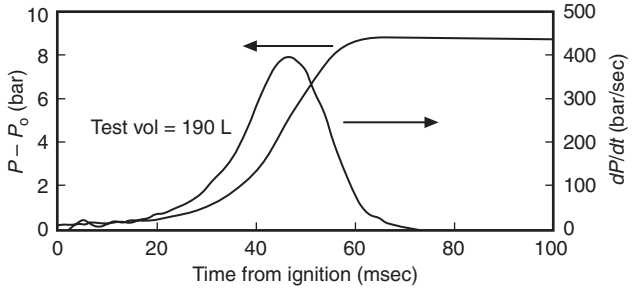


FIGURE 17.8.6 Pressure and dP/dt versus Time at 750 g/m^3 for Closed-Vessel Deflagration of a Proprietary Corn Starch Product. (Courtesy of Kidde-Fenwal, Inc.)

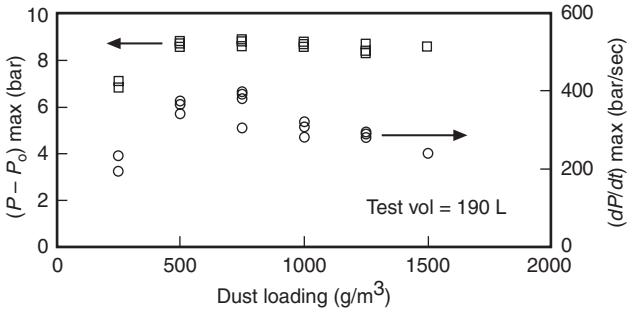


FIGURE 17.8.7 Typical P_{max} and $(dP/dt)_{max}$ Data Obtained in Determination of Explosibility of a Combustible Dust (Corn Starch) (Courtesy of Kidde-Fenwal, Inc.)

It can be shown that the K_{St} value may be used to estimate the effective burning velocity in a flammable dust–air mixture.[13] Thus, the explosibility of a mixture can be related to a burning rate, which can then be compared to the agent delivery characteristics of a suppression system.

Active Deflagration Suppression Systems. Deflagration suppression is a special case of fire extinguishment and may be viewed as a competition between a rapidly rising heat release rate from the combustion zone and the rate of agent delivery. A deflagration will be suppressed when the unburned fuel-air mixture has been rendered noncombustible due to the addition of agent and the flame front has been cooled to the point of extinguishment.

At the onset of ignition there is some minimum uniform concentration of agent that can render the protected space noncombustible; that is the inerting concentration. As deflagration proceeds, larger and larger quantities of agent are required, because the unburned material must be inerted and the burning volume must be quenched. Therefore, the amount of agent that must be dispersed within the protected space to achieve suppression increases with time as the deflagration propagates. Should delivery of agent be delayed too long, the deflagration will pass beyond the point of suppressibility. The result may be the attainment of unprotected deflagration pressures, or even higher pressures. For each application, deflagration suppression system manufacturers resort to propretary design methodologies or test data to ensure adequate system performance. Pressure-time traces of suppressed and unsuppressed deflagrations of a fast-burning dust are shown in Figure 17.8.8. The test was conducted in a 67 ft^3 (1.9 m^3) vessel. A sodium-bicarbonate-based agent was used. This particular case would be considered successful suppression only if the protected equipment could tolerate 8 psig (0.55 bar) over pressure.

Elements of a Suppression System. A deflagration suppression system consists of components for detection, extinguishment, and control/supervision. To ensure suppression success, deflagrations must be detected at a very early (incipient) stage

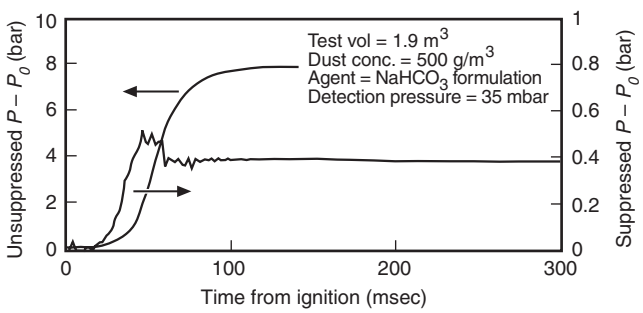


FIGURE 17.8.8 Pressure-Time Traces of Unsuppressed and Suppressed Deflagrations of a Combustible Processed Cellulosic Dust Having a K_{St} Value of 310 bar • m/sec (Courtesy of Kidde-Fenwal, Inc.)

when the volume of the burning material is much smaller than the protected enclosure volume. For this purpose, special pressure detectors, rate-of-pressure-rise detectors, or optical flame detectors are used. Optical detectors, employing ultraviolet (UV) or combination UV and infrared (IR) radiation sensors, are preferred in unenclosed environments with nonabsorbing UV atmospheres. Examples of such environments are solvent storage and pump rooms and aerosol can filling rooms. Pressure and rate-of-pressure-rise detectors are employed in closed process equipment, particularly where dusty atmospheres prevail. Multiple detectors and appropriate detection logic are essential to avoid false actuations.

Extinguishers are of the high-rate-discharge (HRD) type, charged with agent and propelling gas, usually nitrogen. The nitrogen overpressure is normally in the range of 300 to 900 psig (20 to 60 bar), depending on the manufacturer. Explosively or electrically operated high speed valves, usually $^{13}/_{16}$ to 6 in. (30 to 300 mm) in diameter, ensure the high rate of agent delivery necessary for effective suppression. Several types of extinguishing agents are employed, usually selected from among the following:

- Water, with or without additives
- Dry chemical formulations, usually based on sodium bicarbonate or monoammonium phosphate. Other extinguishing powders have also been used.
- Halocarbons (halogenated hydrocarbons). Halon 1301, although no longer manufactured, will continue to be available on a market basis, subject to changes in regulations, for suppression systems meeting critical-use criteria. Chlorobromomethane (Halon 1011) has been used widely, but has come under regulation as an ozone-depleting substance and can no longer be used without special permission from the EPA.* Research continues on the use of environmentally friendly fluorocarbons and hydrofluorocarbons in explosion protection applications.[27]

Extinguishing mechanisms, wherein each agent works as a combination of thermal quenching (100 percent in the case of water) and chemical inhibition, are beyond the scope of this chapter. The selection of agent is usually based on several considerations, such as effectiveness, toxicity, product compatibility, residual inerting, and volatility. Dry chemical agents are most commonly specified in deflagration suppression applications. Distribution of agent within the protected volume is aided by use of nozzles. These may be fixed in position, or of the "pop-out" type that remains recessed until projected into the process volume by the momentum of the discharging suppressant.

*Halon 1011 is environmentally much more benign than Halon 1301. For example, the ozone depletion potential (ODP) of Halon 1011 is a factor of 75 smaller than that of Halon 1301 (i.e. 0.01 for 1011 versus 13.00 for 1301). Similarly, the atmospheric lifetime of Halon 1011 is a factor of 250 smaller than that of Halon 1301 (i.e., 0.23 year for 1011 versus 65 years for 1301). The atmospheric lifetimes of the second generation clean agents (HFC-125, HFC-227ea, and HFC-236fa) range from 36 to 250 years. Therefore, these agents tend to contribute to global warming problems although their ODP is zero, and thus face potential environment regulations limiting their use.

A suppression system is controlled using an electronic power supply having battery backup power. This unit supervises the suppression system circuitry to ensure integrity of the system and supplies the current to explosively or electrically operated valve actuators employed on the extinguishers. Normally the process equipment being protected by the suppression system is automatically shut off on detection of an incipient deflagration. An example of a process layout protected by a deflagration suppression system is shown in Figure 17.8.9.

The protection afforded by a deflagration suppression system depends on several factors, including the size and shape of the protected volume; the explosibility of the material being processed; the initial turbulence scale and intensity; the number, size, and location of HRD extinguishers; and the means, sensitivity, and location of detection devices. The pressure–time profile for a suppressed deflagration of a combustible processed cellulosic dust was shown in Figure 17.8.8.

Deflagration suppression systems are active systems that require periodic inspection and maintenance. The use of deflagration suppression systems is discussed in NFPA 69.

Deflagration Isolation

Deflagration isolation is the strategy of preventing a deflagration initiated in one location from passing to another location where personal injury or additional damage may occur. *It is well known* that deflagration waves allowed to propagate into interconnecting piping and equipment can create much more powerful explosions than the initial explosion. A deflagration may transition to detonation if it is allowed to enter into unprotected piping or equipment. Process equipment such as mills, spray dryers, dust collectors, blowers, and vacuum pumps are regularly connected together by piping, ducts, chutes, or conveyors. (For convenience, such systems will be referred to here simply as "pipes.")

Ducting and Piping. An explosion beginning at one point in the process can propagate through these interconnections to other parts of the process, both upstream and downstream. Generally, isolation techniques are necessary unless a qualified risk analysis is performed and a determination is made based on both probability and consequence that the risk is acceptable. Flame propagation inside ducting or piping is somewhat unpredictable for dusts. Tests have shown that propagation is much less likely under certain conditions. Piping of less than 100 mm (4 in.) in diameter is far less likely to provide a conduit for flame spread than piping of larger diameters.

Dense phase pneumatic transfer (air velocity down near 600 ft/min, and solids loading ratio* greater than 30) is also much less likely to provide a conduit for flame spread propagation than dilute phase pneumatic transfer (air velocity in the region of 2200–3600 ft/min [11–18 m/sec] and solids loading ratio less than 15). As reported by Pineau[28] it is not uncommon for propagation to occur as infrequently as one time in

*Solids loading ratio is the ratio of average solid mass to air mass in the transfer line.

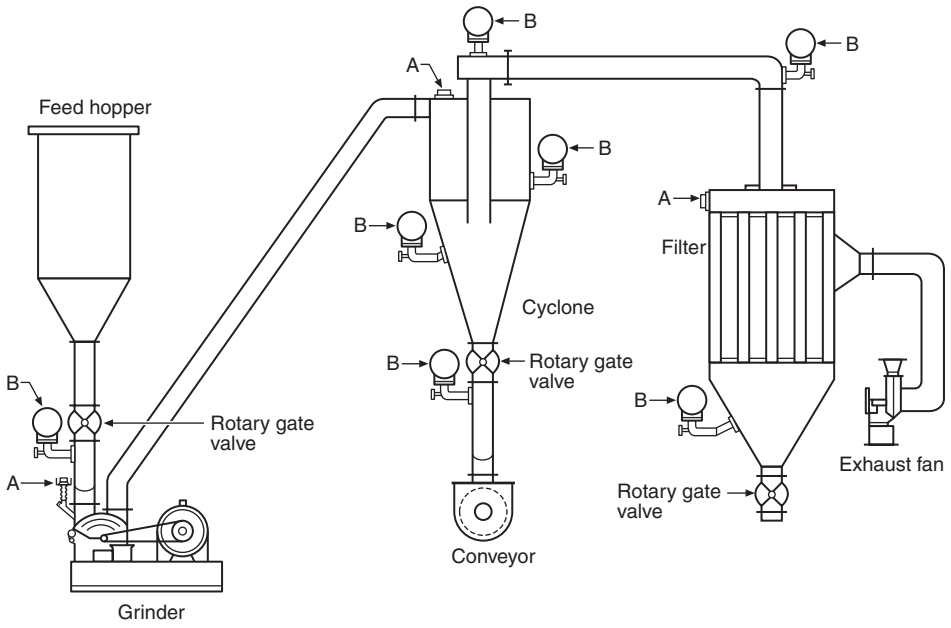


FIGURE 17.8.9 Deflagration Protection System for a Typical Grinding Plant. Deflagration detectors (A) actuate high-rate-discharge extinguishers (B).

ten in controlled experiments for 150 mm piping, even for dilute phase systems. Compared to other dusts, metal dusts and other high K_{St} dusts are more likely to propagate deflagrations through smaller diameter pipes. For interconnected vessels that are relatively close together, measures to reduce P_{red} for each interconnected vessel, taking into account that propagation could occur, would not necessarily eliminate the need for isolation techniques.

Flammable gases and combustible dusts are commonly conveyed between process units in pipe or duct systems. Dust or powdered materials are frequently transported together with air in dilute or dense phase conveying. Combustible vapors may be transported, by design or by accident, in a flammable state. A pipe carrying flammable mixtures can, should ignition occur at one end, act as a fuse. The ignited mixture can propagate flame through the pipe, leading to ignition of a process unit at the other end. Flame propagation, if possible, should be blocked near the point of ignition. Otherwise, the speed at which a flame propagates in the pipe will steadily increase. If the mixture composition is in the detonable range, the flame front can undergo deflagration to detonation transition, developing pressures of about 25 times the initial pressure and reflected pressures (that experienced by an object in the flow path) of up to 50 times the initial pressure.[29] Alternatively, pressure development and flame speeds can be limited with explosion vents placed in accordance with Chapter 9 of NFPA 68. Nevertheless, the flame front can still propagate, though at a moderate speed, through the entire length of the pipes.

Prevention of flame propagation through pipe systems is an important aspect of total protection of a process plant. Isolation methods can be used to interrupt or mitigate flame propagation, deflagration pressure, pressure piling that may lead to blast and shock formation, and flame jet ignition between items of equipment. Each isolation technique has unique application limitations. Some of these limitations are summarized in Table 17.8.9 and are discussed below.

Passive Isolation Devices. Passive protection devices include material chokes (rotary valves), flame front diverters, passive float valves (explosion check valves), static dry flame arresters, and hydraulic-type (liquid seal) flame arresters.

Flame Arresters. Flame arresters are constructed so as to cause the gas flow to pass through small passageways to prevent flame propagation due to thermal quenching. The maximum experimental safe gap (MESG), through which a flame cannot pass, can be determined using a device such as the Westerberg explosion test vessel.[30] These devices are not suitable for dust or saturated vapor service.

Flame arresters are normally placed at the end of a pipeline near a potential source of ignition. Special requirements are placed on flame arresters intended for use at a significant distance from the pipe end, for example, mounted in-line. NFPA 69 includes requirements for installation of in-line flame arresters. The U.S. Coast Guard has promulgated testing requirements for arresters that, when located in mid-pipe positions, may be challenged by a detonation. These requirements have been adopted in ANSI/UL 525, *Standard for Safety Flame Arresters.*[31]

Flame Front Diverters. Pressure piling and flame jet ignition through interconnecting piping can be controlled by means of a flame front diverter. The basic operating principle of this device is to vent the deflagration at a point where the flow direction is typically changed by 180 degrees. Figure 17.8.10 shows

TABLE 17.8.9 Isolation Features of Pipe and Duct Protection Systems

Isolation System	*Type*	*Fuel Type*	*Deflagration Isolation*	*Ignition Source Isolation*	*Flow (Pressure) Isolation*
Chemical barrier	Active	Dust, gas	Yes	Yes	No
Mechanical valve	Active	Dust, gas	Yes	Yes	Yes
Actuated float valve	Active	Gas	Yes	Yes	Yes
Actuated pinch valve	Active	Dust, gas	Yes	Yes	Yes
Rotary valve	Passive	Dust	Yes	*	Yes
Flame arrester	Passive	Gas	Yes	Yes	No
Flame front diverter	Passive	Dust	No	No	Yes
Liquid seal	Passive	Gas	Yes	Yes	No
Float valve	Passive	Gas	Yes	Yes	Yes

*Rotary valves are capable of preventing flame front passage under certain conditions but do not always prevent the passage of burning embers.

several flame front diverter designs. Due to the inertia of the fast flow caused by the deflagration, the flow will tend to maintain its *upward* direction rather than making a sharp turn, as it would when the velocity is low (at normal conditions). When the high-speed deflagration flame continues *upward,* it pushes open either a hinged cover or bursts a rupture disk located at the top of the diverter, allowing the flame to be released to the atmosphere. Some flame front diverters have demonstrated the ability to prevent flame propagation. In most cases, tests have indicated that diverters were not completely effective in preventing flame propagation. Where this has occurred, however, the deflagration severity was reduced; pressure piling did not occur or was less severe.

Siwek[32] discusses some design details concerning flame front diverters. More information about flame front diverters is presented in books by Bartknecht[15] and Eckhoff.[4] Bartknecht

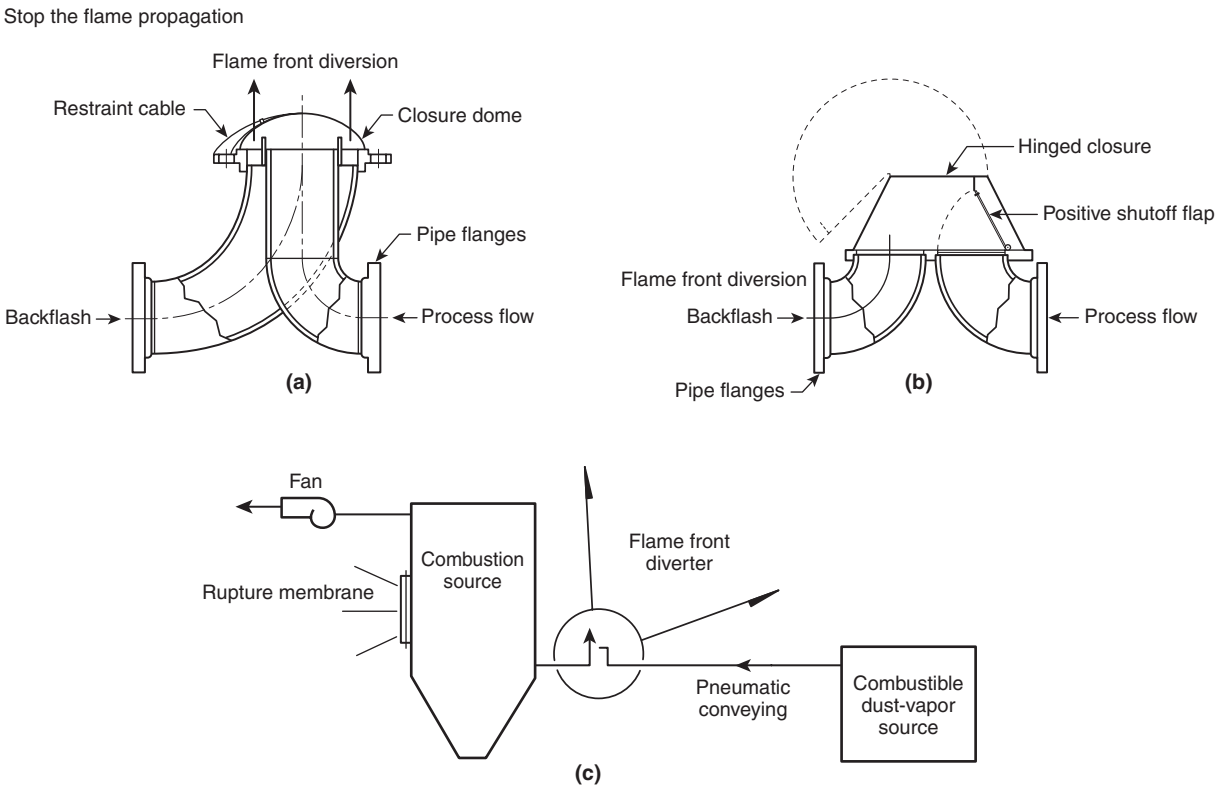


FIGURE 17.8.10 Typical Application and Design of Flame Front Diverters

recommends not using a flame front diverter as the only means of isolation if it is intended to stop flame propagation. Before flame front diverters are specified, they should be tested for the intended application.[32]

Passive Float Valves. A deflagration in pipe can generate flow velocities well in excess of the process flow velocities. Not unlike common check valves in hydraulic systems, passive float valves are designed to close at a specific flow rate, or a rated pressure differential, resulting from the deflagration. Therefore, the deflagration must develop a minimum strength pressure wave in the upstream piping. The valve float seals against a valve seat on closing and is held in place by a retaining device. The float valve remains closed until manually reset. A schematic drawing of a typical flow-actuated passive float valve and its internals is shown in Figure 17.8.11. The float valve typically functions in both directions.

A potential problem with this valve is that an elastomeric seat, if used, could be adversely affected in high-temperature environments. Another possible problem is that powder coating on the seal surfaces can prevent a tight seal, and flame breakthrough is then possible. Since a certain minimum pressure differential is required to close the float valve, the propagation of an explosion through a pipe will not be stopped if its pressure is lower than the minimum actuation pressure of the float valve. The placement of flow-actuated float valves requires a determination of the minimum and maximum distances from the origin of the explosion. Placement at the minimum distance ensures that the float valve closes before flame arrival. Placement at the maximum distance ensures that detonation does not develop in the vicinity of the float valve and that the pressure does not exceed the design pressure of the float valve. These distances are usually recommended by the valve vendor and are affected by the explosibility of the fuel, the pipe diameter, and the expected minimum and maximum P_{red} in the upstream enclosure.

Rotary Valves. Rotary valves are commonly used in process design to maintain pressure differences between interconnecting equipment. They need special operational and mechanical features to perform explosion isolation. If an explosion occurs, the rotary valve has to be automatically stopped to avoid transport of glowing and/or burning material to downstream equipment where it could cause a secondary fire or act as an ignition source to ignite a dust cloud and cause a deflagration.[15]

There are two different isolation concepts from which to chose, either flame quenching by maintaining close clearances or material blocking by maintaining a product layer above the valve. If the close clearance concept is chosen, it is important that actual clearance of such rotary valves is measured before installation and monitored using a preventive maintenance program such that the design clearance is not exceeded due to wear. If the material blocking concept is chosen, it is important that the hopper or vessel located upstream of the valve have a minimum inventory of solids to prevent flames passing through the solids due to the pressure wave from an explosion in the hopper/vessel. To maintain this minimum height of solids in the hopper upstream of the rotary valve, low-level sensors are provided which are interlocked to shut down the rotary valve before the hopper goes empty, thereby maintaining a level of solids above the rotary valve. This level of solids is intended to act as a seal to prevent flame and pressure transfer through the valve. A manual bypass should be provided for the low-level sensor/interlock to allow emptying of the hopper when necessary. However, the rotary valve can still significantly mitigate explosion propagation, even if total isolation is not achieved, by significantly reducing transmission of pressure. Figure 17.8.12 shows a typical rotary valve.

Hydraulic-Type (Liquid Seal) Deflagration Arresters. When an explosive mixture flows through a hydraulic arrester, it is separated into single isolated gas bubbles which rise due to buoyancy. Because of the formation of isolated bubbles continuous channels for the passage of the igniting flame do not exist. If an ignition occurs on the side of the device where the single bubbles reach the surface of the liquid, flame propagation can be blocked. This is the usual direction when hydraulic arresters are applied. In the opposite case, that is, if ignition occurs at the upstream side, separation into single gas bubbles will still take place, but the efficiency of the protection will be low, since the combustion process can be transferred to the surface of the liquid. Typical hydraulic deflagration arrester designs are seen in Figure 17.8.13.

Active Isolation Systems. The design of an active isolation system is based on the relative timing of three key processes: the time required for the detection of an explosion, the time

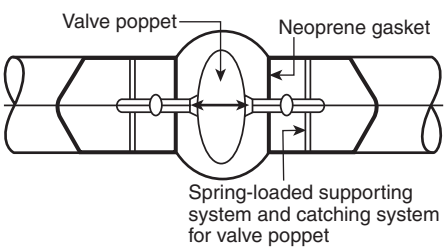


FIGURE 17.8.11 Flow-Actuated Float Valve

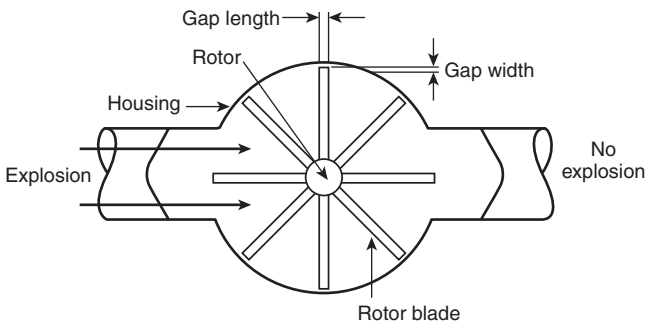


FIGURE 17.8.12 Typical Rotary Valve

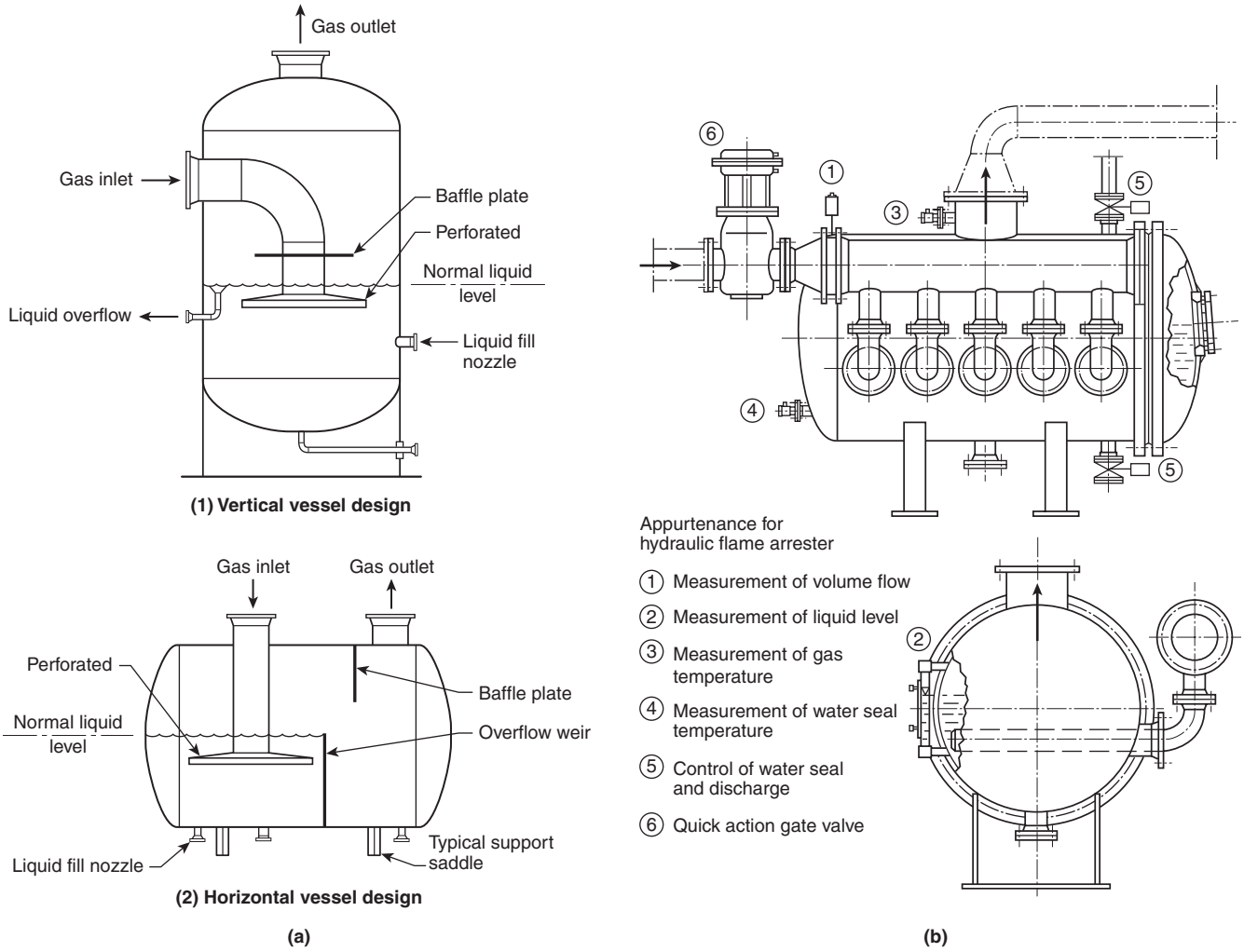


FIGURE 17.8.13 (a) Bubble Screen Hydraulic Flame Arrester; (b) Sparge Tube Hydraulic Arrester

required for the creation of a barrier, and the time it takes for the propagating flame front to reach that barrier. If the flame front can reach the barrier location before a complete barrier is established, then the isolation fails as the flame will travel beyond the barrier location. In such cases, the barrier needs to be placed further downstream to catch the flame front, assuming the pipe is sufficiently long, and the required distance is not too long to promote pressure piling and transition into detonation.

Since the protection is deployed only after the detection of an explosion, the design, fabrication, specification, and installation of these systems pose unique challenges. Establishment of an adequate barrier before the arrival of the flame front is the key to successful protection. The hardware-specific barrier establishment time is one side of this inequality and is carefully controlled as a part of the manufacturing and service quality programs. On the other side of the inequality is the time from the moment of detection to the moment the flame front arrives at the barrier location. Flame travel time is calculated from the three contributors to the flame speed: air velocity in the pipe prior to the explosion, air velocity induced by the explosion pressure rise upstream, and flame acceleration through the pipe. In addition to other occupancy specific parameters, the system design considers both strongest credible explosions, to specify a minimum distance between the possible ignition location and the barrier location, and weakest credible explosions, to ensure detectability.

The time required to create a barrier is the most straightforward to determine when compared to the others and depends on the type of isolation process. For chemical isolation, the time is determined by factors such as the time to initiate discharge, the discharge velocity, and duct diameter. The discharge velocity is affected by the gas pressure used to propel the agent as well as the length and diameter of the discharge piping. Mechanical isolation (fast-acting valves) is characterized by the time required for valve closure, which depends on the closure energetics and duct diameter. Float and pinch valves have similar dependencies. Detection is most often based on the system reaching a preset pressure or a pressure rate of rise. This requires a finite and not insignificant amount of time.

The time required for detection is dependent primarily on the preset conditions, the vessel volume, and the K_{St} or K_G. The detection time will increase as the volume increases and will decrease as K_{St} (K_G) increases. For example, a dust with a low K_{St} in a large volume will take considerably more time for pressure detection than a high K_{St} dust in a small volume. Similarly, ignition near the pipe inlet will be difficult to detect before it is too late. The effect of delayed detection can be to allow the flame to propagate farther and faster before isolation is initiated, and may result in failure of the isolation performance. Optical detection, normally located on the duct close to the inlet, is not affected in this manner. It does, however, require that the flame enter the duct in order to be detected. Optical detection can also be challenging for dust service.

Prediction of the flame propagation time is the most challenging among the three processes. It is well known that flames accelerate in ducts so that flame speed or burning velocity increases as the flame travels. Flame speed and acceleration are affected strongly by fuel characteristic (K_{St}, K_G), turbulence, elbows and other obstructions in the duct, conveyance flow velocity, and the reduced pressure in the primary enclosure. A scientifically valid and universally accepted methodology to predict flame speed and acceleration inside industrial pipes does not exist. As a result, the active isolation system manufacturers have no choice but to resort to using simplified proprietary flame acceleration correlations based on limited data sets. Additional information can be found in Vogl[33], Chatrathi and Going[34], Siwek and Moore[35], Roser et al.[36], Chatrathi et al.[37], Moore and Spring[38], and Pineau[39].

Active protection systems include the following:

- Actuated float valves
- Actuated pinch valves
- Automatic fast-acting mechanical valves
- Chemical isolation systems

Actuated Float Valves. Actuated float valves are similar to the passive float valves described previously. In order to achieve satisfactory performance when low explosion overpressures are expected, these valves are equipped with pneumatic means (such as pressurized gas or gas generator) to effect rapid closure. The system detectors and the control panel logic determines when to close actuated float valves. The actuated float valve typically functions in a single direction.

Actuated Pinch Valves. The valve trim (internals) is an elastomer pinch surrounded by a gas chamber. In the event of a deflagration, an electrical signal is sent from a sensor, typically mounted on a deflagration relief device, to an air tank mounted integral to the valve. The gas tank discharges gas to the chamber surrounding the elastomer pinch and compresses it, which pinches off flow in the pipeline. Because the pinch has relatively little mass, it is both very fast acting and imparts low shock to the piping. The pinch, however, may be adversely affected by sustained high temperatures such as might be encountered in a fire. A schematic of a pinch valve can be found in Figure 17.8.14.

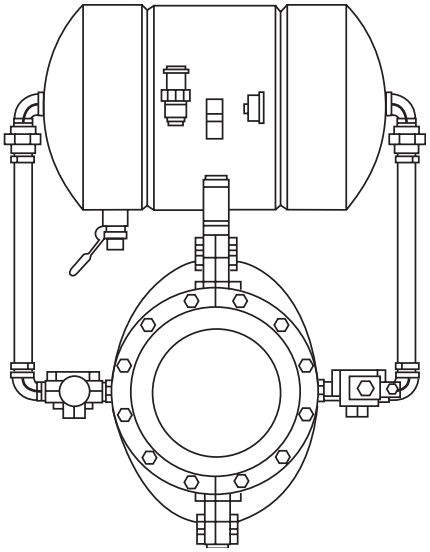


FIGURE 17.8.14 Pinch Valve

Automatic Fast-Acting Mechanical Valves. Positive mechanical isolation of a pipe system is another way to prevent passage of flames or pressure pulses from communicating between process units. Automatic fast-acting mechanical valves are actuated (closed) on a signal from a detector (sensor) in the pipeline between two items of interconnected process equipment. The detector sends a signal to a control device which is relayed to the valve-closure mechanism. Originally this was a compressed gas cylinder which then discharged the compressed gas to a piston-cylinder assembly at the top of the valve, thereby closing the gate. The propellant is generally nitrogen at 33 to 60 barg. The valve separating the compressed gas and the piston must be rapidly opened. Mechanisms for this include rapid pressurization of a rupture disk by pyrotechnical (detonator) devices. In some systems, gas-generating devices have replaced the pyrotechnics. Alternately, gas generators alone have been used to generate the pressure required to rapidly close the valve gate. Plant-air actuated valves are also available. Fast-acting slide gate isolation valves are shown in Figure 17.8.15 and can be mounted in vertical, horizontal, or inclined piping. With this type of valve, the pipe area is completely open and can be built without pockets and dead corners, so that dust will not settle out or accumulate. Special dampers absorb the substantial forces from the closing device and prevent the slide from springing back after closure.

Arrangements of isolation valve systems are shown in Figure 17.8.15 and Figure 17.8.16. A flame sensor is located at a sufficient distance from the valve such that, on detection of flame, the valve has adequate time to close. Fast-closing valves have been tested successfully in these applications to detect and intercept detonations in progress.[40]

Chemical Isolation Systems. Rather than completely blocking a pipe or duct by a valve, an alternative approach is to discharge a chemical extinguishing medium (suppressant) into the pipe,

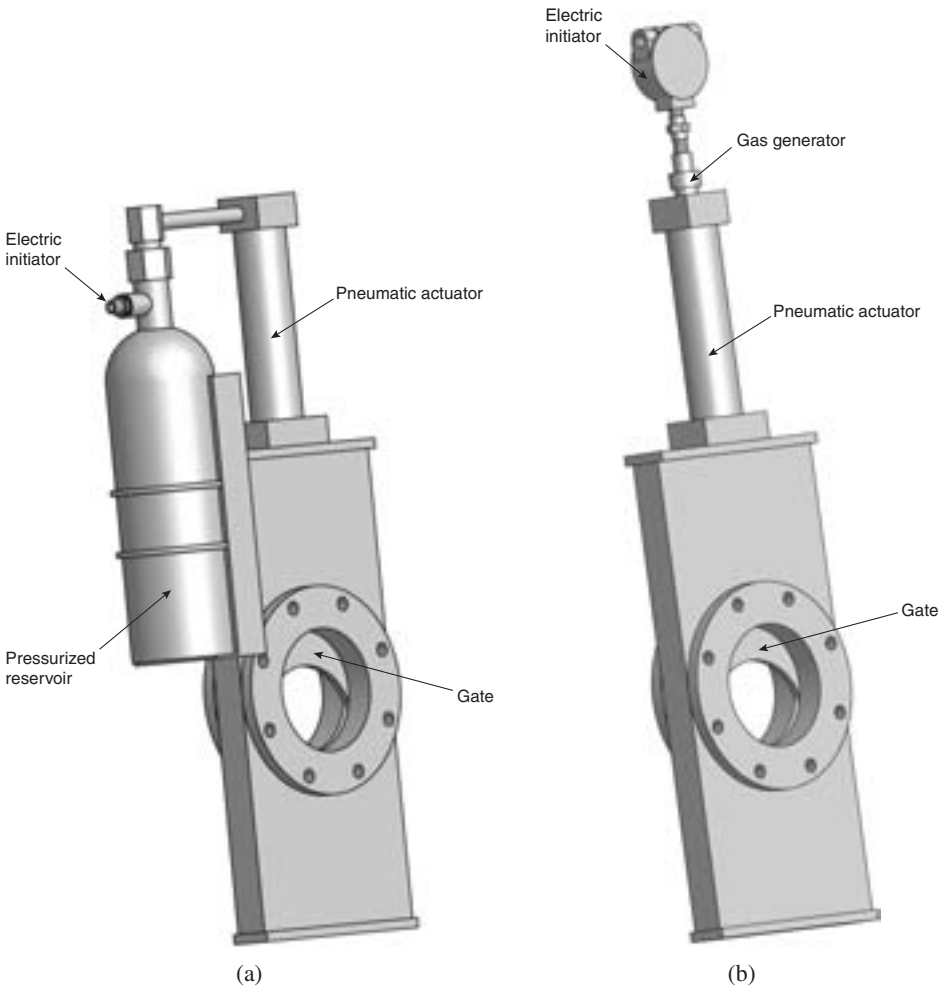


FIGURE 17.8.15 Examples of Automatic Fast-Acting Mechanical Valves

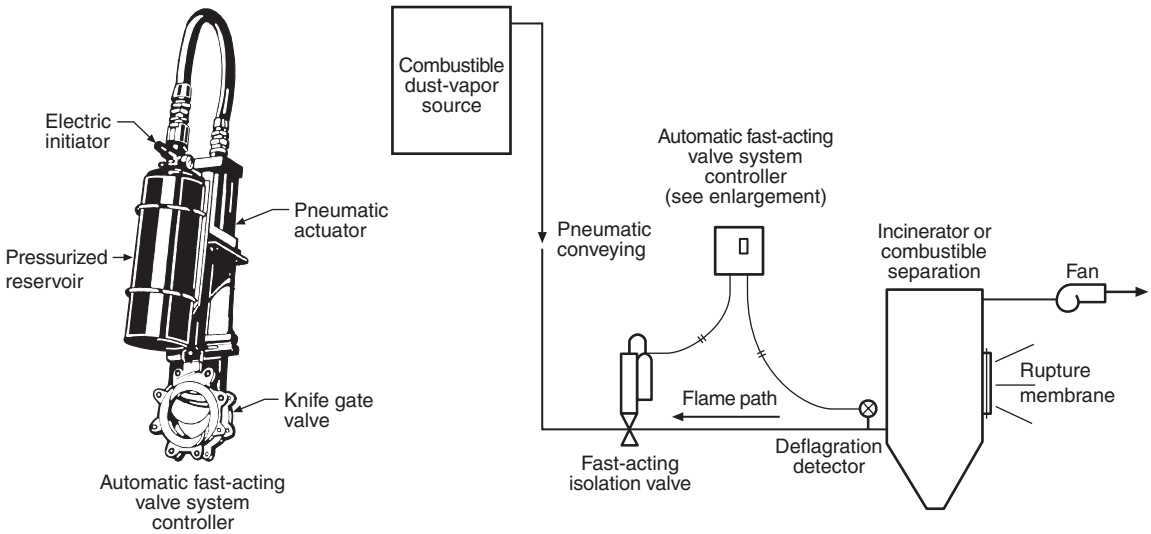


FIGURE 17.8.16 Typical Application of Duct Isolation System Using a Fast-Closing Valve

forming a nonflammable zone. These systems require special consideration in high P_{red} applications, where the induced flow velocity in the pipe can be quite high. As the injected suppressant is free to move with the induced flow, the intended nonflammable zone can be displaced or may have reduced suppressant concentration. Extinguishing compounds such as sodium bicarbonate or ammonium dihydrogen phosphate, chemicals commonly used in fire extinguishers, have been found to be very effective.[41] Halogenated hydrocarbons with low boiling points may be particularly useful, as they provide complete vapor blocks in pipes. Examples of chemicals of this type are HFC-23, HFC-125, HFC-227ea, and HFC-236fa. Halogenated agents leave no residue after discharge, but may form halogen acids upon interacting with flame and hot products of combustion. These acids may be harmful to mechanical components as well as to personnel. Additionally, due to their high global warming potential, these agents face environmental regulations limiting their use. Both dry chemical and gaseous agents have been used successfully in industrial pipe and duct explosion protection systems applications. Applications where chemical barriers are used are often similar to the example shown for fast-acting valves in Figure 17.8.15, where an agent bottle is used in place of a valve to create an inert chemical barrier in the pipe or duct. Chemical isolation systems must be specifically engineered for each application.

SUMMARY

The purpose of this chapter was to provide basic guidance in the prevention of deflagrations and to outline the more commonly employed explosion protection methods. The subject of explosion prevention was presented in the context of deflagration prevention through control or elimination of flammable atmospheres and ignition sources. Careful application of steps to prevent deflagrations is no guarantee that such events will not occur, but only that their likelihood is reduced. Additional protection is afforded through use of any of several explosion mitigation methods. These techniques come into play once ignition has occurred and serve to vent, contain, or redirect the expanding combustion gases, or suppress the combustion process itself. The reader is urged to consult other chapters in this handbook that are relevant to the fundamentals of fires, explosions, and extinguishing systems, and the literature cited at the end of this chapter.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on explosion prevention and protection discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA 70, *National Electrical Code®*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA 484, *Standard for Combustible Metals*
NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment*
NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*
NFPA 499, *Recommended Practice for the Classification of Combustible Dusts and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas*
NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*
NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*

SECTION

18

Confining Fires

Robert J. Vondrasek

18.1 Confinement of Fire in Buildings
18.2 Interior Finish
18.3 Smoke Movement in Buildings
18.4 Venting Practices
18.5 Penetration Sealing
18.6 Deflagration (Explosion) Venting

The *Fire Protection Handbook*® emphasizes the notion that fire safety must be addressed through system design and analysis of all elements and their relationships to each other. Nowhere is this more essential than in the decisions that determine strength, location, and other features of barriers, surfaces, and spaces in buildings. Confining fires is an important aspect of building fire protection. The six chapters of Section 18 describe construction features, built-in equipment, and techniques for confining or containing fire and fire products to within the barrier of the area where the fire began.

Chapter 1, "Confinement of Fire in Buildings," is an overview chapter that discusses barriers (such as fire doors, fire partitions, and fire walls) that are intended to limit the spread of fire.

Chapter 2, "Interior Finish," reviews the effect of interior finish materials on fire growth, examines the method of application of interior finishes and the effect on fire behavior, and summarizes various fire tests of interior materials.

Chapter 3, "Smoke Movement in Buildings," gives information on the techniques used to evaluate the physical characteristics of smoke and assess its movement in both short and tall buildings. It also covers the approaches that can be used to limit the hazard of smoke in buildings. Chapter 4, "Venting Practices," discusses venting theory, venting in industrial buildings, and automatic heat and smoke venting in sprinklered buildings.

In earlier editions of this handbook, the topic of penetration sealing was covered in a chapter on building services. This edition features an entire chapter on the topic: Chapter 5, "Penetration Sealing." Included are discussions of through-penetration/firestop systems, perimeter fire containment systems, and joint systems.

The section concludes with Chapter 6, "Deflagration (Explosion) Venting." The chapter presents the fundamentals of deflagration, detonation, pressure effects, and explosion venting.

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Chapter 1

Confinement of Fire in Buildings

Revised by
Hossein Davoodi

Chapter Contents

Fire Severity
Fire Loads
Effect of Ventilation
Fire Modeling
Fire Spread
Protection of Openings

Key Terms

atria, compartmentation, concealed space, fire barrier, fire blocking, fire confinement, fire door, fire load, fire model, fire partition, fire plume, fire resistance, fire severity, fire spread, firestop, fire wall, Stefan-Boltzman constant, stoichiometric combustion, temperature-time curve

People and property not directly exposed to a fire can be protected by confining heat and smoke to the area of origin until the fire either is extinguished or burns itself out. People can also be protected by delaying the spread of fire and smoke until the occupants can be relocated to a place of safety.

Throughout building codes and standards, several terms are used to represent fire separation barriers, including *fire partition* and *fire barrier.* This chapter discusses barriers that are intended to limit the spread of fire. Smoke movement in buildings is discussed in Section 18, Chapter 3, "Smoke Movement in Buildings," and smoke and heat venting in Section 18, Chapter 4, "Venting Practices." The same barriers used to prevent the spread of fire will almost always be the bulwark of systems designed to prevent the spread of smoke. To be contained, a fire must be bounded by barriers that limit the transmission of heat and hot gases. Such barriers must maintain their continuity and stability under the thermal and physical forces of a fire and during the structural distortions and collapse that sometimes occur within the fire area.

The fire resistance required of a barrier depends on its intended purpose and on the expected severity of the fire to which it may be exposed. In most cases, the temperature history of the fire provides an approximate but adequate description of fire severity. If the purpose of the barrier is to limit probable fire size independent of any fire suppression actions, the barrier must then withstand the maximum expected fire that would occur during a burnout of combustibles inside the fire zone. However, if the purpose of the barrier is to contain the fire until occupants are evacuated and the fire department gains access, the time necessary for these actions determines the time that the barrier must hold back the fire, unless the fire is expected to largely burn itself out first.

Properly designed and constructed barriers that satisfy fire endurance test criteria are assigned a fire resistance rating that is measured in hours or fractions thereof. Any breach or unprotected opening in a fire barrier will negate its fire resistance rating and may indeed contribute to rapid fire spread through the barrier.

See also Section 2, Chapter 5, "Basics of Fire Containment"; Section 3, Chapter 5, "Introduction to Fire Modeling"; and Section 6, Chapter 3, "Concepts and Protocols of Fire Testing."

FIRE SEVERITY

The fire severity to which a barrier can be exposed is related to the intensity of a fully developed fire in the space adjacent to the fire barrier. For a room fire, a fully developed fire would be a postflashover fire; however, in large open volumes, such as those found in many industrial plants, a fully developed fire may occur in one area without flashover of the entire volume. It is the fully developed fire that first imposes extensive thermal and physical stresses on fire barriers. The initial possibility of barrier penetration occurs prior to full development. A typical developing fire is characterized by a flame front moving over a surface and/or flames localized to a stationary source.

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Although such a fire does not massively attack fire barriers, it can spread through faults or openings in the barrier and cause local destruction of barrier fire resistance.

A growing fire may or may not continue to flashover or become a fully developed area-wide fire. Unless it reaches these stages, it is unlikely to threaten fire-resistive barriers except through unprotected openings or serious defects in the construction of the barrier system.

Flashover of an enclosure is likely to occur if the temperature of the upper gas layer reaches approximately 1100°F (600°C). Full-scale fire experiments and energy balance analysis of room fires have shown that the temperature of this upper gas layer depends on the heat released by the burning fire, ventilation of the enclosure, dimensions of the enclosure, and the type of finish material lining the enclosure.[1] These factors are also interdependent with each other to some degree. The larger the enclosure, the higher the heat release necessary to produce the upper gas temperature needed for flashover. The more heat lost through walls, doors, and windows, the larger the fire and/or longer the time needed to produce flashover. Conversely, the greater the combustibility of the enclosure lining, the smaller the fire needed to produce flashover. The combustibility of the lining, or interior finish, is particularly significant. Interior finish in an enclosure can reduce the rate of heat release in the enclosure to below the value necessary for flashover as well as reduce the preburn time before flashover. A practical difficulty in estimating the likelihood of room flashover is in determining a value for the heat-release rate possible from the room contents. Typical heat-release rates from some common furnishings have been summarized from full-scale experimental data.[2] These data can be used in calculating the likelihood of flashover in a particular room.

Combustion

The intensity and duration of a fully developed fire depend on the quantity of combustibles available, their burning rates, the geometry of the material, room geometery, and the air available for combustion. Fire intensity will also be somewhat lower when walls and ceilings absorb significant amounts of energy rather than act primarily as insulation or radiation barriers.

The burning rate of a fully developed fire involving a specific material or grouping of similar materials is determined by either (1) the fuel surface area available to participate in the combustion reaction or (2) the amount of oxygen available for combustion. These are referred to as fuel-surface-controlled and ventilation-controlled combustion, respectively. The maximum rate of heat transfer into fire separation barriers occurs at the point where the ventilation is just sufficient so that combustion is controlled at the fuel surface (*stoichiometric combustion*).[3] At higher ventilation rates, more heat is removed from the fire by the excess air. At lower ventilation rates, the combustion heat-release rate is less, and more unburned pyrolysis products and fuel particles are vented outside the fire area. Burning of unburned pyrolysis products outside fire compartment windows can increase the threat of floor-to-floor and building-to-building fire spread.

The possibility of failure of fire separation barriers can exist long after the fully developed fire begins to decay. However, in many real fires, this threat is mitigated by fire suppression activities. The decay in air temperature in a fire room has been reported as 27 to 36°F (15 to 20°C) per minute after fully developed fires of 10- to 15-minute duration. Other data indicate a decay rate of 18°F (10°C) per minute for longer-duration fires.[4] Cooling can be even slower in large debris piles. Fire endurance testing in the United States does not simulate a fire decay period, although the decay period is simulated by some European testing and has been proposed in U.S. testing. Research has proposed that short-duration, high-temperature fires, followed by temperature decay, should be considered.

Poorly ventilated fires that are encountered in spaces such as basements, ship holds, or enclosed interior rooms can produce sufficient heat over a long period of time to penetrate fire separation barriers. These fires start with or reach flaming combustion and, as the air in the space is consumed, revert to a state of mixed smoldering and glowing combustion with isolated or intermittent flaming. However, at present, there are no adequate experimental data or theoretical approach capable of reliably estimating the effect of these fires on fire-resistive barriers.

Standard Temperature-Time Curve

Fire-resistive barriers are evaluated in a testing furnace by exposure to a fire whose severity follows a time-varying temperature curve known as the standard temperature-time curve. The specified temperature-time history is tabulated in NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials,* and illustrated in Figure 18.1.1. The standard temperature-time curve was adopted by the ASTM in 1918 and has been the basis of almost all fire-resistive testing ever since.

Following adoption of the curve, the National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards (NBS), conducted a number of full-scale fire tests to determine how actual building fires compared with the temperatures represented on the curve.[5,6] The tests included two actual buildings that were allowed to burn to destruction and a series of fires in fire-resistive test buildings containing

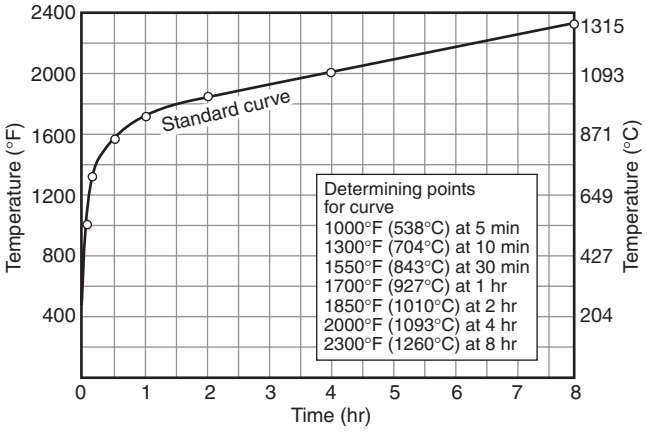

FIGURE 18.1.1 Standard Temperature-Time Curve

contents representative of office, record room, and household occupancies.

The principal variable considered in these occupancy fire tests was the amount of combustible materials present, which is defined as the fire load. Although the ventilation in the test buildings was not reported, the windows were equipped with steel shutters that could be adjusted to control ventilation and maximize fire severity. The quantitative importance of ventilation on fire severity was not identified until the 1950s. These tests conducted by NIST provided quantitative data on the temperature history of fires that were representative of various occupancies and fire load at that period of time. Fire load was expressed as the weight of ordinary combustibles in the room divided by the floor area of the room. Loading is the average amount of ordinary combustible material per square foot (m^2) of floor area. The temperature history of the fully developed fires in three test occupancies was approximately bounded by the standard temperature-time curve.

NIST developed the concept of equivalent fire severity to define the severity of actual fires that had various temperature histories. This concept states that the area above a baseline under the temperature-time curve of a test fire, which is expressed in degree hours, is an approximate representation of the severity of a fire involving ordinary combustibles. The baseline used represents the temperature the materials can be exposed to without impairing their fire-resistive capabilities. Two fires with differing temperature histories are considered to have equivalent severity when the areas under their temperature-time curves are similar. This concept permitted comparison of any fire test data to the standard temperature-time curve by relating the area under the test curve to the area under the standard curve.

TABLE 18.1.1 Estimated Fire Severity for Offices and Light Commercial Occupancies

Total Combustible Content, Including Finish, Floor, and Trim		Heat Potential Assumed*		*Equivalent Fire Severity Approximately Equivalent to That of Test Under Standard Curve for the Following Periods*
(lb/ft²)	*(kg/m²)*	*(Btu/ft²)*	*(MJ/m²)*	
5	24	40,000	454	30 min
10	49	80,000	909	1 hr
15	73	120,000	136	1½ hr
20	98	160,000	1820	2 hr
30	147	240,000	2730	3 hr
40	196	320,000	3640	4½ hr
50	245	380,000	4320	7 hr
60	290	432,000	4910	8 hr
70	340	500,000	5680	9 hr

Note: Data apply to fire-resistive buildings with combustible furniture and shelving.
*Heat of combustion of contents taken at 8000 Btu/lb up to 40 lb/ft²; 7600 Btu/lb for 50 lb; and 7200 Btu for 60 lb and more to allow for relatively greater proportion of paper. The weights contemplated by the table are those of ordinary combustible materials, such as wood, paper, or textiles.
For SI units: 1 lb/ft² = 4.88 kg/m²; 1 Btu/ft² = 1.14 J/m².

FIRE LOADS

Relationship of Fire Load and Fire Severity to Fire Resistance Requirements

The original concepts of fire severity and fire load are very important even though they are technically obsolete. These concepts are the basis for many of the fire resistance requirements of building codes and for government agencies. In many cases, this original fire severity/fire load relationship was more severe than is indicated by more accurate analysis. Such results are conservative since the resultant error is on the safe side.

Analysis of NIST tests developed an approximate relationship between fire loading and an exposure to a fire severity equivalent to the standard temperature-time curve. The weight per square foot (m^2) of ordinary combustibles (wood, paper, and similar materials with a heat of combustion of 7000 to 8000 Btu per lb [16.282 to 18.608 MJ/kg]) was related to hourly fire severity, as described in Table 18.1.1.

The fire severity/fire load relationship was the first method developed to predict the severity of a fire that would be anticipated in various occupancies. It was used to determine resistance required of fire barriers as well as structural components. Although the technique has its limitations, the fire severity/fire load relationship still provides an approximate but conservative estimate of the probable maximum fire severity with combustibles having a high heat-release rate and when fire conditions can produce temperatures significantly higher or lower than the standard temperature-time curve.

Fire load is a measure of the maximum heat that would be released if all the combustibles in a given fire area burned. Maximum heat release is the product of the mass of each combustible multiplied by its heat of combustion. In a typical building, the fire load includes combustible contents, interior finish, floor finish, and structural elements. Fire load is commonly expressed in terms of the average fire load, which is the equivalent combustible weight divided by the fire area in square feet (m^2).

Equivalent combustible weight is defined as the weight of ordinary combustibles having a heat of combustion of 8000 Btu/lb (18,608 kJ/kg) that would release the same total heat as the combustibles in the space. For example, the equivalent weight of 10 lb/ft² (48.8 kg/m²) of a plastic with a heat of combustion of 12,000 Btu/lb (27,912 J/kg) would be

$$10 \text{ lb/ft}^2 \times 12{,}000 \text{ Btu/lb} = 120{,}000 \text{ Btu/ft}^2$$

$$120{,}000 \text{ Btu/ft}^2 \div 8000 \text{ Btu/lb ordinary combustibles} = 15 \text{ lb/ft}^2$$

or

$$48.8 \text{ kg/m}^2 \times 27.9 \text{ MJ/kg} = 1365 \text{ MJ/m}^2$$

$$1365 \text{ MJ/m}^2 \div 18{,}608 \text{ MJ/kg} = 75.36 \text{ kg/m}^2$$

Technically accurate methods for calculating the actual fire severity and fire resistance requirements are available for many common building-occupancy-contents combinations. Technical

TABLE 18.1.2 Characteristic Fire Loads in Office Buildings

	Government Buildings			Private Buildings		
		Total Fire Load (lb/ft^2)			Total Fire Load (lb/ft^2)	
Room Use	*No. of Rooms Sampled*	*Mean*	*Std. Dev.*	*No. of Rooms Sampled*	*Mean*	*Std. Dev.*
General	342	7.3	4.4	479	7.7	4.3
Clerical	77	5.8	5.2	146	6.8	4.0
Lobby	15	2.6	1.4	45	5.0	4.2
Conference	39	4.2	6.1	57	5.9	4.6
File	10	17.9	11.9	20	16.2	12.9
Storage	35	11.7	19.2	77	13.2	11.7
Library	2	30.2	7.8	10	23.6	10.8

Note: Fire in steel enclosures. Weight of combustibles was converted to an equivalent weight of combustibles having a heat of combustion of 8000 Btu/lb.
For SI units: 1 lb/ft^2 = 4.88 kg/m^2.

limitations are primarily related to availability of input data rather than the analytical tools. These methods have been accepted to varying degrees under performance-based building codes adopted in some countries. Such analytical approaches have not yet been widely or routinely accepted by code authorities in the United States. However, third-party reviews are opening up opportunities for this alternative.

Occupancy Fire Loads

A number of surveys have identified the fire loads found in various occupancies[5,7,8] (Tables 18.1.2 and 18.1.3).

Data from some fire load surveys as well as the inherent nature of combustible contents likely to be encountered suggest that the dispersion of fire load within a certain class of rooms can be approximated by either a normal or moderately skewed frequency distribution curve (Figure 18.1.2). The standard deviation, included in Tables 18.1.2 and 18.1.3, can be used to determine the probability that a particular fire load value will not be exceeded in a class of rooms. A fire load that is one standard deviation above the mean value of a normal distribution curve would represent an upper boundary for 84.13 percent of the fire loads in rooms of that class. Two standard deviations above the mean would bound 97.73 percent of the fire loads in that class of rooms, and three standard deviations, 99.86 percent of the fire loads. Thus, if a fire barrier were to be designed on the basis of two standard deviations above the mean, there would be a 97.73 percent probability that this fire load would not be exceeded in a similar room.

The above percentages consider that the distribution of fire loads is perfectly normal. If the distribution is more accurately defined by a moderately skewed curve, the percentages represent only close approximations.

Derated Fire Loads

Ordinary combustibles that are completely or largely enclosed in steel containers will not burn completely during a room fire and, therefore, will not contribute a full 8000 Btu/lb (18.608 MJ/kg) to the fire load. The General Services Administration (GSA) has developed guidelines for determining a derated fire load for office buildings, which can be applied to other occupancies having similar classes of combustibles.[9] The total contents fire load is divided into three categories: (1) weight of materials completely enclosed in containers, such as steel desks or file

TABLE 18.1.3 Typical Fire Loads

Type of Room	*Contents Fire Load (lb/ft^2)*	*Standard Deviation (lb/ft^2)*
Living room	3.9	1.13
Family room	2.7	0.65
Bedroom	4.3	1.15
Dining room	3.6	1.02
Kitchen	3.2	0.77
Hospital patient room	1.2	0.36
Nursing home patient room	2.6	0.62

For SI units: 1 lb/ft^2 = 4.88 kg/m^2.

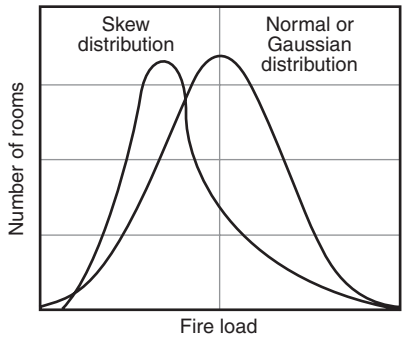

FIGURE 18.1.2 Expected Distributions of Sample Fire Loads

cabinets, (2) weight of materials enclosed on five sides, such as in a steel bookcase, and (3) weight of free combustibles.

Completely enclosed combustibles will be heated by the room fire and pyrolyze, and the escaping pyrolysis products will burn. Therefore, the heat that the enclosed combustibles release depends on the extent to which they are *pyrolyzed.* This is related to the intensity and duration of the room fire, which in turn is related to the total combustibles in the room. The extent to which the enclosed contents are derated is determined by considering the ratio of the total weight of enclosed combustibles to the total weight of all combustibles in the room. Thus,

$$F_T = W_E + W_{PE} + W_{FE}$$

A derating factor is assigned to W_E as tabulated:

Ratio W_E/F	*Derating Factor, K*
Under 0.5	0.4
0.5 to 0.8	0.2
Over 0.8	0.1

Ordinary combustibles enclosed on five sides by steel, such as in a bookcase, are derated to 75 percent of their weight.

The total derated fire load is given by the following equation:

$$F_{DR} = K_{WE} + 0.75W_{PE} + W_{FE}$$

The specific fire load is then computed by dividing by the floor area.

This derating procedure can be applied if other than ordinary combustibles are included in the fire load. The total weight of other combustibles must be expressed in terms of an equivalent weight of ordinary combustibles that would release the same total heat in burning. This is accomplished by multiplying the weight of the other combustibles by the ratio of their heat of combustion in Btu/lb, to 8000 Btu/lb (19 MJ/kg), the heat of combustion of ordinary combustibles.

British Fire Loading Studies

The British also have graded building occupancies according to hazard. Three classifications—low, moderate, and high fire loads—were defined in terms of Btu/ft^2 (J/m^2).

Occupancies of Low Fire Load. The fire load of an occupancy is described as low if it does not exceed an average of 100,000 Btu/ft^2 (1134 MJ/m^2) of net floor area of any compartment, or an average of 200,000 Btu/ft^2 (2268 MJ/m^2) in limited isolated areas, provided that storage of combustible material necessary to the occupancy may be allowed to a limited extent if separated from the remainder and enclosed by appropriate-grade fire-resistive construction. Examples of occupancies of normal low fire load are retail shops, factories, and workshops.

Occupancies of Moderate Fire Load. The fire load of an occupancy is described as moderate if it exceeds an average of 100,000 Btu/ft^2 (1134 MJ/m^2) of net floor area of any compartment but does not exceed an average of 200,000 Btu/ft^2 (2268 MJ/m^2), or an average of 400,000 Btu/ft^2 (4540 MJ/m^2) in limited isolated areas, provided that storage of combustible material necessary to the occupancy may be allowed to a limited extent if separated from the remainder and enclosed by fire-resistive construction of an appropriate grade. Examples of occupancies of moderate fire load are retail shops, factories, and workshops.

Occupancies of High Fire Load. The fire load of an occupancy is described as high if it exceeds an average of 200,000 Btu/ft^2 (6 MJ/m^2) of net floor area but does not exceed an average of 400,000 Btu/ft^2 (4540 MJ/m^2) of net floor area, or an average of 800,000 Btu/ft^2 (9080 MJ/m^2) in limited isolated areas. Examples of occupancies with normal high fire load are warehouses and other buildings used for the bulk storage of commodities of a recognized nonhazardous nature.

Other Fire Loading Studies

Fire loading studies have been conducted in other countries. Results of some of these studies are summarized in Tables 18.1.4 through 18.1.6.

EFFECT OF VENTILATION

The burning rate of fully developed fires may depend on the available fuel surface area or on the air available for combustion. When ample air is available, the burning rate of a fire depends on the exposed surface area and on the properties of the combustible itself. Fully developed fires involving ordinary residential furnishings burn at a rate *R,* which can be approximated by the following equation:

$$R = 0.09A_f \text{ (lb/min)}$$

TABLE 18.1.4 Mean Values of Fire Load and Fire Load Density for the Various Homes

Home Type	*Mean Fire Load (MJ)*	*Mean Fire Load Density Based on Floor Area of 22 m^2 (MJ/m^2)*	*Number of Samples*
Apartment	12,000	550	6
3 story townhome	11,000	500	5
2 story semidetached	10,000	450	4
2 story detached	11,000	500	33
3 story detached	11,000	500	4
2 story townhome	10,000	450	6
Bungalow	10,000	450	13
Duplex	7,000	300	2

Source: Table 2, "Mean Values of Fire Load and Fire Load Density for the Various Homes," *A Pilot Study of Fire Loads in Public Homes,* Institute for Research in Construction, National Research Council Canada, Research Report, No. 159, Mar. 9, 2004.

TABLE 18.1.5 Published Fire Load Densities for Residential Occupancies

Fire Load Density (MJ/m^2)	*Country*	*Reference*	*Notes*
450	United States	8	Survey of basement recreation rooms in 200 single-family detached homes
500	United States	8	Survey of 70 residential recreation rooms
400, 800, 1200	New Zealand	9	Recommended in the New Zealand building code
600	Sweden	11	—
724	New Zealand	12	—
670	Japan	13	Survey of 214 homes
600, 500	Canada	—	This survey (mean values for main floor and basement living rooms in 74 homes)

Source: Table 4, "Published Fire Load Densities for Residential Occupancies," *A Pilot Study of Fire Loads in Public Homes,* Institute for Research in Construction, National Research Council Canada, Research Report, No. 159, Mar. 9, 2004.

TABLE 18.1.6 Fire Load Classifications (MJ/m^2) for Different Occupancies

	Fire Load Density			
		Fractile[a] MJ/m^2		
Occupancy	*Average MJ/m^2*	*80%*	*90%*	*95%*
Dwelling	780	870	920	970
Hospital	230	350	440	520
Hospital storage	2000	3000	3700	4400
Hotel Bedroom	310	400	460	510
Offices	420	570	670	760
Shops	600	900	1100	1300
Manufacturing	300	470	590	720
Manufacturing and storage[b]	1180	1800	2240	2690
Libraries	1500	2250	2550	—
Schools	285	360	410	450

[a]The 80% fractile is the value that is not exceeded in 80% of the rooms or occupancies.
[b]Storage of combustible materials at less than 150 kg/m^2.
Source: Table 5.2.2, Draft Irish National Annex, I.S.EN 1991-1-2: 2002 Actions of Structures, Part 1-2, General Actions on Structures Exposed to Fire, National Standards Authority of Ireland.

where A_f is the exposed fuel surface in ft^2 (m^2).[10] For the general case, the equation becomes

$$R = W_f A_f$$

where W_f = surface rate of burning of the fuel, lb/ft^2 (kg/m^2) of exposed surface per minute.

Typical furniture found in homes and offices has a surface-area-to-weight ratio between 0.55 and 0.90 lb/ft^2 (2.7 and 44 kg/m^2).[11] Loose combustibles, cellular material, hanging clothes, and similar materials have much higher surface-to-weight ratios and are associated with more rapidly developing fires.

When a fire cannot get sufficient air to maintain the burning rate associated with fuel-surface-controlled (stoichiometric) combustion, it will burn at a ventilation-controlled rate. The burning rate for fully developed fires with ordinary combustibles to which air is supplied through broken windows or a doorway is approximated by the following equation:

$$R = 0.62 A_o H_o^{1/2} \text{ (lb/min)}$$

where

A_o = The opening area in ft^2 (m^2)

H_o = The height of the opening in ft (m)[12]

Airflow into the fire, through a single opening, has been found to be approximately equal to the following equation:

$$\dot{m} \simeq 5.06 C_D A_o H_o^{1/2} \text{ (lb/min)}$$

where C_D = the orifice coefficient, normally about 0.5 to 0.7.[13]

Where there are multiple openings or a window wall, the flow is less than predicted by the area, and a coefficient of about 0.35 is recommended.

The maximum fire intensity, from the standpoint of rate of heat input into barriers, occurs at a ventilation rate just sufficient to sustain a surface burning fire. This can be expressed in the following equation:

$$W_f A_f = 5.06 C_D W_a A_o H_o^{1/2}$$

where W_a is the weight of fuel each pound (kg) of air will burn completely. Typical values of W_a are presented in Table 18.1.7.[13]

The preceding relationships assume that wind is not a factor in ventilation. In addition, if the ventilating opening is an interior door, such as from a corridor, adequate combustion air must be available for the fire.

Considerable ventilating area is required for a fully developed fire to burn at a fuel-surface-controlled rate (stoichiometric combustion). For example, over one-fourth of the wall area would have to be open in a 20 ft × 20 ft (6.1 m × 6.1 m) room with an 8 ft (2.4 m) ceiling and an exposed combustible surface of 800 ft^2 (74.3 m^2) of ordinary combustibles. Most building fires will be ventilation controlled during the period when containment is critical from the initial well-developed phase until the start of decay. A fully developed fire can change from

TABLE 18.1.7 Fuel Consumed by 1 Pound of Air at a Stoichiometric Fuel/Air Ratio

Combustible	*lb fuel/lb air*	*g fuel/kg air*
Wood	0.175	175
Polyethylene	0.069	69
Polystryene	0.076	76
Polyurethane	0.135	135
Benzene	0.076	76
Methane	0.060	60

a ventilation-controlled to fuel-surface-controlled fire as ventilation changes (such as when windows break out). Fires in modern buildings that have large glass windows may burn at ventilation-controlled rates.

FIRE MODELING

A number of mathematical models have been developed that include calculations of the temperature history of fully developed room fires as a function of ventilation, fuel, and the walls and ceiling of the room.[3,4,11,13–18] Fire models are increasingly being used in design as well as the evaluation of hazards and reconstruction of incidents. An extensive and expanding database is available that provides histories of heat release rates for combustible contents and finishes as well as the physical and thermal properties of construction materials. The most widely used models in the United States are classified as zone models and exemplified by the Consolidated Firegrowth and Smoke Transport (CFAST) component of HAZARD.[16] Zone models are available with varying degrees of complexity and can be run on personal computers. A typical assumption of zone models is the filling of the fire compartment from the top down with hot gases of a uniform temperature. An advantage of zone-based models is their ability to address smoke spread and a variety of fire-growth profiles. Field models do not make such assumptions but use computational fluid dynamics; this requires numerical solution of the differential equations describing the principles of conservation of mass, energy, momentum, and species. Field models examine a fire in two or three dimensions, breaking the compartment into thousands of cells or elements. Performing these calculations demands the use of powerful computers beyond the capabilities of most personal computers. Network flow models such as CONTAM2.4 are used to evaluate airflow paths composed of doorways, window vents, ducts, and leaks in buildings. These systems are often used to evaluate smoke management systems.

Calculations can also be made that yield the temperature rise on the unexposed wall and ceiling surfaces. Such calculations are meaningful only on the types of barriers that have extensive fire test and actual fire experience, because temperature rise is only one of the ways a fire barrier can fail. Mathematically modeling other failures can be difficult with many common constructions. In determining fire severity, this technique represents an improvement over the single-parameter fire load concept; however, it also is an approximation and has definite limitations.

All fire models have limitations and require some assumptions just as do all other engineering models used to design buildings and building systems. For example, the assumption that the temperature is uniform in the fire room is associated with the less complex postflashover fire models. The turbulence associated with a postflashover fire is assumed to mix the hot gases so that no appreciable temperature gradients exist. In fire models, this assumption is used to calculate mass airflow into the room, heat transfer from the room to walls and ceiling, and pyrolysis of the fuel. This assumption is an approximation, because temperature differences of between 250 and 500°F (139 and 278°C) have been measured within a room during postflashover fires; larger differences could be encountered in larger compartments.[19–21]

The maximum intensity of postflashover room fires occurs when the ventilation is just sufficient to permit fuel-surface-controlled (stoichiometric) combustion.[3] At either higher or lower ventilation levels, the maximum fire temperature is lower.[4] At higher ventilation levels, the fire duration will be shorter, and at lower levels, it will be longer. The ventilation necessary to sustain fuel-surface-limited (stoichiometric) combustion will depend on the combustibles in the room, their exposed surface area, surface burning rate, and the amount of air each pound (kg) of fuel requires for combustion. More ventilation would be needed to sustain fuel-surface-controlled (stoichiometric) combustion if a room contains blocks of foam rubber than if it contains an equivalent fire load of ordinary furnishings. The effect ventilation area has on the temperature of a fully developed room fire is qualitatively shown in Figure 18.1.3.

The majority of experimental fires, which form the basis for the previously described relationships, have emphasized one-room fires, fuel consisting of either ordinary household and business furnishings or wood cribs, fuel loads under 10 lb/ft^2 (48.8 kg/m^2), and at least a level of ventilation provided by an open door or large window representing 10 to 15 percent of the room area. The results of these fires have shown the following:

1. Fire room temperatures may rise much faster than the standard temperature-time curve, remain above the curve for a period of time, and then drop below it.
2. Within a normal ventilation range of about 10 to 15 percent of room area on the low end and 25 to 30 percent on the

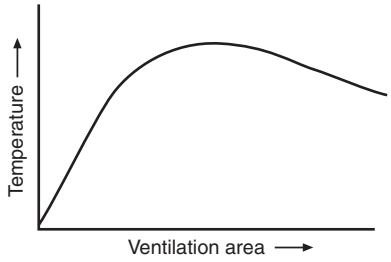

FIGURE 18.1.3 Typical Fully Developed Fire Temperature-Ventilation Curve

high end, the maximum fire temperature depends primarily on fire load, which, in turn, is related to the exposed fuel surface area.

3. Maximum fire temperatures involving ordinary furnishings generally range between 1400 and 1800°F (760 to 982°C). However, ordinary combustible materials with a very high exposed fuel surface area of 8 ft^2/ft^2 (0.74 m^2/m^2) of floor area can result in maximum fire room temperatures over 2000°F (1093°C).

Temperature histories of some typical small room fires in which ventilation was provided by an open corridor door are illustrated in Figure 18.1.4.

Higher temperatures associated with the large fuel surface areas of wood cribs are shown in Figure 18.1.5;[22] the fuel surface area was about 1000 ft^2 (93 m^2) for the 10 lb/ft^2 (48.8 kg/m^2) fire loading.

For more information on fire modeling, see Section 3, Chapter 5, "Introduction to Fire Modeling." For an overview of fire modeling, also see the *SPFE Handbook of Fire Protection Engineering*[23] and *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings.*[24]

FIRE SPREAD

Fire spread rarely occurs by heat transfer through, or structural failure of, walls and floor/ceiling assemblies. The common mode of fire spread in a compartmented building is through open doors, unenclosed stairways and shafts, unprotected penetrations of fire separation barriers, and nonfirestopped combustible concealed spaces. Even in buildings of combustible construction, the common gypsum board or lath-on-plaster protecting wood stud walls or wood joist floors provides 25 to 30 minutes of resistance to a fully developed fire, as determined by a standard fire test.[25] When such barriers are properly constructed and maintained and have protected openings, they will normally

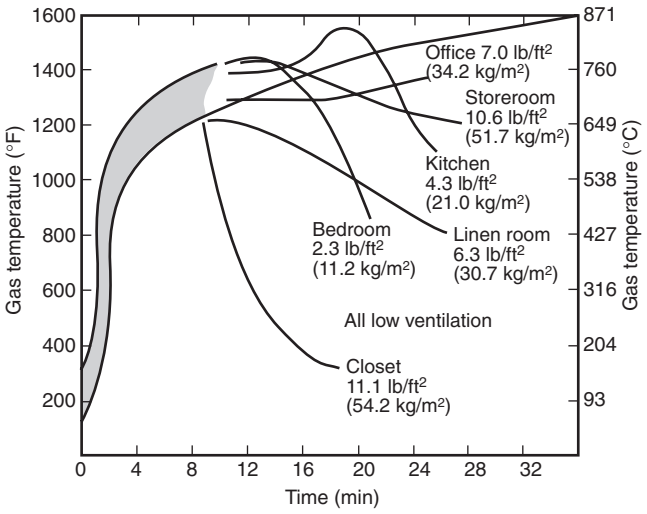

FIGURE 18.1.4 Gas Temperature at Ceiling of Burning Room

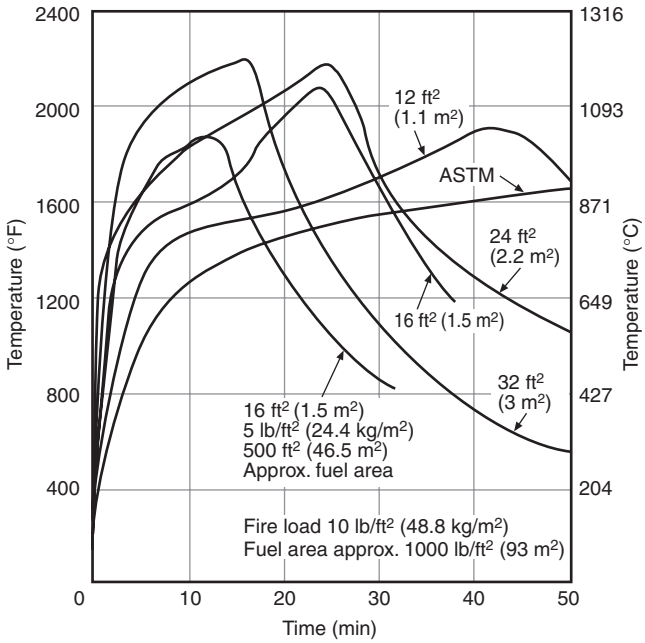

FIGURE 18.1.5 Effect of Window Area on Average Fire Room Temperature

contain fires of maximum expected severity in light-hazard occupancies. However, no fire barrier will reliably protect against fire spread if it is not properly constructed and maintained and openings in the barrier are not protected.

Although typical wall and floor-ceiling constructions generally have adequate inherent fire resistance in light-hazard occupancies, there are practical advantages in requiring rated fire-resistive assemblies in new construction. Materials and construction methods required for fire-rated assemblies provide quality controls not found in typical construction.

Fire can spread horizontally and vertically beyond the room or area of origin and through compartments or spaces that do not contain combustibles. Heated unburned pyrolysis products from the fire will mix with fresh air and burn as they flow outward. This results in extended flame movement under noncombustible ceilings, up exterior walls, and through noncombustible vertical openings. This is a common way fire spreads down corridors and up open stairways and shafts. Similar phenomena have been observed in flame spread underneath the ceiling in industrial and storage buildings. Combustible interior finish in corridors and vertical openings, which by itself may be incapable of propagating flames, will be heated and may produce pyrolysis products. These products add to those from the main fire and increase the intensity and length of flames.

Once a room fire becomes fully developed, fire can spread very quickly to adjacent rooms in the absence of any fire separation barriers. When a building contains similar size rooms, the total volume of the rooms involved in fully developed fires tends to increase at an exponential rate.[26] This is illustrated in Figure 18.1.6, which shows the form of percentage increase in total fire volume, based on the initial room volume as a function of time after the initial room flashed over.

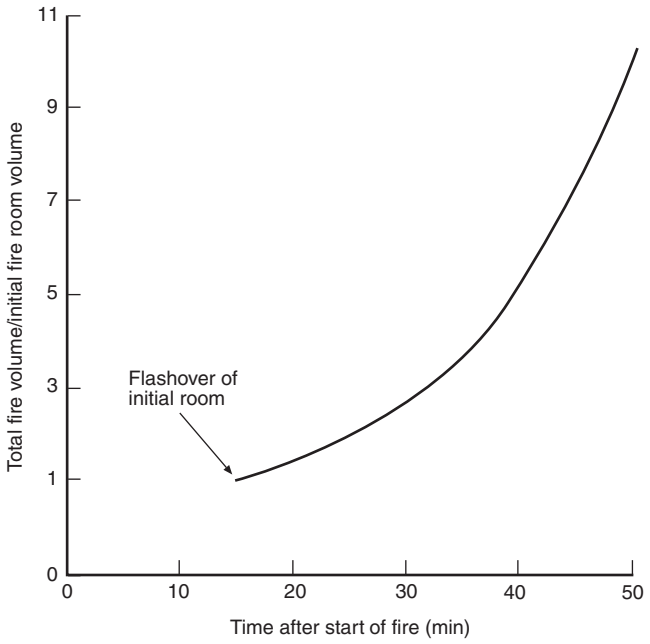

FIGURE 18.1.6 Exponential Fire Volume Increase for a Room Flashover Time of 15 Minutes

Floor-to-floor fire spread along the outside of a building is not a common occurrence, but it can and does occur, such as in the Hilton Hotel fire in Las Vegas, Nevada, in 1981. Glass panes normally break when heated to 550 to 600°F (288 to 316°C), although some breakage may occur at lower temperatures.[27] Glass breakage is actually the result of thermal stress induced by heating the area of the glass panel faster than the area of the frame.[28] The hazard is greater in high-rise buildings because of fire-fighting difficulties and because there are more floors to which fire can spread. Wide spandrels and projections, such as balconies, will reduce the risk of, although not necessarily prevent, external fire spread.

Whether a barrier will or will not contain a fire can be considered as a probability and reliability problem that parallels reliability problems encountered in the operation of electronic, electrical, and mechanical equipment. Using this analogy, barrier failures can be considered to fall into one of three categories: (1) early failures, (2) random failures, and (3) degradation failures. Early failures would be the result of occurrences such as a door not closing or an opening not being protected. Random failures would be the result of faults in materials or construction, a fire of unexpected severity, or design weaknesses not identified by standard testing methods. Random failure probabilities typically follow an exponential law and would predominate until barrier thermal degradation became a factor. Degradation failures would be similar to wear-out failures encountered in electronic, electrical, and mechanical equipment. The probability of a wear-out failure typically follows a normal or Gaussian distribution law, and the probability of barrier degradation failures should be similarly distributed. This technique of considering the three categories of barrier failure probability permits a more realistic comparison to be made between compartmentation and other protective measures. It is also apparent from this analogy that a barrier having a certain fire-resistive rating is not necessarily twice as reliable as one having one-half that rating.

Concealed Spaces

Buildings may contain a wide variety of concealed spaces behind walls, above suspended ceilings, in utility chases, behind soffits, under computer room floors, in attics, and elsewhere. The spaces range in size from 1⅝ in. (41.3 mm) stud spaces to full floor height interstitial spaces. Fires in concealed spaces burn out of sight of building occupants, and detection is frequently delayed. Manual fighting of concealed-space fires can be very difficult because of limited accessibility and inherent venting problems. Vertical concealed spaces also can act as flues to spread fire and hot gases.

Fire development and spread in combustible concealed spaces have long been a cause of large losses in fires. The fire may originate in, or spread into, a combustible concealed space and burn for a long time, spreading throughout the concealed volume. The disastrous Beverly Hills Supper Club and MGM Grand Hotel fires both originated in combustible concealed spaces.[29,30] Fires in horizontal concealed spaces, such as cock lofts, attics, interstitial spaces, and soffits, can spread undetected until they either burn through the floor or roof above or cause parts of the ceiling below to drop. At that time, a fresh air supply, preheated combustible materials, and hot pyrolysis products can combine to produce a rapidly developing fire, which may break out of the concealed space over a wide area. Vertical fire spread inside walls and chases can spread fire between floors and into attic spaces where it mushrooms out horizontally. The rapid vertical spread of fire was quantitatively demonstrated during several full-scale fire tests in wood-frame housing in the Bushwick section of Brooklyn, New York. In one test, temperatures in excess of 1500°F (816°C) were recorded at the top of a 32 ft (9.75 m) shaft 1 minute after a fire was started at the bottom.[31]

Flame spread through horizontal noncombustible concealed spaces is rarely a hazard unless the space contains a significant amount of combustible materials, such as communications or electrical cable trays, plastic pipe, cellular foam insulation, and insulation with a combustible vapor barrier. Isolated combustible items are not likely to propagate fire horizontally; however, they may when grouped together. For example, grouped electrical cables in trays may spread a fire, although any fire spread will be slow and not likely to extend very far from the ignition source; one exception is foam-insulated coaxial cable.[32] This does not mean that such combustibles will not assist in fire spread when they are preheated by hot fire gases from another source. Movement of flame through a noncombustible ceiling plenum space was reported as contributing to the horizontal spread of fire in One New York Plaza.[33] The interstitial space contained a number of electrical communications cables and exposed foam plastic insulation on the inside of the exterior walls. Insulation installed with a combustible vapor barrier exposed can spread fire even if its fuel contribution is very small.

Electrical cables that are difficult to ignite are available and being used in nuclear power plants. New materials have been

developed to meet stringent fire resistance requirements for use in life safety applications. One such application is fire-resistant cables for emergency power supply lines. In tests, fire-resistant cables did not propagate fire horizontally, except in a multiple-stacked tray configuration.[34] Tests have also shown that use of fire-retardant coatings can be effective in inhibiting horizontal fire spread; however, there were major performance differences among the products tested.[35] Although some combustibles do not pose a serious threat of horizontal fire spread in noncombustible concealed spaces, they are likely to pose a serious threat of spread in vertical concealed spaces.

Vertical Openings

Unprotected vertical openings have been responsible for many large loss-of-life fires. These openings can act as a chimney—smoke, hot gases, and burning pyrolysis products flow up under the stack effect and then mushroom out horizontally. Because of their function, openings such as elevator shafts, stairways, laundry chutes, and air shafts cannot be cut off at floor levels. Vertical openings are enclosed with fire-rated walls to prevent fire spread and, in the case of vertical exitways, to provide a safe path of egress for occupants and access for fire department personnel. Vertical interior exitways are often the only avenue of escape to the outside or to adjacent floors for building occupants. NFPA *101*®, *Life Safety Code*®, provides a comprehensive treatment of exits in general and for various types of occupancies involving both new and existing buildings. Detailed requirements are given for enclosing walls, doors, stairs, ramps, escalators, and other components of an exit system.

Shafts containing power, communications cable, combustible ducts or pipes, and other combustible materials should normally be enclosed and often firestopped at each floor. The reliability of the protection of combustible material penetrations through enclosure walls will normally be lower than for noncombustibles. If fire enters a vertical shaft containing combustible materials, it can spread rapidly upward, generate considerable smoke, and possibly spread to other floors.

Room or Suite Compartmentation

The goals of compartmentation in confining a fire to the room or suite of rooms of origin are generally the following:

1. Segregate a space that has a higher fire hazard than the surrounding area. This is commonly found around rooms or suites used for storage, trash, flammable liquids, furnaces, laboratories, maintenance, and shops such as woodworking or painting.
2. Compartmentation is also used to protect locations of high value or critical operations from a fire in the surrounding area. Computer rooms, control rooms, vaults, record rooms, and high-value storage areas are often protected from a fire involving the rest of the building.
3. Minimize risk of loss of an occupant of one space as a result of a fire in space controlled by another. This is common in apartments, office suites, motel/hotel rooms, row houses, and other multitenant buildings.

An added benefit is that compartmentation limits the size of the fire, which limits the amount of smoke that will be generated and facilitates fire suppression.

Properly designed and installed compartmentation has been successful in limiting many fires to the unit of origin. In a number of high-rise fires, occupants who were unable to escape safely through corridors were able to "sit out" a major fire in an apartment adjacent to theirs.[36] A common cause of "failure" of this level of compartmentation has been a door that did not have a closer or was left open.

When a single room is compartmented, there may be insufficient ventilation for a fire to develop fully unless a window is open or happens to break. Occasionally such fires will completely self-extinguish.

Protection of Corridors

Fire-resistive corridor partitions may be required to (1) protect the means of access to an exit for sufficient time to permit occupant evacuation or (2) provide a protected means of access to the fire department personnel. In addition, when used in conjunction with room-to-room or suite-to-suite fire-resistive separation, the corridor wall forms an element in preventing fire spread.

Corridor partitions in nonsprinklered buildings typically are required to have a 1-hour fire resistance rating, and codes may require the partition to extend from the floor to the underside of the floor above. Either automatic or self-closers are generally required on doors opening into the corridor. Since smoke entering the corridor is a significant problem, as the corridor provides access to the exits, automatic door closers, if used, are generally actuated by smoke detectors. Additional information on corridor doors can be found later in this chapter where protection for openings is discussed. Corridor walls that resist the passage of smoke have become common applications in some occupancies that are fully or completely sprinkler protected. These walls generally do not have a specified fire resistance rating. Their intent is strictly to restrict movement of smoke beyond the barrier.

Building Separation

Walls separating two buildings or dividing a building into separate fire areas limit the maximum probable property loss and also can divide one building into what is legally two or more buildings to comply with the height and area limits of building codes. Stability becomes a very important consideration in this class of wall. Although all fire separation walls must maintain their stability under fire exposure for their rated duration, walls separating buildings or dividing a building into two fire areas must maintain stability during a complete burnout on either side, which is often accompanied by structural collapse of the burned-out side.

If at least one of the buildings has a fire-resistive frame—such as reinforced concrete or protected steel—panel walls built in along a column line can provide fire separation. The frame must have sufficient resistance to withstand a fire of the maximum expected severity for that building. Care must be taken so that the floor construction will not adversely affect stability of the wall under fire exposure. In buildings of Type V (wood

frame), Type IV (heavy timber), or Type III (ordinary) construction, the combustible framing members can be tied into the fire wall so that they are self-releasing in case of collapse. The wall then remains supported by the framing on the unexposed side. The use of self-releasing framing is considered to have been generally successful in combustible construction but has questionable reliability in steel-framed buildings. Caution must be exercised in the design of these fire walls because some methods of framing combustible members into the wall will lower its fire resistance.

Freestanding fire walls are most commonly used in one- or two-story industrial and storage buildings of unprotected steel-frame construction. The maximum height is generally limited by economic considerations. A freestanding fire wall is entirely self-supporting under vertical loads and is not directly connected to the building framing. The adjacent building framing can provide support under horizontal loading. During a fire, the wall must be capable of acting as a cantilever to withstand all horizontal forces directed toward the fire side. Freestanding fire walls should be designed to withstand at least a 5 lb/ft^2 (24.5 kg/m^2) uniform lateral loading without any support from the framing on either side.[37]

Tension stress in mortar joints limits the height of unreinforced 12 in. (0.3 m) concrete block walls to 15 ft (4.6 m). Higher walls either require massive construction, which is rarely practical, or reinforcement. A common reinforcement technique is installation of vertical steel bars, anchored to the foundation, within hollow masonry units that are then filled with concrete. Reinforced pilasters can also be built into the wall at periodic points along the perimeter. A typical freestanding fire wall is illustrated in Figure 18.1.7.

Freestanding fire walls have very definite limitations under horizontal forces, which may preclude or restrict their use. They are particularly vulnerable to collapse under seismic loads and wind forces received by exterior walls. Additional support must be provided if the walls are temporarily used as an exterior wall or become an exterior wall as a result of a fire. Piping, conveyors, and similar items whose collapse in a fire will exert a horizontal pull should not pass through freestanding fire walls. Where they must, means should be provided to allow the penetrating items to break away without impacting the wall.

Fire walls in steel-frame buildings may be tied into the building structure so the forces of collapse on one side are resisted by the framing on the other side. The wall may be built along a column line and the columns and horizontal framing tied into the wall. The columns and framing in the wall line must be protected so that they have the same fire resistance as the wall. The walls have to be located in the framing so that the strength of framing on one side will be capable of withstanding the pull of collapsing framing on the other side. The construction of a typical tied fire wall is shown in Figure 18.1.8.

Fire separation between buildings can also be provided by two blank exterior walls of adequate fire resistance and located very close together. Each wall is tied to the frame in its building; collapse of the frame pulls the wall in, leaving the other wall to resist the fire.

Pipes, conveyors, cable trays, and similar through-penetrations of fire walls can present special problems in seismic areas. The need for mobility may conflict with opening protection

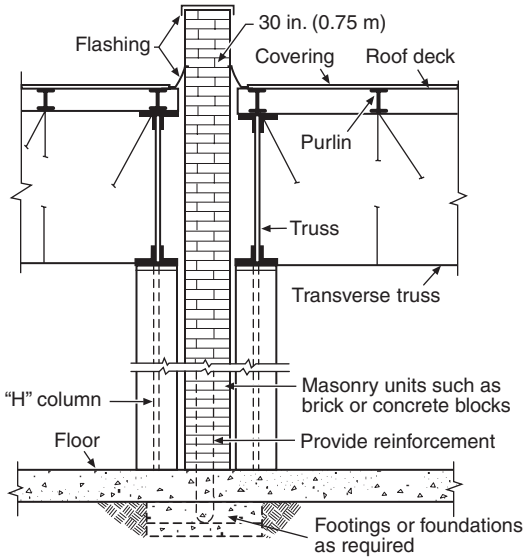

FIGURE 18.1.7 Typical Freestanding Fire Wall, Used at Expansion Joints or at Joints Between Buildings

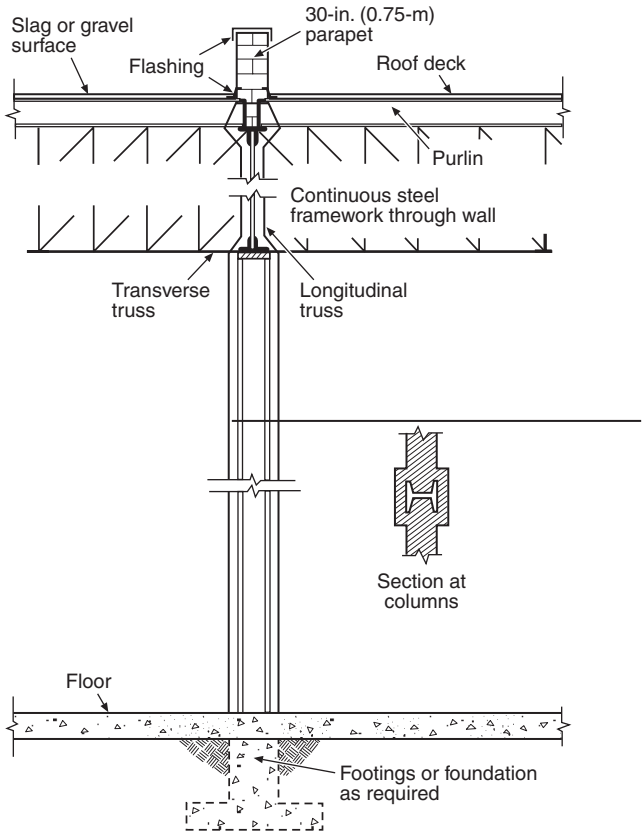

FIGURE 18.1.8 Typical Tied Fire Wall, Used with Continuous Building Framework

criteria. The complexity of the problem depends on whether the systems are to be designed to protect against one hazard at a time (fire or earthquake) or whether the simultaneous or consecutive occurrence of earthquake and fire should be considered in protection. See NFPA 221, *Standard for High Challenge Fire Walls, Fire Walls, and Fire Barrier Walls,* for minimum requirements for walls that separate buildings or subdivide buildings and prevent the spread of fire.

Fire Plumes Above Roofs

Fire walls must extend through and above a combustible roof to reduce the risk of fire spread over the top of the wall. Codes and standards typically call for fire walls to have a parapet 18 to 36 in. (0.46 to 0.9 m) above a combustible roof. The parapet minimizes the risk of direct flame spread over the fire wall and reduces the risk of fire spread by radiant heat from flames above the roof. The risk of direct flame spread over an 18 to 36 in. (0.46 to 0.9 m) high parapet is very low. However, risk of fire spread by radiant heat depends on the ease of combustibility of the roof surface, the height of the parapet, the dimensions of the fire plume through the roof of the fire zone, the wind velocity, and, if the roof covering is resistive to ignition by radiant heat, its insulating properties and the duration of the exposing fire. If a roof surface is combustible, the risk of fire spread by radiant heat past a parapet can be quite high.

The threat of fire spread by radiant heat over a parapet can be calculated using the thermal radiation values identified in Annex A of NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures,* and the plume dimensions.[38] Standard heat-transfer procedures can then be applied, using the formula:

$$I = I_o \Phi$$

where

I_o = Radiating intensity of the fire plume

Φ = Configuration factor or view factor

I = Unit incident radiation on the exposed surface

Instead of using the referenced radiant intensities, the average temperature of the plume flames can be estimated and the radiation calculated using the following relation:

$$I = \sigma T^4 \Phi$$

where

σ = Stefan-Boltzman constant

T = Absolute temperature

This assumes the flame plume is sufficiently thick so that it radiates as a black body.

The configuration factor for plume-roof relationships can be calculated using the formula found in a cited reference.[39] The effect of wind velocity, which deflects the fire plume, must be accounted for in calculation of the configuration factor. At high winds, a fire plume can be deflected such that it is almost horizontal above a burning roof. However, in high winds, a fire plume also tends to break up and is expected to be cooled by excess air. The angle of the fire plume selected is a matter of professional judgment; use of 45 degrees is considered reasonable by some engineers.

If the roof surface is combustible, the value of the incident thermal radiation calculated will indicate whether ignition of the roof is expected. If the surface is noncombustible or resistive to ignition by radiant heat, it is then necessary to calculate the temperature of the combustible subsurface material to which heat will be transferred from the surface. This is an unsteady-state heat transfer problem readily solved by standard numerical procedures.

A simple example of the calculation of incident thermal radiation can be used to illustrate the method of analysis. For the example, consider a 12 ft (3.7 m) high and 60 ft (18.3 m) wide frame building with a wood-surfaced roof. The building is subdivided by a masonry fire wall with a 3 ft (0.9 m) parapet (Figure 18.1.9).

The expected height of flames above the roof would be about 1.4 times the height of the building, or approximately 17 ft (5.2 m).[39] Assuming a flame temperature of 1400°F (760°C), the thermal radiation from the fire plume would be about 5.8 Btu/ft^2/sec (66 kW/m^2). In a moderate wind, a fire plume deflection of 45 degrees is possible. The maximum configuration factor would be about 0.3 and the incident radiation on the wood roof surface about 1.75 Btu/ft^2/sec (20 kW/m^2).

At an incident radiation of 1.1 Btu/ft^2/sec (12.5 kW/m^2), a wood roof can be sufficiently heated so that a small burning brand will ignite it;[40] this is referred to as pilot ignition. Since in the example the incident thermal radiation is well above that required for pilot ignition, flame spread over this fire wall is to be expected if the wind deflects the fire plume toward the exposed roof.

Fire-Resistive Wall Requirements for Structural Stability

Fire-rated wall requirements may be intended to ensure structural stability rather than to provide a fire barrier. In many cases,

FIGURE 18.1.9 Fire Plume Exposing a Wood Roof over a Parapeted Fire Wall

for example, hourly rated exterior bearing walls are permitted to have unlimited unprotected window areas; it is obvious that the rating refers to structural stability rather than provision of a fire barrier. Required fire ratings of interior bearing walls may or may not be intended to provide a fire barrier. Interior bearing walls with an hourly rating for fire separation do require protection of all openings; however, interior bearing walls that have an hourly rating only for structural stability purposes would not need opening protection. Caution must be exercised in selecting the proper hourly rating for interior bearing walls intended for structural stability only. A barrier separation wall is exposed to fire on only one side, where an interior bearing wall that would be providing only structural stability could be exposed to fire on both sides. The same hourly rating wall will not provide the same protection in both cases.

Fire-resistive walls of a high hourly rating are occasionally improperly specified to separate areas for protection against an explosion hazard rather than a long-duration fire. The fire resistance of a wall has no relationship to its ability to withstand explosion forces. A wall with a 1 hour rating may withstand explosion overpressures better than a wall with a 4 hour rating; no conventional wall will remain in place unless the explosion pressure is limited by venting or suppression.

PROTECTION OF OPENINGS

The protection for openings in a fire-rated wall generally has less resistance to fire spread than is provided by the wall. This is allowable because (1) easily ignited combustibles are not normally found against doors and other opening protection constructions, and (2) fire suppression forces can usually extinguish small localized fires that may spread past the wall. However, because openings do reduce the effectiveness of a fire barrier, fire doors generally cannot occupy more than 25 percent of the linear length of any fire separation wall. Clearances may be required in front of and to the sides of the opening to compensate for the differences between a wall rating and door rating.

Factors that reduce the fire resistance of opening protection as compared to resistance of walls include the following:

1. There is no maximum temperature-rise limitation on the unexposed sides of most types of fire doors. The unexposed side of steel doors may actually glow red during fire testing. When there is a limit to, or listing of, a temperature rise on a fire door, it applies only to the temperature rise during the initial 30 minutes of the fire test. (Temperature-rise limits are often specified in building codes for doors on exit stair enclosures.) Fire doors also buckle during the fire tests and are permitted to move out of their frames in a direction perpendicular to the plane of the door as much as 2.88 in. (73 mm). Some flaming is also permitted on unexposed sides of fire doors during the test procedures.

2. Requirements for the protection of duct penetrations place no limit on the temperature rise on the duct itself on the unexposed side of the wall.

3. Piping, cable trays, and conduit can penetrate fire walls and, although the opening must be firestopped, the temperature rise on the metal penetration itself would normally be above the 250°F (121°C) average or 325°F (161°C) single-point temperature-rise limit required of the wall. However, some codes require use of through-penetration firestopping systems that have a temperature-rise limitation on the penetrating item also.

4. The standard fire test furnace is operated at a pressure rating so that a neutral plane is established with the tested assembly. As a result of research studies, ASTM modified the test standards for fire doors and fire windows to require positive pressure testing of some elements. The neutral plane is established based on the assembly being tested. For example, within the first 5 minutes of the window test, the neutral plane is established so that at least the upper two-thirds of the window assembly is under positive pressure.

5. Vision panels and fire windows may transmit heat by both conduction and radiation.

6. Doors can become large radiators during early fire tests.

Thermally induced distortions of between 4 and 5 in. (102 and 127 mm) were observed on some foreign tests of swinging steel fire doors.[41] Considerably smaller distortions were noted with wood and insulated metal swinging doors. However, wood doors were noted as being more likely to fail by localized carbonation at hinges, locks, and knobs. Rolling steel fire doors generally do not deform appreciably during a fire. Large distortions of some rated fire doors, both wood and metal, were also reported in "Project Corridor," a series of fire tests conducted by the California State Fire Marshal in a simulated light-hazard occupancy.[42] In some countries, extensible bolts and latches are added to swinging steel fire doors so that the door is held in the frame at five or six points. Distortions of this type of door were reported to be under 1 in. (2.54 mm) during a standard fire test.[39]

However, the most common failure mode of fire doors observed in actual fires is not closing. This has occurred because of lack of maintenance; physical damage to the closer, door, guides, or tracks; blockage in the doorway; and other faults. Reliable fire door performance cannot be ensured unless doorways are kept clean and doors maintained in operating condition, as specified in NFPA 80, *Standard for Fire Doors and Other Opening Protectives,* and the manufacturer's instructions. Some common faults often observed on swinging fire doors include inoperative latches and improperly adjusted closing devices. Overhead and sliding doors that are not used regularly are particularly susceptible to track and guide damage. The closing mechanism on overhead doors is a more complicated and less visible mechanism than the closing mechanism on most other fire doors. Inspection, testing, and proper preventive maintenance are always essential.

Fire doors, windows, and shutters are the most widely used and accepted means of protecting openings in fire-resistive walls. Suitability of these closures is determined through tests by recognized testing laboratories, and untested doors cannot be relied on for effective protection. Fire door assemblies for the protection of openings depend on the use of labeled fire doors and frames (where frames are required) and listed or labeled hardware. Hardware for fire doors is referred to as "builder's hardware," which includes fire exit hardware and fire door hardware.

Doors must be installed in a properly constructed wall and floor so that fire cannot spread below, around, or above the door. Special noncombustible sills are required for door openings in buildings with combustible floors, except for openings protected by 20 or 30 minute doors. However, combustible floor coverings may extend through openings protected by fire doors rated at 1½ hours or less if the cover has a critical radiant flux of 0.22 W/cm^2 or greater. Critical radiant flux is to be determined per NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source.* In general, the critical radiant flux for vinyl sheet and flooring, wool carpet, and some synthetic carpets will exceed 0.22 W/cm$^{2.}$ Combustible floor coverings may not extend through openings required to be protected by 3-hour or higher-rated doors.

Classification of Openings, Doors, and Windows

Fire doors are now rated according to the duration of fire exposure and, optionally, the temperature rise on the unexposed surface after 30 minutes, when tested as per NFPA 252, *Standard Methods of Fire Tests of Door Assemblies.* Doors are rated as 4 hour, 3 hour, 1½ hour, 45 minute, 30 minute, and 20 minute. Temperature rises are listed at 250, 450, and 650°F (121, 232, and 343°C); absence of a temperature rating indicates a rise of over 650°F (343°C) on the unexposed surface of the door after 30 minutes of testing. There is no temperature rise limitation for most types of fire doors. Fire doors tested under NFPA 252 are exposed to a standard temperature-time curve and a hose stream test. The hose stream test is not always required by the authority having jurisdiction for 20 and 30 minute doors. Those doors that are fire tested without a hose stream test indicate this fact on the label. The categories in which fire doors are classified are also identified on the label; these include access, bullet-resisting, chute, curtain, dumbwaiter, freight elevator, rolling steel, service counter, sliding, special-purpose, and swinging-type doors.

Existing fire doors and windows may be classified by an hourly rating designation, an alphabetical letter designation, or a combination of these. At one time the alphabetical letter designation was one method commonly employed to classify the opening for which the fire door is considered suitable. Traditionally, the relationship between the alphabetical designation and its use was as follows (from NFPA 80, Appendix E):

1. Class A—Openings in fire walls and in walls that divide a single building into fire areas
2. Class B—Openings in enclosures of vertical communications through buildings and in 2 hour rated partitions providing horizontal fire separations
3. Class C—Openings in walls or partitions between rooms and corridors having a fire resistance rating of 1 hour or less
4. Class D—Openings in exterior walls subject to severe fire exposure from outside the building
5. Class E—Openings in exterior walls subject to moderate or light fire exposure from outside the building

The alphabetical classification of the opening does not apply to the closure; however, in actual practice, the distinction between opening classification and door classification was rarely maintained. A 3 hour door for use in a Class A opening was commonly called a Class A door.

Building codes and NFPA 80 commonly specify a door by its fire-protection rating instead of by the classification of opening to be protected. Fire doors are now available with ½ hour and ⅓ hour ratings, which do not fall within the specified protection criteria for the classes of opening. The following paragraphs summarize current application of doors, windows, and shutters for openings in fire-resistive walls.

Four and Three Hour Fire Doors. Openings in walls separating buildings or dividing a building into different fire areas are generally protected by 4 or 3 hour fire doors. Many codes only require 3 hour fire doors in separation walls required to have a fire resistance of 3 hour or more. However, some authorities require two 3 hour fire doors, one on each side of the opening, whenever a wall is required to have a fire resistance of 4 hours. Four-hour fire door listings are relatively recent, and their availability may not be reflected in all codes.

One-and-One-Half Hour Fire Doors. Openings in 2 hour enclosures of vertical openings in buildings are protected by 1½ hour fire doors. Many codes also permit the use of 1½ hour fire doors to protect openings in walls separating buildings or dividing buildings into different fire areas when the wall is only required to have a fire resistance of 2 hours. One-and-one-half hour fire doors are used in walls required to have a 2 hour fire resistance to enclose hazardous areas.

One-and-One-Half Hour Fire Doors and Shutters. Openings in exterior walls that can be subjected to severe fire exposure from outside the building are protected by 1½ hour fire doors and shutters.

One Hour Fire Doors. Openings in 1 hour enclosures of vertical openings in buildings, such as stairs, shafts, and exit enclosures, are protected by 1 hour fire doors.

Three-Quarter Hour Fire Doors. Openings in room partitions and walls around some hazardous areas are protected by ¾ hour fire doors. Sometimes they are also permitted in partitions that subdivide floors of a building. Although ¾ hour fire-rated doors are for use in 1 hour corridor partitions, many codes permit installation of other types of doors, such as ½ or ⅓ hour fire-rated or 1¾ in. (45 mm) solid-bonded wood-core doors. Either automatic closers or self-closers are generally required on corridor doors. Since control of smoke is also necessary to protect a corridor as an access to an exit, automatic closers are generally actuated by smoke detectors.

Three-Quarter Hour Fire Doors and Shutters. Openings in exterior walls subject to a moderate or light fire exposure from outside the building are protected by ¾ hour fire doors and shutters.

Three-Quarter Hour Fire Windows. Openings in corridor or room partitions or in exterior walls subject to a moderate or light external fire exposure can be protected by ¾ hour fire windows.

One-Half Hour and One-Third Hour Fire Doors. Doors with these ratings are for use where control of smoke is a primary consideration. They are also used for the protection of openings in partitions between a habitable room and a corridor when the wall is constructed to have a fire-resistance rating of not more than 1 hour or across corridors where a smoke partition is required. Some codes permit the use of 1¾ in. (45 mm) solid-bonded wood-core doors in corridor, room, and smoke-stop partitions that are required to have a fire resistance of not more than 1 hour. These doors cannot be used for corridor doors to hazardous areas or to protect openings in enclosures of vertical openings in buildings.

Types of Doors

There are several types of construction for fire doors, which are described in the following paragraphs.

Composite Doors. These are of the flush design and consist of a manufactured core material with chemically impregnated wood-edge banding and untreated wood-face veneers or laminated plastic faces or are surrounded by and encased in steel.

Hollow Metal Doors. These are of formed steel of the flush and paneled designs of 20 gauge or heavier steel. These doors may include a honeycomb core.

Metal-Clad Doors. These are of flush and paneled design consisting of metal-covered wood cores or stiles and rails and insulated panels covered with steel of 24 gauge or lighter.

Sheet-Metal Doors. These are of formed 22 gauge or lighter steel and of the corrugated, flush, and paneled designs.

Rolling Steel Doors. These are of the interlocking steel-slat design or plate-steel construction.

Tin-Clad Doors. These are of two- or three-ply wood-core construction, covered with 30 gauge galvanized steel or terneplate (maximum size 14–20 in. [0.36–0.51 m]) or 24 gauge galvanized steel sheets not more than 48 in. (1.2 m) wide.

Curtain-Type Doors. These consist of interlocking steel blades or a continuous formed-spring steel curtain in a steel frame.

Wood-Core Doors. These doors consist of wood, hardboard, or plastic-faced sheets bonded to a wood block or wood particleboard core material with untreated wood edges.

Unrated Door Protection

The fire resistance of existing doors can be improved by coating the doors with an intumescent paint, although no formal fire resistance rating for such a door has been established. This method is not commonly accepted in the United States, although it has been used in England. Intumescent paint is listed for reducing flame spread, not for improving fire resistance. However, tests conducted by NBS showed that a single layer of intumescent paint, 7 to 8 mil (0.18 to 0.20 mm) thick, significantly delayed char penetration into a soft wood joist.[43] Ordinary wood-panel doors, in which both door and frame were coated with two layers of intumescent paint, withstood fully developed room fires similarly to 1¾ in. (44.5 mm) thick solid-core wood doors in simulated nursing home room fires.[19] In another test, a wood-panel door was protected with gypsumboard on the thin panel and intumescent paint on the remainder of the wood. This upgraded door withstood a standard fire test, modified to simulate the positive pressure of a room fire, longer than a 20 minute rated fire door.[44] However, there is no fire protection rating assigned to any upgraded fire doors; it is entirely up to the authority having jurisdiction whether or not this upgraded door is acceptable for improving the fire safety in existing buildings.

Glazing for Fire Doors, Windows, and Walls

Glazing materials are available for use in fire-rated doors, windows, and walls; they are used as vision panels in fire doors and as windows in fire-rated corridor walls. In addition, they are frequently used in smoke-stop barriers and to enclose open stairways in older buildings.

Wired glass was historically the only transparent material that could be used in fire-rated doors and windows. It is a glass sheet containing an imbedded net of steel that helps distribute heat, lowers thermal stresses, and increases the strength of the assembly. When exposed to a fire, the glass starts cracking after a minute or two but does not open up. The glass begins to weaken when heated to about 1470°F (799°C) and gradually starts to soften. At about 1600°F (871°C) it deforms so badly that it will drop out.[39] Its normal 45 minute fire resistance rating corresponds to 1638°F (892°C) on the standard temperature-time curve. In actual fires, the endurance of wired glass is temperature dependent; if it is never heated above the temperature at which it weakens, it could remain in place for an extended period of time. Wired glass has been the most economical fire protection–rated glazing material.

Clear fire protection–rated glazing has been developed as an alternative to wired glass and to provide a higher hourly fire rating than had been possible with wired glass. These products include fire protection–rated glass and transparent ceramics as well as fire resistance–rated glass. The clear glazing provides more architectural freedom to achieve openness while still meeting building codes' often increased compartmentation requirements. Clear fire protection–rated glazing materials that also can provide security protection are available.

Glazing materials for use in fire-rated windows, doors, frames, and sidelights are tested in accordance with NFPA 257, *Standard on Fire Test for Window and Glass Block Assemblies.* This test includes exposure to a standard temperature-time curve fire on one side for the rated period of time, plus the hose stream test. There also are fire-resistant glazing materials that are suitable for use in specific wall and partition assemblies. These are

tested in accordance with NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter.* This test includes the same temperature-rise limitation on the unexposed surface of the glazing material as on the wall.

Vision panels are permitted in fire doors rated at 3 hours or less. However, vision panels in 3 hour fire doors and fire doors with a 1½ hour rating used in protecting severe exterior exposures must be tested as a component of the door assembly in accordance with NFPA 252. These vision panels are limited to 100 in.^{2} (0.065 m^2) or less. Wired glass may not be used in 3 hour fire doors or 1½ hour doors used for severe exposure protection. Vision panels used in 1½ hour and 1 hour fire-rated doors is limited to the maximum area tested. In ¾ hour rated doors and windows and 20 and 30 minute doors, wired glass is limited to 1296 in.^{2} (0.84 m^2) per light with a maximum dimension of 54 in. (1.37 m). In all applications, the maximum exposed area and area per light for glazing material other than wired glass are listed individually for each product.

Glazing materials used in fire doors, windows, sidelights, and commercial lights must also meet applicable safety standards if these are subject to human impact. These current standards include the U.S. Consumer Product Safety Commission (CPSC) *Safety Standard for Architectural Glazing* and the less stringent, in terms of impact resistance, ANSI Z79.1, *Safety Performance Specifications and Methods of Test for Safety Glazing Materials Used in Buildings.* Wired glass is specifically exempt from the CPSC standard but not the ANSI standard.

Glazing materials in fire doors, windows, and frames are commonly installed on the job site and not provided by the manufacturer of the fire door. The door manufacturer provides grooves in the door for the glazing, and the glazing manufacturer or distributor supplies the glazing in the necessary light sizes. NFPA 80 requires each light to have a visible listing mark when installed. This mark may be the only way to identify whether the glazing installed is clear fire protection–rated material or ordinary commercial glass. Installation and caulking requirements are very specific and specified in the individual listings. Grooves and installation methods and materials used for wired glass will generally not be suitable for use with other glazing materials.

Vision panels and windows differ from a solid wall primarily in the transmission of radiant heat. Conductive heat transmission is also increased, but high conductive heat transmission is also found in doors, door and window hardware, and frames. The intensity of radiant heat, I, to which a combustible or person would be exposed through a wired-glass panel from a fully developed room fire, is given by the following formula:

$$I = k\Phi I_0$$

where k is the transmissivity of the window, Φ is the configuration factor, and I_o is the radiant intensity of the exposing fire. This equation may be used for U.S. customary or SI units, as long as their use is consistent.

A radiant intensity of 5 Btu/ft^2/sec (57 kW/m^2) has been measured for a room fire involving ordinary residential furnishings with average ventilation, such as an open door.[45] Measurements of well-ventilated fires in light-hazard occupancies indicate a peak radiant intensity of 7.4 Btu/ft^2/sec (84 kW/m^2).[30] Transmissivity of glass windows is reported to range from 0.4 to 0.6.[40] These values of transmissivity are reasonable for the early period of fire exposure; as the glazing is exposed to the fire for a period of time, its transmissivity will be reduced. The configuration factor can be determined from any specific situation for graphs found in most heat-transfer texts.

If wood on the unexposed side of the wired glass is exposed to a radiant intensity above 3 Btu/ft^2/sec (34 kW/m^2), autoignition may occur. Most synthetic materials will require a higher level of radiant heat intensity for autoignition.

When wired-glass panels are installed in walls on a dead-end corridor or other location in which building occupants have no alternative escape path, the heat radiated through the glass may prevent escape. If persons moving past the glass absorb sufficient heat to cause severe pain, their ability to escape could be impaired. The human threshold of severe pain for exposure to radiant heat depends on both the intensity and the time over which it is received. Experimental data that have defined this limit[46] can be approximated by the following equation:

$$Q_{max} = 2.3t^{0.25} \leq 45 \text{ sec}$$

where Q_{max} is the total heat absorbed by the skin in Btu/ft^2 (W/m^2) over t seconds at the threshold of severe pain. As a person moves past the wired-glass panel, the view factor, Φ, will change. The absorbed heat can be calculated by determining Φ for a number of points along the person's path and using a stepwise integration over the time required to move past each point. The normal walking speed used in exit calculations is 3.5 ft/sec (1.07 m/sec).[9] If the total heat absorbed exceeds the limits in the equation, the escape of occupants past the wired-glass panels may be impaired.

Fire Blocking and Firestop Protection

The term *fire blocking* is used to describe both barriers to restrict the spread of fire in concealed spaces. Materials used to fill gaps around penetrations in walls and ceilings are called firestop devices or systems.

In wood-frame construction, the normal fire block inside walls and ceiling spaces is a 2 in. (50.8 mm) thick (nominal) piece of lumber. However, for other applications, fire blocking should normally be noncombustible and have a sufficiently high melting point so that it will remain in place under fire exposure. Gypsum board, sheet metal, plaster, brick, cement grout, mineral fiber insulation, fire blocking, and ceramic fiberboards are all examples of commonly used fire blocking. Firestop systems protect penetrations of fire-rated walls and floors by noncombustible pipe or tube, and conduit has commonly been provided by filling the annular space around the penetrant with a noncombustible material, such as cement grout, mineral wool, cement plaster, and so forth. This type of firestop system is regarded as having performed effectively in actual fires. However, lack of firestop systems[29,30] or improperly protected openings, such as the combustible foam plastic used at Brown's Ferry Nuclear Plant,[47] have been responsible for a number of serious fire losses.

Considerable attention and research have been directed toward wall and floor penetrations by plastic drain, waste, and vent

(DWV) pipes.[48–51] Full-scale tests have shown that the integrity of a 2 hour fire-resistive chase enclosure could be maintained by encasing the pipe in an 18 in. (0.46 m) steel sleeve and penetrating the chase at a 45 degree downward angle. These results were applicable to 3 in. (76 mm) laterals of both PVC and ABS DWV pipe. Unless otherwise tested and approved, chases should be firestop protected at each floor. In many buildings, much of the plumbing is installed in wall cavities. Use of plastic DWV pipe inside fire-resistive wall assemblies has been extensively tested, and a number of methods of protection that will not compromise the fire resistance or create a risk of vertical fire spread have been identified.

Cable-tray penetrations present another challenge; the size of the penetrant is large and contains a mixture of combustible and noncombustible material. Research and development programs were sponsored by the Nuclear Regulatory Commission (NRC) on firestops for use in nuclear power plants. The results of these programs, plus work by suppliers, led to new firestop products.

Building codes require approved and tested firestops wherever conduit, pipe, cables, or other utilities pass through fire-rated—and sometimes non-fire-rated—walls, floors, and ceilings. These firestop products can be qualified under either ASTM E814, *Standard Test Method for Fire Tests of Through-Penetration Fire Stops,* or under a fire exposure corresponding to ASTM E119, *Standard Test Method for Fire Tests of Building Construction and Materials.* The test furnace must be operated at a specified positive pressure, such as 0.01 or 0.03 in. of water column (2.5 or 7.5 pascal). Currently, neither of these tests evaluates smoke spread.

There are two types of tested firestop protection: (1) through-penetration firestop devices and (2) through-penetration firestop systems. The firestop devices are manufactured products used primarily for protecting cable and poke-through penetrations. Through-penetration firestop systems are field-installed constrictions for protecting penetrations of floors or walls by conduit, pipe, duct, cable, cable trays, and so forth. The basic standard used to investigate these firestops is UL 1479, *Standard for Safety Fire Tests of Through-Penetration Firestops,* which is based on ASTM E814.

ASTM E814 was developed for evaluating firestops that are installed to prevent spread of fire through an opening where cable trays, pipe, conduits, ducts, and so on, pass through a wall or floor. This standard was first published in 1981. The ASTM E814 test has many similarities to ASTM E119, but it can be conducted on a much smaller scale and at a documented positive pressure. In addition, all test items are subject to a hose stream test similar to that required for some constructions tested under ASTM E119. ASTM E119 requires testing of at least a 100 ft^2 (9.3 m^2) sample of a wall and a 180 ft^2 (16.2 m^2) sample of a floor. A wall or floor sample less than 9 ft^2 (0.83 m^2) can be used in ASTM E814. The ASTM E814 furnace is heated to follow the temperature history of ASTM E119. There is no standard "aging" test for the new firestop materials; one proprietary product recently was recalled because its reliability apparently deteriorated with age.

Two types of hourly time ratings are established for a tested firestop: F and T. The conditions for these ratings are broader. The F rating is a measure of the ability of the firestop system to maintain its physical integrity under the fire exposure and hose stream tests and to prevent occurrence or passage of flame on the unexposed surface. The T rating is intended to measure whether combustible materials on the unexposed side of a fire barrier would be ignited by conduction of heat through the firestop material or along the penetrating conduit or pipe. The same maximum temperature limit is used in the ASTM E814 test as in the ASTM E119 test. The hourly F or T rating is the duration of the fire test that the through-penetration firestop system passed.

The T rating achieved can be less than the F rating; there is nothing similar to this in the ASTM E119 test. If the temperature limit is reached before the completion of a successful test for an F rating, the T rating will be based on the time at which the temperature limit was reached. However, the F rating assigned would be the total hourly duration of the successful test. Building codes that require firestop systems tested under ASTM E814 differ as to if and when a T rating is necessary.

There are many types of listed through-penetration firestop system constructions, ranging from relatively simple to complex arrangements. A typical through-penetration firestop system requires installation of both a form and a fill material. The form material is generally a ceramic fiber mat; a hole the size of the penetrating conduit (or pipe) is cut in it and the form is slipped over the conduit into the opening in the wall or floor. The form material serves to place and restrain the fill material that is installed in the annular space around the conduit to a specified thickness. Fill materials include one- and two-part foams, silicone elastomers, proprietary caulking and grouting materials, and specific proprietary cementitious mixtures.

Some through-penetration firestop systems also require use of an additional filling material, such as ceramic fibers, and some only require a single material, such as a proprietary caulk or grout. There are a number of through-penetration firestop systems that are much more complex and require additional features, such as sleeves, special supports to retain the system in the opening, and insulation on the conduit or pipe extending out from the surface of the floor or wall.

Some of these systems permit penetrating items to be easily removed or replaced. This facilitates future additions of pipe, tube, or cable through the penetration opening. However, restoration of the integrity of the original firestop may or may not be possible under the conditions of the system's listing by a testing laboratory. Any additions or changes that require removal and restoration of a through-penetration firestop system have to be tightly controlled so that (1) the restoration is performed in an approved manner, (2) the allowable number of penetrating items is not exceeded, (3) only permitted penetrants are installed, and (4) adequate clearances are maintained among penetrating items and between penetrating items and the sides of the opening.

Some designs for curtain walls, particularly in high-rise buildings, offer the danger of vertical spread of fire behind the curtain walls for the entire height of the building. This can occur when the panels of a curtain wall do not rest tightly for their full length on a floor slab. Rather, there is a continuous relieving angle attachment between the panels and the floor slab, creating vertical flue spaces between the panels and the end of the

floor slab. Where fire blocking is not inherent in the design, it is necessary to fill this space with appropriate fire block materials. This arrangement is generally less satisfactory because of the tendency for both expansion and contraction of the exterior wall and the likelihood of maintenance operations causing unplanned openings through and around the firestopping.

Atria

Atria, which are common in many new buildings, depart from the traditional compartmentation concept of fire containment by enclosing all vertical openings. Alternative arrangements must be provided in atrium buildings to achieve the same level of protection found in buildings using the traditional compartmentation concept. The occupancy should be one in which a rapidly spreading fire would not be encountered, and all occupants should be expected to be aware of any hazards before they are endangered, and in time to move to a place of safety if necessary.

Fire protection in atrium buildings is generally provided by a combination of methods, such as compartmentation, ventilation, automatic suppression, and contents and material control. NFPA *101* requires atria in new construction to be separated from adjacent spaces by fire barriers having at least a 1 hour fire resistance rating. However, as many as three levels of a building may open directly to the atrium without the need for a fire-resistive barrier. As an alternative where 1 hour barriers are normally required, glass walls may be used, provided there are sprinklers spaced 6 ft (1.8 m) apart and not more than 1 ft (0.3 m) from the glass along both sides of the glass wall. The sprinklers must be located to ensure that the glass surface is wet when the sprinklers operate. Sprinklers are not required on the atrium side of the glass wall if there is no walkway or other floor area on that side above the main floor level.

Large-volume atria will dilute fire gases and, with proper ventilation, direct their flow safely to the outside. Small atria may not have the capacity to dilute fire gases, although if they are properly designed and ventilated, fire gases can be channeled to the outside and the risk of horizontal fire spread minimized.

SUMMARY

Barriers can protect people and property by confining a fire to its area of origin until it either is extinguished or burns itself out. Fire resistance ratings of barriers are based on fire endurance tests and are measured in hours or fractions thereof. The basis for almost all fire-resistive testing is the standard temperature-time curve.

The concepts of fire severity and fire load, although technically obsolete, are still used to make conservative estimates of the maximum severity of a fire. Fire load is a measure of the maximum heat that would be released if all the combustibles in a given area burned. Fire modeling is based on mathematical models that calculate the temperature history of room fires as a function of ventilation, fuel, and the walls and ceiling of the room. The most widely used models in the United States are zone models, exemplified by the CFAST component of HAZARD.

Several aspects of a building can affect fire spread, among them concealed spaces, vertical openings, compartmentation, fire-resistive corridor partitions, fire walls, and the protection of openings in the fire walls.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the methods for confinement of fire in buildings discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*
NFPA *101®*, *Life Safety Code®*
NFPA 221, *Standard for High Challenge Fire Walls, Fire Walls and Fire Barrier Walls*
NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 252, *Standard Methods of Fire Tests of Door Assemblies*
NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*
NFPA 257, *Standard on Fire Test for Window and Glass Block Assemblies*
NFPA 271, *Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*

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SECTION 18

Chapter 2

Interior Finish

Revised by

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Chapter Contents

Interior Finish and Trim Concepts
Fire Tests for Interior Wall and Ceiling Finish Materials
Fire Tests for Interior Floor Finish Materials
Types of Interior Finish
Role of Interior Finish in Fires
Methods of Application
Full-Scale Tests

Key Terms

cone calorimeter, critical radiant flux test, flame spread index, flashover, flooring radiant panel test, full-scale test, interior finish material, interior lining material, lateral ignition and flame spread test (LIFT), methenamine pill test, room corner test, smoke density chamber test, smoke developed index, Steiner tunnel test, trim material

The best fire protection strategy for buildings is one that limits fires to a small size. In instances where fires eventually do become large, the fire growth rate must be slow enough to give occupants time to react or to give emergency responders enough time to respond and combat the fire manually and to rescue trapped victims while the fire is still limited in size.

Fires need to be limited in size because fire hazard is related to fire size. A material's burning rate—measured by its heat release rate—is the single most important parameter affecting fire hazard, because burning rates determine fire size. Burning rates directly affect temperature rise and the mass loss rate. Furthermore, mass loss and heat release also control the amount of smoke (and soot) released into a given volume, which determines visibility and thus the ease of escape or rescue of fire victims. Moreover, in a given volume, heat release and mass loss rates also affect the amounts of toxic products generated, which determines toxic hazard.

Large fires in buildings always represent an acute threat to occupants, irrespective of what is burning; and the faster a fire grows to a large size, the greater the threat. Any building material, furnishing, or content will have undesirable fire properties if its presence could cause a fire that would otherwise stay small to become large. For that reason, the use of furnishings and contents, especially including interior finish, with superior fire performance is a way to passively protect building occupants from the dangers of fire. Once a room fire has progressed so that the upper layer temperature approaches 1112°F (600°C) and that layer becomes thick, descending toward the lower portion of the room, all combustible furnishings and combustible room contents may be ignited, leading to flashover or full room fire involvement. Although some fires involve extended periods of slow, undetected fire development, fires that cause large life loss or high property loss nearly always grow rapidly to large size. Such fires typically reach flashover, or full room involvement, within minutes of having been small and easy to control. Therefore, prevention of flashover is a key strategy for lowering fire hazard. NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover,* is a guide for considering ways to prevent flashover.

Building interior finishes, principally wall and ceiling linings, can have a major impact on both fire growth and ultimate fire size. Interior wall and ceiling linings may act like fuses, spreading flames away from fire origin to involve other objects, causing the fire to grow to large size. Interior finishes may also provide a large, unbroken surface over which flame spreads. As the flame spreads to involve greater surface area, a fire's rate of heat release, and, therefore, the fire size increases. If the interior finish exhibits poor fire performance, the flames from the interior finish may release sufficient energy to cause the formation of a hot gas layer. Combustible interior finishes, such as low-density fiberboard ceilings, wood paneling, textile wall coverings, and combustible floor coverings, have been found in the past to be significant factors in many major fires, including some that became multiple death fires.[1–11] In recent years there have been fewer cases where interior finish has led to fire fatalities, but interior finish is still a major fire problem. The NFPA Fire Analysis and Research Division publishes yearly reports on fire loss statistics and the 2005 report[12] shows that interior finish was responsible for being the item first ignited in 22,900 fires in homes annually between 1999 and 2002 (just over 6% of the total) , which resulted in 261 civilian annual fire fatalities (just under 9% of the total). Worldwide, relatively recently there have been two major nightclub fires with multiple fatalities that were primarily associated with the use of inadequate interior finish materials, which were the items first ignited: the West Warwick, Rhode Island, fire on February 20, 2003, caused 100 fatalities [13,14] and the Buenos Aires, Argentina, fire on December 30, 2004,

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caused 193 fatalities.[15] In both fires, there were multiple code violations and other issues.

Interior finishes are regulated by codes, including NFPA *101*®, *Life Safety Code*®, and by *NFPA 5000*®, *Building Construction and Safety Code*®, to slow initial fire growth and to reduce the likelihood of fire growing to a large size. In fact, the sections addressing interior finish in NFPA *101* and in *NFPA 5000* (Chapter 10 in both codes) are correlated, and both are under the jurisdiction of the same NFPA technical committee, the Technical Committee on Furnishings and Contents.

This chapter reviews the effect of interior finish materials on fire growth. In order to properly evaluate the fire performance of interior finish materials, the fire tests to be used must be suitable for that use. Thus, after broadly looking at what interior finish and interior floor finish entails, the fire tests that can be used for evaluation of interior wall, ceiling, and floor finish materials will be addressed. This chapter then examines ways in which fire behavior requirements can be amended for certain specific interior finish materials to ensure that each type of material can be used safely. This chapter examines the method of application of interior finishes and the effect this can have on fire behavior. This chapter also contains some discussion of decorative materials, mainly by contrast to interior finish materials, and with an indication of the unique issues associated with them.

See also Section 3, Chapter 5, "Introduction to Fire Modeling"; Section 6, Chapter 1, "Fire Hazards of Materials"; and Section 6, Chapter 3, "Concepts and Protocols of Fire Testing."

INTERIOR FINISH AND TRIM CONCEPTS

Most codes, such as NFPA *101* or *NFPA 5000,* define interior wall and ceiling finishes as "the exposed surfaces of walls, ceilings, and floors within buildings" with the following explanation: "Interior finish is not intended to apply to surfaces within spaces, such as those that are concealed or inaccessible. Furnishings that, in some cases, might be secured in place for functional reasons should not be considered as interior finish." Thus, interior finish are those materials or assemblies of materials that form the exposed interior surfaces of walls and ceilings in a building. Interior wall finishes also include the interior finish of columns, fixed or movable walls, and fixed or movable partitions. Interior finish materials include materials such as wood, plaster, wallboard, acoustical tile, wall and ceiling coverings, plastics (including light-transmitting plastics), and insulating materials. Interior finish materials also include interior floor finishes, which tend to be a less severe fire problem, because heat and smoke rise in a fire. Interior floor finishes are the exposed floor surfaces of buildings (floors, ramps, stair treads and risers, and other walking surfaces) and include floor coverings, such as carpets and floor tiles, that may be applied over, or in lieu of, a finished floor. The term *interior lining* or *lining material* is used by the international fire community to define interior finish and the role of interior surfaces in the growth of fire in the room of origin. The term *interior lining* is not gaining very wide acceptance in North America and is unlikely to replace the term *interior finish,* at least in the near future.

There is some variability in the way interior finish regulations are applied. For example, some regulatory officials consider countertops and building cabinets as interior finish, and they are explicitly regulated as such in many transportation environments. It is sometimes difficult to differentiate between interior finishes and furnishings. Furnishings, although in some cases fastened in place, are not normally considered interior finish. For example, fixed plastic-covered restaurant "booth" seating and permanently mounted work counters and cabinets at a nursing station in a health care facility are not usually classified as interior finish.

Interior trim represents the picture moldings, baseboards, handrails, door and window frames, and similar decorative or protective materials used in fixed applications. Interior trim is ordinarily regulated as an interior finish. However, the requirements for trim and other incidental finish materials (like doors) are more lenient than those for the remainder of the wall and ceiling interior finish, when the trim or incidental finish is less than 10 percent of the aggregate wall and ceiling area. The "10 percent rule" is intended to be based on the trim or incidental finish being uniformly distributed and lacking sufficient continuity to allow flames to spread over any significant surface area. Concentration of the trim in one area, so that the trim forms one "fuel package," would violate the principle underlying the "10 percent rule."

Movable walls, folding partitions, and flexible or folding door assemblies are all normally treated as interior finishes. Movable partitions, used for example as a portion of office furnishings or work stations, are regulated as interior finish. Office cubicle partitions and work stations are sometimes formed of textile materials mounted over various substrates. Full-scale tests at the National Institute of Standards and Technology (NIST) involving office work stations consisting of computer terminals, 5 ft (1.5 m) high partitions of textile covering over fiberglass on metal frames, wood desks, and typical office contents revealed that fires involving such work stations may reach large sizes in 300 to 600 seconds.[16,17]

FIRE TESTS FOR INTERIOR WALL AND CEILING FINISH MATERIALS

The nature of interior finish materials and the fire environment to which they may be exposed vary so widely that development of a fire test becomes highly complex. The following three factors must be taken into account:

1. The start and growth of fire in a building is affected by the ignition source, space geometry, ventilation, and by the nature, amount, and location of other processes and materials in the building.
2. There are many time-varying events associated with fires, such as oxygen concentration, rate of heat release, and effects caused by protection systems.
3. Materials vary in form, composition, density, and application.

With these variables in mind, the difficulty in designing a test that will provide a basis for predicting performance under a specific fire exposure becomes obvious. Equally obvious is the impracticality of designing tests to represent all fire conditions. A test designed to represent a "typical" fire or to expose materials to one set of "standard test" conditions may not provide a reliable basis for predicting real-life performance of all materials tested. Thus, there is a constant search for improved test methods that will provide a range of results for a variety of fire conditions.

However, the traditional test for interior finish fire performance, which is NFPA 255, *Standard Method of Test of Surface*

Burning Characteristics of Building Materials (Steiner tunnel test, which also has equivalent designations ASTM E84 and UL 723), is still being widely used in the United States. In recent versions of codes alternative testing of interior finish materials is permitted by the use of a room-corner test: NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth.* The major reason for using the room-corner test is that it assesses interior finish in a realistic room scenario and measures the key fire property, heat release,[18] and therefore results of room-corner tests are more reliable than results of tunnel tests. The Steiner tunnel test has been found to be an adequate fire test for traditional building materials and for materials that are not very thin and that remain in place during the test. However, many modern interior finish materials and systems are more complex than that and may not be suitably assessed by the Steiner tunnel fire test. A discussion on fire testing of interior finish was published recently.[19]

The use of bench-scale test data to predict product behavior through the use of models has been under study for many years, but there is no agreement yet in the United States on using such tests for regulatory purposes. Use of data from bench-scale tests, such as the cone calorimeter and the lateral ignition and flame spread test (LIFT apparatus),[20,21] to predict product behavior under a variety of circumstances may result in improved regulation of interior finish materials in the future. The models are fairly adequate in linking the actual fire hazard associated with the use of a product in a specific situation to regulatory limits.[22–26] This future form of regulation must be contrasted with the current regulation of interior finishes using the traditional standardized procedure (NFPA 255) or the more modern heat release tests (such as NFPA 286) in which the behavior of one product is simply compared with another. At present, this is still a practical approach for building regulation; however, one should understand that good behavior in a standardized test (such as NFPA 255) does not necessarily ensure good behavior in an actual fire, particularly when dealing with nontraditional materials and with complex systems. For example, it has been industry practice to evaluate movable partitions as an assembly in the Steiner tunnel test. There is concern that the NFPA 255 flame spread indices may not be suitable to predict the performance of certain movable or fixed partitions in fires without the benefit of adding supplemental restrictions such as the presence of sprinklers or limiting the height of the partition. Similarly, products such as foam plastic insulation have been identified, in building and fire codes, as materials for which NFPA 255 test protocol is not appropriate.

Steiner Tunnel Test

The 25 ft (7.62 m) Steiner tunnel test, also known as NFPA 255, ASTM E84, and UL 723, was developed by A. J. Steiner at Underwriters Laboratories Inc.[27–30] After a series of fatal fires, the need for a method of controlling interior finishes was recognized and the use of the tunnel test proposed. The method was adopted by the American Society for Testing and Materials (ASTM, now ASTM International) as a tentative standard in 1950 and as an official standard in 1958 (as ASTM E84). NFPA adopted the test method tentatively in 1953 and officially in 1958 as NFPA 255. In both organizations it has been revised periodically.

Figures 18.2.1 and 18.2.2 show the general appearance and basic layout of the tunnel test apparatus. A detailed description can be found in NFPA 255. In summary, a 20- to 24-in. (508- to 610-mm) wide by 24-ft (7.3-m) long test specimen (normally up to 0.15 m thick) is placed face down on a ledge at the top of the furnace to form the ceiling of the test chamber. A gas burner projects a 4½-ft (1.4-m) long flame (89 kW intensity) onto the underside of the test specimen while air flows through the tunnel at a controlled linear air velocity of 240 ft/min (approximately

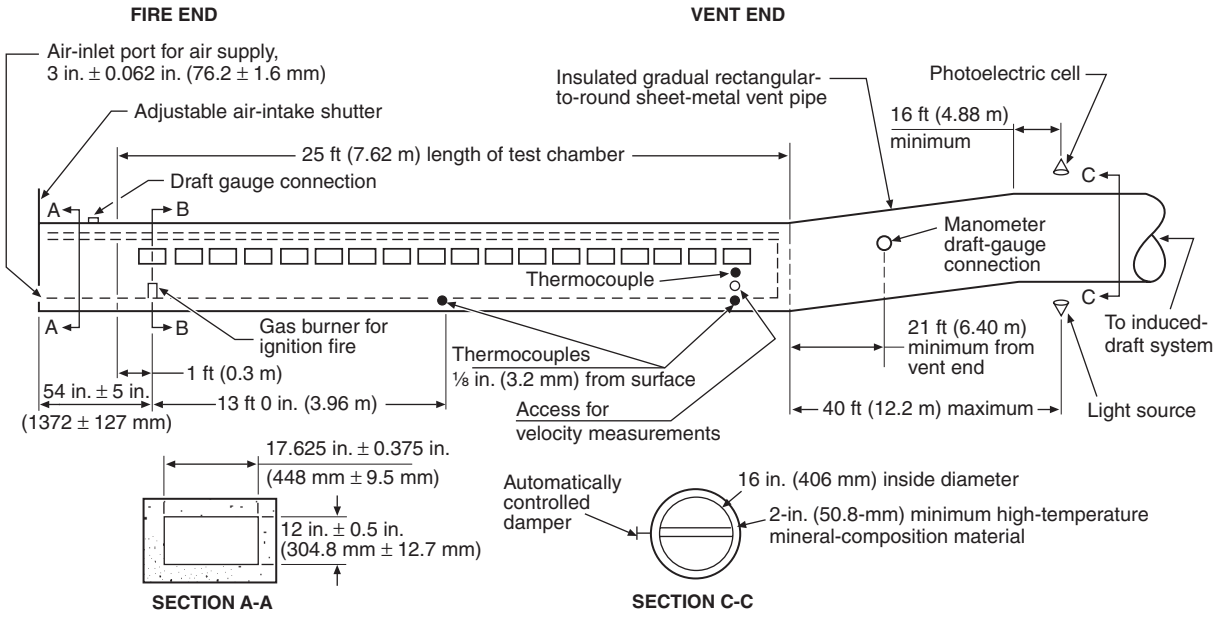

FIGURE 18.2.1 Steiner Tunnel Test Apparatus Used for the Fire Hazard Classification of Building Materials

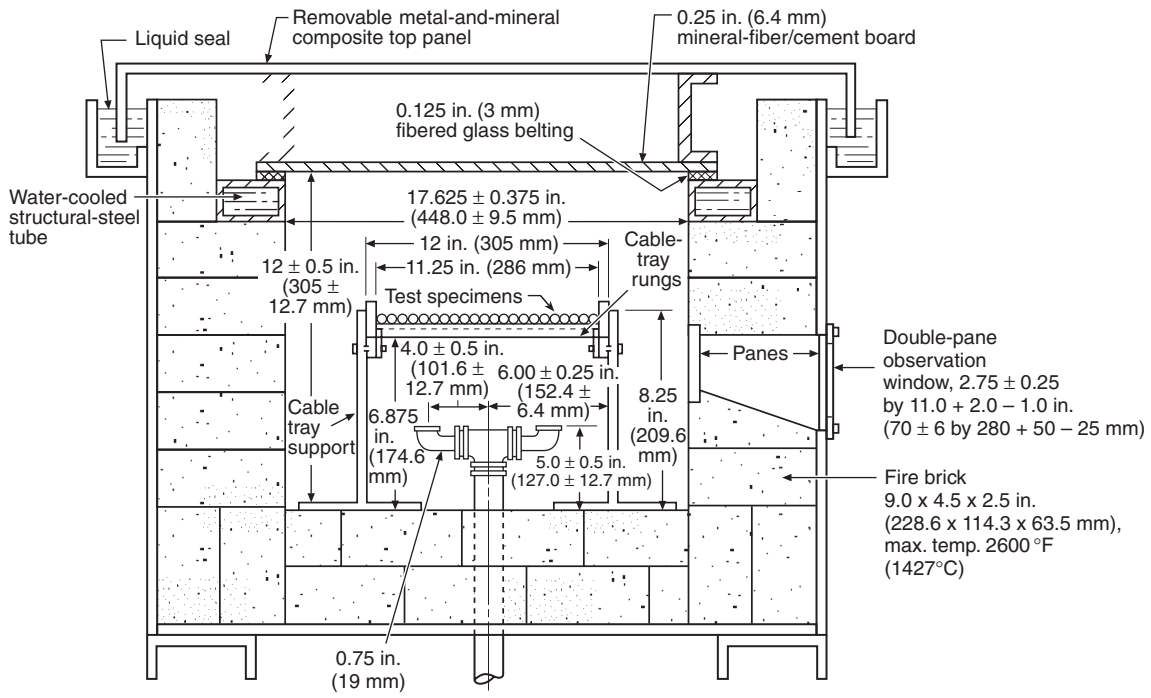

FIGURE 18.2.2 Cross-Sectional View of the Steiner Tunnel Test Apparatus

73 m/min). Flame spread over the face of the test specimen is observed through windows in the side of the "tunnel." Flame propagation is recorded as a function of time over the 10 minute test duration. The record of flame propagation versus time is used to calculate a flame spread index, by comparison with two standard reference materials. Red oak flooring is arbitrarily assigned a flame spread index of 100 and a cementitious board material is assigned a flame spread index of 0. According to the test standard, red oak flooring spreads flame 24 ft (7.3 m) to the end of the test specimen in 5½ minutes ± 15 seconds. The flame spread indices of products are calculated on the basis of a graph of flame spread versus time. The lower the flame spread index, the better the presumed performance. However, as stated above, there is not necessarily a correlation between the measured flame spread index and product behavior in actual fires. NFPA 255 simply provides a basis for comparing one product with another under a standardized set of test conditions.

The reduction in light across the tunnel exhaust caused by smoke generated during the test is measured by a photometer system consisting of a lamp and photo cell. The attenuation of light by the passing smoke and particulate is used to compute a smoke developed index. The smoke developed index for a test specimen is determined by comparing the reduction in light caused by the smoke from red oak flooring to the reduction of light by smoke from a test specimen. Red oak flooring is arbitrarily assigned a value of 100 and the cementitious board material is assigned a smoke developed index of 0. Therefore, a product achieving a 450 smoke developed index produces a curve of light attenuation versus time which has 4.5 times the area of the curve produced by red oak flooring (in comparison with the results for the cementitious board). In simplistic terms, one may think of a product having a 450 smoke developed index as one that produces 4.5 times the amount of smoke that red oak flooring generates during a 10 minute tunnel test.

Factors Affecting Test Results. Products should be tested as proposed for use. For example, the use of high-temperature mortar cement to mount a thin wall covering to an inorganic reinforced cement board substrate may result in artificially good test performance, but such an assembly is not likely to simulate actual installation practices. A product installed in a manner different from that used in testing may perform differently and, in some cases, unsatisfactorily. To illustrate, products that are to be installed over gypsum board with adhesives, such as vinyl wall covering, must be tested over gypsum board, because the paper facing on the gypsum board and the adhesives used can affect fire behavior. ASTM has issued two standard practices which address mounting and testing some materials: pipe and duct insulation materials (ASTM E2231[31]) and vinyl and paper wall and ceiling covering materials (ASTM E2404[32]) and is in the process of developing other practices.

The significance of adhesives has been briefly addressed in the previous paragraph: its fire performance can significantly affect the flame spread index and the smoke developed index measured in the tunnel test. Products should be tested with fastening details that represent conditions of actual use. NFPA *101* and *NFPA 5000* require that interior finish materials be tested as they are to be installed. For example, Paragraph 10.2.1.1 of NFPA *101* (2006) states, "Classification of interior finish materials shall be in accordance with tests made under conditions simulating actual installations, provided that the authority having jurisdiction shall be permitted to establish the classification of any material on which a rating by standard test is not available, unless otherwise provided." This idea is reinforced in the

test method itself. For another example, Paragraph 4.2.1.3 of NFPA 255 (2006) states, "The specimen shall be representative of the material for which test results are desired."

Specimen thickness can also affect flame spread. Thinner sections of the same material often will spread flame more rapidly than thicker sections. For example, data show that the flame spread rate remains constant for an acrylic sheet (polymethyl methacrylate or PMMA) with a thickness greater than approximately ⅜ in. (9.5 mm).[33] Decreasing thickness increases the rate of flame spread for that acrylic sheet. These findings indicate that products to be used in varying thicknesses must be tested at the thickness at which they are to be used. Similarly, products that are offered in different densities should be tested in a range of densities.

Other mounting details can be important too. Thermally thin products, such as wood paneling with thickness of ¼ in. (6.4 mm) or less, that are tested when directly applied to an inorganic-reinforced cement board (as noted earlier) may behave differently if they were installed over furring strips with air space. The installation of paneling with air space will likely result in a greater tendency for surface flame spread. Similarly, where a product is to be applied in multiple layers, it should be tested in the maximum thickness intended for use. For example, a wall covering tested by itself may perform satisfactorily, but multiple layers of the same product applied to a wall covering may spread flame and, in recent years, multiple layers of wall coverings applied to gypsum board have contributed to flame propagation in a number of fires where multiple lives were lost.

As discussed throughout this section, the tunnel test is not able to adequately evaluate certain types of materials. Some materials, such as foam plastic insulation, can achieve a low flame spread index and still spread flames readily in actual fires. A research program involving textile wall coverings demonstrated that NFPA 255 is often unable to evaluate textile wall coverings properly.[34]

One should be suspicious of tunnel results for lightweight materials with low thermal inertia and for thermoplastic materials that drip to the floor of the tunnel during testing. When questions arise about the fire performance of a material or product, the product should be evaluated on a full-scale basis, using an ignition source simulating the type of fire likely to be encountered in actual use. Products should be mounted in a manner that is representative of the conditions of actual use, as it has been shown that often each layer of a system may "pass" a certain set of fire test criteria, but the entire system will perform much worse.

Application of Tunnel Test Results. NFPA *101* and *NFPA 5000* classify interior finish materials using flame spread and smoke developed indices. It is recognized that considerable variability exists in tunnel data, and precise values are not likely to be obtained in replicate tests. Further, small differences in indices (10 to 20 points, for example) are not likely to be discernible in terms of actual fire behavior. Accordingly, flame spread indices are usually rounded to the nearest whole number divisible by 5.

Classification	*Flame Spread Index*	*Smoke Developed Index*
A	0–25	0–450
B	26–75	0–450
C	76–200	0–450

Interior wall and ceiling finish classifications are based mainly on flame spread index with a single smoke developed index limit value of 450, which is common to all classifications.

Flame spread indices are used to provide information on the rate of flame spread across the surface of a material. Heat transfer would be the principal hazard associated with flame spread and would only affect a person who was in close proximity to the fire. As a consequence, different classes of interior finish materials are specified within a building, depending on location. For example, exit enclosures in which travel paths are severely restricted have the most severe flame spread index limitations, since individuals in such a location would be restricted in their travel paths and, therefore, might not be able to avoid the heat from the flame.

A smoke developed index of 450 is used for all interior finish classifications. The smoke developed indices assess product behavior in terms of obscuration of exit paths and loss of visibility by smoke. Smoke interferes with visibility on the basis of the accumulated soot and other particles within a given volume. The smoke level will depend on both time and rate of smoke production. A product that has a low smoke developed index would be expected to maintain visibility in egress paths for a longer period of time than a material with a high smoke developed index. The same smoke developed index criterion is used for all three classifications (i.e., classes A, B, and C). The recommended 450 limit acknowledges that smoke affects visibility both in the immediate vicinity of the fire and in remote areas as well. Large buildings can be quickly filled with smoke as the result of a fire. An upper limit has been established that is applicable to interior finishes, regardless of where the materials are installed.

The smoke developed index limit of 450 was originally developed from research conducted by Underwriters Laboratories Inc. (UL).[35] In this research, products were burned in the NFPA 255 "tunnel test" and the smoke discharged into a 5000 ft^3 (141.5 m^3) room. The room was equipped with illuminated exit signs. The time required for exit signs to be obscured was recorded and compared to the smoke developed index for the different materials tested. The UL report stated that materials with smoke developed index values above 325 showed "good" to "marginal" visibility in a few cases, whereas other materials produced conditions of "marginal" to "obscuration" in the 6-minute period. The 450 limit has been used for many years and has long been thought to set a "reasonable" limit for smoke developed index values in rooms. The 450 smoke developed index limit takes into account both the time required to produce the smoke and the effect of the smoke on vision distance.

There is no direct relationship between flame spread index and smoke developed index. In the UL report referenced above,[35] for example, one material had a flame spread index of 490 and a smoke developed index of 57, whereas another had a flame spread index of 44 and a smoke developed index of 1387.

The smoke developed index from NFPA 255 is determined solely on the basis of obscuration of light. It should be recognized that, in some cases, smoke may also act as an irritant, further affecting visibility, and the smoke may, in addition, have a debilitating effect on persons attempting to escape. The irritability and other physiological effects are not evaluated by the 450 smoke developed index limit.

Different classes of interior finish materials are specified, depending on location within a building and on the occupancy involved. Interior finish restrictions are less stringent for a general office area, for example, than would be the case for an exit stair enclosure or exit access corridor. Similarly, occupancies having less capable occupants have stricter interior finish requirements than occupancies used by mobile and alert occupants. For example, the interior finish restrictions for health care facilities are quite restrictive, due to the inability of hospital patients to take action for their own self-preservation.

The limits on interior finish are set forth in the 2006 editions of NFPA *101* and *NFPA 5000*. The limits for interior wall

TABLE 18.2.1 *Life Safety Code* (2006) Requirements (Classes) for Interior Wall and Ceiling Finish[a,b]

Occupancy	*Exits*	*Exit Access Corridors*	*Other Spaces*
Assembly—new			
>300 occupant load	A	A or B	A or B
≤300 occupant load	A	A or B	A, B, or C
Assembly—existing			
>300 occupant load	A	A or B	A or B
≤300 occupant load	A	A or B	A, B, or C
Educational—new	A	A or B	A or B; C on low partitions[c]
Educational—existing	A	A or B	A, B, or C
Day-care centers—new	A	A	A or B
Day-care centers—existing	A or B	A or B	A or B
Day-care homes—new	A or B	A or B	A, B, or C
Day-care homes—existing	A or B	A, B, or C	A, B, or C
Health care—new	A	A; B on lower portion of corridor wall[c]	A; B in small individual rooms[c]
Health care—existing	A or B	A or B	A or B
Detention and correctional—new (sprinklers mandatory)	A or B	A or B	A, B, or C
Detention and correctional—existing	A or B	A or B	A, B, or C
One- and two-family dwellings and lodging or rooming houses	A, B, or C	A, B, or C	A, B, or C
Hotels and dormitories—new	A	A or B	A, B, or C
Hotels and dormitories—existing	A or B	A or B	A, B, or C
Apartment buildings—new	A	A or B	A, B, or C
Apartment buildings—existing	A or B	A or B	A, B, or C
Residential board and care		(See Chapters 32 and 33 of NFPA *101*)	
Mercantile—new	A or B	A or B	A or B
Mercantile—existing			
Class A or Class B stores	A or B	A or B	Ceilings: A or B; walls: A, B, or C
Class C stores	A, B, or C	A, B, or C	A, B, or C
Health care—new			
Business and ambulatory	A or B	A or B	A, B, or C
Health care—existing			
Business and ambulatory	A or B	A or B	A, B, or C
Industrial	A or B	A, B, or C	A, B, or C
Storage	A or B	A, B, or C	A, B, or C

Notes:
1. Class A interior wall and ceiling finish—flame spread index 0–25, (new applications) smoke developed index 0–450.
2. Class B interior wall and ceiling finish—flame spread index 26–75, (new applications) smoke developed index 0–450.
3. Class C interior wall and ceiling finish—flame spread index 76–200, (new applications) smoke developed index 0–450.
4. Automatic sprinklers: The annex of NFPA *101* states that where a complete standard system of automatic sprinklers is installed, interior wall and ceiling finish with a flame spread rating not exceeding Class C is permitted to be used in any location where Class B is required and with a rating of Class B in any location where Class A is required. These provisions do not apply to new detention and correctional occupancies.
5. Exposed portions of structural members complying with the requirements for heavy timber construction are permitted.

[a]*Life Safety Code* requirements for interior wall and ceiling finish materials apply as shown in this table where specified elsewhere in the *Life Safety Code* for specific occupancies (see Chapter 7 and Chapters 11 through 42), unless otherwise specified in the sections addressing individual materials.

[b]Note that everywhere that a Class A, Class B, or Class C interior wall or ceiling finish material is required, a material that has been tested by NFPA 286 and complies with the appropriate criteria is also permitted.

[c]See corresponding chapters for details.

and ceiling finish are summarized in Table 18.2.1 and those for interior floor finish are summarized in Table 18.2.2. As noted in footnotes to the tables, automatic fire suppression, such as automatic sprinklers, will significantly mitigate the hazard associated with a fire, including one associated with interior finish materials. Accordingly, codes often allow materials, including interior finish materials, to comply with a less severe fire performance classification when the area is fully provided with protection from automatic sprinkler systems, in accordance with the appropriate system, namely either NFPA 13, *Standard for the Installation of Sprinkler Systems,* NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes,* or NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height.* The code will explicitly discuss these trade-offs. Accordingly, the informational annexes of NFPA *101* and *NFPA 5000* talk about allowing interior finish materials to drop one classification when automatic sprinkler systems are provided. For example, if the code normally requires a Class A interior finish and automatic sprinklers are installed, then a Class B interior finish is normally allowed. This trade-off is not written in code language and is different from the one incorporated into the International Building Code, for example.

Room-Corner Test

Seeking a more realistic assessment of the hazard of interior finishes, several laboratories started conducting room-corner tests around 1970. These originally comprised an 8 ft (2.44 m) high corner construction with 2 to 4 ft (0.1 to 1.22 m) long wing walls. A simulated ceiling of the same material was provided. A wood crib placed in the corner at floor level was used for ignition. The degree of flame spread and the rate and amount of smoke developed were the primary observations. Interest in the rapidity of flame spread across the surface of what was considered low-flame-spread cellular plastics in actual fires reinforced the use of the corner test. Large-scale corner tests conducted by Factory Mutual Research (now FM Global) and UL (Underwriters Laboratories) have used corners up to 25-ft (7.6-m) high with wing walls up to 50-ft (15.4-m) long to determine the burning characteristics of cellular plastics and the effectiveness of protective measures such as automatic sprinkler protection or thermal barriers.[36] Results have reinforced the premise that fire hazard cannot be fully judged on the basis of a traditional fire test method.[37]

Building codes and NFPA *101* now specify the use of room-corner tests for judging the flammability behavior of certain interior finishes. NFPA *101* and *NFPA 5000,* for example, use NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Coverings on Full Height Panels and Walls,* to evaluate the performance of textile and expanded vinyl wall coverings. In the 1980s, researchers at the University of California–Berkeley Fire Research Laboratory showed that wall coverings with NFPA 255 (ASTM E84) ratings as low as 15 sometimes performed poorly, producing flashover in room-corner tests.[34–38] It was determined that room-corner tests (such as NFPA 265) provide a better indication of the hazard presented by these particular wall coverings than do the

TABLE 18.2.2 *Life Safety Code* (2006) Requirements (Classes) for Interior Floor Finish[a]

Occupancy	*Exits*	*Exit Access Corridors*
Assembly—new		
>300 occupant load	I or II	I or II
≤300 occupant load	I or II	I or II
Assembly—existing		
>300 occupant load		
≤300 occupant load		
Educational—new	I or II	I or II
Educational—existing		
Day-care centers—new	I or II	I or II
Day-care centers—existing		
Day-care homes—new	I or II	
Day-care homes—existing		
Health care—new	I or II	I or II
Health care—existing		
Detention and correctional—new (sprinklers mandatory)	I or II	I or II
Detention and correctional—existing	I or II	I or II
One- and two-family dwellings and lodging or rooming houses		
Hotels and dormitories—new	I or II	I or II
Hotels and dormitories—existing	I or II[b]	I or II[b]
Apartment buildings—new	I or II	I or II
Apartment buildings—existing	I or II[b]	I or II[b]
Residential board and care	(See Chapters 32 and 33 of NFPA *101*)	
Mercantile—new	I or II	
Mercantile—existing		
Class A or Class B stores		
Class C stores		
Health care—new		
Business and ambulatory	I or II	
Health care—existing		
Business and ambulatory		
Industrial	I or II	I or II
Storage	I or II	

Notes:
1. Class I interior floor finish—critical radiant flux, not less than 0.45 W/cm^2.
2. Class II interior floor finish—critical radiant flux, not more than 0.22 W/cm^2 but less than 0.45 W/cm^2.
3. Automatic sprinklers: The annex of NFPA *101* states that where a complete standard system of automatic sprinklers is installed, Class II interior floor finish is permitted to be used in any location where Class I is required, and no critical radiant flux rating is required where Class II is required. These provisions do not apply to new detention and correctional occupancies.

[a]*Life Safety Code* requirements for interior floor finish materials apply as shown in this table where specified elsewhere in the *Life Safety Code* for specific occupancies (see Chapter 7 and Chapters 11 through 42), unless otherwise specified in the sections addressing individual materials.

[b]See corresponding chapters for details.

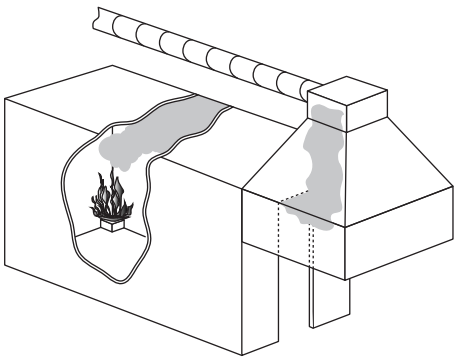

FIGURE 18.2.3 Schematic of Modern Room-Corner Test Apparatus

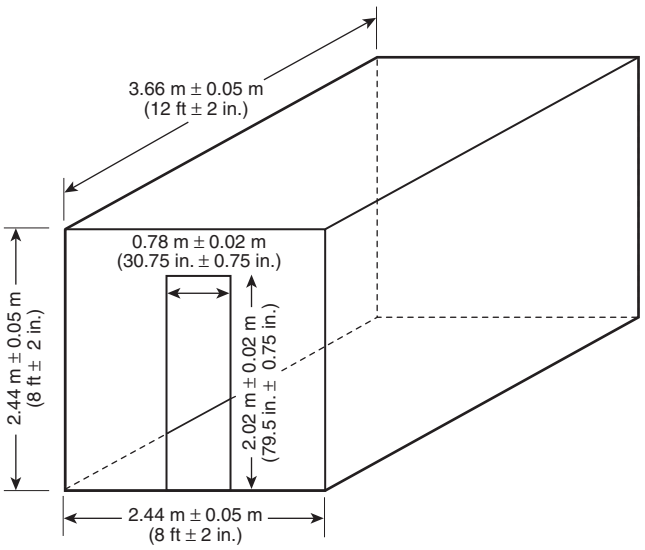

FIGURE 18.2.4 Interior Fire Test Room Dimensions and Interior Doorway Dimensions (Source: Figure 4.2.1, NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth,* 2006 ed.)

NFPA 255 flame spread indices. The general layout of modern room corner tests is shown in Figure 18.2.3.

The NFPA 265 test method consists of an 8-ft (2.44-m) wide by 12-ft (3.66-m) long by 8-ft (2.44-m) high room with a single door opening (Figures 18.2.4 through 18.2.6). Products are mounted on three walls, opposite the room door. A diffusion burner is positioned near the corner of the room and provides the required fire exposure. The smoke from the room is collected in a hood and duct exhaust system where instrumentation is used to determine heat release rate (through oxygen depletion) and smoke release (as optical density). Heat flux and temperature measurements are also, optionally, made within the room. Key visual observations are the extent of flame spread and the occurrence of flashover. In NFPA 265, the burner (placed 2 in. [51 mm] away from each wall, near a corner) provides 5 minute, 40 kW fire exposure (which simulates a "waste basket"–sized fire exposure) followed by a 10 minute, 150 kW exposure. A key issue is the fact that the 150 kW burner flame does not reach the

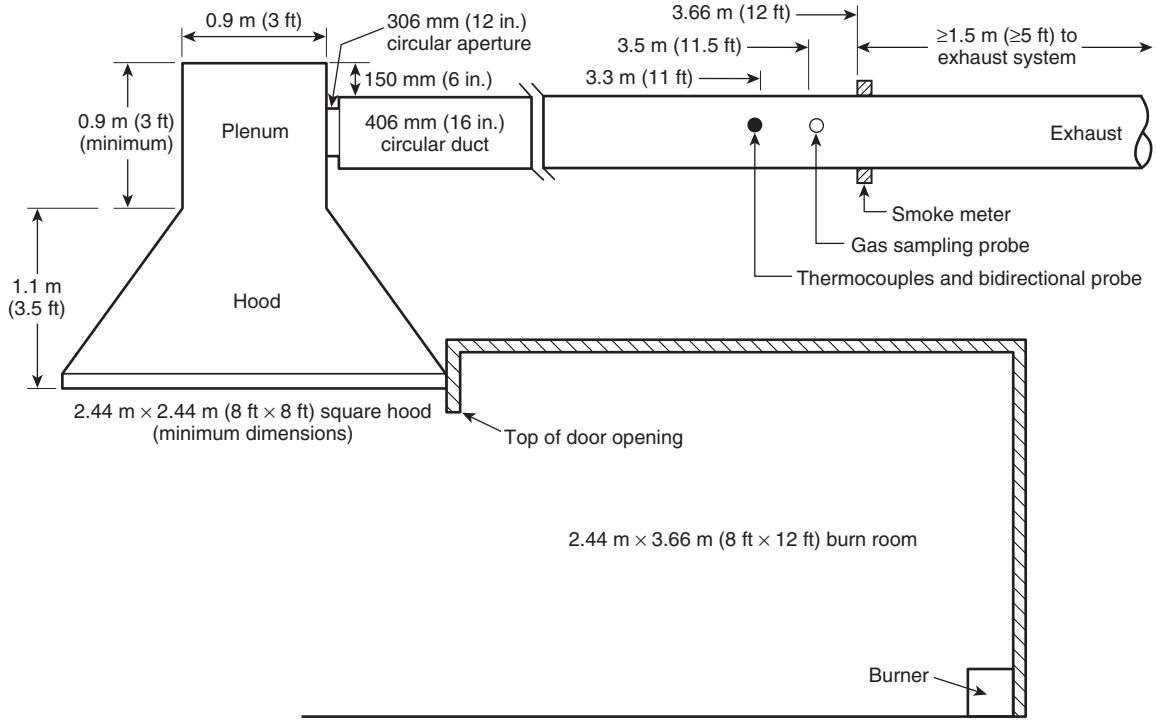

FIGURE 18.2.5 Canopy Hood and Exhaust Duct (Source: Figure 7.2.1, NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth,* 2006 ed.)

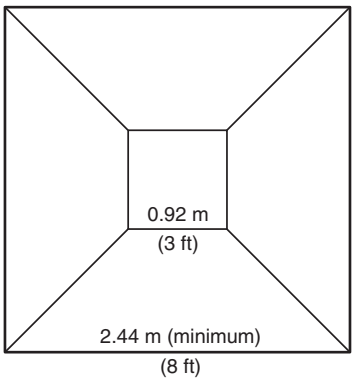

FIGURE 18.2.6 Plan View of Canopy Hood (Source: Figure 7.2.1.3, NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth,* 2006 ed.)

ceiling, and the test method is, therefore, not applicable to ceiling coverings. Thus, although the fire exposure specified within NFPA 265 is believed to be appropriate for wall coverings, ceiling coverings are not adequately evaluated by this procedure since the burner placement and 150 kW output (assuming no involvement of a wall test specimen) produces a flame that does not reach the ceiling. The codes set limits for products tested in accordance with NFPA 265, which is for textile and expanded vinyl wall coverings only. The 2006 editions of the codes require that materials tested using the complete NFPA 265 test (also known as Protocol B, namely not the screening test) must meet the following test criteria:

1. Flame shall not spread to the ceiling during the 40 kW exposure.
2. During the 150 kW exposure, flame shall not spread to the outer extremities of the sample on the 8 ft × 12 ft (2.44 m × 3.66 m) wall and flashover shall not occur.

For ceiling coverings and for other interior finish materials, the codes use a different burner placement and output, as detailed in NFPA 286. The NFPA 286 test places the test specimen on the three walls of the room (just like the NFPA 265 test) but also covering the entire ceiling. The test uses a 5 minute, 40 kW initial exposure, followed by a 10 minute, 160 kW exposure, with the burner flush against both walls in the corner. The 160 kW exposure (even absent any contribution by the products undergoing test) will result in burner flames hitting the ceiling and turning to expose the underside of the ceiling for 18 to 24 in. (457 to 610 mm). The direct flame exposure to the ceiling is considered necessary to adequately evaluate ceiling finish. The codes also set limits for products tested in accordance with NFPA 286 (all interior finish materials). Interior finish materials tested by NFPA 286 must meet the following test criteria:

1. Flames shall not spread to the ceiling during the 40 kW exposure.
2. During the 160 kW exposure, flame shall not spread to the outer extremities of the sample on the 8 ft × 12 ft (2.44 m × 3.66 m) wall and flashover shall not occur.
3. The peak heat release rate throughout the test shall not exceed 800 kW.
4. For new installations, the total smoke released throughout the test shall not exceed 1000 m^2.

Clearly the room-corner test is a much more suitable way of assessing fire performance than the NFPA 255 tunnel test. However, the codes admit the NFPA 286 room-corner test results based on the premise that materials that don't cause flashover (or high smoke release) in the room-corner test are known to also have flame spread indices of less than 200 and smoke developed indices of less than 450 in the Steiner tunnel test. This is excellent as far as it goes, but needs refinement. The Steiner tunnel test is very likely to give falsely favorable results (in fact, that happens often with materials that melt and drip and with materials that are thin films) but it rarely gives falsely unfavorable results (meaning that a high flame spread index, or FSI, is almost always indicative of a material with mediocre or poor fire performance). The room-corner test results are potentially much more suitable to classification of materials, because the heat release rate history is obtained in the test. However, the fact that the heat release rate history is not used for code classification purposes results in some inconsistencies occurring when comparing results from both tests. Therefore, it would be important to use the heat release rate history in the room-corner test and not just whether flashover does or does not occur, and the codes have started in that direction by requiring a peak heat release rate not exceeding 800 kW and not just the absence of flashover. Work based on a survey of published data[19] analyzed the comparative fire performance of 25 materials tested in the Steiner tunnel and in the room-corner test, the following points illustrate the problem:

- Five materials had an FSI of 200 or less (i.e., Class A, B, or C) in the Steiner tunnel and yet led to flashover in the room-corner test. The Steiner tunnel test classifies them as acceptable and the room-corner test as unacceptable.
- Fourteen materials had an FSI of 25 or less (i.e., Class A) in the Steiner tunnel and released less than 400 kW in the room-corner test. Both tests consider them satisfactory materials.
- Two materials had an FSI of greater than 25 but not exceeding 75 (i.e., Class B) in the Steiner tunnel and also released less than 400 kW in the room-corner test. The Steiner tunnel test classifies them as Class B and yet the codes would allow such materials to be used instead of Class A materials.
- Two materials had an FSI of 25 or less (i.e., Class A) in the Steiner tunnel and released more than 400 kW but less than flashover in the room-corner test. The codes classify the materials as Class A but these materials are clearly less fire safe than those that release less than 400 kW.
- Two materials had an FSI of 200 or less (i.e., Class C) in the Steiner tunnel and heat release very close to but less than flashover in the room-corner test. The Steiner tunnel test classifies them as Class C and the codes consider them equivalent to Class A materials.

In terms of smoke release by interior wall and ceiling finish, the question has been posed whether it is necessary to test for smoke release if a material shows excellent fire performance in the room-corner test, or is it enough to just develop low heat

release products? Recent work[19] shows that of five series of tests conducted in room-corner tests (two in Europe and three in the United States), with a total of 84 materials tested, systematically some 10 percent of the materials (in fact 10 of the 84) give low heat release but very high smoke release. Therefore, it is important to also assess smoke release of interior wall and ceiling finish in a large-scale test. Thus, a smoke release criterion is included in the codes for use with the NFPA 286 room-corner test. The code requirements, total smoke release (TSR) of 1000 m^2 in the NFPA 286 room-corner test, is roughly equivalent to the 450 smoke developed index (SDI) criterion used for the Steiner tunnel test.

A different version of the room-corner test procedure was developed as the result of a research project sponsored by the National Association of Garage Door Manufacturers.[39,40] It is referenced in the 2006 editions of building codes such as *NFPA 5000®*, *Building Construction and Safety Code®*, for the regulation of foam plastic–insulated garage doors in commercial applications. This room-corner test method and associated regulatory limits are particularly notable in that heat release and smoke release limits have been developed that are linked to the actual fire hazard. The heat release rate and smoke limits eliminate the need for subjective judgments of product behavior required by the older editions of room-corner tests.

If foam or cellular plastics are to be used exposed within a building, the application should be substantiated on the basis of tests that are representative of the conditions of actual use. Room-corner tests, such as NFPA 265, NFPA 286, and ISO 9705[41] or ASTM E2257,[42] have been used to evaluate foam plastic insulation materials. They all use a gas diffusion burner as the fire source, with ISO 9705 or ASTM E2257 being the most severe one (the ignition source is 100 kW for the first 10 minutes and 300 kW for the next 10 minutes).

Full-scale test procedures, like room-corner tests, allow products to be evaluated because they will be installed using an ignition source representative of those likely to be encountered during actual use. Accordingly, results of room-corner fire tests are more indicative of product behavior during actual fires than are traditional tests, such as NFPA 255. Codes exempt materials tested in accordance with an appropriate room-corner test from classification in accordance with NFPA 255. In other words, the codes allow products shown to perform acceptably by a room-corner fire test to be used as interior finish in those locations otherwise requiring Class A, B, or C materials. Furthermore, the data from room-corner fire tests is also suitable for use as input into fire models for performance-based design.

Other Flame Spread Tests

Attempts have been made to develop a smaller scale test that could be used in place of the nominally 25 ft (7.6 m) long "tunnel" test. The advantages of such a method are obvious: less space required for the equipment, smaller specimens needed, and lower costs. The Forest Products Laboratory developed a reduced-scale version of the tunnel. The reduced-scale tunnel was 8 ft (2.4 m) long and used flame spread observations as a function of time to determine flame spread ratings. The 8 ft (2.4 m) tunnel test was adopted by ASTM in 1968 as ASTM E286[43] and withdrawn by ASTM in 1991.

A radiant panel apparatus was developed at the National Bureau of Standards (NBS), now NIST. The radiant panel apparatus uses a much smaller test specimen of 6 in. by 18 in. (152 mm by 457 mm) and measures hazard in terms of both flame spread and, potentially, heat release rate after ignition. The test method was adopted as a standard by ASTM in 1967 as ASTM E162.[44] In the radiant panel test, *Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source,* the specimen is positioned at an angle of 30° to vertical in front of a gas-fired, porous, refractory, vertical panel. The specimen slants toward the radiant panel at the top and a small pilot flame at that location ignites flammable gases released from the surface of the specimen. Air is drawn over the surface of the specimen at a controlled rate by a fan in the hood under which the equipment is located. The rate of flame travel from the top of the specimen to the bottom is noted, as are temperatures that develop in the stack. The amount of smoke generated can be measured by weighing deposits on a filter located in the stack. The test is continued for 15 minutes or until surface flaming reaches the lower edge of the specimen. This radiant panel apparatus is available commercially and is used in many research, commercial, and industrial laboratories. The results of tests are expressed on a scale and reported as the "radiant panel index." In the radiant panel, the air flow is against or across the direction of flame travel. This provides a clear definition of the interfacial burning. With the Steiner tunnel test (NFPA 255), the flame travel and airflow coincide, and, with some materials, the flame front may be several feet in front of the interfacial burning (see Figure 18.2.3).

ASTM E162 was not originally intended for regulatory use and is not used in codes (building code, fire code, or life safety code) as a substitute for evaluating products in accordance with the Steiner tunnel test, such as NFPA 255. It is, however, used for some transportation vehicles and for manufactured housing. In the case of rail transportation vehicles, both the Federal Railroad Administration[45,46] and NFPA 130, *Standard for Fixed Guideway Transit and Passenger Rail Systems,* require that lining materials pass the ASTM E162 test, with radiant panel indices ranging from 25 to 100, depending on the application. ASTM E162 is also used in NFPA 1192, *Standard on Recreational Vehicles,* for assessing the flame spread performance of cabinet door and drawer faces, exposed cabinet bottoms and end panels, and tub/shower walls in recreational vehicles, and in NFPA 501, *Standard on Manufactured Housing,* as an alternative to the Steiner tunnel test to assess flame spread performance of interior finish materials in manufactured housing; for both applications a radiant panel index of 200 is required.

Smoke Density Chamber Test

A "bench test" for measuring smoke generation, the smoke density chamber, has been available for many years. Described in ASTM E662,[47] it measures the specific optical density of smoke generated in a chamber from test specimens up to 1 in. (25.4 mm) thick. Despite the existence of a clause in ASTM E662 that intends to limit the test procedure for use as a research and development tool, it is actually widely used for regulatory purposes (including its use for lining materials in trains by the Federal Railroad Administration[45,46] and in airplanes by the

Federal Aviation Administration[48]) but not normally for interior finish in codes. A variation of the test (ASTM E1995,[49] also known as NFPA 270, *Standard Test Method for Measurement of Smoke Obscuration Using a Conical Radiant Source in a Single Closed Chamber,* and ISO 5659-2[50]) is used for regulating interior finish in ships by the International Maritime Organization (IMO), the U.S. Coast Guard, and NFPA 301, *Code for Safety to Life from Fire on Merchant Vessels.* ASTM E1995 differs from ASTM E662 mainly in that the burner is a conical heater and the sample is tested horizontally. The smoke density chamber test is known to have numerous shortcomings. The method involves a closed, static chamber, whereas smoke transfer in actual fires is dynamic. The chamber is closed, and oxygen-deficient atmospheres can develop that may artificially affect the burning behavior of the products being tested. Deposits of soot on wall surfaces and optics can affect measurements. In summary, numerous questions exist as to the relevance of data from ASTM E662 to the behavior of products in actual fires.

FIRE TESTS FOR INTERIOR FLOOR FINISH MATERIALS

Fire tests for interior finishes were developed primarily with wall and ceiling finishes in mind, long before carpeting became popular as an interior floor finish. Official attention was directed toward a possible hazard with soft floor coverings in 1960 and 1961 as a result of a series of small fires in the Washington, D.C., area.[51] A well-publicized dwelling fire on the West Coast in 1967, followed by the Harmer House Nursing Home fire in Ohio in 1970, focused attention on carpet floor coverings, although carpets were a contributing, rather than a causative, factor in these incidents.[52,53]

In 1965, the Public Health Service of the U.S. Department of Health, Education, and Welfare issued a directive setting flame spread limits on floor coverings in federally funded hospitals, citing the Steiner tunnel test as the test method. In the Steiner tunnel test, a floor covering would be mounted upside down and on the ceiling of the apparatus. Since neither the mounting nor location correctly simulated an actual installation, it is not surprising that the tunnel test was ultimately judged to be inadequate for floor coverings. Moreover, the Steiner tunnel cannot assess ignitability and its fuel source is not appropriate to assess slow flame spread. It was also found to be inadequate for carpets made with synthetic fibers of the type that melt, drip, or delaminate when exposed to elevated temperatures. As a further deficiency, carpets with separate underlayments could not be effectively tested in the tunnel. Thus, the need for a test specifically designed for interior floor finishes was clearly identified.

In 1969, UL started work on a new test for floor coverings with the test specimens mounted in a floor position.[54] The program was sponsored by the U.S. Public Health Service and resulted in what became known as UL Subject 992, the floor covering chamber test. In essence, UL Subject 992 is an 8 ft (2.44 m) version of the Steiner tunnel, with the test specimen mounted on the floor of the tunnel and with appropriate modifications in heat input, burner design, airflow, and other test specifications. This test never gained widespread acceptance and is no longer used.

Methenamine Pill Test

NIST (formerly NBS) developed the methenamine pill test as a means of preventing the use of highly flammable carpet floor coverings. The pill test was adopted by the federal government in 1970 as DOC FF-1-70 (Federal Register 1970a) for carpets and DOC FF-2-70 for rugs[55–57] and was also adopted by ASTM as ASTM D2859.[58] In this test, eight 9 in. (229 mm) square sections of a carpet are conditioned to drive off excess moisture, brought to room temperature in a desiccator, and tested. Each specimen, in turn, is placed on the bottom of a 1 ft (0.3 m) enclosed cube, which is open at the top. The specimen is held in place by a 9 in. (229 mm) square metal plate having an 8 in. (203 mm) circular cutout. A methenamine tablet is placed at the center of the circle and lighted. The pill produces a candlelike flame for about 100 seconds. A specimen fails if the flame advances to within 1 in. (25.4 mm) of the metal ring in the holddown plate. At least seven of the eight specimens must pass the test to meet the established criteria. All carpet manufactured for sale in the United States has been required, since April 1971, to pass this test (Figure 18.2.7).

Although the pill test is a small-scale test, the results have large implications in terms of floor covering performance. It has been shown that the pill test provides adequate "first to ignite" protection for carpet located in rooms.[59,60] Experiments conducted at NIST[61,62] revealed that carpet and floor coverings were unlikely to be involved in a fire or propagate flame in rooms until room fires approach or exceed flashover unless the fire started at the floor level. As a consequence, little additional safety is to be gained by regulating floor coverings within rooms beyond the pill test. These findings were used, in part, to establish the current code restrictions for floor coverings.

Experience has shown that many flooring materials (traditional floor finishes such as wood flooring or resilient materials) will not ignite unless exposed to an ignition source of well over 1 kW/m^2, but that some carpetlike or loose-fill materials may ignite at lower heat fluxes. A study of precision of the flooring radiant panel test method (ASTM E648,[63] NFPA 253, *Standard Method*

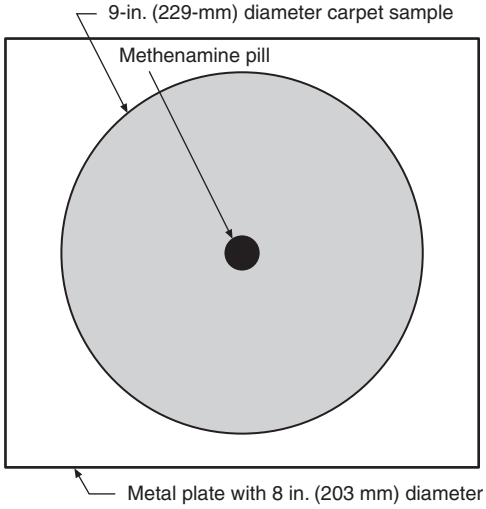

FIGURE 18.2.7 Methenamine Pill Test

of Test for Critical Rdiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source) found carpets with critical radiant heat fluxes well under 2 kW/m^2.[64] The minimum critical radiant flux of a product that will still pass the pill test has been determined to be 0.4 kW/m^2.[61] Therefore, as stated above, all carpets sold in the United States must meet the "methenamine pill" test, which ensures that flame spread will be minimal.

Flooring Radiant Panel Test or Critical Radiant Flux Test

Floor coverings having modest resistance to flame spread are unlikely to become involved in the early growth of a fire within a room. Thus, regulation of floor coverings is generally where specified by the code or where a need is indicated by some unusual product. It has been shown that floor coverings will tend to propagate flame only under the influence of a sizable exposure fire (often after flashover). Corridor floor coverings, for example, may spread flame when subjected to radiant heat from the hot gases discharging from the doorway of a fully fire-involved room.[65,66] The fire discharges flame and hot gases into the upper level of the corridor, which results in radiant heat energy transfer to the floor. The level of energy radiating onto the floor is a significant factor in determining whether progressive flaming will occur. Corridors with combustible wall and ceiling finishes would be expected to produce a potentially greater fire hazard. Experimental results suggest that floor coverings would contribute much less to fire spread than wall or ceiling finish in the initial growth of fires.[67]

Codes specify the use of the flooring radiant panel test for floor coverings in exits and corridors of certain occupancies. The flooring radiant panel test consists of a closed chamber having a radiant panel inclined at a 30° angle from a 39 in. (1000 mm) long test specimen. The test specimen is exposed to radiant heat that ranges from approximately 11 kW/m^2 to 1 kW/m^2. Flame spread over the face of the floor covering specimen is initiated by flames from a gas burner (Figure 18.2.8). The test determines the minimum energy required for a floor covering to spread flame. The flooring radiant panel test simulates conditions that have been observed and defined in large-scale corridor experiments, particularly when there is little or no combustible wall or ceiling finish. The test method assesses the critical incident flux required for continued flame propagation. It does so by determining the distance between the igniter and the point where flame propagation stops, and obtaining the heat flux from a calibration curve of heat flux versus distance. The flooring radiant panel measures the minimum energy required to be impinged on floor coverings to sustain flame propagation. The minimum value required to

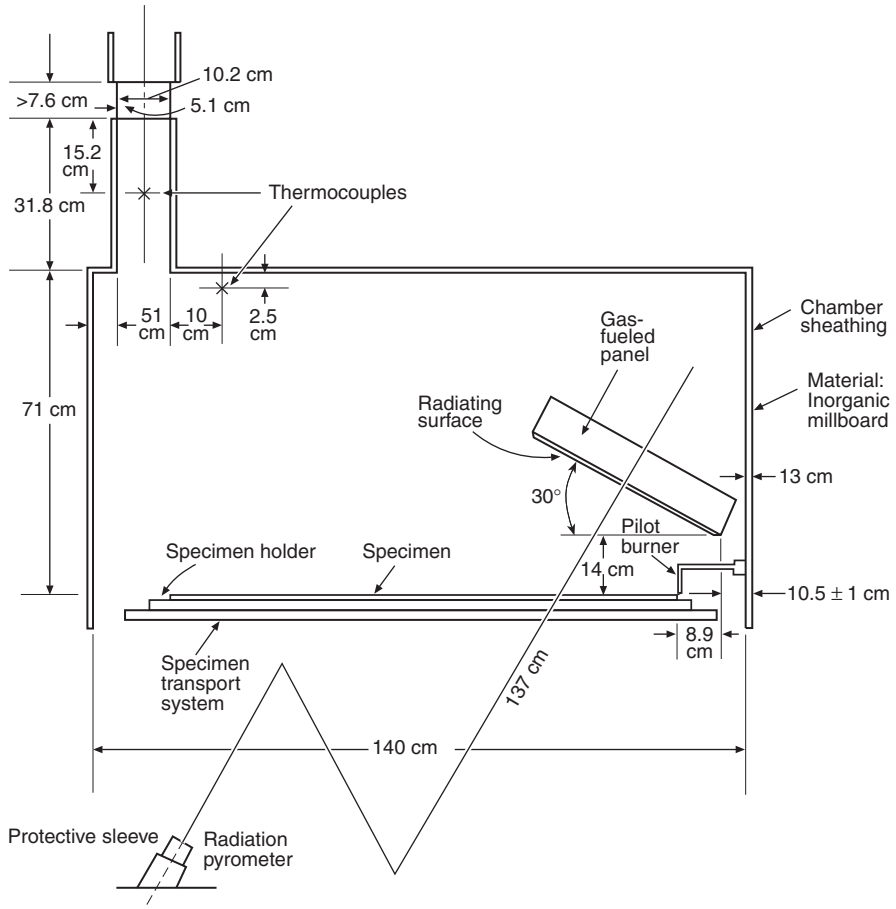

FIGURE 18.2.8 Flooring Radiant Panel Test Schematic (Size Elevation).
Note: in. = cm × 0.3937.

sustain flame propagation is termed *critical radiant flux*. The higher the critical radiant flux, the better the performance. In summary, the flooring radiant panel test is used for evaluating the fire performance of a floor covering in a building in areas where risks need to be especially minimized. Floor coverings in open building spaces and in rooms within buildings generally merit no further regulation, provided the floor covering is at least as resistant to flame spread as a material that will meet the federal flammability standard FF-1-70/ASTM D2859 methenamine pill test. Therefore, most codes regulate interior floor finish to be tested with the flooring radiant panel (ASTM E648, NFPA 253).

The codes classify interior floor finishes on the basis of critical radiant flux and group them into the following two classes:

- *Class I.* A minimum critical radiant flux of 0.43 Btu per ft^2 per second (0.45 W/cm^2)
- *Class II.* A minimum critical radiant flux of 0.19 Btu per ft^2 per second (0.22 W/cm^2)

See Table 18.2.2 for assignment of the two classes of floor finishes to the various occupancies identified in NFPA *101*.

The flooring radiant panel test requires test specimens to be representative of the product to be installed. Where carpet is to be loose-laid over concrete, for example, it should be tested over a thick, high-density inorganic reinforced cement board that simulates concrete. Where carpet, with or without integral pad, is to be bonded to concrete, an adhesive should be used, following the manufacturer's directions as to the type and application rate. The use of a separate underlayment (pad) will normally lower the critical radiant flux of a test specimen and, therefore, increase the tendency for flame spread. Research at NIST[68] has shown that underlayment lowers the critical radiant flux of a test specimen due to the insulative effect of the underlayment. The flooring radiant panel test formerly allowed a manufacturer of carpet to test over a "standard" pad or the actual underlayment proposed for use. Research at NIST has shown that using what was formerly considered the standard pad—a rubber-coated jute and animal hair or fiber pad a minimum of ⅜ in. (9.5 mm) thick and weighing 50 oz/yd^2 (1.86 kg/m^2)—is likely to yield lower critical radiant flux values than those associated with other underlayments in use.[68,69] If the manufacturer tests a carpet over the "standard pad," NFPA 253 allows the results to be applied to any carpet/underlayment combination. Alternatively, if the manufacturer chooses to test using the actual pad proposed for use, the results would be valid only for the actual combination tested.

Floor coverings are not generally regulated on the basis of smoke generation in codes. Regulation of floor coverings on the basis of smoke is usually not considered necessary. Floor coverings will not normally spread flame until after a fire grows to large size and most fires will be so large and the smoke production so great when floor coverings become involved that the minimal benefits achieved by imposing smoke limits on floor coverings would not generally warrant such regulation. Nevertheless, some jurisdictions and many transport environments (including trains and ships) establish criteria for floor finishes based on a test for smoke generation. In such instances, the ASTM E662 test method has been used for trains (and for some building regulations) and the ISO 5659-2 test method has been used for ships. These test methods provide procedures for measuring the specific optical density of smoke generated in a closed chamber, as discussed previously.

TYPES OF INTERIOR FINISH

The types of interior finish materials are numerous and include such commonly used materials as plaster, gypsum wallboard, wood, plywood paneling, fibrous ceiling tiles, several different plastic products, and a variety of wall coverings. Collectively, these finishes serve several functions: aesthetic, acoustical, and insulating, as well as protecting against wear and abrasion.

Wall and ceiling finish classification needs to be based on test specimens that are representative of actual installations (particularly in terms of the various layers involved and of components such as adhesives). Building, fire, and life safety codes single out certain specific interior finish materials. The interior finish materials singled out are very thin materials, structural members, textile wall and ceiling coverings, expanded vinyl wall and ceiling coverings, foam plastic insulation, interior trim (foam plastic or otherwise), light-transmitting plastics, wall base, metal panels, and fire retardant coatings (not discussed in building codes). NFPA *101* also has a specific reference to the fact that decorations and furnishings not meeting the definition of interior finish should not be tested by the test methods for interior finish. Electrical nonmetallic raceways are normally considered a subset of interior trim.

Very Thin Materials

Codes exempt very thin materials applied directly to the surface of walls and ceilings in a total thickness of less than 1/28 in. (0.9 mm) from testing as interior finish "if they meet the requirements of Class A interior wall or ceiling finish when tested in accordance with the Steiner tunnel test, using fiber cement board as the substrate material." This exemption for 1/28 in. thin materials that attain a flame spread index of 25 or less applies to products such as gypsum wallboard, single layers of paints, and thin paper, vinyl, or textile wall coverings. The exception for thin materials is based on the understanding that thin coverings secured to a substrate will tend to behave like the substrate. Thin coverings, such as paint on steel and paper over gypsum, will not generally spread flames or contribute to fire growth during the developing stage of a fire. However, thicker coverings, such as multiple layers of a wall covering or paint, can contribute to rapid fire growth.

Structural Members

Exposed portions of structural members complying with the requirements for Type IV(2HH) construction are exempt from testing and classification as interior finish in codes.

Textile Wall and Ceiling Coverings

Some textile wall and ceiling coverings are able to achieve good flame spread indices (less than 25) when tested in accordance with NFPA 255, and yet these same textile wall coverings in room-corner tests sometimes propagate flame and cause fires to grow to full-room size, that is, flashover, within minutes.[34] The codes mandate three options for textile wall coverings: (a) automatic suppression (sprinklers) as well as a Class A

performance in the Steiner tunnel test, (b) satisfactory behavior in the NFPA 265 room-corner test, or (c) satisfactory behavior in the NFPA 286 room-corner test. Since the ignition source of the NFPA 265 room-corner test does not reach the ceiling, textile ceiling coverings are allowed only options (a) or (c) and not (b). Satisfactory performance in accordance with NFPA 265 requires (a) no flame spread to the ceiling during the initial exposure, (b) no flame spread to the extremities of the sample, and (c) no flashover. Satisfactory performance in accordance with NFPA 286 is more difficult to achieve, because it requires two additional criteria: heat release rate not exceeding 800 kW and total smoke release not exceeding 1000 m^2. Since NFPA *101* applies to existing buildings, textile wall or ceiling coverings are not allowed to be tested by NFPA 286.

Expanded Vinyl Wall and Ceiling Coverings

Expanded vinyl wall or ceiling coverings are another example of products that may attain good flame spread indices in the Steiner tunnel test and yet perform unsatisfactorily in an actual fire. The codes establish special criteria for the use of expanded vinyl wall and ceiling coverings, similar to the requirements for textile coverings. The code also allows the use of expanded vinyl wall coverings for walls (but not ceilings) if the wall covering has been tested to the less severe room-corner test in NFPA 265.

Foam Plastic Insulation

The development of certain types of cellular plastics in board, poured-in-place, and sprayed-on foam has yielded lightweight materials with exceptional thermal insulation. The incorporation of fire retardants into some cellular plastic products makes it possible for them to meet the NFPA 255–related requirements for interior finishes. As a result, cellular plastics, particularly the sprayed-on type, have been used as exposed insulation. Rapid fire spread in several widely publicized fires (including the two nightclub fires described earlier[13–15]) involving exposed cellular polyurethane and polystyrene materials resulted in recommendations for protection of such surfaces against ignition and fire spread by the use of 15-minute thermal barriers.[70,71] NFPA *101* and *NFPA 5000* state that cellular or foam plastic materials are not allowed for use as interior finish unless actual fire tests substantiate, on a reasonable basis, their combustibility characteristics for the intended use.

Interior Trim

Codes also state that interior trim (for example around doors or windows or as chair rails) materials (other than cellular or foam plastics) must comply with an NFPA 255 flame spread index classification of Class C, without smoke developed index limitation, provided they do not exceed 10 percent of the aggregate wall or ceiling area. The rationale for this requirement is that typical wood products exhibit a Class C flame spread index classification. On the other hand, cellular or foam plastics may be used as interior trim only if they meet three criteria: (1) they do not exceed 10 percent of the aggregate wall or ceiling area, (2) the density is not less than 20 lb/ft^3 (320 kg/m^3) and they are no more than ½ in. (12.7 mm) thick and 4 in. (102 mm) wide, and (3) they comply with a NFPA 255 Class B flame spread index without the smoke developed index limitation. The exception for "plastic trim" is based on the assumption that the fire performance of the foam plastic trim will be comparable or better than that of traditional wood products. The required Class B flame spread index is better than the flame spread index achieved by most wood materials. A minimum density of 20 lb/ft^3 (320.4 kg/m^3) is set to prohibit the use of lightweight foam plastics, which typically have densities of 1 to 3 lb/ft^3 (16 to 48 kg/m^3). The width and thickness limits are to restrict the combustible mass. The concept of the "10 percent rule," which applies the same way for foam plastic as for other trim, has already been discussed in the section on concepts.

Electrical Nonmetallic Raceways. Electrical nonmetallic raceways are a special case of interior trim. Raceways are not normally regulated as interior finish. However, concerns have been expressed about the potential contribution of a sizable number of raceways mounted along a wall or ceiling. If the raceways collectively form a substantial surface area over which fire may spread, they could behave like combustible interior finish. Where the authority having jurisdiction judges that a potential hazard exists because of the number, area exposed, or type of material involved, NFPA *101* and *NFPA 5000* currently require nonmetallic raceways to attain a flame spread index of 25 or less when tested "in the form in which they are used." Similar to foam plastic trim, when the raceway constitutes less than 10 percent of the wall area, the smoke index is not limited.

Light-Transmitting Plastics

Light-transmitting plastics are permitted for use if they meet several small-scale fire test criteria and meet other severe area limitations.

Wall Base

Interior floor trim material used at the junction of the wall and the floor to provide a functional or decorative border, and not exceeding 6 in. (150 mm) in height, is permitted for use by NFPA *101* and *NFPA* 5000 if it meets the interior wall finish requirements for its location or the requirements for Class II interior floor finish.

Metal Panels

Listed factory-finished NFPA 255 Class A metal ceiling and wall panels are permitted by NFPA *101* and *NFPA 5000* to be finished with one additional application of paint and to be used in areas where Class A interior finishes are required. The total paint thickness is not allowed to exceed 1/28 in. (0.90 mm).

Fire-Retardant Coatings

Fire-retardant coatings are permitted by NFPA *101* if they are maintained to retain the effectiveness of the treatment under service conditions encountered in actual use.

Decorations and Furnishings

Free-hanging draperies that cover most or all of a wall surface have, on occasion, been subject to the requirements for interior

finish but are considered decorations by NFPA *101* and fire codes and are not addressed by building codes such as *NFPA 5000.* The traditional test for interior finish combustibility, NFPA 255, does not adequately assess the fire behavior of such products. Free-hanging drapery materials are more properly evaluated by NFPA 701*, Standard Methods of Fire Tests for Flame Propagation of Textiles and Films,* although the test is less severe than NFPA 255. When applied to a solid backing, such as gypsum wallboard, a drapery material needs to be considered as a textile wall covering and would be evaluated as interior finish (textile wall or ceiling covering, as appropriate). Other decorations and furnishings are often also required to meet the fire performance of NFPA 701, for example in NFPA *101*. However, when these are stand-alone decorations, they are no longer associated with interior finish and are often not regulated.

ROLE OF INTERIOR FINISH IN FIRES

Most building fires begin when decorative materials, furnishings, or waste accumulations ignite. Interior finishes are less often the first items ignited. For example, in 1999–2002 home fires, interior finish on walls, floors, or ceilings was cited as the first item ignited in only about 6 percent of fires, about 9 percent of civilian fire deaths, about 6 percent of civilian fire injuries, and about 10 percent of direct property damage from fires.[15] When interior finish is ignited, typical heat sources are equipment installed adjacent to interior finish (e.g., wiring, switches, receptacles, outlets, cords and plugs, fireplaces, chimneys or flues), equipment placed near interior finish (e.g., stoves, space heaters, water heaters, dryers, furnaces), equipment used near interior finish (e.g., torches), and open flame sources (e.g., matches, lighters, candles) used by adults or children to intentionally or unintentionally start a fire. Once a fire has started and intensified, however, the interior finish can become involved and contribute extensively to the spread and growth of fire. For example, multiple layers of wall coverings contributed to fire growth in the multideath fires at the Holiday Inn in Cambridge, Ohio, in 1979,[72] and at an office building in Atlanta, Georgia, in 1989.[7] Similarly, the use of non-fire-retarded wood paneling as interior finish in corridors, stairways, or exits (which does not comply with code requirements) often leads to an enhancement of the heat release in the fire; 0.25 inch luan paneling, 0.125 inch plywood paneling, and heart pine boards mounted on furring strips contributed to the severity of fires in a fraternity dormitory in Berkeley, California, in 1990; in a board-and-care facility fire in Detroit, Michigan, in 1992; and in a fraternity house fire in Chapel Hill, North Carolina, in 1996, respectively.[10,11,73,74]

Mechanisms

Interior finish affects fire hazard in four ways: (1) affecting the rate of fire buildup to flashover conditions, (2) contributing to fire extension by flame spread over its surface, (3) adding to the intensity of a fire by contributing additional fuel, and (4) producing smoke and toxic gases that can contribute to life hazard and property damage.[75] From a fire safety standpoint, the most desirable interior finish is one made of a relatively dense and noncombustible material that is a good conductor of heat, does not speed up flashover, does not add fuel to the fire, provides no path for surface flame spread, and produces little or no smoke or toxic gases. Materials that exhibit high rates of flame spread, contribute substantial quantities of fuel to a fire, or produce hazardous quantities of smoke or toxic gases are undesirable.

Interior Finish Materials and Flashover

Combustible interior finish in an enclosure can reduce the heat release rate necessary for flashover and can reduce the time to flashover. Flashover is caused by thermal radiation feedback from the ceiling and upper walls, which have been heated by the fire. This radiation feedback gradually heats the contents of the fire area. When all the combustibles in the space have become heated to their ignition temperatures, simultaneous ignition occurs. Interior finish plays an important role in the occurrence of flashover; that is, an insulating interior finish that lowers heat transfer to upper walls or ceilings can reduce both the time and the rate of heat release required to reach flashover. Any interior finish material that is combustible will contribute fuel to an existing fire, but those with better fire performance are likely to have minimal effects. Considering the nature of thermal radiation, the size and shape of the space in which the fire occurs becomes a critical factor.[76] In some corridor tests conducted by NIST, rapid spread of flame over one or more surfaces was found,[77] an obviously undesirable feature unlikely to be found with materials that meet the NFPA 286 room-corner test.

Once a room fire reaches full involvement, or flashover, heat, smoke, and combustion gases escape through openings to adjoining spaces. In those cases, the ignition of combustible interior finish may become a significant factor in the spread of fire to other areas. Several full-scale fire tests have demonstrated that heat, smoke, and combustion gases from burning furnishings are often sufficient to create a threat to the life safety of persons unable to evacuate the room of fire origin, without any contribution from combustible interior finishes if the interior finish materials have adequate fire performance.[78,79] However, even in such a case, the life safety of occupants remote from the fire and, in addition, potential property damage may be affected by the nature of the interior finishes. It is critical, therefore, to ensure proper fire performance of interior finish.

METHODS OF APPLICATION

The method of applying an interior finish both in actual practice and during the fire test can have a large effect on its fire behavior. For this reason, the manufacturer's specifications for material application should be strictly followed. Special attention must be paid to fastening details, including the type and application of adhesives and the number of coats and the application rate of any fire-retardant coatings. Application details are equally important in repair or replacement of interior finishes. Any new material used in retrofit must meet the code requirements in effect at the time of the retrofit.

The substrate material to which surface finishes are attached plays an important role in the flame spread behavior of thin products.[80] A thin combustible finish applied to a noncombustible substrate may sometimes present little hazard. The same finish material on a combustible backing could constitute a much more serious hazard. In the former situation, the substrate

will not ignite and, thus, will absorb heat during early fire development. In the latter case, both the surface finish and the backing material may ignite and the system will spread flames much more rapidly than either material would alone.

A particularly important case is that of paints. Testing[81] has shown that adding up to two layers of paint with a dry film thickness of about 0.007 in. (0.18 mm) will not change the fire properties of surface-covering systems. Testing has also shown that the fire properties of the surface-covering systems are highly substrate-dependent and that thin coatings generally take on the characteristics of the substrate. When exposed to fire, the potential for partial delamination, bubbling, and blistering of paint has been shown to result in an accelerated rate of flame spread.

The adhesive used is also a crucial factor in the fire behavior of interior finishes. The best performance is likely when an intimate bond is maintained between the face product and the substrate. However, adhesives can, and often do, also contribute fuel to a fire, and too much adhesive or the use of a highly flammable or inappropriate adhesive may result in faster flame propagation. The failure in bond between a surface finish and a substrate can also result in poor performance. Adhesives that soften at moderate temperatures may allow wall and ceiling finishes to drop or partially peel away during the growth stage of a fire. Perhaps the "worst case" for an interior finish is where partial release or partial delamination occurs. In such a case, the material separates from the substrate but remains in position. This not only increases the susceptibility of the surface material to ignition but it also exposes the substrate material, which, if combustible, adds fuel to the fire.

Some interior finishes, such as polystyrene ceiling tiles, achieve acceptable performance in an entirely different manner. They are designed to fall away early in a fire, thereby avoiding fire exposure. Satisfactory performance for such products results from evading flame during the fire growth phase. However, if the products fall or delaminate too early in a fire, they may interfere with persons attempting to escape. Where interior finish materials may fall or delaminate at relatively low temperatures and where the products involved have a significant mass, the behavior of such products should be assessed in terms of their impact on occupants and their effect on potential evacuation. Some building codes specify that wall and ceiling finishes should not become detached when exposed to elevated temperatures of 175 to 300°F (79 to 149°C) for a specified time interval, usually 30 minutes.

Thermally thin products, such as wood paneling 0.25 in. (6.4 mm) thick or less, will tend to spread flame more rapidly when the paneling is installed over studs or furring strips with air space than would be the case if installed over a solid substrate, such as cement board or gypsum board. As a consequence, in such cases some codes require that Class B and C interior finish materials less than 0.25 in. (6.4 mm) thick be permitted for use only when applied over a substrate of noncombustible material. Concern also exists about the possibility of flame spread over concealed surfaces of combustible interior finish materials where air space exists behind the finish. Building codes have application sections that restrict the application of interior finishes over air space in noncombustible assemblies. Interior finishes installed over an air space are restricted to products having a Class A flame spread index on both faces. Building codes regulate concealed spaces created by furring strips by requiring either firestopping or that the space be filled with inorganic or Class A materials.

The use of sprayed-on materials for interior finishes has proliferated. Some of these materials are coatings that are inherently fire safe. Other materials, however, especially the sprayed-on cellular or foam plastics used for insulation or decorative effects, may readily spread flames. The use of such products should be permitted only if fire behavior can be substantiated by large-scale tests conducted under actual fire conditions.

FULL-SCALE TESTS

Many large-scale fire tests have been conducted using existing buildings slated for demolition or available for other reasons. When carefully planned, such tests can add significantly to knowledge about the growth and spread of fire in buildings.

One of the first of these tests was conducted in Great Britain in 1949, under the auspices of the Fire Research Station (now Building Research Establishment).[82] Two 2 story dwellings were used, one with cellulose fiber insulation board lining and the other with plasterboard over fiberboard. One test was conducted in each house, both with real or simulated furnishings, with the bedroom doors open. Another test was conducted in each house with the doors closed. With both types of lining, temperatures in the living room, which was the room where the fire was started, became intolerable within a few minutes. As in many other tests and actual fires, the value of the closed door also was clearly demonstrated in decreasing fire hazard in bedrooms.

In 1958, the Division of Building Research of the National Research Council of Canada (NRCC) conducted a series of full-scale tests, known as the "St. Lawrence Burns," in six dwellings and two larger buildings.[83] Again, the one objective was to study fire spread as it would affect the life safety of the occupants of the second-floor bedroom behind open and closed doors. All dwellings became "smoke logged" within 6 minutes of the ignition of the wood cribs, regardless of the type of interior finish. Temperatures and gaseous combustion products developed much faster in the dwellings with combustible finishes and in those tests in which the bedroom doors were open.

Many large buildings scheduled for demolition were partially burned under the auspices of the Illinois Institute of Technology (ITT) Research Institute. In those tests and in extensive room/corridor tests, much information was developed relative to fire spread, flashover phenomena, and factors affecting life safety in fires.

The Office of the State Fire Marshal in California sponsored a series of tests in unused buildings at Camp Parks in the early 1970s. The objective was to develop criteria for egress facilities, particularly corridors. The final report includes a discussion of the reaction and interaction of wall, ceiling, and floor finishes.[84] Precedent for the full-scale corridor burns was established earlier in 1959 and 1960 by the City of Los Angeles (CA) Fire Department. Final reports on the Los Angeles tests were published in two volumes by NFPA.[85,86]

Furnished room burnout and corridor tests conducted at the Forest Products Laboratory of the U.S. Department of Agriculture compared the relative importance of room furnishings

versus room finishes.[78] A conclusion was reached that lethal levels of combustion products usually developed from burning furnishings before the wall finishes were seriously involved; this was supported by later work at Southwest Research Institute.[79] These and other studies recognize that once a fire is well established, it is highly probable that all combustibles in the room will become involved. Thus, the attainment of flashover, which is often associated with full room involvement in fire statistics, is an indication that life is untenable in the room of fire origin. It is also recognized that early detection, containment, and extinguishment in the room of fire origin is important, not only for early evacuation from the fire area, but also for the safety of persons elsewhere in the building and for the protection of the building itself.

Full-scale experiments have also been conducted to determine how the location and area of a wall finish affects the spread of fire in a corridor.[87] A series of experiments were conducted in a 6-ft (1.83-m) wide by 8-ft (2.44-m) high by 55-ft (16.76-m) long corridor exposed to hot gases from a burner. The corridor ceiling and upper walls were exposed to temperatures of approximately 1450°F (788°C). Corridor ceiling finish materials had flame spread indices between 0 and 25, whereas the wall coverings had a flame spread index of 90. These experiments revealed that ceiling interior finish plays an important role in flame spread behavior of walls. It was determined that wall coverings with a flame spread index of 90 could be used safely with ceiling finish materials having a flame spread index of no more than 25 when the wall covering was limited to the lower 4 ft (1.2 m) of wall surface. Most test configurations using material with a flame spread index of 90 covering the full height of the corridor walls and with ceiling finish materials having a flame spread index of 25 resulted in rapid flame propagation and unsafe conditions. It was deduced that some Class A (FSI < 25) ceiling materials increased flame spread mainly due to the fact that they were better insulators than materials with a zero flame spread index. In other words, the ceiling finish material influenced flame spread over walls by its resistance to heat transfer. This was a unique and unusual situation. These full-scale experiments support the application of materials with flame spread indices greater than those normally allowed when such interior finishes, such as a wainscot, are located in the lower portion of a wall. Codes occasionally recognize this principle and allow Class C materials as a corridor wall finish where Class B is normally required, for example, in health care occupancies, as long as the interior finish does not exceed 4 ft in height and is restricted to the lower half of the wall.

From 1979 to 1980, the U.S. Fire Administration sponsored a series of 75 tests to evaluate the performance of residential sprinklers in single-family and mobile homes. These tests showed the rapid buildup of heat and toxic gases that was possible with ordinary-hazard furnishings, particularly when the fire was ignited in the corner of the room or near curtains. There was a significant difference in the levels of combustion products and the times to reach those levels between fires in noncombustible interior finish and combustible interior finish.[88]

Room fire tests were commonly used in the 1980s for research purposes to evaluate interior finishes, wall coverings, and room furnishings. To help make sense of the proliferation of testing procedures, ASTM E603, *Standard Guide for Room Fire Experiments,*[89] and ASTM E2067, *Standard Practice for Full-Scale Oxygen Consumption Calorimetry Fire Tests,*[90] were developed. The ASTM E603 guide provides information on how room fire tests can be implemented and what combustion parameters are measured. Testing instrumentation may include, but is not limited to, oxygen, carbon dioxide, carbon monoxide, and other gas measurements; rate of heat release; heat flux; flame spread; temperature; air velocity profiles; mass loss rates; and smoke optical densities. The subsequent ASTM E2067 practice goes into considerably more detail but addresses mainly the tests that are intended to make heat release measurements rather than demonstration-type tests; it is a companion to ASTM E603.

See also Section 6, Chapter 3, "Concepts and Protocols of Fire Testing."

SUMMARY

Building interior finish materials can have a significant effect on fire growth and, ultimately, fire size. Interior finish materials can affect the rate of fire buildup to full room involvement and flashover, contribute to fire extension, add to the intensity of a fire, and produce smoke and toxic gases.

Several tests have been developed to try to predict the behavior of interior finish products in a fire. The Steiner tunnel test (NFPA 255 or ASTM E84) is used to calculate the flame spread index and smoke developed index of an interior wall or ceiling finish material, based on flame spread over the face of the test specimen. Room-corner tests are used to determine the probability of flashover and the heat release rate (measured through oxygen depletion) and smoke release in a room in which finish products are mounted on three walls forming a corner (and usually also on the ceiling). Fire testing of interior finish as conducted today is probably adequate to eliminate the poorest performers (both in terms of heat release, or flame spread, and smoke release). However, the emphasis on the supremacy of the Steiner tunnel test for all interior wall and ceiling finish materials means that the full capabilities of the room-corner test, including the actual heat release rates measured, are not being used, and improvements in that area would be welcome.

Fire tests for interior floor finishes include the methenamine pill test, which is a required safety test for all carpet manufactured for sale in the United States, and the critical radiant flux test, which measures the minimum energy required to be impinged on a floor covering to sustain flame propagation.

In addition to controlled laboratory tests, many large-scale fire tests of interior finishes have been conducted by various research organizations on buildings slated for demolition. Such tests yield important data concerning the behavior of interior finishes and furnishings in a fire.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on interior finish discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*
NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA *101®*, *Life Safety Code®*
NFPA 130, *Standard for Fixed Guideway Transit and Passenger Rail Systems*
NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 265, *Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Coverings on Full Height Panels and Walls*
NFPA 286, *Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth*

NFPA 301, *Code for Safety to Life from Fire on Merchant Vessels*
NFPA 501, *Standard on Manufactured Housing*
NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*
NFPA 1192, *Standard on Recreational Vehicles*
NFPA 5000®, Building Construction and Safety Code®

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Chapter 3

Smoke Movement in Buildings

James A. Milke ❑ John H. Klote

Chapter Contents

Description of Smoke
Smoke Production
Hazard of Smoke
Principles of Smoke Movement
Smoke Management

Key Terms

atria, buoyancy, compartmentation, dilution, pressurization, smoke (cool), smoke (hot), smoke movement, smoke production, stack effect, wind effect

Smoke is inherent in all fires and contains dangerous products of combustion that have critical influences on life safety, property protection, and operations by fire fighters in buildings. In some fires, the volume of visible smoke is so great that it may fill an entire building and obscure visibility at street level to such an extent that it is difficult to identify the fire-involved building. In other incidents, the volume of visible smoke generated may be considerably less, although the danger to life is not necessarily diminished because of the presence of invisible airborne products of combustion.

This chapter gives information on the techniques used to evaluate the physical characteristics of smoke and assess its movement in both short and tall buildings. Information on smoke properties and the forces inducing movement are used as a basis for designing smoke-control systems. The approaches that can be used to limit the hazard of smoke in buildings are also covered.

This chapter provides a general background on the subject, including a discussion of relationships, and selected equations useful in understanding smoke movement and smoke management in buildings. Detailed design information is available from a number of sources. The book by Klote and Milke,[1] *Design of Smoke-Management Systems,* provides a consolidation and systematic presentation of data and calculations necessary for the design of systems to manage smoke movement. Specific design information is provided in that publication for pressurized stairwells, pressurized elevators, zoned smoke control, and smoke management in large spaces, including atria and shopping malls. Klote and Milke each have written chapters in the third edition of the *SFPE Handbook of Fire Protection Engineering,*[2] which summarize much of the general information from the book by those two authors. First published in 1988, NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences,* provides additional recommendations for stairwell pressurization systems and zoned smoke-control systems, including suggested levels of pressurization for such systems in sprinklered and unsprinklered buildings. NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces,* first published in 1991, is a technical guide for the design of smoke management systems in shopping malls, atria, and other large-volume spaces.

For related topics see, Section 3, Chapter 5, "Introduction to Fire Modeling"; Section 3, Chapter 6, "Applying Models to Fire Protection Engineering Problems and Fire Investigations"; Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations"; Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems"; and Section 18, Chapter 4, "Venting Practices."

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DESCRIPTION OF SMOKE

As a fire burns, it generates heat and also generates products of combustion as a result of the chemical reactions associated with the combustion process. These products of combustion include the following:

1. Gases, such as carbon dioxide, carbon monoxide, water vapor, and possibly many others depending on the fuel
2. Solids, such as "soot," and liquids

A major portion of the heat generated by a fire remains in the mass of combustion products generated by the fire. This mass expands, is lighter than the surrounding air, and rises as a plume. The rising plume is turbulent and, because of this, entrains large quantities of air from the surrounding atmosphere into the rising gases, as indicated in Figure 18.3.1. This entrainment has the following effects:

1. Increases the total mass and volume of the plume
2. Cools the plume by mixing the cool entrained air with the rising hot gases; normally, the rising plume is hotter at its center and cooler toward the edges where cooler air is entrained
3. Dilutes the concentration of fire products in the plume

Smoke is defined in NFPA 92A and 92B as "The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, along with the quantity of air that is entrained or otherwise mixed into the mass."[1,2]

SMOKE PRODUCTION

The volume of combustion products contained in a rising plume is relatively small compared to the volume of air in the total mixture. Consequently, the volume of smoke produced by a fire approximates the volume of air drawn or entrained into the rising plume. Figure 18.3.1 illustrates the process.

In situations in which the height of the plume, measured from the top of the fire to the level of the smoke layer, is greater than the height of the solid body of flame, reasonably accurate estimates of the rate of smoke production can be obtained using empirical formulas.[3,4]

In general, the equations given in this chapter should be used where the fire is small compared to the height of the space involved. Alternatively, where this is not true, approaches such as those contained in Section 18, Chapter 4, "Venting Practices"; Section 3, Chapter 5, "Introduction to Fire Modeling"; and Section 3, Chapter 9, "Closed Form Enclosure Fire Calculations" are more appropriate.

The following equation is based on research conducted at Factory Mutual Research (FMR) and is the equation used for smoke production in NFPA 92B. The rate of smoke production (i.e., mass entrainment rate) can be estimated as[5]

$$\dot{m} = 0.071k^{2/3}Q_c^{1/3}z^{5/3} + 0.0018Q_c \qquad (1)$$

where

$\dot{m}$ = Mass flow in plume at height z (kg/sec)

k = Wall factor (Figure 18.3.2)

Q_c = Convective heat release rate of fire (kW)

z = Height above top of fuel (m)

Equation 1 is the same as the corresponding equation in NFPA 92B for the value of $k = 1$. Equation 1 includes a series of assumptions, the most important of which are the following:

1. The tip of the flame is a significant distance below the bottom of the smoke layer as is often the case in malls and atria. The formula is less accurate in spaces with a low ceiling relative to the height of the fire involved. In such cases, see NFPA 92B for the applicable equation.

2. The fire bed itself covers an area whose length and width are reasonably approximate to each other. The original formula is based on the assumption of a circular fire. The degree of error in the formula increases as the ratio of length to width increases.

3. The ceiling is sufficiently high so that a correction for the "virtual origin" of the fire is unnecessary (see Klote and Milke[1] for a description of virtual origin). This is true where the fire is small compared to the height of the space involved, as is the case for small fires in rooms or for design applications involving atria or other large-volume spaces.

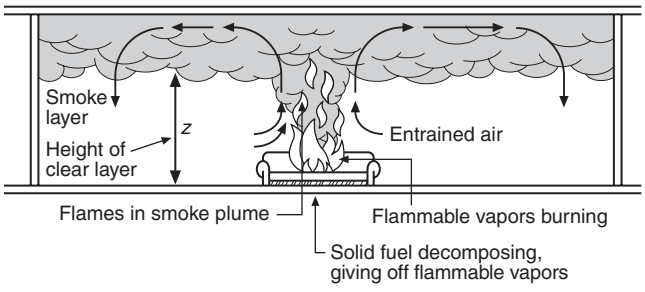

FIGURE 18.3.1 Production of Smoke from a Fire

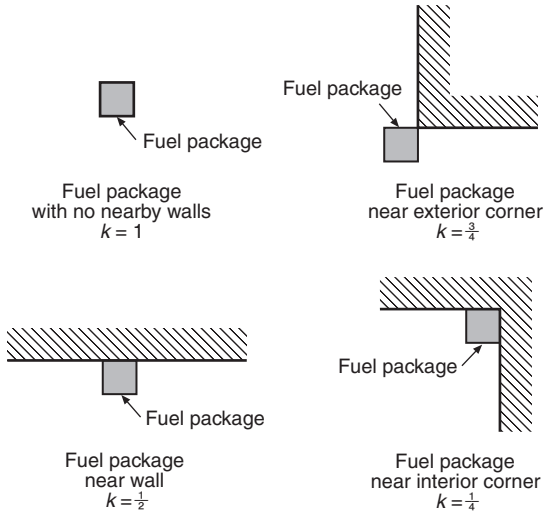

FIGURE 18.3.2 Wall Factors for Fuel Package Locations

Flame Height

A reasonable estimate of the visible flame height[6] can be obtained from the equation:

$$z_f = 0.166(Q/k)^{0.4} \quad (2)$$

where

z_f = Mean flame height (m)

Q = Heat release of the fire (kW)

k = Wall factor (see Figure 18.3.2).

Equation 2 is the same as the corresponding equation in NFPA 92B for the value of $k = 1$. The convective portion of the heat release rate, Q_c, can be expressed as

$$Q_c = \xi Q \quad (3)$$

where ξ is the convective fraction of heat release. The convective fraction depends on the heat conduction through the fuel and the radiative heat transfer of the flames, but a value of 0.7 is often used for ξ. The results of Equation 3 for a convective fraction of 0.7 are shown graphically in Figure 18.3.3.

Average Plume Temperature

Detailed engineering equations for fire plumes have been presented.[5,6] The average temperature of a fire plume is needed to express the rate of smoke production as a volumetric rate rather than as a mass rate (as in the previous section).

$$T_p = \frac{Q_c}{\dot{m} C_p} + T_o$$

where

T_p = Average plume temperature (°C)

$\dot{m}$ = Mass flow in plume at height z (kg/sec)

Q_c = Convective heat release rate of fire (kW)

C_p = Specific heat of plume gases, 1.00 kJ/kg°C

T_o = Ambient temperature (°C)

The average plume temperature decreases with increasing height above the fuel. This can be realized by recalling that the mass flow in the plume increases with the clear height, z.

The average plume temperature should not be confused with the centerline plume temperature. The plume centerline temperature is greater than the average plume temperature. Where the average plume temperature is approximately equal to the ambient temperature, the buoyancy of the plume is relatively weak. Because the mass entrainment equation (Equation 1) is for a strongly buoyant plume, the correlations may yield answers with significant errors in cases where the plume has low buoyancy. This topic needs further study, but in the absence of better data, it is recommended that the plume equations not be used when the average temperature increase is small—less than 4°F (2°C). The average temperature rise of a plume for a fuel package with no nearby walls is shown in Figure 18.3.4.

Volumetric Plume Flow

The volumetric flow rate of a plume is

$$\dot{V} = 1.1\dot{m}(T_p + 460)$$

where

$\dot{V}$ = Volumetric flow rate of plume at height z (ft^3/min)

$\dot{m}$ = Mass flow in plume at height z (lb/sec)

T_p = Average temperature of plume gases at height z (°F)

In SI units, this equation is

$$\dot{V} = \frac{\dot{m}(T_p + 273)}{353}$$

where

$\dot{V}$ = Volumetric flow rate of plume at height z (m^3/sec)

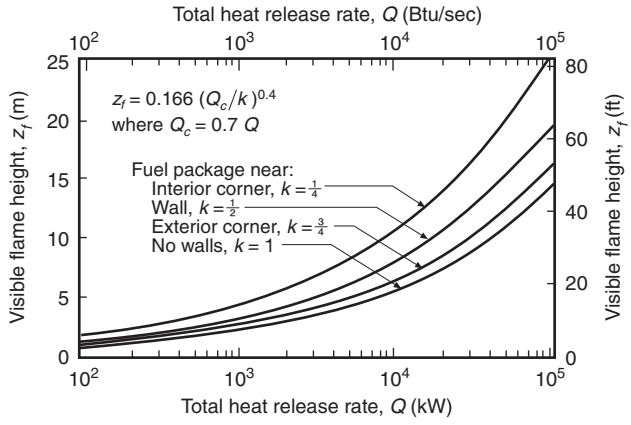

FIGURE 18.3.3 Flame Height Versus Fire Heat Release Rate

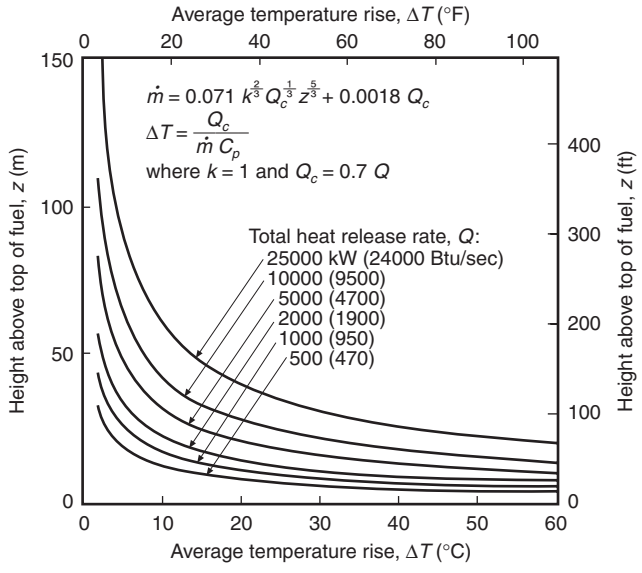

FIGURE 18.3.4 Average Plume Temperature Rise

$\dot{m}$ = Mass flow in plume at height z (kg/sec)

T_p = Average temperature of plume gases at height z (°C)

HAZARD OF SMOKE

Smoke can adversely affect people, property (including the building structure and contents), and mission continuity. The effect of exposure to smoke is dependent on the magnitude of the properties of the smoke (concentration of various gases, visibility reduction, temperature, and radiant flux) and the duration of the exposure.

People who are exposed to smoke may be harmed as a result of exposure to toxic gases, elevated temperature, or radiant energy. The toxic effects of the gases in smoke are described in Purser[7] and Klote and Milke.[1] For short duration exposures (on the order of 1 to 2 minutes), a carbon monoxide concentration of 0.1 to 0.8 percent may cause humans to become incapacitated while walking or being involved in a similar level of activity.

Exposure to radiant energy from a smoke layer at a temperature of at least 320°F (160°C) for a short duration (5 to 10 seconds) may be sufficient to inflict pain, considering the smoke to be a black body. Such a smoke layer temperature will provide a radiant heat flux of approximately 2 kW/m^2 (20 Btu/sft^2). Alternatively, people can typically tolerate being submerged in a smoke layer up to 212°F (100°C) for approximately 10 minutes.

A reduction of visibility by smoke may cause people evacuating to become disoriented or reduce their walking speed, thereby increasing the amount of time required for evacuation. Klote and Milke[1] describe the relationship between visibility and movement speed based on the work by Jin.[8] In addition, a reduction of visibility may increase the susceptibility of building occupants to trip over obstructions or fall over balcony railings.[9] A review of tenability analysis methods is provided by Purser as well as Milke, et al.[10]

Building contents can be affected by exposure to corrosive gases, particulate matter, and the elevated temperature of smoke. Electronic components may be damaged by temperatures and gas concentrations well below that needed to harm humans. Electronic equipment and data storage media are particularly sensitive to elevated temperature, being damaged at temperatures as low as 104°F (40°C) for diskettes and 176°F (80°C) for computer hardware. Smoke may contain several corrosive components, either as gases or absorbed into solid particles. Electronic equipment can be damaged by exposure to smoke containing only 0.01 percent of HCl or 0.1 percent of HF, especially if restoration activities are not initiated promptly after the incident. Contamination of food and pharmaceuticals is generally acknowledged, given exposure to smoke of virtually any concentration.

Mission continuity may be threatened following a fire, while a building or portion thereof is closed for restoration. This results in loss of revenue for the building owner, temporary unemployment of workers in the building, and loss of service of the facility to the community, among other effects.

PRINCIPLES OF SMOKE MOVEMENT

Smoke moves from an area of high pressure to one of low pressure. Pressure differences from one space to another may be caused by buoyancy from the fire, stack effect, wind, and forces from building heating, ventilating, and air-conditioning (HVAC) systems. Where multiple effects are present, smoke movement will depend on a combination of effects, one of which may be dominant.

Hot Smoke Versus Cool Smoke

The temperature of hot smoke results in the smoke being naturally buoyant. As such, the movement of hot smoke is directed toward the ceiling while clean (or at least less polluted) air is drawn in through the lower portion of the space. Hot smoke may be transported to adjacent rooms or corridors, depending on the level of energy produced by the fire and the size of connecting openings, such as open doors. Industrial and warehouse smoke and heat venting are effective smoke management methods because hot smoke is particularly buoyant.

As smoke is transmitted from the area of fire origin, it is cooled by the entrainment of air, heat transfer from the smoke body to surrounding walls and ceiling, and by radiant energy losses to all surroundings. When smoke from a fire flows through a relatively small crack, the entrainment of cool air on the unexposed side tends to cool the smoke very quickly. When the leakage is through larger openings, there may be less entrainment relative to the mass of smoke movement at such junctures and, therefore, cooling will be slower.

Where mixing and other forms of heat transfer have significantly reduced the temperature of the smoke, the effect of the buoyancy force is moderated. In such cases, stack effect, wind, and the mechanical HVAC or other air-movement systems become the primary controlling forces affecting smoke movement. Consequently, the movement of cool smoke is essentially the same as the movement of any other pollutant.

When hot smoke is transported from one area of a building to another through a confined passageway, such as a duct, shaft, or stairwell, there will be little or no cooling due to entrainment. In such cases, cooling will be limited to heat lost by conduction from the moving smoke through the shaft material. Often, this loss is modest, and hot smoke can be transported significant distances with only minor cooling by such confined passageways.

Smoke Movement in Tall Buildings

Smoke can behave very differently in tall buildings than in low buildings. In low buildings, the influences of the fire, such as heat, convective movement, and fire pressures, are generally the major factors that cause smoke movement. Smoke removal and venting practices reflect this behavior. In tall buildings, these same factors are complicated by the stack effect, which is the vertical natural air movement through the building caused by the differences in temperatures and densities between the inside and outside air. Stack effect in tall buildings can become an important factor in smoke movement and in building design features used to combat that movement.

The predominant factors that cause smoke movement in tall buildings are stack effect, the influence of external wind forces, and the forced air movement within the building. The next two parts of this chapter describe theoretical natural air movement, which is affected by the stack effect and external wind forces. Forced air movement caused by the building air-handling equipment is presented in Section 18, Chapter 4, "Venting Practices," and Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems," and is not discussed here except to note that air movement can be influenced significantly by the mechanical systems of the building. Many smoke management systems use emergency operation of the mechanical systems.

Flow Through Openings

Where a pressure difference exists across a crack, gap, or other opening, a flow will result from the higher pressure side to the lower pressure side. The *orifice equation* is commonly used to describe such flow:

$$\dot{V} = CA\sqrt{\frac{2\Delta P}{\rho}}$$

where

$\dot{V}$ = Volumetric flow rate through the path (m^3/sec)

C = Dimensionless flow coefficient

A = Flow area (also called leakage area) (m^2)

ΔP = Pressure difference across path (Pa)

ρ = Density of gas in path (kg/m^3)

In the context of flows through gaps around doors and through construction cracks, the coefficient C is generally 0.6 to 0.7. For standard air density of $\rho = 0.075$ lb/ft^3 (1.20 kg/m^3) and for $C = 0.65$, the flow equation above can be expressed as

$$\dot{V} = 2610A\sqrt{\Delta P}$$

where

$\dot{V}$ = Volumetric flow rate through the path (ft^3/min)

A = Flow area (also called leakage area) (ft^2)

ΔP = Pressure difference across path (in. of water)

In SI units, this equation is

$$\dot{V} = 0.839A\sqrt{\Delta P}$$

where

$\dot{V}$ = Volumetric flow rate through the path (m^3/sec)

A = Flow area (also called leakage area) (m^2)

ΔP = Pressure difference across path (Pa)

Stack Effect

Under normal conditions, stack effect can account for a major part of the natural air movement in buildings. During a fire, stack effect is often responsible for the wide distribution of smoke and toxic gases in high-rise buildings. "Normal" stack effect, present when the indoor air temperature is greater than the outdoor air temperature, is characterized by a strong draft from the ground floor to the roof of a tall building. The magnitude of this stack effect is a function of the building height, the airtightness of the exterior walls, the air leakage between floors of the building, and the temperature difference between the inside and outside of the building.

To illustrate the principle of stack effect, consider the schematic of a box with a single opening near the bottom and another near the top, as shown in Figure 18.3.5. The theoretical natural draft between the two openings is caused by the difference in weight of the column of air within the box and that of a corresponding column of air of equal dimensions outside the box. The magnitude of the theoretical natural draft may be computed by using the following formula:

$$\Delta P = 2.96HB_o\rho\left(\frac{1}{T_o} - \frac{1}{T_i}\right)$$

where

ΔP = Theoretical pressure difference (in. of water)

H = Vertical distance between the inlet and the outlet (ft)

B_o = Barometric pressure (in. of mercury)

T_o = Temperature of outside air (°F)

T_i = Temperature of inside air (°F)

ρ = Density of air at 0°F and 1 atmosphere pressure (lb/ft^3)

Assuming values of $B_0 = 29.9$ in. and $\rho = 0.0862$ lb/ft^3, this expression reduces to

$$\Delta P = 7.63H\left(\frac{1}{T_o} - \frac{1}{T_i}\right)$$

Vertical air movement in a building is caused by this natural draft, or stack effect. The magnitude of the stack effect depends on the difference between the inside and outside temperatures

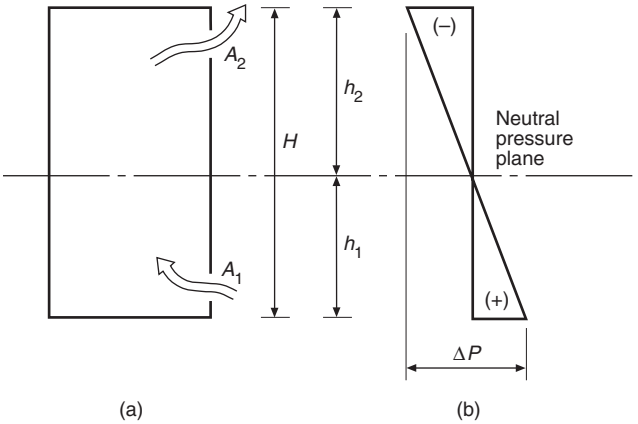

FIGURE 18.3.5 Air Movements Caused by (a) Pressure and (b) Location of Neutral Pressure Plane in a Structure Without Horizontal Barriers and With the Two Openings Shown

and on the vertical distance between openings. If the inside and outside temperatures are equal ($T_i = T_o$), no natural air movement takes place. When T_o is less than T_i, the air moves vertically upward, with the lower opening acting as the inlet and the upper opening as the outlet. A reverse stack effect occurs when T_o is greater than T_i. In this case, the upper opening is the inlet and the lower opening becomes the outlet.

Part (b) of Figure 18.3.5 illustrates the pressures that cause these movements. In this figure, if T_o is assumed to be equal to T_i, the exterior pressure will be greater than the interior pressure at the lower opening. Consequently, outside air is forced into the building at that location. Because the outside pressure at the upper opening is lower than the inside pressure, a negative pressure difference at that location is present, which forces the inside air to the outside. Based on basic engineering principles, the pressure distribution between these two locations is assumed to be linear.

If an opening were present in the exterior wall in a region of positive pressure, air would flow into the building. An opening in a region of negative pressure would cause air to flow out of the building. The neutral pressure plane indicates where inside and outside pressures are equal. If there were an opening at this level, air would move neither inward nor outward. The location of the neutral pressure plane in a structure without horizontal barriers and with the two openings shown in Figure 18.3.5 can be determined from the following relationship:

$$\frac{h_1}{h_2} = \frac{A_2^2 T_o}{A_1^2 T_i}$$

where

h_1 and h_2 = Distances from the neutral pressure plane to the lower and upper openings, respectively

A_1 and A_2 = Cross-sectional areas of the lower and upper openings, respectively

T_i and T_o = Absolute temperatures of the air inside and outside the building, respectively

The magnitude of the pressures created by stack effect are described by the equation

$$\Delta p = 7.63H\left(\frac{1}{T_o} - \frac{1}{T_i}\right)$$

where

Δp = Pressure difference (in. of water)

T_o = Temperature of outside air (°F)

T_i = Temperature of inside air (°F)

Examination of Figure 18.3.6 illustrates the significant differences between tall and short buildings with regard to air movement by stack effect. For example, assume that a fire develops a pressure of 0.06 in. of water (15 Pa) in a compartment, the outside temperature is 50°F (10°C) lower than the inside temperature, and the fire occurs at the same level as the lower opening. The curve $T_i \pm 50$°F (10°C) indicates that if the upper outlet were approximately 40 ft (12 m) above the fire, the inlet stack pressure would balance the pressure caused by the fire. A building taller than 40 ft (12 m) would create a greater stack pressure, and, theoretically, the outside air would move into the building.

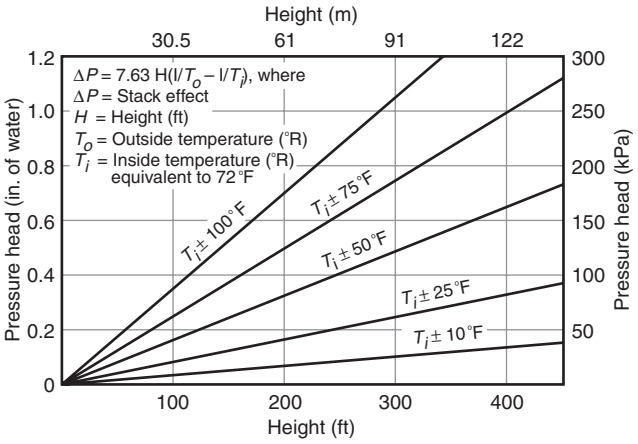

FIGURE 18.3.6 Stack Effect Due to Height and Temperature Difference (°C = [°F – 32] × 5/9)

Influence of Floors and Partitions

The theoretical draft described by Figure 18.3.5 and the net pressure difference present in real buildings is modified by the presence of floors and partitions. These barriers impede the free movement of air, although a significant flow can take place through openings in the assemblies.

The magnitude and location of the leakage areas in a building naturally vary with the building's function and type of construction. The National Research Council of Canada (NRCC) conducted studies of airtightness for major separations on four buildings ranging from 9 to 44 stories high. The measurements were used for computer modeling of the air movement for a simulated 20 story building with a floor plan dimension of 120 ft by 120 ft (36 m by 36 m) and a floor to floor height of 12 ft (3.6 m).[11] The data from the NRCC are given in Table 18.3.1 in the form of a ratio of the net leakage area to the surface area of the building component.

These leakage areas are sufficient to allow substantial air movement throughout the building. Most of the air will flow into vertical shafts, such as stairwells and elevator shafts. Some will flow vertically from floor to floor through the minor openings in the floor-ceiling assembly. This floor-to-floor movement is always caused by a pressure differential between the floors.

Part (a) of Figure 18.3.7 illustrates the pressure difference characteristics of a building in which stack effect causes air movement. The slopes of the pressure lines represent differences between any two regions at the same height. Airflow from one region to another is illustrated by the airflow directions represented by the arrows in Part (b) of Figure 18.3.7.

Wind Effects

Wind is another important factor influencing the movement of smoke. Again, tall and short buildings behave somewhat dif-

TABLE 18.3.1 Typical Leakage Areas for Walls and Floors of Commercial Buildings[a]

Construction Element	*Tightness*	*Area Ratio*[b]
		A/A_w
Exterior building walls (includes construction cracks, cracks around windows and doors)	Tight	0.50×10^{-4}
	Average	0.17×10^{-3}
	Loose	0.35×10^{-3}
	Very Loose	0.12×10^{-2}
Stairwell walls (includes construction cracks but not cracks around windows or doors)	Tight	0.14×10^{-4}
	Average	0.11×10^{-3}
	Loose	0.35×10^{-3}
Elevator shaft walls (includes construction cracks but not cracks around doors)	Tight	0.18×10^{-3}
	Average	0.84×10^{-3}
	Loose	0.18×10^{-2}
		A/A_f
Floors (includes construction cracks and gaps around penetrations)	Tight[c]	0.66×10^{-5}
	Average	0.52×10^{-4}
	Loose[c]	0.17×10^{-3}

[a]Flow area ratios for $C = 0.65$ at 0.3 in. H_2O (75 Pa).
[b]A is flow area, A_w is wall area, and A_f is floor area. Values of area ratios based on pressurization measurements in buildings by Tamura and Wilson,[12] Tamura and Shaw,[13–15] and Shaw, Reardon, and Cheung.[16]
[c]Values extrapolated from average floor tightness based on range of tightness of other construction elements.

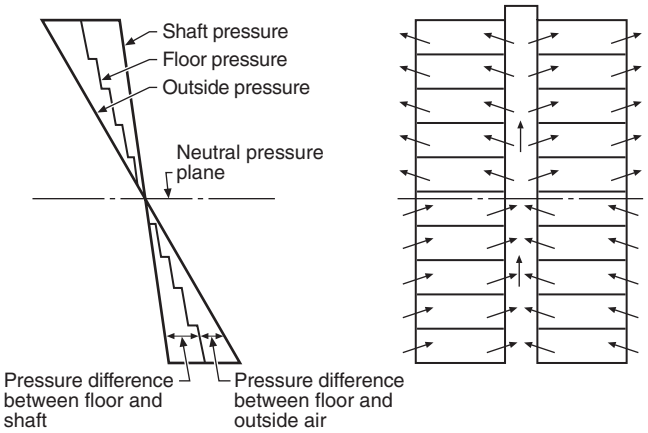

FIGURE 18.3.7 Pressure Difference Characteristics of a Building in Which Stack Action Causes Air Movement

ferently in this regard. Figure 18.3.8 illustrates the air pressure distribution along the four sides and the roof of a building. The plan view of the pressures shows that the windward wall is subjected to an inward pressure, whereas the leeward wall and the

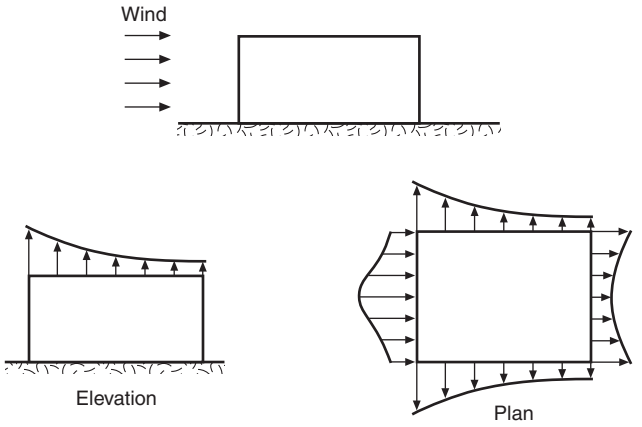

FIGURE 18.3.8 Air Pressure Distribution Along the Four Sides and Roof of a Building

two side walls have an outward pressure, or suction. The flat roof has an upward pressure, with the maximum amount occurring at the windward edge.

These pressures are caused by the movement of a mass of air over and around the structure. A short, wide building will cause the major volume of air to move over the roof, with correspondingly less air movement around the sides. A tall, narrow building, on the other hand, will cause the major volume of air to follow the path of least resistance around the building, with less movement over the top. The velocities of these movements are the primary cause of the amount and directions of the pressures on the building.

Wind velocities and direction vary over any face of a building. The following are the most important effects:

1. *Wind velocity.* The higher the wind velocity, the greater the effects of the following two influences.
2. *Ground effect.* Unless influenced by unusual arrangements of structures or terrain, the friction and turbulence that occur as air moves over the ground result in the lowest velocity at ground level, which increases with increasing height.
3. *Structures.* Buildings and other artificial or natural features, such as trees, can produce localized effects that can increase, decrease, or alter the direction of wind forces.

The effect of wind pressures and suctions modifies the natural air movement within a building. For example, the negative pressure on the roof of a tall building can have an aspirating effect on a vertical shaft opened at the roof level. This can cause the observed draft to exceed the theoretical draft shown in Figure 18.3.9. Note how the neutral pressure plane changes location throughout the building in the presence of significant wind.

Horizontal pressures and suctions cause the neutral planes in exterior walls to move. Positive wind pressure tends to raise the neutral pressure plane, whereas negative pressure lowers it. Figure 18.3.9 illustrates the influence of wind action on air movement in a building.

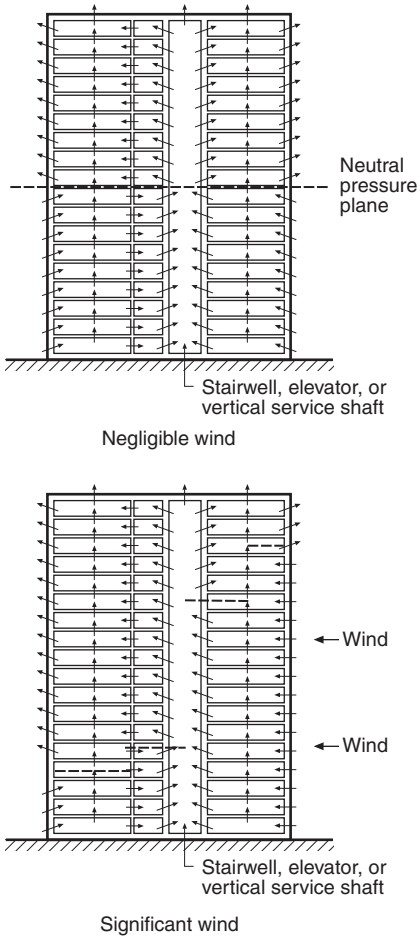

FIGURE 18.3.9 Influence of Wind Action on Air Movement in a Building

SMOKE MANAGEMENT

The term *smoke management,* as used in this section, includes all methods that can be used alone or in combination to modify smoke movement for the benefit of occupants or fire fighters or to reduce property damage. Compartmentation, dilution, airflow, pressurization, and buoyancy of the smoke itself can be used alone or in combination to manage the hazard of smoke in fires.

Compartmentation

Barriers such as walls, partitions, floors, and doors with sufficient fire resistance to remain effective throughout a fire exposure have a long history of providing protection against fire spread. These same barriers provide some level of smoke protection to spaces remote from the fire. Many codes, such as NFPA *101®*, *Life Safety Code®*, and NFPA 105, *Standard for the Installation of Smoke Door Assemblies and Other Opening Protectives,* provide specific criteria for the construction of smoke barriers, including doors and smoke dampers in these barriers. The amount of smoke leakage through such barriers depends on the size and shape of the leakage paths in a barrier and on the pressure difference across the leakage path.

There is no formalized analytical method for determining the rate of smoke leakage through barriers and the resulting levels of hazard in areas to be protected. A first-order approximation of the leakage can be made using the equation for flow through an opening. Typical leakage areas for barriers are listed in Table 18.3.1. Estimates of the leakage areas for gaps around doors can be obtained by considering the dimensions of paths around doors. Where multiple leakage paths are present, an effective leakage area can be determined following the methods in Klote and Milke.[1] In lieu of using the simple algebraic equation, fire and smoke transport models can address the smoke leakage through barriers (though these still require information to be provided concerning the size of the leakage paths). Full appraisal of the impact of such leakage requires knowledge of the smoke toxicity or an assumed design value of the acceptable smoke concentration in protected spaces. More effort is needed to increase the understanding of the capabilities and reliability of passive barriers in order to maximize the usefulness of this oldest and most fundamental method of smoke management.

Dilution

Dilution of smoke is sometimes referred to as smoke purging, smoke removal, smoke exhaust, or smoke extraction. Dilution can be used to maintain an acceptable smoke concentration in a compartment subject to smoke infiltration from an adjacent space. This can be effective if the rate of smoke leakage is small compared to either the total volume of the safeguarded space or the rate of purging air supplied to and removed from the space. Dilution also can be beneficial to the fire service for removing smoke after a fire has been extinguished. Sometimes, when doors are opened, smoke will flow into areas intended to be protected. Ideally, doors will be open only for short periods during evacuation. Smoke that has entered spaces remote from the fire can be purged by supplying outside air to dilute the smoke.

Some expectations may be unrealistic regarding what dilution can accomplish in the fire space. There is no theoretical or experimental evidence that using a building's HVAC system for smoke dilution will result in any significant improvement in tenable conditions within the fire space. Even though HVAC systems promote a considerable degree of air mixing within the spaces they serve, building fires produce very large quantities of smoke. As such, dilution of smoke by an HVAC system in the fire space does not usually result in any practical improvement in the tenable conditions of that space. Thus, smoke-purging systems intended to improve hazard conditions should not be used within a fire space or in spaces connected to a fire space by large openings.

The following is a simple analysis of smoke dilution for spaces in which there is no fire. At time zero ($t = 0$) a compartment is contaminated with some concentration of smoke, and no further smoke flows into or is generated within the compartment. In addition, the contaminant is considered uniformly distributed throughout the space. The concentration of contaminant in the space can be expressed as

$$a = \frac{1}{t} \log_e \left(\frac{C_o}{C} \right)$$

where

C_o = Initial concentration of contaminant

C = Concentration of contaminant at time t

a = Dilution rate in number of air changes per minute

t = Time after smoke stops entering space or time after which smoke production has stopped (minutes)

e = Constant, approximately 2.178

The concentrations C_o and C must be expressed in the same units, and they can be any units appropriate for the particular contaminant being considered. McGuire, Tamura, and Wilson[17] evaluated the maximum levels of smoke obscuration from a number of fire tests and a number of proposed criteria for tolerable levels of smoke obscuration. Based on this evaluation, they stated that the maximum levels of smoke obscuration are greater by a factor of 100 than those relating to the limit of tolerance. According to their observation, an area can be considered "reasonably safe" with respect to smoke obscuration if its atmosphere will not be contaminated to an extent greater than 1 percent by the atmosphere prevailing in the immediate fire area. Because a toxicity analysis can be somewhat involved and dilution will reduce concentrations of toxic smoke components as well as improve visibility, a first-order analysis can be done on a basis of smoke obscuration.

EXAMPLES: Smoke purging after the fire is extinguished.

1. After the fire department puts out a fire, the smoke must be cleared quickly so that an inspection can be made to determine if the fire is completely out. If the smoke HVAC system is capable of a dilution rate of six air changes per hour, how long will it take to reduce the smoke concentration to 1 percent of the initial value? The dilution rate, a, is 0.1 change per minute, and C_o/C is 100. $t = \frac{1}{0.1} \log_e(100) = 46$ minutes to purge smoke to 1 percent of initial value.

2. Considering the fire department's desire to inspect the area quickly, such a long purging time will probably be excessive. If the fire department wants the space to be purged in 10 minutes, what dilution rate is needed? The dilution time, t, is 10 minutes, and C_o/C is 100. $a = \frac{1}{10} \log_e(100) = 46$ change per minute (28 changes per hour).

In reality, it is impossible to ensure that the concentration of the contaminant is uniform throughout the compartment. Because of buoyancy, it is likely that higher concentrations would tend to be near the ceiling. Therefore, an exhaust inlet located near the ceiling and a supply outlet located near the floor would probably dilute smoke even faster than indicated by the preceding equations. Caution should be exercised in locating the supply and exhaust points to prevent the supply air from blowing into the exhaust inlet and thus short-circuiting the dilution operation.

Pressurization

Systems using pressurization produced by mechanical fans are referred to as smoke-control systems in NFPA 92A. Pressurization results in airflows of high velocity in the small gaps around closed doors and in construction cracks, thereby preventing smoke backflow through these openings. The pressurization systems most commonly used are pressurized stairwells and zoned smoke control. Elevator smoke control is rarely used, though interest in elevator smoke control may rise with the increasing interest in using the elevators as part of the means of egress for all or part of the building population. A public domain computer program, CONTAM,[18] may be applied to assess the pressure differences provided by a smoke-control system.

Many pressurized stairwells are provided with the goal of maintaining a tenable environment within the escape route in the event of a building fire. As such, a pressurized stairwell is designed to limit the amount of smoke migration into the stairwell, though not necessarily to keep the stairwell perfectly smoke-free. The following are the three major design concerns with pressurized stairwells:

1. Varying pressure differences that occur over the stairwell height
2. Large pressure fluctuations caused by doors being opened and closed
3. Location of supply air inlets and fans

Intuitively, it might appear that the pressure differences from the stairwell to the building would be approximately the same over the height of the stairwell. Unfortunately, this is not the case. For a building without vertical leakage through floors or shafts other than the stairwell, the pressure profile is linear. Of course, actual buildings have other shafts (elevators, pipe chases, etc.) and also have floor assemblies that are not airtight. However, this case is useful because it represents the most challenging situation to formulate a design. Its minimum pressure difference is less than that for buildings with more realistic leakage configurations and its maximum pressure difference is greater than that for other leakage configurations. A solution in the form of an algebraic equation exists to determine the pressure differences in a pressurized stairwell, neglecting vertical air movement in the building. In contrast, computer analyses are required to include the effects of more complicated building leakage arrangements.

When a door is opened in a pressurized stairwell, the pressure difference across the remaining closed doors can drop substantially. The two classes of design concepts that have been used to deal with this problem are overpressure relief and feedback control. An overpressure relief system that has gained attention as being simple and cost-effective is the "Canadian system." The essential features of this system are that air is supplied by one or more fans at relatively constant flow rates, and the ground-floor exterior stairwell door opens automatically when the system activates. This system eliminates the source of the most severe pressure fluctuations—the opening and closing of the exterior door.

There is concern about locating supply air inlets near the exterior ground-floor doors of the stairwell. If a supply inlet is located near this door, it is possible that much of the supply air will flow directly through the exterior doorway when it is opened, thus compromising the stairwell pressurization system. It is believed that locating inlets only one floor away from exterior doors eliminates this potential.

In the late 1960s, the concept of the "pressure sandwich" or "zoned smoke control" evolved. This consisted of exhausting the fire floor and pressurizing surrounding floors to limit

smoke movement to the fire floor by creating pressure differences between floor levels. According to the concept of zoned smoke control, a building can be divided into a number of smoke zones, each separated from the others by partitions and floors. A smoke-control zone can consist of one floor, more than one floor, or part of a floor. In the event of fire, pressure differences and airflows produced by mechanical fans can be used to restrict smoke spread to the zone in which the fire began, or the smoke zone. One of the factors affecting successful performance of a zoned smoke control system is accurate identification of the zone of fire origin. As such, fire alarm initiating devices used to actuate a zoned smoke control system need to be carefully selected. Failure to identify the correct fire zone, such as a case where a manual pull station is activated outside the fire zone, may result in a positive pressurization of the fire zone, which may encourage smoke spread to other zones.

When using zoned smoke control, careful integration of smoke zones, barriers, and the initiating devices is required. Physical barriers (walls or floors) must coincide with the spatial definition of the smoke control zone. Where HVAC equipment is used to supply and exhaust air, the HVAC zones must agree with the smoke zones. If fire alarm initiating devices or sprinkler waterflow alarms are used to actuate the zoned smoke-control system, the zones for these systems must coincide with the smoke-control zones.

As a caution, the design of zoned smoke-control systems is not intended to improve conditions in the fire zone. The concentration of smoke in this zone may render it untenable. Accordingly, in zoned smoke-control systems, building occupants should evacuate the zone in which the fire occurs as soon as possible after the fire has been detected.

Airflow

Airflow has been used extensively to manage smoke from fires in subway, railroad, and highway tunnels. Large flow rates of air are needed to control smoke flow, and these flow rates can supply additional oxygen to the fire. Because of the need for complex controls and large airflows, airflow is not used as extensively in buildings. The control problem consists of having very small flows when a door is closed, and then having those flows increase significantly when that door opens.

Thomas[19] determined that airflow in a corridor in which there is a fire can almost totally prevent smoke from flowing upstream of the fire. As illustrated in Figure 18.3.8, the smoke forms a surface that slopes into the direction of the oncoming airflow. Molecular diffusion is believed to result in the transfer of trace amounts of smoke, producing only an odor of smoke, but no hazard upstream. There is a minimum velocity below which smoke will flow upstream, and Thomas[19] developed the following empirical relation for this critical velocity. This relation, evaluated at an air density of 0.081 lb/ft^3 (1.3 kg/m^3) and temperature of 81°F (27°C), is

$$V_k = 5.68\left(\frac{E}{W}\right)^{1/3}$$

where

V_k = Critical air velocity to prevent smoke backflow (ft/min)

E = Energy release rate into corridor (Btu/hr)

W = Corridor width (ft)

This relation can be used when the fire is located in the corridor or when the smoke enters the corridor through an open doorway, an air transfer grille, or some other opening. Although the critical velocities calculated from the above equation are approximate, these critical velocities are indicative of the kind of velocities required to prevent smoke backflow from fires of different sizes.

EXAMPLES: Rough estimates of airflow for a doorway.

1. Thomas[19] indicated that his relationship for critical velocity can be used to obtain a rough estimate for doorways. A room fully involved in fire could have an energy release rate on the order of 8×10^6 Btu/hr. What estimate of critical velocity is obtained from the Thomas equation for a door 3 ft (0.9 m) wide?

$$V_k = 5.68\ (8 \times 10^6/3)^{1/3} = 800 \text{ ft/min}$$

If the door has an area of 20 ft^2 (1.9 m^2), this would amount to a flow of 1600 ft^3/min (0.76 m^3/sec).

2. Consideration of a smaller fire, such as a wastebasket fire, may be appropriate for many situations. What flow rate does the Thomas relation indicate is needed to prevent backflow for the door in Example 1? A wastebasket fire has a peak energy release rate near 0.5×10^6 Btu/hr (146 kW).

$$V_k = 5.68\ (0.5 \times 10^6/3)^{1/3} = 300 \text{ ft/min (1.5 m/sec)}$$

For a door area of 20 ft^2 (1.9 m^2), this would amount to a flow of 6000 ft^3/min (2.8 m^3/sec).

In any smoke management design with airflow, the effect of providing a significant quantity of fresh air to the fire needs to be considered. Also, the airflow must be exhausted at some point downstream.

Buoyancy in Large Spaces

Buoyancy of hot combustion gases is employed in both fan-powered and nonpowered smoke management systems for large-volume spaces. The spaces where such systems are employed include atria, arcades, covered shopping malls, sports arenas, and exhibition halls. In general, these buoyancy systems are used for spaces with floor to ceiling heights of at least 33 ft (10 m) and may be much greater. The following approaches can be used to manage smoke in large spaces.[20,21]

Smoke Filling. This approach consists of allowing smoke to fill the large-volume space while occupants evacuate the atrium. This approach applies only to spaces where the smoke-filling time is sufficient for both decision making and evacuation. Evacuation time can be estimated by people movement analysis.[22,23] Smoke-filling time can be estimated by computer fire models or by the filling time equations in NFPA 92B.

Unsteady Clear Height with Upper Layer Exhaust. This approach consists of providing a sufficient exhaust rate of smoke from the top of the atrium to delay the descent of the smoke layer to permit occupants to have sufficient time for decision making and

evacuation. This approach requires an analysis of people movement and analysis of the smoke-filling process with a fire model.

Steady Clear Height with Upper Layer Exhaust. This approach consists of exhausting smoke from the top of the atrium in order to achieve a steady clear height for a steady fire (Figure 18.3.10). Design analysis of this system is based on the fact that the mass flow of smoke entering the upper smoke layer equals that of the exhaust. For a fuel package away from walls, the exhaust airflow rates are shown in Figure 18.3.11.

Design Considerations

The design of exhaust systems for large-volume spaces includes more than the overall exhaust rate needed. Additional items include makeup air supply, stratification, and plugholing.

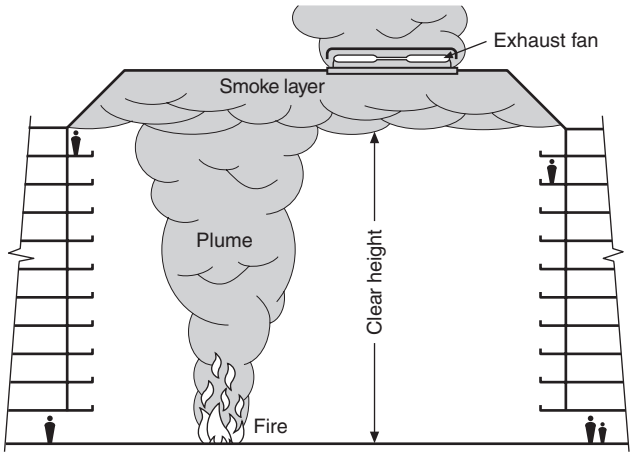

FIGURE 18.3.10 Atrium Smoke Exhaust to Maintain a Smoke-Free Clear Height

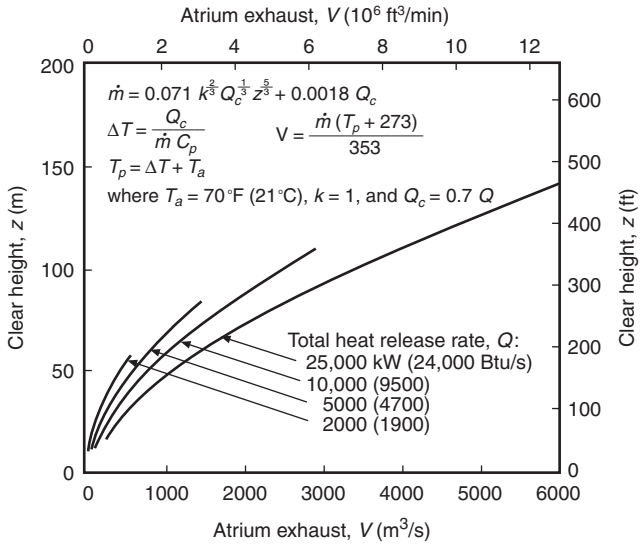

FIGURE 18.3.11 Atrium Exhaust Needed to Maintain a Clear Height for Various Heat Release Rates

The makeup air supply needs to be provided at a relatively low velocity (200 fpm [1 m/sec] or less at the fire) to avoid disrupting the plume and increasing entrainment of air in the plume. In addition, the makeup air supply should be distributed around the entire perimeter of the design fire to avoid tilting the flames or increasing the turbulence of the plume. If the makeup air velocity is provided at too great a speed or from one side only, the exhaust capacity may not be sufficient for the system to perform as intended.

Stratification of the smoke layer below the ceiling will delay or prevent actuation of ceiling-mounted smoke detectors and sprinklers. The solar load on an atrium often results in the formation of a layer of hot air under the ceiling. Stratification is expected if the temperature of the rising smoke plume is less than the surrounding air. If stratification of the smoke occurs at an intermediate height, smoke will not be able to reach ceiling-mounted smoke detectors, delaying or preventing smoke detection. This problem can be overcome by using projected beam detectors, as discussed in NFPA 92B.

Plugholing relates to the situation where a hole is "punched" through the smoke layer by a relatively high-velocity exhaust fan. The condition necessary for plugholing can be identified using calculations in NFPA 92B. If plugholing occurs, some of the exhaust capacity of the fan will be utilized to exhaust the "clean" air from below the smoke layer that is pulled through the hole in the smoke. As such, the efficiency of the exhaust system will decrease and the smoke layer will descend, perhaps to unacceptable levels.

Computational Tools for Design

NFPA 92B recognizes the following types of computational tools that can be used for analysis of smoke management systems in large-volume spaces: (1) scale modeling, (2) algebraic equations, and (3) compartment fire models. These tools can be used singularly or in combination. In scale modeling, a scale model of a building is made, and the design fire and results of the modeling are scaled in accordance with established scaling laws. Chapter 6 of NFPA 92B lists the algebraic equations that can be used for analysis of smoke management systems in large-volume spaces. Compartment fire models consist of zone fire models and computational fluid dynamics (CFD).

The algebraic equations and the zone fire models are based on the following assumptions: (1) a smoke plume rises from the fire, (2) the plume entrains air from the surroundings as it rises, (3) a smoke layer forms under the ceiling, (4) the concentration of contaminants is uniform throughout the smoke layer, (5) the smoke temperature is uniform throughout the smoke layer, and (6) the transition between the smoke layer and the room air is a plane. While the last three assumptions are not completely realistic, they are considered to be justified by the proven utility of the algebraic equations and the zone fire models.

If the algebraic equations are not applicable for a particular space of design fire, then computer fire models need to be applied to develop the design parameters of the system. When algebraic equations and the zone fire models are used for analysis of atrium smoke control, specific calculations need to be made concerning plugholing, and the makeup air velocity needs to be 200 fpm (1 m/sec) or less.

Computer fire models include the ASET,[24] ASET-B,[25] the BRI Model,[26] FIREFORM,[27] CCFM,[28] and CFAST.[29] The University of Maryland has made modifications to CCFM, specifically for atrium smoke management design.[30] Joglar-Billoch and Mowrer[31] have developed a model, FIRE-MD, to assess the impact of either mechanical or natural ventilation on the smoke layer position or properties. Descriptions of zone models are provided by Bukowski,[32] Friedman,[33] Jones,[34] Mitler and Rockett,[35] and Quintiere.[36] Klote[37] provides an overview of atrium smoke management and the public domain computer program, Atrium Smoke Management Engineering Tools (ASMET).

Zone fire models are best applied in cases where the changes in the geometry with respect to height are minimal. Further, because of the homogeneous smoke layer assumption that is part of the zone models, the zone models may not be appropriate for spaces with very large open areas or where horizontal spread needs to be modeled. In such cases, the computational fluid dynamics (CFD) models are more appropriate.

CFD models consist of dividing the large volume space into a large number of cells and solving the governing equations for each cell to obtain the flows and temperatures throughout the space. It is not unusual for atrium applications to consist of hundreds of thousands of cells. CFD models have the ability to realistically simulate smoke flow, and they can be used to evaluate tenability. There are a number of general purpose CFD models suitable for smoke management analysis. The fire dynamic simulator (FDS) model was developed at NIST specifically for fire application, and a number of projects have been conducted to verify FDS.[38] Because CFD models realistically simulate smoke flow, they can simulate plugholing without other algebraic equations, and CFD can simulate the consequences of exceeding the 200 fpm (1 m/sec) limit on makeup air.

SUMMARY

Smoke is defined as the "airborne solid and liquid particulates and gases" resulting from a fire, "along with the quantity of air that is . . . mixed into the mass." Smoke, whether or not it is highly visible, can contain dangerous products of combustion and pose a considerable threat to life and property.

Smoke moves from areas of high pressure to areas of lower pressure. Factors that affect smoke movement include the temperature of the smoke, the height of the building involved, the existence of openings in the building, stack effect, and wind. Smoke management methods use compartmentation, dilution, airflow, pressurization, and buoyancy of the smoke itself to control the smoke hazards of fires.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on smoke movement in buildings discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*
NFPA *101®*, *Life Safety Code®*
NFPA 105, *Standard for the Installation of Smoke Door Assemblies and Other Opening Protectives*
NFPA 204, *Standard for Smoke and Heat Venting*

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Chapter 4

Venting Practices

Gunnar Heskestad

Chapter Contents

Historical Background
Industrial Building Ventilation
Installed Vent Area
Elements of Venting Theory
Addendum: Automatic Heat and Smoke Venting in Sprinklered Buildings

Key Terms

curtain boards, curtained area, curtained compartment, General Motors fire, LAVENT, Livonia fire, unit vents, vent areas, venting

The importance of the buoyant properties of heat and smoke was realized at an early date, as evidenced by an NFPA standard adopted in 1903 that called for smoke vents over theater stages and in the ceilings of theater auditoriums. However, until the advent of effective artificial lighting, buildings were generally small enough so that windows provided adequate smoke venting, other than venting of fire through the roof.

The main body of this chapter covers venting practices as they would be applied to nonsprinklered buildings, based on NFPA 204, *Standard for Smoke and Heat Venting* (formerly 204M). An addendum to the chapter (in which the several different approaches are incorporated) discusses the current state of the technology involving the sprinkler/vent issue.

See also Section 10, Chapter 4, "Air-Conditioning and Ventilating Systems"; and Section 18, Chapter 6, "Deflagration (Explosion) Venting."

HISTORICAL BACKGROUND

Large undivided floor areas present extremely difficult fire-fighting problems, since fire fighters must enter these areas to fight fires in central portions of the building. If fire fighters are unable to enter because of the accumulation of heat and smoke, fire-fighting efforts may be reduced to ineffective application of hose streams to perimeter areas while fire consumes the interior (Figure 18.4.1). Venting through roof openings can mitigate the accumulation of heat and smoke, enabling fire fighters to reach the origin or seat of the fire. In addition, venting provides occupants with the opportunity to travel to a safe area and, furthermore, can reduce damage to buildings and contents due to smoke and hot gases.

Great impetus to the subject of smoke and heat venting was provided by the General Motors fire at Livonia, Michigan, in 1953, when fire spread horizontally under an unvented metal roof, with 34 acres (137,600 m^2) of undivided area. Fire protection engineers were in general agreement that this fire could have been greatly reduced if there had been effective roof venting. The General Motors fire led to a new approach to the subject by the NFPA Committee on Building Construction, which prepared NFPA 204M, adopted by NFPA in May 1961. In 1968, the venting guide was expanded to include a new section on inspection and maintenance.

A reconfirmation action failed in 1975, as concerns had surfaced over use of NFPA 204M in conjunction with automatically sprinklered buildings. Because of this controversy, work on a revision of NFPA 204M continued at a slow pace but concluded with the 1982 edition.

The 1982 edition of NFPA 204M distinguished between unsprinklered and sprinklered buildings. The unsprinklered part was considered to represent a major advance in engineered smoke and heat venting. The sprinklered part, limited to a single chapter (Chapter 6), did not recognize that venting is necessarily desirable in a sprinklered building and did not offer a design basis, pending the resolution of some technical questions.

No changes were made for the 1985 edition of NFPA 204M, except for a limited revision of Chapter 6 dealing with venting of sprinklered buildings. Reference was made to new test data on deploying vents in a test building with automatic sprinklers. However, the new data did not permit conclusions to be developed whether sprinkler control was impaired or enhanced by the presence of automatic roof vents of typical spacing and area.

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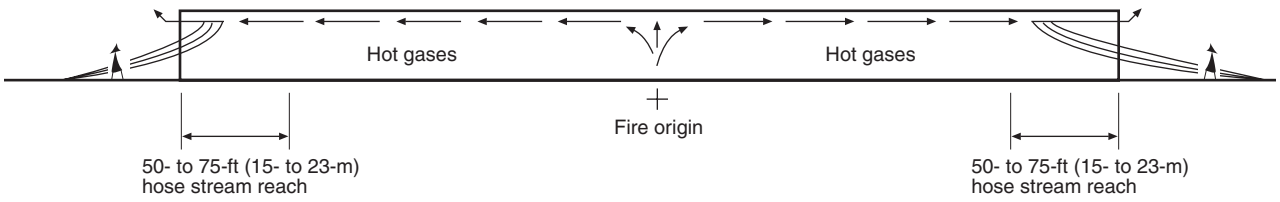

FIGURE 18.4.1 Behavior of Hot Gases in a Flat-Roofed Building

Changes for the 1991 edition of NFPA 204M again focused on Chapter 6. While the two previous editions had stated that a generalized design basis had not been developed and was not available for using sprinklers and vents together for hazard control, the 1991 edition stated that such a design basis "has not been universally recognized" and did not offer one. Furthermore, words were added to the effect that the concern for combining sprinklers and vents relates to "occupancies that present a high challenge to sprinkler systems." As in previous editions, "the designer is encouraged to use the available tools and data referenced in the document for solving problems peculiar to a particular type of hazard control."

The 1998 edition, designated NFPA 204, represented a significant revision. Tables in the previous editions that listed vent areas were deleted, and, instead, engineering equations and referenced computer models provided the designer with the tools to develop vent designs based on performance objectives. The engineering equations were updated based on new research and did not assume that the base of the fire and the so-called virtual origin coincided with the floor level, a simplifying assumption used in preceding editions (NFPA 204M). Additional data on heat release rate were presented, together with a new chapter dealing with techniques for estimating heat release rates of untested fuel arrays. As before, there was a single chapter devoted to sprinklered buildings (Chapter 8). The new chapter was little changed from Chapter 6 of the preceding edition, except for recognizing *curtain boards,* usually part of a venting system, as potentially detrimental to the outcome of sprinklered fires. In addition, there was reference to a new series of large-scale fire tests that the designer may consult.

The 2002 edition of NFPA 204 was converted from a guide to a standard, thus implementing mandatory requirements and updated language. The document was also updated to meet NFPA *Manual of Style* requirements. The only significant technical change is the treatment of venting for sprinklered buildings, presented in Chapter 11, "Venting in Sprinklered Buildings." This chapter is a single-paragraph statement: "Where provided, the design of venting for sprinklered buildings shall be based on a performance analysis acceptable to the authority having jurisdiction, demonstrating that the established objectives are met." An annex includes objectives that may be selected for the design, a review of research as in the preceding edition, subsequent research, and design considerations for venting of sprinklered buildings. Subsequent research (reviewed in this chapter under the heading "FPRF Program" in the Addendum) was deemed to be inconclusive as to benefits of automatic venting in sprinklered buildings. The design considerations are based on preventing automatic vents and draft curtains from interfering with sprinkler control of a fire, subject to the overall guide: "Draft curtains and open vents of venting systems should not adversely affect sprinklers that are capable of discharging water onto the fire, either in time of operation or in the water discharge pattern."

The technical questions that remain unresolved in application of venting to sprinklered buildings are related to the effects of (1) sprinkler discharge on venting effectiveness; (2) fresh air introduced into the building on the burning process and the water demand of the sprinkler system; and (3) curtain boards on the operation of sprinklers. Sprinkler discharge will cool the fire gases, perhaps to the extent that the vent discharge is reduced, hence reducing venting effectiveness. Additionally, the sprinkler sprays will entrain ambient smoke and air, transporting smoke to the floor level and possibly drawing gas from the vent exhaust wherever nozzles are located close to vents, further reducing venting effectiveness. Unless the building is very large, fresh air flowing into the building and replacing smoke escaping through the vents will increase the oxygen concentration in the fire space. The increased oxygen concentrations may cause a more vigorous fire than would otherwise exist, with the possible outcome of an increased number of operating sprinklers, in some cases overtaxing the water supply. Curtain boards may prevent or delay the operation of sprinklers capable of delivering water to the fire or interfere with the discharge of such sprinklers. Against these possible adverse effects must be balanced the likelihood that some improvement in visibility for fire fighting will result in many cases and the possibility that the number of operating sprinklers may sometimes be reduced because of the cooling effect of vent flows.

Many of the problems of combining sprinklers and vents may not appear if all the vents in the fire area are gang operated the moment a predetermined number of sprinklers have operated. Limited experiments on model scale[1] showed that opening all the vents in a test building at the moment of the *first* sprinkler operation could reduce the total number of sprinkler operations, compared to the corresponding unvented fire, and also prevent the total loss of visibility through the smoke which occurred in the corresponding unvented fire. Requiring more than one sprinkler to operate before the vents are opened, ideally all sprinklers that are capable of delivering water to the fire, would be a conservative approach for ensuring that sprinkler effectiveness is not compromised. Alternatively, prior to gang operation of the vents at the first sprinkler operation, any vent located within a small distance of the initial fire (to be determined) may be blocked from opening by signal from a fire proximity sensor. Experimental studies would be needed to confirm feasibility and establish design information.

Essential features specified in NFPA 204 include roof vents actuated by heat or smoke, curtain boards to confine heat and

prevent lateral fire spread, and openings for fresh air makeup at low levels (Figure 18.4.2). Two general classes of fires are considered: (1) limited growth fires, which are not expected to grow past a predictable maximum size, and (2) continuous growth fires, which can be expected to grow indefinitely until intervention by fire fighters. Guidance to vent design is based on engineering equations (hand calculations) or the use of the computer model LAVENT (or equivalent). Mechanical exhaust at ceiling apertures is treated as an option to natural ventilation at roof vents and is deemed a highly favorable option in sprinklered occupancies because of near immunity to adverse effects on venting efficiency of cooled fire gases and entrained fire gases by nearby sprinklers. The provisions of NFPA 204 may be applied to one-story buildings or to the top story of multiple-story buildings. With mechanical exhaust, lower stories of multiple-story buildings can also be vented.

INDUSTRIAL BUILDING VENTILATION

Although any opening in a roof will reduce some heat and smoke, building designers and fire protection engineers cannot rely on casual inclusion of skylights, windows, or monitors as adequate means of venting. Standards now exist (FM Approvals, Underwriters Laboratories Inc. [UL], etc.) that include design criteria and test procedures for unit vents and also call for simulated fire tests as well as engineering analysis.

Unit Vents

Unit vents are relatively small, usually 16 to 100 ft^2 (1.49 to 9.29 m^2) in area. Automatic unit vents are of two types, based on manner of operation—fusible link or drop-out plastic (Figure 18.4.3). The fusible link type consists of a metal housing with lids that depend on a temperature-rated fusible link to trip the lid mechanism, but alternative modes of operation are possible, for example, by heat or smoke detectors. The drop-out plastic type depends on a temperature-sensitive, transparent or translucent, thermoplastic dome that deforms from its setting and falls out of the roof. Vents designed for manual operation are constructed with metal lids to resist elevated fire temperatures and may be opened from the floor with wires and cables. These units can also be modified for automatic operation.

Vents may be a single unit, in which the entire unit opens fully with a single sensor, or multiple units in rows, clusters, groups, or other arrays that will satisfy the venting requirements for the specific hazard.

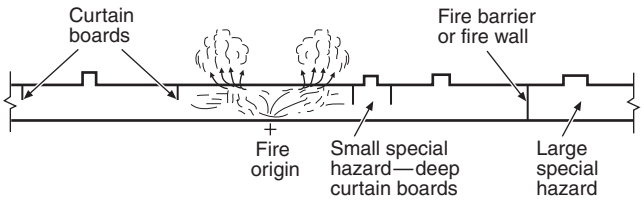

FIGURE 18.4.2 Behavior of Combustion Products Under Vented and Curtained Roof

FIGURE 18.4.3 Building with Roof Vents

Mechanical roof ventilators actuated by fire conditions are possible—and often preferable—alternatives to roof vents based on natural ventilation, especially in lower stories of multiple-story buildings. These ventilators must be capable of functioning under expected high-temperature fire conditions.

Curtain Boards

In large-area buildings, unless vented areas are subdivided by means of walls or partitions, curtain boards are important for prompt and positive actuation of vents because they bank up heat in the curtained area. They also limit the spread of heat and smoke beneath the ceiling during the design duration of the venting system. Curtain boards can be made from any substantial noncombustible material that will resist the passage of smoke.

The depth of curtain boards would normally be selected to correspond with the design depth of the smoke layer. However, the depth should not be less than 20 percent of the ceiling height, to prevent spillage of smoke under the curtain, where depth and ceiling height are referenced to the center of the lowest roof vent. It would rarely be desirable to have the curtain extend below 10 ft (3 m) from the floor. Around special hazards, the curtain should preferably extend down to this limit (Figure 18.4.4). Equipped

FIGURE 18.4.4 Deep Curtain Boards Around a Special Hazard (a Heat-Treating Department)

with proper venting, a noncombustible curtain board extending down from a ceiling around special hazards will prevent smoke and heat from mushrooming throughout the facility.

The distance between curtain boards should not exceed eight times the ceiling height, to ensure that vents remote from the fire will be effective within the curtained compartment. Smaller curtained areas may be desirable where occupancies are particularly vulnerable to damage. However, it is important that the distance between curtain boards not be less than two times the ceiling height, unless the curtain boards extend down to a depth of at least 40 percent of the ceiling height. The increased curtain depth is needed for these small curtain spacings to prevent significant spillage of fire gases underneath the curtain because of the close proximity of the fire.

Dimensioning and Spacing of Vents

When the area of an individual vent becomes sufficiently large, there is a possibility that a core of clear air from beneath the smoke layer will be included in the exhaust from the vent, which reduces the effectiveness of the vent. To prevent inclusion of clear air, called *plugholing,* the area of a unit vent or cluster of vents should not exceed $2d^2$, where d is the design depth of the smoke layer or curtain board. In the case of a row of unit vents or a monitor vent, the width of the row or monitor should not exceed d.

A large number of small vents on close spacing is preferable to a small number of large vents on wide spacing. This ensures early operation of the first vents in a fire, reducing the likelihood of initial smoke excursions beyond the curtained area above the fire. In no case should the vent spacing in a rectangular matrix exceed $4H$, where H is the ceiling height measured from the floor to ceiling for flat roofs, and from the floor to the center of the vent for sloped roofs. Alternatively, in a nonrectangular vent matrix in plan, the distance between any point on the floor and the nearest vent should not exceed $2.8H$ (the diagonal of a square whose side is $2H$). (The maximum vent spacings indicated in the 2002 edition of NFPA 204 are incorrect representations of the original formulation in NFPA 204M, 1982 edition.)

The total vent area for each curtained compartment under the ceiling depends on the severity of the expected fire and is discussed later in this chapter.

Fresh Air Makeup

Openings must be provided at or near floor level to allow the introduction of makeup air. This is critical in today's tightly constructed and insulated buildings. The total area of these openings must normally be at least as great as the largest installed vent area for a curtained compartment; otherwise, the inlets may effectively throttle the vent flow. The vent flow equation in NFPA 204 indicates the degree to which the vent flow rate is reduced by limiting the inlet opening area. If doors and windows below the designed smoke layer cannot meet the total required inlet area, special air inlet provisions are necessary.

It is essential that a dependable means be provided for admitting inlet air within approximately one minute after the first vent opens. If prompt air inlet is not provided, the entire building may quickly fill with smoke, which will clear slowly at lower levels (in the design clear layer) in response to the fully developed vent flow after the air inlets have been actuated.

Fire Characterization*

Each curtained compartment or the ceiling area of buildings requiring no curtain boards must be furnished with a total installed vent area (or exhaust capacity in case of mechanical ventilation) sufficient to vent fires of the expected severity. In addition to the expected fire severity, the installed vent area (or exhaust capacity) will depend on the depth of the curtain boards or design depth of the smoke layer. Furthermore, unless the occupancy or hazard is such that the expected fire will peak or level off at a predictable maximum size, the installed vent area (or exhaust capacity) will also depend on the minimum clear visibility design time as measured from the time the vents first operate. The fire severity is expressed differently according to the class of the fire, which for purposes of calculating vent areas is classified as either a limited-growth or a continuous-growth fire.

Limited-Growth Fires. These are fires that are not expected to grow past a predictable maximum size in terms of heat release rate, expressed in Btu per second or kW. Special-hazard fires can be assigned to this class, as can fires in occupancies with concentrations of combustibles separated by sufficiently wide aisles. The minimum aisle width to prevent lateral spread (by radiation), W_{min}, can be estimated from an equation[2] for radiant flux from a fire and a (conservatively low) value for the ignition flux of most materials (1.8 Btu/ft^2/sec or 20.4 kW/m^2):

$$W_{min}(\text{ft}) = 0.13\ [Q\ (\text{Btu/sec})]^{1/2} \qquad (1)$$

For example, if the predicted maximum fire size is 30,000 Btu/sec (31,600 kW), the aisle width should be at least 24 ft (7.3 m). Table 18.4.1 contains examples of heat release data, expressed as Btu per second per ft^2 of floor area. To obtain heat release in Btu per second, a number in the table is multiplied by the floor area underneath the combustible.

Continuous-Growth Fires. These are fires that can be expected to grow indefinitely until intervention by fire fighters (Figure 18.4.5). Starting after an incubation period, the heat release rate of these fires grows continuously, proportional to the square of time, sometimes referred to as "t-squared fire growth." The growth time of a given fire is defined as the interval of time between the effective ignition time and the time when the fire reaches an intermediate energy release rate of 1000 Btu/sec (1054 kW). Any reference heat release rate

*The theory and application of venting outlined in this chapter are presented in U.S. customary units. These units reflect the system used in the original research and are consistent with the background materials contained in NFPA 204. For those more familiar with SI units, quantities such as curtain board depth (in m) and heat release rate (in kW) should be converted to the appropriate conventional units (ft and Btu/sec, respectively), using the conversion factors given at the end of this footnote and at various points throughout the text. After conversion, design data should be inserted in unit-dependent formulas to calculate vent areas and mass flow rates. 1 ft = 0.305 m; 1 Btu/sec = 1.054 kW.

TABLE 18.4.1 Heat Release Rates of Some Limited-Growth Fires*

	Btu/sec/ft² of Floor Area
1. Wood pallets, stacked 1½ ft high (6–12% moisture)	120
2. Wood pallets, stacked 5 ft high (6–12% moisture)	340
3. Wood pallets, stacked 10 ft high (6–12% moisture)	600
4. Wood pallets, stacked 15 ft high (6–12% moisture)	900
5. Mailbags, filled, stored 5 ft high	35
6. Cartons, compartmented, stacked 15 ft high	200
7. PE letter trays, filled, stacked 5 ft high on cart	750
8. PE trash barrels in cartons, stacked 15 ft high	260
9. FRP shower stalls in cartons, stacked 15 ft high	110
10. PE bottles packed in Item 6	550
11. PE bottles in cartons, stacked 15 ft high	170
12. PU insulation board, rigid foam, stacked 15 ft high	170
13. PS jars packed in Item 6	1300
14. PS tubs nested in cartons, stacked 14 ft high	450
15. PS toy parts in cartons, stacked 15 ft high	180
16. PS insulation board, rigid foam, stacked 14 ft high	280
17. PVC bottles packed in Item 6	300
18. PP tubs packed in Item 6	380
19. PP and PE film in rolls, stacked 14 ft high	540
20. Methyl alcohol	65
21. Gasoline	200
22. Kerosene	200
23. Diesel oil	170

Note: PE = polyethylene; PS = polystyrene; PVC = polyvinyl chloride; PP = polypropylene; PU = polyurethane; FRP = fiberglass-reinforced polyester.
For SI units: 1 ft = 0.31 m; 1 ft² = 0.093 m²; 1 Btu/sec = 1.054 kW.
*Heat-release rate per unit floor area of fully involved combustibles, assuming 100 percent combustion efficiency.

could have been chosen with a corresponding change in the growth time. The rate 1000 Btu/sec (1054 kW) was chosen for convenience. Mathematically, *t*-squared fire growth can be expressed as

$$Q\ (\text{Btu/sec}) = 1000(t/t_g)^2 \qquad (2)$$

where t is the time in seconds from the effective ignition time and t_g is the growth time in seconds. Table 18.4.2 contains examples of growth times for continuous-growth fires.

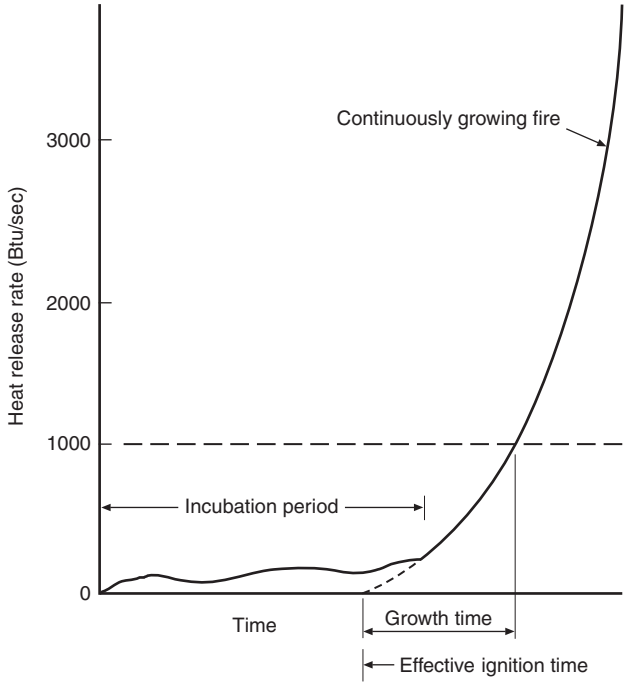

FIGURE 18.4.5 Conceptual Illustration of Continuous Fire Growth

INSTALLED VENT AREA

Limited-Growth Fires

Using the theory for air entrainment in fire plumes and gas flow through roof vents presented in NFPA 204, required vent areas can be calculated. Results for the minimum recommended curtain depth, 20 percent of the ceiling height, are presented in Figure 18.4.6 for vent area per curtained compartment (in ft²) versus expected maximum heat release rate (in Btu/sec) of the combustibles underneath the curtained compartment. These curves have been adopted from the 1991 edition of NFPA 204M, which employed the assumption that the base of the fire and the so-called "virtual origin" were both at the floor level. The simplified curves are useful for illustrating results of venting calculations and issues. Several ceiling heights in the range 15 ft to 60 ft (4.6 m to 18.3 m) are represented. An aerodynamic discharge coefficient of 0.6 has been assumed, which is normal for commercial unit vents. If the discharge coefficient is different from 0.6, the recommended vent areas need to be multiplied by the ratio of 0.6 to the actual discharge coefficient.

For each ceiling height in Figure 18.4.6, the respective curve begins at a heat release rate where vents operated by fusible links rated at 100°F (37.8°C) to 220°F (104°C) above ambient are first expected to operate promptly. Furthermore, for each ceiling height, the respective curve terminates near a heat-release rate, Q_{feasible}, beyond which the feasibility of roof venting, using the present approach, might be questioned. Q_{feasible} can be estimated from the equation

$$Q_{\text{feasible}}\ (\text{Btu/sec}) = 1130(H - d)^{5/2} \qquad (3)$$

TABLE 18.4.2 Growth Times of Some Continuous-Growth Fires*

		Growth Time (sec)
1.	Wood pallets, stacked 1½ ft high (6–12% moisture)	160–320
2.	Wood pallets, stacked 5 ft high (6–12% moisture)	95–190
3.	Wood pallets, stacked 10 ft high (6–12% moisture)	80–120
4.	Wood pallets, stacked 16 ft high (6–12% moisture)	75–120
5.	Mail bags, filled, stored 5 ft high	190
6.	Cartons, compartmented, stacked 15 ft high	60
7.	Paper, vertical rolls, stacked 20 ft high	17–27
8.	Cotton (also Pe, Pe/Cot Acrylic/Nylon/Pe), garments in 12-ft-high rack	22–43
9.	"Ordinary combustibles" rack storage, 15–30 ft high	40–270
10.	Paper products, densely packed in cartons, rack storage, 20 ft high	470
11.	PE letter trays, filled, stacked 5 ft high on cart	190
12.	PE trash barrels in cartons, stacked 15 ft high	55
13.	FRP shower stalls in cartons, stacked 15 ft high	85
14.	PE bottles packed in Item 6	85
15.	PE bottles in cartons, stacked 15 ft high	75
16.	PE pallets, stacked 3 ft high	150
17.	PE pallets, stacked 6–8 ft high	32–56
18.	PU mattress, single, horizontal	120
19.	PU insulation board, rigid foam, stacked 15 ft high	8
20.	PS jars packed in Item 6	55
21.	PS tubs nested in cartons, stacked 14 ft high	110
22.	PS toy parts in cartons, stacked 15 ft high	120
23.	PS insulation board, rigid foam, stacked 14 ft high	7
24.	PVC bottles packed in Item 6	9
25.	PP tubs packed in Item 6	10
26.	PP and PE film in rolls, stacked 14 ft high	40
27.	Distilled spirits in barrels, stacked 20 ft high	25–40

Note: Pe = polyester; Cot = cotton; PE = polyethylene; PS = polystyrene; PVC = polyvinyl chloride; PP = polypropylene; PU = polyurethane; FRP = fiberglass-reinforced polyester.
For SI units: 1 ft = 0.305 m.
*Growth times of developing fires in various combustibles, assuming 100 percent combustion efficiency.

where H is the ceiling height and d is the curtain depth ($0.2H$ in this case). At $Q_{feasible}$, the fire may become controlled by the ventilation rate allowed by the roof vents. Ventilation-controlled fires do not support a clear layer. Venting at heat release rates greater than $Q_{feasible}$ to maintain a clear layer would require larger vent areas than indicated in Figure 18.4.6.

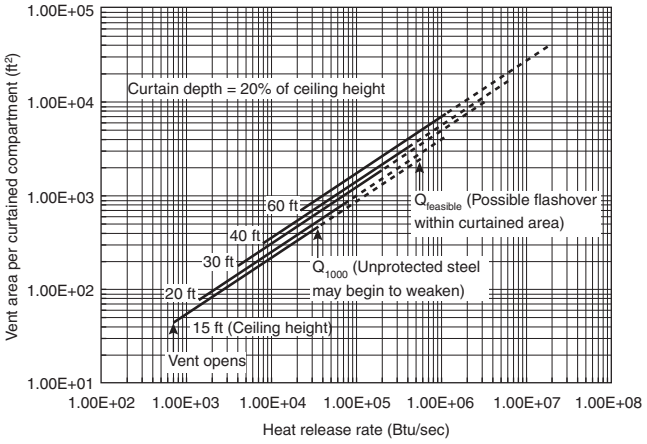

FIGURE 18.4.6 Limited Fire Growth: Recommended Vent Areas for Each Curtained Compartment for Various Maximum Heat Release Rates (Btu/sec)

Along the dashed segments of the curves in Figure 18.4.6, gas temperatures in excess of 1000°F (538°C) may be reached; unprotected structural steel may begin to lose strength and the possibility of flashover exists within the curtained area. The lowest rate of heat release at which this may occur, Q_{1000}, has been estimated from the equation

$$Q_{1000}\,(\text{Btu/sec}) = 69(H - d)^{5/2} \qquad (4)$$

where, in the case of Figure 18.4.6, $d = 0.2H$.

For curtain depths greater than 20 percent of the ceiling height, the vent areas read from Figure 18.4.6 may be multiplied by the factors indicated in Table 18.4.3. New values for $Q_{feasible}$ and Q_{1000} can be calculated using Equations 3 and 4, respectively, by inserting the appropriate values of H and d.

Continuous-Growth Fires

Required vent areas for each curtained compartment for fires in this class depend on ceiling height (H), growth time, spacing of

TABLE 18.4.3 Multiplication Factors for Vent Areas in Figure 18.4.6 for Curtain Depths Other Than 20 Percent of Ceiling Height

Curtain Depth as Percent of Ceiling Height	*Multiplication Factor*
30	0.71
40	0.53
50	0.40
60	0.29
70	0.20
80	0.13

curtain boards (S_c) vent spacing, and means of vent actuation. They also depend on the desired minimum clear visibility time from the time the first vents operate. The minimum clear visibility design time will facilitate such activities as locating the fire, appraising the severity and extent of the fire, evacuating the building, and making an informed decision on deployment of personnel and equipment to be used for fire fighting.

Table 18.4.4 has been adapted from the 1991 edition of NFPA 204M (base of fire and virtual origin at floor level), and the values are limited to the minimum recommended curtain depth, 20 percent of the ceiling height. Table 18.4.4 lists vent areas per curtained compartment for vents spaced at no more than one-half the curtain board spacing. For other than square curtains, the spacing S_c is interpreted as the largest spacing defined by the curtained area. The tabulated areas are approximate, pertaining to vents that are operated by heat-responsive devices of an average response-time index (RTI) of 520 $(ft \cdot sec)^{1/2}$ [287 $(m \cdot sec)^{1/2}$] and rated between 100°F (37.8°C) and 220°F (104°C) above ambient temperature.[3,4] Each entry in the table gives the range of vent areas in 1000 ft^2 (92.9 m^2) associated with the selected range of temperature ratings. Boxed entries are not possible (since the vent areas exceed the largest possible curtained area of $S_c \times S_c$); however, these entries may be needed for curtain depths greater than 20 percent of ceiling height, as treated later in this chapter.

TABLE 18.4.4 Vent Areas for Curtained Compartments*

Ceiling Height, H	*Growth Time (sec)*	$S_c = 2 \times H$			$S_c = 4 \times H$			$S_c = 8 \times H$		
		5 min	*10 min*	*15 min*	*5 min*	*10 min*	*15 min*	*5 min*	*10 min*	*15 min*
15 ft	20				(1.9–2.1)			(2.2–2.5)		
	40	0.87–0.97			(0.98–1.1)	(1.8–2.0)		(1.1–1.4)	(2.0–2.3)	
	80	(0.44–0.52)	(0.82–0.90)		(0.52–0.64)	(0.90–1.0)	(1.3–1.4)	(0.64–0.83)	(1.0–1.2)	(1.5–1.7)
	150	0.25–0.32	(0.43–0.50)	(0.63–0.70)	0.31–0.41	(0.50–0.60)	(.70–.80)	(0.41–0.58)	(.60–.77)	(0.81–0.98)
	300	0.15–0.20	0.23–0.29	0.32–0.38	0.20–0.28	0.28–0.36	0.37–0.46	0.27–0.41	0.36–0.51	(0.46–0.61)
	600	0.10–0.14	0.13–0.18	0.17–0.23	0.13–0.21	0.17–0.25	0.21–0.29	0.20–0.34	0.24–0.38	0.29–0.43
20 ft	20	2.2–7.3			(2.5–2.7)			(2.7–3.2)		
	40	(1.1–1.2)	2.1–2.2		(1.2–1.5)	(2.2–2.5)	(3.3–3.6)	(1.5–1.8)	(2.5–2.9)	(3.6–4.0)
	80	0.56–0.68	(1.0–1.1)	1.5–1.6	0.68–0.86	(1.1–1.3)	(1.6–1.8)	(0.87–1.2)	(1.3–1.6)	(1.8–2.1)
	150	0.34–0.43	0.55–0.65	(0.77–0.88)	0.43–0.58	0.64–0.80	(0.88–1.0)	0.58–0.83	(0.80–1.1)	(1.0–1.3)
	300	0.21–0.29	0.30–0.39	0.40–0.50	0.28–0.41	0.38–0.52	0.48–0.63	0.40–0.65	0.51–0.76	0.62–0.88
	600	0.14–0.22	0.19–0.27	0.23–0.32	0.20–0.33	0.25–0.38	0.30–0.44	0.32–0.56	0.37–0.61	0.42–0.67
30 ft	20	(2.9–3.2)	5.6–6.0		(3.2–3.8)	(6.0–6.6)		(3.8–4.6)	(6.7–7.6)	
	40	1.5–1.8	(2.7–3.0)	4.0–4.3	(1.8–2.2)	(3.0–3.4)	(4.3–4.8)	(2.2–2.9)	(3.5–4.2)	(4.8–5.6)
	80	0.82–1.0	1.4–1.6	(2.0–2.2)	1.0–1.4	1.6–2.0	(2.2–2.6)	1.4–2.0	(2.0–2.6)	(2.6–3.2)
	150	0.51–0.71	0.78–0.99	1.1–1.3	0.68–0.99	0.96–1.3	1.3–1.6	0.97–1.5	1.3–1.8	(1.6–2.2)
	300	0.34–0.53	0.47–0.66	0.59–0.80	0.48–0.77	0.61–0.91	0.74–1.1	0.74–1.3	0.88–1.4	1.0–1.6
	600	0.26–0.44	0.32–0.50	0.38–0.57	0.38–0.67	0.44–0.74	0.50–0.81	0.62–1.2	0.69–1.2	0.76–1.3
40 ft	20	(3.6–4.1)	6.7–7.3	10–11	(4.1–4.9)	(7.4–8.2)	(11–12)	(5.0–6.3)	(8.3–9.7)	(12–13)
	40	1.9–2.3	(3.3–3.8)	(4.8–5.3)	2.3–3.0	(3.8–4.5)	(5.3–6.1)	(3.0–4.1)	(4.5–5.6)	(6.1–7.3)
	80	1.1–1.5	1.7–2.1	2.4–2.8	1.4–2.0	2.1–2.7	2.8–3.4	2.0–3.0	2.7–3.7	(3.4–4.5)
	150	0.72–1.1	1.0–1.4	1.4–1.8	0.98–1.5	1.3–1.9	1.7–2.2	1.5–2.4	1.8–2.8	2.2–3.2
	300	0.51–0.84	0.66–1.0	0.81–1.2	0.74–1.3	0.89–1.4	1.1–1.6	1.2–2.2	1.4–2.3	1.5–2.5
	600	0.41–0.74	0.48–0.81	0.55–0.89	0.61–1.1	0.69–1.2	0.77–1.3	1.1–2.0	1.1–2.1	1.2–2.2
60 ft	20	4.9–5.9	(8.9–10)	(13–14)	5.9–7.4	(10–12)	(14–16)	(7.5–10)	(12–14)	(16–19)
	40	2.8–3.6	4.6–5.5	6.5–7.4	3.5–4.8	5.4–6.7	(7.3–8.8)	4.8–7.0	(6.7–9.1)	(8.7–11)
	80	1.7–2.5	2.5–3.4	3.4–4.3	2.3–3.5	3.2–4.4	4.1–5.4	3.4–5.6	4.3–6.6	5.2–7.6
	150	1.2–2.0	1.6–2.4	2.1–2.9	1.7–2.9	2.2–3.4	2.6–3.9	2.8–4.9	3.2–5.4	3.7–5.9
	300	0.95–1.7	1.2–1.9	1.3–2.1	1.4–2.6	1.6–2.8	1.8–3.1	2.4–4.6	2.6–4.8	2.9–5.1
	600	0.82–1.6	0.92–1.7	1.0–1.8	1.3–2.4	1.4–2.6	1.5–2.7	2.2–4.4	2.3–4.5	2.5–4.6

Notes:
1. Vents are assumed to be spaced at one-half of the curtain board spacing.
2. Curtain depth assumed at 20 percent of ceiling height.
3. Each entry is the vent-area range (in 1000 ft^2) associated with heat-responsive devices rated between 100 and 220°F (37.8 and 104°C) above ambient temperature.
4. No entries: Heat release rates greater than $Q_{feasible}$.
5. Entries boxed-in: Not possible, but needed for curtain depths greater than 20 percent.
6. Entries in parentheses: Correspond to levels of heat release greater than Q_{1000}.

For SI units: 1 ft = 0.305 m; 1 ft^2 = 0.093 m^2.

*Vent area (in 1000 ft^2) per curtained compartment for heat-responsive device-operated vents with various curtain board spacings (S_c) and minimum clear-visibility design times (5, 10, or 15 min).

Where values are not given, heat-release rates are greater than $Q_{feasible}$, as given in Equation 3; the vent area associated with $Q_{feasible}$ is $A_{feasible}$, which has been calculated from the following equation from the 1991 edition of NFPA 204M:

$$A_{feasible}\ (ft^2) = 8.5(H - d)^{5/2}/d^{1/2} \quad (5)$$

where, in the case of Table 18.4.4, $d = 0.2H$. Entries in parentheses in the table correspond to levels of heat release greater than Q_{1000}, as given in Equation 4. The vent area associated with Q_{1000} is A_{1000}, which has been calculated from the following equation from the 1991 edition of NFPA 204M:

$$A_{1000}\ (ft^2) = 1.6(H - d)^{5/2}/d^{1/2} \quad (6)$$

where, in the case of Table 18.4.4, $d = 0.2H$.

To illustrate the use of Table 18.4.4, consider an installation with heat-responsive devices rated approximately 100°F (37.8°C) above ambient, a ceiling height of 20 ft (6.1 m), a growth time of approximately 150 seconds, a (square) curtain spacing of 80 ft or 24.4 m ($S_c = 4 \times H$), a curtain depth of 4 ft or 1.2 m (4/20 = 20 percent of ceiling height), and a minimum clear visibility time of 10 minutes. In Table 18.4.4, the lower limit 100°F (37.8°C) of the appropriate entry indicates a vent area per curtained compartment of $0.64 \times 1000 = 640$ ft^2 (59.5 m^2) for this case.

The recommended vent area for each curtained compartment is reduced if larger curtain depths than minimum (20 percent of ceiling height) are installed. The reduced areas are calculated by multiplying the values listed in Table 18.4.4 by the appropriate multiplication factor listed in Table 18.4.3. To determine if Note 4 or 6 from Table 18.4.4 applies to the newly derived values for vent area, the value of $A_{feasible}$ associated with $Q_{feasible}$ is calculated from Equation 5, and the value of A_{1000} associated with Q_{1000} is calculated from Equation 6. Note 4 applies if a vent area is larger than $A_{feasible}$, and Note 6 applies if a vent area is larger than A_{1000}.

Vent areas for each curtained compartment should be distributed among individual vents within the constraints discussed in the subsection "Dimensioning and Spacing of Vents," earlier in this chapter. In some cases, the calculated number of vents may be so large that the vent spacing will be considerably smaller than the design spacing for vents assumed in Table 18.4.4 (½S_c) The closer vent spacing implies earlier operation of the first vents than is the case for the designs of Table 18.4.4. Earlier operation, such as that provided by an auxiliary fire detection system, would provide extra clear visibility times beyond the values of 5, 10, and 15 minutes selected in Table 18.4.4. The extra time available with vents spaced at less than ½S_c may be considered to represent a safety factor.

Selection of Design Basis

The vent area in a curtained compartment need not exceed the vent area recommended for the largest limited-growth fire predicted for combustibles beneath the curtained area. Using sufficiently small concentrations of combustibles and minimum aisle widths according to Equation 1, it may be possible to satisfy the venting needs using smaller vent areas than required by a continuous-growth fire vent design. For example, in the illustration discussed previously for the use of Table 18.4.4, the continuous-growth fire vent design for a growth time of 150 seconds led to a required vent area for each curtained compartment of 640 ft^2 (59.5 m^2). A limited-growth fire vent design for a 50 ft^2 (4.7 m^2) floor area concentration at 200 Btu/sec per ft^2 (2271 kW/m^2) (if that is the heat release rate per unit floor area of the combustible considered) involves a total heat release rate per fuel concentration of 10,000 Btu/sec (10,540 kW) and a minimum aisle width of 14 ft (4.3 m), according to Equation 1. For the relevant vent parameters of a ceiling height of 20 ft (6.1 m), curtain depth at 20 percent of ceiling height, and heat release rate of 10,000 Btu/sec (10,540 kW), Figure 18.4.6 indicates a vent area per curtained compartment of 250 ft^2 (23.2 m^2), which is considerably smaller than the 640 ft^2 (59.5 m^2) vent area according to the design for continuous-growth fire. Of course, the combustible and floor area concentrations must be carefully controlled when limited-growth fire vent designs are selected. Furthermore, designs incorporating heat release rates greater than Q_{1000} are risky, since the fire may flash over to all the combustibles under the curtained area. Such designs should be based on the potential heat release rate of all the combustibles under the curtained area and should not be attempted at all if the resulting heat release rate approaches $Q_{feasible}$. For continuous-growth fires, designs giving vent areas greater than A_{1000} cannot be recommended because of the flashover potential.

Mechanical Ventilators

For mechanical venting systems capable of functioning under the expected fire exposure, recommended exhaust capacities per curtained compartments are obtained by simple conversion from the recommended vent areas per curtained compartment. The conversion depends on the depth of the curtain board or the design depth of the smoke layer, according to Table 18.4.5. To avoid plugholing (i.e., inclusion of clear air from below the smoke layer in the vent flow), the exhaust flow (SCFM) for a vent should not exceed a maximum rate:

$$SCFM_{max} = 452 d^{5/2} \left[\frac{T_o}{T_s} \left(1 - \frac{T_o}{T_s} \right) \right]^{1/2} \quad (7)$$

TABLE 18.4.5 Conversion from Vent Area of Gravity Vents to Equivalent Mechanical Exhaust Capacity

Curtain Depth (ft)	*Mechanical Exhaust Capacity per Unit Area of Gravity Vent (SCFM*/ft^2)*
6	354
8	409
10	457
12	501
16	578
20	647
24	708

For SI units: 1 ft = 0.305 m; 1 ft^2 = 0.093 m^2.
*SCFM = Standard cubic ft per min (standard temperature and pressure).

where d is the depth of the smoke layer (ft), T_0 is the ambient temperature (°R), and T_s is the smoke layer temperature (°R).

ELEMENTS OF VENTING THEORY

To stop the descent of a smoke layer, the mass flow rate of hot gas out of the vents, $\dot{m}_v$, must match the mass injection rate of gas by the fire plume at the interface with the smoke layer, $\dot{m}_P$ (Figure 18.4.7). Therefore, expressions are needed for the vent flow and for the plume flow.

Vent Flow

The vent flow for sufficiently large area of inlet opening (see NFPA 204 for effect of restricted inlet area) can be calculated from the following equation:[5,6]

$$\dot{m}_v = (2\rho_o^2 g)^{1/2} \left[\frac{T_o(T_s - T_o)}{T_s^2} \right]^{1/2} A_v d^{1/2} \tag{8}$$

where $\dot{m}_v$ is the mass flow rate through the vent (lb/sec or kg/sec); ρ_o is the density of the ambient air (lb/ft^3 or kg/m^3); g is the acceleration of gravity (ft/sec^2 or m/sec^2); T_o is the ambient temperature (°R or K); T_s is the smoke layer temperature (°R or K); A_v is the aerodynamic vent area (ft^2 or m^2); and d is the depth of the smoke layer (ft or m), generally interpreted as the height of the center of the vent above the smoke interface.

The aerodynamic vent area, A_v, is always smaller than the geometric vent area. For simple apertures, A_v may be taken as 0.6 times the geometric through-flow area.

The temperature function $\left[\frac{T_o(T_s - T_o)}{T_s^2} \right]^{1/2}$ can be approximated at 0.50 for smoke layer temperatures in the range of 275 to 1400°F (135 to 760°C), which covers most vent applications. Then Equation 8 becomes simply

$$\dot{m}_v = (\rho_o^2 g)^{1/2} A_v d^{1/2} \tag{9}$$

To prevent air from the clear layer below from being entrained in the vent exhaust (plugholing), the area of the vent should not exceed $2d^2$.[7] If the vent is long and narrow, an analogous requirement would be that the width of the vent not exceed d.

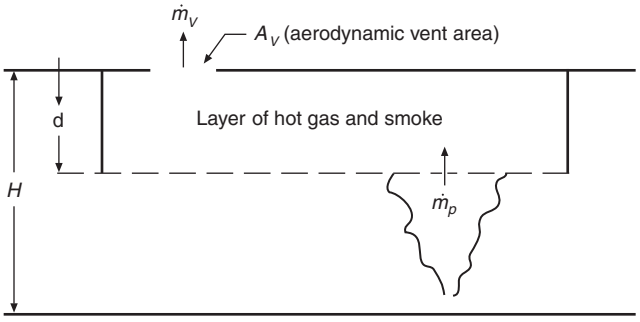

FIGURE 18.4.7 Schematic of a Venting System

Plume Flow

The mass flow rate injected into the smoke layer by the fire plume is practically equal to the air entrainment rate of the plume from the clear layer; the contribution of the fire source itself is small in comparison. The equations presented here are based on the updated engineering relations of NFPA 204, rather than the simplified equations of the 1991 edition of NFPA 204M.

The plume flow, $\dot{m}_p$, is calculated according to either of two equations, depending on whether the mean flame height is below the smoke layer (interpreted as below the curtain boards) or has entered the smoke layer (interpreted as at or above the bottom of the curtain boards). The mean flame height is calculated from

$$L = -1.02D + 0.79Q^{2/5} \tag{10}$$

where

L = Mean flame height above the base of the fire (ft)

D = Base diameter of fire (ft)

Q = Total heat release rate (Btu/sec)

When the mean flame height is below the smoke layer ($L < H - d$) the plume flow into the smoke layer is calculated from

$$\dot{m}_p = 0.022Q_c^{1/3}(H - d - z_0)^{5/3}[1 + 0.20Q_c^{2/3}(H - d - z_0)^{-5/3}] \tag{11}$$

where

$\dot{m}_p$ = Mass flow rate into the smoke layer (lb/sec)

Q_c = Convective heat release rate (approx. 0.7 Q) (Btu/sec)

z_0 = Height of virtual origin above base of fire (below the base if negative) (ft) calculated from

$$z_0 = 0.28Q^{2/5} - 1.02D \tag{12}$$

When the mean flame height reaches into the smoke layer ($L \geq H - d$),

$$\dot{m}_p = 0.0130Q_c(H - d)/L \tag{13}$$

Note that when the flames are just entering ($L = H - d$),

$$\dot{m}_p = 0.0130Q_c \tag{14}$$

For continuous-growth fires, the instantaneous fire diameter D in Equations 10 and 12 can be calculated from the instantaneous heat release rate, Q, and data on the heat release rate per unit floor area, Q'' (according to listings such as Table 18.4.2):

$$D = \left(\frac{4Q}{\pi Q''} \right)^{1/2} \tag{15}$$

Required Vent Area

For $L < H - d$, the expression for $\dot{m}_p$ in Equation 11 is set equal to the expression for $\dot{m}_v$ in Equation 9 and solved for A_v, the aerodynamic vent area. For $L \geq H - d$, the expression for $\dot{m}_p$ in Equation 13 is set equal to the expression for $\dot{m}_v$ in Equation 9 and solved for A_v. The aerodynamic vent area, A_v, is divided by the vent discharge coefficient, usually 0.6, to establish the geometric vent area.

For continuous-growth fires, the vent area is calculated for the fire conditions prevailing at the time $t = t_d + t_r$, where t_d is the detection time (often, but not necessarily, the actuation time of the first vent) and t_r may be selected to correspond to various critical events ("clear-visibility time" in context of Table 18.4.4):

1. Arrival of emergency response team
2. Arrival of fire fighters from the public fire department
3. Completion of evacuation
4. Other critical events

Detection times (t_d) for heat responsive devices (fusible links, heat detectors) can be calculated for *t*-squared fires, using a thermal response equation for heat responsive devices[3,4] together with generalized data on gas temperatures and velocities under flat ceilings.[8]

Limiting Heat Release Rates

Q_{1000} was defined in conjunction with Equation 4 as the heat release rate at which gas temperatures in excess of 1000°F (538°C) may be reached with possible weakening of structural steel and potentials for flashover within the curtained areas. The expression for Q_{1000} was derived first using Equation 13, with substitution for L from Equation 10 (suppressing $-1.02D$, which usually makes a relatively small contribution to the calculated value of L, and setting $Q_c = 0.7Q$), to obtain $\dot{m}_p$ expressed as

$$\dot{m}_p\,(\text{lb/sec}) = 0.0143(H - d)Q_c^{3/5} \tag{16}$$

where Q_c is in Btu/sec, and H and d are in ft.

The average temperature rise in the smoke layer, ΔT_s (°F), follows from

$$\dot{m}_p c_p \Delta T_s = \lambda Q_c \tag{17}$$

where c_p (Btu/lb/°F or kJ/kg/K) is the specific heat of air and λ is the surviving fraction of convective heat after heat loss to the ceiling and walls. With substitution of Equation 16 for $\dot{m}_p$, $c_p = 0.24$ Btu/lb/°F (1.00 kJ/kg/K) and $\Delta T = 1000$°F (538°C) in Equation 17, the resulting expression can be solved for Q_c. The result is Equation 4 if it is assumed $\lambda = 0.63$ which is a realistic convective fraction.[9]

Q_{feasible} was described in conjunction with Equation 3 as a heat release rate beyond which the feasibility of roof venting, using the present approach, might be questioned because of the onset of ventilation control of the burning process. Ventilation-controlled fires do not support a clear layer as, for example, in the case of the typical, flashed-over room fire. According to experiments on wood crib fires in enclosures, vented through doors or windows,[10] ventilation control appears to set in when the so-called ventilation parameter, $A_w\sqrt{h_w}$, in ratio to the mass burning rate, R, is less than 266 $\text{ft}^{5/2}$/lb/sec, where A_w is the window (or door) area, and h_w is the window (or door) height. Generalized to any combustible, the limiting ratio might be expressed as $A_w\sqrt{h_w}$ in ratio to the stoichiometric air requirement associated with the mass burning rate, Rr, where r is the stoichiometric mass ratio, air to combustible (assumed at 5.5 for wood). Now, the ventilation parameter, $A_w\sqrt{h_w}$, is proportioned to the mass flow rate of air through a window or door opening, $\dot{m}_v$:[11]

$$\dot{m}_v\,(\text{lb/sec}) = 0.064\,A_w\sqrt{h_w}. \tag{18}$$

where A_w is in ft^2, and h_w is in ft.

The limiting condition for ventilation control can, therefore, be expressed in terms of the mass venting rate of air in ratio to the stoichiometric air requirement, $\dot{m}_v Rr$, which turns out to be approximately 3. Using the fact that Rr can be written $Q/(\Delta H_c/r)$, where Q is the heat release rate and ΔH_c is the heat of combustion, the limiting mass rate ratio can be converted to a limiting heat release rate:

$$Q = \frac{1}{3}\,\dot{m}_v(\Delta H_c/r) \tag{19}$$

In application to roof vents, $\dot{m}_v$ can be expressed as in Equation 9. Furthermore, $\Delta H_c/r$ is quite constant among common combustibles. Substituting Equation 9 and taking $\Delta H_c/r =$ 1328 Btu per lb (3086 kJ/kg), Equation 19 becomes:

$$Q\,(\text{Btu/sec})\ 133A_v d^{1/2} \tag{20}$$

where A_v is in ft^2, and d is in ft.

In the simplified venting approach of the 1991 edition of NFPA 204M, an equation for A_v was presented (Equation 12 in that edition), applicable to heat release rates above a lower limit likely to be exceeded in all practical cases. When this equation is combined with Equation 20, the result is the expression for Q_{feasible} in Equation 3.

SUMMARY

Adequate venting in a building is necessary to prevent the buildup of heat and smoke during a fire, which can severely hamper fire-fighting efforts. Ventilation in industrial buildings is accomplished by the use of unit vents or mechanical ventilators and curtain boards. Unit vents are manufactured specifically to provide ventilation during a fire. Curtain boards contain smoke and heat, and the buildup of heat in the curtained area actuates the venting system. The required vent areas in a building are calculated on the basis of limited-growth fires, which involve maximum heat release rates, versus continuous growth fires, which involve growth times. Information is provided to calculate mechanical exhaust rates equivalent to required vent areas.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on venting practices discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 204, *Standard for Smoke and Heat Venting*

ADDENDUM

AUTOMATIC HEAT AND SMOKE VENTING IN SPRINKLERED BUILDINGS

This addendum supplements the venting practices in this chapter as written by Dr. Heskestad. It presents in summary the various views on the controversial and unresolved subject of automatic venting in sprinklered buildings. The history of research testing on the subject is traced. Original contributors (sixteenth edition, 1986) include Ernest E. Miller, Thomas E. Waterman, and Edward J. Ward.* The author has expanded the section "New Sprinkler/Vent Research," which he wrote for the eighteenth edition of the *Fire Protection Handbook,* with material on additional research included in the nineteenth edition ("FPRF Program") and new material for this edition from the literature ("New Analysis of Past Studies").The updated section is headed "More Recent Sprinkler/Vent Research and Analysis".

*Ernest E. Miller was an executive engineer with Industrial Risk Insurance (IRI) at the time he contributed his views. Thomas E. Waterman was employed by the IIT Research Institute and conducted the IITRI test series of 1980–1981. Edward J. Ward was employed by Factory Mutual Research Corporation.

Differing Views

There has been controversy for more than four decades over automatic venting for sprinklered buildings.

Proponents of automatic venting in sprinklered buildings claim that venting will aid manual fire fighting by delaying loss of visibility, reduce the risk of structural failure by venting gases with dangerously high temperatures, vent the equivalent of an unsprinklered fire if the installed sprinklers are defeated by human failure or mechanical damage, and substitute for manual roof venting by fire service personnel.

Opponents believe that, in some cases, venting may be detrimental because it draws in fresh makeup air, keeping oxygen levels higher than they would be otherwise, causing more vigorous combustion with an increase in fuel consumption, and creating potential for loss of sprinkler control. They also believe sprinkler discharge will cool the fire gases, perhaps to the extent that the vent discharge is reduced, hence reducing venting effectiveness. Further, the sprinkler sprays will entrain ambient smoke and air, transporting smoke to the floor level and possibly drawing gas from the vent exhaust wherever sprinklers are located close to vents and further reducing venting effectiveness. Additionally, opponents see little, if any, evidence from research testing of the benefit to fire control obtained from the use of vents in a sprinklered building and believe that the high cost of installation does not justify their use.

Sprinkler/Vent Research

Research testing on the subject includes large-scale tests, FMRC model study, other FMRC large-scale testing, and IITRI full-scale venting research testing.

Large-Scale Tests. In 1956 Factory Mutual Research Corporation (FMRC), now FM Global, ran a series of large-scale tests from which it concluded that the effects of venting in sprinklered buildings are different from those in unsprinklered buildings. The research project[1] was conducted in a 120- by 60-ft (36.6- by 18.3-m) test building equipped with 5 ft (1.5 m) draft curtains and vent areas ranging up to 32 ft^2 (3 m^2) within a curtained area of 2280 ft^2 (212 m^2). This is a vent ratio of about 1:70—that is, 1 ft^2 (0.093 m^2) of vent area for every 70 ft^2 (6.5 m^2) of floor area. A 5-gal/min (18.9-L/min) gasoline spray fire was used as the exposure, and protection consisted of 160°F (71°C) automatic sprinklers installed on a 10 ft by 10 ft (3 m by 3 m) spacing.

The tests in the series were conducted using various combinations of vents, draft curtains, and sprinklers. Six of these were sprinklered tests (Table 18.4.6).

Comparison of average temperatures indicates that vents contributed significantly to temperature reductions in the unsprinklered tests in the series; however, they were of marginal value in the sprinklered tests. The greatest reduction in sprinkler operation was attributed to increased sprinkler discharge.

FMRC Model Study. In the early 1970s, an FMRC study was conducted.[2] The objective was to investigate experimentally the performance of automatic heat and smoke vents in sprinklered

TABLE 18.4.6 FMRC Test Results

Test Number	*Curtain ft (m)*	*Vent ft² (m²)*	*Sprinkler Discharge gpm (L/min)*	*Number of Sprinklers Operated*
1	None	None	15 (57)	48
2	None	32 (3.0)	15 (57)	44
3	5 (1.5)	32 (3.0)	15 (57)	24
4	5 (1.5)	16 (1.5)	15 (57)	24
5	5 (1.5)	None	15 (57)	28
6	5 (1.5)	None	25 (95)	15

fires in one-story buildings, principally in terms of sprinkler water demand, but also in terms of visibility conditions and fuel consumption. The study was performed at FMRC's Norwood, Massachusetts, laboratory and involved a 1:12.5 scale model of FMRC's fire test facility at West Gloucester, Rhode Island. Automatic, individually fused vents on 50 ft (15.2 m) spacing were employed, often in combination with a draft curtain encompassing a 10,000 ft^2 (929 m^2) curtained area.

Of primary interest were venting installations conforming to recommendations of standards-setting groups that were state of the art at the time. For a fire in cellulosic material that opened about fifty 212°F (100°C) sprinklers at a density of 0.27 gpm per ft^2 [11 (L/min)/m^2], distributed vents alone (without draft curtains) had no effect on the water demand but delayed loss of visibility from 13.1 to 15.7 minutes and increased fuel consumption by 31 percent. Vents and draft curtains caused a 35 percent increase in water demand relative to the unvented fire, delayed loss of visibility from 13.1 to 20.2 minutes, and increased fuel consumption by 66 percent.

Favorable effects of venting were observed for a series of large, heptane fires that opened an average of 112 sprinklers at 0.27 gpm per ft^2 [11 (L/min)/m^2]. Vents alone reduced the water demand by 8 percent and markedly improved visibility conditions; vents and draft curtains reduced the water demand by 18 percent but did not improve visibility conditions as much as without draft curtains.

The test results were based on ignition points that were equidistant from the four nearest vents in the vent matrix. Experiments with ignition directly under a vent indicated that some reduction in water demand could be expected for fires that opened fifty sprinklers or less. It was concluded, however, that for randomly started fires, less than about 13 percent of the fires would benefit, respective to water demand, from closeness to a nearby vent.

Critics counter that the 0.08-scale-model experiments, although carefully designed and executed, incorporated numerous uncertainties. Of particular concern was modeling of a full-scale fuel bed (rack storage configuration), by using ½-in. (12.7-mm) thick triwall cardboard. Some 10 years later, the modeling of room fire development has proceeded to an advanced state in all respects, except for the burning fuel; both analytical and experimental models address only the simplest of fuel configurations. Yet the model study assumed that both flame spread and burning rate of the fuel bed were modeled under conditions of depleted oxygen and impacting water droplets.

The FMRC model study was also criticized because of the configuration of the water discharge devices that were used. The study pioneered the use of nondescript miniature nozzles (representing sprinklers) arranged to be operated in small open-head deluge systems of groups of five to eleven nozzles controlled by individual sensors. Critics claim this arrangement magnified the known imprecision in measuring comparative sprinkler performance. It required multiplying the normal spread experienced in full-scale sprinkler operation by a variable factor of 5 to 11. Due to the small deluge systems, which operated as groups, sprinkler skipping occurred in units of five or more open nozzles, rather than the skipping of individual sprinklers as would be customary in full-scale fire research.

Lastly, the critics agreed that, although up to three times as much combustible material was consumed in the vented tests as compared to the unvented tests, the implication of detriment was improper. They claimed the explanation for the increased fuel consumption in the vented tests lies in the customary manner of conducting fire tests involving sprinklers. The test fires are allowed to continue far beyond sprinkler control to give the fires every opportunity to escape. During the additional minutes of these tests, the oxygen reduction in the unvented tests limited the fuel consumption, whereas oxygen remained abundant in the vented tests and resulted in greater fuel consumption. Since sprinkler-controlled fires continue to smolder and burn, it was felt that the reported increased fuel consumption was attributable to more complete burning of the rubble and did not represent increased fire damage. Had the fires spread to involve a significantly larger area, additional sprinklers would have operated.

Other FMRC Large-Scale Testing. More than 80 full-scale rack storage tests were conducted between 1968 and 1975. Only three tests employed perimeter ventilation (not to be confused with roof venting directly over a fire) and only one of these three (No. 72) was identical to two other tests (Nos. 65 and 66), except for the ventilation variable. Results of these tests are given in Table 18.4.7.

Comparing Test Nos. 65 and 66 to Test No. 72, researchers discovered that venting caused a dramatic detriment to the performance of the sprinklers. However, it is pointed out that Test No. 72 had a significantly different initial fire growth behavior compared to the other tests, which may have affected the outcome. FMRC's position on the effects of ventilation in these tests is that they are not conclusive.

TABLE 18.4.7 Rack Storage Tests

Test Number	*Ventilated*	*Number of Ceiling Sprinklers Operated*
65	No	45
66	No	48
72	Yes	92

Venting proponents argue that, although the influence of venting was inconclusive because the perimeter windows were too remote, the ventilated tests maintained visibility for 48:40 and 33:00 (minutes:seconds), as compared to 10:30 and 18:00 for the unventilated tests.

Venting opponents claim the effect of ventilation on fire control was best demonstrated during FMRC's large-scale fire testing of rubber tires in 1970. This test was made to evaluate sprinkler protection for automobile tires stored in portable steel racks. Storage was located in a single pile 35 ft by 50 ft by 18 ft (11 m by 15 m by 5.4 m) high. Protection consisted of 286°F (141°C), ½ in. (12.7 mm) sprinklers, spaced 50 ft^2 (4.6 m^2), each with a controlled discharge of 0.6 gal per minute per ft^2 [24.4 (L/min)/m^2]. There was no ventilation at the start of the test.

The fire was started at the base of a rack. The first sprinkler operated 2 minutes and 15 seconds after ignition. By 8 minutes and 20 seconds, 43 sprinklers had operated and controlled the fire. Only one additional sprinkler operated at 28 minutes. The fire remained under control until 60 minutes into the test, when all doors and windows were opened to ventilate the building and sprinklers were left on. The fire then began to spread and grow in intensity. At 117 minutes, when it was apparent that sprinklers were failing to control the fire, all doors and windows were closed. A total of 95 sprinklers operated, and water was discharged for over 5 hours. Only the ninety-fifth sprinkler operated after doors and windows were closed, and that was at 118 minutes, 1 minute after closure.

Critics reappraised the ventilated rubber tire fire test[3] and contended that the loss of initial sprinkler control was not due to remote window ventilation, as reported. Ceiling temperature gradients revealed that during the hour delay before hose extinguishment of the sprinkler-controlled fire was attempted, the fire had burrowed to the other end of the pile where sprinklers were not operating and had erupted with great intensity. The tightly stacked tires, stored on tread, formed horizontal tunnels that offered avenues of fire spread that were sheltered from sprinkler discharge.

IITRI Full-Scale Venting Research Testing. In 1977, the IITRI was commissioned by the intra-industry Fire Venting Research Committee to review past research and fire experience related to vent/sprinkler interactions in large-area single-story structures. Based on IITRI's review and other considerations, the committee ultimately funded some 45 large-scale segment experiments in 1980–1981.[4] The experiments were conducted in a 75 ft by 25 ft by 17 ft (23 m by 7.6 m by 5.2 m) high portion of IITRI's fire laboratory. Fires were placed in a corner to represent one-quarter of a larger fire in the center of a 150 ft by 50 ft (46 m by 15.2 m) room. To simulate the test area as part of an even larger area, two garage doors on the wall farthest from the fire were partially opened to represent a draft curtain. The area beyond the curtains was also enclosed by vertical air stacks to minimize extraneous wind effects.

To allow variations in vent area, two pairs of automatic roof vents were installed in the laboratory roof. A diagonal sprinkler pattern was chosen to eliminate aisles between sprinklers that were located between the test fires and the vents. Experiments were conducted using propane diffusion burners or stacked pallets as the fuel source. For each fuel source, fire size and sprinkler water supply pressure were varied until a condition of "marginal" sprinkler control was achieved. Then, vent areas were varied to assess effects of venting on sprinkler performance (number of operating sprinklers and temperature levels at various locations). The laboratory size and excessive recirculation of smoke due to the substitution of vertical stacks for added rooms precluded useful measures of smoke obscuration.

Propane-source fires produced results suggesting a slight reduction in water demand for vented fires when either 165 or 286°F (74 or 141°C) sprinklers were employed (vents were operated either with 165°F [74°C] links or by simulated smoke detector or waterflow switch actuation).

All pallet fire experiments employed 165°F (74°C) sprinklers and the same vent arrangement previously described. These experiments demonstrated that, under marginal sprinkler protection, the configuration of the test facility was extremely sensitive to variations in fire intensity from any cause. Once this possibility appeared, a final series of 10 "replicate" experiments was conducted, alternating between vented and unvented configurations. These experiments proved to produce widely varying results, apparently independent of the presence of automatic venting. The number of operating sprinklers varied from 7 to 22 per test, and the pattern of sprinkler operating times appeared unrelated to the time that vents opened. Other measured factors (temperature, O_2) varied in the same way. Although the number of operating sprinklers varied widely in these experiments with marginal sprinkler control, 84 sprinklers operated in the five unvented tests and 85 in the five vented tests. Earlier tests at higher water supply pressures produced good replication, independent of venting.

On the basis of the IITRI experiments, the test sponsors concluded that automatic roof venting did not detract from current state-of-the-art automatic sprinkler performance. Likewise, no particularly significant benefit to sprinkler performance was noted. Thus, it was suggested that automatic vents, if used in sprinklered properties, will perform the following functions:

1. Vent unsprinklered fires, if installed sprinklers are defeated by human failure or mechanical damage
2. Substitute for manual roof venting on arrival of fire service personnel

Primarily on the basis of the first listed application, the researchers recommended that, where they are used for sprinklered properties, the design and installation of automatic roof vents follow guidance provided by NFPA 204 for unsprinklered properties, until further research, testing, or experience suggests more beneficial alternative configurations.

Critics of the IITRI research effort do not agree that the experimental results support the main conclusion of the investigation, which is that automatic roof vents do not impair sprinkler control of fires capable of growth.[5] The critics also claim that the finding that automatic roof vents do not impair the ability of 165°F (74°C) sprinklers to control fires capable of growth contradicts the other studies described here, which have indicated that the increased availability of oxygen associated with open vents may lead to increased fire intensity (of

fires capable of growth), water demand, and consumption of combustibles.

The critics concluded that the reported results do not justify the overall conclusions and recommendations of the IITRI researchers. Their critique suggested the investigation suffered from a number of defects: (1) situations claimed to be unvented were not; (2) one of the most important principles of venting was violated (i.e., the provision of adequate openings for inlet air); and (3) inadequate control was exercised over the experimental conditions to the extent that major variations observed in fire behavior could not be attributed to the parameter under study.

Conclusions of the Research

The proponents of automatic venting in a sprinklered building cite the IITRI research work as substantiation of the merit of vents in sprinklered buildings. On the basis of those data, they believe that automatic roof venting can provide two major contributions to 165°F (74°C) sprinkler-protected (large one-story) properties:

1. Perform as vents in unsprinklered properties should installed sprinklers be defeated by human failure or mechanical damage.
2. Substitute for manual roof venting on arrival of the fire services.

The opponents of automatic venting in a sprinklered building believe that the high installation cost of vents is difficult to justify when one considers the limited benefits and possible detriment. They are not cost-effective because it is unlikely that a large loss will be averted solely due to the presence of vents when automatic sprinkler protection is inadequate or impaired.

Venting may or may not be detrimental, depending on many factors, such as the location of the fire origin in relation to the location of vents. More often than not, vents will increase the water demand.[2] Even when automatic vents result in some improvement, the improvement is not required for sprinklers to gain control. Vents can also create conditions that will inhibit or prevent sprinkler control.[5]

Installing automatic vents in unsprinklered buildings is acceptable. It would certainly be more beneficial to the building owner, however, to install sprinklers rather than vents to obtain active rather than passive fire control.

Installing manual vents in a sprinklered building is also acceptable, if desired by the building owner. These vents can be used during manual overhaul or at locations that would be expected to produce dense smoke. However, a similar effect can be achieved by venting through windows, by fire fighters cutting holes in the roof, or by ventilation equipment or smoke exhausters.

Through NFPA's consensus-making standards process, NFPA members agreed to the following statements for the 1985 edition of NFPA 204M:

> A series of tests was conducted to increase the understanding of the role of automatic roof vents simultaneously employed with automatic sprinklers [Section 6-5(c)]. The data submitted did not permit consensus to be developed as to whether sprinkler control was impaired or enhanced by the presence of automatic (roof) vents of typical spacing and area. (Section 6-3)
>
> While the use of automatic venting in sprinklered buildings is still under review, the designer is encouraged to use the available tools and data referenced in this document for solving problems peculiar to a particular type of hazard control. (Section 6-4)

Even though the issue has been argued for years, proponents maintain venting critics have been unable to cite a single fire in which automatic venting was blamed for loss of fire control by sprinklers. Thus, to proponents it is paradoxical that fire research, which is typically motivated only by adverse fire experience, should be the sole basis of suspecting venting to be a detriment. They urge that serious students of venting should obtain and carefully examine this research and compare it with related research, both direct and indirect.

More Recent Sprinkler/Vent Research and Analysis

Ghent Experiments. During the latter part of 1989, the Fire Research Station of the Building Research Establishment (U.K.) and Colt International (together with Verband der Sachversicherer eV and City of Ghent Fire Brigade) undertook a collaborative test program in a unique test building constructed in Ghent, Belgium, the Multifunctioneel Trainingcentrum.[6] The main objective was to validate a theoretical model for predicting the effect of venting on sprinkler operations, but the direct data are being generally used to assess the efficacy of venting in sprinklered buildings.

The test building in Ghent is designed for fire service training purposes and incorporates a hall of the dimensions 164 ft × 59 ft × 33 ft high (50 m × 18 m × 10 m). For the tests, a 10-ft (3.1-m) deep draft curtain was hung from the ceiling, creating a curtained, flat-ceiling area of 89 ft × 59 ft (27 m × 18 m) under which test fires were burned. A total of 20 roof vents, each with an area of 18 ft^2 (1.67 m^2), were installed in this area, centered on a grid measuring 15.9 ft × 14.8 ft (4.85 m × 4.5 m). Sprinklers on a spacing of 12 ft × 8 ft (3.7 m × 2.4 m) were also installed in this area (temperature rating of 155°F [68°C]). The ceiling area on the other side of the draft curtain was provided with 20 roof vents that were always open. A total of 16 inlet vents were installed at ground level in the sides of the building, each having an aerodynamic free area of 33.7 ft^2 (3.1 m^2). As fire sources were used, *n*-hexane floated on water near the floor level. One source had a steady output of 5100 Btu/s (5.4 MW). The other source provided an exponentially growing heat release rate (roughly equivalent to a continuous-growth fire of 50 seconds growth time) until the first sprinkler operated, at which time the heat releaser rate was leveled off (8700 to 12,300 Btu/sec [9.2 to 13.0 MW]).

Note that the vents were very closely spaced (although not all of the vents were used in all the tests) and, furthermore, that the building space on the side of the draft curtain away from the fire was amply ventilated, which may have been factors in the outcome. Other unusual features were that the vents were in effect short chimneys about 5 ft (1.5 m) high and, when venting was used, the vents were open from the start of the test.

The first test series involved the steady fire source. Combinations of 0, 1, and 5 operating sprinklers (at approximately 30 psi [2 bar]) with 0, 10, and 20 open vents were investigated.

With no sprinklers operating, the ceiling gas temperatures decreased significantly with the number of open vents, from 220°F (104°C) to 153°F (67°C) at a 20 ft (6 m) radius from the fire axis when conditions changed from no vents to 20 open vents. With 5 sprinklers operating, the drop in gas temperature at the same location was from 203°F (95°C) with no vents to 130°F (54°C) with 20 open vents. Extensive temperature, velocity, and CO_2 concentration data were recorded.

The second test series involved the growing-fire source and automatic operation of the sprinklers. The number of open vents in a test were mostly 0, 10, or 20, but a few tests were conducted using special patterns of 9 and 16 open vents. The water supply in the first tests was very weak. For the test providing data for this review, the water supply was boosted with a fire pump, yielding a pressure of about 88 psi (6 bar) for one open sprinkler, decaying to about 15 psi (1 bar) for 40 open sprinklers (roughly linear decay with number of open sprinklers). The time of the first sprinkler operation ranged from an average of 148 seconds for no open vents to an average of 160 seconds for 20 open vents. Subsequent sprinkler operations depended on the particular test scenarios, that is, the original, Scenario A, where the fire size was maintained constant to the end of the test at the value when the first sprinkler operated (leading to operations of all installed sprinklers with no open vents), or the revised, Scenario B, where the fire size was maintained constant for 30 seconds and then reduced by 20 percent. In Scenario B, an initial group of 6 sprinklers operated within an interval of 60 seconds for both 10 and 20 open vents, compared to an initial group of 9 sprinklers in the same interval with no vents. With 20 open vents, only one additional sprinkler operated (no additional operations for 10 open vents). With no vents, additional sprinkler operations began about 2 minutes after the first sprinkler operated, accumulating to a final total, nearly 6 minutes from ignition, of 37 sprinklers.

With respect to the issue of visibility through smoke, the report offers the following observation: "In the experiments with growing fires and the pumped supply, the water pressure was higher and the number of operating sprinklers greater than in the experiments with steady fires. There was then some tendency for the fire gases to be pulled down in both vented and unvented experiments." On other issues, the experiments provided no evidence that the flow through the vents was affected by the wind (wind speeds up to 26 ft/sec [7.8 m/sec]), and there were no observable effects of nearby sprinklers on the vent flow (nearest sprinkler about ¾ vent width from any part of the vent opening). The author often finds fair agreement between his theory and the experimental results but identifies areas needing further study, which are issues beyond the scope of this review.

On the effect of venting on sprinkler operations, the report concludes that (1) the prior opening of vents will have little effect on the operation of the first sprinkler with fast growing fires; (2) venting substantially reduced the total number of sprinkler operations; and (3) there was no indication that venting could increase the total number of sprinkler operations.

These conclusions of the report are deemed, by this reviewer, to be highly dependent on the special circumstances of the experiments, primarily (1) the use of a fire source that did not respond in heat output to the sprinkler spray per se, and (2) the fact that even unvented fires were supplied with unvitiated air, arriving from the adjacent, amply ventilated part of the building.

Further to the issue of responsiveness of the fire source to sprinkler spray, Gustafsson[7] observed from the sprinkler operation maps in the report that, in vented tests, sprinklers near the fire source often were delayed or did not operate altogether. Gustafsson makes the point very strongly: "It is clearly seen that the effect of ventilation on the operation of sprinklers was strong and detrimental in all cases. It must be appreciated that prevented or substantially delayed operation of any sprinkler close to, or directly above, the fire must be avoided."

Additional research and testing will be needed before definitively establishing the benefits and detriments of automatic venting in a sprinklered building.

FPRF Program. Large-scale tests to study the interaction of sprinklers, roof vents, and draft curtains were organized by the Fire Protection Research Foundation (FPRF), formerly known as the National Fire Protection Research Foundation (NFPRF), and reported in 1998 by McGrattan et al.[8] The tests were conducted in a building provided with a free-hung test ceiling underneath a fixed ceiling provided with exhaust to an abatement system, which made the tests difficult to interpret for field applications.

The 120 ft by 120 ft (36.6 m by 36.6 m) test building employed a 100 ft by 100 ft (30.5 m by 30.5 m) free-hung ceiling at a height of 27 ft (8.2 m) above the floor, underneath which the fires were burned. Smoke exhausted above the free-hung ceiling to a smoke abatement system, and makeup air entered through duct openings at four locations around the building perimeter, 10 ft (3.1 m) above the floor. Roof vents (4 ft by 8 ft [1.2 m by 1.2 m]), normally operated by fusible links, were installed on 50 ft by 50 ft (15.3 m by 15.3 m) spacing within a 70 ft by 75 ft (21.4 m by 22.9 m) draft-curtained area. Some tests were run without draft curtains.

A series of tests employed *heptane spray fires* with *t*-squared growth to a constant heat release rate of 10 MW in 75 seconds. Smoke exhaust and air supply for the test building were held constant at 24,000 scfm (13.6 kg/sec). Unless a fire was ignited directly under a roof vent, roof venting had no significant effect on sprinkler operations or near-ceiling gas temperatures. Ignitions directly under an automatic roof vent decreased the number of operated sprinklers compared to tests without vents. When 6-ft (1.8-m) deep draft curtains were installed (depth corresponding to 22 percent of the ceiling height), the number of sprinkler operations was considerably larger than without curtains.

Five tests were conducted with a 19-ft (5.8-m) high array of *cartoned plastic commodity.* In these tests, smoke exhaust and air supply for the test building were at a constant 60,000 scfm (34.1 kg/sec), requiring a velocity of make-up air at the building perimeter duct openings of 13 fps (4.0 m/sec). Three of the tests operated 20 to 23 sprinklers, with a potentially higher upper limit since sprinklers operated to the edge of the test ceiling. The remaining two tests operated 5 to 7 sprinklers. This large span was attributed[8] to variability in the initial fire growth and not to any variables under study. One of the tests with ignition near a draft curtain resulted in much larger fuel consumption than the other tests, attributed[8] to fire spread under the draft curtain. In a test in which four vents were opened manually at the same time as the first sprinkler operated, vent flow rate was one-third the

expected rate, attributed[8] to reduction in gas temperatures by the sprinklers.

In the test in which four vents were opened manually (series of five tests), the total vent flow rate is estimated from the report[8] to have been only one-quarter the flow rate of the smoke abatement system for these tests (60,000 scfm [34.1 kg/s]). Hence any observations on smoke behavior would be difficult to interpret for field applications. Furthermore, differences in oxygen vitiation and their effects on combustion, vented versus unvented cases, would be much smaller than in many field situations.

The FPRF tests can be summarized as follows:

1. In the heptane spray fires, venting had no significant effect on sprinkler operations unless a fire was ignited directly under a vent, in which case the number of sprinkler operations decreased.
2. When a draft curtain was installed in the heptane spray fires, the number of operating sprinklers increased.
3. In five tests with the cartoned plastic commodity, three tests operated 20 to 23 sprinklers and two tests operated 5 to 7 sprinklers, attributed to variability in the initial fire growth and not to any of the variables under study.
4. One of the tests with ignition near a draft curtain consumed much more fuel than the other tests did, attributed to fire spread under the draft curtain.
5. Effects of venting through roof vents on smoke obscuration could not be determined because of the dominant effect of the building smoke abatement system.

New Analysis of Past Studies

In January 2001 Beyler and Cooper presented a review of past studies deemed to have some relevance to assessing combined use of sprinklers and smoke/heat vents.[9] The authors conclude that (1) venting clearly does not have a negative effect on sprinkler performance, (2) venting limits spread of combustion products, and (3) venting remains a valuable aid to manual control of the fire in the event the sprinklers do not operate. In a letter to the editor following the publication of this paper, Heskestad[10] argues the view that the first two of the authors' conclusions are performance measures that are not met, or not well met, by current technology, based on the studies cited by the authors. With respect to the third conclusion, Heskestad refers to the FM Global position that venting, installed as a backup to an automatic sprinkler system that is inadequate or impaired, is not cost effective because it is unlikely a large loss will be averted solely due to the presence of vents.

Beyler and Cooper[9] recommend that design practice move to methods that ensure early operation of vents, that vent operation be ganged, and that draft curtains be placed over aisles rather than over storage. It is agreed that this recommendation may lead to much improved technology (as reflected in the next-to-last paragraph of the section headed "Historical Background"), but it will require a significant research effort.

ADDENDUM SUMMARY

Automatic venting in sprinklered buildings is a controversial and unresolved subject. Proponents contend that venting will delay loss of visibility, reduce the risk of structural failure by venting gases with dangerously high temperatures, offset problems caused by failure of the sprinkler system, and substitute for manual roof venting by fire fighters. Opponents claim that venting may be detrimental by drawing in fresh makeup air, thus raising oxygen levels and causing more vigorous combustion. Opponents also believe that sprinkler operation would reduce the effectiveness of automatic vents to the point where installation costs would not justify their use.

Research on this dispute has included a large-scale test run by FMRC in 1956, the FMRC model study conducted in the 1970s, more than 80 full-scale rack storage tests carried out by FMRC between 1968 and 1975, and IITRI full-scale testing in 1977. The results of that research failed to resolve the issue, and consensus is yet to be reached. More recent research involves a collaborative test program in Ghent, Belgium, and large-scale tests organized by the FPRF to study the interaction of sprinklers, roof vents, and draft curtains. Again, the results of the research were not conclusive as to the definitive benefits and detriments of automatic venting in sprinklered buildings. A fresh review of past research has suggested benefits, but its conclusions have been challenged.

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Chapter 5

Penetration Sealing

John E. Kampmeyer

Chapter Contents

Historical Background
Through-Penetration Firestop Systems
Perimeter Fire Containment Systems
Joint Systems

Key Terms

Browns Ferry nuclear power plant fire, fire barrier, fire containment, fire resistance, firestop, health care facility, penetration sealing

As construction for new buildings or renovations to existing buildings are planned, it is important to include fire containment penetration sealing systems, which include through-penetration firestop systems, perimeter fire containment systems, and joint systems. These systems must be properly installed to contain fires and smoke and prevent their spread.

A series of tests has been developed for testing materials in combination with various fire barrier constructions, so that today, the Underwriters Laboratories (UL) Fire Resistance Directory devotes 2975 pages in two volumes to sealing of penetrations. These are divided into the following three categories:

1. *Through-penetration firestop systems.* Used to seal openings where mechanical or electrical systems pass through rated walls or floors
2. *Perimeter fire containment systems.* Used to seal openings between floors and curtain walls
3. *Joint systems.* Used to seal openings where two elements of construction come together such as joints where two walls meet or where two different floor systems meet

For related topics, see Section 12, Chapter 8, "Effect of Building Construction and Fire Protection Systems on Fire Fighter Safety"; Section 18, Chapter 1, "Confinement of Fire in Buildings"; and Section 18, Chapter 3, "Smoke Movement in Buildings."

HISTORICAL BACKGROUND

Prior to 1975, sealing of penetrations through fire-resistant assemblies was relatively simple. Once an opening was made through a fire barrier and a pipe, conduit, or other similar penetrating service was installed, the annular space was filled with a noncombustible material such as mineral wool, fiberglass, or asbestos (before asbestos was known to be a carcinogen).

On March 22, 1975, workers at the Browns Ferry nuclear power plant in northern Alabama were using a candle to check for air leaks at openings in a wall where trays of electrical cables pass from one room to another. As a worker held a candle near one of the openings, the flow of air through it drew the flame toward polyurethane foam that had recently been installed to seal the openings. The foam ignited and fire spread along the cables, shorting out backup safety systems as the cable insulation burned off.[1]

This fire demonstrated that it was not only important to properly seal penetrations to limit the spread of fire, but also to limit the spread of smoke. Previously used materials were found to be inadequate for this purpose. One of the first materials used to provide safer sealing of penetrations was silicone room temperature vulcanizing (RTV) foam, which can withstand high temperatures and confine hazards such as smoke, fire, and gases.

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THROUGH-PENETRATION FIRESTOP SYSTEMS

Through-penetration firestop systems represent the majority of the systems contained in the Underwriters Laboratories Directories. Each system deals with a specific firestop material, penetrating element, and construction system. In order to apply the systems, there are a number of steps that must be developed.

Determining the Fire Barrier Location and Rating

The first step in determining the proper firestop method to be used is to identify the location of the fire barriers and their hourly rating. In new construction projects, these are generally shown on the architectural drawings or, in the case where a fire protection engineer is part of the design team, a separate set of fire barrier drawings may be provided which show their locations and hourly ratings.

In existing construction, there may be little or no guidance from drawings. It will be necessary to study the building and the local building code to determine the locations of fire barriers. In multistory buildings, each floor is generally separated by 1 or 2 hour rated construction, although it could be greater in some cases. Shafts and stairs are generally separated by 1 or 2 hour rated construction depending on the height of the building. Boiler rooms, incinerator rooms, storage rooms over 100 ft^2 (9.3 m^2), paint shops, and maintenance shops will often be separated by 2 hour rated construction. Enclosed corridors used for access to exits, separations between tenants, and separations between dwelling units generally carry a 1 hour rating, although in some cases these may be nonrated partitions in buildings that are provided with automatic sprinklers. Storage rooms under 100 ft^2 (9.3 m^2), trash chute access rooms, linen chute access rooms, and laboratories are examples of rooms which may be separated by 1 hour rated construction.

Health Care Occupancies

Health care occupancies such as hospitals and nursing homes have an additional requirement for smoke barriers to separate floors, so that patients can be moved to an area protected from smoke in the event of fire. Unlike other occupancies, these smoke barriers must also carry a 1 hour fire resistance rating, and penetrations through them must be protected with through-penetration firestop systems. One method which may be used, although not always accurate (since rated assemblies may have been used because they were available but not required), is to look for labels on doors and door frames which contain hourly ratings. Generally, the ratings of fire doors are as listed in Table 18.5.1.

TABLE 18.5.1 Fire Door Ratings

Door Rating	*Wall Rating*
20 min	½–1 hr
¾ hr	1 hr
1 hr	1 hr
1½ hr	1½–2 hr
3 hr	3–4 hr

F, T, and L Ratings

Firestop systems are tested in accordance with either ASTM E814, *Standard Test Method for Fire Tests of Through-Penetration Fire Stops*[2] or UL 1479, *Fire Tests of Through-Penetration Firestops*.[3] These tests yield three ratings which are used in the published listings for the systems:

- *F rating.* Evaluates the time that the system will withstand the passage of flame expressed in hours
- *T rating.* Evaluates the time that the system will limit the temperature on the unexposed side to not more than 325°F (163°C) expressed in hours
- *L rating.* Evaluates the air leakage through the system at ambient and/or 400°F (204°C) at an air pressure differential of 0.30 in. of water (74.6 Pa) expressed in cubic feet per minute per square foot of opening (cfm/ft^2); the test for L ratings is not a requirement of ASTM E814 and is optional in UL 1479.

Both the 2006 edition of *NFPA 5000®, Building Construction and Safety Code®,* and the 2006 edition of the ICC *International Building Code* (IBC)[4] require that penetrations through all fire barriers be protected with a through-penetration firestop system having an F rating equal to the hourly rating of the assembly. NFPA places the additional requirement that the F rating cannot be less than 1 hour. There is an exception in both codes: where the penetrating items are 6 in. diameter (152 mm) maximum steel, copper, or cast iron pipes, the annular spaces can be filled with grout to the full depth of the assembly. The T rating is not required for these assemblies, because they are generally located above any combustible materials which could come in contact with the penetrating item.

For horizontal fire barriers (floors and floor/ceiling assemblies), both building codes require additionally that the T rating of the through-penetration firestop system be equal to the hourly rating of the assembly, except where the penetration is contained within a fire-rated wall or partition assembly. The additional T rating requirement is in recognition of the fact that many vertical pipes may come in contact with combustible materials that are on the floor of the areas where the penetration firestop system is located. If it can be assured that there will be no combustibles near the piping, NFPA allows that the T rating requirement may be dropped.

Neither of the building codes call for an L rating on smoke barriers at the present time. The only reference to a pressure differential is in the IBC, which requires the firestop system to be tested under a differential pressure of 0.01 in. of water (2.484 Pa). The ASTM E814 and UL 1479 standards require a 0.01 in. of water (2.484 Pa) positive pressure as a minimum for all through-penetration firestop system tests. This is done to assure that the system will withstand a fire pressure attempting to push the heat through it. It is typically more of an issue with nonmetallic penetrating items, where the fire could push through burned-off sections, penetrating piping or conduits.

Firestop System Selection

Once the required hourly ratings for the through-penetration firestop system have been determined, the search for a specific system begins. Note that the term "system" and not "product" has been used. In order to determine the proper application of any product, it is necessary to know more about the construction of the fire barrier as well as the penetrating item. These three elements, fire barrier, penetrating item, and firestop product go together to form a system that makes up the through-penetration firestop. The testing laboratories list thousands of systems, each of which is specific to a type of construction, hourly rating, and manufactured product(s). On the surface, this appears to be a formidable task. In order to solve these difficulties, it is necessary to consider the elements of the construction described in the sections that follow.

Type of Fire Barrier Designation. The first consideration is the configuration of the fire barrier being penetrated. Is the barrier a floor (or horizontal barrier) requiring protection from vertical fire spread or is it a wall (or vertical barrier requiring protection from horizontal fire spread)?

Fire Barrier Construction Type. The second consideration is the type of construction used to create the fire barrier. Some examples follow, each having different firestop systems associated with it:

- Concrete floors of varying thicknesses
- Framed floors
- Steel
- Floor/ceiling assemblies consisting of layers of construction materials with horizontal spaces for ductwork, piping, and wiring
- Concrete or masonry walls of varying thickness
- Framed walls
- Bulkheads in marine vessels
- Composite walls

A through-penetration firestop system tested for a concrete block wall may not be applicable to a wall constructed of metal studs and drywall.

Penetrating Item Designation. The last consideration is the general type of penetrating item through the rated assembly, examples of which are the following:

- No penetrating item where a void in construction is to be sealed
- Metallic pipe, conduit, or tubing
- Nonmetallic pipe, conduit, or tubing
- Electric cables
- Cable trays with electric cables
- Insulated pipes
- Miscellaneous electrical items such as bus ducts
- Miscellaneous mechanical penetrating items, including air ducts
- Combinations of penetrating items including any combination of items listed above

Each of the systems will be listed for a particular size of penetrating item and the specific material of the penetrating item. For example, a system may be listed for steel pipes up to 24 in. (0.61 m) and copper pipes up to 6 in. (152.4 mm) with 2 in. (50.8 mm) or less insulation in diameter, whereas another system is listed for steel or copper pipes up to 4 in. (101.6 mm) with 1 in. (25.4 mm) or less insulation.

These systems illustrate a major problem facing designers in finding systems for floor penetrations using metallic pipes. It is difficult to get T ratings that will equal the F rating. This is because the metal transmits heat through the fire barrier at a greater rate than either the fire barrier construction or the firestop sealant, resulting in less time to reach the 325ºF (163º C) maximum temperature. Generally, it will be necessary to use insulation on the piping and the result will probably be an F rating greater than needed for the particular fire barrier. This is generally not as great a problem when using nonmetallic piping because of the lower heat transmission rate.

Thus, the search can be narrowed down to 1000 to 2000 possible choices. Each of these choices is very specific as to the size and type of penetrating items, as well as the details of the construction of the floor or wall being penetrated. It is necessary to study these details to be certain that the construction details in the listing meet the details of the fire barrier being penetrated before choosing a system to be used.

In summary, to select the appropriate firestop sealant for a particular project you need to determine the following:

- Fire resistance rating of the construction being penetrated
- Type of pipe, conduit, or other item being using to penetrate the fire barrier
- Type of penetrated construction—floor, wall, or both
- F, T, and L ratings required or desired
- Construction details and materials of the rated construction

PERIMETER FIRE CONTAINMENT SYSTEMS

Building Construction and Fire Resistant Materials

Perimeter fire containment systems were developed as the result of the increased use of exterior curtain wall construction in buildings, particularly high-rise buildings. In typical building construction used prior to the turn of the twentieth century, the exterior walls were either load bearing or were supported on the floor slabs and extended between the floors (See Figure 18.5.1). In the late nineteenth century and early twentieth century, lightweight panelized systems were developed that could cover the exterior of the building more economically but covered the edge of the floor slab only, leading to the term "curtain wall" construction.[5] In this construction, the floor slab does not extend to the exterior wall but is separated by a nonrated vertical construction, which extends unbroken past the edge of the slab, creating a void through which fire can pass from floor to floor (Figure 18.5.2).

Early methods employed to firestop these voids involved the use of fibrous fire retardant materials such as mineral wool. These materials provided an effective method of restricting

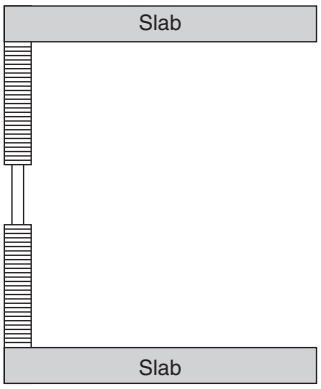

FIGURE 18.5.1 Floor Slabs in Typical Building Construction Before 1900

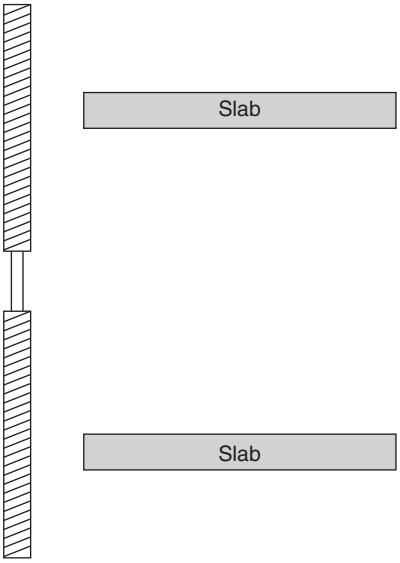

FIGURE 18.5.2 Floor Slab for Curtain Wall Construction

flame passage between floors, but were not effective in controlling the movement of smoke. Therefore, elastomeric sealants were developed that, in conjunction with fire-resistant materials, could effectively limit the spread of both flame and smoke between floors.

Testing and Ratings

Systems designed to protect curtain wall construction are tested in accordance with ANSI/UL 2079, *Tests for Fire Resistance of Building Joint Systems,*[6] using test methods and conditions given in NFPA 285, *Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components.*

Integrity Rating and Insulation Rating. Just as fire resistance ratings are given for through-penetration firestop systems, two fire resistance ratings are given in hours for perimeter fire containment systems: integrity rating and insulation rating. The integrity rating is analogous to the F rating on firestop systems and is a measure of the system's ability to limit the spreads of flame through the construction. The insulation rating is analogous to the T rating on firestop systems and is a measure of the system's ability to limit the temperature 1 in. (2.54 cm) above the fill material to 325°F (163°C). Where space between the slab and the curtain wall exceeds 6 in. (15.24 cm), there is an additional restriction on the insulation rating that the temperature will not rise more than 250°F (121.1°C) above the starting temperature.

Maximum Linear Opening Width Rating. A third listing for perimeter fire containment systems is the maximum linear opening width. This places a limitation on the width of the protected space between the slab and the curtain wall. Where the system is subject to movement, the components of the system are cycled prior to the fire test for 500 or 100 complete movement cycles at a minimum rate of 1, 10, or 30 cycles per minute. This results in the system being given a Class I, II, and/or III designation as shown in Table 18.5.2.

Using these tests, the joints are assigned a nominal joint width and a percentage factor for either compression or extension. From these, the minimum and maximum allowable joint widths are calculated using the formulae:

$$W_{min} = W_{nom} [1 - (\% \text{ Exp}/100)] \quad (1)$$

where

W_{min} = Minimum joint width (in.)
W_{nom} = Nominal joint width (in.)
% Exp = Percent movement capability in the compression direction

and

$$W_{max} = W_{nom} [1 - (\% \text{ Comp}/100)] \quad (2)$$

where

W_{max} = Maximum joint width (in.)
W_{nom} = Nominal joint width (in.)
% Comp = Percent movement capability in the extension direction

Movement Capabilities Rating. When a system has capabilities of resisting shear movement, the system is given a movement capabilities rating expressed in percent vertical shear. From this

TABLE 18.5.2 System Movement Capabilities

Movement Class	*Mininum Number of Cycles*	*Minimum Cycling Rate (cycles per minute)*
Class I	500	1
Class II	500	10
Class III	100	30

data, the maximum vertical shear the system can withstand can be calculated from the formula:

$$\text{Shear} = W_{nom} (\% \text{ Shear}/100) \quad (3)$$

where

Shear = Vertical shear movement
W_{nom} = Nominal joint width (in.)
% Shear = Percent in shear movement

Leakage Rating. There is a fifth rating, leakage rating, which is optional and not part of every listing. This rating determines the amount of air leakage in cfm per lineal foot through the joint at ambient temperatures and/or 400ºF (204ºC). The test is conducted at a differential pressure of 0.20 in. of water (49.8 Pa) and provides an indication of the amount of smoke which could be transmitted through the joint.

Curtain Wall Penetration Protection

When evaluating curtain wall penetration protection, there are two considerations which must be investigated: movement capabilities and maximum clearance.

Movement Capabilities. It must be determined whether the through-penetration fire stop system is static (i.e., the system does not have movement capabilities) or dynamic (i.e., the system has movement capabilities).

Maximum Clearance. This system will be listed for varying maximum clearance distances between the curtain wall and perimeter of the floor. The following are the usual ranges of clearances:

Less than or equal to 2 in. (50.8 mm)
Greater than 2 in. (50.8 mm) and less than or equal to 6 in. (152.4 mm)
Greater than 6 in. (152.4 mm) and less than or equal to 12 in. (304.8 mm)

JOINT SYSTEMS

Testing and Ratings

Fire resistance rated construction is tested and rated to provide a barrier which can resist the passage of fire and smoke for the period given in the hourly rating of the construction. However, the mating of two construction elements creates a space through which fire, heat, and/or smoke can pass, thereby reducing the effectiveness of the fire-resistant barrier. Joint systems protect these gaps. These systems are tested per ANSI/UL 2079, *Tests for Fire Resistance of Building Joint Systems.*

Similar to perimeter fire containment systems, systems with movement capabilities are tested by cycling the components of the system prior to the fire test under one of three conditions. The movement class, minimum number of cycles, and minimum cycling rate per minute are the same as those shown in Table 18.5.2.

Using these tests, the joints are assigned a nominal joint width and a percentage factor for either compression or extension. From these, the minimum and maximum allowable joint widths are calculated using the formulae:

$$W_{min} = W_{nom} [1 - (\% \text{ Exp}/100)] \quad (4)$$

where

W_{min} = Minimum joint width (in.)
W_{nom} = Nominal joint width (in.)
% Exp = Percent movement capability in the compression direction

and

$$W_{max} = W_{nom} [1 - (\% \text{ Comp}/100)] \quad (5)$$

where

W_{max} = Maximum joint width (in.)
W_{nom} = Nominal joint width (in.)
% Comp = Percent movement capability in the extension direction

As was the case with perimeter fire containment systems, there is an optional L (leakage) rating, which determines the amount of air leakage in cfm per lineal foot through the joint at ambient temperatures and/or 400ºF (204ºC). The test is conducted at a differential pressure of 0.3 in of water (74.6 Pa), and provides an indication of the amount of smoke which could be transmitted through the joint.

There is an L rating which is the same as for through-penetration firestop systems. This evaluates the air leakage through the system at ambient and/or 400ºF (204ºC) at an air pressure differential of 0.3 of water (74.6 Pa). and is expressed in cubic feet per minute per square foot of opening (cfm/ft^2). The test for L ratings is optional in ASI/UL 2079.

Factors to Consider Before Beginning Construction

When evaluating joint systems, there are three factors to consider: arrangement of construction elements, movement capabilities designation, and maximum clearance.

Arrangement of Construction Elements. Several types of joint systems can be used depending on the particular construction arrangement as follows:

- Floor-to-floor (typically at expansion joints in floors)
- Wall-to-wall (typically at expansion joints or corner joints in walls)
- Head of wall
- Bottom of wall

Movement Capabilities Designation. A decision must be made on whether the through-penetration fire stop system is static (i.e., the system does not have movement capabilities) or dynamic (i.e., the system has movement capabilities).

Maximum Clearance. This system will be listed for varying maximum clearance distance between the curtain wall and perimeter of the floor. The following are the usual ranges of clearances:

Less than or equal to 2 in. (50.8 mm)
Greater than 2 in. (50.8 mm) and less than or equal to 6 in. (152.4 mm)
Greater than 6 in. (152.4 mm) and less than or equal to 12 in. (304.8 mm)
Greater than 12 in. (304.8 mm) and less than or equal to 24 in. (61 m)
Greater than 24 in. (0.61 m)

A further complication is introduced when a floor-to-floor joint system is considered. This is the situation which is often represented by expansion joints in concrete floors. Not only will the joint require consideration of its movement, it is often necessary to consider the probability of smoke movement through the joint. Therefore, these systems also carry L ratings.

SUMMARY

The Browns Ferry nuclear power plant fire of 1975 demonstrated that building construction must be properly sealed to limit the spread of both fire and smoke. Because materials used before 1975 to seal penetrations were found to be inadequate, new sealing materials were developed along with a series of tests for rating the use of these materials in combination with various fire barrier constructions. The initial concentration was on sealing of pipes and conduits penetrating fire barriers. However, the sealing of joints around pipes and conduits and in joints between elements of fire resistance rated construction has come a long way from the simple selection of a "fire caulk" and then using it to plug up the opening. The sealing of joints requires consideration of a number of factors including the following:

- Desired fire resistance rating
- Maximum allowable opening width
- Nature of the item penetrating to fire resistance rated construction where applicable
- Allowable temperature rise where applicable
- Need for the system to resist movement
- Need for the system to resist the passage of smoke as well as fire

This chapter outlines three categories of sealing penetration systems: through-penetration firestop, perimeter fire containment, and joint. The chapter describes steps for determining which firestop method should be used, the unique sealing requirements of different types of facilities, rating systems, and building codes, standards and regulations for the application of penetration sealing.

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5. Ochshorn, J., "Curtain-Wall Systems in 20th-Century Architecture," *Encyclopedia of Twentieth Century Architecture,* Fitzroy Dearborn (Taylor and Francis) Publishers, 2003.
6. ANSI/UL 2079, *Tests for Fire Resistance of Building Joint Systems,* Underwriters Laboratories (UL), Northbrook, IL, 2004, revised 2006.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on penetration sealing discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 285, *Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components*
NFPA 5000®, Building Construction and Safety Code®

Chapter 6

Deflagration (Explosion) Venting

Richard F. Schwab

Chapter Contents

Fundamentals of Deflagrations
Fundamentals of Deflagration Venting and Enclosure Design Considerations

Key Terms

combustible dust, deflagration, detonation, enclosure, explosion venting, fireball, flammable gas, pressure effect

The first document by NFPA concerning explosion (deflagration) venting was NFPA 68-T, *Standard on Explosion Venting,* tentatively adopted by NFPA in 1945. The *Guide for Explosion Venting,* tentatively adopted by NFPA in 1954, brought together the best available, albeit sparse, information on the design and utilization of vents to limit pressures developed by "explosions." The 2007 edition of NFPA 68 is titled *Standard on Explosion Protection by Deflagration Venting.*

NFPA 68 clearly differentiates the terms *deflagration, detonation,* and *explosion.* A *deflagration* is defined as the propagation of combustion zone from the ignition point at less than the speed of sound in the unreacted medium. A *detonation* results when the combustion zone proceeds at greater than the speed of sound. An *explosion* is the bursting of an enclosure or container due to the development of internal pressure. The standard refers to cases in which vents are designed to relieve pressures developed by the combustion process proceeding at less than the speed of sound as explosion (deflagration) venting. Detonations cannot be vented.

Unfortunately, the data available in 1954 was primitive and without theoretical basis. It was customary at the time to express vent area in terms of vent ratios (square feet/cubic feet of enclosure volume). Very little regard was given to the strength of the enclosure and its effect on vent sizing, although it was recognized that a strong enclosure or a heavy building did not need as much vent area as a weak enclosure or building. It was qualitatively recognized that the rate of pressure rise had an effect on the size of vent required for a given enclosure; that is, a combustible or flammable gas showing test data with high rates of pressure rise required a larger vent ratio than those with lower rates of pressure rise. Also, increasing the mass of the vent closure was undesirable because it slowed down the opening of the closure, resulting in the buildup of destructive pressures within the enclosure.

This unfortunate state of affairs prevailed into the late 1960s and early 1970s, when work done at the U.S. Bureau of Mines and more extensive work done in Great Britain, Germany, and Switzerland increased the pool of knowledge to the extent that the 1974 edition of NFPA 68, *Guide for Venting of Deflagration,* was issued. Bartknecht provides additional historical information on the development of deflagration venting.[1]

For related topics, see Section 2, Chapter 8, "Explosions"; Section 6, Chapter 15, "Explosives and Blasting Agents"; Section 17, Chapter 8, "Explosion Prevention and Protection"; and Section 18, Chapter 4, "Venting Practices."

FUNDAMENTALS OF DEFLAGRATIONS

The following conditions are necessary to initiate a deflagration:

- A fuel concentration between upper and lower combustible limits
- Sufficient oxidant (usually air) to support combustion
- An ignition source of sufficient energy to ignite the combustible mixture

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Once a deflagration has been initiated, the associated pressure needs to be characterized. The deflagration pressure in the enclosure generally follows the gas law equation, which can be expressed as follows:

$$P = \frac{n \times R \times T}{V} \quad (1)$$

where

R = Universal gas constant

P = Pressure

T = Absolute temperature

V = Volume

n = Number of moles of gases generated by the deflagration

The maximum deflagration pressure P_{max} and the maximum rate of pressure rise $(dP/dt)_{max}$ are determined by test. For most fuel, the maximum deflagration pressure is 6 to 10 times the absolute pressure at the time of the ignition.

The fundamental basis for deflagration venting theory is the so-called cubic law that can be stated as follows:

$$K = \left(\frac{dP}{dt}\right) \times V^{1/3} \quad (2)$$

The deflagration index K is computed from the maximum rate of pressure rise in a closed vessel multiplied by the cube root of the enclosure volume. It should be noted that the deflagration index is not a constant, although it has been referred to as such in some of the older literature. The deflagration index for gases is K_G; for dusts it is K_{St}. The maximum rate of pressure rise occurs at an optimum concentration. If the optimum concentration is either not reached or exceeded, the rates of pressure rise are less than the optimum. Further, the energy of the ignition source affects the rate of pressure rise. If the energy is less than standard test method requirements, then the rate of pressure rise will be lower.

Test methods are usually used by laboratories to measure these factors; the determination of optimum concentration requires a series of tests over a range of concentrations. The ignition energy used is high to ensure that the rate of pressure rise is at its maximum.

Table 18.6.1 provides values for the key factors, P_{max} and K_G, for some common flammable materials.

Three hazard classes have been defined for dusts based on the magnitude of the dust deflagration index, K_{St}. Table 18.6.2 displays three hazard classes for dust deflagrations

TABLE 18.6.1 Typical Flammability Parameters of Gases Measured in a 5 L Sphere (0.005 ft^3) with an Ignition Energy of 10 J

Flammable Material	P_{max} *(bar)*	K_G *(bar-m/sec)*
Acetophenone[a]	7.6	109
Acetylene	10.6	1415
Ammonia[b]	5.4	10
β-Napthol	4.4	56
Butane	8.0	92
Carbon disulfide	6.4	105
Diethyl ether	8.1	115
Dimethyl formamide[a]	8.4	78
Dimethyl sulfoxide[a]	7.3	112
Ethane[a]	7.8	106
Ethyl alcohol (ethanol)	7.0	78
Ethyl benzene[a]	7.4	96
Hydrogen	6.8	550
Hydrogen sulfide	7.4	45
Isopropanol[a]	7.8	83
Methane	7.1	55
Methanol[a]	7.5	75
Methylene chloride	5.0	5
Methyl nitrite	11.4	111
Neopentane	7.8	60
Octanol[a]	6.7	95
Octyl chloride[a]	8.0	116
Pentane[a]	7.8	104
Propane	7.9	100
South African crude oil	6.8–7.6	36–62
Toluene	7.8	94

Note: The method for developing K_G values has not been standardized. See NFPA 68 (2007) Paragraph E.2 and Bartknecht.[1]

[a]Measured at elevated temperatures and extrapolated to 25°C (77°F) at normal conditions.

[b]E = 100–200 J.

[c]200°C (392°F).

Source: Bartknecht.[1]

TABLE 18.6.2 Hazard Classes of Dust Deflagrations

Hazard Class	K_{St} *(bar-m/sec)**	P_{max} *(bar)**
St-1	≤200	10
St-2	201–300	10
St-3	>300	12

*K_{St} and P_{max} are determined in approximately spherical calibrated test vessels of at least 20 L capacity per ASTM E1226, *Standard Test Method for Pressure and Rate of Pressure Rise for Combustible Dusts.*

Source: NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* 2007 ed., Table B.1.

Fuel

Any mixture that is capable of reacting with an oxidizing medium (which in most cases is air) can be classified as a fuel. The fuel can exist in the gaseous, liquid, or solid state. Liquid fuels are dispersed in air as fine mists, solid fuels are dispersed in air as dusts, and hybrid mixtures can be mixtures of dusts and flammable or combustible gases (or mists) very similar to gaseous fuels.

The concentration of a gaseous fuel is usually expressed in volume percent (vol%) or mole percent (mol%) and concentrations of combustible dusts and mists are expressed as mass per unit volume, such as grams per cubic meter (g/m^3) or ounces per cubic foot (oz/ft^3).

Flammable Gas

The flammable gas must be present in air (the oxidizing media) between the lower and upper flammable limits (LFL and UFL).

LFL is the lowest concentration of material that will propagate a flame from an ignition source through a mixture of flammable gas or combustible dust dispersion with a gaseous oxidizer; LFL is also known as the minimum explosible concentration. UFL, on the other hand, is the highest concentration of material that will propagate a flame from an ignition source through a mixture of flammable gas or combustible dust dispersion with a gaseous oxidizer. Ignition can occur between the lower and upper flammable limits. The maximum deflagration pressure of a flammable gas in a particular oxidizing medium is determined by test and is generally on the fuel rich side of the stoichiometric mixture. The concentration at which the maximum rate of pressure rise $(dP/dt)_{max}$ and the maximum pressure P_{max} occur can differ slightly. These experimental values are used to calculate K_G values according to Equation 2.

Combustible Dust

Solid particulates smaller than 0.017 in. (420 μm) capable of passing through a U.S. No. 40 standard sieve are classified as dusts. The fineness of the dust is characterized by the particle size distribution. Generally speaking, the maximum rate of pressure rise increases with a decrease in dust particle size, along with the maximum pressure. The experimental K_{St} of a combustible dust sample is determined by the optimum rate of pressure rise at the optimum concentration multiplied by the cube root of the test enclosure volume as shown in Equation 2.

The minimum ignition energy of the dust cloud decreases as the particle size decreases. Experimental data shows this trend, though it is generally not extensively reported. Particle shape also has an effect on the combustion characteristics of dusts. Dust particles with an irregular shape, such as those that would be obtained from polymer dust generated in a hammer mill, have different combustion characteristics from a dust with a spherical shape, such as those that would be obtained from a similar polymer generated by a suspension polymerization process, even though the general particle size distribution of the two may be similar. The irregularly shaped dust particles of the hammer mill product show a higher rate of pressure rise. This is one of the reasons for testing sample dusts coming from a particular process and not trying to extrapolate dust test data from a completely unrelated process even though particle size distribution may appear to be similar.

The lower combustible limit of a dust-air mixture, also called the minimum explosible concentration (MEC), exists along with the upper limit, although upper combustible limit numbers are of no practical value for designing a viable explosion protection system. The upper combustible limit is usually not reported.

Burning Velocity and Flame Speed

The burning velocity is the rate of flame propagation relative to the unburned gas that is ahead of it. The fundamental burning velocity, S_u, is the burning velocity of a laminar flame under stated conditions of composition, temperature, and pressure of the unburned gas. Table 18.6.3 lists typical fundamental burning velocities of flammable gases in air.

Flame speed is the speed of a flame front relative to a fixed reference point. Its minimum value is equal to the fundamental burning velocity times the expansion factor equal to the ratio of the density of the unburned gas to the density of the burned gas. Flame speed is influenced by the degree of turbulence in the gas-air mixture, which can be induced by obstructions in the flame path, volume of the enclosure, ignition energy, temperature of the mixture, and so on, and cannot be determined by the properties of the flammable gas mixture alone.

Hybrid Mixtures

The addition of a flammable gas to a dust-air mixture is called a hybrid mixture. The presence of a flammable gas in a dust-air mixture reduces the LFL and the ignition energy required to initiate the deflagration. This effect can occur even though flammable gas is below its LFL (when considered alone as a flammable gas-air mixture) and the dust is below its LFL (MEC). The addition of the flammable gas to a combustible dust cloud will increase the effective K_{St} value, which means that the required vent area will have to be increased (Figure 18.6.1).

Introduction of an inert gas into the fuel-air mixture will reduce the rate of pressure rise and the maximum pressure attained. If it is desired to take these effects into account when designing the deflagration vents, the effects on the rate of

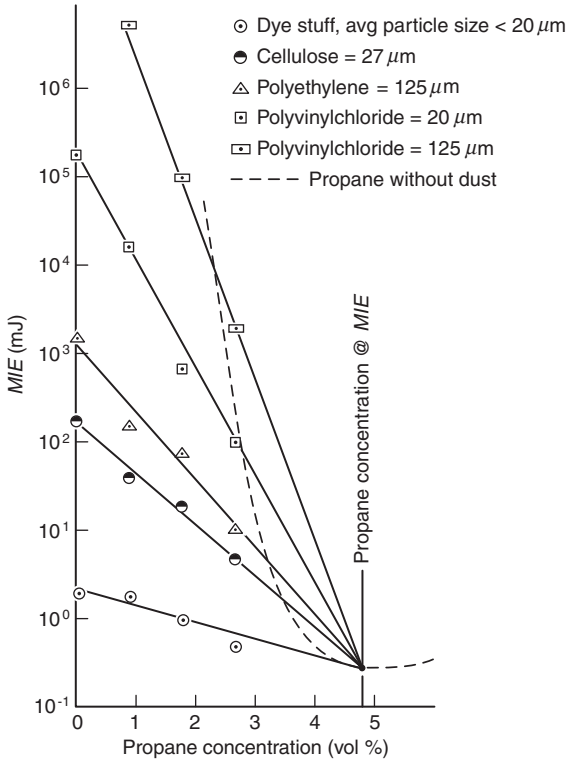

FIGURE 18.6.1 Lowest Minimum Ignition Energy (MIE) of Hybrid Mixtures Versus Propane Content

TABLE 18.6.3 Fundamental Burning Velocities of Selected Gases and Vapors

Gas	*Fundamental Burning Velocity (cm/sec)*	Gas	*Fundamental Burning Velocity (cm/sec)*	Gas	*Fundamental Burning Velocity (cm/sec)*
Acetone	54	Cyclohexane	46	Methyl alcohol	56
Acetylene	166	methyl-	44	1,2-Pentadiene	61
Acrolein	66	Cyclopentadiene	46	(ethylal lene)	
Acrylonitrile	50	Cyclopentane	44	*cis*-1,3-Pentadiene	55
Allene (propadiene)	87	methyl-	42	*trans*-1,3-Pentadiene	54
Benzene	48	Cyclopropane	56	(piperylene)	
,n-butyl-	37	*cis*-1,2-dimethyl-	55	2-methyl-(cos or trans)	46
,tert.obutyl-	39	*trans*-1,2-	55	1,4-Pentadiene	55
,1,2-dimethyl-	37	dimethyl-		2,3-Pentadiene	60
1,2,4-trimethyl-	39	ethyl-	56	*n*-Pentane,	46
1,2-Butadiene	68	methyl-	58	2,2-dimethyl-	41
(methylallene)		1,1,2-dimethyl-	52	2,3-dimethyl-	43
1,3-Butadiene	64	*trans*-Decalin	36	2,4-dimethyl-	42
2,3-dimethyl-	52	(decahydro-		2-methyl-	43
2-methyl-	55	naphthalene)		3-methyl-	43
n-Butane	45	*n*-Decane	43	2,2,4-trimethyl	41
2-cyclopropyl-	47	1-Decene	44	1-Pentene	50
2,2-dimethyl-	42	Diethyl ether	47	2-methyl-	47
2,3-dimethyl-	43	Dimethyl ether	54	4-methyl-	48
2-methyl-	43	Ethane	47	*cis*-2-Pentene	51
2,2,3-trimethyl-	42	Ethane (ethylene)	80	1-Pentene	63
Butanone	42	Ethyl acetate	38	4-methyl-	53
1-Butene	51	Ethylene oxide	108	2-Pentyne	61
2-cyclopropyl-	50	Ethylenimine	46	4-methyl-	54
2,3-dimethyl-	46	Gasoline	40	Propane	46
2-ethyl-	46	(100-octane)		2-cyclopropyl-	50
2-methyl-	46	*n*-Heptane	46	1-deutero-	40
3-methyl-	49	Hexadecane	44	1-deutero-2-methyl-	40
2,3-dimethyl-	44	1,5-Hexadiene	52	2-deutero-2-methyl	40
2-butene		*n*-Hexane	46	2,2-dimethyl-	39
2-Buten 1-yne	89	1-Hexene	50	2-methyl-	41
(vinylacetylene)		1-Hexyne	57	2-cyclopropyl	53
1-Butyne	68	3-Hexyne	53	2-methyl-	44
3,3-dimethyl-	56	Hydrogen	312	Propionaldehyde	58
2-Butyne	61	Isopropyl alcohol	41	Propylene oxide	82
Carbon disulfide	58	Isopropylamine	31	(1,2-epoxypropane)	
Carbon monoxide	46	Jet fuel, grade JP-1	40	1-Propyne	82
Cyclobutane	67	(average)		Spiropentane	71
ethyl-	53	Jet fuel, grade JP-4	41	Tetrahydropyran	48
isopropyl-	46	(average)		Tetralin (tetra-	39
methyl-	52	Methane	40	hydronaphthalene)	
methylene	61	diphenyl-	35	Toluene (methylbenzene)	41

pressure rise and the maximum pressure must be determined experimentally.

Introduction of an inert gas into a combustible dust-air cloud affects the rate of pressure rise (which will decrease) and the maximum pressure attained (which will decrease) after ignition of the cloud. When considering this technique for reducing the hazard of combustible dust, additional problems concerning the possibility of segregation of inert material from the combustible material must be considered. See Bartknecht,[1] Eckhoff,[2] and NFPA 68.

FUNDAMENTALS OF DEFLAGRATION VENTING AND ENCLOSURE DESIGN CONSIDERATIONS

Deflagration venting is intended to limit the amount of damage to a protected enclosure. It is not a preventative measure. It presupposes that a combustible mixture will occur in the enclosure and that it will ignite. Properly designed venting will limit the damage to a predetermined acceptable level. Some users will ac-

cept a permanently deformed enclosure, while others will only accept elastic deformation. Accepting permanent deformation means that while the enclosure will not rupture during the event, a rectangular box might well become somewhat spherical and unserviceable. The user must weigh the probability of the event against the potential for lost productivity.

A deflagration vent is an opening in an enclosure through which material expands and flows, thus relieving pressure. If no venting is provided, the maximum pressures developed during the deflagration are typically 6 to 10 times the initial absolute pressure. In most cases it may be impractical to construct an enclosure that can withstand or contain such pressures. The reduced pressure P_{red} is the maximum pressure developed in a vented enclosure during a vented deflagration.

The rate of pressure rise is the most important parameter that is used in the design of deflagration venting. A rapid rate of pressure rise means that only a short time is available for successful venting, whereas a slower rate of pressure rise allows the venting to proceed more slowly while remaining effective. It also follows that, all other factors being equal, the more rapid rate of pressure rise requires the greater area for effective venting.

The vents provided are intended to limit the buildup of pressure within the enclosure so that damage to the enclosure does not occur or is limited to acceptable levels. As the vent area increases, the reduced pressure for a given static activation pressure of the vent closure decreases. Open vents are more effective than covered vents. Lightweight closures are more responsive than heavy closures. Damage can result if a deflagration occurs in an enclosure that is too weak to withstand the pressure of a deflagration. An ordinary masonry wall of 8 in. (20 cm) brick or concrete block cannot withstand a pressure difference greater than 0.5 psi (0.035 bar).

Since the pressure development during deflagration is rapid, it could be experienced as a dynamic load by the enclosure (building) rather than a static load. Therefore, a suitable design safety factor is applied to P_{red} in the absence of detailed structural response analysis.

Common design standards allow P_{red} to be selected for up to two-thirds of the enclosure strength (see Taminini and Valiulis[3] and NFPA 68). NFPA 68 should be consulted for specific guidance for enclosure design pressure requirements when permanent deformation can or cannot be accepted.

Flames and pressure waves that emerge from an enclosure during the venting process must be taken into account to ensure that they do not ignite nearby combustible material or injure personnel who may be exposed to their effects.

Enclosure Length to Diameter

In NFPA 68, the combustion process in an enclosure involves the ignition of a combustible with an oxidant where the length/diameter (L/D) ratio is 2 or less. If the L/D ratio is greater than 2, modifications in the calculation, leading to an increase in the necessary vent area, must be taken into account for the venting design. The P_{red} developed within an enclosure decreases as the available vent area for the enclosure increases. If the enclosure is small and relatively symmetrical, then one large vent can be effective; however, for large enclosures, it is recommended that the vents be distributed over the surface area of the enclosure to the greatest extent possible.

The L/D of an elongated enclosure is determined based on the general shape of the enclosure, the location of the vent, the shape of any hopper extensions, and the furthest distance from the vent at which the deflagration could be initiated. The calculation involves the worst case flame path length to the farthest side of the vent and an effective diameter of the enclosure. The position of the vent along the enclosure can change the effective L/D. In this way a single vent located midway along the central axis of an elongated vessel would result in a smaller L/D than the same vent located at one end of the vessel. In no case can the effective L/D of an enclosure be less than 1, meaning that as the vents get closer together along the central axis, at some point the controlling flame path length would become, for instance, the diameter of the cylindrical enclosure. Detailed explanation of this approach can be found in NFPA 68.

Effect of Vent Duct Length

When a vent duct is added to the vent closure to direct the vented combustion gases to a safe outside area, this introduces a resistance to the relief of the vented gases from the enclosure and must therefore be taken into account. This basically means that the size of the vent area must be increased to accommodate this restriction. Different equations are used to determine the vent duct effect for gases as compared to dusts. In general, the solution for required vent area with a vent duct is trial and error and the calculations limit the length of the vent duct. This solution is iterative (trial and error). The following equations are to be used for this iterative calculation:

$$A_{vf} = A_{v4} \times (1 + 1.18 \times E_1^{0.8} \times E_2^{0.4}) \times \sqrt{\frac{K}{K_0}} \qquad (3)$$

where

A_{v4} = Vent area after adjustment for turbulence (m^2)

A_{vf} = Vent area required when duct is attached to the vent opening (m^2)

K_0 = 1.5, the resistance coefficient value assumed for the test configurations that generated the data used to validate the basic dust venting equations

$$E_1 = \frac{A_{vf} \times L_{\text{duct}}}{V} \qquad (4)$$

where

L_{duct} = Vent duct overall length (m)

$$E_2 = \frac{10^4 \times A_{vf}}{(1 + 1.54 \times P_{\text{stat}}^{4/3}) \times K_{St} \times V^{3/4}} \qquad (5)$$

where

P_{stat} = Nominal static opening pressure of the vent cover (bar)

V = Enclosure volume (m^3)

$$K \equiv \frac{\Delta P}{{}^1/_2 \times \rho \times U^2} = K_{\text{inlet}} + \frac{f_D \times L}{D_h} + K_{\text{elbows}} + K_{\text{outlet}} + \ldots \qquad (6)$$

where

K = Overall resistance coefficient of the vent duct application

K_{inlet}, K_{elbows}, K_{outlet} = Resistance coefficients for fittings

U = Fluid velocity (m/sec)

D_h = Vent duct hydraulic diameter (m)

f_D = D'Arcy friction factor for fully turbulent flow (see NFPA 68 Annex)

ρ = Fluid density × $1/G_c$

Note: In this chapter pressure is expressed as bar gauge (bar g) unless it is otherwise noted as bar absolute (bar a). It is recommended that NFPA 68 (2007) be consulted for details describing this calculation.

Enclosure Strength

The vent designed for an enclosure according to NFPA 68, whether for a high strength enclosure or a low strength enclosure, is intended to allow the deflagration pressure P_{red}, to attain two-thirds the strength of the enclosure without rupturing the enclosure. In all cases

$$P_{red} \le \frac{P_{es}}{\text{DLF}} \tag{7}$$

where

P_{red} = Maximum pressure developed during venting (bar [psi])

P_{es} = Enclosure strength evaluated bases on static pressure calculations for either deformation or burst (bar [psi])

DLF = X_m/X_s

X_m = Maximum dynamic deflection

X_s = Static deflection or, in other words, the displacement produced in the system when the peak load is applied statically

In the absence of detailed structural response analysis, a conservative value of DLF = 1.5 is used and design is based on the weakest structural element of the enclosure.

Two alternative conditions apply to the concept of enclosure strength, presuming that the enclosure is a ductile design, that is, designed to be somewhat elastic or deform without rupture under pressure:

- Permanent deformation, but not rupture, of the enclosure can be accepted.
- Permanent deformation of the enclosure cannot be accepted.

When the enclosure is a pressure vessel designed according to ASME or similar code, the allowable P_{red} is greater than the maximum allowable working pressure (MAWP) for the vessel. The ASME code specifically allows the NFPA 68 method for determining the allowable reduced pressure P_{red} during a deflagration.

If permanent deformation, but not rupture, of the enclosure can be accepted,

$$P_{red} \le \left(\frac{2}{3}\right) \times F_u \times P_{\text{MAWP}} \tag{8}$$

If permanent deformation of the enclosure cannot be accepted,

$$P_{red} \le \left(\frac{2}{3}\right) \times F_y \times P_{\text{MAWP}} \tag{9}$$

where

P_{red} = Maximum pressure developed in a vented enclosure (bar [psi])

F_u = Ratio of the ultimate stress of the enclosure to the allowable stress of the enclosure per ASME *Boiler and Pressure Vessel Code*[4]

P_{MAWP} = Enclosure design pressure [bar (psi)] according to ASME *Boiler and Pressure Vessel Code*

F_y = Ratio of the yield stress of the enclosure to the allowable stress of the materials of construction of the enclosure per ASME *Boiler and Pressure Vessel Code*

Note: The ASME *Boiler and Pressure Vessel Code* contains data on the ultimate and yield stresses for various materials of construction plus the allowable stress. The ratios can be calculated from this information. It is anticipated that ambient conditions will apply when applying Equations 8 and 9.

Venting of Gas or Mist Deflagrations in Low Strength Enclosures

A low strength enclosure is capable of withstanding a P_{red} of not more than 1.5 psi (0.1 bar g).[5,6]

$$A_v = \frac{C \times A_S}{P_{red}^{1/2}} \tag{10}$$

where

A_v = Vent area (m^2 or ft^2)

C = Venting parameter, in units consistent with P_{red}

A_S = Internal surface area of the enclosure (m^2 or ft^2)

P_{red} = Maximum pressure developed in a vented enclosure during a deflagration (bar [psi])

The venting parameter shall be defined by the following equations for fundamental burning velocity (less than 60 cm/sec):

For C ($bar^{1/2}$):

$$C = 1.57 \times 10^{-5} \times (S_u)^2 + 1.57 \times 10^{-4}(S_u) + 0.0109 \tag{11}$$

where S_u is fundamental burning velocity (less than 60 cm/sec).

For C ($psi^{1/2}$):

$$C = 6.1 \times 10^{-5} \times (S_u)^2 + 6.1 \times 10^{-4}(S_u) + 0.0416 \tag{12}$$

Figure 18.6.2 shows the venting parameter as a function of fundamental burning velocity.

In contrast to the earlier editions of NFPA 68, the available data on fundamental burning velocity can now be used to determine venting parameters for more individual fuels. This introduces the need to understand the potential range of fuels that could be present in the enclosure. The designer should consider the material with the highest fundamental burning velocity when designing the vent.

Venting Gas Deflagrations in High Strength Enclosures

The recommended equation for venting enclosures with an L/D of 2 or less is

$$A_v = \{[(0.127) \times \log_{10}(K_G) - (0.0567)] \times P_{red}^{-0.582}\} \times V^{2/3} + [(0.175) \times P_{red}^{-0.572}(P_{stat} - 0.1)] \times V^{2/3} \quad (13)$$

where

$K_G \leq 550$ bar-m/sec

$P_{red} = 2$ bar and at least 0.5 bar $> P_{stat}$

$P_{stat} \leq 0.5$ bar

$V \leq 1000$ m^3

For L/D values from 2 to 5 and for P_{red} no higher than 2 bar, the vent area A_V calculated from Equation 13 should be increased as follows:

$$\Delta A = \frac{A_v \times K_G \left(\frac{L}{D} - 2\right)^2}{750} \quad (14)$$

where D is the hydraulic diameter. For noncircular cross sections it is determined by $4(A/p)$, where A is the cross sectional area normal to the longitudinal axis of the space and p is the perimeter of the cross section.

In the case where the vent mass is greater than that calculated in Equation 15

$$M_T = \left(6.67 P_{red}^{0.2} \times n^{0.3} \times \frac{V}{K_G^{0.5}}\right)^{1.67} \quad (15)$$

where

n = Number of panels

M_T = Threshold mass (kg/m^2)

P_{red} = Vented pressure (bar)

K_G = Gas deflagration index (bar-m/sec)

$V > 1$ m^3

If the vent mass is within the above constraints and greater than M_T calculated, then Equation 16 is used to determine the incremental vent area to maintain the desired P_{red}.

$$\Delta A_i = A_v \times (0.0075) \times M^{0.6} \times \frac{K_G^{0.5}}{n^{0.3}} \times V \times P_{red}^{0.2} \quad (16)$$

where

M = Mass of vent panel (kg/m^2) ≤ 40 kg/m^2

A_v = Vent area calculated by Equation 12

$V > 1$ m^3

If K_G is less than 75 bar-m/sec, use $K_G = 75$ in the equation.

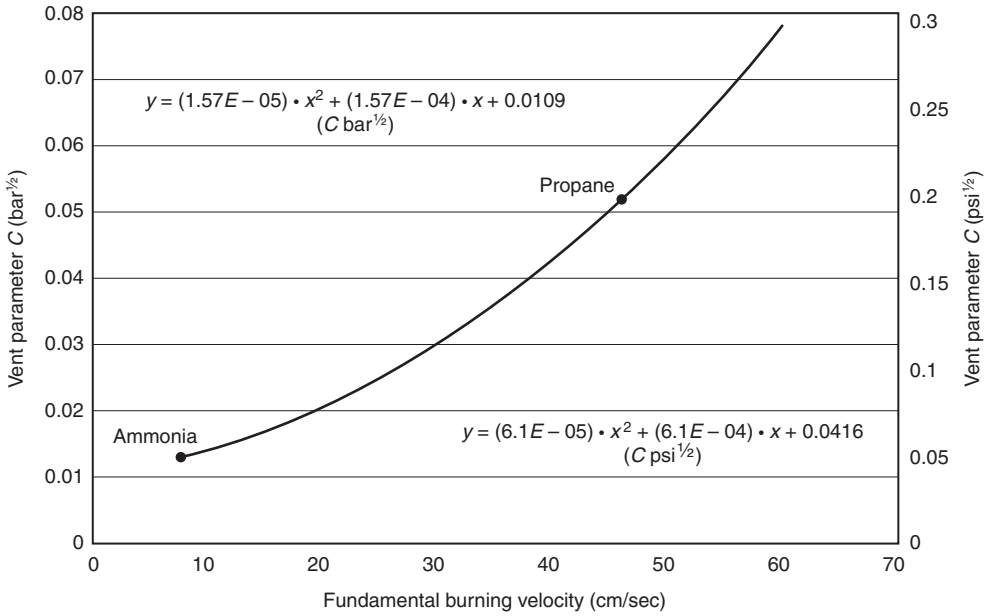

FIGURE 18.6.2 Venting Parameter as a Function of Fundamental Burning Velocity (Source: NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* 2007 ed., Figure 7.2.2.2)

When dealing with enclosures that require ducts to carry the forces of the deflagration and the fireball to a safe location, several problems introduced by using ducts have to be considered. For example, the introduction of ducts results in an increase of pressure inside the enclosure being vented. Consequently, the forces of reaction on the enclosure being vented (dust collector, silo, etc.) must be taken into account, along with considering where the fireball that will be emitted from the ductwork will be vented.

In a situation in which a vent duct is installed after the vent closure to direct the discharge of the gases to an outside safe location, a pressure drop occurs that must be taken into account. The way to do this is to increase the area of the vent. The ductwork leading to the discharge point must be as short and straight as possible. This is the intent of NFPA 68.

NFPA 68 also intends to keep the mass of the vent closure as low as possible. Where vent panels with insulation are needed to prevent heat loss, this need requires a higher vent mass and can affect the achieved P_{red}. It is the intention of NFPA 68 to encourage keeping the relieving panels as light as possible and keeping the relieving ductwork as short and direct to a safe location as possible.

Venting of Deflagrations of Dusts and Hybrid Mixtures

Equation 17 is intended to apply to the design of vents for dust deflagration and hybrid mixtures for high-strength—greater than 1.5 psi (0.1 bar)—enclosures. The recommended design equations for the dust deflagration and the hybrid mixture deflagration for high-strength enclosures are given next. The *L/D* ratio of the design equation is limited to 2 or less. With the initial pressure before the ignition being 1 bar (absolute ±0.2 bar)

$$A_{vo} = 1 \times 10^{-4} \times (1 + 1.54 \times P_{stat}^{4/3}) \times K_{St} \times V^{3/4} \left(\frac{P_{max}}{P_{red}} - 1 \right)^{0.5} \quad (17)$$

where

A_{vo} = Vent area calculated from Equation 17 (m^2)

P_{stat} = Nominal static burst pressure of the vent (bar)

K_{St} = Deflagration index (bar-m/sec)

V = Enclosure volume (m^3)

P_{red} = Reduced pressure after vent operation (bar)

P_{max} = Maximum deflagration pressure (bar)

The following limitations must also apply to Equation 17:

- 5 bar ≤ P_{max} ≤ 12 bar
- 10 bar-m/sec ≤ K_{St} ≤ 800 bar-m/sec
- 0.1 m^3 ≤ V ≤ 10,000 m^3
- P_{stat} ≤ 0.75 bar

In cases where *L/D* is greater than 2 but less than or equal to 6, the calculated A_{v1} is determined by Equation 18:

$$A_{v1} = A_{vo} \left[1 + 0.6 \times \left(\frac{L}{D} - 2 \right)^{0.75} \times \exp(-0.95 \times P_{red}^2) \right] \quad (18)$$

For the case where we have a top-fed bin, hopper, and silo the *L/D* can be increased to 8.

Effects of Initially Elevated Pressure

In the case where we have a combustible dust cloud in an enclosure that is pressurized at greater than 0.2 bar, deflagration vents can only be used when the following conditions are met:

- Vent duct length *L/D* is to be ≤ 1
- $M \le M_T$ (threshold mass, kg/m^2) and $M < 40$ kg/m^2
- V_{axial} and $v_{tan} < 20$ m/sec
- No allowance for partial volume
- 0.2 bar < $P_{initial}$ < 4.0 bar
- Use Equation 19 to calculate the needed vent area

$$A_{vep} = \frac{A_{v1}}{A_{vo}} \cdot 10^{-4} \cdot \left[1 + 1.54 \cdot \left(\frac{P_{stat} - P_{initial}}{1 + P_{effective}} \right)^{4/3} \right] \cdot K_{St} \cdot V^{3/4} \cdot \sqrt{\frac{1}{\pi_{effective}} - 1}^{0.5} \quad (19)$$

where

A_{vep} = Vent area (m^2)

P_{stat} = Static burst pressure of the vent (bar)

$P_{initial}$ = Enclosure pressure at the moment of ignition (bar)

$P_{effective}$ = ⅓$P_{initial}$ (bar)

K_{St} = Deflagration index (determined at atmospheric pressure) (bar-m/sec)

V = Enclosure volume (m^3)

$\pi_{effective}$ = $(P_{red} - P_{effective}) / (P^E_{max} - P_{effective})$

P_{red} = Reduced pressure (bar)

P^E_{max} = Maximum pressure of the unvented deflagration at initially elevated pressure (bar) [$(P_{max} + 1)$ $(P_{initial} + 1)/(1$ bar-abs $- 1)$]

P_{max} = Maximum pressure of the unvented deflagration initially at atmospheric pressure (bar)

Discharge of Fireballs from Explosion Vents

When flammable gas, combustible dust, or a hybrid mixture is ignited in a vented enclosure, consideration must be given to the discharge of the resultant fireball and its effects. See NFPA 68 for similar treatment of fireball effects for gases. In the case of dust deflagration or hybrid mixture, the distance which this expected fireball will travel is estimated from the following equation:

$$D = K \left(\frac{V}{n} \right)^{1/3} \quad (20)$$

where

D = Axial distance (front) from the vent (ft or m)

K = Flame length factor ($K = 10$ for metal dusts; $K = 8$ for chemical and agricultural dusts)

V = Volume of vented enclosure (m^3 or ft^3)

n = Number of evenly distributed vents

The axial distance calculated by Equation 20 shall be limited to 200 ft (60 m).

In the case of a vented gas or vapor deflagration the equation is

$$D = 3.1\left(\frac{V}{n}\right)^{0.402} \quad (21)$$

where

D = Axial distance (front centerline) from vent (m)

V = Volume of the vented enclosure (m^3)

n = Number of evenly distributed vents

The hazard zone measured radially (to the sides, measured from the centerline of the vent) shall be calculated as one-half D.

In the case where it is necessary to vent an enclosure containing a combustible dust or a hybrid mixture internally into a building through a flame-arresting and particulate retention device, the resulting pressure increase in an unvented building is estimated to be

$$\Delta P = 1.47 \times P_o \times \left(\frac{V_1}{V_o}\right) \quad (22)$$

where

V_o = Free volume of the building

V_1 = Volume of the protected equipment

P_o = Ambient pressure (14.7 psia or 1.013 bar absolute)

ΔP = Pressure rise in the building (in same units as P_o)

External Pressure Effects

When a deflagration is vented from an enclosure, pressure effects are created in the atmosphere external to the enclosure. These effects are due to the vented products and in the case of a dust explosion are the further effects of the combustion of the unburned dusts and the gases external to the enclosure. NFPA 68 allows the designer to calculate the maximum external pressure that will be seen when an explosion vent opens, where those pressure effects will be seen as a function of the distance from the vent opening, and the distance that the fireball travels from that vent opening.

NFPA 68 allows a designer to calculate the maximum external pressure effects as follows:

$$P_{\max,a} = 0.2 \times P_{red} \times A_v^{0.1} \times V^{0.18} \quad (23)$$

where

$P_{\max,a}$ = External pressure

A_v = Vent area (m^2)

V = Volume of the vented enclosure (m^3)

Once this is known, the designer can estimate the pressure at any point from the vent knowing the distance that the fireball will travel from the vent. The pressure at any point from the vent can be estimated from the following equation:

$$P_{\max,r} = P_{\max,a} \times \left(\frac{0.20D}{r}\right) \quad (24)$$

where

D = Axial distance traveled by the fire ball from the vent (m) (Equation 20)

$P_{\max,r}$ = Maximum external pressure

r = Distance from vent ≥ 0.2D (m)

SUMMARY

Explosion venting is a damage limiting protection technique. It is intended to protect an enclosure against damaging pressures generated by a deflagration within the enclosure by safely venting these pressures to a safe location. The chapter discusses the design techniques used to accomplish this objective.

Deflagration is the propagation of combustion zone from the ignition point at less than the speed of sound in the unreacted medium. Three conditions are necessary to initiate a deflagration: a fuel concentration between the upper and lower combustible limits, sufficient oxidant (usually air) to support combustion, and an ignition source of sufficient energy to ignite the combustible mixture (e.g. flammable gases, combustible dusts, or hybrid mixtures). An explosion (deflagration) vent is an opening in an enclosure through which material expands and flows, thus relieving pressure.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on deflagration (explosion) venting discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 68, *Standard on Explosion Protection by Deflagration Venting*
NFPA 69, *Standard on Explosion Prevention Systems*

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SECTION 19

Structural Fire Protection

Milosh T. Puchovsky

19.1 Types of Building Construction
19.2 Structural Integrity During Fire
19.3 Structural Fire Safety in One- and Two-Family Dwellings
19.4 Analyzing Structural Fire Damage
19.5 Approaches to Calculating Structural Fire Resistance

Fire can present a significant challenge to the structural integrity of buildings. Section 19 of the *Fire Protection Handbook*® provides information on protecting structural elements from fire. A new chapter in the section describes techniques for calculating structural fire resistance.

Chapter 1, "Types of Building Construction," identifies the basic types of building construction in terms of their anticipated performance during a fire. It also addresses fire protection of building elements; the value of exterior walls, interior walls, and partitions; floor framing systems; trusses; floor/ceiling assemblies; and roof framing and coverings.

The first part of Chapter 2, "Structural Integrity During Fire," describes common fire resistance test procedures. The chapter also introduces methods of calculating fire endurance (resistance) ratings, the behavior of building materials at elevated temperatures, and design approaches for structural integrity in a fire.

Chapter 3, "Structural Fire Safety in One- and Two-Family Dwellings," addresses the structural elements of one- and two-family dwellings and manufactured homes as they affect fire safety.

Chapter 4, "Analyzing Structural Fire Damage," reviews building types and structural systems before providing guidance on evaluating fire-damaged structures and specific materials. The chapter also considers fire during construction.

The section concludes with a new chapter: Chapter 5, "Approaches to Calculating Structural Fire Resistance." The chapter provides an overview of structural fire resistance calculation techniques and includes information on alternative approaches to fire resistance and selecting a design fire for structural analysis.

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Chapter 1

Types of Building Construction

Revised by
Peter J. Gore Willse

Chapter Contents

Construction Classifications
Classification of Building Construction Types
Fire Protection of Building Elements
Walls
Exterior Walls
Interior Walls and Partitions
Floor Framing Systems
Trusses
Floor/Ceiling Assemblies
Roof Framing
Roof Coverings
Roof Deck Insulations and Vapor Barriers

Key Terms

building construction (types of), combustible construction, construction (Type I), construction (Type II), construction (Type III), construction (Type IV), construction (Type V), fire-resistive construction, floor framing system, heavy timber construction, noncombustible construction, ordinary construction, roof, structural element, truss, wood frame construction

A well-established means of codifying the performance of a building's structural elements during a fire is to classify them by types of construction, based on the materials used for the structural elements and the degree of fire resistance afforded by each element.

In early codes, only two classifications of construction were identified: fireproof and nonfireproof. The term *fireproof* was replaced by the term *fire resistive,* because it was recognized that no material or building is totally fireproof and that the building contents can produce a significant fire without involving the structure. It is possible, however, to design buildings that will resist a fire without suffering serious structural damage. Appropriate fire-resistive design, balanced against anticipated fire severity, is the objective of structural fire protection requirements in modern codes.

Several distinct types of construction that use combustible framing were originally classified based on the materials—masonry or wood—used in the exterior wall construction and the type and size of the framing members (i.e., heavy timber versus conventional framing). As fire resistance ratings for construction assemblies were recognized in building codes, subclassifications of building types were added for both noncombustible and combustible types of construction, based on the degree of fire resistance provided.

Code regulations governing the size, area, and height of buildings and their allowable uses are usually predicated on the relative fire load and other factors represented by the occupancy and the construction materials used in the building.

This chapter identifies the basic types of building construction in terms of their anticipated performance during a fire. These construction types are recognized in NFPA 220, *Standard on Types of Building Construction,* and in the model building codes. It also recognizes the current classification system of building construction equated with the traditional descriptive terms used to identify building types (e.g., *fire resistive, noncombustible, ordinary, frame,* etc.) that no longer are prime references to construction types. It also addresses fire protection of building elements; the value of exterior walls, interior walls, and partitions; floor framing systems; trusses; floor/ceiling assemblies; and roof framing and coverings.

For related topics, see the following: Section 1, Chapter 2, "Fundamentals of Structurally Safe Building Design"; Section 12, Chapter 1, "Planning for Public Fire-Rescue Protection"; Section 18, Chapter 1, "Confinement of Fire in Buildings"; Section 19, Chapter 2, "Structural Integrity During Fire"; and Section 19, Chapter 4, "Analyzing Structural Fire Damage."

CONSTRUCTION CLASSIFICATIONS

U.S. Classifications

The construction types currently identified by NFPA and the International Code Council (ICC) fall into ten subtypes in the NFPA system and nine subtypes in the ICC system. Subtypes are derived from

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five fundamental construction types, in almost every case: (1) fire resistive, (2) noncombustible, (3) ordinary (exterior protected), (4) heavy timber, and (5) wood frame. The previously published Standard Building Code (SBC) used six construction types. These descriptive names, while still referenced, no longer define the construction types as precisely as needed. The names are helpful, however, in tracing the development of building types.

ICC was formed by Building Officials and Code Administrators (BOCA), International Congress of Building Officials (ICBO), and Southern Building Code Congress International (SBCCI). The 2000 ICC International Building Code (IBC) was meant to succeed the building codes of these organizations. However, earlier editions of their building codes are still being adopted in some places—for example, California. Drawing on its experience with addressing structural fire protection, NFPA has also developed a building code as documented in NFPA 220 and NFPA *101®*, *Life Safety Code®*.

Classification Notation

To achieve better uniformity of building construction classifications, the Model Codes Standardization Council (MCSC) established a committee in 1972 to study the classifications and fire resistance requirements for the types of construction used in the model building codes and to develop recommendations for the model building code organizations.

As a result of the MCSC comparative study, its successor, the Board for the Coordination of the Model Codes (BCMC) proposed that the basic types of construction now recognized in the codes be continued but that they be reordered to some degree and be divided into two groups: (1) noncombustible and (2) combustible. It was also proposed that the identifying names for types of construction, such as *fireproof, ordinary, heavy timber,* and so on, be dropped because current design methods and architecture no longer follow the concepts in use when the named building types were established. The classifications proposed are shown in Table 19.1.1. These are the classifications recognized in NFPA 220 and *NFPA 5000®*, *Building Construction and Safety Code®*.

The MCSC also concluded that to rationally compare the various types of construction, a notational system was needed to identify the fire resistance required for three basic elements of the building. These elements are: (1) the exterior wall, (2) the primary structural frame, and (3) the floor construction. A three-digit notation was developed, as follows:

1. *First digit*. Hourly fire resistance requirement for exterior-bearing wall fronting on a street or lot line
2. *Second digit*. Hourly fire resistance requirement for structural frame or columns and girders supporting loads from more than one floor
3. *Third digit*. Hourly fire resistance requirement for floor construction

A comparison of types of construction, based on the MCSC notational system, as found in five building codes, is shown in Table 19.1.2.

For heavy timber construction, the notation *H* and not a digit was used for the structural frame and floor construction designations. Heavy timber construction is unique because it is identified by detailed requirements relating mainly to the size of structural members and their connections. Properties such as combustibility or fire resistance are not specifically included in the requirements for heavy timber construction, except that exterior walls are required to be of noncombustible construction.

Thus, for example, a "332" building would have 3 hour fire-resistant exterior bearing walls, a 3 hour fire-resistant structural frame, and 2 hour fire-resistant floor construction, and would correspond to the *NFPA 5000* Type I (332) building, the BOCA National Building Code Type 1B building, the ICBO Uniform Building Code Type I FR (fire resistive) building, the SBCCI Standard Building Code Type II building, and the ICC International Building Code Type 1A.

A standard nomenclature was also developed for identifying and defining the structural elements in buildings as they relate to fire resistance. For example, it was found in reviewing various codes and fire protection standards that floor construction was referred to by such terms as "floors," "floor assemblies," "floor and ceiling assemblies," and "floor deck construction." If codes agree, for example, that "floor construction" includes the floor deck and all structural elements directly supporting the loads from the floor, as recommended by MCSC, then some misinterpretation of a code's intent would be avoided.

TABLE 19.1.1 Model Codes Standardization Council Recommended Types of Construction

Noncombustible		
Type I (443) Type I (332)	Type II (222) Type II (111) Type II (000)	
Combustible		
Type III (211) Type III (200)	Type IV (2HH)	Type V (111) Type V (000)

TABLE 19.1.2 Comparison of Construction Types (Based on the MCSC National System)

NFPA 220	I (443)	I (332)	II (222)	II (111)	II (000)	III (211)	III (200)	IV (2HH)	V (111)	V (000)
UBC	—	I FR	II FR	II 1-hr	II N	III 1-hr	III N	IV HT	V 1-hr	V-N
BNBC	1A	1B	2A	2B	2C	3A	3B	4	5A	5B
SBC	I	II	—	IV 1-hr	IV unp	V 1-hr	V unp	III	VI 1-hr	VI unp
IBC	—	1A	1B	IIA	IIB	IIIA	IIIB	IVHT	VA	VB

International Perspective

With regard to building construction in Australia, Belgium, Canada, Denmark, Finland, France, Germany, Great Britain, Italy, Japan, Netherlands, New Zealand, Norway, Russia, Sweden, Switzerland, and the United States, time temperature curves used to conduct fire resistance tests for building materials are virtually identical for the first 2 hours. After that period of time, most countries use a slightly similar curve, except for Japan, which uses a less severe exposure after 2 hours. Some countries limit heat transmission as a requirement for fire doors. In most cases this is not a requirement in the United States, and when it is a requirement, it is for only the first 30 minutes of the test. Two other building construction-related differences are that fire departments tend to be more aggressive in the United States than they are in most European countries and that there are many more unsprinklered properties outside the United States than there are within the United States.

Construction type classification in building codes is more of a convenience than a necessity. The National Building Code of Canada (NBCC) does not classify buildings in the traditional manner as do United States codes but rather specifies fire-resistive requirements for the structural components of a building, depending on its occupancy and its story height and floor area. In this code, two basic types of construction (i.e., combustible and noncombustible) are recognized. These are further subdivided by the characteristics of the materials used in construction under fire conditions.

CLASSIFICATION OF BUILDING CONSTRUCTION TYPES

Following the completion of the MCSC recommendations in 1974, a number of changes were adopted to the requirements for types of construction to agree with the MCSC classifications. However, it was recognized that some conflicts still remained among building codes. In 1975, the BCMC established a committee to develop more detailed recommendations for types of construction.

In 1980 the committee's recommended definitions of types of construction and fire resistance requirements were finalized. The requirements are based on five basic types of construction. Two are identified as noncombustible construction (Types I and II) and three as combustible construction types (Types III, IV, and V). Table 19.1.3 gives the fire resistance requirements for the structural frame, interior bearing walls, floor construction, and roof construction of the five basic types of construction. The table lists the building components that are essential to the stability of the building as a whole and comprise the "structural frame." The members of floor or roof panels that have no connection to the columns are considered part of the floor or roof construction and are not classified as a part of the structural frame.

Some of the terminology used to describe and classify building construction types is presented as follows:

- *Fire resistance rating.* The time, in minutes or hours, that materials or assemblies have withstood a fire exposure as determined by tests, or methods based on tests, as prescribed by the applicable building code. Applicable test methods include NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials,* ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials,* or UL 263, *Standard for Fire Tests of Building Construction and Materials.* Where other methods such as calculation procedures are used to determine fire resistance, the calculations are to be based on the fire exposure and acceptance criteria specified in standardized test procedures such as NFPA 251. Standardized calculation methods include ASCE/SFPE 29, *Standard Calculation Methods for Structural Fire Protection,* and ACI 216.1/TMS 0216.2, *Standard Method for Determining Fire Resistance of Concrete and Masonry Assemblies.* The referenced test methods and associated calculation methodologies are useful in comparing the fire resistance of building materials but are not necessarily indicative of how the building materials might perform in an actual building fire. See Section 19, Chapter 2, "Structural Integrity During Fire," for more information on how the fire performance of building materials is determined.
- *Noncombustible material.* A material that, in the form in which it is used and under the conditions anticipated, will not ignite, burn, support combustion, or release flammable vapors when subjected to fire or heat. Materials that are reported as passing ASTM E136, *Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750 Degrees C,* shall be considered noncombustible materials.
- *Limited-combustible material.* Refers to a building construction material not complying with the definition of noncombustible material that, in the form in which it is used, has a potential heat value not exceeding 3500 Btu/lb (8141 kJ/kg) where tested in accordance with NFPA 259, *Standard Test Method for Potential Heat of Building Materials,* and includes either of the following: (1) materials having a structural base of noncombustible materials, with a surfacing not exceeding a thickness of 1/8 in. (3.2 mm) that has a flame spread index not greater than 50; and (2) materials, in the form and thickness used, having neither a flame spread index greater than 25 nor evidence of continued progressive combustion, and of such composition that surfaces that would be exposed by cutting through the material on any plane would have neither a flame spread index greater than 25 nor evidence of continued progressive combustion, when tested in accordance with NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials.* Materials subject to increases in combustibility or to a flame-spread index beyond the limits herein established through the effects of age, moisture, or other atmospheric conditions are considered combustible.
- *Combustible material.* A material that, in the form in which it is used and under the condition anticipated, will ignite and burn. It is further described as a material that does not meet the definition of noncombustible material or limited-combustible material.

Type I Construction

Type I construction (formerly referred to as fire resistive) is construction in which the structural members are noncombustible

TABLE 19.1.3 Fire Resistance Ratings for Type I Through Type V Construction (hr)

	Type I		Type II			Type III		Type IV	Type V	
	442	*332*	*222*	*111*	*000*	*211*	*200*	*2HH*	*111*	*000*
Exterior Bearing Walls										
Supporting more than one floor or columns or other bearing walls	4	3	2	1	0	2	2	2	1	0
Supporting one floor only	4	3	2	1	0	2	2	2	1	0
Supporting a roof only	4	3	1	1	0	2	2	2	1	0
Interior Bearing Walls										
Supporting more than one floor or columns or other bearing walls	4	3	2	1	0	1	0	2	1	0
Supporting one floor only	3	2	2	1	0	1	0	1	1	0
Supporting roofs only	3	2	1	1	0	1	0	1	1	0
Columns										
Supporting more than one floor or columns or other bearing walls	4	3	2	1	0	1	0	H	1	0
Supporting one floor only	3	2	2	1	0	1	0	H	1	0
Supporting roofs only	3	2	1	1	0	1	0	H	1	0
Beams, Girders, Trusses, and Arches										
Supporting more than one floor or columns or other bearing walls	4	3	2	1	0	1	0	H	1	0
Supporting one floor only	2	2	2	1	0	1	0	H	1	0
Supporting roofs only	2	2	1	1	0	1	0	H	1	0
Floor-Ceiling Assemblies	2	2	2	1	0	1	0	H	1	0
Roof-Ceiling Assemblies	2	1½	1	1	0	1	0	H	1	0
Interior Nonbearing Walls	0	0	0	0	0	0	0	0	0	0
Exterior Nonbearing Walls	0	0	0	0	0	0	0	0	0	0

Note: See applicable building requirements for more information.
H = Heavy timber members.
Source: *NFPA 5000®*, *Building Construction and Safety Code®*, Table 7.2.11, 2006, p. 5000-89.

and have a fire resistance as specified in Table 19.1.3. This classification is divided into two subtypes, Type I (442) and Type I (332). Reductions in the hourly rating might be permitted by the applicable building code. The basic difference between the subtypes is in the level of fire resistance specified for the structural frame. The fire resistance requirements for Type I (442 and 332) construction were selected because they provide reasonable fire safety for the structure for occupancies with moderate- and low-combustible contents. In occupancies with higher fire loads and hazardous uses, fire resistance may be supplemented by additional protection, usually including an automatic fire-extinguishing system. Even in occupancies with moderate fire loads, such as in mercantile and in some factory industrial and storage uses, supplementary fire safety precautions are usually required. These include restrictions on the building size or requirements for automatic fire-extinguishing equipment.

In Type I construction, only noncombustible or limited-combustible materials are permitted for the structural elements of the building. This regulation is well accepted and appears in practically every modern building code. Obviously, if combustible structural materials were allowed in noncombustible building types, the whole concept of their allowable use (height and area) would become meaningless. However, for practical reasons, the use of some combustible materials in Type I and Type II buildings are permitted for other than structural components. Roof coverings, some types of insulating materials, and limited amounts of interior finish and flooring do not add significantly to the fire hazard or fire load if these materials are properly regulated and qualified by fire tests.

Some codes have attempted to regulate combustible materials by using two or three alternatives that allow for the acceptance of materials having relatively low fuel content and surface burning characteristics. The purpose of this definition was to recognize certain materials or nonhomogenous assemblies containing limited amounts of combustible materials, such as gypsum wallboard which, although covered with paper, is used as a fire-resistive material. These alternate definitions include limits on surface flame spread rating (per NFPA 255) and on the heat content (per NFPA 259)—the latter being 3500 Btu per lb (8050

J/kg) for limited-combustible material, somewhat less than half that of untreated wood.

Rather than complicate the definition for the accommodation of certain materials, a more fundamental approach is to define limited uses and combustibility characteristics of materials that may be acceptable in buildings of Type I construction. This approach was followed in the NBCC and by the BCMC committee in its recommendations for the allowable kinds and extent of use of combustible material in the construction of Type I and II buildings.

Type II Construction

Type II construction (formerly referred to as noncombustible construction) is a construction type in which the structural elements are entirely of noncombustible or limited-combustible materials. Type II construction can be further classified as protected—Type II (222) or Type I (111)—in which the structural members have some degree of fire resistance, either 2 hour or 1 hour, or unprotected—Type II (000)—in which the structural members have no fire resistance rating. An example of protected construction is structural steel with spray-on fire proofing applied. Applicable building codes typically include additional provisions for exterior structural bearing walls of Type II construction.

The fire resistance required in Type II (222 or 111) construction will afford adequate fire safety for residential, educational, institutional, business, and assembly occupancies, without supplementary restrictions. Height limits, however, are commonly prescribed for this type of construction. When used for other occupancies involving a greater fire loading, additional fire safety precautions are usually required, such as more stringent area limitations and automatic fire-extinguishing equipment. In occupancies with a low fire load attributed to contents, the absence of fuel in noncombustible construction not only helps prevent the spread of fire but also reduces potential risk of a fire starting within the structure itself.

The limitation on combustible material is valuable because it acts to prevent fire from spreading through concealed spaces or involving the structure itself. Because of this attribute, a fire in a building of Type I and Type II construction can be controlled more readily (Figure 19.1.1). Requirements for exterior walls of Type II construction are specified by the applicable building code or standard that is used by the authority having jurisdiction (AHJ).

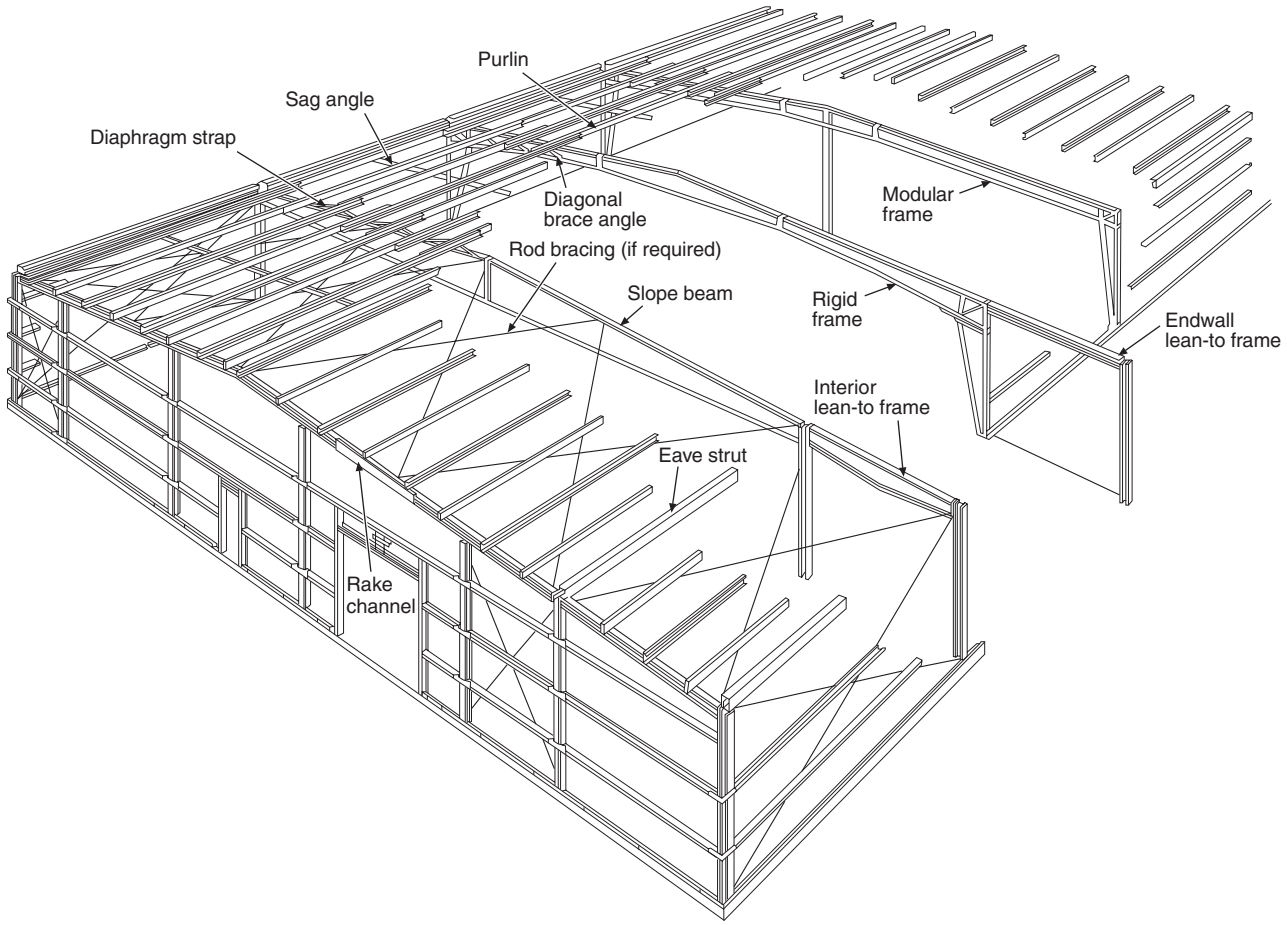


FIGURE 19.1.1 Framing System Representative of Type II (Noncombustible, Unprotected) Construction, Showing Preengineered Pitched Roof and Lean-To Framing with Structural Elements of Unprotected Steel

Type III Construction

Type III construction (formerly referred to as exterior protected or ordinary construction) is a construction type in which all or part of the interior structural elements may be of noncombustible, limited-combustible, or approved combustible materials as permitted by the applicable building code. The exterior walls are required to be of noncombustible or limited-noncombustible materials possessing a fire resistance rating in accordance with the applicable building code. Type III construction is further divided into protected and unprotected subtypes. Protected construction, Type III (211), has a 1 hour fire resistance for the floors and structural elements. Type III (200) construction has no fire resistance for the floors or structural elements. Whether or not fire resistance is provided, it is essential that all concealed spaces be properly fire blocked in buildings of combustible construction. This must be done with care in all furred spaces, partitions, ceiling spaces, and attics. Codes are very specific as to the materials used for fire blocking and the locations where it is required. To be effective, fire blocking must completely close off and subdivide the combustible construction into limited areas, thereby restricting the spread of fire and hot gases and allowing additional time for detection and evacuation of the building or area involved.

The 1 hour fire resistance provided in Type III (211) construction offers a measure of safety for fire fighting and evacuation before the construction itself becomes involved. However, combustible parts of any fire-rated assembly are likely to be burning actively before the end of the rated time period. For this reason, that portion of the fire load represented by combustible structural elements must be considered as part of the total potential fire load, whether or not the construction is protected.

Type IV Construction

Type IV construction (formerly referred to as heavy timber) is a construction type in which structural members—that is, columns, beams, arches, floors, and roofs—are basically of unprotected wood (solid or laminated) with large cross-sectional areas, with minor exceptions. No concealed spaces are permitted in the floors and roofs or other structural members. NFPA 220 and most model building codes are specific in the minimum dimensions permitted for the various wood structural members and minimum fire-resistive ratings required for interior columns, arches, beams, girders, and trusses of materials other than wood that may be permitted as acceptable alternatives to wood members (Table 19.1.4).

Walls, both interior and exterior, including structural members framed into them, can be of noncombustible or limited-combustible materials acceptable to the code being applied. Brick and stone were the traditional materials used in early heavy timber, or "mill," construction.

During a fire, heavy timber construction resists failure longer than a conventional wood frame structure because the structural members are larger, have a smaller surface to mass ratio, and take longer to burn. As the wood member burns, a layer of char develops, which acts like insulation and slows down the rate of burning. The large wood members, therefore, can continue to carry their structural loads due to the mass of unburned wood.

TABLE 19.1.4 Recommended Nominal Dimensional Requirements for BCMC Type IV (2HH) Construction

	Supporting Floors	*Supporting Roofs*
Columns	8 in. × 8 in.	6 in. × 8 in.
Beams and girders	6 in. × 10 in.	4 in. × 6 in.
Arches	8 in. × 8 in.	6 in. × 8 in., 6 in. × 6 in., 4 in. × 6 in.
Trusses	8 in. × 8 in.	4 in. × 6 in.
Floors	3 in. T & G or 4 in. on edge w/1-in. flooring	
Roofs		2 in. T & G or 3 in. on edge or 1⅛ in. plywood

Note: T & G = tongue and groove.
For SI units: 1 in. = 25.4 mm.

Heavy timber construction is more properly considered a building system, not just a construction type using large-size framing members. It was developed during the mid-1800s by insurance interests for the purpose of reducing fire losses in the many textile factories, paper mills, and storage buildings in the New England states. Through the intelligent use of combustible materials of sufficient mass, the absence of concealed spaces, and by paying attention to details to avoid sharp corners and ignitable projections, the chance of rapid spread of fire is lessened and the probability of serious structural damage is reduced. Examples of heavy timber construction are shown in Figures 19.1.2 and 19.1.3.

Type V Construction

Type V construction (formerly referred to as wood frame) is a type of construction in which the structural members are entirely of wood or any other material permitted by the code being applied (Figure 19.1.4). Depending on the exterior horizontal separation to adjacent buildings, the exterior walls may or may not be required to be fire resistive.

Type V construction is probably more vulnerable to fire, both internally and externally, than any other building type. Accordingly, it is essential that greater attention be given to the details of construction of this basically light wood-frame building. Fire blocking in exterior and interior walls at ceiling and floor levels, in furred spaces, and other concealed spaces can retard the spread of fire and hot gases in these vulnerable areas. Type V construction is subdivided into two subtypes: Type V (111) construction, which has 1 hour fire resistance throughout, including the exterior walls; and Type V (000) construction, which has no fire protection or fire resistance requirements, except for the exterior walls when horizontal separation is less than 10 ft (3 m).

FIGURE 19.1.2 Elements of a Building of Type IV (Heavy Timber) Construction. Note the large size of the columns and beams and the absence of concealed spaces. The exterior nonbearing wall at far left is of lightweight corrugated steel.

FIGURE 19.1.3 A Variation of Type IV (Heavy Timber) Construction with Haunched Arches of Laminated Wood (Glue-Laminated Construction) and Beams Anchored to Arches by Steel Hangers

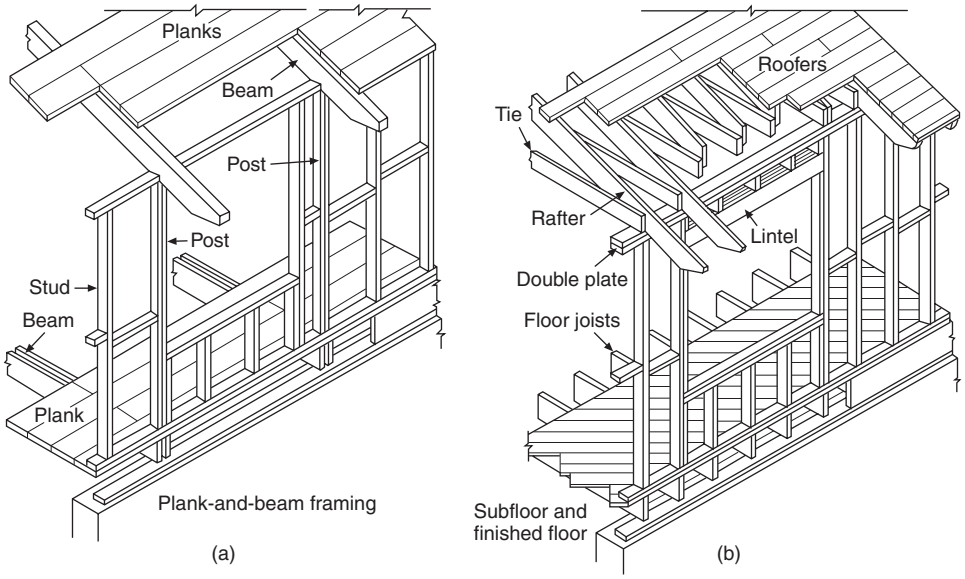


FIGURE 19.1.4 Two Variations on Basic Type V (Wood Frame) Construction: (a) Plank-and-Beam Framing in Which a Few Large Members Replace Many Small Members Used in Typical Wood Framing, (b) Conventional Wood Framing (Western or Platform Construction). Fire blocking is essential in concealed spaces.

Mixed Types of Construction

Where two or more types of construction are used in the same building, it is generally recognized that the requirements for occupancy or height and area would apply for the least fire-resistive type of construction. However, in cases where each building type is separated by adequate fire walls or area separation walls (see NFPA 221, *Standard for High Challenge Fire Walls, Fire Walls, and Fire Barrier Walls*) having appropriate fire resistance, each portion may be considered as a separate building.

Another general limitation included in some codes prohibits construction types of lesser fire resistance to support construction types having higher required fire resistance. In the event of a fire, the risks of a major structural collapse are generally too great to permit this type of design. This limitation does not necessarily apply where construction supports nonbearing separating partitions that provide protection for exit corridors or tenant spaces.

FIRE PROTECTION OF BUILDING ELEMENTS

Fire protection of structural elements is provided for two reasons: (1) to minimize the likelihood that the structural member will contribute to the fuel load, and (2) to ensure that the structural elements will maintain their integrity when exposed to fire. Loss of integrity of the building structure (total or partial collapse) will render fire-fighting measures less effective. Protection of other building elements, such as non-load-bearing interior walls, is also desired under certain conditions to mitigate the spread of fire within or into the building. See Section 19, Chapter 2, "Structural Integrity During Fire," for further discussion.

There are two groups of building elements: (1) load-bearing and (2) non-load-bearing. Load-bearing elements are those that support significant loads other than their own weight. Non-load-bearing elements support only limited loads in addition to their own weight. Removal of non-load-bearing elements would have no effect on the structural behavior of the building as a whole. Table 19.1.5 lists the structural elements that are common to most buildings, separated into these two general categories.

Building codes provide requirements for both structural loads and superimposed live loads. Structural failures are generally the result of application of unanticipated loadings. In a fire situation, "loads" are induced by heat which may cause thermal stresses. These stresses may be increased if the members are in any way restrained against expansion. Also, heat from fire may cause a loss of strength and increase in deflection, if not actual consumption of the member. Although restraint in some designs may offset any loss in strength, there is the increased likelihood of collapse in the event of a protracted fire. Properly designed and constructed assemblies having a fire resistance adequate for the exposure will retain adequate strength during fire exposure and continue to resist collapse.

Columns serve to carry building loads to the foundation where the loads are distributed to the supporting ground or rock. The material of the column is established by the type of construction—steel or reinforced concrete if noncombustible, or wood, including heavy timber designs, if combustible. In a fire, interior columns are the most severely exposed of any structural members, as they may be enveloped in fire on all sides.

TABLE 19.1.5 Structural Elements of a Building

Load-Bearing Elements	*Non-Load-Bearing Elements*
Compressively stressed columns	Curtain or panel walls
Walls, exterior or interior	Partitions
Flexurally stressed beams, girders, trusses, floors, roofs	Ceilings

WALLS

Building walls may serve one or more functions and they may be either bearing or nonbearing and exterior or interior. The following brief definitions describe the general functions that walls may serve:

Bearing wall: A wall that supports significant vertical loads in addition to its own weight

Cavity wall: A wall of two parallel wythes (vertical wall of bricks or concrete blocks) with an air space between them. The wythes are connected by metal ties.

Curtain wall: An exterior wall supported by the structural frame of the building. Also called a panel wall.

Exterior wall: A wall that forms a boundary to a building and is usually exposed to the weather

Faced wall: A wall composed of two different masonry materials: (1) the facing wythe and (2) the backup wythe, which are bonded together to act as a single unit

Fire partition or *fire barrier wall:* An interior wall that serves to restrict the spread of fire, but does not qualify as a fire wall

Fire wall: A wall of sufficient fire resistance, durability, and stability to withstand the effects of an uncontrolled fire exposure, which may result in collapse of the structural framework on either side. Openings in the wall, if allowed, must be protected.

Hollow wall: A wall of two parallel wythes, with an air space between them, but without ties to hold the wythes together

Nonbearing wall: A wall that supports only limited loads in addition to its own weight

Parapet wall: A portion of an exterior, fire, or party wall that penetrates through and extends above the roof line

Partition: An interior wall, not more than one story in height, that separates two areas in the same building but is not intended to serve as a fire barrier

Party wall: A wall that lies on a common lot line for two buildings and is common to both buildings. These walls may be constructed with a wide range of materials or assemblies.

Sandwich wall: A nonbearing wall whose outer faces enclose an insulating core material

Shaft wall: An interior wall that separates a vertical opening for a stairway, elevator, duct space, and so on, and connects two or more floors

EXTERIOR WALLS

The primary function of all exterior walls is to protect the inside of the building from the elements, such as heat and cold, water, wind, and windblown dust and dirt. In addition, some exterior walls may support floor and roof framing systems and may include portions that support girders or beams.

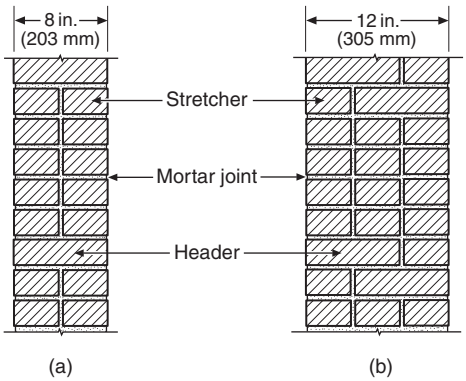


FIGURE 19.1.5 Typical Types of Wall and Partition Assemblies: (a) 8 in. (203 mm) Brick Bearing Wall, (b) 12 in. (305 mm) Brick Bearing Wall

The fire resistance required for exterior walls is determined not only by the type of construction but also by the distance the wall is set back from a lot line or an exposing structure. The greater that distance, the less severe the exposure and, hence, the less fire resistance that would be needed. NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures,* may be used to determine acceptable combinations of separation distance and exterior wall fire resistance or active protection.

Load-Bearing Exterior Walls

Load-bearing exterior walls are generally constructed of either masonry units (such as stone, brick, concrete block, or a combination of these materials) or concrete. Brick veneer is sometimes used as a facing in wood or metal-stud wall construction. In this case, the studs support the applied loads, while the veneer provides an attractive, useful exterior surface. Veneers are also used as the exterior face of cavity walls. Figures 19.1.5, 19.1.6, 19.1.7, 19.1.8, and 19.1.9 illustrate some common forms of exterior wall construction.

Exterior walls of reinforced concrete are poured-in-place, precast, or tilt-up type. Masonry veneers are sometimes used as the exposed surface of reinforced concrete walls. The brick veneer is tied to the concrete by metal ties fastened to the concrete and set into the mortar bed joints of the masonry. If the walls are load-bearing, the reinforced concrete is designed to support all of the applied loads.

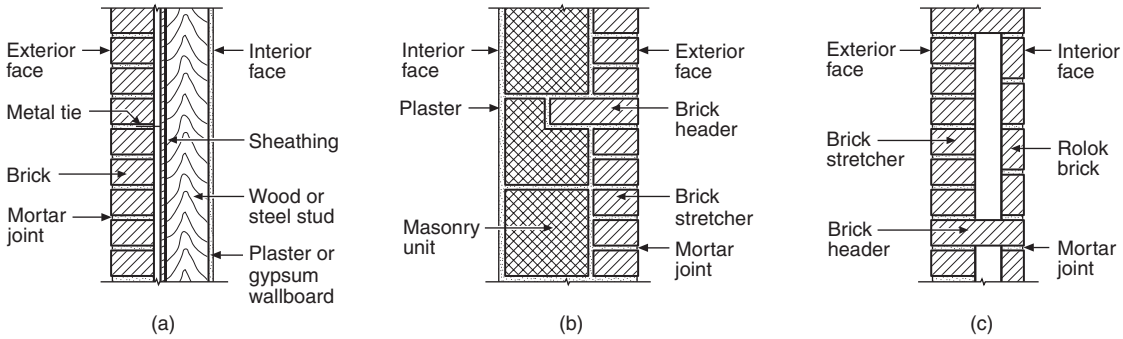


FIGURE 19.1.6 Typical Types of Wall Assemblies: (a) Exterior Brick Veneer on Wood-Frame Wall, (b) 12 in. (305 mm) Exterior Faced or Veneered Wall, (c) 8 in. (203 mm) Exterior Hollow Rolok Bak® Brick Wall

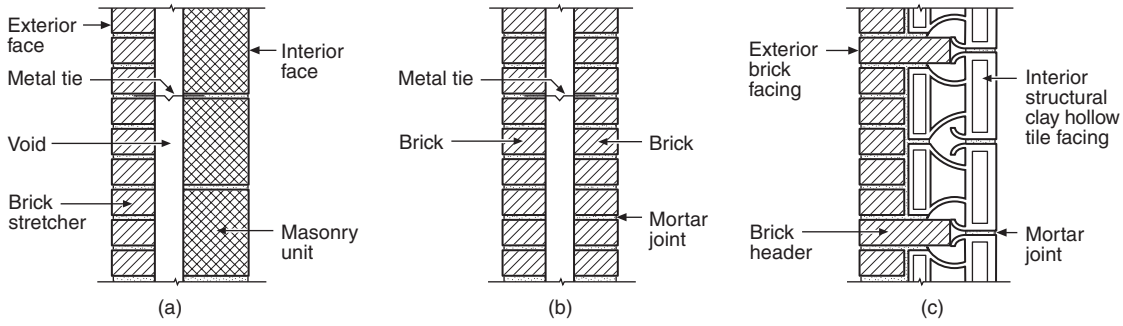


FIGURE 19.1.7 Typical Types of Wall Assemblies: (a,b) Two Examples of Exterior Nonbearing Cavity Walls, (c) 12 in. (305 mm) Exterior Bearing Wall

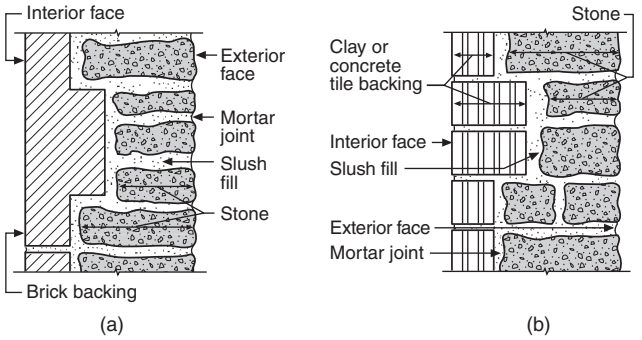


FIGURE 19.1.8 Stone-Faced Wall Assemblies: (a) with Brick Backing, (b) with Tile

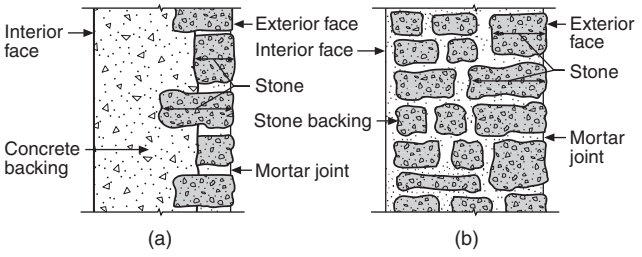


FIGURE 19.1.9 (a) Wall of Concrete Backing and Stone Face, (b) Solid Stone Wall

Exterior masonry walls may be non-load-bearing, that is, essentially supporting only their own weight. The floor and roof framing is supported by columns that transfer the loads to the foundation. Usually each story of the exterior wall is supported on spandrel beams, which frame into the columns. Some of the structural difficulties experienced with masonry walls in fires are illustrated in Figure 19.1.10.

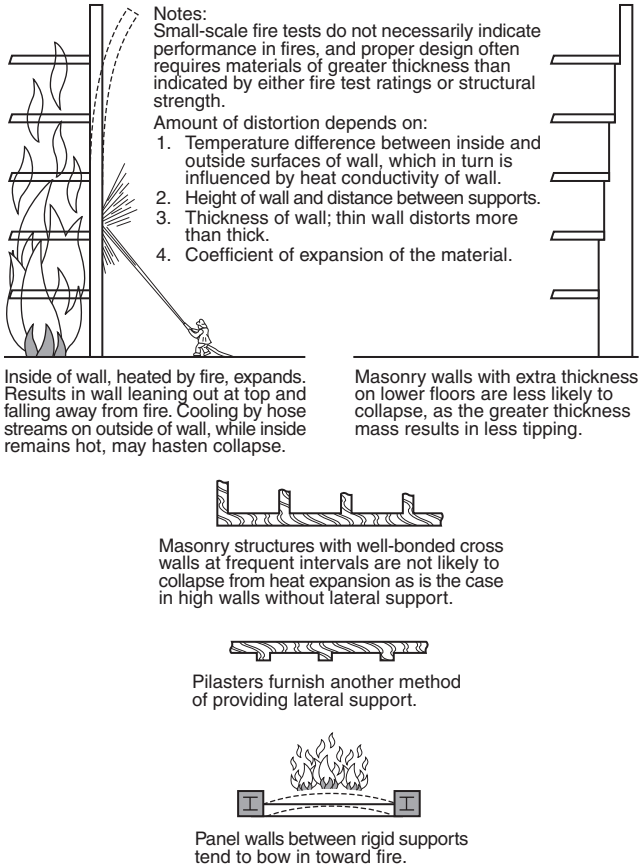


FIGURE 19.1.10 Heat Expansion Effects on Ordinary Masonry Walls

Openings in Exterior Walls

Openings such as doors and windows in masonry walls must have supports to carry the weight of the wall structure above the openings. These supports, called lintels, can be constructed of several materials, including steel shapes, precast concrete beams, and stone or brick arches. Figures 19.1.11 and 19.1.12 illustrate several types of lintels. Steel lintels used in fire-resistive walls should have a fire-protective covering, such as concrete, or a spray-applied cementitious or mineral coating to prevent failure of the lintel and wall section above the opening. Openings may need to be limited in size and number when the exterior wall is close to the lot line. Openings that are protected do not have fire resistance as such but can impede the spread of fire. See the section entitled "Protection of Openings" in Section 18, Chapter 1, "Confinement of Fire in Buildings."

Openings for which protection (windows, doors) does not have the insulating value as that of the fire barrier wall or fire wall may hamper egress, cause personal injury in a fire, or allow autoignition of combustibles located near the unexposed face of

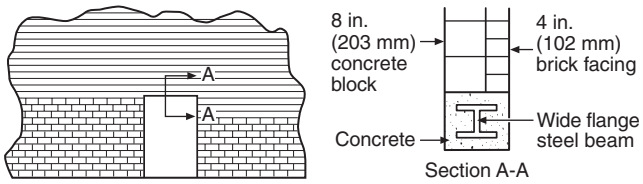


FIGURE 19.1.11 Lintels in Brick-Faced, Concrete Block Wall

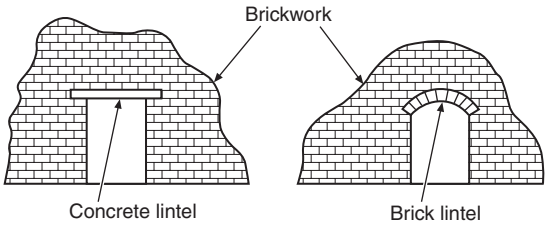


FIGURE 19.1.12 Use of Concrete and Brick Lintels in Masonry Walls

the opening. Maintaining a minimum separation distance (perpendicular to the face of the opening) equal to the maximum dimension of the opening will help prevent this.

Curtain Walls

Most multistory buildings consist of a protected steel or reinforced-concrete frame (columns, girders, and beams). The building envelope may be enclosed with nonbearing walls supported at each level. These walls are often identified as either curtain or panel walls. Many materials and types of construction are used for curtain walls. Aluminum and stainless steel curtain walls are, by far, the most common, but copper and copper alloys, carbon steel, galvanized metals, porcelain enamel finish, concrete, glass, and plastics are also used. Large window areas are common in this type of wall. Figure 19.1.13 shows an example of contemporary curtain wall construction.

A complete curtain wall assembly may consist of a panel with finished outside and inside surfaces, insulation, and means of attachment to the building frame. However, this type is not used as frequently as is a metal or glass skin assembly reinforced by conventional construction. Curtain walls are required to have fire resistance ratings up to 2 hours, depending on the separation distance between the wall and a lot line or exposing structure. Secure fastening of curtain walls is important for many reasons, including stability during fire exposure. Curtain walls are generally bolted to clips attached to the columns, spandrel, or floor slab. There is usually a space between the outer end of the floor slab and the inside face of the curtain wall. Unless adequately fire blocked, this space may act as a route for vertical fire spread for the entire height of a building.

Parapet Walls

A parapet wall is an extension of the wall construction above the roof line. The parapet on a fire wall helps to prevent a fire from spreading across the roof over the fire wall and can aid manual fire fighting. Where walls extend only a few inches above the roof, ignition of an adjoining roof is more likely to occur, depending on wind direction and velocity and the type of the roof covering. NFPA 220, *NFPA 5000,* GAP Guideline GAP 2.2.1, and FM Global Data Sheet 1-22,[1] for example, specify a parapet height of 30 in. (762 mm). Many building codes permit lesser heights, and in large sections of the country, 18 in. (457 mm) parapets are considered standard. The higher the parapet, the greater the degree of safety, but considerations of expense and appearance often dictate overall compromises.

Fire may also extend around the ends of fire walls where the exterior walls of the building on both sides of the fire wall are combustible. There are two methods of minimizing this danger: (1) extend the fire wall several feet out beyond the wall of the building or (2) provide blank fire-resistive exterior wall construction at each end of the wall (Figure 19.1.14 and Table

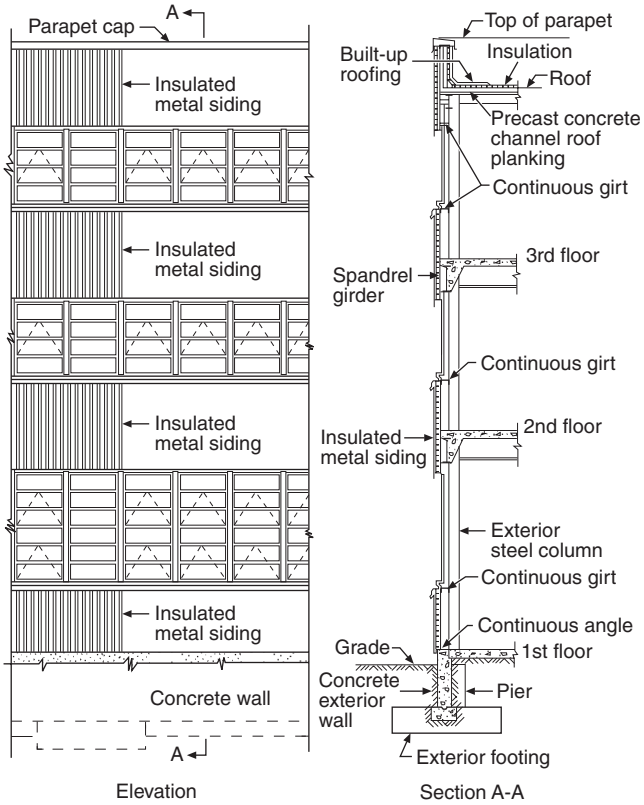


FIGURE 19.1.13 Elevation of Typical Bay of Steel Frame Curtain Wall Construction

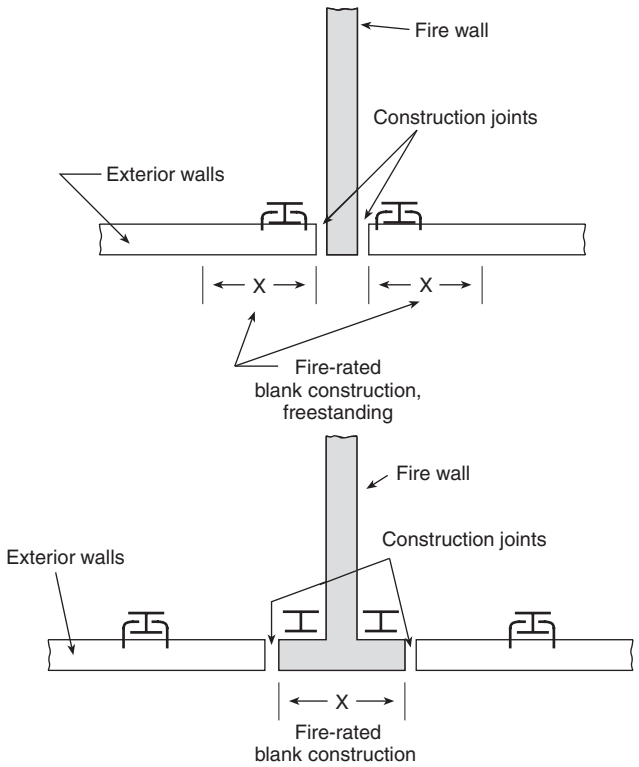


FIGURE 19.1.14 End Wall Exposure Protection: (a) End Walls Tied to Structural Framing, (b) End Walls Not Tied to Structural Framing (see Table 19.1.6)

19.1.6). The fire resistance rating of the end walls should be from the outside and should be a minimum of 1 hour but not more than 2 hours less than that of the fire wall. Where combustible roofs or cornices project beyond the walls of the building, fire walls should be extended to form a break in such combustible construction, as shown in Figure 19.1.15. Otherwise effective fire walls have failed because wood platforms or projecting canopies along the sides of buildings have spread fire from one fire area to another.

INTERIOR WALLS AND PARTITIONS

Interior walls and partitions used for building corridors or rooms may be either bearing or nonbearing. Bearing partitions are common in the older, wall-bearing construction systems and are also employed with industrialized building systems, particularly those of precast concrete. Newer construction tends to use nonbearing partitions.

The need for open space flexibility in modern construction has led to floor and interior partition design that allows nonbearing partitions to be installed at any location. These moveable partitions are often made of steel studs and gypsum board, and they may be installed, then dismantled and reinstalled at another location when occupancy needs change. Normally, moveable partitions extend only from the floor to the underside of the ceiling.

Interior partitions, particularly non-load-bearing partitions, can be installed with a number of other different materials. Wood stud and gypsum board or plaster is another very common type of partition. Partitions constructed of masonry units, such as concrete block, structural clay tile, terra cotta, and gypsum block are or have been commonly used in a wide variety of buildings and are more permanent. Figure 19.1.16 shows typical partition constructions.

Properly designed interior partitions can act as barriers to the spread of fire. To protect certain areas more completely than would be possible with ordinary partitions, wall assemblies possessing a fire resistance rating such as fire walls or fire barrier

TABLE 19.1.6 Length of End Wall Protection

Height of Exposing Area (ft [m])	*Length of End Wall Protection* (ft [m])*
Up to 40 (12.2)	6 (1.8)
41 to 70 (12.3)	10 (3.1)
71 (21.6) and over	14 (4.3)

*Protection should consist of blank, fire-rated construction.

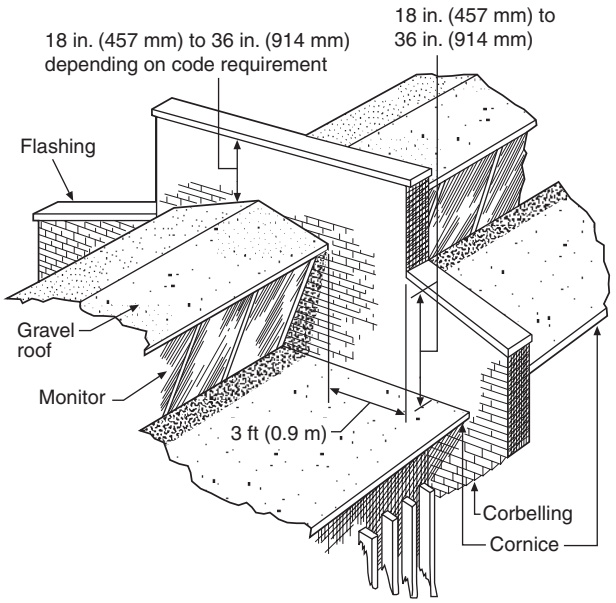


FIGURE 19.1.15 Fire Wall Installation on Building with Combustible Roof and Monitor

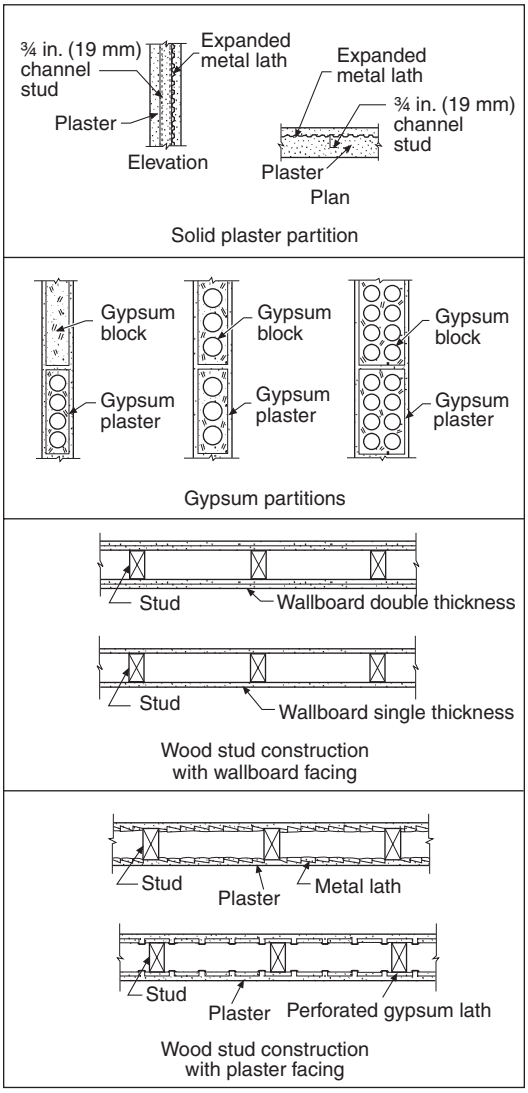


FIGURE 19.1.16 Typical Interior Wall and Partition Constructions

walls are constructed. Fire partitions may also be referred to as fire barrier walls; however, they are often incorrectly called fire walls.

Fire Walls and High Challenge Fire Walls

Fire walls and high challenge fire walls are interior walls providing a fire separation between areas of the same building. These walls are fire resistive, of noncombustible construction, often self-supporting, and cannot be readily modified to meet changing building needs. They are designed to maintain structural integrity, even in cases of complete collapse of the structure on either side of the fire wall. They are constructed of reinforced concrete, concrete block, prestressed concrete, and sometimes brick. Concrete or masonry walls generally require some type of steel reinforcement to withstand heat expansion effects. Adequate cover thickness of concrete must be provided over steel reinforcement. This is particularly important in the case of prestressed concrete walls. When designing prestressed concrete walls, refer to *Design for Fire Resistance of Precast Prestressed Concrete.*[2] Also, they may be buttressed by pilasters if of considerable height or length. In fire-resistive buildings, structure-supported fire division walls may be used, provided the structure has equal or greater fire resistance than that of the wall. Requirements for fire walls can be found in NFPA 221 and *NFPA 5000.*

Fire Barrier Walls

Usually, a fire barrier wall (or fire partition) subdivides a floor or an area and is erected to extend from the floor to the underside of the floor or roof above. Fire partitions may be constructed of noncombustible, limited-combustible, or protected combustible materials, and should be attached to and supported by structural members having fire resistance at least equal to that of the partition. A fire barrier wall normally possesses somewhat less fire resistance than a fire wall and does not extend from the basement through the roof, as does a fire wall. The fire resistance ratings for such partitions range from a half hour to as much as 4 hours. Requirements for fire barrier walls are less involved than those for fire walls and are also contained in NFPA 221 and *NFPA 5000.*

FLOOR FRAMING SYSTEMS

Floor framing systems typically include not only the flooring assembly but also its supporting beams, girders, or trusses. Beams and girders are nearly always an integral part of the floor system, whereas trusses may serve other purposes (and, hence, are discussed separately). The range of different types of floor framing systems that include beams and girders and the variety of components that may be included in a given assembly is best portrayed through drawings. Figures 19.1.17 through 19.1.27 are typical of many designs that are currently used.

Types of Floor Systems

Steel and Reinforced-Concrete Floor Assemblies. Figures 19.1.17 and 19.1.18 are generalized framing plans for steel and reinforced-concrete floor assemblies. The steel beams shown in Figure 19.1.17 support the floor assembly and are, in turn, supported by girders. Interior girders support beams on both sides. Girders are often concealed within partitions where their depth is not apparent, and they can directly support the weight of partitions in the space above. The girders frame into steel columns. Figure 19.1.18 illustrates a slab beam girder column system cast

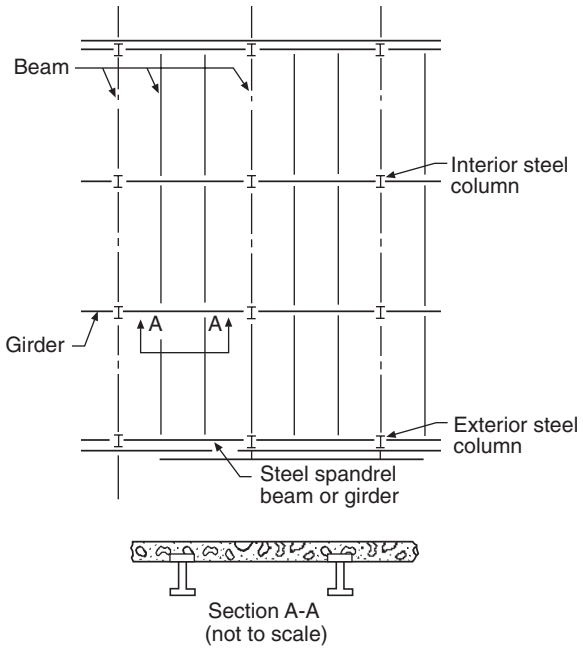


FIGURE 19.1.17 Portion of Floor Plan of Steel Frame Structure

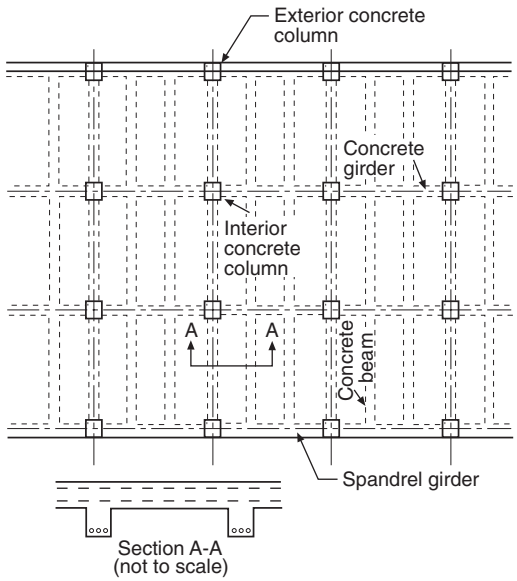


FIGURE 19.1.18 Portion of Floor Plan of Reinforced Concrete Beam and Girder Construction

monolithically (no joints) of reinforced concrete. The functions of the various components are the same as those described for the steel frame.

The floor slab supported by the steel beams shown in Figure 19.1.17 need not be of reinforced concrete. Alternative types of deck are the composite decks shown in Figures 19.1.19 and 19.1.20. This type of floor system offers many construction advantages. The metal deck acts as a form for the concrete and remains in place after curing. In addition, the cellular panels can be used for building service raceways where desired. The cellular panels can carry all three basic building services—power, telephone, and data transmission lines. A feature of this floor system is that the steel deck also acts as the tensile reinforcement of the concrete floor slab. A spray-applied fire-resistive coating on the steel deck underside may be required in some cases.

Another floor deck modification is to replace the reinforced-concrete floor slab with a precast concrete system. Figure 19.1.21 illustrates three common precast concrete floor slabs. The precast concrete planks generally have voids through their length that reduce the weight of the planks and act as building service raceways. The planks may be supported by either steel beams or reinforced concrete beams.

Open-web joists, which are lightweight prefabricated trusses, may replace steel beams as the intermediate flexural framing and are a very common type of construction both for floors and roofs. The spacing of floor joists is approximately 2 ft (0.61 m), and generally about 6 ft (1.8 m) for roof joists. Figure 19.1.22 illustrates this type of construction.

Because the spacing of the joists is so close, the floor slab can be thinner and still support the same load. Corrugated steel forms with 2½ in. (64 mm) of concrete as a wearing surface is a

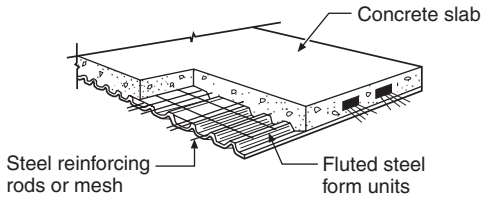


FIGURE 19.1.19 Concrete Floor Construction Showing Composite Floor Assembly

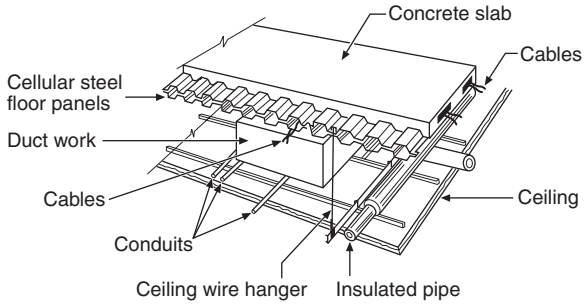


FIGURE 19.1.20 Concrete Floor Poured over Light Gauge Cellular Floor Panels

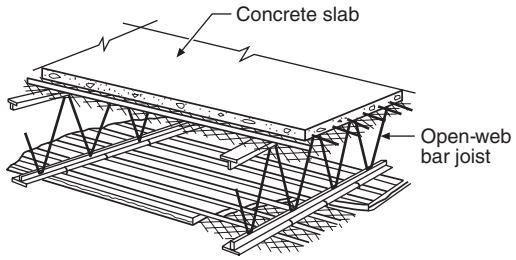


FIGURE 19.1.22 Concrete Floor Construction Showing Open-Web Steel Joist

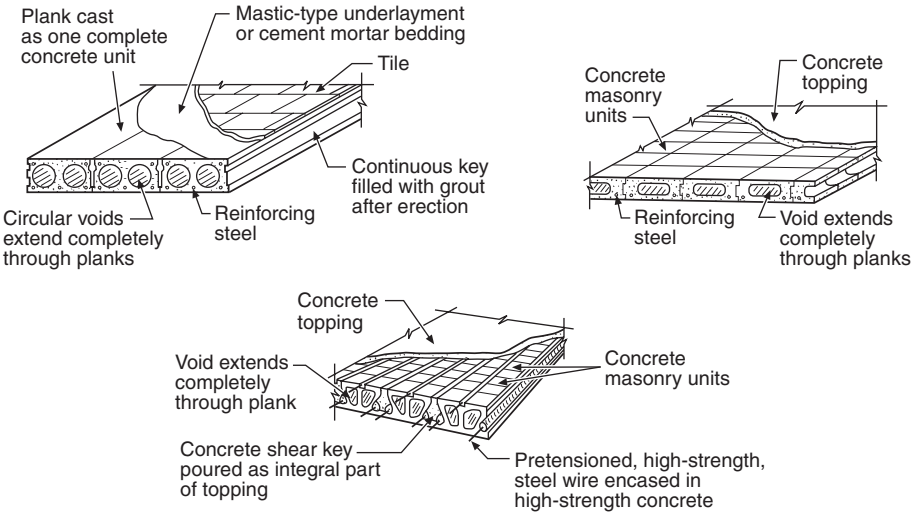


FIGURE 19.1.21 Three Precast Concrete Floor Slabs

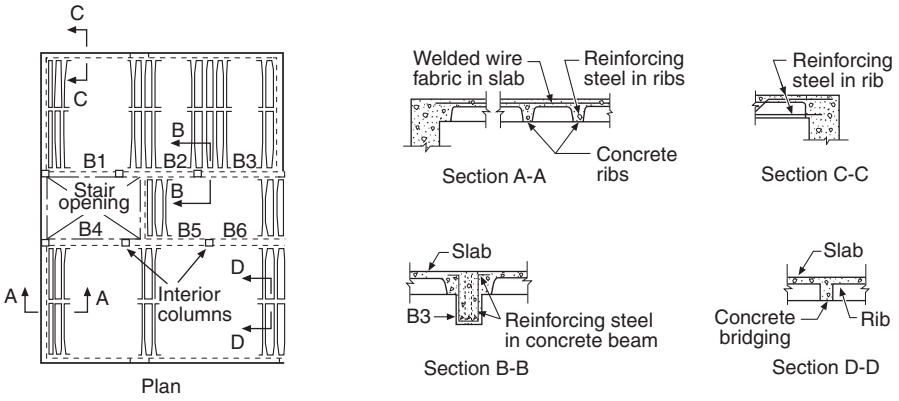


FIGURE 19.1.23 Partial Plan of a Concrete Joist Floor with Four Sectional Views

typical design. The corrugated deck acts as a form for the concrete and contributes to the support of live loads. Lightweight concrete is often used in place of normal-weight concrete to reduce the dead load.

Similarly, the reinforced concrete beams shown in Figure 19.1.18 may be spaced more closely together, permitting both a thinner floor slab and smaller beams. This type of construction is generally called a ribbed reinforced-concrete system or a concrete joist system. The ribbed system can be either cast in place or precast. Figure 19.1.23 illustrates the concrete joist floor, while Figure 19.1.24 illustrates two of the more common forms of ribbed precast systems. In each illustration, the ribs are the intermediate flexural framing.

The two-way flat slab is an increasingly popular floor system. Two-way reinforced-concrete slabs, used since the turn of the century, include reinforcement placed in two directions. The slab performs the functions of deck, intermediate flexural framing, and primary flexural framing. The underside of the slab may be either flat or ribbed in two directions. Figures 19.1.25 and 19.1.26 illustrate two different forms of this type of construction.

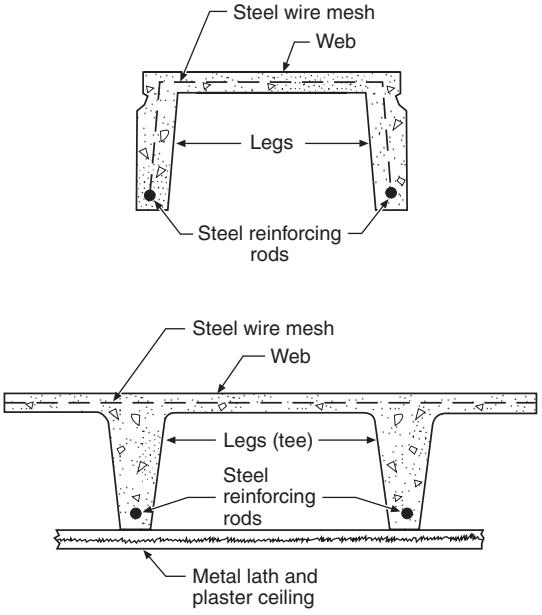


FIGURE 19.1.24 Sections Through Channel and Double-Tee Concrete Slabs. The slab at bottom shows a metal lath and plaster ceiling attached directly to the ribs of the slab. These slabs may be used as part of floor or roof framing systems.

Wood Floor Systems. Wood floor systems can be designed to perform the same functions as the basic model in Figure 19.1.17. If the reinforced-concrete deck were replaced with heavy wood planking 2 in. (51 mm) or more in thickness, and

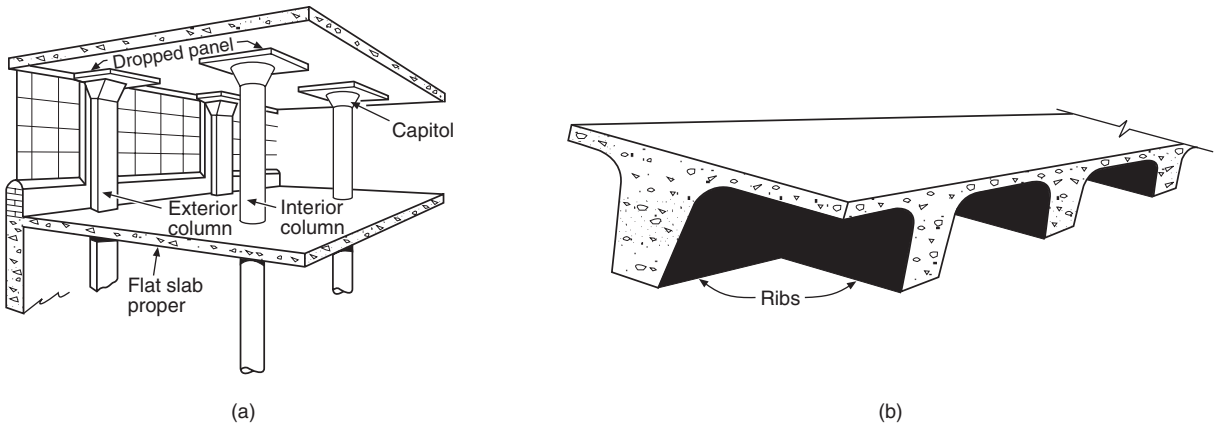


FIGURE 19.1.25 Two Types of Two-Way Flat Slabs: (a) Flat Underside, (b) Two-Way Ribbed Underside

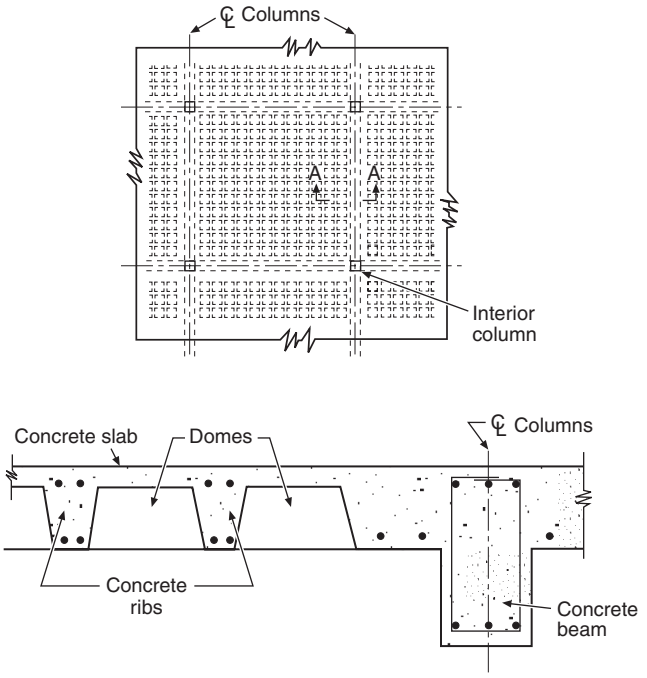


FIGURE 19.1.26 Partial Typical Interior Two-Way Ribbed Floor Slab with Section View A-A

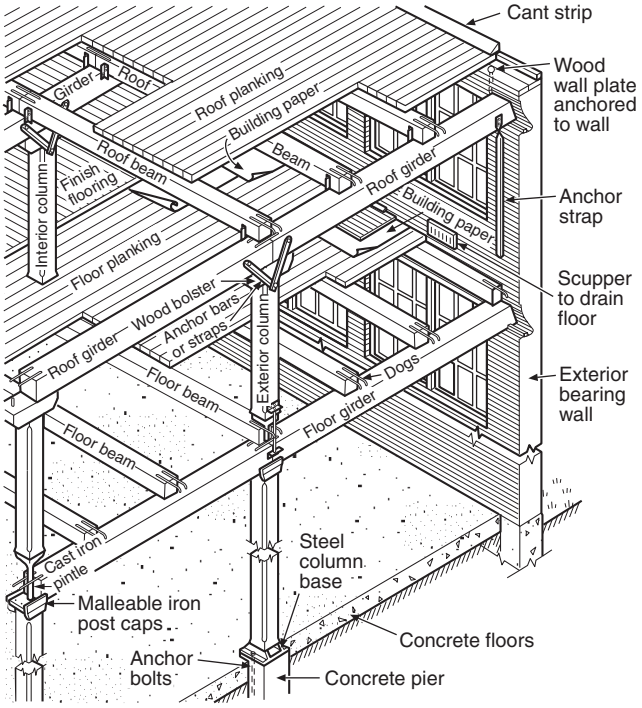


FIGURE 19.1.27 Components of a Heavy Timber Building Showing Floor Framing and Identifying Components of a Type Known as Semimill

the steel beams, girders, and columns with large wood members with a minimum dimension of 6 in. (152 mm), the basic form would be that of mill construction. This construction, shown in Figure 19.1.27, was quite common for industrial buildings and warehouses during the nineteenth century. The general design is still used in locations where wood has aesthetic appeal.

Lightweight, wood-frame construction is usually used in buildings of limited size. Floor joists in such construction are normally spaced 16 in. (406 mm) on center, and the vertical supports are often 2 in. by 4 in. (51 mm by 102 mm) or 2 in. by 6 in. (51 mm by 152 mm) wall-bearing studs, again spaced 16 in. (406 mm) on center. The stud walls may extend only from floor to floor in platform framing (Figure 19.1.28), or they may be extended continuously for two or three floors, a type of framing identified as balloon construction (Figure 19.1.29).

Wood-frame construction has little fire resistance because flames and hot gases can penetrate into the spaces between the joists or the studs. Fire blocking must be installed at critical locations throughout the building to prevent the rapid vertical and horizontal spread of fire. Fire blocks are normally made of wood blocks or noncombustible material. Figures 19.1.29 and 19.1.30 illustrate critical locations for fire blocking in balloon frame and in platform frame construction; Figure 19.1.31 shows the fire blocking for these constructions in greater detail.

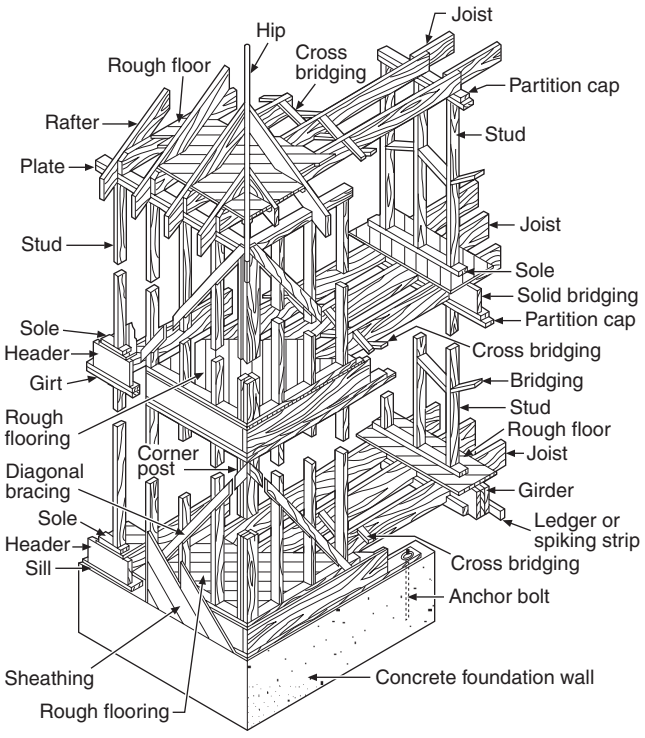


FIGURE 19.1.28 Wood-Frame Platform Construction Common to Dwellings with Structural Members Identified

Watertightness and Drainage of Floors

In addition to the effectiveness of floor framing systems as barriers to fire spread, there is another consideration involving floors in multistory buildings that can have a bearing on their performance in fires. This consideration is the degree of wa-

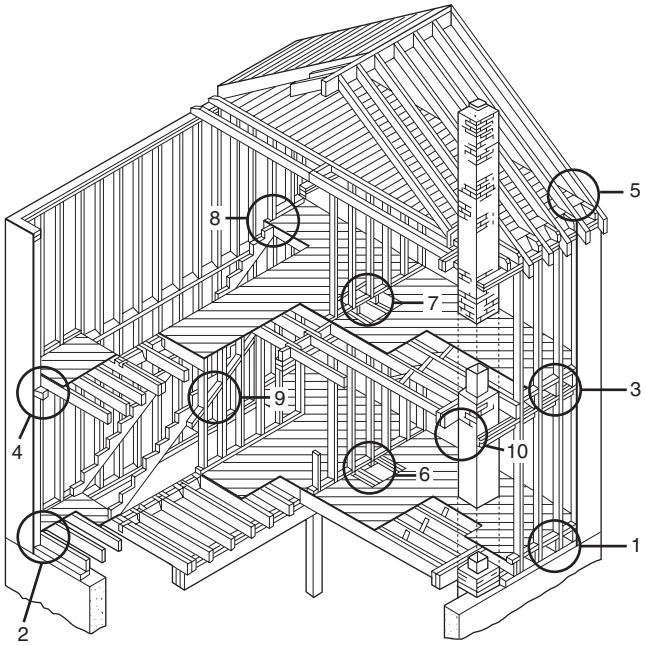


FIGURE 19.1.29 Wood Balloon Frame Construction Showing Points to Be Fire Blocked. Expanded views of points are shown in Figure 19.1.31.

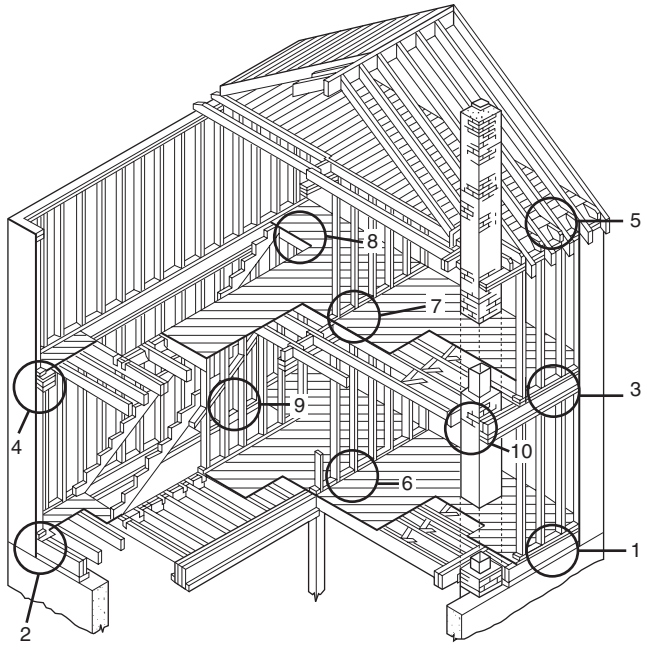


FIGURE 19.1.30 Wood Platform Frame Construction Showing Points to Be Fire Blocked. Expanded views of points are shown in Figure 19.1.31.

tertightness of construction and drainage arrangements for the floors. Massive quantities of water are sometimes needed on fires in unsprinklered buildings of combustible construction or buildings of noncombustible construction with significant occupancy fuel loads. Without good drainage and/or waterproofing arrangements, water could pose the threat of increased water damage on floors below.

TABLE 19.1.7 Sizes for Scuppers and Drains

Floor Areas	*Number of 4 in. (102 mm) Scuppers or Drains*
500 ft^2 (46 m^2) or less	2
750 ft^2 (70 m^2)	3
1000 ft^2 (93 m^2)	3

Note:
Additional scuppers for areas over 1000 ft^2 (93 m^2):
For Extra-Hazard Occupancies, Group 1 or 2 (quantity and combustibility of contents is very high), or floors of questionable watertightness, or contents especially subject to water damage—one scupper for each additional 500 ft^2 (46 m^2).
For Ordinary-Hazard Group 2 Occupancies (quantity and combustibility of contents is moderate) with watertight floors—one scupper for each additional 1000 ft^2 (93 m^2) or fraction thereof.
For Ordinary-Hazard Occupancies Group 1, or Light-Hazard Occupancies (quantity and combustibility of contents is low) with strictly watertight floors—one scupper for each additional 2000 ft^2 (186 m^2) or fraction thereof.

Where acceptable, one inexpensive method of drainage is to provide scuppers in the exterior walls. Floor drains connected to ample size headers or a combination of scuppers and floor drains may be used. The number of scuppers or drains is dependent upon the hazard and the amount of water likely to be used. For average conditions, the recommendations in Table 19.1.7[3] are considered good practice.

Waterproofing techniques, such as waterproof membranes, hot mastics, asphalt emulsions, cementitious surfacings, and so on, are available that can be applied to the floors depending on the basic type of floor construction in question. The intent of these applications is to provide a watertight barrier on the floor itself, which extends up 4 to 6 in. (100 to 150 mm) at walls and columns. Water impounded by these protective measures must be carried off before its weight becomes a loading threat to the building.

TRUSSES

Where large areas must be column free or where special occupancy requirements may warrant, trusses may be used for purposes other than roof support. Three such applications are identified as (1) transfer trusses, (2) staggered trusses, and (3) interstitial trusses.

Transfer Trusses

Load transfer trusses create a clear space on a lower floor by directly supporting the loads from columns above the truss or, at times, from tension members below. This design allows large, column-free areas for auditoriums, ballrooms, and so on, at any level in a multistory building. Since transfer trusses carry loads from more than two floors, building codes generally require that the fire protection be provided by individual protection for each of the truss elements, or by complete enclosure of the truss (for its entire height and length) with envelope protection.

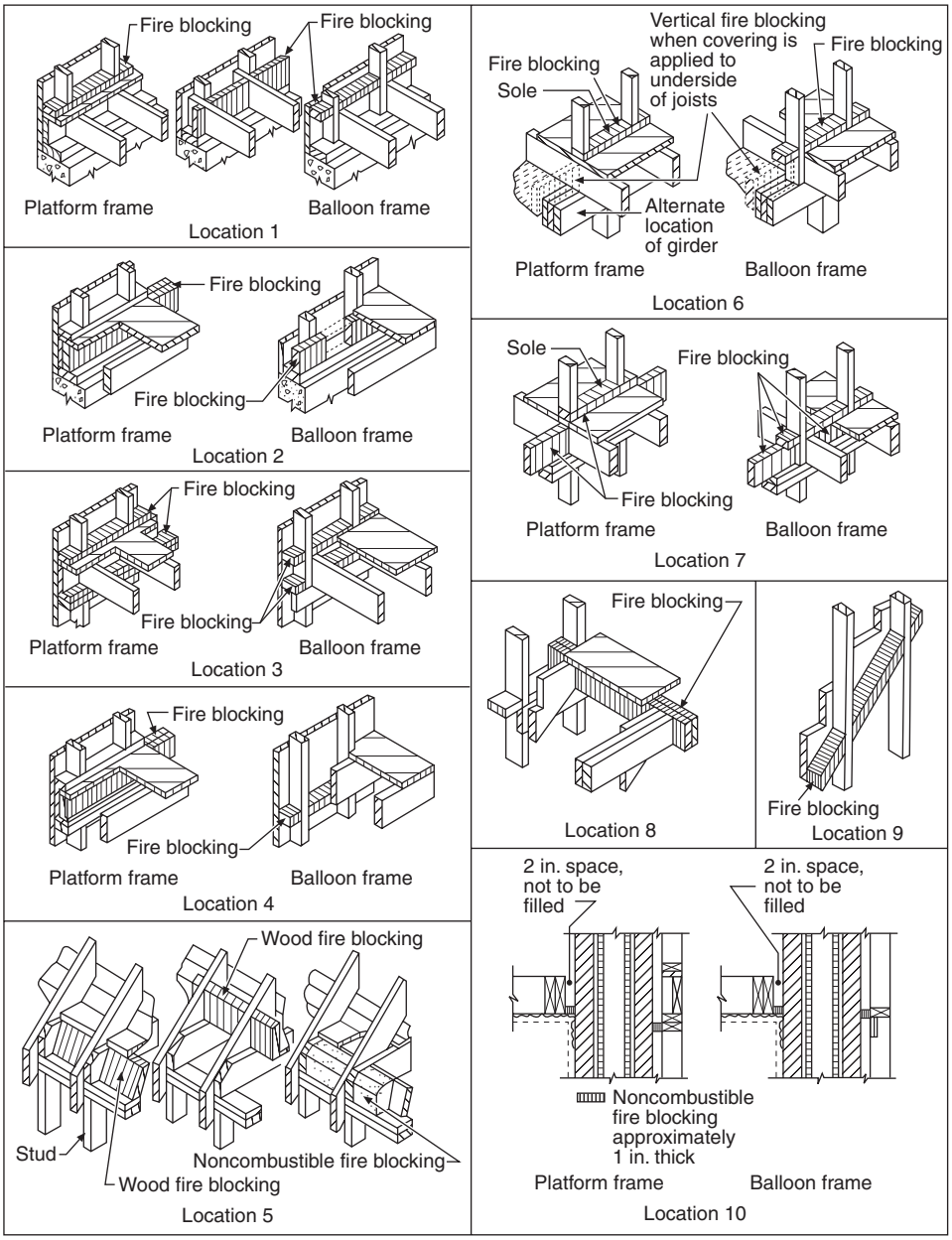


FIGURE 19.1.31 Details of the Application of Fire Blocking to Platform and Balloon Framing. Location numbers coincide with locations circled in Figures 19.1.29 and 19.1.30. For SI units: 1 in. = 25.4 mm.

Staggered Trusses

The staggered truss system is primarily intended for high-rise residential buildings. Typically, in a staggered truss design, story-high trusses span the full building width at alternate column lines on each floor. These trusses are supported only on the two rows of exterior columns. Thus, the interior of the building is column free; at any given elevation, floor construction is alternately supported on the top and bottom chords of adjacent trusses.

It is characteristic of staggered truss applications that these trusses are enclosed in wall construction that separates individual apartments or hotel/motel guest rooms. There may be a control opening in the truss that permits passage space for a corridor. Since staggered trusses are usually enclosed in walls, the entire wall assembly must have a fire resistance required for this condition.

Interstitial Trusses

The interstitial truss concept was first developed to solve the functional needs of hospitals. Although steel trusses in interstitial framing systems are quite deep (on the order of 8 ft [2.5 m]

in height), they do not extend from floor to floor as do staggered trusses. The top chords support the floor above, while the bottom chords support a suspended ceiling system and a walking surface for maintenance purposes. As such, interstitial trusses are analogous to very deep open-web steel joists.

The interstitial space thus created provides a convenient location for the complex mechanical and electrical systems that are necessary components of a modern hospital. Direct access for maintenance, renovation, and replacement of the various system components within these interfloor spaces is provided without significant interference with normal operations.

Because each interstitial truss supports only one floor, all three conventional fire protection methods for trusses are permitted by the model building codes. However, because of practical considerations, individual protection of each truss element or ceiling membrane protection are the methods most widely used.

FLOOR/CEILING ASSEMBLIES

Ceiling components are important elements in the performance of a fire-resistive floor/ceiling assembly. In the event of fire within a room, the ceiling acts as a barrier to protect the structural framing above it. The degree of protection, of course, depends on the type of material, its installation, and its completeness. Combustible ceilings or ceilings that do not remain in place when subjected to the pressures and temperatures of a fire do not provide a significant degree of protection. It is important to note that the membrane ceiling is one part of the floor/ceiling assembly. The entire assembly, acting together, provides the designated fire resistance. The ceiling itself has insufficient fire resistance.

Ceilings may be applied directly to or suspended from the underside of the floor framing. Figure 19.1.24 illustrates a ceiling connected directly to the floor framing system; Figure 19.1.20 shows a ceiling suspended from the floor slab. It is also common to apply a fire-protective material, such as a plaster or sprayed mixture, directly to the bottom surface of the floor slab. Figure 19.1.32 illustrates a floor slab with plaster applied directly to the steel floor deck.

There are several types of suspended membrane ceilings in common use. One type consists of a lay-in system in which the ceiling panels are supported by an exposed metal grid. Another common type of membrane has the metal grid concealed by recesses in the edges of the ceiling panels. Suspended membrane ceilings may also consist of traditional lath and plaster or permanently secured gypsum wallboard with finished joints. Both of these latter systems can be either suspended below or attached directly to the basic subflooring system.

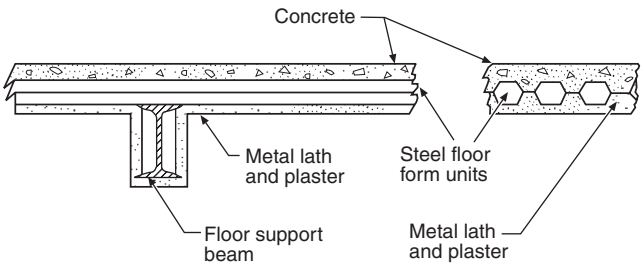


FIGURE 19.1.32 Plaster Applied Directly to Underside of Floor Slab Construction

In the variety of arrangements currently used, the space above the ceiling may be of combustible construction and may also contain other combustible materials, such as duct insulation, wire insulation, and vapor seals. Air-handling systems may use ducts or the void space itself (plenum) as a means of supplying, exhausting, or recirculating air, but associated materials must meet stringent requirements for combustibility and smoke evolution.

The material used for the membrane ceiling is important. Gypsum plaster and lath were a common construction of early membranes. Today special mineral tile formulations are generally used for acoustical panel systems that will not warp during fire exposure. The support framing is designed to accommodate thermal expansion with a minimum of distortion, so that the ceiling panels stay in place.

If lighting fixtures and duct openings are included in membrane ceilings that are part of fire-rated assemblies, they both must be of suitable design and properly spaced, and they often require shielding to reduce heat transmission into the ceiling space. Fire test performance is based on specific lighting fixtures and spacing, so indiscriminate substitution of lighting fixtures can cause premature failure. If air duct openings are installed in a membrane-type ceiling, they should be suitably protected or dampered, as determined by a fire test on the ceiling assembly that incorporates the air-handling components.

ROOF FRAMING

The design and construction of roof framing follow the general pattern for floor framing systems—both must support vertical loads and distribute these loads to walls or columns. Roof loads are usually smaller than floor loads. In addition, architectural considerations may demand longer spans than floor framing, and the shape of the roof need not be flat.

The roof deck and covering may be supported by steel or wood joists or by a truss where a longer span is needed. Roof trusses can be made to conform to any roof shape, whether flat, pitched, or curved.

Open-web steel or wood joists are often used in flat roof construction. An open-web joist is merely a lightweight, parallel chord truss. Open-web steel joists are typically used to support 1½-in. (38-mm) deep steel deck and are usually spaced about 6 ft (1.8 m) on center. This close spacing allows the roof deck to be designed to span between the joists. Figure 19.1.33 illustrates this type of roof framing.

In single-story buildings that require a large open space, rigid frames are sometimes used both as columns and roof supports. The portion spanning the roof is rigidly connected to columns on opposite sides of the building to form a single member. The frame itself may provide for a sloping roof. Figure 19.1.34 shows a rigid frame structure.

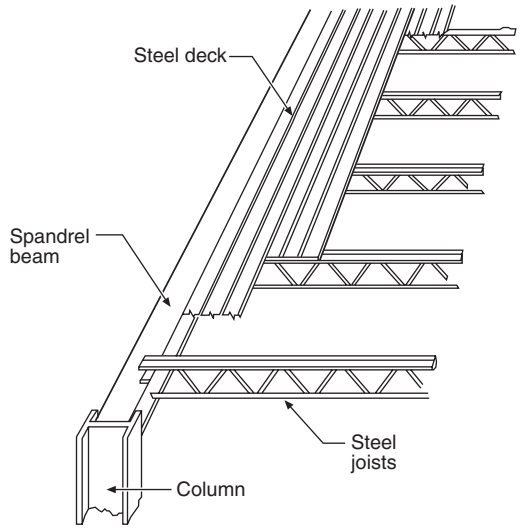


FIGURE 19.1.33 Long-Span Joist Framing

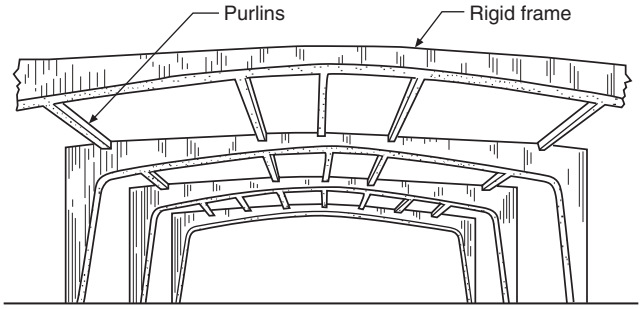


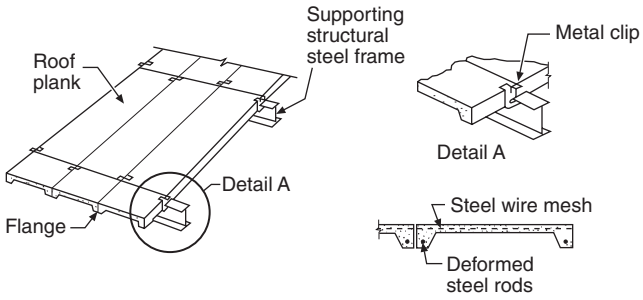
FIGURE 19.1.34 Rigid Frame

Flat slab and ribbed concrete slab systems may be used for roof construction in buildings in which that is the predominant type of framing. Other systems utilizing long-span prestressed concrete double-tee or channel sections are also common. These units serve both as support and as the deck (see Figure 19.1.24).

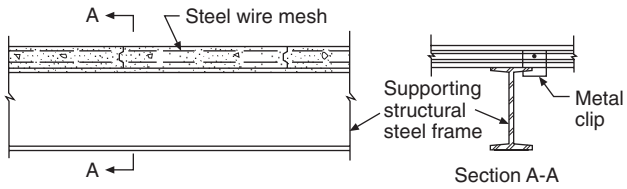
Roof decks may also consist of precast reinforced concrete planks fastened to the structural steel supports by galvanized metal clips, as shown in Figure 19.1.35. These planks are manufactured in three general shapes: (1) square edge, (2) channel slab, and (3) tongue and groove. To reduce weight they may be fabricated with aerated concrete using lightweight aggregates.

ROOF COVERINGS

In resistance to ignition and burning from exterior fire exposure, roof coverings range from combustible wood shingles with no fire-retardant treatment to built-up or prepared coverings that are effective against severe external fire exposure. Insofar as well-designed roof coverings can protect buildings from exposure fires, the likelihood of fire spread from one building to another can be reduced considerably.



Lightweight precast concrete channel roof plank



Lightweight tongue and groove concrete roof plank

FIGURE 19.1.35 Lightweight Precast Concrete Planks

Fire performance for any given roof assembly subjected to exterior fire exposure is not necessarily the same as that for interior fire exposure. The presence of pea stone gravel, large stone ballast, concrete paver blocks, or some coatings such as fibrated aluminum or asphalt emulsions on top of roof coverings can greatly enhance resistance to exterior fire exposure.

Fire-Retardant Roof Coverings

The test standard for roof coverings is NFPA 256, *Standard Methods of Fire Tests of Roof Coverings.* The three classes of roof coverings that rank resistance to exterior fire exposure are the following:

Class A Coverings. Class A coverings include roof coverings that are effective against severe fire exposures. These coverings are not readily flammable, do not carry or communicate fire, afford a fairly high degree of fire protection to the roof deck, do not slip from position, and possess no flying brand hazard.

Class B Coverings. Class B coverings include roof coverings that are effective against moderate fire exposures. These coverings are not readily flammable, do not readily carry or communicate fire, afford a moderate degree of fire protection to the roof deck, do not slip from position, and possess no flying brand hazard; however, they may require repairs to maintain their fire retardant properties.

Class C Coverings. Class C coverings include roof coverings that are effective against light fire exposure. These coverings are not readily flammable, afford at least a slight degree of fire protection to the roof decks, do not slip from position, and pos-

sess no flying brand hazard; however, they may require repairs or renewals to maintain their fire-retardant properties.

Building codes commonly require Class A or B coverings within the fire limits of cities or wherever fire-resistive construction is required. Class C roofing is appropriate for other buildings. Many cities specify Class C as the minimum standard for roofing. Fire testing laboratories classify metal deck roof assemblies by type of construction (Table 19.1.8).[4]

Built-Up and Prepared Coverings

Fire-retardant roof coverings fall within one of several groups. One is the built-up covering which, as the name implies, consists of several layers of materials applied or "built up" on the roof decks according to specifications. What is known as a "tar and gravel" roof is actually a built-up roof covering consisting of several layers of roofing felts and insulating panels or sheets bonded together by hot or cold cements and topped with roofing gravel (Figure 19.1.36).

Another group (prepared coverings) includes fire-retardant shingles and sheet coverings, which can be applied only to roof decks capable of receiving and retaining nails and which are sloped sufficiently to permit drainage (Figure 19.1.37). In some instances, however, the slope must not exceed a specified maximum in order to qualify for Class A, B, or C fire-retardant rating. Asphalt organic felt shingles (i.e., "composition" roofs) are a common example of prepared roof coverings and are frequently used on dwellings.

Prepared roof coverings also include such noncombustible coverings as brick, concrete, tile, and slate. Tables 19.1.8 and 19.1.9 list various types of prepared and built-up roof coverings, respectively, and their fire-retardant classifications. Any roof covering can be used for a less severe exposure than the one for which it is listed.

In addition to the built-up roof coverings described in Table 19.1.9, there are several other types consisting of organic felt, glass fiber, aluminum, steel, and tile applied in a special manner with special listed proprietary securements that are listed by testing laboratories. Single-ply membranes are a very popular type of roof covering. Exterior fire exposure ratings for these coverings are dependent on the type of material, whether it is fire retardant, the type of insulation directly below, and the presence of a coating or topping. Such classifications can be found in publications by fire testing laboratories.

Wood Shingles

Untreated wood shingles may be readily ignited by small sparks from chimneys or exposure fires, by radiated heat, or by burning brands. Burning shingles themselves also produce brands, which may be carried by the wind to start other fires. Age and humidity increase the susceptibility of wood-shingled roofs to ignition.

Treatment of wood shingles in place with fire-retardant coatings has not proved practical to date. Ordinary flame-resistant treatments lose their effectiveness with continued exposure to the weather. Wood shingles impregnated with a fire-retardant solution are more durable. Shingles of this type have been tested and carry a Class B or C rating.

Untreated wood shingle roofs are prohibited by law in the congested sections of practically all large cities, and a very large number of cities and towns prohibit their use altogether within municipal limits.

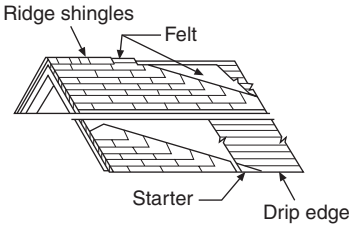


FIGURE 19.1.37 Installation of a Typical Prepared Roof Covering

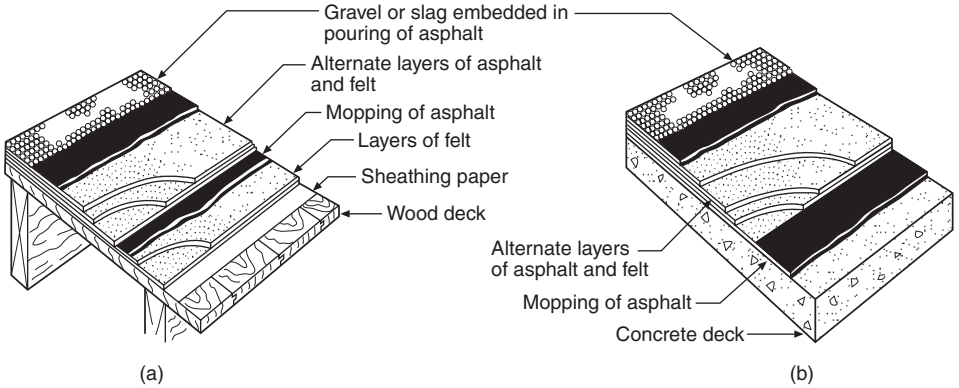


FIGURE 19.1.36 Typical Built-Up Roof Coverings with Hot Asphalt Mopping or Coal Tar Pitch Between Each Two Layers: (a) 5 Ply Built-Up Roof over Wood, (b) 4 Ply Built-Up Roof over Concrete

TABLE 19.1.8 Some Typical Prepared Roof Coverings

Roof Covering[a]	*Minimum/ Maximum Roof Slope, in. per ft*	*Class A*	*Class B*	*Class C*
Brick Concrete Tile Slate	Minimum required for drainage/ unlimited	Brick, 2¼ in. thick Reinforced Portland cement, 1 in. thick Concrete or clay floor or deck tile, 1 in. thick Flat or French-type clay or concrete tile, ⅜ in. thick with 1½ in. or more end lap[b] and head lock, spacing body of tile ½ in. or more above roof sheathing, with underlay of one layer of Type 30 or two layers of Type 15 asphalt-saturated organic felt Clay or concrete roof tile, Spanish or Mission pattern, 7⁄16 in. thick, 3 in. end lap,[b] same underlay as above Slate, 3⁄16 in. thick, laid American method		
Metal roofing	12/unlimited	Sheet roofing of 16 oz copper or of 30 gauge steel or iron protected against corrosion—limited to noncombustible roof decks or noncombustible roof supports when no separate roof deck is provided	Sheet roofing of 16 oz copper or of 30 gauge steel or iron protected against corrosion or shingle-pattern roofings with underlay of one layer of Type 30 or two layers of Type 15 asphalt-saturated organic felt[b]	Sheet roofing of 16 oz copper or of 30 gauge steel or iron, protected against corrosion, or shingle-pattern roofings, either without underlay or with underlay of rosin-sized paper
	¼ (standing seam) or ½ (lap seam)/ unlimited	Standing or lap seam metal panel with glass fiber batts below on steel purling or joints		Zinc sheets or shingle roofings with an underlay of one layer of Type 30 or two layers of Type 15 asphalt-saturated organic felt[b]
Organic felt (previously referred to as *rag felt*) sheet coverings	¼/unlimited			Sheet coverings of asphalt organic felt either grit surfaced or aluminum surfaced
Organic felt (previously referred to as *rag felt*) shingle covering, with special coating	Sufficient to permit drainage[c]	Mineral surfaced, two or more thicknesses	Mineral surfaced, two or more thicknesses	
Organic felt (previously referred to as *rag felt*) shingle coverings	Sufficient to permit drainage[c]	Mineral surfaced, two or more thicknesses	Mineral surfaced, two or more thicknesses	Mineral surfaced shingles, one or more thicknesses

TABLE 19.1.8 Continued

Roof Covering[a]	*Minimum/ Maximum Roof Slope, in. per ft*	*Class A*	*Class B*	*Class C*
Asphalt glass fiber mat shingle coverings	Sufficient to permit drainage[c]	Mineral surfaced, two or more thicknesses	Mineral surfaced, one or more thicknesses	Mineral surfaced shingles, one or more thicknesses
Asphalt glass mat sheet covering	Sufficient to permit drainage[c]			Mineral surfaced
Fire-retardant treated red cedar wood shingles and shakes				Treated shingles or shakes, one or more thicknesses; shakes require at least one layer of Type 15 felt underlayment

Note: Roofing materials containing asbestos are no longer used in the United States; however, they may still be encountered in existing construction.

[a]Prepared roof coverings as classified as applied over square-edge wood sheathing of 1 in. nominal thickness, or the equivalent, unless otherwise specified. See footnotes (built-up roof coverings) to Table 19.1.9. Laid in accordance with instruction sheets accompanying package. Limited to decks capable of receiving and retaining nails. Prepared roofings are labeled by Underwriters' Laboratories to indicate the classification when applied in accordance with direction for application included in package.

[b]*End lap* means the overlapping length of the two units, one placed over the other. *Head lap* in shingle-type roofs is the distance a shingle in any course overlaps a shingle in the second course below it. However, with shingles laid by the Dutch-lap method, where no shingle overlaps a shingle in the second course below, the head lap is taken as the distance a shingle overlaps one in the next course below.

[c]Typically ¼ in. per ft.

For SI units: 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 oz = 0.0284 kg; 1 lb = 0.454 kg.

ROOF DECK INSULATIONS AND VAPOR BARRIERS

Since the 1953 General Motors fire at Livonia, Michigan, major attention has been paid to the combustibility of insulated metal roof decks. In that fire, the asphalt mopping in the felt vapor barrier beneath the insulation on the 1,502,500 ft^2 (139,582 m^2) flat steel-deck roof melted and vaporized. Asphalt vapor under pressure entered the building through the joints in the steel deck and burned inside. As a result of this and similar fires, research was conducted to find a solution to the problem.

The combustibility of a roof was historically determined by the physical characteristics of the roof deck and its supporting structure, with no consideration given to the combustibility of the roof insulation and covering. Thus, combustible fiberboard insulation and asphalt-impregnated felt roof covering normally were not considered to affect the classification of a noncombustible roof deck on noncombustible supports. Large-scale fire tests, confirmed by actual fire experience, however, have shown that under certain conditions some metal deck assemblies can contribute to an interior fire.[4]

A series of full-scale tests was conducted in 1955 at Factory Mutual Research (FMR) testing facilities to compare the performance of various metal roof deck constructions with respect to fire propagation along the underside of the deck. The tests were run in cooperation with the Metal Roof Deck Technical Institute (now Steel Deck Institute) and the Insulation Board Institute, and the results were published in a technical report.[5] With the insulation or vapor barriers adhered to the metal deck with complete moppings of asphalt, it was shown that the asphalt contributed a significant amount of fuel when exposed to the heat of an intensive interior fire below the deck (Figure 19.1.38). The asphalt was vaporized by the heat of the fire below and, unable to escape upward through the roof covering, was forced down through the joints in the deck, when it ignited and contributed to the spread of fire under the roof deck. This type of assembly is called combustible or a Class 2 steel deck. Because of poor wind-loss experience, FM Global no longer recommends using adhesives to secure above-deck components to steel decks. However, other combinations of combustible above-deck components (such as vapor barriers, insulation, and roof covers) may create a Class 2 steel-deck assembly.

Recognized fire testing laboratories now list metal roof deck construction and components that will not contribute significantly to an interior fire and that meet certain performance standards. Such assemblies are called noncombustible, fire-classified, or Class 1 steel decks.

Metal roof deck constructions use both combustible and noncombustible insulation fastened with mechanical fasteners to the upper surface of the deck. Prior to the early 1980s, asphalt was accepted as an adhesive to secure certain insulation to steel decks if it was applied in strips (with a mechanical applicator), and if the total amount used between the deck and the insulation did not exceed 12 to 15 lb per 100 ft^2 (5.4 to 6.8 kg/9.3 m^2) of roof area.

There is no restriction on the use of asphalt in conventional built-up roofing used above the insulation. When a vapor

TABLE 19.1.9 Built-Up Roof Coverings

*Roof Covering**	*Minimum/ Maximum Roof Slope, in. per ft*	*Class A*	*Class B*	*Class C*
Asphalt organic felt, bonded with asphalt and surfaced with 400 lb of roofing gravel or crushed stone, or 300 lb of crushed slag per 100 ft^2 of roof surface, on coating of hot mopping asphalt	¼/2	4 (plain) or 5 (perforated) layers of Type 15 felt 1 layer of Type 30 felt and 2 layers of Type 15 felt 1 layer of Type 15 felt and 2 layers of Type 15 or 30 cap or base sheets 3 layers of Type 15 or 30 cap or base sheets 3 layers of Type 15 felt—limited to noncombustible decks	4 layers of perforated Type 15 felt 3 layers of Type 15 felt 2 layers of Type 15 or 30 cap or base sheets	
Organic felt bonded with tar and surfaced with 400 lb of roofing gravel or crushed stone, or 300 lb of crushed slag per 100 ft^2 of roof surface on a coating of hot mopping tar	¼/2	4 layers of Type 15 organic felt 3 layers of Type 15 organic felt	3 layers of Type 15 organic felt	
Steep tar organic felt	¼/2	4 layers of Type 15 tar-saturated organic felt, bonded with steep coal-tar pitch, surfaced with 275 lb of ⅝ in. crushed slag per 100 ft^2 of roof surface on steep coal-tar pitch		
Asphalt organic felt, plain or perforated, bonded and surfaced with a cold application coating	¼/12			3 layers of Type 15 felt 1 layer of Type 30 felt and 1 layer of Type 15 felt 2 layers of Type 15 or 30 cap or base sheets 2 layers of Type 15 felt and 1 layer of Type 15 or 30 cap or base sheets

Note:

From the standpoint of relative effectiveness of the different types of wood sheathing, the tongue-and-groove boards and ¾ in. moisture-resistant plywood give better results in the brand and flame tests than square-edge sheathing with boards spaced about ¼ in. apart. For classifications based on square-edge sheathing, tongue-and-groove or plywood sheathing can be substituted. Square-edge sheathing boards should be butted together as closely as possible. Reference to ¼ in. spacing is to indicate fire test procedure intended to simulate actual conditions after shrinkage of boards due to age or other reasons.

The minimum weight of cementing material between separate layers of felt is considered to be 25 lb per 100 ft^2 of roof surface.

Types 15 and 30 felts are defined as saturated felts weighing a minimum of 14 lb and 28 lb per 100 ft^2 of the finished materials, respectively. Where saturated felts are referred to be weight, the weight is minimum and is expressed in pounds per 100 ft^2 of the finished material.

Materials intended for built-up roof coverings are labeled by Underwriters Laboratories. The classifications indicated are of generally accepted combinations.

*Built-up roof coverings are classified as applied over square-edge wood sheathing of 1 in. nominal thickness, or the equivalent, unless otherwise specified.

For SI units: 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 ft^2 = 0.0929 m^2; 1 lb = 0.454 kg.

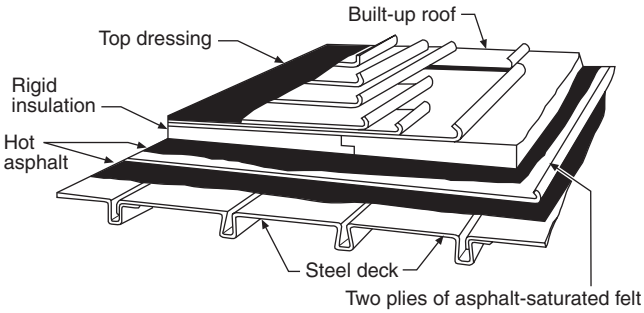


FIGURE 19.1.38 Typical Built-Up Roof Covering with a Combustible Vapor Barrier Adhered to the Roof Deck and to Roof Insulation by a Combustible Adhesive

barrier is used between the deck and the insulation, a listed, noncombustible, or material with limited fuel contribution is recommended. Testing laboratories list various manufacturers of acceptable vapor barriers and adhesives.

FM Global divides insulated metal deck roof assemblies into two classes. Class 1 construction is any insulated steel roof deck construction having a combination of above-deck components that will not contribute significantly to an interior fire and that will meet or equal FMR performance standards. Class 2 construction is any insulated metal roof deck construction using a combination of above-deck components which, when exposed to fire locally, will produce sufficient heat release to allow a self-propagating fire on the underside of an unprotected deck.

Constructions that are found acceptable to FM are listed by FM Global Research.[6] Underwriters Laboratories list those roof deck constructions that have been tested in the UL Building Construction Directory or online at http://database.ul.com.

SUMMARY

Building construction is classified based on the materials used for the structural elements and the degree of fire resistance afforded by each element. In the United States, construction is classified according to subtypes derived from five fundamental construction types: Type I, formerly referred to as fire-resistive construction; Type II, formerly referred to as noncombustible construction; Type III, formerly referred to as exterior protected combustible or ordinary construction; Type IV, formerly referred to as heavy-timber construction; and Type V, formerly referred to as wood-frame construction.

The classification of construction recommended by the MCSC and the BCMC comprises two major groups, noncombustible and combustible, with subtypes based on the fire resistance of the three basic elements of a building: the exterior wall, the primary structural frame, and the floor. The designs of exterior walls, interior walls and partitions, floor framing systems, trusses, floor/ceiling assemblies, roof framing, roof coverings, and roof deck insulations and vapor barriers also play an important role in the fire safety of a building.

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3. FM Global Loss Prevention Data Sheet 1-24, *Protection Against Liquid Damage,* FM Global, Johnston, RI, 2001.
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5. "Insulated Metal Roof Deck Fire Tests," Factory Mutual Research Corp., Norwood, MA, 1955.
6. "Approval Guide," Building Materials Volume, FM Global Research, Norwood, MA (published annually).

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on types of building construction discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*
NFPA *101®*, *Life Safety Code®*
NFPA 220, *Standard on Types of Building Construction*
NFPA 221, *Standard for High Challenge Fire Walls, Fire Walls, and Fire Barrier Walls*
NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 252, *Standard Methods of Fire Tests of Door Assemblies*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 256, *Standard Methods of Fire Tests of Roof Coverings*
NFPA 259, *Standard Test Method for Potential Heat of Building Materials*
NFPA 285, *Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components*
NFPA 703, *Standard for Fire Retardant–Treated Wood and Fire-Retardant Coatings for Building Materials*
NFPA 5000®, *Building Construction and Safety Code®*

Chapter 2

Structural Integrity During Fire

Revised by
Richard J. Davis

Chapter Contents

Fire Resistance Testing
Fire Resistance Tests of Structural Assemblies
Illustrative Fire Resistance Ratings for Structural Frame and Barrier Constructions
Calculating Fire Endurance
Structural Materials at Elevated Temperatures
Fire Behavior of Other Building Materials
Contemporary Trends in Structural Fire Protection

Key Terms

ceiling assembly, fire barrier, fire endurance, fire resistance, fire test, floor assembly, glass, gypsum, partition, prestressed concrete, reinforced concrete, roof assembly, structural assembly, structural frame, structural integrity, structural steel, timber, wall, wood

The selection of building materials and the design of the details of construction always play an important role in overall building fire safety. Two important fire safety considerations regarding the building structure are to minimize the likelihood of collapse of the structural frame during a fire and to ensure that fire barriers remain intact to prevent ignition and fire spread to adjoining spaces.

The following are the three general approaches to structural frame and barrier design for fire resistance that are in use or under development today:

1. Standard fire resistance testing combined with building code requirements
2. Analytical calculations to determine the resistance to a standard fire test exposure as a substitute for laboratory testing
3. Analytical structural fire engineering design methods based on real fire exposure characteristics

The traditional method of treating the structural aspects of fire protection is through building code requirements. Codes generally require structural frames and barrier assemblies to be selected based on ratings determined through standardized laboratory fire resistance tests (approaches 1 and 2 above).

Classification of building construction with regard to fire resistance requirements is an approach that has the principal advantage of being relatively easy to incorporate into the design process and to administer from a code enforcement viewpoint. It has a major disadvantage of being unable to represent the performance of the structural member or fire barrier under the broad range of "real world" fire loads. In other words, code compliance alone is not sufficient to ensure performance success of the barriers or structural frame in an actual fire. Studies that correlate building code requirements and fire test results with field performance need to be further pursued.

Although the century-old approach for determining fire resistance can be criticized for its shortcomings, it is the only method universally accepted in U.S. building codes today. The first part of this chapter describes the fire resistance test procedures common in building construction today. Latter parts of the chapter discuss methods of calculating fire-endurance (resistance) ratings and the behavior of building materials at elevated temperatures. The chapter concludes with a brief discussion of some of the more advanced approaches to designing for structural integrity in a fire.

For related topics, see Section 6, Chapter 3, "Concepts and Protocols of Fire Testing"; Section 18, Chapter 1,"Confinement of Fire in Buildings"; Section 19, Chapter 1, "Types of Building Construction"; Section 19, Chapter 4, "Analyzing Structural Fire Damage"; and Section 19, Chapter 5, "Approaches to Calculating Structural Fire Resistance."

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FIRE RESISTANCE TESTING

The fire resistance rating of the beams, girders, columns, and other members that comprise the structural frame and the fire resistance rating of the walls, partitions, floor/ceiling assemblies, and roof/ceiling assemblies that serve as fire barriers serve as the basis for classifying building construction and codifying frame and barrier capabilities. This part of the chapter describes the history and procedure for standardized fire testing and discusses the interpretation of laboratory fire test results.

History of Fire Resistance Tests

One review of fire test methods for building constructions refers to tests on metal and masonry conducted in Germany as early as 1884–1886.[1] The first large-scale fire tests in this country are reported to have been conducted on masonry arches in Denver, Colorado, in 1890. These were followed by tests in New York City in 1896.

Efforts to establish an acceptable test procedure were initiated by Professor Ira H. Woolson of Columbia University and Rudolph P. Miller, Chief Engineer, Building Bureau, New York City. Preliminary tests by the bureau, "necessitated by the rapid development of the skyscraper," led to the development of a test furnace (using railroad ties as fuel). This provided a means of establishing hourly fire ratings for floor constructions.

After the Baltimore, Maryland, conflagration of 1905, the American Society for Testing and Materials (ASTM) established a committee to standardize the test method, with Woolson as chairman and Miller as secretary. A test method for floor constructions was proposed in 1906 and adopted by ASTM in 1907. A procedure for testing wall and partition constructions was proposed in 1908 and adopted in 1909.[2]

These standards were presented to the NFPA Committee on Fire-Resistive Construction for consideration in 1914. In 1916, a joint committee composed of representatives from eleven engineering societies, including NFPA, was organized to revise and update the standard. This was done, and the revised standard test method controlled by a standard time-temperature curve was adopted subsequently by NFPA, ASTM, and the American Engineering Committee (now the American National Standards Institute [ANSI]). NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials,* was adopted by NFPA as a tentative standard in 1917 and advanced to official standard status in 1918. Time-temperature curves and testing procedures developed in other countries follow the same general pattern, with minor differences. See Section 19, Chapter 5, "Approaches to Calculating Structural Fire Resistance," for discussion of international approaches.

Fire Test Procedures

Fire test procedures usually require that columns, floors, partitions, walls, and other structural elements be loaded in a manner calculated to develop, as nearly as practicable, the theoretical working stresses expected by the structural design. Separate test procedures are provided for load-bearing and non-load-bearing arrangements and for arrangements involving restrained and unrestrained beams and girders.

The Appendices to NFPA 251 contains detailed specifications for test procedures, a guide to the determination of restraint required, if any, and a suggested report form. The standard specifies in detail the preparation and conditioning of the test specimens.

Acceptance criteria are specific for the assembly or structural element tested based on predetermined conditions of test (load or no load, restrained or unrestrained). The criteria include the following:

1. Failure to support load
2. Temperature increase on the unexposed surface 250°F (121°C) above ambient
3. Passage of heat or flame sufficient to ignite cotton waste
4. Excess temperature (as specified) on steel members
5. Failure under hose streams (walls and partitions)

The end restraint conditions during the fire test influence significantly the test results and, consequently, the ratings. Appendix E of NFPA 251 defines a restrained condition as one in which expansion at the supports of a load-carrying element is prevented during the test. A restrained condition is intended to account for some degree of rotational restraint at the ends of the element in addition to prestressing some parts of the assembly. An unrestrained condition is one in which the load-carrying element is free to expand and rotate at its supports.

One justification for incorporating two differing means of end restraint is to simulate simple (statically determinant) and continuous (statically indeterminant) conditions. Figure 19.2.1 illustrates simple and continuous arrangements. All else being

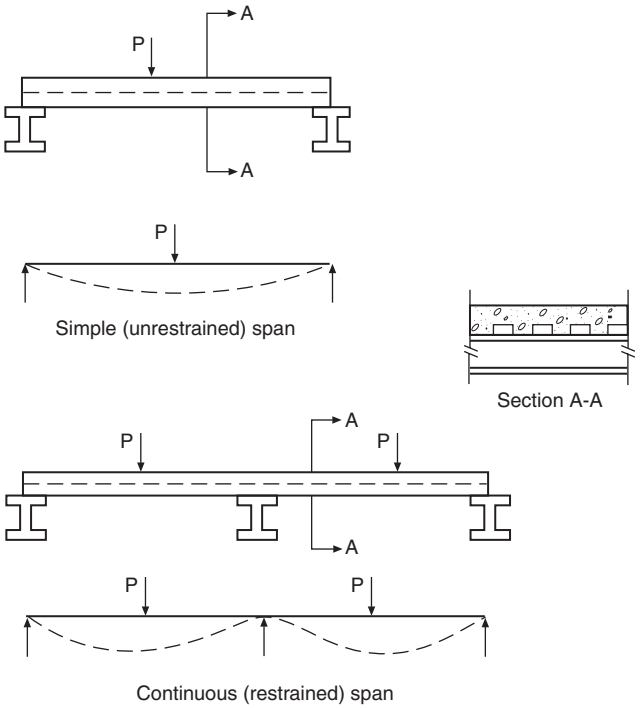


FIGURE 19.2.1 Influence of Structural Continuity on Collapse Mechanisms

equal, continuous span construction is inherently stronger than simple span construction. It is possible to calculate the increase in load-carrying capacity of statically indeterminant structural members. However, the amount of increased strength in an indeterminant structure can be quite variable, depending on the type of construction materials used, the location of structural members within the structure, the degree of indeterminance, the loading conditions, and the details of construction.

Requirements to evaluate structural members based on restrained and unrestrained conditions were introduced in standardized fire testing in 1970. The degree of restraint for structural members and assemblies tested and accepted for building construction prior to 1970 is unknown.

Fire Resistance Ratings

Fire resistance ratings represent the time duration the structural member or assembly withstood the fire test without failure. Although the actual time is recorded to the nearest integral minute, fire resistance ratings are given in standard intervals. The usual fire resistance ratings for all types of structural members and assemblies are 15 minutes, 20 minutes, 30 minutes, 45 minutes, 1 hour, 1½ hours, 2 hours, 3 hours, and 4 hours. Therefore, a 1 hour rating indicates that the assembly withstood the standard test for 1 hour or longer. A 2 hour rating indicates that the assembly withstood the standard test for a minimum of 2 hours without failure of any of the criteria listed in the fire test protocol.

Some agencies in the United States that test assemblies of building construction materials for fire resistance are Underwriters Laboratories Inc. (UL), Omega Point, Southwest Research Institute, and Intertek Testing. A number of other organizations have furnaces or equipment for conducting fire tests of various special assemblies. Some of these include the Forest Products Laboratory at Madison, Wisconsin; University of California at Berkeley; Armstrong Cork Co., Lancaster, Pennsylvania; and the National Gypsum Co., Buffalo, New York. Some of these test facilities may not conform to the specifications described in NFPA 251. Consequently, those facilities may be used more for research purposes rather than for establishing fire resistance ratings.

The results of fire tests conducted by Underwriters Laboratories Inc., Omega Point, Southwest Research Institute, and Intertek Testing are published in company directories, which are now available in electronic as well as in print formats. The *Fire Resistance Directory* is published by UL. Omega Point, Southwest Research Institute, and Intertek Testing each have their own *Directory of Listed Products.* FM Approvals has access to a facility to conduct the tests and publishes the results in its *Approval Guide.* These guides and directories have illustrations of building assemblies that have met the test criteria for specific fire resistance hourly ratings.

The results of fire tests conducted by governmental agencies have been published in various reports and technical papers. Those issued by the National Institute of Standards and Technology (NIST) may be consulted in many depository libraries, and lists of those available may be obtained from NIST. In Canada, there are facilities at the Underwriters Laboratories of Canada in Toronto and the Building Research Division of the National Research Council of Canada in Ottawa. Throughout the world, many well-equipped fire-testing laboratories are making significant contributions to the literature and to the development of international fire test standards.

In Europe, there are a number of public and private facilities available. Some of the facilities that have furnaces include the Centre Technique Industriel da la Construction, Metz, France; Netherlands Organization for Applied Scientific Research, Ja Delft, Netherlands; Danish Institute of Fire and Security Technology, Hvidovre, Denmark; Federal Institute for Materials Research and Testing, Berlin, Germany; University of Ghent, Ghent, Belgium; Warrington Fire Research Center, Warrington, UK; Timber Research and Development, Buckinghamshire, UK; Swedish National Testing and Research Institute, Borås, Sweden; VTT Technical Research Centre of Finland, Espoo, Finland; and The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology, Trondheim, Norway. The bulletins and reports of the British Ministry of Technology on the subject are obtainable by purchase from H. M. Stationery Office or the British Information Services, New York. Throughout the world, many well-equipped fire-testing laboratories are involved with determining structural fire resistance.

Building codes may include tabulations of construction assemblies that will be accepted as meeting code requirements for terms of fire test results and may include tabulations of construction forms that will be accepted as meeting code requirements for specific fire resistance ratings. Such tables are usually based upon fire test data, but some include ratings determined by experience, judgment, and extrapolation of specific test data.

Not included are the many useful data sheets and summaries published by trade associations of the building materials manufacturers. These sources are not cited because they are so numerous and because the information published either pertains to the products of a specific manufacturer or consists of tabulated ratings for a single type of construction material.

The number of test facilities in use today and the variety of published test results make it almost impossible to tabulate in a single useful form all the data on the various assemblies that have been tested. Users of this handbook are urged to consult the fire resistance directories and reports mentioned previously for the specifics on design specifications for assemblies that have been tested and for which fire resistance ratings have been assigned.

As a matter of information and to illustrate the scope of testing activities, tabular compilations of test results or representative assemblies will be found later in this chapter. They are included in this handbook to help give an understanding of basic requirements for test specimens and how the results of tests are recorded. In addition, the information contained in the tables can be useful in identifying, within reasonable limits, the fire resistance capabilities of assemblies as they are found in the field and for which precise data on their fire resistance are not available or are no longer available. The tables are not presented as references for design but to familiarize handbook users with the type of test information available.

Variations in Test Results

The standard fire test attempts to provide a relative measure of fire performance of comparable assemblies under uniform fire exposure conditions. It does not consider suitability for use after the fire. Many effects from fire tests are observed indirectly, if at all. For example, the temperature gradient through a wall or floor slab results in internal strains and deflections. The strains may cause spalling or other disruptions, and distortions may be severe enough to crack floor slabs and walls, sometimes leading to collapse or excessive heat transmission. The greater the area exposed, the more serious are the results of unequal expansion. General deterioration of the test specimen is not considered when determining the fire resistance rating, except when it contributes to the failure of the test specimen.

It should be recognized that the fire resistance rating is the amount of time the member of assembly withstood a standard laboratory fire test. It is not necessarily the time duration the assembly will perform without failure under actual fire conditions. For example, a 2 hour assembly can withstand failure for at least 2 hours when subjected to the standard fire test exposure. Under actual field conditions, the same assembly may fail in a considerable shorter or longer time duration. One of the major misconceptions in fire protection is the belief that an assembly rating indicates the time that the assembly will survive an actual fire. Rather, it is the time the assembly survived, without failure, the fire test exposure. Differences between the standard test and field conditions can be substantial.

The fact that test-time duration and field performance may be vastly different is not intended to demonstrate that fire resistance ratings do not have value or purpose. Over the years this procedure has resulted in improved fire performance of code-complying buildings. However, one must understand the limitations of the procedure so that unrealistic reliance is not placed on the construction.

Although the test standard specifies the preparation and conditioning of specimens, there are many opportunities for differences between a test specimen and an actual structural element in the field. The test specimen may be superior in both materials and workmanship to those found in the field; the test specimen is usually smaller than the construction assembly it represents. Restraints to thermal expansion may be of different magnitudes. Therefore, discretion in the interpretation of fire test results is in order. Differences in the results of fire tests on apparently equal test specimens of building constructions arise from many factors, such as undetermined differences in the quality of materials, workmanship, moisture content, and test procedures. While the standard method of test requires that materials in the specimen and the workmanship be representative of those in actual buildings, considerable variation in field practice can occur.

The test method permits the intensity of the fire exposure to deviate as much as 10 percent (formerly 15 percent) from that prescribed as standard and requires adjustment in the reported results to correct for such deviations only for tests of ½ hour duration or greater. The effects of several of the variables encountered in fire testing procedures are found in the technical reports listed in the bibliography at the end of the chapter.

The character and proportions of aggregates and binders have an important influence on the results of fire resistance tests. For example, gypsum plaster with lightweight aggregates, mixed with 2 to 3 ft^3 (0.057 to 0.085 m^3) to each 100 lb (45 kg) of gypsum, provides fire resistance from 10 to 70 percent greater than equal thicknesses of sanded gypsum plaster. The use of such aggregate in specific constructions should be adopted only after consulting the publication of ratings based on tests in which these aggregates have been used.

Vermiculite aggregate plaster, if too wet when applied, may be subject to shrinkage cracks. Such cracks, if they develop, are likely to occur within a short time. Some expanded perlite aggregates tend to absorb atmospheric moisture and may show destructive expansion after a few years. There may be considerable variation in this effect, as perlite is a natural volcanic glass or rock from many sources and varies in composition.

Finishing lime produced from dolomite contains magnesium oxide. That which is designated as "normal" finishing hydrate may not be sufficiently hydrated, and sometimes subsequent gradual hydration results in destructive expansion. Plasters containing such lime are subject to rapid destruction in the event of fire. This difficulty is avoided with lime hydrated under high temperature and pressure and known as "special" or "autoclaved" lime.

So-called stabilized gypsum plaster containing a small percentage of the normal hydrated lime may similarly be subject to deterioration with age and, in tests, may not provide the fire resistance to be expected from such constructions.

The effects mentioned are not such as to preclude the use of these materials where long life is not a factor or where adequate guarantees are provided. They are merely illustrations of the variability in test results that can occur as a result of differences in materials.

Although standard fire tests are made on fairly large specimens representative of building constructions or assemblies, they do not necessarily produce heat-expansion effects similar to those of fires in buildings having larger wall or floor areas. It may be necessary to specify thickness of construction or lateral support in addition to rated fire resistance to guard against the adverse effects of heat expansion or temperature gradients.

In addition to the material variation noted, construction differences may be even more significant. For example, a test does not provide full information on performance of assemblies constructed with components or lengths other than those tested. Performance is often reduced when the spans are increased. Also, approving "or equal" clauses in construction specifications need to be thoroughly evaluated. Sometimes substitutions in materials are approved for components that have not been listed with the assembly. Consideration also needs to be given to the connection methods used in constructing the various elements of the assembly.

The standard test does not incorporate information regarding the effect on fire resistance of conventional openings in the assembly, such as electrical receptacle outlets, pipe chases, and so on. Poke-through construction for electrical services or piping often is not patched properly. Transfer grilles, windows, and other penetrations are often incorporated into barriers without considering their impact on fire resistance.

The factors noted above, in addition to the many deviations to plans and specifications during and after construction,

significantly affect the fire resistance of members and assemblies. Often the code calls for—and the designer may think he or she is providing—a specified fire resistance, only to have that resistance reduced because of inattention to penetrations and important details of construction.

FIRE RESISTANCE TESTS OF STRUCTURAL ASSEMBLIES

Structural Frame Systems

The fire resistance rating of structural framing members, such as beams, girders, and columns, may be achieved in several ways. Generally, the members are protected by encasing them in a material with sufficient insulating qualities to prevent excessive thermal penetration or by providing a membrane protection that delays thermal penetration to the members. The general behavior of reinforced concrete, structural steel, and barrier assemblies are described in the following paragraphs. Illustrative fire resistance ratings are shown in tabular form later in this chapter.

Reinforced Concrete Systems

Reinforced concrete construction has exhibited good performance with regard to its ability to withstand structural collapse. Because concrete has a low thermal conductivity and a low thermal capacity, it provides an effective cover for reinforcing steel. For example, Figure 19.2.2 shows the temperature gradient in a 6 in. (152 mm) slab after a 2 hour fire exposure.[3] Although undoubtedly the moisture in the concrete greatly influences the values, the significant feature is the fact that the temperatures vary considerably throughout the thickness, even after a considerable time exposure.

This feature provides some insight into one reason that reinforced-concrete systems usually perform comparatively well during fire exposure. Consider, for example, a continuous, monolithic reinforced-concrete beam or slab, as shown in Figure 19.2.3. Considering the temperature gradient of Figure 19.2.2, it will take some time before the tension steel at midspan is affected. Even after the tension steel at midspan reaches its yield value, the steel reinforcement in the negative moment region near the top of the beam or slab over the supports has not been seriously affected because of the insulating effect of the concrete and the moisture.

Continuous (restrained) construction of this type has inherent capabilities far greater than statically determinant (simple unrestrained) construction. Considerable stress redistribution can take place before collapse will occur. It takes time before excessive rotation will develop at all the necessary locations, causing structural collapse of the restrained member. Although the member is weakened by the fire, structural stability against collapse will remain for a considerable period of time.

The level of stress in a reinforced-concrete member exposed to the elevated temperatures of a fire has a significant influence on its fire resistance. A series of tests was conducted on 15 in. × 15 in. (381 mm × 381 mm) columns with four number-nine reinforcing bars.[3] Each column was loaded at a different percentage of the design load. Table 19.2.1 illustrates the effects of stress level on the fire resistance of reinforced-concrete columns. It can be seen that the magnitude of stress during a fire causes significant reductions in capacity. This is attributed primarily to the reduction in the mechanical properties of steel and concrete at elevated temperatures.

Steel Construction

The popularity of steel-frame building construction is due to its high strength, ease of fabrication, and ensured uniformity of quality. Exposed structural steel, however, is vulnerable to fire

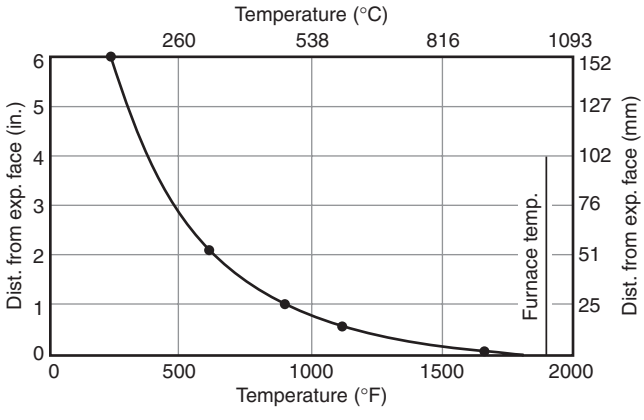


FIGURE 19.2.2 Thermal Gradient in a 6 in. Slab After 2 Hour Fire Exposure. For SI units: 1 in. = 25.4 mm; °C = ⅝ (°F – 32).

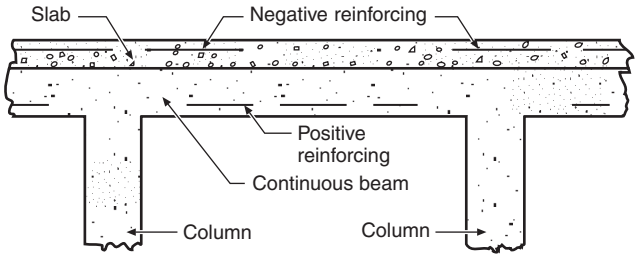


FIGURE 19.2.3 Monolithic Reinforced-Concrete Beam and Slab

TABLE 19.2.1 Influence of Stress on Fire Resistance of Concrete Columns

Applied Load (% Design Load)	*Fire Resistance (min)*
150	68
100	124
75	198
50	248
30	358

damage. In order to possess fire resistance, it must be protected from high temperatures encountered in fires with other materials. Protection for steel beams, girders, and columns, such as encasements of concrete, clay, tile, masonry, or gypsum blocks, has been generally superseded by plastered or sprayed-on applications applied either to a furred plaster base, such as expanded metal lath, or directly to the surface of the member to be protected. The applications may be conventional plasters of portland or gypsum cements combined with appropriate aggregates, or one of the many combinations of mineral fibers with binders. Gypsumboard encasement is a popular technique for protecting steel structural elements. Deliberate efforts must be taken to ensure that the materials used to protect the steel members from fire are maintained and not removed for the installation of hangers, supports, and other purposes.

Barrier Systems (Walls and Partitions)

Exterior walls, interior partitions, floors, and floor/ceiling assemblies are components that define the functional layout of rooms and spaces in a building. In the normal functional use of a building, these components are used to provide privacy, security, protection from the elements, and noise control. They can also provide fire protection by delaying or preventing heat and particles of combustion from spreading throughout the building.

The effectiveness of a barrier in preventing fire spread depends on several factors. One is fire severity, which is influenced by the fuel in the space, as well as the size and location of openings, the size of the room, and the thermal properties of the wall and ceiling construction. The fire severity represents the thermal load applied to the barrier surface. The performance of the barrier is affected by the materials of construction, as well as other factors such as the applied structural loads, the details at connections, and the dimensions. Of even greater importance is the effect of openings and penetrations in the barrier. The most common cause of fire spread from one room to an adjacent room is through unprotected openings in barriers. Information on protection of openings can be found in NFPA 80, *Standard for Fire Doors and Other Opening Protectives.* Often code requirements and expensive constructions are rendered ineffective because of lack of attention to the details of opening protection.

Building codes through construction classifications identify the fire resistance requirements of barriers. In addition, special locations, such as around vertical shafts, are required to provide specific resistances. Fire resistance ratings are determined by subjecting the barrier assembly to a standard fire test, as described in NFPA 251. The length of time the assembly withstands the laboratory fire without failure describes the fire resistance and is similar to how ratings are obtained for structural building elements. Both combustible and noncombustible barriers can obtain fire resistance ratings in the standard fire test.

The limitations expressed earlier in this chapter with regard to the interpretation of the fire resistance time durations also apply here. That is, the time durations reflect laboratory times and are not necessarily the values to be expected in a real fire. For example, one should not expect a 2 hour barrier assembly to withstand an actual building fire for 2 hours. Failure could occur earlier or later, depending on construction details.

Many fire tests are stopped arbitrarily before an end-point criterion has been attained. In some cases, the indications are that, had the test been continued, the construction would have qualified for a higher fire resistance rating than that assigned to it. For a more detailed discussion of fire barrier systems, see Section 18, Chapter 1, "Confinement of Fires in Buildings," NFPA 221, *Standard for High Challenge Fire Walls, Fire Walls, and Fire Barrier Walls,* and *NFPA 5000®, Building Construction and Safety Code®*.

Floor/Ceiling Assemblies

The fire resistance of floor/ceiling assemblies is important in the prevention of flame movement vertically from floor to floor. Fire resistance ratings from the standard fire test are determined from unpenetrated assemblies. The anticipated fire resistance may be reduced greatly or eliminated in building construction when holes and poke-throughs are not protected adequately or when details do not conform to the tested assembly.

The method of attaching ceilings is a major factor in determining the fire resistance of floors. For example, the nailing of gypsum lath, metal lath, or gypsum wallboards to the soffits of wood joists is often critical in plaster construction. The longer, thinner nails, particularly those with cement coatings, conduct less heat to char the wood surrounding them than do the common types of wire nails. Similarly, the integrity of suspended ceilings must be maintained to reduce the likelihood of premature failure on some assemblies. Details such as attention to expansion of the supporting framework are essential to preventing premature ceiling failures.

Self-tapping screws, made particularly for the attachment of gypsumboard, offer greater holding power and less damage to the core materials than do nails. Such screws can be used to attach wallboards to either wood or cold-rolled channels without previous drilling.

Consideration must also be given to the character of the plaster base with respect to loosening of plaster mixes from the base on application of heat sufficient to char combustible surfaces. The use of wire or, better yet, wire fabric to reinforce the plaster mixes applied to such plaster bases ensures increased fire resistance. Clearances for longitudinal expansion of metal furring members are required to prevent damage from buckling. The tendency of certain plaster bases and plaster mixes to expand or contract with changes in atmospheric humidity should also be given consideration where resultant cracking might affect the fire resistance of structures incorporating such plaster.

Suspended ceilings with openings for air diffusers and light troughs should be designed so that such openings are not points of vulnerability to fire. Continuous construction above recesses for lighting fixtures and properly designed self-closing dampers for air ducts provide protection.

Roof/Ceiling Assemblies

Roof/ceiling assemblies are tested and rated in a manner similar to the floor/ceiling assemblies. The results are generally comparable. However, it should be noted that roof assemblies often have a given thickness of insulation in place at the test. If ad-

ditional thicknesses of insulation are desired, the fire resistance rating may be reduced.

ILLUSTRATIVE FIRE RESISTANCE RATINGS FOR STRUCTURAL FRAME AND BARRIER CONSTRUCTIONS

Fire resistance testing has produced a large amount of performance data. To illustrate the effect of materials and construction materials on the fire resistance rating of assemblies and structural members, several graphs and tables are included. These graphs and tables can be used to give guidance on the needs to achieve fire resistance ratings and to provide a basis for interpretations of the fire resistance of construction encountered in field evaluations.

TABLE 19.2.2 Reinforced-Concrete Beams and Girders of Medium Size

Concrete Grade[a]	*Protective Cover of Reinforcement (in.)*	*Fire Resistance Rating*[b] *(hr)*
	¾	1
	1	2
1	1¼	3
	1½	4
	¾	½–1[c]
	1	1–2[c]
2	1½	2–3[c]
	2	2–4[c]

[a]For lightweight concrete having an oven-dried density of 110 pcf or less, the cover shown for concrete Grade 1 may be reduced 25 percent.
[b]May be increased if some bars are better protected by being away from corners or in an upper layer or if beam is large. Should be decreased if beam is small.
[c]Variable depending on spalling characteristics of aggregate. The use of mesh to hold cover in place will give ratings about as high as for concrete of Grade 1.
For SI units: 1 in. = 25.4 mm.

Reinforced-Concrete Members

The details of construction and the kind of aggregates affect the fire resistance of concrete structures. The fire resistance ratings for reinforced concrete beams are given in Table 19.2.2 and for prestressed concrete girders, beams, joists, and slabs in Table 19.2.3. As the cold-drawn, high-strength steel tendons used in prestressed concrete are more adversely affected by high temperatures than normal reinforcement steel, these tendons require a thicker protective cover than is required in conventional reinforced concrete. The fire resistance of reinforced concrete columns is shown in Table 19.2.4.

Structural Steel Members

As previously noted, fire resistance generally is provided for structural steel by encasing the members in concrete, lath and plaster, gypsumboard, or spray-applied cementitious or material fiber coatings. Another common method of providing fire resistance is by installing a membrane barrier to delay or prevent the heat from raising the temperature of the steel to critical failure temperatures. Table 19.2.5 gives minimum thicknesses of portland cement encasement for steel beams, whereas Tables 19.2.6 and 19.2.7 illustrate the influence on the fire resistance of columns for various methods of encasement. Figures 19.2.4 and 19.2.5 illustrate different methods of encasement for steel columns. Figure 19.2.6 provides a means to estimate the necessary encasing requirements for steel columns.

TABLE 19.2.3 Prestressed Concrete Girders, Beams, Joists, and Slabs (Grade 1 Concrete)

Type of Unit	*Condition of Restraint*	*Cross-Sectional Area (in.²)*[b]	Cover for Fire Rating Shown (in.)[a]			
			1 hr	*2 hr*	*3 hr*	*4 hr*
Girders, beams, and joists	Unrestrained	40 to 150	2	2.5	—	—
		150 to 300	1.5	2.5	3.5[c]	—
		Over 300	1.5	2.25	3[c]	4[c]
	Axially restrained	40 to 150	1.5	2	—	—
		150 to 300	1	1.5	2	—
		Over 300	1	1.5	1.5	2
Slabs, solid or covered, with flat undersurface	Unrestrained		1	1.5	2	2.5
	Biaxial restraint		0.75	1.25	1.5	2

Note: Data in this table are based on 67 standard ASTM fire tests.
[a]Cover for an individual steel tendon is measured to the nearest exposed surface. For several tendons in the same member having different concrete covers, the minimum cover may be reduced slightly. The covers shown may be reduced 25 percent for lightweight concrete having an over-dried density of 110 pcf or less. For Grade 2 concrete, the cover may need to be increased.
[b]In computing the cross-sectional area of joists, the area of the flange must be added to the area of the stem, but the total width of the flange so used must not exceed three times the width of the stem.
[c]Provide against spalling of the cover by means of a light, 2-in., U-shaped mesh, covered about 1 in.
For SI units: 1 in. = 25.4 mm; 1 in.^{2} = 645 mm^2.

TABLE 19.2.4 Fire Resistance of Reinforced-Concrete Columns*

Column				Concrete			Reinforcement							
	Section		Load	Aggregates		Mix	Vertical			Lateral		Concrete Cover	Fire Resistance	
No.	*(in.)*	*Area (in.²)*	*in 1000 lb*	*Fine*	*Coarse*	*Cement Fine Coarse*	*Number*	*Bar Size No.*	*(in.²)*	*Diam. (in.)*	*Spacing (in.)*	*Thickness*	*hr*	*min*
70	16 × 16	256	101	Fox River sand	Chicago limestone	1:2:4	4	9	4.00	¼	12	2¼	8 (13+	40 —)
71	16 × 16	256	101	Long Island sand	New York trap rock	1:2:4	4	9	4.00	¼	12	2¼	7	22
72	17 dia	227	107.5	Fox River sand	Chicago limestone	1:2:4	6	9	6.00	¼	12	2½	8 (12+	04 —)
73	17 dia	227	107.5	Long Island sand	New York trap rock	1:2:4	6	9	6.00	¼	12	2½	7	57
74	17 dia	227	129	Fox River sand	Chicago limestone	1:2:4	6	6	2.64	¼	1½	2¼	8 (13+	06 —)
75	17 dia	227	129	Long Island sand	New York trap rock	1:2:4	6	6	2.64	¼	1½	2¼	8	02
25	16 × 16	256	92	Pittsburgh sand	Pittsburgh gravel	1:2:4	4	8	3.16	¼	12	1½	4 (6	— 30)
44	16 × 16	256	92	Long Island sand	Pure quartz gravel	1:2:4	4	8	3.16	¼	12	1½	4 (6	— —)
51	16 × 16	256	92	Pittsburgh sand	Blast furnace slag	1:2:4	4	8	3.16	¼	12	1½	4 (8	— —)
56	16 × 16	256	92	Pittsburgh sand	New Jersey trap rock	1:2:4	4	8	3.16	½	12	1½	4 (7	— —)
7	18 dia	254	99.75	Pittsburgh sand	Pittsburgh gravel	1:2:4	8	6	3.52	¼	12	1½	5 (6	— —)
2	18 dia	254	141	Pittsburgh sand	Pittsburgh gravel	1:2:4	8	6	3.52	3/16	2	1½	4	—
48	18 dia	254	141	Pittsburgh sand	Blast furnace slag	1:2:4	8	6	3.52	3/16	2	1½	4 (10+	— —)
85	18 dia	254	141	Elgin, IL, sand	Elgin, IL, sand	1:2:4	8	6	3.52	3/16	2	1½	4 (12+	— —)
12	18 dia	254	81	Pittsburgh sand	Pittsburgh gravel	1:2:4	None	—	—	—	—	—	4	—
33	12 dia	113	51	Pittsburgh sand	Pittsburgh gravel	1:2:4	4	5	1.24	¼	2⅛	1½	Avg. 3	of 2 —

*Column Nos. 70 to 75 tested at UL. Test No. 70 of the group was stopped at 8 hours 40 minutes; others at failure or at 8 hours, and all loaded to failure at end of fire exposure (NBS Tech. Paper 184). All other columns tested at NBS Laboratory at Pittsburgh, PA. The fire endurance test of Col. No. 7 stopped at 5 hours, all others of series stopped at 4 hours. Figures in parentheses are estimates of fire resistance if tests had continued to failure (NBS Tech. Paper 272).

For SI units: 1 in. = 25.4 mm; 1 in.² = 645 mm²; 1 lb = 0.45 kg.

TABLE 19.2.5 Concrete Protection for Steel Beams (All re-entrant portions filled)

Fire Resistance Rating		Thickness of Concrete Protection (in.)							
		Grade 1 Size of Member (Flange Width)				Grade 2 Size of Member (Flange Width)			
hr	*min*	*2 to 3¾ in.*	*4 to 5¾ in.*	*6 to 7¾ in.*	*8 in. and over*	*2 to 3¾ in.*	*4 to 5¾ in.*	*6 to 7¾ in.*	*8 in. and over*
4	—	4	3¼	2½	2	4¾	3¾	3	2½
3	—	3½	2½	2	1½	4	3	2½	2
2	—	2½	2	1½	1	3	2½	1¾	1¼
1	30	2	1½	1	1	2½	1¾	1¼	1
1	—	1½	1	1	1	1¾	1¼	1	1

Note: Protective concrete having thickness one-fourth of flange width or less must have steel wire reinforcement spaced nor more than four times the thickness of the concrete covering the flange.
For SI units: 1 in. = 25.4 mm.

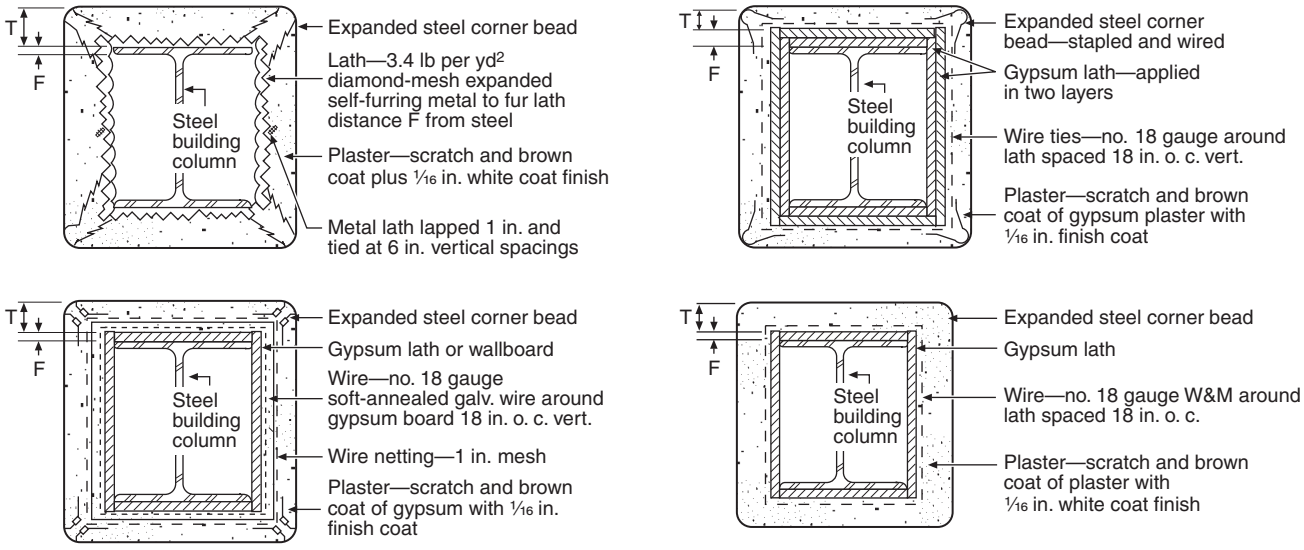


FIGURE 19.2.4 Typical Steel Column Protection of Lath and Plaster Assemblies. For SI units: 1 in. = 25.4 mm; 1 lb = 0.454 kg.

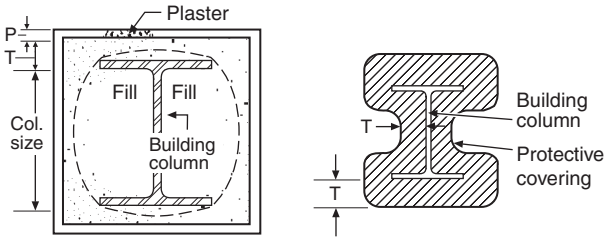


FIGURE 19.2.5 Typical Steel Column Protection of Concrete, Masonry, or Sprayed Fibers

Floor/Ceiling Assemblies

Fire resistance for floor/ceiling assemblies of reinforced concrete, structural steel, and wood can be achieved in several ways. For example, Figure 19.2.7 illustrates the influence of floor thickness and aggregate type on the fire resistance of reinforced-concrete slabs, whereas Table 19.2.8 shows the fire resistance for several types of concrete floor constructions. Table 19.2.9 shows the test results for structural steel joist floor and roof constructions, and Table 19.2.10 provides some data on the fire resistance of steel-formed concrete floor systems.

TABLE 19.2.6 Fire Resistance of Steel Columns with Lath and Plaster Protective Coverings

Metal Column					Protective Covering						Total Area of Materials ($in.^2$)	Fire Resistance Rating		
					Type of Covering									
					Plaster									
Type of Section	Size (in.)	Weight per Lin Ft (lb)	Area of Metal ($in.^2$)	Design	Type	Aggregate	Mix, Volumes	Thickness T^b (in.)	Furring T^b (in.)	Bond of Covering		hr	min	Notes
H	6	44	13	—	Portland cement and lime	Sand	1:1/10:2½	⅞	1	Metal lath	40	—	45	Metal lath furred out
H	6	31	9	—	Two thicknesses of above	Sand	1:1/10:2½	⅞ + ⅞	1 & 1	Metal lath	80	1	30	Metal lath furred out
H	10	49	14.5	A	Gypsum-cement mixture	Lightweight[a]	Mill mix	1¾	⅜	Wire fabric	125	3	25	
H	10	49	14.5	A	Gypsum	Lightweight[a]	Mill mix	1⅞	⅝	Metal lath	125	4	—	½-in. channel behind lath
H	10	49	14.5	A	Gypsum	Lightweight[a]	1½:2 1½:3	1¾	⅜	Metal lath	125	4	—	Self-furring lath
H	10	49	14.5	A	Gypsum	Lightweight[a]	1½:2 1½:3	1⅜	⅜	Metal lath furred out	102	3	—	Self-furring lath
H	10	49	14.5	A	Gypsum	Lightweight[a]	1½:2 1½:3	1	⅜	Metal lath	78	2	—	Self- furring lath
H	10	49	14.5	B	Gypsum	Lightweight[a]	½:3½ ½:4	2⅛	½	18-gauge wire and wire fabric	145	4	—	Gypsum
H	10	49	14.5	C	Gypsum	Lightweight[a]	1½:2 1½:3	1½	1	18-gauge wire and wire fabric	140	4 to 15 4 to 40		Gypsum lath
H	10	49	14.5	B	Gypsum	Lightweight[a]	1½:2½	1½	½	18-gauge wire and wire fabric	110	3	40	Gypsum lath
H	10	49	14.5	D	Gypsum	Lightweight[a]	1:2½	½	⅜	18-gauge wire ties	53	1	20	Perforated gypsum lath
H	10	49	14.5	D	Gypsum	Lightweight[a]	1:2½	⅝	⅜	18-gauge wire ties	60	1	30	Perforated gypsum lath
H	10	49	14.5	D	Gypsum	Lightweight[a]	1½:2 1½:3	1	⅜	18-gauge wire ties	80	2	15	Perforated gypsum lath
H	10	49	14.5	D	Gypsum	Lightweight[a]	1½:2 1½:3	1½	⅜	18-gauge wire ties	104	2	30	Perforated gypsum lath
O	7	51	15.5	—	Portland cement and lime	Sand	1:1/10:2½	1¼	⅞	⅞-in. rib lath	70	2	45	Metal lath on cast column

[a]Lightweight aggregate can be either perlite or vermiculite.
[b]Dimensions as shown in Figure 19.2.4.
For SI units: 1 in. = 25.4 mm; 1 $in.^2$ = 645 mm^2; 1 ft = 0.305 m; 1 lb = 0.454 kg.

TABLE 19.2.7 Fire Resistance of Steel Columns Encased with Concrete, Masonry, or Sprayed Fibers

Steel Column			Protective Covering							Fire Resistance Rating		
Type of Section	*Size (in.)*	*Weight per Lin Ft (lb)*	*Design*	*Type of Covering*	*Thickness Outside Steel TI (in.)*	*Reentrant Portion Filled*	*Plaster Thickness (in.)*	*Section Area of Solid Material ($in.^2$)*	*Bond of Covering*	*hr*	*min*	*Notes*
H	8[e]	34		None	0	No	0	8	—	—	10	Bare column
H	6[e]	20	E	Siliceous gravel concrete, 1:2½:3½ mix	2	Yes	0	100	8 gauge wire spiral 8 in. pitch	3	30	NBS test
Plate and angle	6[e]	34	E	Trap rock or cinder concrete, 1:6 mix[a]	2	Yes	0	130	6 gauge wire spiral	3	45	UL test
H	8[e]	34	E	Limestone concrete, 1:6 mix[a]	2	Yes	0	144	6 gauge wire spiral	6	30	UL test
H	8[e]	34	E	Limestone concrete, 1:6 mix[a]	4	Yes	0	256	6 gauge wire spiral	7	30	UL test
H	8[e]	34	E	Trap rock, granite, cinders, 1:6 mix[a]	4	Yes	0	256	6 gauge wire spiral	7	—	UL test
Plate and angle	6[e]	34	E	Gypsum concrete[b]	2	Yes	½	114	4 in. mesh fabric	6	30	NBS test gypsum plaster
Plate and angle	6[e]	34	E	Gypsum block	2	No	½	107	1 by ⅛ in. O clamps Block bond	4	—	NBS test gypsum plaster
Plate and angle	6[e]	34	E	Cinder block	3¾	Yes	¾	240	Brick bond	7	—	NBS test gypsum plaster
H	8[e]	34	E	Common brick	4¼	Yes	0	270	Wire ties	7	—	UL test
H	8[e]	34	E	Semi-fire clay hollow tile	2	No	0	96	Wire ties	1	30	UL test
H	8[e]	34	E	Semi-fire clay hollow tile	4	No	0	158	No special adhesive	1	30	UL test
H	10[e]	49	F	Sprayed mineral fiber[c]	2¼	Yes	—	164	Special adhesive	5	—	
H	10[e]	49	F	Sprayed mineral fiber[c]	3⅜	Yes	—	238	Special adhesive	5	—	
H	8[e]	28	F	Sprayed mineral fiber[c]	2	Yes	—	44	No special adhesive	5	—	
I	8[e]	28	F	Sprayed asbestos fiber[c]	2	Yes	—	38	No special adhesive	3	—	
	8[e]	35	E	Sprayed asbestos fiber[c]	1	Yes	—	90	No special adhesive	2	—	
	8[e]	35	E	Sprayed asbestos fiber[c]	1¾	Yes	—	98	No special adhesive	4	—	
	8[e]	35	E	Sprayed asbestos fiber[c]	1⅞	Yes	—	120	No special adhesive	4	—	
I	8[e]	28	F	Sprayed asbestos fiber[c]	1½	Yes	—	28	—	2	—	UL test
O	7.6[f]	24		None (bare steel pipes filled with concrete)[d]	0	Yes	0	46		—	35	UL test

[a]Concrete mix—1 part cement to 6 parts total aggregate including sand and coarse aggregate.
[b]Gypsum concrete—7 parts gypsum stucco to 1 part wood shavings, by weight.
[c]Mineral fibers, with bonding agent as required, sprayed on to all surfaces of column shaft to thicknesses indicated. (Thickness different on account of characteristics of fiber and binder.)
[d]Concrete-filled columns require vent holes to prevent explosion in the event of fire.
[e]Approximate depth, flange width per Table 19.2.5.
[f]Inside diameter.
For SI units: 1 in. = 25.4 mm; 1 $in.^2$ = 645 mm^2; 1 ft = 0.305 m; 1 lb = 0.454 kg.

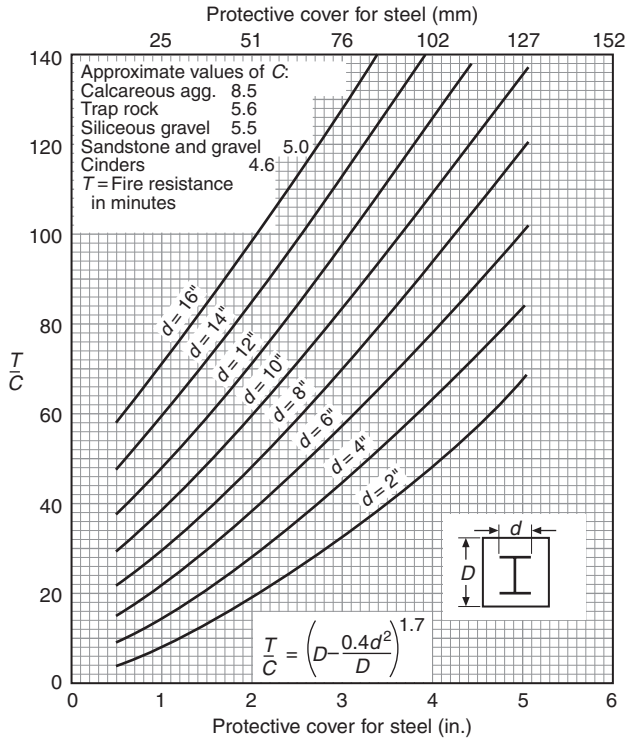


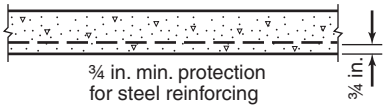
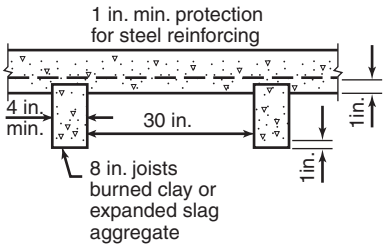
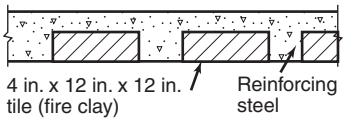
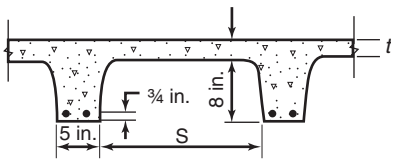
FIGURE 19.2.6 Encasing Requirements of Steel Columns and Other Free-Standing Steel Members. For SI units: 1 in. = 25.4 mm.

FIGURE 19.2.7 Fire Resistance Ratings of Reinforced-Concrete Floors of Varying Thicknesses. The dotted line represents concrete floors made with regular aggregates, and the solid line represents lightweight concretes.

Walls and Partitions

Walls and partitions are commonly constructed of masonry, wood, or metal studs faced with fire-resistant materials. Table 19.2.11 gives the fire resistance of load-bearing brick or clay tile walls. Figure 19.2.8 shows a graph that allows the fire resistance of burned clay brick walls to be estimated. Tables 19.2.12 and 19.2.13 provide fire resistance ratings for wood stud walls, whereas Figure 19.2.9 gives the fire resistance of stud walls

TABLE 19.2.8 Concrete Floor Constructions

Materials	Fire Resistance Rating *hr*	*min*
Reinforced Concrete (free or partly restrained, 1500–2500 psi)		
		
3 in. thick	—	45
4 in. thick	1	15
6 in. thick, 1 in. minimum protection for steel	2	—
Reinforced Concrete on Precast Joists		
		
Reinforced concrete, 1:3½:4, 3 in. thick, no ceiling	45	—
Reinforced concrete, 1:3½:4, 3 in. thick, ceiling of gypsum wallboard ½ in. thick, nailed to wood, strips wired to joists	1	—
Combination of Tile and Concrete Floors		
		
Concrete 2 in. or 1½ in. thick, and fire clay tile 6 in. or 4 in. thick, no ceiling finish	1	—
Concrete 1½ in. thick, and tile 4 in. thick with gypsum-sand plaster ceiling finish, 1:3 mix, ⅝ in. thick	1	30
Concrete 2 in. thick, and fire clay tile 6 in. thick with gypsum plaster ceiling finish, 1:3 mix, ⅝ in. thick	2	—
Concrete 2½ in. thick, limestone aggregate 4 in. thick, expanded slag concrete tile	3	—
Reinforced Concrete Ribbed Slab		
		
Concrete, ribbed slab, limestone aggregate, t = 1½ in., S = 20 in.	—	20
Concrete, ribbed slab, limestone aggregate, t = 2½ in., S = 20 in.	—	45
Same with metal lath and ⅞ in. gypsum-sand plaster ceiling, 1:2, 1:3 mix	2	30
Concrete, ribbed slab, limestone aggregate, t = 3 in., S = 30 in.	1	—

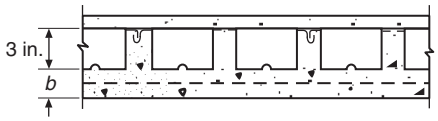
For SI units: 1 in. = 25.4 mm; 1 psi = 6.89 kPa.

TABLE 19.2.9 Steel Joist Floor or Roof Constructions

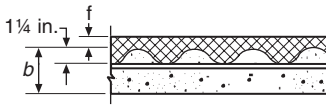
Joists							Fire Resistance Rating	
Type	*Depth (in.)*	*Floor Slab*	*Thickness (in.)*	*Furring*	*Ceiling Kind*	*Thickness (in.)*	*(hr)*	*(min)*
I or S[a]	8	T & G wood flooring on 2 in. by 2 in. wood strips	25/32	3.4 lb metal lath	Gypsum—sand plaster	¾	—	45[b]
I or S[a]	8	T & G wood flooring on 2 in. by 2 in. wood strips	1⅝	3.4 lb metal lath	Gypsum—sand plaster	¾	1[b]	—
I or S[a]	8	Reinforced concrete, precast concrete, or gypsum planks	2	3.4 lb metal lath	Gypsum—sand or portland cement-sand plaster	¾	1	—
S	8	Reinforced concrete or precast gypsum tile	2¼	3.4 lb metal lath	Gypsum—sand plaster, 1:2; 1:3 mix	¾	2	—
S	10	Reinforced concrete or reinforced gypsum tile or planks	2	3.4 lb metal lath	Neat[h] gypsum, or gypsum-vermiculite plaster, 1:2; 1:3	1¾	2	30
S	10	Reinforced concrete	2½	3.4 lb metal lath	Gypsum—sand plaster	⅞	2	30
		Reinforced concrete	2½	3.4 lb metal lath	Gypsum-perlite of gypsum-vermiculite plaster, 1½:2; 1½:3	¾	3	—
S	8	Reinforced concrete perlite or vermiculite aggregate	2½	3.4 lb metal lath	Gypsum-perlite or gypsum-vermiculite plaster, 1½:2; 1½:3	¾	3	—
S	10	Reinforced concrete, 1:2:4 gravel aggregate	2½	3 lb metal lath	Gypsum-vermiculite or gypsum-perlite plaster,1½:2; 1½:3	1	4	—
S	10	Reinforced concrete, 1:2:4 gravel aggregate	2	Gypsum lath[c]	Gypsum-perlite or gypsum-vermiculite plaster, 1½:2½	⅝	1	—
S	10	Reinforced concrete, 1:2:4 gravel aggregate	2	Gypsum and wires[c,d]	Gypsum-perlite or gypsum-vermiculite plaster, 1½:2½	½	2	—
S	10	Reinforced concrete, 1:2:4 gravel aggregate	2	Gypsum[c,e]	Gypsum-vermiculite or perlite plaster, 1½:2; 1½:3	1	4	—
S	10	Reinforced concrete, 1:2:3.4 gravel	2½	Gypsum and wires[c,d]	Sprayed-on mineral fiber	¾	3	—
S	10	Reinforced concrete, 1:2.5:3.5 gravel	2	Special Z section[f]	Special acoustical tiles (see UL list)	⅝	2	—
S	12	Reinforced concrete, gravel aggregate	2	Nailing channels 16 in. o.c. 2¾ in. × ⅞ in.	Type X[g] wallboard	⅝	1	30
S	12	Reinforced concrete, 1:3:3⅔ gravel aggregate	2	26 gauge 14 in. o.c. channels	Type X[g] wallboard applied with No. 6 by 1 in. wallboard screws	⅝	1	30
S	10	Reinforced concrete, 1:2:4 gravel aggregate	2	25 gauge nailing channels 16 in. o.c.	Gypsum wallboard applied with 1¼ in. long barbed nails ⅜ in. diam. head	⅝	1	—

[a]I-beam or open-web type joists.
[b]Combustible construction.
[c]All gypsum lath ⅜ in. perforated type.
[d]Gypsum lath and No. 20 gauge wires attached to nailing channels. Wires attached diagonally to reinforce and support lath and plaster.
[e]1 in. hexagonal mesh wire fabric to reinforce plaster and hold up lath and plaster.
[f]Special No. 25 gauge galvanized steel Z runners 12 in. o.c.
[g]Type X gypsum wallboard designates gypsum wallboard with a specially formulated core that provides greater fire resistance than regular gypsum wallboard of the same thickness.
[h]Unsanded wood-fiber plaster.
For SI units: 1 in. = 25.4 mm; 1 lb = 0.454 kg.

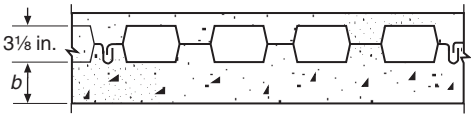
TABLE 19.2.10 Floors of Concrete on Steel Floor and Form Units (Plaster or Sprayed-On Fire Protective Covering)



Type A



Type B



Type C

Type of Floor Unit	*Thickness of Floor (in.)*	*Furring*	*Protective Covering Material*	*Application*	*Thickness (in.)*	Fire Resistance Rating *hr*	*min*
A	5⅝	None	Mineral fibers applied to floor units	Sprayed	½ to 2	5	—
C	5½	None	Same	Sprayed	1½	5	—
A	5⅝	None	Vermiculite or perlite acoustical plastic	Sprayed	1 1/16 to 3 1/16	4	—
B	4½	None	Same	Sprayed	4	—	—
B	4½	[a]	Gypsum-vermiculite or perlite plaster	Troweled or sprayed	⅜ to 1⅝	4	—
C	4	None	Mineral fiber applied to floor units	Sprayed	¾	3	—
A	5⅝	None	Vermiculite acoustical plastic, cellular floor units	Sprayed	½ to 2	2	—
B	5¼	None	None[b]	—	—	2	—
B	4¼	None	None[c]	—	—	1	—
A	8	[d]	Gypsum-vermiculite or perlite plaster, 100 lb gypsum to 2 ft^3 for scratch coat and 3 ft^3 for browncoat plaster, white finish 1/16 in.	Troweled	⅜	4	—
A	8	[d]	Same	Troweled	1	5	—
A	6⅝	[e]	Acoustical tiles, T & G edges with saw kerfs	Sheet metal clips	¾	4	4

[a]Expanded metal lath tack welded or tied to bottom of corrugated steel floor units.
[b]Floor slab, limestone concrete, 5¼ in. thick.
[c]Floor slab, limestone concrete, 4¼ in. thick.
[d]24 gauge, 3.4 lb, ⅜ in. mesh expanded metal lath suspended 2½ to 7½ in. below floor units.
[e]Special furring system to which acoustical tiles are clipped 10¾ in. below floor units.
For SI units: 1 in. = 25.4 mm; 1 lb = 0.454 kg; 1 ft^3 = 0.0283 m^3.

TABLE 19.2.11 Load-Bearing Brick and Clay Tile Walls

Material	*Wall Thickness (in.)*	*Solid Content of Walls (percent)*	Hollow Units *Number of Cells in Wall Thickness*	Hollow Units *Thickness of Shells of Unit (in.)*	Fire Resistance Ratings (hr) Combustible Members Framed 4 in. into Wall *No Plaster*	Combustible Members Framed 4 in. into Wall *Plaster on Two Sides*	No Combustible Members Framed into Wall *No Plaster*	No Combustible Members Framed into Wall *Plaster on Two Sides*
Brick, clay, or shale	12	90 to 100	—	—	8	9	10	12
	10[a]	72	2 in. cavity	—	2	2½	5	7
Load-bearing hollow tile (not partition tile)	8	90 to 100	—	—	2	2½	5	7
	4[b]	90 to 100	—	—	—	—	1	1½
	12	45	3	0.7	2½	3½	3	6
	12[c]	48	4	⅝	2½	4	5	7½
	10[a]	36	2 + 2 in. cavity	—	—	1¼	—	4
	8	48	3 or 4	—	1	1¾	2½	3½
	8	40	2	—	¾	1½	2	3
	6[b]	40	2	⅝	—	—	¾	1½

[a]Cavity wall with metal ties across cavity.
[b]Non-load-bearing wall restrained in all edges.
[c]Two units, 8 in. by 12 in. by 12 in. 6-cell and 3¾ in. by 12 in. by 12 in. 3-cell tiles, in wall thickness.
For SI units: 1 in. = 25.4 mm.

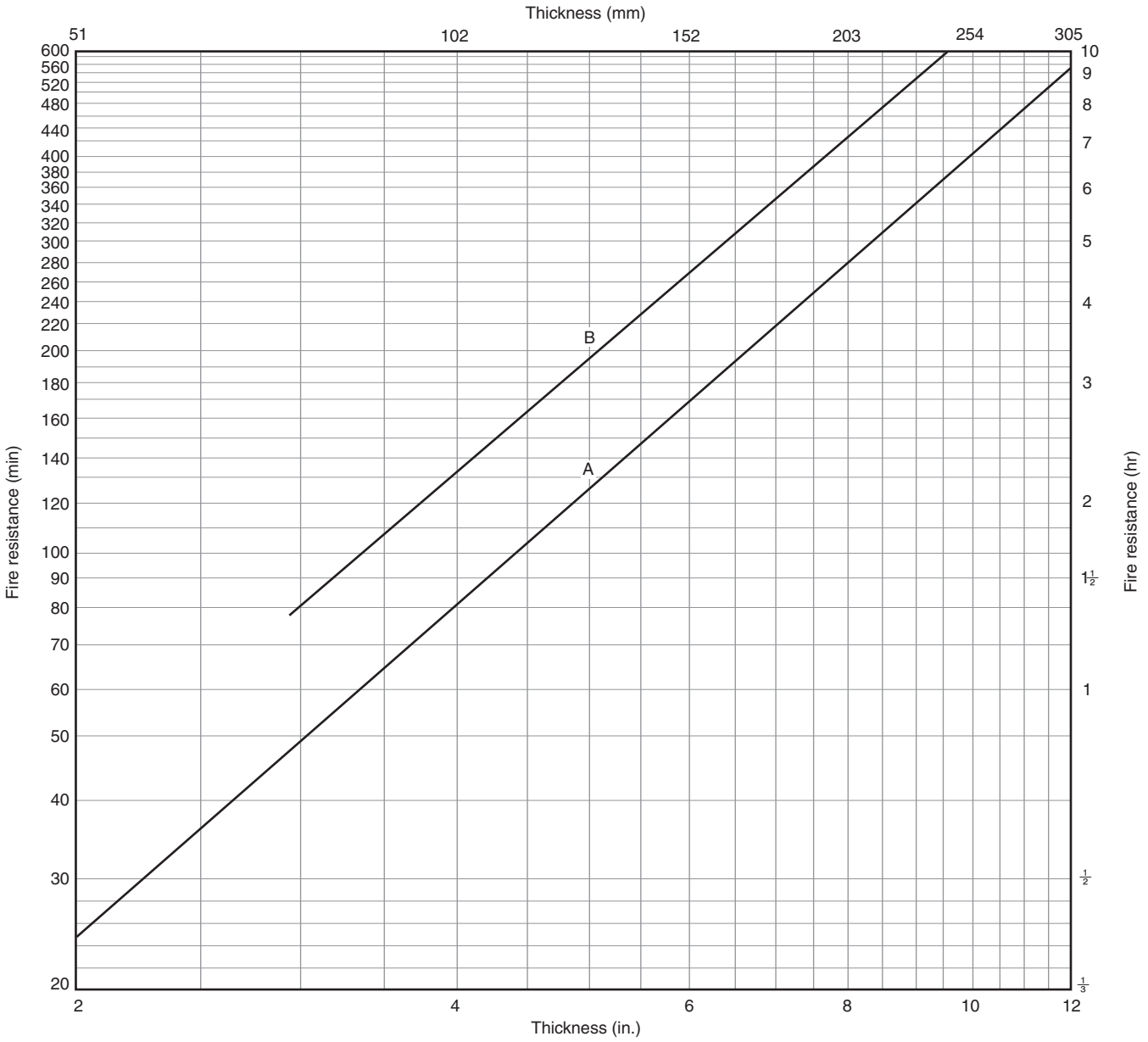


FIGURE 19.2.8 Fire Resistance of Burned Clay Brick Walls: (A) Unplastered; (B) Plastered Both Sides

faced with common construction materials and can be used to estimate quickly and conveniently. Table 19.2.14 and Figure 19.2.10 are very useful descriptions of the fire resistance of solid, non-load-bearing partition materials.

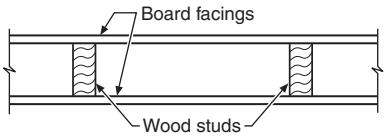
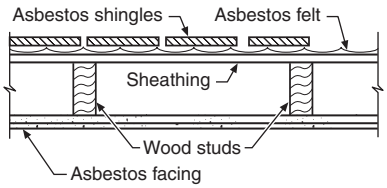
CALCULATING FIRE ENDURANCE

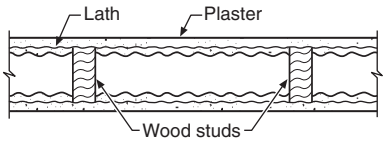
As previously noted, the traditional approach to structural fire protection is by specification of fire resistance ratings through building and safety regulations. Structural members and assemblies are evaluated to the standard fire test (NFPA 251) to establish fire resistance ratings.

Over the past five decades, a substantial amount of research has been conducted on behavior of structural elements in fires. One development is the use of computer models to approximate compartment fire behavior, heat transfer, and structural performance at elevated temperatures. These models utilize scientific research on mechanical and thermal properties of materials at elevated temperatures with some having undergone a degree of validation. This research and computer model application resulted in a broader range of predictions of structural behavior in fires than has been possible with only the traditional code and standard fire test procedures.

A fairly recent development occurred in 1999 when the American Society of Civil Engineers (ASCE) and the Society of Fire Protection Engineers (SFPE) published a jointly developed standard intended for the calculation of fire resistance of structural elements. ASCE/SFPE 29, *Standard Calculation Methods for Structural Fire Protection,* provides the methods of

TABLE 19.2.12 Wood Stud Walls and Partitions (Combustible) (Bearing and nonbearing: 2 in. by 4 in. studs spaced 16 in. on center, firestopped)

Material	Fire Resistance Rating: Partition Hollow hr	Partition Hollow min	Partition Filled with Mineral Wool* hr	Partition Filled with Mineral Wool* min
Plasterless Types of Construction				
				
The following are applied to both sides of studs:				
Sheathing boards (tongue-and-groove) ¾ in. thick	—	20	—	35
Gypsum wallboard, ⅜ in. thick	—	25	—	—
Gypsum wallboard, ½ in. thick (non-load-bearing only for mineral wool filled)	—	40	1	—
Gypsum wallboard, ⅜ in. thick, in two layers each face	1	—	—	—
Gypsum wallboard, ½ in. thick, in two layers each face	1	30	—	—
Gypsum wallboard, ½ in. thick, Type X, one layer each face	—	45	—	—
Gypsum wallboard, ⅝ in. thick, Type X, one layer each face	1	—	—	—
Gypsum wallboard, ⅝ in. thick, Type X, on fire retardant wood fibreboard, ½ in. thick	1	—	—	—
Fir plywood, ¼ in. thick	—	10	—	—
Fir plywood, ⅜ in. thick	—	15	—	—
Fir plywood, ½ in. thick	—	20	—	—
Fir plywood, ⅝ in. thick	—	25	—	—
Cement-asbestos board, 3/16 in. thick	—	10	—	40
Cement-asbestos board, 3/16 in. thick, on gypsum wallboard, ⅜ in. thick	1	—	—	—
Cement-asbestos board, 3/16 in. thick, on gypsum wallboard, ½ in. thick	1	25	—	—
Exterior Bearing Wall				
				
Outside: Cement-asbestos shingles, 5/32 in. thick, on layer of asbestos felt on wood sheathing, ¾ in. thick, on wood studs; inside: Cement-asbestos facing, ⅛ in. thick on fiberboard, 7/16 in. thick	—	30	—	—
Outside: Gypsum sheathing, ½ in. thick; inside 1:2 gypsum-sand plaster, ½ in. thick on ⅜ in. perforated gypsum lath	1	30	—	—

Material	Fire Resistance Rating: Partition Hollow hr	Partition Hollow min	Partition Filled with Mineral Wool* hr	Partition Filled with Mineral Wool* min
Plaster and Lath Construction				
				
The following are applied to both sides of studs:				
Gypsum-sand plaster, 1:2, 1:3, ½ in. thick on wood lath	—	30	1	—
Lime-sand plaster, 1:5, 1:7.5, ½ in. thick on wood lath	—	30	—	45
Gypsum-sand plaster, 1:2, 1:2, ½ in. thick on ⅜ in. perforated gypsum lath	1	—	—	—
Gypsum-sand plaster, 1:2, 1:2, ¾ in. thick on metal lath	1	—	1	30
Gypsum lath, ½ in. thick, Type X, and ⅛ in. gypsum-sand plaster, each face	1	—	—	—
Gypsum wallboard, ½ in. thick, Type X, and 1/16 in. gypsum plaster, each face	1	—	—	—
Portland cement-lime-sand plaster, 1:1/30: 2, 1:1/30:3 and asbestos-fiber plaster, ⅞ in. thick on metal lath	1	—	—	—
Gypsum-vermiculite, or perlite plaster, 100 lb gypsum to 2½ ft^3 aggregate, ½ in. thick on ⅜ in. perforated gypsum lath	1	—	—	—
Gypsum perlite plaster, 1:2, ¾ in. thick on metal lath	1	—	—	—

*Mineral wool fill requires some degree of anchorage so as to be held in place after partition facing has been burned away.

For SI units: 1 in. = 25.4 mm; 1 lb = 0.454 kg; 1 ft^3 = 0.0283 m^3.

TABLE 19.2.13 Various Finishes over Wood Framing, One Side (Combustible) with Exposure on Finish Side

Material	*Fire Resistance Rating[a] (min)*
Fiberboard, ½ in. thick	5
Fiberboard, flameproofed, ½ in. thick	10
Fiberboard, ½ in. thick, with ½ in.-1:2, 1:2 gypsum-sand plaster	15
Gypsum wallboard, ⅜ in. thick	10
Gypsum wallboard, ½ in. thick	15
Gypsum wallboard, ⅝ in. thick	20
Gypsum wallboard, laminated, two ⅜ in.	28
Gypsum wallboard, laminated, one ⅜ in. plus one ½ in. thick	37
Gypsum wallboard, laminated, two ½ in. thick	47
Gypsum wallboard, laminated, two ⅝ in. thick	60
Gypsum lath, plain or indented, ⅜ in. thick, with ½ in.-1:2, 1:2 gypsum-sand plaster	20
Gypsum lath, perforated, ⅜ in. thick, with ½ in.-1:2, 1:2 gypsum-sand plaster	30
Gypsum-sand plaster, 1:2, 1:3, ½ in. thick, on wood lath	15
Lime-sand plaster, 1:5, 1:7.5, ½ in. thick, on wood lath	15
Gypsum-sand plaster, 1:2, 1:2, ¾ in. thick, on metal lath (no paper backing)	15
Neat gypsum plaster, ¾ in. thick on metal lath (no paper backing)[b]	30
Neat gypsum plaster, 1 in. thick, on metal lath (no paper backing)[b]	35
Lime-sand plaster, 1:5, 1:7.5, ¾ in. thick, on metal lath (no paper backing)	10
Portland cement plaster, ¾ in. thick, on metal lath (no paper backing)	10
Gypsum-sand plaster, 1:2, 1:3, ¾ in. thick, on paper-backed metal lath	20

[a]From National Bureau of Standards BMS-92.
[b]Unsanded wood-fiber plaster.
For SI units: 1 in. = 25.4 mm.

calculating the fire resistance ratings that are equivalent to the results obtained from the standard fire test method (NFPA 251, ASTM E119). The calculation methods in ASCE/SFPE 29 are used as an alternative to the laboratory test results. These calculation methods are applicable only to structural steel, plain and reinforced concrete, timber and wood, concrete masonry, and clay masonry. Limitations of applicability are also identified.

Calculation methods offer advantages in economy and better predictability over the traditional test approach. The calculation methods may be grouped into two categories: (1) calculation of the fire endurance that would have been obtained in the standard fire test and (2) calculation of structural or thermal performance in an actual building fire compartment. Careful consideration must be given when using the latter category. If

TABLE 19.2.14 Solid Partitions: Nonbearing

Materials	Fire Resistance Rating *hr*	Fire Resistance Rating *min*
Sheathing planks (tongue-and-groove), in 2 layers, each ¾ in. thick (1 in. nominal) and with joints staggered	—	15[a]
Same, with layer of 30 lb asbestos felt between planks	—	25[a]
Planking, pine (tongue-and-groove), 2 in. thick (nominal), wet vertically	—	12[a]
Wallboard, ⅜ in. gypsum, full height facings on two thicknesses ½-in. coreboard, full height, cemented with staggered vertical joints to form 1¾ in. thick partition, external joints finish taped	1	—
Wallboard, ⅝ in. gypsum, Type X[c], full height facings, cemented and nailed or screwed to ribs made of two thicknesses of ½ in. gypsumboard 3½ or 6½ in. wide and 1 in. by ⅝ in. wood runners top and bottom, external joints finish taped	1	—
Wallboard, ½ in. gypsum, full height, nailed and cemented to 1 in. thick coreboard factory laminated from two ½ in. thick by 24 in. wide coreboards with staggered edges, external joints staggered, butted and finish taped with joint finisher	2	—
Gypsum tile, 3 in. thick, cored	2	—
Gypsum tile, 4 in. thick, cored	2	—
Gypsum tile, 3 in. solid, no cores	3	—
Gypsum tile, 3 in. cored, ½ in. of 1:3 gypsum-sand plaster on each side	3	—
Gypsum tile, 4 in. cored, ½ in. of 1:3 gypsum-sand plaster on each side	4	—
Gypsum-vermiculite or perlite plaster, 1½:2, 1½:3 by vol., ¾ in. thick on each side of 1½ in. gypsum lath, vertical full height, tied to floor and ceiling runners, no studs	1	30
Gypsum-sand plaster, 1:2, 1:3 by wt, ¾ in. thick on each side of ½ in. gypsum lath vertical full height, tied to floor and ceiling runners, no studs	1	—
Partition tile, burned clay, 4 in. thick, 1 cell in thickness	—	10[b]
Cinder block, 4 in. thick, solid	1[b]	—
Cinder block, 6 in. thick, 1 cell in thickness	1	15[b]
Calcareous gravel concrete tile, 4 in. thick, 65 percent solid	—	45[c]
Calcareous gravel concrete tile, 8 in. thick, 55 percent solid	2	30

[a]Combustible.
[b]When plastered on both sides with ½ in. 1:3 gypsum-sand plaster, the tile partition described has 45 minute fire resistance and the cinder block and 4 in. concrete tile assemblies described have 2 hour fire resistance.
[c]Type X gypsum wallboard designates gypsum wallboard with a specially formulated core that provides greater fire resistance than regular gypsum wallboard of the same thickness.
For SI units: 1 in. = 25.4 mm; 1 lb = 0.454 kg.

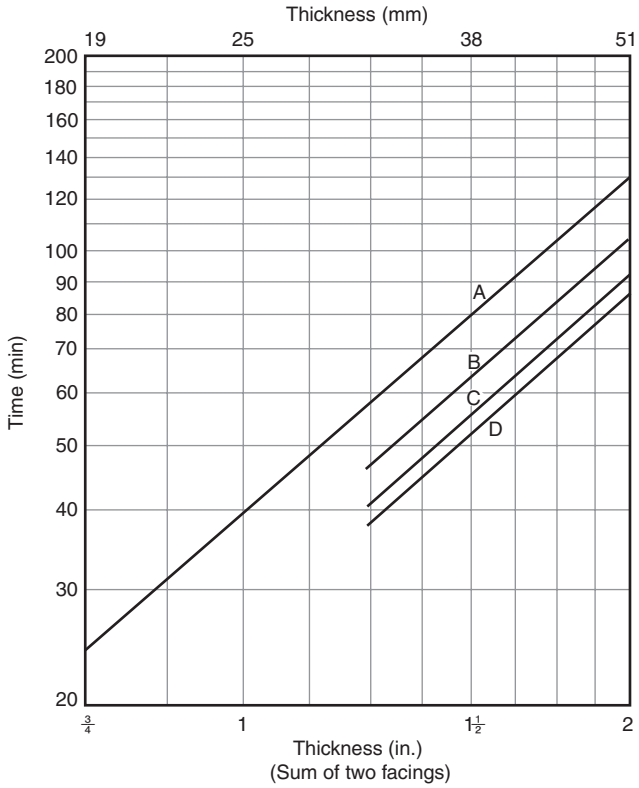


FIGURE 19.2.9 Fire Resistance of Wood or Metal Stud Partitions Faced with Gypsum Wallboards or Gypsum Plaster on Metal Lath: (A) Type X gypsum wallboards or wood fiber gypsum plaster; (B) 1:1 gypsum-sand plaster; (C) 1:2 gypsum-sand plaster; and (D) 1:2 and 1:3 gypsum-sand plaster

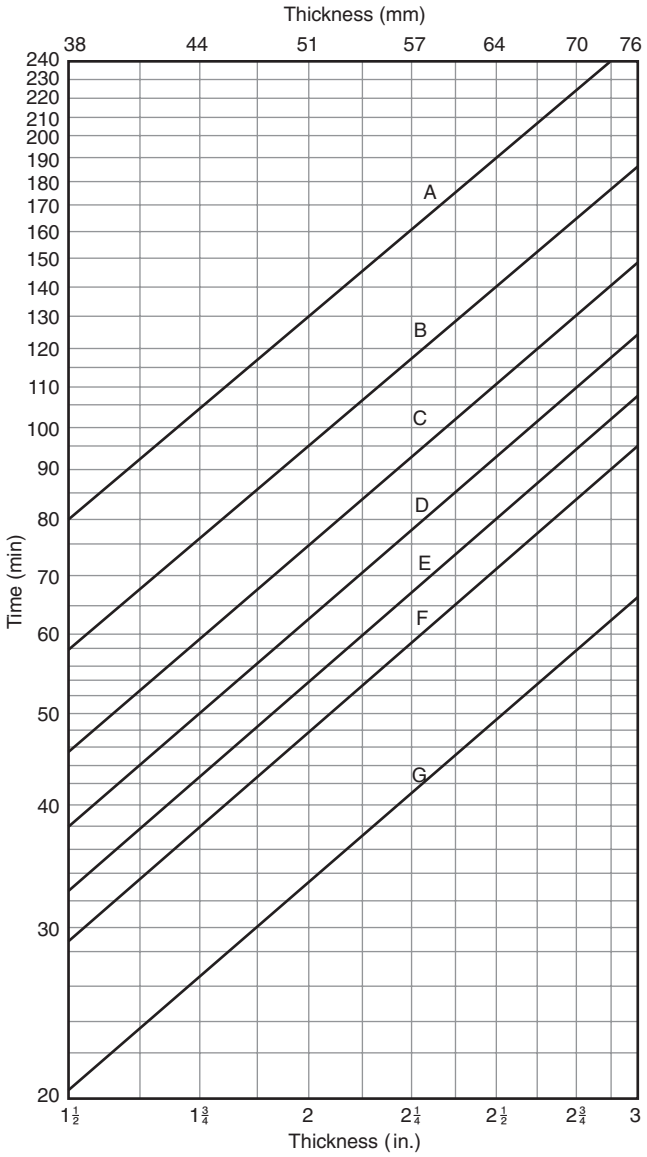


FIGURE 19.2.10 Fire Resistance of Solid Partitions of Metal Lath and Plaster: (A) wood fiber gypsum; (B) 1:½ gypsum-sand; (C) 1:1 gypsum-sand; (D) 1:1½ gypsum-sand; (E) 1:2 gypsum-sand; (F) 1:2 and 1:3 gypsum-sand; (G) 1:2 and 1:3 Portland cement + 0.2 lime to cement

a wall is calculated for a certain duration using a less severe fire (thermal) load and the occupancy changes (increased fire loading), the expected fire resistance of the wall with the new occupancy must be recalculated.

Building code requirements specify fire resistance ratings as reflected by the standard fire test. Consequently, it has been beneficial to develop methods to calculate the fire resistance that would have been obtained in the standard fire test. Illustrative equations and graphs for this type of evaluation are given later. A brief description of procedures to calculate performance in actual building fires is given at the end of this chapter.

Equivalent Fire Endurance of Structural Steel

As noted previously, fire testing has been ongoing for many years, yielding a large amount of data and experience. The procedures described here reflect the type of methods that will enable equivalent fire resistance to be calculated. It should be noted that many of these calculation methods are obtained from test data. Consequently, one should be critical when applying these methods to materials that have not been used in the tests that were the basis for the calculation procedures. For example, the data for structural steel has been based on testing of A7 or A36 structural steel. High-strength steels have become popular. The mechanical properties of high-strength steels at both normal and elevated temperatures are different from those of A7 and A36 steel. Consequently, for fire resistance calculations, when the term *structural steel* is used in this section, A7 and A36 steels are intended.

The fire resistance of structural steel beams and columns can be improved by insulating the members. Equation 1 calculates the fire resistance of steel columns protected by light insulation.[4,5] The members may be protected by boxing the slope or by a contour protection. The equation is:

$$R = \left(C_1 \frac{M}{D} + C_2\right) l \qquad (1)$$

where

R = Fire endurance (min)

M = Mass of the member (lb/ft)

D = Heated perimeter (in.)

l = Thickness of protection (in.)

C_1, C_2 = Constants that are empirically derived for the insulating units

In SI units:

$$R = \left(0.672C_1\frac{M}{D} + 0.039C_2\right)l \qquad (1m)$$

where

R = Fire endurance (min)

M = Mass of the member (kg/m)

D = Heated perimeter (mm)

l = Thickness of protection (mm)

C_1, C_2 = Empirical constants, the same as used for U.S. customary units

The heated perimeter, D, varies depending on whether the structural member is a column or beam. It also varies depending on the shape of the member and whether the coating is directly applied to the contour of the member, or in a box fashion.

Most commonly, insulating materials will have densities less than 20 lb/ft^3. For the cementitious material in UL Design Nos. X701, X704, X722 and X723, $C_1 = 69$ and $C_2 = 31$. For the mineral fiber material in UL Design Nos. X801, X807, X818, X821 and X822, $C_1 = 63$ and $C_2 = 42$.

Empirical coefficients that should be used for other coatings can be found in the AISC Steel Design Guide 19.[6] It should be noted that the version of the above formula used in that document calculates the fire resistance in hours instead of minutes (as done in the original derivation), so the values of the coefficients have been adjusted accordingly. The formula for determining the heated perimeter (D, in.) for beams and columns in contour or box profiles, can also be found in that document.

For insulating materials, such as mineral fibers, vermiculite, and perlite, having densities r in the range of 20 to 50 lb per ft^3 (32 to 80 kg/m^3), the factors C_1 and C_2 are:

$$C_1 = \frac{1200}{r}, \text{ and } C_2 = 30$$

For insulating materials of the same range of densities but incorporating cement pastes or gypsum, the factors C_1 and C_2 are:

$$C_1 = \frac{1200}{r}, \text{ and } C_2 = 72$$

To calculate the fire resistance of columns boxed with gypsum wallboard, the total weight of the column plus wallboard must first be calculated using the following formula:

$$W' = W + \frac{50\,(hD)}{144}$$

where

W' = Total weight of the column plus wallboard

W = Weight of steel shape (lb/ft)

h = Thickness of gypsum wallboard (in.)

D = Heated perimeter of column (in.)

Using W' (instead of W), the column fire resistance, R, is then calculated as follows:

$$R = 130\left[\frac{h(W'/D)}{2}\right]^{0.75}$$

Most columns normally used only offer a few minutes of fire resistance when unprotected. Very heavy, unprotected steel columns are capable of exhibiting some significant fire resistance. Equations 2, 3, 2m, and 3m can be used to predict the fire resistance of unprotected steel columns.[4]

$$R = 10.3\left(\frac{M}{D}\right)^{0.7} \quad \text{for} \quad \frac{M}{D} < 10 \qquad (2)$$

$$R = 8.3\left(\frac{M}{D}\right)^{0.8} \quad \text{for} \quad \frac{M}{D} > 10 \qquad (3)$$

where

R = Fire endurance (min)

M = Mass of the member (lb/ft)

D = Heated perimeter (in.)

In SI units:

$$R = 75.1\left(\frac{M}{D}\right)^{0.7} \quad \text{for} \quad \frac{M}{D} < 171 \qquad (2m)$$

$$R = 60.5\left(\frac{M}{D}\right)^{0.7} \quad \text{for} \quad \frac{M}{D} > 171 \qquad (3m)$$

where

R = Fire endurance (min)

M = Mass of the member (kg/m)

D = Heated perimeter (mm)

Beams with a larger W/D ratio can always be substituted for the structural member listed with a specific fire-resistive covering without changing the thickness of the covering.

Beams with different shapes than those listed in a fire-resistive assembly may be substituted for the listed shape as long as the coating thickness is adjusted as a function of the W/D ratio according to the following equation:

$$h_1 = \left(\frac{W_2/D_2 + 0.6}{W_1/D_1 + 0.6}\right)h_2$$

where

h = Thickness of the spray-applied fire protection (in.)

W = Weight of steel beam (lb/ft)

D = Heated perimeter of the steel beam (in.)

Subscript 1 refers to the substitute beam and required protection thickness

Subscript 2 refers to the listed beam and protection thickness

The following are the limitations of this formula:

1. W/D values must be 0.37 or greater.
2. h must be ⅜ in. (9.5 mm) or greater.
3. The unrestrained beam rating and restrained beam rating must both be at least 1 hour.
4. For restrained beams, the beam must be a "compact" section per AISC Steel Construction Manual.[7]

Equivalent Fire Endurance of Reinforced Concrete

Thermal and mechanical properties vary for all materials with the temperature of the material. Because the heat transmission through concrete is quite slow, the variability of properties throughout the member is quite nonuniform. As a result, the behavior of reinforced concrete in fire is very complex. Nevertheless, equations have been developed to predict the fire resistance of reinforced concrete columns. The resistance depends on the weight and aggregate of the concrete, the minimum dimension of the column, the area of vertical reinforcement in the column, and the effective length of the column.

The effective length of the column is equal to the length of the column multiplied by a factor. The factor can range from 0.65 to 2.1, depending on how the column is secured in the top and the bottom. If the exact method of securement is unknown, a factor of 1 can be used. When the column is constructed of normal-weight siliceous aggregate and columns 1 and 3 are used in Table 19.2.15, use Equation 4. When the column is constructed of normal-weight carbonate aggregate and columns 1 and 3 are used in Table 19.2.15, use Equation 5. When the column is constructed of normal-weight carbonate or siliceous aggregate and column 2 is used in Table 19.2.15, use Equation 6. When the column is constructed of lightweight aggregate and any column is used in Table 19.2.15, use Equation 7.

TABLE 19.2.15 Values for f

	f		
		Effective length, kL 12 ft < kL < 24 ft	
Overdesign Factor	Effective Length, kL (kL_{max} = 12 ft)	$\rho \le 0.03$ $t \le 12$ in.	All Other Cases
Column	*1*	*2*	*3*
1.00	1.0	1.2	1.0
1.25	0.9	1.1	0.9
1.50	0.8	1.0	0.8

For SI units: 1 in. = 25.4 mm; 1 ft = 0.305 m.
L = column length (feet).
k = effective length factor (dimensionless); if unknown, assume k = 1.

$$R = \frac{t}{3.2f} - 1 \quad (4)$$

$$R = \frac{t}{3.2f} - 0.75 \quad (5)$$

$$R = \frac{t}{4f} - 1 \quad (6)$$

$$R = \frac{t}{3f} - 1 \quad (7)$$

where

R = Fire resistance (hr)

t = Minimum dimension of the column (in.)

f = A factor that considers overdesign (Table 19.2.15 provides values for f)

In SI units:

$$R = \frac{t}{81.3f} - 1 \quad (4m)$$

$$R = \frac{t}{81.3f} - 0.75 \quad (5m)$$

$$R = \frac{t}{101.6f} - 1 \quad (6m)$$

$$R = \frac{t}{76.2f} - 1 \quad (7m)$$

where

R = Fire endurance (hr)

t = Minimum dimension of the column (mm)

f = A factor that considers overdesign (Table 19.2.15 provides values for f)

Equation 8 gives calculated fire endurance for normal-weight concrete slabs,[8,9]

$$R = 0.031\rho^{1.2}L^{1.85} \quad (8)$$

where

R = Fire resistance (hr)

ρ = Concrete density (lb/ft^3)

L = Slab thickness (ft)

In SI units:

$$R = 0.031\rho^{1.2}L^{1.85} \quad (8m)$$

where

R = Fire resistance (min)

ρ = Concrete density (kg/m^3)

L = Slab thickness (m)

Equivalent Fire Endurance of Timber

When timber members are tested, they burn. As burning continues, a char layer is formed on the exposed surfaces. This char layer reduces the usable strength of the timber members. The time duration that elapses before the member reaches its critical failure load is the fire endurance. The fire endurance for wood beams is calculated by determining the breaking strength of the uncharred residual cross section. The time to reach a critical depth may be calculated using the applicable equations in ASCE/SFPE 29. The critical residual depth, *d,* can be obtained from Figures 19.2.11 and 19.2.12.[10]

STRUCTURAL MATERIALS AT ELEVATED TEMPERATURES

All structural materials used in building construction are adversely affected by the elevated temperatures caused by fire. The degree and significance of this adverse behavior depend primarily on the function of the elements and on the degree of protection afforded. The mechanical properties of strength and stiffness decrease as the temperature rises. Other adverse behavior, such as excessive expansion and accelerated creep, also develops with increasing temperatures. In general, however, the design parameters that are of concern at normal temperatures are the same parameters that are of concern at elevated temperatures.

Structural Steel

Property of Structural Steel. Steel is the backbone of modern building design. Whether it acts as the reinforcement for concrete or the skeleton framework for buildings, it constitutes the major load-carrying material in modern building construction. From the designer's viewpoint, steel possesses many qualities, such as high strength and good ductility, that make it an ideal structural material. However, steel, like all other materials, is adversely affected by fire.

Steel is noncombustible and does not contribute fuel to a fire. In the past, these properties have sometimes provided a false sense of security with regard to its durability in a fire because they overshadow the fact that steel loses strength when subjected to temperatures easily attained in a fire. The relative seriousness of the problem depends on several factors, such as the function of the steel element, its level of stress, the support conditions, its surface area and thickness, and the temperature within the steel itself. This temperature can be quite different from the ambient temperature in the compartment.

From a structural viewpoint, the yield stress of steel is the significant parameter in establishing load-carrying capacity. The tensile stress strain diagram for A36 steel at various temperatures is shown in Figure 19.2.13.[11] It can be seen that both the yield strength and the modulus of elasticity decrease

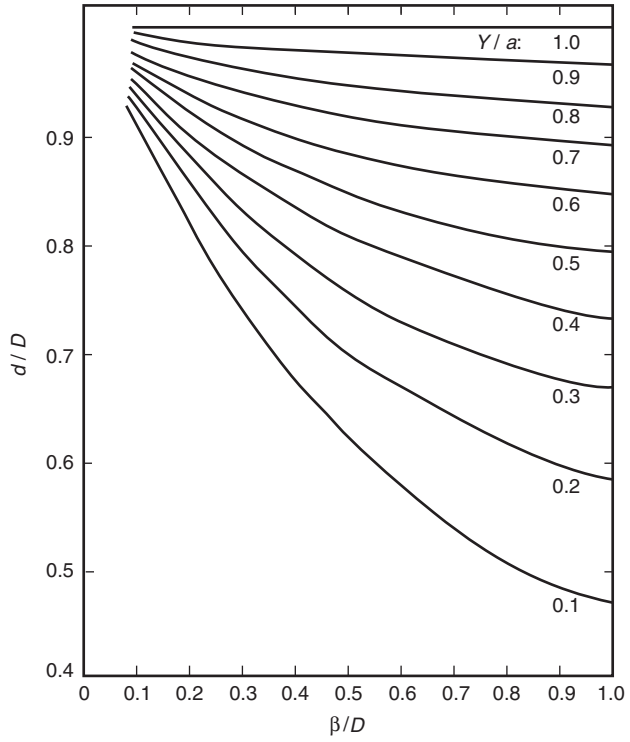


FIGURE 19.2.11 Critical Depth of Solid Timber Beams of Rectangular Cross Section Exposed on Three Sides to Fire

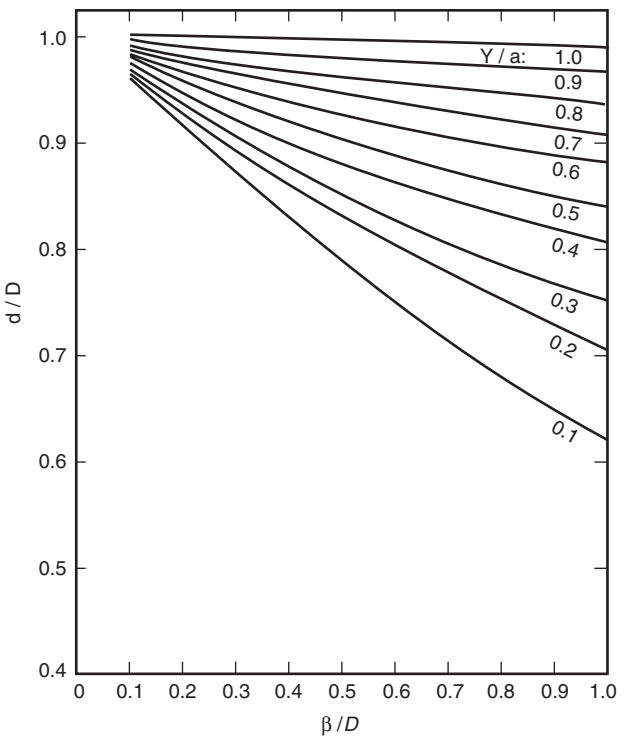


FIGURE 19.2.12 Critical Depth of Solid Timber Beams of Rectangular Cross Section Exposed on Four Sides to Fire

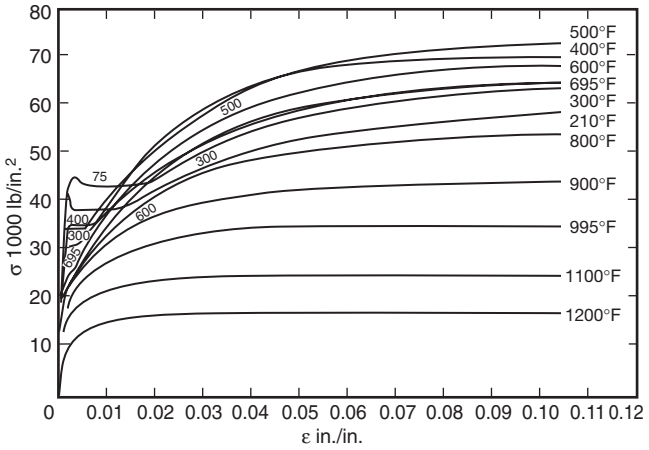


FIGURE 19.2.13 Stress-Strain Curves for an ASTM A36 Steel

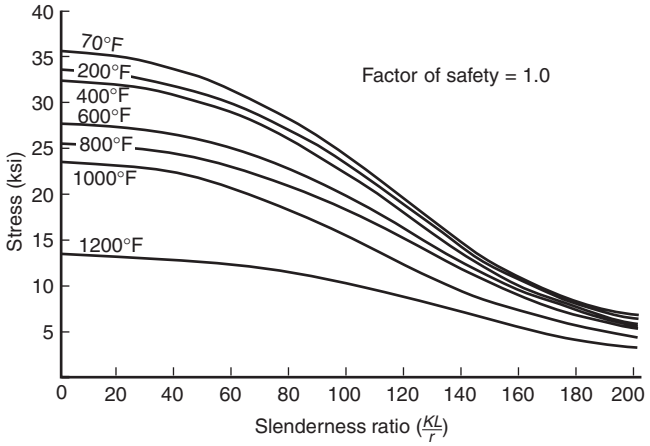


FIGURE 19.2.15 Critical Stress as a Function of the Slenderness Ratio for Various Temperatures—A36 Steel

with increasing temperatures. Figure 19.2.14 shows the ratios of modulus of elasticity and yield stress for A36 steel at various temperatures.[12] As can be seen, both values decrease with an increase in temperature.

This reduction in strength, combined with the reduction in the modulus of elasticity, causes compression members to be more sensitive to higher temperatures than tensile or flexural members. Figure 19.2.15 shows the influence of temperature on the critical stress of compression members of A36 steel.[12]

It should be recognized that the temperature considered for stress limitations is the temperature within the steel and not the ambient temperature. Because steel has a high thermal conductivity, it can transfer heat away from a localized heat source rather quickly. This property, in conjunction with its thermal capacity, enables steel to act as a heat sink. When the steel has an opportunity to transfer heat to cooler regions, it can take a relatively long time for a member to reach its critical value. On the other hand, an extensive fire that distributes heat simultaneously over a greater area reduces this time considerably.

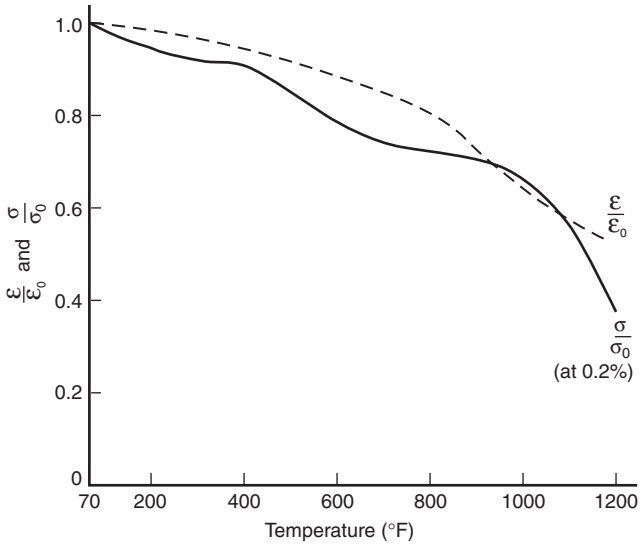


FIGURE 19.2.14 Ratio of Modulus and Yield Strength with Temperature—A36 Steel

Related to this thermal activity is the effect of mass and surface area of structural steel members. Heavy, thick sections have a far greater resistance to the effects of building fires than do lighter ones. Unprotected lightweight sections, such as those found in trusses and open-web joists, can collapse after 5 or 10 minutes of exposure.

Another property of steel that has an effect on its performance at elevated temperatures is its coefficient of expansion. The linear coefficient of expansion of steel at temperatures up to 1100°F (600°C) is given as:

$$\alpha = 0.0000061 = 0.0000022\Delta t$$

where

α = The coefficient of expansion

Δt = Temperature change in degrees Fahrenheit

In SI units:

α = The coefficient of expansion

Δt = Temperature change in degrees Celsius

$$\alpha = 6.1 \times 10^{-6} + 3.96 \times 10^{-9}\Delta t$$

This high coefficient affects the structure in two ways. If the ends of a structural member are axially restrained, the attempted expansion due to the heat causes thermal stresses to be induced in the member. These stresses combine with those of the normal loading, causing more rapid collapse. If the structural member is not axially restrained, the increased stresses described do not occur; instead, movement takes place. This movement causes the ends of steel columns to be moved laterally, producing an eccentrically loaded column. In other cases, walls can be moved to the point of collapse by expansion of beams. This creates an

extremely hazardous condition both for the building itself and for fire fighters.

In October 2006, NIST issued their final report on the September 11, 2001, collapse of the World Trade Center Towers.[13,14] In this report they note very limited test data that indicates that, all else being equal, as the length of a horizontal structural member increases, the fire endurance may be reduced. Insufficient data currently exists to either substantiate or quantify this relationship. The limited testing also leaves questions regarding benefits of restrained versus unrestrained conditions on fire endurance of protected steel structural members. The discussion of potential research studies began in 2006 to evaluate current fire endurance test methods to see if changes in test procedures, or adjustments to the thickness of a tested fire-resistive coating (to reflect an increase in length over the tested span), are needed.

To illustrate the magnitude of movement, consider a 50 ft (15.24 m) long steel beam that is heated uniformly over its length from 72 to 972°F (22.2 to 522°C). The average value for alpha is 0.0000073, and the increase in length, delta, becomes approximately

$$\delta = \alpha L\, \Delta t = (7.3 \times 10^{-6})(50 \times 12)(900)$$

Thus, $\delta = 3.9$ in.

In NFPA 251, alternate tests may be used to evaluate protection of steel beams and columns. These alternate tests evaluate the thermal protection of the insulating materials by measuring the temperature in the steel for the standard time-temperature exposure. In these alternate tests, failure occurs when the average temperature reaches 1000 to 1100°F (538 to 593°C).

If critical temperature for structural steel is intended to describe the steel temperature at which collapse is impending, temperatures in the range of 1000 to 1100°F (538 to 593°C) can be viewed as a reasonable failure criteria. The actual temperatures at which collapse will occur will likely differ from the 1000 to 1100°F range, depending on the load and support conditions, dimensions, and geometry of the structural member. The actual temperature at which collapse is likely to occur is the temperature at which the yield stress is reduced to the point where it is approximately equal to the stress the member was designed to have applied to it, at or near its full design load.[15] The yield stress is the force per unit area at which permanent deformation occurs. In other words, that temperature range is where the safety factor utilized in the structural design has been reduced to unity due to the reduction in strength.

The modulus of elasticity (E), or ratio of stress to strain, is also reduced at elevated temperatures. Since the deflection of a horizontal structural member is inversely proportional to E, all else being equal, deflection will increase with increased temperatures.

Rather than focus exclusively on temperature, it is more appropriate to focus on the load-carrying capacity of a member at different temperatures. For example, one may question, what is the load-carrying capacity of the structural member when the temperature reaches x°F? The related question may then be asked: What is the likelihood that the steel temperature will reach this value in a room fire? Modern calculation methods enable both of these questions to be addressed with a reasonable degree of confidence, although not yet as a simple, routine evaluation.

Fire Protection of Structural Steel. Because unprotected structural steel loses its strength at high temperatures, it must be protected from exposure to the heat produced by building fires. This protection, often referred to as "fireproofing," insulates the steel from the heat. The more common methods of insulating steel are encasement of the member and application of a surface treatment. Installation of a suspended ceiling as part of a floor-ceiling assembly has been used to increase the fire resistance of the assembly. Additional methods, such as sheet steel membrane shields around members and box columns filled with liquid, have been introduced.

Over the years, encasement of the structural steel member has been a very common and a very satisfactory method of insulating steel to increase its fire resistance. In floor systems of reinforced-concrete slabs supported by structural steel beams, the encasement can be placed monolithically with the floor. Figure 19.2.16 illustrates an older technique of encasement. The major disadvantage of this procedure is the cost, which is related both to the added formwork and concrete and to the increased weight of the supporting members due to the added dead load. To reduce the cost of encasement, systems utilizing lath and plaster or gypsumboard, or spray-on mineral fiber or cementitious coatings, have been developed, as shown in Figures 19.2.17[16] and 19.2.18.

Because of labor costs and the weight increases of encasement, surface treatments applied directly to the member have become quite popular. Low density (13 pcf) sprayed-on

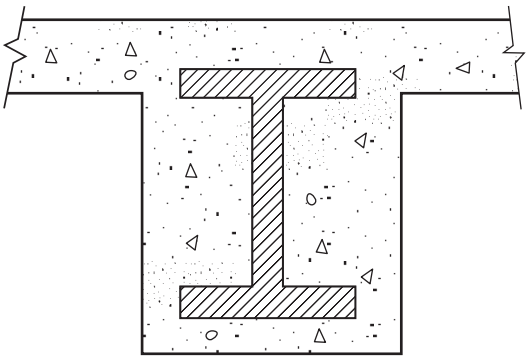


FIGURE 19.2.16 Encasement of a Steel Beam by Monolithic Casting of Concrete Around the Beam

FIGURE 19.2.17 Spray-On Fireproofing

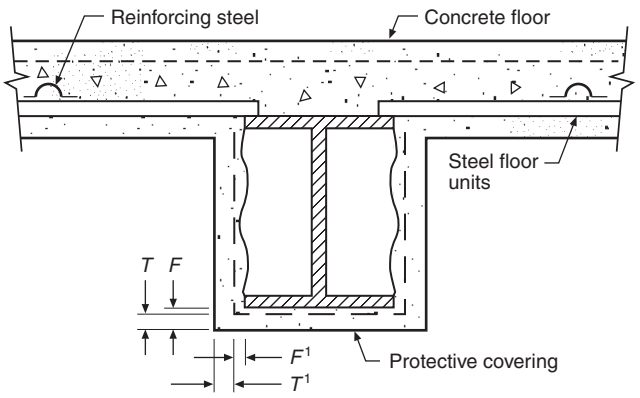


FIGURE 19.2.18 Furred Steel Beams with Noncombustible Protective Coverings

cementitious and mineral fiber coatings are widely used for protecting structural steel. While the protection is excellent if applied correctly, it can easily be scraped off the member during construction or renovations. Consequently, sprayed-on coatings are suspect in their effectiveness over long-term use.

Sprayed-on coverings can spall, and adhesion problems also have been experienced. Thus, effective application, complete coverage, and long-term maintenance are attributes that must be evaluated in considering sprayed-on applications. The application of sprayed-on material must be monitored. The material being applied has specific guidelines that must be met. Conditions that are too humid or too cold may cause the material to fail earlier than it normally would.

The proper surface condition of structural steel is important to assure adequate adhesion of sprayed fire-resistive materials (SFRM) to the steel. The steel surface must be free of dirt, grease, oil, and loose mill scale. Blast cleaning of the surface is generally not required. Also, for common SFRM, such as cementitious or mineral fiber type, the use of primer paint is generally not required or recommended. In most cases, the use of a primer paint will result in a considerable reduction in adhesive strength of the coating to the steel and, if a primer paint is to be used, it is imperative that it be approved for use with the specific SFRM that is to be used. Whether or not a primer is used, conducting field tests to assure adequate thickness, density, adhesion and cohesion is achieved in the actual installation is recommended. Guidance can be found in ASTM E 605 and E 736. The NIST WTC report[14] confirmed existing concerns regarding how surface preparation for structural steel affects the adhesion of spray-applied fire-resistive material. Prior to selecting a coating, lab test information should be reviewed to assure that the coating is appropriate for the conditions of service. Guidance on these tests can be found in ASTM E759, E760, E761, E859 and E937.

Intumescent coatings have been utilized to increase the fire endurance of structural steel. These coatings intumese, or swell, when heated, thus forming an insulation around the steel. Prolonged exposure to flame can destroy the char coating.

Suspended ceilings consisting of lath and plaster, gypsum panels, or acoustical tile supported on a grid system as part of a floor-ceiling assembly are a popular method of fireproofing. The grid system can be suspended from wire hangers or it can be attached directly to the bottom chord of joists or to the bottom flange of beams. Sometimes ceiling tiles are either mechanically fastened or fitted into splines to prevent the pressures that occur in building fires from lifting them out of place.

The overall effectiveness of this type of barrier protection, often called membrane protection, is questionable. This is due to experiences where a lack of control during construction resulted in improper installation procedures, such as inattention to expansion control in the suspension system. In addition, maintenance of ductwork and fixtures in the plenum area may be done by personnel who are not aware of the importance of the integrity of the ceiling to the fire protection system. Removed tiles are not replaced in a manner that will ensure their integrity during a building fire. Consequently, the unprotected steel in the plenum area is exposed to fire and hot gases, which significantly reduce its strength.

Structural steel members also can be protected by sheet steel membrane shields. The sheet steel holds inexpensive insulation materials in place, thus providing a greater fire resistance. In addition, polished sheet steel has been used in tests to protect spandrel girders. The shield reflects radiated heat and protects the load-carrying spandrel.

Reinforced Concrete

Concrete is often used as a protective covering for other materials, as well as a primary load-bearing structural material. Consequently, reinforced-concrete buildings give a sense of fire security. However, concrete as a material also is adversely affected by heat from a fire. Although collapse of reinforced-concrete structures is comparatively rare, there is some experience with collapse of such structures in a fire. Loss in strength, spalling, and other deleterious effects do occur. The collapse of several multistory reinforced concrete buildings during fire exposure is discussed in the report, NIST GRC 02-843.[17]

When the temperature of a reinforced-concrete member is raised, the member loses strength. The amount of strength reduction is influenced by a number of factors. Among the most significant from a structural viewpoint are the type of aggregate, moisture content, type of loading, and level of stress during the fire exposure.

One of the more significant factors in determining the change in strength and the thermal characteristics of concrete is the type of aggregate. Aggregate types can vary widely from region to region. Consequently, numerical values of strength properties are related to a percentage of the original strength, rather than a specific stress value. The qualitative behavior of concrete is generally accurate, however.

Lightweight concrete performs better at elevated temperatures than does normal-weight concrete. Not only does it retain more of its strength during heat buildup, but it also has a lower coefficient of thermal conductivity. Concrete using aggregates of vermiculite of perlite is particularly good at protecting structural steel from a heated environment.

Figures 19.2.19 and 19.2.20 illustrate the effect of aggregates on the fire resistance of reinforced-concrete slabs.[3] The lightweight aggregates, such as expanded shale and expanded slag, have considerably more fire resistance than do normal-weight concretes made from carbonate and siliceous aggregates.

The moisture content of concrete has a significant influence on its thermal performance. A considerable quantity of the heat energy of a fire is expended in vaporizing the absorbed and capillary moisture in concrete. In the case of horizontal members, the water vapor is driven upward and maintains a temperature at the top of the member of 212°F (100°C) until the water has been driven off. This increases the fire resistance, as it keeps the temperature on the unexposed side below that defined as the failure temperature. However, the voids caused by the evaporation of water contribute to shrinkage and a decrease in concrete strength.

The mechanical properties of concrete are significantly reduced at elevated temperatures. Figure 19.2.21 shows the effect on the compressive strength and modulus of elasticity by increasing the temperature.[3] There is some question about whether concrete completely regains its strength after exposure to high temperatures.

Concrete structures generally have less stringent requirements regarding expansion joints for normal thermal expansion.

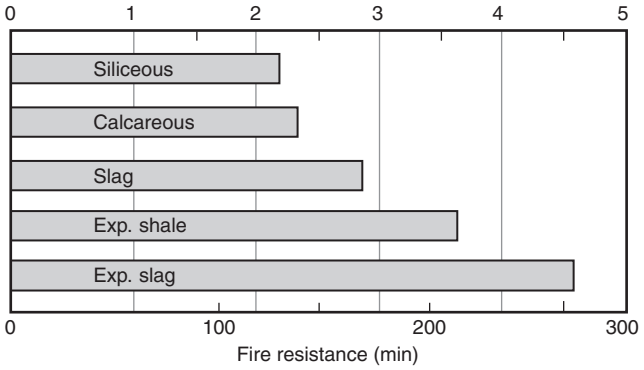


FIGURE 19.2.19 Effect of Various Types of Aggregate on the Fire Endurance of 4¾ in. (121 mm) Slabs

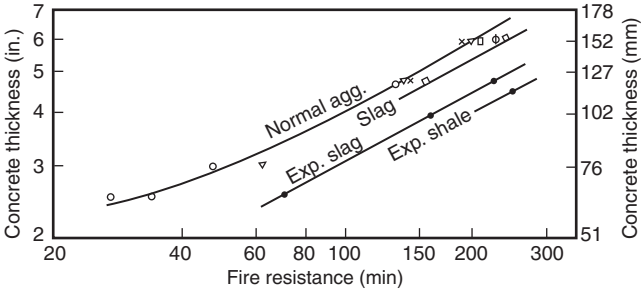


FIGURE 19.2.20 Relationship of Slab Thickness and Type of Aggregate to Fire Endurance

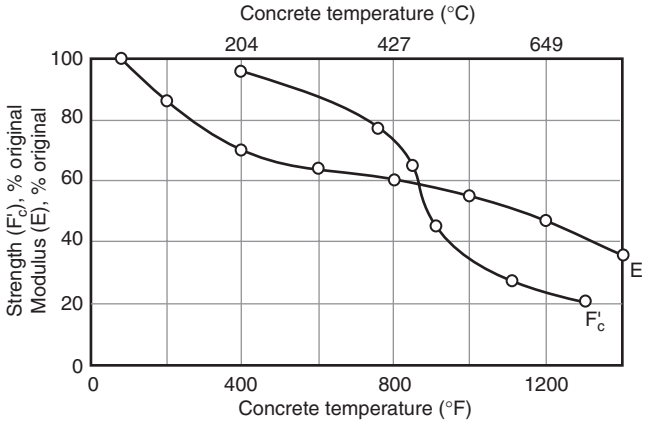


FIGURE 19.2.21 Effect of Temperature on Modulus of Elasticity and Compressive Strength. The curves are taken from two differing specimens.

Consequently, a large concrete structure exposed to an uncontrolled fire can experience large horizontal forces due to the expansion of beams, which can cause structural damage at the junction of beams and columns. In 1973, an uncontrolled fire occurred in a military personnel records storage center in Overland, Missouri. The building was 730 ft (222 m) long, but had no expansion joints. Floors, beams, and columns (20 in. × 20 in. [508 mm × 508 mm]) were made of reinforced concrete. An estimated 28 in. (700 mm) of horizontal expansion occurred during the fire, causing severe structural damage at the junction of the beams and columns, resulting in partial collapse.[18]

Prestressed Concrete

The factors that are significant in the behavior of prestressed concrete are similar to those that affect reinforced concrete. In addition to the influences of moisture content and aggregate, the higher strength concrete and the function and type of steel used for prestressing are important considerations. The concrete used for prestressed concrete is of a higher strength than that used in ordinary reinforced-concrete construction. The overall fire resistance of this concrete is somewhat better than the lower-strength concrete. The heat transmission is about the same for the two systems. However, there is a somewhat greater tendency for prestressed concrete to spall, thus exposing the prestressing steel.

The greatest problem of prestressed concrete subjected to elevated temperatures involves the prestressing steel. The fact that the steel is put under high initial stress, coupled with the fact that the reinforcing wires are high-carbon, cold-drawn, rather than low-carbon, hot-rolled steel, is the root of the problem. Normal prestressing losses due to deformation and creep are considered in prestressed concrete design. At elevated temperatures these losses are accelerated. Creep in the steel increases, and the modulus of elasticity of the prestressing wires is reduced by about 20 percent when the temperature reaches 600°F (316°C). These losses reduce the carrying capacity of the member.

Another problem of prestressed concrete relates to thermal expansion. Because of the prestress in the design procedures, the compressive stresses near the top of a beam are less than those for reinforced concrete design. The thermal expansion of the concrete at the bottom of a beam can induce an upward movement, resulting in an initial failure opposite in direction to that normally assumed in collapses.

The type of steel used for prestressing is more sensitive to elevated temperatures than the steel used in reinforced-concrete construction. Not only is its strength reduced at temperatures somewhat less than those for hot-rolled steel, but also that strength is not regained after cooling. Prestressing wires are permanently weakened when they reach a temperature of about 800°F (427°C).

Wood

Depending on its form, wood may or may not provide reasonable structural integrity in a fire. The important factors that influence fire resistance are the physical size and the moisture content of the members. Fire-retardant treatments may be used to delay ignition and retard combustion. This provides time for extinguishing procedures. However, all wood will burn.

The burning of wood produces a charcoal on the surface at an average rate of about 1/40 in. per minute (0.6 mm/min). This charcoal provides a protective coating that insulates the unburned wood and isolates it from the flame, thus retarding pyrolysis. Therefore, thick members provide much more structural integrity over the period of fire exposure than do thin ones.

Heavy timber construction has proved to be an excellent form of construction. It maintains its integrity during a fire for a relatively long time, providing an opportunity for extinguishment. When the fire is extinguished relatively soon, much of the original strength of the members is retained and reconstruction is possible.

Glued laminated frames, arches, and beams have become increasingly popular. These members also provide reserve strength during a fire, and, if the layer is not deep, the char may be removed by sandblasting to restore the aesthetic appearance.

Wood-frame construction utilizes structural members considerably smaller than mill construction. The exposed area is greater, relative to mass, and the fire resistance considerably reduced. When this type of construction is exposed to a fire, it offers relatively little structural integrity. Therefore, protective surfaces, such as gypsum wallboard or plaster, are important to provide fire resistance. Lightweight wood trusses, due to their connection design, usually offer very limited integrity during fire exposure. Several related articles are referenced in Section 19, Chapter 1, "Types of Building Construction."

FIRE BEHAVIOR OF OTHER BUILDING MATERIALS

Many materials other than steel, concrete, and wood are commonly used in modern building construction. They frequently make up a large volume and/or surface area of the structure. Nonbearing partitions, insulation, building services, and finish materials are all important parts of building construction. Some of the nonstructural, thermally inert materials are used as fireproofing. Others may contribute significant fuel to a potential fire.

Glass

Glass is utilized in three common ways in building construction. The most obvious is glazing for windows and doors. In this capacity the glass has little resistance to fire. It quickly cracks because of the temperature difference between the surfaces. Double glazing does not provide much improvement. Wire-reinforced glass is an improvement, as it provides somewhat greater integrity in a fire if it is properly installed. However, no glazing should be relied on to remain intact in a fire. Ordinary annealed glass has minimal resistance to fire and will break at heat fluxes near or below that required for piloted ignition of ordinary combustibles like wood. Fully tempered glass can resist higher heat fluxes but will break if engulfed in flames.

Glass block and ceramic glass also provide some duration (45 minutes or more) of endurance against fire, although the reduction of heat transmission is limited. The test standard for such assemblies is NFPA 257, *Standard on Fire Test for Window and Glass Block Assemblies.* Only certain types of glass significantly limit heat transmission, such as a special double or triple layer glass with a clear gel between layers of glass. When exposed to fire, the gel becomes opaque, reducing radiant heat transfer in addition to conductive heat transfer. Such insulating glass has been tested in NFPA 251.

A second common use of glass in buildings is in fiberglass insulation. The fiberglass does not burn and is an excellent insulator. Glass fiber is often coated with a combustible resin binder. When used as an insulation, the amount of resin binder and resultant fuel load is such that the insulation is considered limited-combustible (see NFPA 220, *Standard on Types of Building Construction,* and NFPA 259, *Standard Test Method for Potential Heat of Building Materials*). Facings used as vapor barriers over glass fiber insulation, such as asphalt-coated kraft paper and some plastics, generally present more potential for fire spread than the insulation itself.

A third form in which glass is found in buildings is as reinforcement for fiberglass-reinforced plastic building products. The products include translucent window panels, siding, and prefabricated bathroom units. They have distinct advantages of economy and aesthetic appeal. The fiberglass acts as reinforcement for a thermosetting resin, usually a polyester. The resin, combustible even with fire retardants incorporated in the composition, frequently comprises 50 percent or more of the material. Although the fiberglass itself is noncombustible, the products are quite combustible.

Gypsum

Gypsum products, such as plaster and plasterboard, are excellent fire protection materials. The gypsum has a high proportion of chemically combined water. Evaporation of this water requires a great deal of heat energy, making gypsum an excellent, inexpensive, fire-retardant building material. A detailed description of numerous fire-rated assemblies using gypsum can be found in the "Fire Resistance Design Manual" by the Gypsum Association.

Lightweight Concrete

Lightweight concrete, made with noncombustible aggregates, resists high temperatures extremely well without degradation. Vermiculite and perlite are the most common types of light concrete used for this purpose. Vermiculite is an inert aggregate made from weathered mica. The mica is crushed and roasted, which causes it to expand to form pellet-like aggregates. Perlite is a volcanic rock that is crushed and heat treated. The heat treatment causes the rock to expand in volume. During the process, water vapor is absorbed by the rock particles, and the perlite takes the form of glasslike, cellular-structured particles.

Asbestos

Asbestos is a mineral fiber that historically had been used in several forms in building construction. It was used with a cementitious binder and sprayed onto structural members to form an excellent fireproofing agent. Asbestos was combined with portland cement to make asbestos cement products. Although these products are noncombustible, they often shattered during the temperature buildup of a fire, thus reducing their effectiveness. Asbestos was also combined with materials other than portland cement to form products such as asbestos insulation board and asbestos wood. These products behaved quite well in fires, providing a great deal of fire resistance and protection. However, because of health hazards during application, construction, occupancy, and demolition, asbestos products are now banned. Nevertheless, it is still found in older buildings undergoing renovation.

Masonry

Brick, tile, and concrete masonry products behave well when subjected to the elevated temperatures of a fire. Hollow concrete blocks may crack from the heat, but they generally retain their integrity. Brick can withstand high temperatures without severe damage. The fire resistance of masonry can be determined based on the type of aggregate used and the equivalent thickness of material.[19]

Plastics

There is a wide range of plastic products used by the building industry. They provide numerous aesthetic, physical, and economic advantages in building applications. Their major disadvantage is that all plastics are combustible. Although there are certain treatments that increase ignition temperatures or inhibit flame spread, there is no known additive that will make them noncombustible.

CONTEMPORARY TRENDS IN STRUCTURAL FIRE PROTECTION

There is an increased interest internationally in the development of more rational methods of structural fire design. These methods attempt to establish a theoretical base for the design of structural members and assemblies that will predict their actual fire performance more accurately than present methods. This section briefly addresses some of these modern trends. A more detailed discussion is provided in Section 19, Chapter 5, "Approaches to Calculating Structural Fire Resistance."

Usual Structural Design Procedures for Fire Conditions

The standard fire resistance test, combined with building code requirements that specify fire resistance ratings for structural frames and barrier assemblies, is the usual basis for structural fire design. The building code identifies building construction classifications based on materials and fire resistance requirements for barriers and structural framing members. The code relates these construction classifications with use groups, the building height and area, and adjustments for fire protection features. These code requirements for fire resistance are the subjective judgments of the code-writing groups.

The numbers and assemblies are laboratory tested in accordance with a standard fire test. This test is the equivalent to NFPA 251 or ASTM E119 for the jurisdiction served by the code. An acceptable design occurs when the test results exceed the code requirements. Although this procedure is common, its validity is subject to increasing doubts. The fire test itself is being severely criticized. In addition to the concerns identified earlier in this chapter, considerable variation can occur for the same assembly when it is tested in different laboratories. The relationship between test results and field performance is subject to debate. The code requirements have a weak technical base. The procedure, however, is relatively easy to administer from a regulatory viewpoint, and many other code requirements can be related to the form of construction anticipated by the fire resistance ratings.

Analytical Methods of Design

Research has been conducted along two different but related aspects of structural fire design.[20] Both attempt to provide rational analytical procedures for predicting structural fire behavior. One procedure is to develop analytical methods by which the fire resistance of a member or assembly may be calculated. The American Society of Civil Engineers (ASCE) and the Society of Fire Protection Engineers (SFPE) jointly developed ASCE/SFPE 29, *Standard Calculation Methods for Structural Fire Protection.* ASCE/SFPE 29 can be used for the calculation of fire resistance of structural elements. The calculation method computes the fire resistance that one would expect from the standard fire test. This method uses structural characteristics of the members, thermal properties of the materials, heat transfer characteristics of the assembly, mechanical properties of structural materials and compartment, and design service loads. This method enables the important considerations of structural restraint to be taken into account more easily than the standard fire test. This procedure is identical to the traditional design procedure, except that calculated fire resistance ratings are substituted for fire test ratings.

The provisions of the American Concrete Institute and the Masonry Society standard ACI 216.1/ TMS 0216.1 can be used to calculate the fire resistance of concrete and masonry elements

or assemblies. The two above references are acceptable to use for calculated fire resistance per the *NFPA 5000* building code.

Another approach to which considerable research effort has been devoted is an analytical design based on real fire-exposure characteristics. There are basically two methods in this approach. The first relates the time-temperature characteristics of real fires to the structural behavior at elevated temperatures. In connection with this approach, NFPA and SFPE have recently initiated two independent projects to establish fire loads for engineering design of structural fire resistance in buildings. The second method relates the properties of real fire development to an equivalent standard time-temperature curve. This method relates a theoretically equivalent time to experimental fire test results. It is important to understand that exposure fires estimated for the proposed occupancy will change with future occupancy changes.

Design Procedure

The Swedish Institute of Steel Construction publishes a design manual, entitled "Fire Engineering Design of Steel Structures."[21] A building designer has the option of designing the structural system in accordance with the traditional code or by the procedures described in the manual.

The manual describes a rational fire-engineering design process for steel structures on the basis of performance requirements. The manual consists of four parts. The first part is a relatively detailed description of fire energy impacts and structural behavior at elevated temperatures. This part provides the foundation for the design procedures. The second part presents the detailed design procedure. Design charts and curves which provide the numerical base are provided. Worked examples comprise the third part, and an alternate design method based on the concept of equivalent fire duration is given in the fourth.

The American Iron and Steel Institute (AISI) published *Firesafe Structural Steel, A Design Guide,*[22] for exterior structural members. Exterior members, of course, cannot be tested in the standard laboratory test. The guide provides a design procedure by which interior members can be designed for fire conditions. The design guide presents step-by-step procedures to arrive at a design. The basis for this design guide is *Design Guide for Fire Safety of Bare Exterior Structural Steel.*[23] Part One of the AISI guide presents the theory and validation of the method, while Part Two reviews the state of the art of relevant research programs conducted during the past 20 years.

The Prestressed Concrete Institute has published a procedure to analytically determine the fire resistance of prestressed concrete structures. This method is described in *PCI Design for Fire Resistance of Precast Prestressed Concrete.*[24] The method calculates fire resistance by obtaining temperatures at various locations for the various standard fire test times, using tables and diagrams based on test results. This information is then used to compute a fire resistance value.

SUMMARY

Two important considerations in designing for structural integrity of a building during a fire are the ability of the structure to avoid collapse and the ability of barriers to prevent the fire from spreading to adjacent spaces. Three approaches to structural frame and barrier design for fire resistance include (1) standard fire resistance testing and building code requirements; (2) analytical calculations to determine fire resistance; and (3) analytical structural methods based on real fire exposure characteristics. Currently, the first two approaches are accepted in building codes. Testing of structural assemblies determines the fire resistance rating, as well as the behavior of structural materials at elevated temperatures. Several methods are under development that would establish a more scientific base for the design of structural members and assemblies that will predict their fire performance under a broader range of conditions than the standard fire tests.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on structural integrity during fire discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA 220, *Standard on Types of Building Construction*
NFPA 221, *Standard for High Challenge Fire Walls, Fire Walls, and Fire Barrier Walls*
NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 252, *Standard Methods of Fire Tests of Door Assemblies*
NFPA 257, *Standard on Fire Test for Window and Glass Block Assemblies*
NFPA 259, *Standard Test Method for Potential Heat of Building Materials*
NFPA 5000®, Building Construction and Safety Code®

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Chapter 3

Structural Fire Safety in One- and Two-Family Dwellings

Revised by
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Chapter Contents

Modern Construction
Construction Considerations for Fire Safety

Key Terms

construction (Type III), construction (Type V), dwelling, manufactured home, structural integrity

According to the 2003 American Housing Survey data, 76.4 percent of occupied housing units were in single-family attached or detached dwellings, including manufactured homes.[1] Another 8.0 percent were in buildings having two to four housing units. Therefore, one- and two-family dwellings can be estimated to represent approximately 80 percent of all occupied U.S. housing units in 2003. This chapter addresses the structural elements of one- and two-family dwellings as they affect the fire safety of the structure. Manufactured homes are also included in the discussion of one- and two-family dwellings.

This chapter does not cover the influence of interior finish or energy conservation measures, the hazards of building facilities (heating and electrical installations), or the role of detection, extinguishing, or egress systems as fire and life safety features. Those subjects are included in other chapters of this handbook. See Section 1, Chapter 2, "Fundamentals of Structurally Safe Building Design"; Section 8, Chapter 13, "Electrical Systems and Appliances"; Section 10, Chapter 2, "Heating Systems and Appliances"; Section 14, Chapter 6, "Household Fire Warning Equipment"; Section 18, Chapter 2, "Interior Finish"; Section 20, Chapter 6, "One- and Two-Family Dwellings"; Section 20, Chapter 7, "Manufactured Housing"; and Section 21, Chapter 6, "Recreational Vehicles."

MODERN CONSTRUCTION

Various types of construction are used in the design and building of one- and two-family dwellings. Specific requirements are dictated by state and local building codes and, in the case of manufactured homes, by federal regulation, via the Manufactured Housing Consensus Committee administered by the National Fire Protection Association. In general, most one- and two-family residential buildings are built of Type V (frame) or Type III (ordinary) construction, as defined by building codes such as *NFPA 5000®, Building Construction and Safety Code®,* the International Residential Code, and NFPA 220, *Standard on Types of Building Construction.* There are, of course, exceptions: some dwellings are erected of Type I (fire resistive), Type II (noncombustible), or possibly Type IV (heavy timber) construction.

Type V (Frame) Construction

The principal categories of Type V construction are (1) platform or western, (2) balloon, (3) braced, (4) plank and beam, and (5) veneer (a combination of one of the previous four with a facing wythe of brick, concrete masonry units, or stone on the exterior walls). The buildings may be constructed on foundations that consist of slab on grade or which incorporate basements, cellars, or crawl spaces. Geographical peculiarities or the needs of the owner generally dictate which foundation type is used. Where basements, cellars, or crawl spaces are provided, they play a distinct role insofar as residential fire safety is concerned, since heating, air-conditioning, and water heating equipment

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are often installed in these spaces, and this equipment can be an ignition source. These spaces are also often used for storage of combustible materials by building occupants. Roof framing can be either of rafter or trusses. Where trusses are used, interior bearing partitions might not be required.

Platform or Western, Balloon, and Braced Framing. This construction type is often referred to as stick-built. The basic difference among platform or western, balloon, and braced framing is the manner in which the floor, roof, and bearing walls are supported and/or erected.

In platform or western framing (Figure 19.3.1), which is by far the most common type of framing, walls made of studs nailed to top and bottom plates are set on top of the floor sheathing and joists, with the joists bearing on sills at the foundation level and on beams or partitions at intermediate locations. Platform construction combines safety for framers working on a building with inherent firestopping qualities once the walls are sheathed. In both balloon and braced framing, the stud-bearing walls are set on sills at the foundation level.

In balloon framing (Figure 19.3.2), the studs in exterior-bearing walls extend for two stories, with the joists supported by 1 in. by 6 in. (25.4 mm by 152.4 mm) ledger strips or ribbon boards at the intermediate level.* Early house construction was balloon framed. Unless firestopping is added, fire within the wall can easily spread vertically, since there are no top plates in the wall cavity. Fire originating in the floor/ceiling assembly can spread horizontally and eventually vertically through the walls.

In braced framing, the bearing wall extends for only one story, with joists at the second level of bearing walls bearing on 4 in. × 6 in. (101.6 mm × 152.4 mm) girths. In both framing types, the interior bearing partitions are erected in one-story heights.

Plank and Beam Framing. In plank and beam framing, a few larger structural members replace the more closely spaced smaller wood members used in typical wood framing. In other words, larger dimensional beams (4 in. × 10 in. or 5 in. × 12 in.) are spaced 4 ft or 6 ft on center. This arrangement is used rather than the standard floor and/or roof framing in which smaller dimensioned members such as 2 in. × 8 in. or 2 in. × 10 in. joists or rafters are spaced on 16 in. centers. The decking for floors and roofs is planking in nominal thicknesses of 2 in. or more, as opposed to ½ in., ⅝ in., or ¾ in. plywood sheeting. Instead of 2 in. × 4 in. bearing partitions supporting the floor or roof joist or rafter systems, the beams are supported by posts. Wood foundation walls are used for some homes, and crawl spaces can be utilized as return air plenums.

Veneer. The exterior wall finish of buildings of frame construction, except for masonry veneer, generally consists of stucco, wood, plastic siding, metal, or concrete siding over wood, foam plastic, or gypsum sheathing. Masonry veneer exteriors utilize one of the wood framing systems, with the addition of a wythe of masonry secured by metal ties to the wood frame exterior walls. Usually an insulating board of some type is provided between the studs and the masonry veneer. Although the exterior exposed surfaces can be of masonry, veneer construction is generally considered a combustible frame construction because the load-bearing members are usually wood.

*Nominal dimensions are used throughout this chapter. For comparison, 1 in. = 25.4 mm, 1 ft = 0.305 m, and 1 ft^2 = 0.0929 m^2.

FIGURE 19.3.1 Platform Construction

Steel Framing. Steel framing for residential building is becoming more widely used. Steel framing has many similarities to conventional wood framing classified as either Type III or Type V construction. Steel framing methods are available for stick-built (balloon or platform), panelized, and pre-engineered building types. Steel, like the exterior masonry walls of Type III construction, is noncombustible. However, unprotected steel loses its structural capacity under severe exposure to heat. Extensive testing has been conducted on steel-framed assemblies. The Steel Framing Alliance has compiled a summary of fire resistance testing of floor-ceiling, roof-ceiling, and wall assemblies utilizing combinations of metal studs and other building products, such as concrete, plywood, and gypsum wallboard. This compilation is available at http://www.steelframing.org.

Type III (Ordinary) Construction

The significant difference between Type III (ordinary) and Type V (frame) construction lies mostly with the construction of the exterior walls. Whereas in Type V (frame) construction

FIGURE 19.3.2 Balloon Framing

the load-bearing components of the walls are usually of wood, in ordinary construction the exterior walls are masonry or other noncombustible materials. The interior partitions, floor, and roof framing systems are of wood and, in general, utilize either the platform or braced framing methods previously described.

Manufactured Home Construction

The structural system of the manufactured home comprises four major components or subassemblies: (1) chassis, (2) floor system, (3) wall system, and (4) roof system. Manufactured homes are designed specifically to meet the requirements of an efficient assembly-line production.

The chassis, the structural base of the manufactured home, receives all vertical loads from the walls and floor and transfers them to a substructure of either the wheel assembly (when the home is in transit) or to a foundation (when the home is installed at a permanent site). The chassis generally consists of two longitudinal steel beams, braced by steel cross members. Steel outriggers cantilevered from the outsides of the main beams bring the width of the chassis to the approximate overall width of the superstructure. The running gear used when the unit is in transit is also considered part of the chassis.

The floor system consists of its framing members, generally conventional 2 in. × 6 in. or 2 in. × 8 in. (50.8 mm × 152.4 mm or 50.8 mm × 203.2 mm) wood joists, with wood structural panels glued and nailed to the joists, glass fiber insulation blankets installed between the joists, and an asphalt-impregnated insulation board sealing the bottom of the floor system. Ductwork and piping are installed longitudinally within the floor system, often requiring the cutting of the joists. The floor finish is generally carpeting or resilient flooring, such as linoleum or tile.

The wall system sometimes utilizes the stressed-skin principle and consists of an interior skin of wood structural panels glued and nailed to wood studs and an exterior skin of aluminum siding. The actual sizing of members is dictated by the structural loads. Often, however, conventional 2 in. × 4 in. (50.8 mm × 101.6 mm) exterior bearing walls are used.

The roof system consists of either a rafter and ceiling joist system or a wood truss system. Roof decking is generally a rigid insulation board attached to the top of the roof rafters or trusses. Finished roofing is galvanized steel, aluminum decking, or asphalt shingles. The ceiling is either acoustical planks or gypsum wallboard attached directly to the bottom of the ceiling joists or the bottom chords of the trusses. Insulation blankets provide the roof insulation. Steel tie plates reinforce connections between wall and floor systems; diagonal steel strapping binds the floors, walls, and roof into a complete unit.

CONSTRUCTION CONSIDERATIONS FOR FIRE SAFETY

One- and Two-Family Dwellings

A dwelling unit is defined as a one or more rooms arranged for complete and independent housekeeping purposes, with space for eating, living, and sleeping; facilities for cooking; and provisions for sanitation. A one-family dwelling unit is generally defined as a building that consists solely of one dwelling unit with independent cooking and bathroom facilities. A two-family

dwelling unit is a building that consists solely of two dwelling units with independent cooking and bathroom facilities.

In terms of size and occupant density, one- and two-family dwellings present lower overall occupant loads when compared to other building types. However, fire in single-family homes results in a significant portion of the overall life loss and injury statistics when compared to other building types.

Means of Escape. Some building regulation requirements concerning fire safety for one- and two-family dwellings differ substantially from those for other types of buildings. For example, depending upon certain conditions, single-family dwellings are required to have a primary means of escape that leads directly to the outside of the building. Single-family dwellings are also required, depending on certain conditions, to have a secondary means of escape. The secondary means is most often at least one escape window or outside door from basements with habitable spaces and from every sleeping room. Unlike office buildings, which require a certain number of means of egress, single-family homes require means of escape, which is a different egress concept.

Automatic Sprinklers. Building codes such as *NFPA 5000* limit the height of Type V unprotected one- and two-family dwellings that are not equipped with automatic sprinkler systems to two stories. The structural members in Type V unprotected construction do not possess any fire resistance rating.

Fire-Rated Separation. Within dwelling units, fire-rated separation between spaces is not generally required. However, attached garages are typically required to be separated from other parts of the dwelling by ½ in. (12.7 mm) gypsum wallboard on the garage side. In addition, doors to attached garages must be solid wood, steel, or 20 minute fire-rated doors. No door is permitted to connect garages and bedrooms. Within dwelling units, unrated gypsum wallboard, which is the most commonly used wall and ceiling material in the housing industry, affords a certain degree of passive fire protection.

Flame Spread Testing. The 2006 edition of *NFPA 5000* and the 2006 edition of NFPA *101®, Life Safety Code®,* no longer exempt materials less than 1/28 in. thick from flame spread testing. Wall and ceiling finishes must have a flame spread classification of not greater than 200. Wall and ceiling finishes must have a smoke developed index of not greater than 450. Testing must be done in accordance with NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials. NFPA 5000* prohibits the use of foam plastic materials unless they are tested in a full-scale fire test or fire test that simulates conditions of actual use. There is an exemption in *NFPA 5000* for the limited use of cellular or foamed plastic.

Building Codes and Regulations. Building codes require that, with the exception of windows, doors, and moldings, wall and ceiling finishes have a flame spread classification of not greater than 200. As stated above, as of the 2006 editions, *NFPA 5000* and NFPA *101* no longer exempt materials less than 1/28 in. (0.91 mm) thick from flame spread testing. Wall and ceiling finishes must have a smoke developed index of not greater than 450. Testing must generally be done in accordance with NFPA 255 or ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials.* Building regulations also place limitations on foam plastic insulation, such as requiring it have a flame spread classification of not greater than 75 and be covered with ½ in. (12.7 mm) gypsum board or other thermal barrier to retard ignition and flame spread.

The majority of one- and two-family dwellings are built of frame or ordinary construction. The physical nature of these construction types necessitates the addition of certain features that will inhibit the spread of fire. The combustible materials in the structural framework of these construction types, in conjunction with the presence of voids and concealed spaces, create conditions that can contribute to the propagation and migration of fire throughout the concealed spaces of the structure. These conditions are addressed in building regulations by the requirement for the installation of draft stops, fire blocking, and firestopping materials.

Fire Blocking and Draft Stopping. In wood frame construction, fire blocking is generally required in walls at ceiling and floor levels; at 10 ft (3.05 m) intervals, both vertically and horizontally; at interconnections between concealed vertical and horizontal spaces such as occur at soffits, drop ceilings, and cove ceilings; at concealed spaces between stair stringers at the top and bottom of the stairs; at openings around vents, pipes, and ducts at ceiling and floor levels; at chimneys and fireplaces; and at cornices of a two-family dwelling at the line of dwelling unit separation.

Draft stopping is generally required within all open-web floor and ceiling systems and between a suspended ceiling and the floor or ceiling above it, to reduce the size of the concealed spaces to not more than 1000 ft^2 (92.9 m^2). The spaces must also be divided into nearly equal areas.

Construction Contributing to Flame Spread. A 1977 study of fires in multifamily residential buildings of frame or ordinary construction revealed a number of built-in contributing factors to the spread of fire that may also be relevant to some one- and two-family dwellings:[2]

1. *The use of nonrated soffit materials, both combustible and noncombustible, and the use of soffit or eave vents.* These practices can allow fires that break through an exterior wall opening to spread into the attic or roof space by the flue action of the attic or roof ventilation system (Figure 19.3.3).

2. *Mansard roofs extending below the top-story windows with the windows recessed.* The soffit extending from the face of the window to the edge of the roof is typical of nonrated materials. In addition, the wall construction is not extended in back of the plane of the mansard roof, thus providing an interconnected void. A fire breaking through the window impinges on this soffit, burning through in a relatively short time and involving the attic and roof spaces.

3. *Unfirestopped penetrations of the gypsum wallboard partitions by plumbing, mechanical, and electrical work.*

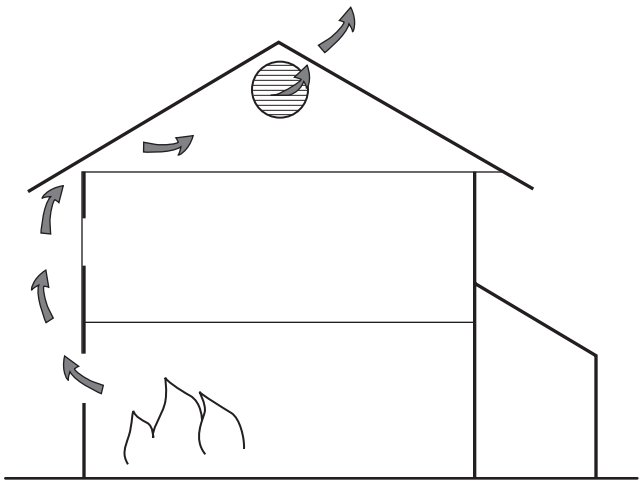

FIGURE 19.3.3 Attic Vents Under Eaves Presenting Serious Potential for Outside Extension of Fire into Attic Space

FIGURE 19.3.4 Soffits (arrow) over Kitchen Cabinets Connecting Wall Voids to Ceiling Voids, Permitting Fire Extension Both Vertically and Horizontally in Concealed Spaces

4. *The widespread use of wood-trussed roof and floor framing.* Such use precludes the need for the interior bearing partitions normally required where solid sawn joists and rafters are provided. Regulations typically required joists to be doubled under interior bearing partitions running parallel to joists and bridging to be installed under partitions running perpendicular to joists. This results in a minimum amount of firestopping of joist spaces. Current building codes compensate for this by requiring draft stopping of the trussed floor systems to reduce the spread of fire.

5. *Installing cabinets and other fixtures directly to stud framing, without an intervening protective diaphragm.* Such installation presents a situation where the only firestopping between a room fire and the concealed stud spaces are the materials that constitute the bottoms and backs of the cabinets or fixtures (Figure 19.3.4). This same practice exists in the installation of bathtubs or shower stalls.

Manufactured Housing

In 1999, manufactured homes constituted 6.6 percent of U.S. occupied housing units.[1] This share has generally been growing, as households sought more affordable housing in a rapidly increasing real estate market.

Over the years, the growth in popularity of manufactured housing was viewed with some concern within the fire service and the fire protection community, because manufactured homes were considered to pose a greater life safety risk than stick-built homes. In response to this concern, in 1976 the U.S. Department of Housing and Urban Development (HUD) promulgated "Mobile Home Construction and Safety Standards," later termed "Manufactured Home Construction and Safety Standards," which was then based on NFPA 501B, *Standard for Mobile Homes.* NFPA 501B has since been withdrawn and replaced by NFPA 501, *Standard for Fire Safety Criteria for Manufactured Home Installatinos, Sites, and Communities.* These standards have been amended several times to strengthen requirements for interior finish and firestopping and to identify acceptance criteria limiting the use of materials that generate smoke and gases more toxic than those produced by untreated wood.[3] Today HUD regulations depend heavily on the requirements in NFPA 501 and the recently published NFPA 225, *Model Manufactured Home Installation Standard.* In December 2000, the Manufactured Housing Improvement Act of 2000 (MHIM-2000) was passed by Congress. MHIM-2000 established a 21-person Federal Advisory Committee. This committee operates utilizing many of the principles for consensus standards development as outlined by the American National Standards Institute (ANSI). This Federal Advisory Committee has made numerous recommendations to the Secretary of the Department of Housing and Urban Development to improve both the quality and safety of manufactured homes. See Section 20, Chapter 7, "Manufactured Housing," for more discussion on fire and life safety of manufactured housing units.

SUMMARY

The structural elements of one- and two-family dwellings, including manufactured homes, affect the fire safety of those structures. Most one- and two-family residential buildings are of Type V (frame) or Type III (ordinary) construction, as defined in NFPA 220. Manufactured homes have four major components: chassis, floor system, wall system, and roof system. Building and life safety regulations concerning fire safety for one- and two- family dwellings differ from those for other types of buildings. Several factors may contribute to the impact of fires in one- and two-family dwellings, including attic vents, mansard roofs, unfirestopped penetration of gypsum wallboard partitions, wood-trussed roof and floor framing, and cabinets affixed directly to stud framing. Manufactured homes pose their own set of problems in relation to fire safety. However, standards established by HUD and NFPA continue to be updated to address these concerns.

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3. HUD, "Manufactured Home Construction and Safety Standards," http://www.hud.gov/offices/hsg/sfh/mhs/mchss.cfm, U.S. Department of Housing and Urban Development, Washington, DC, 2002.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on structural fire safety for one- and two-family dwellings discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA *101®*, *Life Safety Code®*
NFPA 220, *Standard on Types of Building Construction*
NFPA 225, *Model Manufactured Home Installation Standard*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 501, *Standard on Manufactured Housing*
NFPA 5000®, *Building Construction and Safety Code®*

Reference

" A Study of the HUD Minimum Property Standards for One- and Two-Family Dwellings," http://www.huduser.org/publications/polleg/mps_tsp.html, U.S. Department of Housing and Urban Development, Washington, DC, 2003.

Chapter 4

Analyzing Structural Fire Damage

Revised by
Stephen Pessiki

Chapter Contents

Building Types
Structural Systems
Evaluating Fire-Damaged Structures
Evaluating Damage to Specific Materials
Fire During Construction

Key Terms

building code, building collapse, construction (type of), fire resistant, lateral load, prestressed concrete, structural steel, vertical load, World Trade Center

This chapter addresses several factors that should be considered in evaluating the integrity of structures for safe use and occupancy after exposure to fire. Initially, the focus will be on evaluating structural systems and identifying the structural damage that may affect overall and local structural stability. Subsequently, special attention is directed to the techniques for evaluating the postfire strengths and weaknesses of basic building materials—that is, steel, concrete, masonry, and wood—in structural assemblies; the use of plastic materials is also discussed. Finally, unique problems of fires at construction sites are considered.

All structural materials, whether classified as combustible or noncombustible, inherently possess a degree of fire resistance. However, they are adversely affected when exposed to elevated temperatures during a fire. The degree of damage varies with the different materials and building configurations. Where there is no visible cosmetic damage to the building after a fire, such as glass breakage, concrete spalling, or steel distortion, there is little chance of serious damage, although this is no guarantee. Thorough inspection is necessary to verify that no further damage has occurred due to the effects of excessive expansion, contraction upon cooling, and hidden deterioration. A building that is deemed safe for occupancy requires that the structural system and all its individual elements and their connections are able to safely support the structure's weight, contents, and environmental loads.

Other chapters in this handbook address structural fire protection and provide necessary background information. For topics related specifically to this chapter, see the following chapters: Section 11, Chapter 4, "Fire Hazards of Construction, Alteration, and Demolition of Buildings"; Section 18, Chapter 1, "Confinement of Fire in Buildings"; Section 19, Chapter 1, "Types of Building Construction"; Section 19, Chapter 2, "Structural Integrity During Fire"; and Section 19, Chapter 5, "Approaches to Calculating Structural Fire Resistance."

BUILDING TYPES

As discussed in Section 19, Chapter 1, building codes classify buildings by types (I, II, III, etc.) according to fire resistance. In general, the fire resistance of the construction varies from the most fire resistant for Type I to the least fire resistant for Type V. Though this classification system is useful in codifying levels of fire resistance, other more descriptive nomenclature could better differentiate a structure's performance during and after a fire. One would be better served by a more comprehensive system for identifying structures subjected to fire.

The text *Building Construction for the Fire Service*[1] discusses various aspects of the following construction and building arrangements:

1. Wood
2. Ordinary
3. Garden apartments

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4. Steel
5. Concrete
6. High Rise

Each has unique characteristics relative to its susceptibility to fire damage and to the challenges that it presents to fire fighting. Here one can begin to appreciate that the fire performance of two structures built of the same construction type can differ—for example, a convention center versus a high-rise building, both of Type I construction. Differences in various building construction types are addressed in this book.

Dunn's book, *Collapse of Burning Buildings,*[2] addresses the collapse hazards of the five standard types of constructions when exposed to fire, but the work also expands to cover the following:

- Masonry wall and parapet collapse
- Wood floor collapse
- Wood roof collapse, including peaked, flat, and timber truss types
- Lightweight steel roof collapse
- Ceiling collapse
- Stairway and fire escape collapse
- Wood frame building collapse

This text is another comprehensive guide for building performance during and after a fire. The collapse types that Dunn covers are those that have caused the majority of fire fighter casualties in the recent past.

ATC-20, *Post Earthquake Safety Evaluation of Buildings,* and its companion Field Manual, ATC-20-1,[3] present a state-of-the-art guide for evaluating structures after devastating earthquakes. ATC-20 provides detailed guidance for evaluating various combinations of materials in structural types as indicated in Table 19.4.1 and addresses unique structural damage patterns. These structure types were originally presented in ATC-21, *Rapid Visual Screening of Buildings for Potential Seismic Hazards,*[4] and are referenced in NFPA 1670, *Standard on Operations and Training for Technical Search and Rescue Incidents,* Annex C.

It should be understood that some buildings may have structures that have elements of more than one category, such as wood buildings that are braced with shear walls and steel frames, or steel frame buildings with moment frames and diagonally braced frames. Also, the category URM usually indicates structures with exterior masonry walls and wood framed floors (ordinary construction).

The ATC-20-1 Field Manual has been especially helpful in enabling engineers to provide more consistent postearthquake evaluations since its introduction in 1989 (just prior to the Loma Prieta earthquake). Much can be learned from its systematic approach in providing guidelines that help differentiate between "significant" and "acceptable" degradation of structural systems when subjected to severe environmental loading. ATC has also published *Field Manual for Post Flood and Windstorm Safety Evaluation of Postal Buildings;* but, unfortunately, no similar publication is available to aid in postfire building evaluation. The authors strongly recommend that those involved in evaluating buildings after any type of event that could cause degradation should become familiar with the ATC-20 methodology.

TABLE 19.4.1 Combinations of Materials in Structural Types

Structural Type Identifier	*General Description*
W	Wood buildings of all types
S1	Steel moment-resisting frames
S2	Braced steel frames
S3	Light metal buildings
S4	Steel frames with cast-in-place concrete shearwalls
C1	Concrete moment-resisting frames
C2	Concrete shearwall buildings
C3/C5	Concrete or steel frame buildings with unreinforced masonry in-fill walls
TU	Tilt-up buildings
PC2	Precast concrete frame buildings
RM	Reinforced masonry
URM	Unreinforced masonry

Source: NFPA 1670, *Standard on Operations and Training for Technical Search and Rescue Incidents,* Table C.1, 2004, p. 1670-46.

STRUCTURAL SYSTEMS

Every building has some sort of a vertical and lateral load resisting system. Even though these systems may be poorly organized and difficult to determine, the essential first step in evaluating any structure is to define and assess the competency of these systems.

Vertical Load Resisting Systems

Vertical load resisting may be described using a plumbing analogy. Building loads derived from component weights, contents, occupants, and so on are collected by the smallest members in the horizontal planes, then collected by beams, and finally delivered by columns to the foundation. The connections of all components are required to competently transfer the loads. The failure of any member or its connection can cause a collapse.

Vertical load resisting systems may be framed systems consisting of a coherent system of beams and columns. They may also be unframed systems that have some beams and columns, but with bearing walls that provide most of the vertical support. The size of the collapse will be determined by the importance of the member or members that are compromised. In general, a framed system has a greater potential for a larger collapse. These easily understood concepts sometimes become lost in the chaos of a disaster situation.

Lateral Load Resisting Systems

Lateral load resisting systems (LLRS) may not be as apparent upon examination of a structure. They can be described using a "pushover" analogy. The structure must have elements and interconnections that will transfer lateral loadings, acting in any horizontal direction, into the foundation system. Without a competent system, the structure will rack; that is, rectangular spaces will become parallelograms, and possibly collapse to the

ground. LLRS can be categorized as one of the following three types, or a combination of types:

1. Box buildings
2. Moment resistant frames
3. Diagonally braced frames

Box Buildings. The majority of buildings are box-type structures. They maintain their stability by having horizontal (roof and floor) planes that need to be strong, relatively rigid, and well interconnected. Plywood or solid wood diagonal sheathing on roof/floors usually performs this function in modern wood structures. Less desirable materials, such as parallel wood sheathing or decking, may be found in older and/or more poorly braced buildings. The floor sheathing provides lateral stability to joist and beams as well as transferring lateral forces to the walls. Wall sheathing, if adequately connected to the floors and wall structure, will keep the structure from racking as it transfers the forces to the foundation. The term *shear wall* is used to describe a wall that has this ability to prevent racking, which may also serve as a bearing wall. Again, plywood and diagonal wood sheathing are the most desirable sheathing types; but wallboard, plaster, and parallel sheathing may be the only type found on walls in marginally braced buildings. Box buildings may also be constructed with concrete or masonry shear walls/bearing walls. Also, floors of concrete or concrete-filled corrugated steel decking are normally strong enough to act as "floor diaphragms."

Moment Resistant Frame Structures. Moment resistant frame (MRF) structures are usually constructed using steel or reinforced concrete. The frames provide both vertical and lateral resistance. MRF structures require a competent floor plane (diaphragm) for lateral stability and load transfer. As previously stated, this is easily provided by a concrete or concrete-filled steel floor system. The interconnection of beam and column is the most critical feature of the MRF, since, in order to resist the repeated loading during high winds or earthquakes, the joints must exhibit great toughness and ductility. Prior to the 1970s, few concrete structures were capable of the required ductile performance. The 1994 Northridge earthquake demonstrated that the then standard welded joints did not possess the required ductility to reliably transfer severe earthquake stresses.[5] One needs to be aware of these difficulties when evaluating MRF structures after a severe fire. It is possible that connection damage caused by expansion or contraction forces could be hidden by fireproofing.

Diagonally Braced Frame Structures. Diagonally braced frame structures are similar to MRF, except that diagonal steel braces are strategically placed between columns to prevent racking by acting similarly to shear walls. In most occupied buildings, where rigidity is important, the diagonals are proportioned to resist both tension and compression forces. The toughness and rigidity of the diagonals and their connections are very important. Again, these members may be subjected to expansion or contraction damage during a prolonged fire.

In light industrial buildings, thin rods or small angles capable of only tension resistance are used as diagonal braces. They need to be configured as "X" bracing and need competent connections to function properly.

EVALUATING FIRE-DAMAGED STRUCTURES

Evaluation of structural damage to buildings following exposure to fire needs to be undertaken at any one or at all three time periods in the fire episode. The first would take place while the fire is still in progress, the second immediately after the fire, and the third somewhat later when the structure has been stabilized. The urgency and focus of an evaluation would be different in each of these conditions. Fire fighter safety is paramount in the first instance; public safety, including the protection of adjacent structures and their occupants, is the focus in the second; and safety issues involving long-term occupancy is the main consideration of the final, more detailed evaluation.

When considering damage incurred from fires, one must take into account deterioration of structural elements that accompanies normal aging. Wood is subjected to shrinkage/drying effects, rotting due to wetting/drying cycles, animal and insect infestations, corrosion of fasteners, and the effects of poor repair and maintenance practices. Steel may have deteriorated because of inadequate corrosion protection or thermal insulation.

Evaluation During a Fire

The primary purpose of evaluation during a fire is to ascertain whether it is safe for fire fighters to conduct control operations in or near the fire-involved building. Fire unit commanders need to quickly assess the risk of entry versus the likelihood of saving lives and property. Obviously there needs to be a different calculation for each. In some instances, such an early and preliminary evaluation can also be helpful in determining the necessary strategy for fighting the fire. As with all stages of structure evaluation, identification of building type along with vertical and lateral load resisting systems should be done immediately. Assessment should then be made based on a systematic approach to the problem. In some cases the choices may be very limited, as was the case in the 1991 fire at One Meridian Plaza in Philadelphia. There, based on inadequacy of available water supply, the decision was made to withdraw fire forces, with the result that the fire burned through ten floors prior to being controlled at an upper floor by sprinklers.

In noncombustible and significantly fire-protected structures, the decision to enter may be made with greater confidence than is the case in other buildings. Structure collapse is usually not an immediate problem. However, in the case of steel frame structures, thermal expansion may cause very high stresses in floor beams that are restrained by shear walls or diagonal braces. In addition, expansion in unrestrained floor systems can cause the enclosing walls to become dangerously out of plumb. Thermal expansion and material degradation may also cause damage to both cast-in-place as well as precast concrete structures.

At the opposite end of the spectrum, wood buildings, especially those with small member roof framing and trusses, provide the conditions that can lead to a collapse in minutes. Since these structures are relatively small and common, their performance

should be well understood by most fire-fighting units. An NFPA review examined 69 incidents from 1985 through 1997 involving fire fighter deaths or injuries as a result of roof or floor collapses in wood frame buildings. Although the data being used were anecdotal rather than statistically representative or comprehensive, the report illustrates failure modes that have been reported. A number of the cited cases involved fires in attic spaces, where the structural elements can be directly exposed to fire.[6] It should be noted that most sloped, roofed wood structures with flat ceilings are framed with some sort of wood truss. These trusses may have been constructed in place in older structures or prefabricated using metal plate connectors in more modern ones, but all present a difficult problem for fire fighting.

Structures with Timber Trusses. Timber trusses have been constructed in the United States for more than one hundred years. They are a very efficient way of spanning large spaces. Most roof trusses have some sort of a sloped, top compression member (upper chord), a level, bottom tension member (lower chord), and a series of interconnected diagonal tension or compression members (webs). Flat roof and floor trusses usually have parallel upper and lower chords connected by the webs, and some sloped roof trusses (scissors trusses) have sloped bottom and top chords. Prior to the advent of the glued laminated beam in the early 1950s, large timber trusses were used in industrial and commercial structures to span up to 100 ft (30.5 m) and more, spaced 16 to 24 ft (4.9 to 7.3 m) apart, with wood joist infilling members. These trusses were configured in a bowstring shape, or had partly sloped and partly near flat upper chords that were interconnected with steel plates and bolts (strap and pin) or diagonal steel rods and vertical wood posts (rod and block). The lower chords in these trusses are most critical since they are highly stressed in tension and interconnected by bolts. Due to normal defects in sawn timber, these bolted connections may deteriorate with time, especially in hot attic spaces. They may be a disaster waiting to happen when exposed to fire, and they should be approached with extreme caution when fire-fighting tactics are considered. A single lower chord failure could result in a large collapse. Fortunately, these trusses are limited to older buildings. The informed observer should be able to easily recognize structures with these trusses.

Structures with Light Timber Trusses. Light timber trusses, spaced from 2 to 4 ft (0.6 to 1.2 m) on center have also been constructed for more than one hundred years. Since the 1960s, with the advent of the metal plate connection, they have been engineered using very small wood members for maximum economy. As roof trusses, they are often configured with a sloped top and a flat bottom (A trusses) or may be made as scissors trusses. When intended for floors or flat roofs, parallel chord trusses are used. Some parallel floor and roof trusses may use a combination of wood chords and tubular metal webs.

Unfortunately, the attributes that make light timber trusses economical and efficient construction elements can lead to sudden, catastrophic collapse during a fire. This type of construction has the undesirable properties of highly stressed, small, easily consumed wood members that are placed in concealed spaces where fire may grow and spread between members. Collapse can and has occurred within minutes. NFPA: Alert Bulletin #97-1 of the NFPA Fire Investigations Department states that 30 fire fighters were killed in 16 incidents involving wood trusses from 1977 to 1995. Before planning interior operations in wood structures, one must identify the type of roof and floor structures. It is most difficult to determine the presence of floor trusses, but it should be assumed that any building with a sloped roof and flat ceiling is framed with trusses until determined otherwise.

Heavy-Wall Buildings. Heavy wall buildings can present some difficult and dangerous problems for fire fighters, during and immediately following a fire. These buildings are characterized as structures that are surrounded by masonry or concrete walls and are framed with wood roof/floors, and include ordinary, URM, tilt-up, and various other classifications. Since the walls usually act to confine the fire, the roof and floors can rapidly lose strength and collapse. Older buildings have the potential of containing deteriorated wood members, and newer, long span structures have the potential for a large area collapse. Both conditions can lead to a sudden entrapment of fire fighters. The 1999 Worcester, Massachusetts, cold storage building fire is a tragic example of the catastrophic performance of this type of structure.

In some cases, masonry walls, even with "fire cut" ends (i.e., ends cut at an angle to allow the floor beam to collapse without levering the masonry wall over) on wood members, have been pulled in by the collapsing floors with lethal results. The potential for this type of collapse is even greater in the western United States earthquake regions, by the practice of mechanically tying masonry and concrete walls to the roof and floor structures to limit wall collapse during seismic events. Also, walls can be forced outward by the ladder-type forces generated when an interior collapse results in large floor or roof sections being angled up against the wall. As discussed earlier, structures of this type, built prior to the 1950s, may have large, long span roof trusses, with their associated risk of sudden collapse. For more information on assessing the potential for building collapse during a fire, see *Structural Fire Fighting*.[7]

Initial Postfire Evaluation

Depending on the severity of the fire, the number of victims, the type of collapse, and so on, the authority having jurisdiction (AHJ), fire chief, or building official may require that a recovery and stabilization operation be conducted. This is the essential first postfire requirement. In cases where building departments normally have jurisdiction over certification of whether a building is safe for occupancy, there will be instances in which the necessary technical competence and experience to conduct a postfire investigation is not available within such agencies. In such cases appropriate expert consultation must be engaged.

In cases where roof and/or floor burnout have occurred, the remaining unsupported structures may require stabilization. The public way and adjacent, occupied structures must be protected, since heavy, freestanding exterior walls can collapse due to high wind forces. If major supporting elements have been weakened or if parts of the structure have become misaligned,

the building must be stabilized. The vertical and lateral load resisting systems need to be identified, and significant degradation needs to be addressed. A careful, well-documented, step-by-step evaluation should be performed. The investigator needs to identify and assess all structural systems and provide an adequate load path of resistance for all probable environmental loadings, including wind, water, and snow. To accomplish this, shoring may need to be constructed and/or safety evaluation and monitoring may be required. If the fire has produced trapped victims, recovery operations must be allowed to proceed safely and carefully. In addition, fire investigators also need time to do their essential work in a reasonably safe environment. All these operations may need to be performed prior to allowing the owner's engineer and insurance investigator access. This may appear to impede their investigations, and may cause complaints to be filed. However, safety should not be compromised at this time. If local fire and building officials do not have the necessary technical competence and experience to conduct the recovery operations or the postfire investigation within their agencies, it is imperative that expert help and consultation be engaged. This help may be available from federal, state, or local sources. The Federal Emergency Management Agency (FEMA) Urban Search and Rescue (US&R) system has developed coherent emergency shoring systems that are being taught to US&R teams throughout the United States. The U.S. Army Corps of Engineers, through its Readiness Support Center in San Francisco, California, has published *Structure Specialist Field Operations Guide,* which includes information and step-by-step procedures for constructing this emergency shoring. It also includes other information useful during rescue situations. The FEMA US&R system can also provide assistance. This system is composed of 28 locally based task forces made up of individuals with special search, rescue, engineering, communication, and medical skills (Figure 19.4.1).

CASE STUDY: Oakland, California. Following the 1992 firestorm in Oakland and at the request of the California Office of Emergency Services, a structural evaluation performed just prior to final search and recovery operations at a multibuilding apartment project. The original three-story wood apartment buildings, built over one-story concrete parking garages, had burned down to a deep pile of debris on top of the concrete structure. The parking structure was partly subterranean, and it was observed that large cracks had developed in the longitudinal, spaced shear/bearing walls of the 150 ft (46 m) long structures. The 10 in. (250 mm) thick slab was still warm to the touch a week after the fire. It was most probable that thermal expansion had caused the cracking in the restraining walls, but that the damage was not severe enough to preclude the recovery operation. Since the search could be completed within 4 hours, the risk of a major earthquake that could further compromise the walls was judged to be minimal. There was no possibility of live recovery, but there was little risk to search dogs and handlers, especially after formulating a good escape plan.

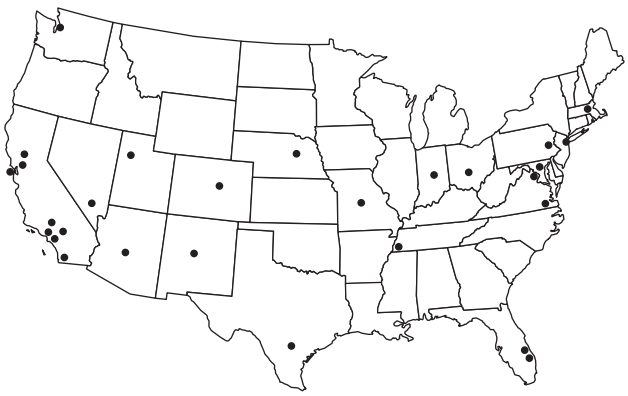

FIGURE 19.4.1 Location of the 28 FEMA US&R Task Forces

CASE STUDY: Worcester, Massachusetts. Immediately after the 1999 Worcester cold storage building fire, search and engineering elements from the FEMA Massachusetts US&R Task Force I (MA-TF-1) were dispatched to aid the Worcester Fire Department with the recovery operations involving six missing fire fighters. The search element included teams of canines with handlers that were experienced in forensic and cadaver search work. They were instrumental in locating all six victims.

The engineers deployed by MA-TF-1, known in the US&R system as structure specialists, provided initial analysis of the six-story high, unreinforced masonry walls. They then developed a safety strategy for the weeklong recovery operation that included 24 hour monitoring of the walls and the wind speed. Recommendations for safe deconstruction of the structure to aid recovery efforts were also provided by rigging experts from the task force.

CASE STUDY: Sacramento, California. In early 2001, structure specialists from the Sacramento US&R Task Force 7 provided initial evaluation of the fire hazard when a large truck rammed the state capitol building while the legislature was in session. Fortunately, in this case, there was only one casualty, the truck's driver.

Postfire Building Evaluation and Reoccupancy

Most often, inspection and evaluation of fire damage would be undertaken immediately after the fire department has extinguished the fire and declared the building stable and able to safely support an engineering investigation. There is a tendency for owners to quickly remove fire debris from the scene and thereby disturb evidence of interest in damage assessment. For this reason it is necessary that cleanup and repair operations be carefully monitored and controlled while the investigation of fire damage is underway. Some aspects of the fire damage evaluation process require that certain transient conditions regarding fire deterioration of materials and the loss of strength be allowed

to take place prior to the initiation of detailed study. This is particularly true in the case of estimating residual strength of concrete materials, which may undergo cracking, calcination, layering, and discoloration in the weeks following exposure to fire temperatures.

It should also be noted that the work and reports of engineers engaged in the assessment of fire damage will often be of interest in litigation following severe and high-loss fires. For this reason, the methodology for conducting inspections, testing, and the manner of reporting should, as a minimum, follow the evaluation procedures outlined in ATC-20, and a report should be written that documents all observations made by the investigator and any physical tests that are performed. Owners or their insurance companies will normally pay for the reports and choose the engineer. However, tenants or their legal representatives, and even the local building official, may also be involved in the selection process.

A detailed engineering study will be necessary to determine the parameters for repair and/or partial replacement of the building. Damage to vertical and lateral load resistant systems as a whole, as well as to individual members, will need to be assessed and carefully tabulated. The determination of significant degradation versus cosmetic damage requires well-informed engineering judgment. A qualified professional engineer specializing in structures should conduct the evaluation, since the influence of distortion and residual stresses may have a significant negative effect on parts of the structure. Prudence and legal liability concerns may cause engineers to err on the conservative side. Insurance interests and the owner's needs for reoccupancy may argue for a greater acceptance of partly damaged structural elements. This natural conflict should be anticipated, and it may need to be emphasized that, since the building is being renewed at least in part, it needs to be at least as safe as in its prefire condition or satisfy current code requirements.

If a significant percentage of the structure needs to be rebuilt, the entire building may be required to meet current building codes. Some building codes, such as *NFPA 5000®*, *Building Construction and Safety Code,* specifically address building rehabilitation and include provisions for damaged and unsafe buildings. More specifically, Chapter 15 of *NFPA 5000®* indicates that where the structure of a building is damaged, an evaluation is to be conducted to determine whether such damage is substantial as defined by the code, and whether the building was structurally unsafe prior to the damage. *NFPA 5000®* determines that a building has substantial damage when either:

(a) The total strength of a structural element or group of elements, supporting more than 30 percent of the structure's vertical loads has been reduced by more than 25 percent from the pre-damaged condition, and the remaining capacity with respect to all dead and live loads is less than 75 percent of that required by this Code, or
(b) The combined lateral strength of resisting structural elements in any story has been reduced by more than 20 percent from the predamaged condition.

Depending on the degree of damage and the determination as to when the damage occurred, the building structure is to be restored to either conditions prior to the damage or into compliance with the Code. As indicated by the description of unsafe buildings in *NFPA 5000®*, the damage or unsafe structural condition can result from a number of events, including fire, explosion, wood-destroying pests, winds, earthquake, vehicular impact, or ground subsidence.

Some building codes might have requirements for "abatement of dangerous buildings" that are less restrictive than *NFPA 5000®*. Buildings that are significantly damaged by fire are considered dangerous. It should be noted that local building officials have considerable discretion in applying abatement requirements. Changed zoning requirements and economic considerations may also influence reconstruction. In some codes, buildings may be reconstructed according to prior regulations, providing the cost for renovation does not exceed a given percentage of the original cost.

Historic buildings may be treated somewhat differently. Many historic buildings do not meet current codes, and if significantly damaged by fire, they may not be able to be economically upgraded to current code requirements. Chapter 15 of *NFPA 5000®* has specific provisions that address historic buildings and structures. As a result of what preservationists considered unnecessary demolition following earthquakes, a guidebook, *Temporary Shoring and Stabilization of Earthquake Damaged Historic Buildings,*[8] was developed in 1998. It discusses the difficult issues facing local building, emergency, and other governmental officials regarding the saving of damaged historic buildings.

Finally, cooperation with the fire department is essential to establish the path and progress of fire, including the method of extinguishment. It may be possible to establish maximum temperatures reached during the fire by examining debris from melted material and by inspecting structural members for spalling, cracking, discoloration, deflection, and so on. The influence of temperature on the mechanical properties of structural materials raises the question of the usability of the material after it has cooled down to ambient temperature. The evaluation of the structural behavior of steel, concrete, masonry, and wood is described in general in the following section. A more detailed evaluation procedure and a case study of renovations is given in Chapters 12 and 13 of *A Complete Guide to Fire and Buildings.*[9]

EVALUATING DAMAGE TO SPECIFIC MATERIALS

Design of Structures Against Fire[10] contains useful information on the behavior of common building materials, including structural steel, reinforced concrete, and wood, when exposed to high temperatures. Of interest in this same publication is information on repair of fire-damaged structures that includes an assessment procedure for fire-damaged structures and a visual damage classification system for reinforced concrete elements. Also of interest to the fire investigator is the ASCE publication, *Guidelines for Failure Investigation.*[11] Here, the organization and details of postfire examinations are outlined in enough detail to better suit the rigors of forensic inquiries. NFPA 921, *Guide for Fire*

and Explosion Investigations, is also a useful resource in this regard.

Structural Steel

Thermal and mechanical properties of steel are given in ASCE's manual of practice, entitled *Structural Fire Protection.*[12] This publication presents information on the modulus of elasticity at elevated temperatures, stress-strain curves for structural steel at various temperatures, and deformation properties. Most important for evaluating load-carrying capacity following exposure to fire is the loss of strength suffered as temperatures rise from about 212 to 1292°F (100 to 700°C). Steel loses significant stiffness above 600°F (316°C) and loses significant strength above 1000°F (538°C). A second factor that influences the behavior of steel during fire incidents is the coefficient of thermal expansion, which increases with increasing temperatures and reaches a value of approximately 0.008 in./in. at a temperature of 1112°F (600°C).

The use of several grades of steel in buildings and bridges is accepted in modern building codes and design standards. Although different grades of steel have a wide range of strengths, tensile and yield strengths of all steel grades are similarly affected by the temperatures that may be expected in building fires.

The behavior of beams or other members subject to bending stresses under fire conditions is complex (Figure 19.4.2). In a building fire, the steel temperature may vary considerably over a single cross section, as well as along the length of a structural member. Information relating to the strength properties of steel at elevated temperatures has been derived from the results of tests on small specimens heated so that the entire specimen was at or close to the measured temperature. Conclusions relating to strength characteristics from such small-scale tests may not be applicable to steel structural members. Moreover, plastic action results in the redistribution of stresses in steel members that are loaded close to the design limit. This characteristic permits steel members to sustain loads greater than those calculated to be safe on the base of yield strength alone; therefore, the strength of a given steel member cannot be determined only from isolated temperature data.

FIGURE 19.4.2 Unprotected Steel Damage on Floor of Office High Rise with Minimal Fire Load but Extensive Loss

In a building fire, parts of the structure may have been exposed to heating followed by abrupt cooling by water from hose streams. This temperature change is usually less severe than what accepted practice allows in heat-treating of steel during manufacture. Tests performed on structural steel specimens taken from buildings that experienced fire during and after construction have indicated that yield strengths did not drop below the specified minimums. However, when a postfire test is compared with the original mill tests, one can find that the original yield strength, usually at least 10 percent above minimum, has dropped to the minimum value. This can be explained as a loss in the nominal gain in strength that occurs during the rolling process. The members that exhibited scorched paint will most often suffer this loss. It then becomes the responsibility of the investigating engineer to determine if the loss is significant. Steel members that show some distortion due to heat, but that can be straightened, should have their physical properties thoroughly evaluated. Connections between members should also be examined for cracks around fastener holes and welds.

Occasionally, steel exposed to a fire will have a somewhat roughened appearance due to excessive scaling and grain coarsening. The coarsening is caused by exposure of steel to temperatures around 1600°F (870°C) or higher. The steel will usually have a dark gray color, although other colors may be present if certain chemicals have been involved in the fire. Steel so modified is commonly called "burnt" steel. Members that have become burnt will usually be severely corroded as well, and their suitability for further use is a matter for individual judgment. The FEMA Report 403, "World Trade Center Performance Study,"[13] Appendix A, presents a detailed discussion on the effects of fire on steel structures. The NIST report on the collapses of the World Trade Center towers also includes an analysis of the structural fire response of steel.

Protective Coating on Structural Steel. Excluding other factors that affect fire growth, such as extinguishing systems, low fire loads, compartmentalization, and so on, damage to structural steel members may be minimized by application of protective coatings that provide a period of fire resistance. Generally, a mineral fiber or cementitious mixture is applied by spray application; however, the adherence and durability of such coatings, even under normal circumstances, has been the subject of some concern. Too often, questionable application resulted in unreliable fire resistance and subsequently, considerable structural damage. The absence of protective coatings over even relatively small areas of the flange or web of steel beams and columns can have a dramatic impact on the structural fire behavior of these elements.[14,15] The local heating of the structural steel at the exposed location can reduce the resistance of the beam or column. In contrast, even a small remnant thickness of protective coating can significantly improve the behavior of the structural element as compared to bare steel (Figure 19.4.3).

A large fire in a 50 story office building known as One New York Plaza occurred in 1970 in New York City and resulted in three fatalities. Much of the $10 million in physical damage

FIGURE 19.4.3 Large Unprotected Steel Girders Damaged Beyond Repair, Illustrating Vulnerability of Steel in a Fire

arose from failure of sprayed-on thermal insulation. This incident was instrumental in the passage of New York City's Local Law Number 5, which is a comprehensive approach to improving life safety in high-rise office buildings.

Sprayed-on protective coverings can be expected to be easily dislodged during fire-fighting and overhaul operations. Usually problems of this kind are easily detected, but a complete examination of the structure must be made to determine the extent of damage. Also, before occupancy is permitted, it is imperative to determine that fire damage to a specific section of a building does not impair the integrity of zones of safety, means of egress, and smoke towers, or the operation of fire doors, fire dampers, or other protective devices or systems in areas not damaged by fire.

Fire Tests. The principal fire test used to establish fire resistance for structural elements is NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials,* or its ASTM equivalent, ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials.* In using test results, however, it is essential that architects and design engineers look closely at differences between standard test conditions and potential fire conditions the structure may be exposed to. Only with such a review can accurate and safe conclusions be drawn about the performance of a building design. At best it is a destructive comparative test with little relation to actual fire conditions.

For fire-resistive purposes, many floor/ceiling and roof/ceiling assemblies are considered as a single fire-resistive element. The ceiling by itself does not provide a specific fire resistance rating. It should be noted that many floor or roof and ceiling tests provide an assembly rating, as well as a beam rating. The beam rating should not be interpreted as a measure of protection afforded by the ceiling. Unfortunately, if the ceiling membrane does not provide fire resistance, structural components above the ceiling are subject to damage in a fire.

Cast Iron. The use of cast iron as structural material has all but ceased. If found, these buildings are undoubtedly archaic historical preservations. A number of such buildings may still be found in New York City and elsewhere. In some instances, only the facades are of cast iron; in other cases, both the structural elements and facades are of this material. The behavior of cast iron when exposed to fire temperatures is substantially different from that of steel. Cast iron exposed to temperatures of 800°F (427°C) will deteriorate and fracture if struck with water from a fire hose.

Concrete

In a fire lasting 1 to 2 hours, concrete will generally suffer only moderate damage, so routine cutting and patching procedures will usually be adequate for repairs. In intense and long-lasting fires, such as those that may occur in large, heavily stocked warehouses and department stores, severe damage to concrete may occur. Restoration may entail the removal of severely damaged areas and patching in areas less severely damaged. Experienced engineering judgment is required for evaluating the residual strength of those areas that are somewhere between moderately and severely damaged. An example of one approach to the problem of evaluating the residual strength of apparently marginally damaged concrete structural units can be found in the article "Prestressed Concrete Resists Fire" by Zollman and Garavaglin.[16]

Damage Analysis. Over the past two decades much progress has been made in the improvement of methods for analysis of properties and behavior of concrete exposed to elevated temperatures. Better understanding of the fire behavior of concrete is a result of full-scale test results, model studies, and analytical methodologies directed to long-standing issues, including influence of restraints on reinforced concrete columns, deformation behavior, and thermal damage. These developments offer valuable tools for estimating the extent of fire damage and residual strength following fire exposure of structural elements and systems. *Fire Safety Design & Concrete,*[17] discusses structural response of concrete elements to fire. This work presents basic engineering concepts for considering flexural elements, compression elements, and complex structures and frames.

The use of admixtures to produce various desired characteristics in concrete has increased over the years. There are now on the market dozens of products for strength enhancement, set acceleration and retardation, shrink reduction and flowability, early strength, reduced permeability, and other qualities. Long-term effects of some of these additives on strength and durability are not well researched, and the same is true for behavior of these concretes during and following exposure to fire conditions.

With the increasing use of high-performance concrete (HPC) with compressive strengths exceeding 16,000 psi (110,000 KPa), the matter of spalling at high temperatures has become of interest. Research in the United Kingdom and elsewhere indicates that *explosive spalling* greatly reduces the fire resistance of concrete and that increasing the strength of concrete can be expected under certain conditions to reduce fire performance.[18,19] The identification and control of unfavorable factors, such as curing and drying conditions, aggregate size

and type, and concrete permeability, remain under investigation. Research indicates that the addition of polypropylene fibers to the concrete mixture will reduce spalling and improve the fire load behavior of high strength concrete columns.[20] Work on the characterization of high-performance concrete is underway at the National Institute of Standards and Technology (NIST), using quantitative image analysis to determine the macro- and microstructures of HPC in relation to the response to fire.

A waiting period of perhaps several weeks should elapse after the fire has been extinguished before careful study of structural damage is initiated. This delay will allow any damage to the concrete, such as cracking, layering, calcination, and discoloration change from the natural gray color to pink or brown, which is indicative of heating to temperatures in excess of 450°F (232°C), to become more discernible. The thickness of fire-damaged concrete in structural members can be determined by chipping with a pick or geologist's hammer. Unsound concrete may be colored and will be more or less soft and friable, whereas sound concrete will give a distinctive ring when struck with a pick or hammer. Cored concrete samples for compressive strength tests and reinforcing steel for tensile strength determinations will enable a closer evaluation of the residual strength of damaged members. Load tests may be applied but should only be conducted under the supervision of a registered structural engineer. ACI Committee Report 437R-03, "Strength Evaluation of Existing Buildings," provides guidance on the planning, conduct, and interpretation of load tests.[21]

A variety of nondestructive evaluation (NDE) test methods may be deployed to help evaluate the postfire condition of a concrete structure. A detailed explanation of these methods is beyond the scope of this chapter. Two ACI Committee Reports provide the state of the art on NDE methods for concrete. ACI Committee Report 228.1R, "In-Place Methods to Estimate Concrete Strength,"[22] describes procedures to estimate the in-place strength of concrete in existing construction, including methods that may be applicable to a postfire evaluation, such as rebound number penetration resistance and ultrasonic pulse velocity. The principle, inherent limitations, and repeatability of each method are reviewed, and procedures are presented for developing the relationship needed to estimate compressive strength from in-place results. A second report, ACI Committee Report 228.2R-98, "Nondestructive Test Methods for Evaluation of Concrete in Structures,"[23] reviews nondestructive test methods for evaluating the condition of concrete and steel reinforcement in structures. The methods discussed include visual inspection, stress-wave methods, nuclear methods, penetrability methods, magnetic and electrical methods, infrared thermography and ground-penetrating radar. The principle of each method is discussed and the typical instrumentation is described. In addition, the testing procedures are summarized and the data analysis methods are explained. Finally, the advantages and limitations of each of the methods are summarized. Severe exposure of heavy concrete sections to fire may cause layering, that is, partial separation of the outer 1 to 2 in. (25 to 51 mm) of concrete of a building member from the interior mass. Such layering can complicate the application of the NDE methods described in the ACI Committee 228 reports. Successful application of the methods described in the reports requires an experienced operator.

A complete report dealing with a survey of fire damage to a multistory reinforced-concrete building and the subsequent repair procedure can be found in the paper "Fire Damage to General Mills Building."[24]

CASE STUDY. A severe fire occurred in 1951 in an unsprinklered paper warehouse. This fire lasted for more than 44 hours, and it is estimated that heat intensities of more than 1600°F (870°C) existed for 3 hours or longer. Even after severe fire, the structure was still standing and the concrete floors prevented the spread of fire and major water damage. An inspection of the structure after the fire showed that the concrete roof and columns appeared to have suffered little damage, except that the roof showed deflection up to a maximum of approximately 2½ in. (64 mm) in a 20 ft (6.1 m) span. When holes were cut through the roof, it was found that the concrete was calcined and had a light brown color in varying depths. This damaged concrete had almost no strength and began to disintegrate after a period of several weeks. As a result, the portions of the roof slab that showed appreciable amounts of calcined concrete were replaced. Many of the columns required removal of the concrete down to the reinforcing steel spiral, and, in some cases, calcining appeared inside the spiral. In these cases, the entire column was replaced. The column caps were replaced completely if more than one-half of the column showed evidence of calcining. Reinforcing rods showed some reduction in tensile strength, but most were salvaged and reused and downgraded to about three-quarters of their original strength.

If a decision is made to repair the damage, the usual procedure is to shore up the structure, if necessary, and to remove the fire-damaged concrete, using a hammer, chisel, or a lightweight mechanical hammer. (Use of heavy hammers is discouraged, since they might aggravate the damage by inadvertently chipping good concrete.) The steel reinforcements are then cleaned and, if necessary, additional reinforcements are added and, finally, the concrete is built up with air-blown grout. Durable concrete repairs have been made with epoxy resins also (unfortunately, epoxy is subject to significant strength loss at temperatures above 150°F [66°C]).

The significant difference between conventional reinforced concrete and prestressed concrete in fires is the performance of the high-strength steel wire, strands, or rods used for prestressing. Under fire conditions, the prestressed steel concrete units are susceptible to rapid loss of strength at temperatures in excess of 752°F (400°C). A load test is recommended in postinspection for significant pronounced sag or an indication of excessive temperature in a range where stress loss may have been sufficient to seriously affect the strength.

Tilt-up construction is a popular, simple, and effective type of concrete construction. As the name implies, slabs are site precast adjacent to their final location and lifted into place. In older structures, dating from the 1950s and 1960s, the reinforcing steel projecting from adjoining wall panels was encased in cast-in-place concrete columns. These systems provided relatively reliable fire resistance. In more recent construction, the

wall panels are connected by exposed steel weldments, which are vulnerable to fire damage. The joints in this type of newer "value engineered" construction are filled with flexible, combustible mastic instead of concrete.

Tilt-up construction does not normally allow the walls to be as well connected to the foundations as in normal cast-in-place construction. This can result in an even more potentially dangerous condition when the roof has been burned away. The then unsupported walls are quite vulnerable to tip-over in windy conditions. Some building codes require that this and similar "heavy wall" buildings be designed for "burn-out " conditions, and mandates more competent wall foundations. One should be especially aware of this inherent weakness, during and immediately after a fire.

Several fires on the West Coast have displayed these inherent weaknesses (Figure 19.4.4). Complete collapse and highly damaged panels precluded any effort of cost-effective repair.

Brick

During production, clay bricks are exposed to temperatures in excess of 2000°F (1093°C); hence their strength is retained in actual fires. Reinforcing steel embedded in the center of a clay brick wall would normally be protected by a minimum of 3 to 4 in. (76 to 102 mm) of brick and not be affected. Spalling should be expected, especially if hot bricks are drenched with water from a fire hose. In most cases, temporary repairs can be made with epoxy cement or air-blown grout. Permanent repairs are more appropriately made by replacement, in kind, of the defaced brick.

Wood

Wood is one of the oldest and most widely used building materials. Its behavior in fire conditions varies considerably, depending on the species of wood and the design configuration, that is, solid sawn lumber, glue laminates, plywood, wood chipboard, and so on. The effect of fire on glue laminates may be considered the same as that on solid sawn lumber (heavy timber), assuming that the adhesives used were not affected by heat and that metal plates joining members and their attachment are not damaged. Generally, the phenol-resorcinal and melamine adhesives are not affected by heat. Plywood and chipboard are also dependent on proper adhesives, the difference potentially being slow burning versus a hazardous flash fire caused by delamination.

FIGURE 19.4.4 Fire Damage to Building of Tilt-Up Construction (Source: Oakland, CA, Fire Department)

There are two primary aspects of the behavior of wood materials exposed to fire and other sources of ambient heat. The first involves loss of strength as a result of burning away of material. The second is its contribution to the energy released in a fire through its combustion. Time rates of loss of material and strength can be estimated in terms of char depth and direction of fire spread can be estimated by developing char depth contours. This was the procedure used to trace the extension of fire in the Happy Land Social Club that took 87 lives in New York City in 1991. Ignition temperatures and contributions to heat release in a specific fire depends on a number of factors, including species, density, and moisture content. Long-term exposure of wood to elevated ambient temperatures reduces strength and lowers ignition temperature. Both of these effects can be important in the overall investigation and evaluation of structural damage from fire.

ASCE's "Guide and Commentary for the Evaluation, Maintenance and Upgrading of Wood Structures"[25] provides detailed information on serviceability factors, inspection, evaluation of load-carrying capability of timber structures and methods of repair.

Redwood, found on the West Coast of the United States, withstands high fire exposures. It is reported that the high resistance is due to the lack of the usual volatile resins and oils found in other woods. Redwood forests have resisted fire for centuries.

When wood structural members are subjected to fire, the ability to withstand the imposed loads is dependent to a degree on the remaining undamaged cross-sectional area. The average rate of penetration of char when flame is impinged upon an exposed wood member is approximately 1½ in. (38 mm) per hour. Beyond the char area to a distance not more than ¼ in. (6 mm), the structural properties of wood may be affected by its exposure to high temperatures. The degree of strength loss in this small zone adjacent to the char is not exactly known but is presumed to be insignificant.

Fire tests made on two solid sawn wood joists, 4 × 14 in. (102 × 356 mm), nominal size, at the Southwest Research Institute showed that, after 13 minutes of fire exposure, 80 percent of the original wood section remained undamaged and available to carry the load. In another test of two 7 × 21 in. (178 × 533 mm) glued laminated beams, after a 30 minute fire exposure, 75 percent of the original wood section remained and continued to support the design load.[26]

The previous tests, as well as actual fire experience, substantiate the fact that large-dimension wood members will remain in place under fire conditions and continue to support design loads. It is usually in the larger or heavy timber members that char can be scraped clear and an evaluation made by a qualified engineer or architect to determine the remaining load-supporting capacity of the wood member. As previously discussed, trussed wood roof structures constructed with 2 × 4 and 2 × 6 members have a history of lethal, sudden collapse when exposed to fire.

The practice in older, wood frame buildings was to diagonally cut the tops of wood beams within the bearing wall pocket so that in the event of failure due to fire, the weight of the member would not tear out the wall masonry and/or cause collapse. Further, on reuse of older wood beams it was the practice to invert the beam, which then placed the cut in the pocket, resulting in a reduced bearing area and ability to take shear load. The notching of wood structural members can play an important role in determining the time for failure and the estimation of residual strength of structural timber constructions in fires. The inverting of these members on reuse can also contribute to early failure and collapse. Because of the large number of wood framed buildings in existence, the condition of floor and roof beams at bearing walls should be carefully examined following exposure to fire.

Unanticipated problems often arise following building conversions and other structural and spatial renovations, which may either conceal spaces that were originally open or expose spaces and structural members that were originally concealed and protected from fire. The latter can be particularly hazardous in unsprinklered buildings.

A good example of the complexity of restoration work following a fire is described in the paper "Saving the Exeter Street Theater."[27] This landmark building in Boston, Massachusetts, was constructed in 1885 and ravaged by fire in 1985. One of four 80 ft (24.4 m) long, 18 ft (5.5 m) deep wood trusses and the roof were severely damaged. Besides preserving the original character of the building, engineers were obliged to meet structural requirements of the modern building code. Among other conditions, designers were faced with serious truss decay at the bearing locations and distortion and shrinkage defects of the top and bottom chords. Restoration efforts plus changes in the useable spaces in the building required use of a full range of structural technology. The paper illustrates the importance of careful evaluation of all aspects of wear and aging in addition to fire damage that must be addressed when older buildings are to be repaired.

The special case of evaluating and predicting possibilities for collapse while a fire is still in progress is of interest to fire forces engaged in rescue and fire control operations. Here there is need for the evaluator to recognize early signs of impending failure of both structural and nonstructural elements and systems. Failure resulting in collapse of ceilings, sheathing, glass, and other elements of construction that do not directly affect structural integrity can endanger fire fighters and can contribute to the growth and extension of fire.

Plastics

Plastic construction has been limited to small structures, such as cabins and radomes. However, the use of plastics in building contents and as building materials has steadily increased,[28] as has the resultant fire load. The products of combustion of plastic can be very corrosive and can severely damage structural elements in buildings during a fire. The Munich Reinsurance Company reported extensive losses due to corrosion from gaseous decomposition of burning plastic. Twelve buildings were listed as having extensive corrosion-damaged structural steel members. In several cases, it was necessary to destroy the buildings. Steel members moderately damaged by corrosion may be sandblasted, but it is suggested that a stress analysis be conducted before repairs are started. Damage to reinforcement concrete is more complex, since corrosion, in time, is apt to penetrate to the reinforcing material. Preliminary analysis is necessary before power hammers are used to inspect the extent of damage to reinforcing steel.

FIRE DURING CONSTRUCTION

A dangerous practice is often found during the course of construction of steel-frame buildings; it is common during the application of fireproofing to structural steel members that the coating on the lower first and second stories is postponed until the final stages of construction. The application of fireproofing to these lower floors is often delayed due to the potential physical damage to the coating in these high-traffic areas. These heavy-working areas usually also contain storage of construction materials and equipment, much of which is highly combustible (Figure 19.4.5). The amount of combustible material can provide a fire load capable of destroying the building.

Buildings of reinforced concrete may depend on wood shoring supports and form work to support the fresh concrete pour and to retain their shape until the concrete gains sufficient strength to support its own weight and possibly portions of the floors above that are under construction (Figure 19.4.6). At this stage of construction the building is also highly vulnerable to fire damage. A fire before the concrete curing process is complete could result in a total loss.

Awareness of this problem was demonstrated at the reconstruction of St. Mary Cathedral in San Francisco, California. Built at a cost of $10 million to replace a former church destroyed by fire, its cupola walls extended some 150 ft (46 m) above the ground floor. The supporting scaffolding filled the interior with 1½ million board feet (3500 m^3) of lumber at a cost of $100,000. The chief building superintendent, aware of the fire loss potential, directed that a temporary sprinkler system be installed.

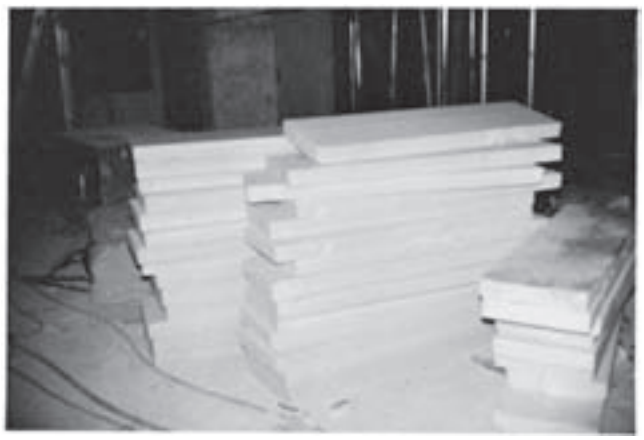

FIGURE 19.4.5 Lower Floor Used for Storage of Materials and Equipment

FIGURE 19.4.6 Timber Used as Shoring and Support of Reinforced-Concrete Construction, Essentially a Forest of Wood

SUMMARY

Several factors must be considered in the evaluation of the integrity of a structure after a fire. First, structural damage that may affect overall or local stability must be identified. Then the postfire strengths and weaknesses of the basic materials of the structural assembly must be assessed. Structural steel, concrete, brick, wood, and plastics exhibit different behaviors both during and after exposure to fire. The age and deterioration (e.g., from corrosion, animal infestation, or poor maintenance practices) of the individual materials must also be taken into account. Finally, thorough engineering studies are necessary to determine the parameters for repair and/or replacement of the building's structural elements, as well as to document insurance and litigation claims.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the processes for analyzing structural fire damage discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of the current editions of the following documents.)*

NFPA 220, *Standard on Types of Building Construction*
NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 921, *Guide for Fire and Explosion Investigations*
NFPA 1670, *Standard on Operations and Training for Technical Search and Rescue Incidents*
NFPA 5000®, Building Construction and Safety Code®

Chapter 5

Approaches to Calculating Structural Fire Resistance

Barbara Lane

Chapter Contents

Understanding Structural Response to Fire
Alternative Approaches to Fire Resistance
Determining a Design Fire for a Structural Analysis
Single Structural Element Analysis
Application of Single Structural Element Analysis to Steel
Application of Single Structural Element Analysis to Concrete
Application of Single Structural Element Analysis to Composite Steel and Concrete Members
Application of Single Structural Element Analysis to Wood Elements
Application of Single Structural Element Analysis to Aluminum
Use of Advanced Analysis in Global Structural Response to Fire

Key Terms

aluminum, composite steel, concrete, design fire, fire resistance, fire test, heat transfer, postflashover fire, section factor, single element analysis, spalling, structural integrity, structural performance, structural steel, time-temperature curve, wood

This chapter provides an overview of structural fire resistance calculation techniques, developed over many years, to address the critical parameters that can affect structural performance in actual building fires. It concentrates on the international body of work on the subject. As discussed in the first few sections, determination of structural fire resistance is typically associated with standardized laboratory fire resistance testing, which finds its roots in the 19th century. However, over several decades, researchers have investigated structural response of building elements to real-world fire loads and postulated various theories for use in the design domain.

It is a misnomer to conclude that any standard fire resistance test can demonstrate or approximate the full-scale complex structural fire performance of building elements. Instead, standard test methods serve well as a comparative assessment method, providing valuable data on the relative performance of materials and small-scale assemblies for a specified fire load.

Concern with the limitations of these standardized tests in providing a comprehensive assessment of full-scale structural fire resistance and the use of these test results as the primary basis for fire-resistant design in building structures has led to the development of alternative assessment and calculation methods over the years. The primary concern is the reliance on the assumption that a structural system tested at a relatively short span, in a laboratory furnace, can robustly translate into a basis for design at the scale required in real buildings. Concerns also exist regarding the lack of assessment of the performance of structural connections as well as the universal application of a standardized fire load during the test.

Initially researchers concentrated on the concept of a standardized fire load (time-temperature curve) and whether it adequately represented the broad range of fire conditions that could be experienced in actual building fires. As such, initial efforts attempted to gain a better understanding of the heating regime that can occur in a compartment (enclosure containing a fire). These investigations concentrated on determining whether a common set of parameters affected overall fire loading such as duration of the fire, the peak temperatures and heat release rates attained in the enclosure, the rate of heating in the compartment once flashover had occurred, and so on. The section "Alternative Approaches to Fire Resistance" describes some of the techniques that address the fire resistance rating appropriate to specific compartment geometry and its contents.

Further clarification on the critical parameters to consider when specifying the fire load that forms the basis of a structural fire design are outlined in the section "Determining a Design Fire for a Structural Analysis" and result in temperature-time relationships that form the basis for calculating structural fire resistance that is not based on standardized tests.

Over time, it became apparent that not only was a better understanding of fire parameters required to understand real fire resistance, but also the performance of structural elements in these fires. As such, individual structural element response to the elevated temperatures that occur in fires was investigated. Analytical methods to capture these very specific responses to fire are presented in the section "Single Structural Element Analysis."

This growing understanding of basic structural response was further developed over the years in part by more critical observations during fires, as well as formal full-scale testing. The data produced

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have resulted in the creation of more advanced structural analysis techniques specifically targeted for fire conditions. The increasing work in this domain is resulting in a substantially greater understanding of true building structural performance in response to fire and is prompting the view that structural detailing and specific structural design for fire is the next and much needed step in optimizing building safety. Methodologies that exist to carry out such assessments are presented in the section "Use of Advanced Analysis in Global Structural Response to Fire."

It is increasingly clear that this important topic requires the attention of fire protection engineers and structural engineers, and that only through successful integration of the expertise in both professions can the result be a robust and commercially beneficial approach to improving the effectiveness of structural design for fire safety.

For related topics, see Section 19, Chapter 2, "Structural Integrity During Fire"; and Section 19, Chapter 4, "Analyzing Structural Fire Damage."

UNDERSTANDING STRUCTURAL RESPONSE TO FIRE

Standardized Fire Resistance Test and Refinements to Fireproofing Thickness

The standard fire resistance test (NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials;* ASTM E119; ISO 834; BS 476; etc.) has formed the basis of fire resistance ratings in building codes worldwide for more than a century, resulting in structural fire resistance being treated separately from the concerns typically addressed by structural design. The implementation of the standardized fire resistance tests called for establishing adequate protection to the structural material with respect to limiting its temperature rise in fire. Time was the sole emphasis—providing fire resistance time to meet code requirements for building structure elements. See Section 19, Chapter 2, "Structural Integrity During Fire," for more discussion on the implementation of the standardized fire resistance test.

Typical building code requirements call for ratings appropriate to specific structural elements as a function of the building use, height, and area, and remain an established "best practice" approach to designing structures for fire resistance worldwide.

In brief, therefore, steel structures require varying amounts of applied fireproofing as a function of building height and use; concrete structures require varying amounts of cover for reinforcement; and timber structures require varying section sizes to allow for the loss of material in elevated temperatures. These measures, in the case of steel, were simply to limit the temperature rise beyond the material's estimated failure temperature of 550°C. For concrete, requirements sought to prevent the reinforcement bars from similarly exceeding these temperatures, whereas for timber, to ensure that the remaining timber portion could still carry its design loads once the charred portion of timber was no longer considered.

Small changes were made over the years, mainly coming from continuing strides to bring efficiency to fire protection costs. In the United Kingdom particularly, the ability of structural elements to sustain the load path in fire was increasingly studied to reduce the amount of fireproofing materials required. Refinements to the formulized fireproofing thicknesses were made, based on individual structural element failure temperatures rather than on the assumption of the generic 550°C concept. The refinements were also made based on the postulated theory that structural elements carry less of a load in the fire (fire limit state) relative to the "normal temperature" conditions (BS 5950-8: 2003). In addition, the sensitivity of section size to heat was incorporated via the heated perimeter to cross-sectional area concept.

Studies After Broadgate Building Fire

This refined single element approach served the design community well, albeit in the specialist domain only. More change was to come, however, after a real fire at the Broadgate building in London, where the steel structure was in essence unprotected and yet managed to survive the severe fire that occurred there. The steel industry in the UK and also in Australia started to question just how much real understanding of structural performance in fire existed and established a major program of full-scale fire tests on real-scale structures.[1–4] The findings caused a fundamental change in the understanding of steel structural performance in fire. It is worth noting that the concept of specific fire-related structural mechanisms is also being investigated and applied to other types of structural materials.

The studies after the Broadgate fire made it clear that the traditional emphasis on limiting temperature rise in materials to prevent degradation of strength was just one important parameter in the fire condition. Similarly, it became clear that refinements to fireproofing thickness based on generic reduced loading conditions for fire, and taking account of the specific strength of an individual structural element and therefore its unique failure temperature, were only touching the surface of what in fact was an incredibly complex problem. The effect of the expansion of structural materials in fire was shown to be of dominant concern, even at very low temperatures. Work such as the British Steel data from the Cardington fire tests,[5,6] the Cardington Fires Main Report from Edinburgh University,[7] and Usmani et al.[8] provide detailed background information on the test observations and structural mechanics in fire.

Although it is true that strength of steel structural materials decreases with increasing temperature, the geometry of the structural component itself also changes over the time of the fire due to the expansion of structural materials. This expansion effect is not just a function of very high temperatures experienced during a fully developed fire, but also a function of the span of the structural elements, their arrangement, and strength losses. These structural responses during fire were observed at temperatures as low as 100°C.

The results of the test program at both Cardington and William Street indicated that, for some structural arrangements, less fireproofing than expected was needed to provide structural stability as well as to maintain compartmentation (i.e., fire separation) requirements for the duration of a severe fire, including the cooling regime as the fire died out.[2]

To clarify this point, fire resistance is classified in two ways: (1) rating for the structural elements to maintain the structural

stability of the building in fire and (2) rating for walls, floors, shaft walls, and so on, whose aim is to limit fire spread from one fire compartment to the next. For example, one story in a building may be one compartment, or, for a different use, one story may in fact contain several fire compartments. The work at Cardington looked at the effect of removing fireproofing from specific—namely, secondary—beams and observing whether (1) structural integrity was maintained (i.e., there was no overall building collapse) and (2) compartmentation was maintained. In other words, if the floor, for example, was deforming in the fire, it might not interfere with the overall stability of the building, but it could cause a breach in a compartment wall (as the result of the deforming floor pulling on the wall) and therefore could create a gap that allowed the fire to spread to another fire compartment.

Robust Response Analysis

Thus, there is a growing trend to apply this increasing understanding to real buildings, as well as carry on with investigations of full-scale structural response mechanisms in fire. Prior to the collapse of the World Trade Center, particularly in the United Kingdom and Europe, the emphasis for such detailed analysis of structures in fire and its practical implementation was very much on bringing efficiency to mostly steel design arrangements. However, since the collapse of the World Trade Center, robustness of response has formed the theme of this analysis, particularly for tall building structures. This means understanding the potential structural fire response mechanisms associated with a proposed structural design, and making refinements where weaknesses are identified that can result in global or local failures (either in the ability to maintain the design load or in the necessary compartmentation). Specifically, if structural designs are based on structural assemblies at a scale, span, or extent that have never been fire tested, there is an increasing onus on the profession to better approximate the design's performance in fire, particularly in buildings where the consequences of collapse are significant. For example, some long-span structures have shown through calculation methods to possess unsatisfactory fire performance because of the resulting effect they have on columns in fire. By conducting specific structural fire analysis and quantifying the structure's response, guidance can then be provided to enhance structural detailing needed to improve the performance of the columns during fire. In essence the future of structural design seems to be leading toward considering fire as a design load, similar to the approach taken for wind effects, snow effects, earthquake effects, or other environmental design events.

The standard fire resistance test, along with traditional fireproofing and fire resistance methods, will likely continue to serve as a fundamental basis for the design of structures, but will need to be supplemented with quantified structural responses during real fires, as the structural response of a building not only affects the stability of the structure but also the performance of compartmentation (or fire separation). This need requires the establishment of some fundamental performance objectives for structures in fire. For example, what are the acceptable behaviors that robustly confirm stability of the structural system itself during a fire? Then, to maintain compartmentation—to stair cores, to other stories in the building, or from compartment to compartment on the same story—what fundamental performance demonstrates that this stability is being maintained?

The need for risk-based design approaches should be considered as a way forward. Currently, some specialists in this structural fire engineering field design for absolute events, unlike earthquake design, for example, which addresses likely events. Earthquake designs that satisfy such requirements are deemed to be acceptable, safe, and best practice. Such confidence is not yet available in the regulatory environment for structural fire engineers.

A significant amount of work now remains to be done to firmly establish structural fire engineering knowledge and the techniques presented here as a mainstream part of any building and fire safety regulation. In the meantime, fundamental questions must be answered and substantial work is required to establish safe and reliable design techniques within the approvals process for the authorities having jurisdiction, as well as for building insurers and other key stakeholders. All of this is deemed necessary such that real structural performance in fire is no longer omitted from the design process. The techniques described in this chapter are presented as a first step in this process.

ALTERNATIVE APPROACHES TO FIRE RESISTANCE

Traditionally, standard temperature-time relationships, such as those described in ASTM E119,[9] NFPA 251, BS 476, Part 20,[10] or ISO 834,[11] have formed the basis of standard furnace tests to determine the structural response of building elements in fire conditions. However, it is well understood that the standard temperature-time curve does not always represent real postflashover fire (Law,[12] Thomas,[13] Malhotra[14]). This is due to the number of variables that can affect the heating regime in a compartment.

Postflashover fires can be more or less severe in terms of duration, rate of heating, and peak temperature than the standard temperature-time relationship in a furnace test. In addition, real fires are a function of fuel load and geometry, compartment dimensions, thermal properties of the compartment boundaries, and the quantity of unprotected openings that allow ventilation in a postflashover fire. In addition, in Europe—and to some extent New Zealand and Australia—active fire safety systems, compartment area, occupancy type, numbers of water supplies to the compartment, provisions for fire fighters, and even smoke extraction are assigned risk factors that increase or decrease the likelihood of a flashover and its possible extent. The resulting compartment fire is a complex mix of relationships. For structural fire resistance, this fire—the design fire—is the most important input variable, as it greatly influences the structural response. It is important, therefore, to understand its origin.

However, explicitly defining temperature-time relationships as a function of a specific compartment is a relatively new phenomenon in structural fire resistance calculations (also called structural fire engineering). Initially, research work concentrated on fire resistance periods and refining these periods as a function of the compartment in question.

Historically, therefore, due to concerns with the standard furnace test temperature-time relationship, work was carried out by Ingberg, Law, and Pettersson, among others, to determine what is known as *equivalent fire resistance* or *time-equivalent* methods. For these methods, the heating effect in a compartment is based on real compartment fire behavior and therefore takes into account fuel load density, ventilation openings, compartment dimensions, and enclosure thermal properties. This allows some improvement in the grading method, based on the standard furnace test that is currently assumed in building codes worldwide.

Time-equivalent methods can be described as methods that define the thermal exposure of a particular compartment fire in terms of the duration of the *equivalent standard fire.* This is important when engineers and designers want to use published fire resistance ratings from standard tests but based on estimates of real fire exposure.

Equivalence of thermal exposure has been defined in two ways:

1. *Fire load or equal area concept.* Equal areas under the temperature-time curves
2. *Equal temperature concept.* Equal temperatures at the critical part of the structural element

The two methods give similar results where the element selected has a fire resistance on the order of half an hour or more. Samples of both methods developed in the last 80 years, which form the basis of popular calculation methods internationally, are described in the following paragraphs. What these methods provide is an overall building rating, based on building-specific compartment factors.

It is important to note that time-equivalent methods do not assess local or global structural response mechanisms. They relate only to heating effects and their relationship with the standard furnace test. In addition, time-equivalent methods typically apply to protected steelwork but have been extended to include concrete. Some of these methods have recently also been applied to unprotected steelwork and timber construction, but their use with these building materials is not well validated. For unprotected steelwork, it is important to note that in general such elements can achieve 30 minutes standard fire resistance; attempts to extend use beyond this level result in the errors observed, for example, in the Natural Fire Safety Concept study.[15]

Fire Load or Equal Area Concept

By 1918 there was a widespread concern in the fire protection and code enforcement community[16] that there was no accepted method for establishing appropriate levels of fire endurance (now referred to as fire resistance) for buildings of different sizes and occupancies. The original work had been based on "fireproofing" large commercial buildings. It was recognized that these differed significantly from residential fires but it was not understood how their severity related to the conditions in the now formulated standard fire resistance test.

The Building Code recommended by the National Board of Fire Underwriters (NBFU), 1905 edition, contained a series of tables specifying certain wall thicknesses of buildings based on the use and number of stories. Sections 106 to 108 of this code specified other criteria for "fireproof" building construction, which was generally applicable to any structure more than 55 stories in height regardless of use.

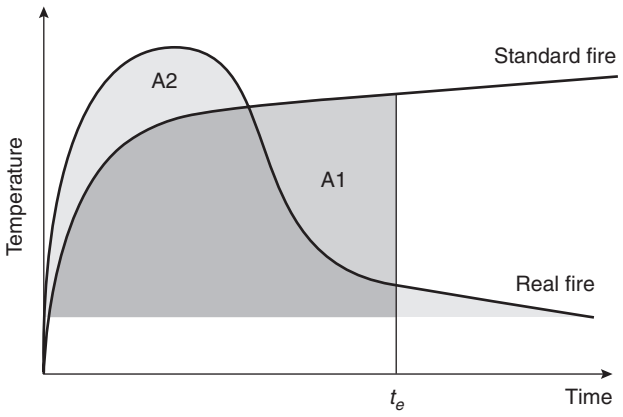

FIGURE 19.5.1 Fire Severity Concept (Source: A. H. Buchanan, *Structural Design for Fire Safety.* Copyright John Wiley and Sons Limited, 2001. Reproduced with permission.)

In order to develop a solution to this problem, in 1922 the National Bureau of Standards in the United States (now called the National Institute of Standards and Technology) investigated the nature of building fires under the direction of Simon Ingberg.[17] The main aim was to determine the intensity and duration of uncontrolled fires in particular occupancies resulting from different levels of fire load. Ingberg was also to investigate the validity of the standard time-temperature curve, which had been accepted as the basis for testing since 1918.

Ingberg investigated office and record storage type occupancies, including the effects of the building size and fire load, the effects of combustible and noncombustible flooring, and the effect of wood and steel furniture. As a result of these tests, Ingberg established a simple relationship between the average weight of combustible material within a room and the fire endurance necessary to withstand a complete burnout of the contents, known as the "fire load concept." It assumes that the area under any time-temperature curve from ignition through decay provides a comparative measure of fire severity, and that fire severity is a function of only the fire load.

Ingberg compared the area under the time-temperature curves generated in the burnout tests to an equivalent area under the standard time-temperature curve. The areas below a threshold temperature of about 300°C were not taken into account. The graph in Figure 19.5.1 shows the basis for Ingberg's work.

Ingberg developed the following relationship for time-equivalence:

$$t_e = k_1 L'' \tag{1}$$

where

t_e = t-equivalent (min)

L'' = Fire load (wood) per unit floor area

k_1 = 1 when L'' is in units of kg/m^2

k_1 = 5 when L'' is in units of lb/ft^2

Ingberg's work became widely accepted as the general basis for establishing fire endurance requirements. This method, however, neglects the effects of ventilation, fuel type, and fuel geometry on fire severity, and therefore its application and usefulness with engineered fire safety solutions is limited.

Equal Temperature Concept

The equal temperature concept is a more realistic method, where the equivalent fire severity is the time of exposure that a protected steel member would endure under the standard fire that would result in the same maximum temperature if it were exposed to a real postflashover fire. This concept was developed by Law,[12] Pettersson et al.,[18] and others and is applicable to insulating elements and materials with a limiting temperature such as wood with a charring temperature of 300°C.

The equal temperature concept is widely used, but can give misleading information if the maximum temperature of the structural element is not the limiting or failure temperature. Several factors, such as building geometry, section details, loading, connections, end conditions, continuity, and so on, can markedly influence the critical temperature for structural performance. This is discussed in more detail later in this chapter.

Kawagoe and Sekine. In 1963, after further small-scale tests and analysis, Kawagoe et al.[19] went on to show the importance of the ventilation parameter as follows:

$$\sqrt{h}\frac{A_B}{A_T} \tag{1}$$

where

h = Window height in the compartment (m)

A_B = Total area of windows (m^2)

A_T = Total area of inside compartment surfaces, including window area (m^2)

Kawagoe and Sekine also developed a formula for fire duration and defined it as the period from the beginning of temperature rise until the time the temperature drops after most of the combustible material is consumed. This time, T, is approximated as:

$$T = WA_F/5.5\sqrt{h}A_B \text{ (min)} \tag{2}$$

where

T = Time (min)

W = Fire load (kg/m^2)

A_F = Floor area (m^2)

h = Height of the window (m)

A_B = Area of the windows (m^2)

Law's Time Equivalent Method. In 1971, Law developed a time-equivalent formula based on the equal temperature concept.[12] This formula was based on small-scale compartment tests, as conducted by Thomas and Heselden,[20] and some large-scale compartment tests.[12]

The maximum temperature, which would be attained by a protected steel element in a real fire compartment, was chosen as a basis for comparison with the corresponding heating effect on the element if heated in a standard fire.

For a temperature-time curve, the maximum temperature obtained by a protected steel element in a compartment fire was calculated as:

$$\frac{d\theta_s}{dt} = \frac{\theta_f - \theta_s}{RC} \tag{3}$$

where

θ_s = Steel temperature (°C)

t = Time (sec)

θ_f = Fire temperature (°C)

R = Thermal resistance of the protective layer

C = Thermal capacity of the steel (J k^{-1})

The temperature of the heated surface of the protective material is assumed to be the same as the fire temperature. The heat transfer through the steel section can then be calculated.

For a given time-temperature curve the value RC was determined so that the maximum temperature of the protected member was 550°C. The time for the protected member to attain 550°C when exposed to the standard temperature-time curve then gives the value of time equivalent.

The best correlation was obtained from the product (L/A_v) and a term taking into account A_v and the solid surface to which heat is lost:

$$t_e = \frac{k_3 L}{\sqrt{A_v\,(A_t - A_F - A_v)}} \text{ (min)} \tag{4}$$

where

t_e = Time equivalent (min)

A_F = Floor area of the compartment (m^2)

L = Fire load (wood equivalent) (kg)

A_v = Area of ventilation opening (m^2)

k_3 = 1.3 to 1.5, depending on the stick spacing in the cribs used as fuel min m^2/kg

A_t = Area of internal envelope (walls, floor, ceiling, and openings) (m^2)

In this correlation, A_F was not included in the evaluation of solid surfaces because the floors were very well insulated. In all experiments, the openings were the full compartment height. The values of t-equivalent were found to be independent of scale and height of ventilation openings.

Law then analyzed temperature-time curves for a number of burn-out fires in larger brick and concrete compartments (approximately 3 m high) with fire loads ranging from wood cribs, furniture, and liquid fuels, and developed:[12]

$$t_e = k_4 L/[A_v(A_t - A_v)]^{1/2} \text{ (min)} \tag{5}$$

where k_4 is 1.0. This was due to the little effect fuel arrangement appeared to have in these larger-scale tests. In this correlation the floor area was included in the evaluation of solid surfaces to which heat is lost. The larger-scale data also showed no significant effect of ventilation opening height on t_e.

Law concluded that this Equation 5 was most suitable for engineering purposes for protected steel columns and went on to demonstrate that it gave good results for reinforced concrete also. She did discover that it overestimates the time prediction for tightly baled paper and cloth.

This formula is valid only for compartments with vertical openings in the walls, and cannot be used for rooms with openings in the roof.

Pettersson's Time Equivalent Method. Pettersson et al.[18] adopted Law's approach to *t*-equivalent but, instead of the experimental curves on which Law's work was based, used the family of calculated temperature-time curves for particular compartments, as derived by Magnusson and Thelandersson.[21] When the fuel load is expressed in mass (kg) of wood instead of "effective calorific value" (MJ), Pettersson's expression for *t*-equivalent is as follows:

$$t_e = 1.21L/(A_v\sqrt{h}A_t)^{1/2} \text{ (min)} \quad (6)$$

where

t_e = Time equivalent (min)

L = Fire load (wood equivalent) (kg)

h = Height of vertical opening (m)

A_t = Total area of internal envelope (walls, floor, ceiling, and openings) (m^2)

A_v = Area of ventilation opening (m^2)

Note that in his original heat balance work he excluded A_v appropriately, but for an unstated reason does not in his final equations presented in his design guide.[18] This equation includes $\sqrt{h}$ because of the input parameters in the method for calculating the temperature-time curves from Magnusson and Thelandersson,[21] on which this equation is based.

Equation 7 can be modified to take into account the thermal properties of the compartment enclosure by applying the factor k_f to each input parameter.

This yields

$$t_e = 1.21k_f^{1/2}L''A_F/(A_v\sqrt{h}A_t)^{1/2} \text{ (min)} \quad (7)$$

where

k_f = Factor applied to input parameters to take account of the thermal properties $k\rho c$ of the compartment enclosure expressed as a proportion of the $k\rho c$ for Pettersson's "standard" compartment. This standard compartment, defined in the Swedish Building Regulations in 1967, is where the surrounding structure has the thermal properties of an average of concrete, brick, and lightweight concrete of thickness 20 cm. (Note also the fire is ventilation controlled and with a cooling phase of 10°C/min.)

L'' = Fire load (wood equivalent) (kg/m^2)

A_F = Floor area of the compartment (m^2)

Eurocodes and British Standards

Eurocode 1: Actions on Structures—Part 1.2: General Actions—Actions on Structures Exposed to Fire, dated 2002,[22] has now also been adapted as a British Standard BS EN 1991-1-2:2002. It is understood that the time equivalent method defined within originates from the German standard DIN 18230, version 94.[23] The derivation of this formula has never been published but it is understood to have come from an empirical analysis of calculated steel temperatures in a large number of simulated fires computed by the German program "Multi Room Fire Code."[24] Though this German reference refers to an earlier published version of this Eurocode, the basic formulations remain and therefore this origin is believed to still apply. This method is dependent on ceiling height of the compartment but not the opening height. The fuel type assumed in the original work is unknown, although it is widely believed to be a cellulosic-type.

The time-equivalent is defined in Eurocode 1, Part 1.2[22] as:

$$t_e = q_{f,d}k_b w_f k_c \text{ (min)} \quad (8)$$

where

$q_{f,d}$ = Fire load density related to the floor area (MJ/m^2)

$$q_{f,d} = q_{f,k}m\delta_{q1}\delta_{q2}\delta_n \quad (9)$$

where

$q_{f,k}$ = Fire load density determined from a fire load classification of occupancies (see Table 19.5.1)

m = Combustion factor, which for cellulosic materials is defined as 0.8

δ_{q1} = Safety factor taking account of the fire activation risk due to the size of compartment (see Table 19.5.2)

δ_{q2} = Safety factor taking account of the fire activation risk due to the type of occupancy (see Table 19.5.3)

$\delta_n = \prod_{i=1}^{10}\delta_{ni}$ = A factor taking account of the different active fire-fighting measures such as sprinklers, detection, fire brigade, etc. (see Table 19.5.4)

k_b is a conversion factor and can be taken as 0.07 ($min\cdot m^2$ /MJ) when no detailed assessment of the thermal properties of the boundary are pursued and when q_d is given in MJ/m^2. Otherwise k_b may be related to the thermal property $b = \sqrt{\rho c\lambda}$ in accordance with Table 19.5.5.

w_f is the ventilation factor and is calculated as

$$w_f = \left(\frac{6}{H}\right)^{0.3}\left[0.62 + \frac{90(0.4-\alpha_v)^4}{1+b_v\alpha_h}\right] \geq 0.5 \quad (10)$$

where

$\alpha_v = A_v/A_f$ = Area of vertical openings A_v in the facade related to the floor area of the compartment where the limit $0.025 \leq \alpha_v \leq 0.25$ should be observed

$\alpha_h = A_h/A_f$ = Area of horizontal opening in the roof related to the floor area of the compartment

$b_v = 12.5(1 + 10\alpha_v - \alpha_v^2) \geq 10$

H = Height of the compartment (m)

For small fire compartments (defined in the Eurocode as $A_f < 100\ m^2$) without openings in the roof, the factor w_f may also be calculated as

$$w_f = O^{-1/2} A_f/A_t \quad (11)$$

where

O = Opening factor = $A_v h^{1/2}/A_t$ with $0.02 \leq O \leq 0.20$ with the default value $k_b = 0.07$ and assuming 18 MJ/kg for wood, Equation 6 becomes the same as Equation 8

k_c = A newly incorporated correction factor, which is a function of the material composing structural cross sections and as defined as $13.7 \times O$ for unprotected steel

Reinforced concrete and protected concrete remain as 1.

The basis of this method is that it should be verified that:

$$t_{e,d} < t_{fi,d} \quad (12)$$

where

$t_{fi,d}$ = The design value of the standard fire resistance of the members, assessed according to the relevant parts of the Eurocodes (Table 19.5.1 to Table 19.5.4)

Note according to the BS EN 1991-1-2[22] for "normal fire-fighting measures" such as safe access routes, fire-fighting devices, and smoke exhaust systems in staircases, the factors should be taken as 1.0. If these measures have not been foreseen but provided, then the values can be taken as 1.5 (Table 19.5.5).

New Zealand Codes

The New Zealand *Fire Engineering Design Guides*[25] gives the same empirical expression for equivalent fire severity t_e (min) as the British Standards (BS EN 1991-1-2[22]). The upper and lower k_b values have been increased by a factor of 1.3 compared to the Eurocode due to what they declare are inherent uncertainties in the Eurocode formula, the use of fuels other than wood, application to structures other than steel, and deep compartment effects. If the properties of the linings are not known, a value of $k_b = 0.09$ is suggested. This formula is based on cellulosic-type fuels. The ventilation factor limits of use are retained, although the small compartment formula in the Eurocode does not form part of the New Zealand guidance.

Comparisons

Time-equivalent methods are an improvement on the grading method in building codes worldwide, which is based on the standard fire temperature-time relationship such as ASTM E119,[9] NFPA 251, BS 476, Part 20,[10] and ISO 834.[11] This is because they attempt to account for compartment geometry, ventilation openings, fuel load density, and compartment boundary materials in addition to fuel load density, which are the key factors that affect full-scale fire development. However, the temperatures calculated on these principles are then related back to

TABLE 19.5.1 Fire Load Densities $q_{f,k}$ (MJ/m^2) for Different Occupancies

Occupancy	*Average*	*80% Fractile*
Dwelling	780	948
Hospital (room)	230	280
Hotel (room)	310	377
Library	1500	1824
Office	420	511
Classroom	285	347
Shopping center	600	730
Theater (cinema)	300	365
Transport (public space)	100	122

Note: Gumbel distribution is assumed for the 80% fractile.

Source: British Standards Institute. Permission to reproduce extracts from British Standards is granted by BSI. British Standards can be obtained from BSI Customer Services, 389 Chiswick High Road, London W4 4AL. Tel: +44 (0)20 8996 9001. email: cservices@bsi-global.com.

TABLE 19.5.2 Factors for δ_{q1}

Compartment Floor Area A_f (m^2)	*Danger of Fire Activation (δ_{q1})*
25	1.10
250	1.50
2,500	1.90
5,000	2.00
10,000	2.13

Source: British Standards Institute. Permission to reproduce extracts from British Standards is granted by BSI. British Standards can be obtained from BSI Customer Services, 389 Chiswick High Road, London W4 4AL. Tel: +44 (0)20 8996 9001. email: cservices@bsi-global.com.

TABLE 19.5.3 Factors for δ_{q2}

Danger of Fire Activation (δ_{q2})	*Examples of Occupancies*
0.78	Art gallery, swimming pool
1.00	Offices, hotel, residential
1.22	Manufacturing for machinery and engines
1.44	Chemical lab, painting workshop
1.66	Manufacturing of fireworks or paints

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TABLE 19.5.4 Factors for δ_{ni}

δ_{ni} Function of Active Fire-Fighting Measures											
Automatic Fire Suppression				Automatic Fire Detection			Manual Fire Suppression				
Automatic Water Extinguishing System	Independent Water Supplies (δ_{n2})			Automatic Fire Detection and Alarm		Automatic Transmission to Fire Brigade	Work Fire Brigade	Off-Site Fire Brigade	Safe Access Routes	Fire-Fighting Devices	Smoke Exhaust System
				By Heat	*By Smoke*						
(δ_{n1})	*0*	*1*	*2*	(δ_{n3})	(δ_{n4})	(δ_{n5})	(δ_{n6})	(δ_{n7})	(δ_{n8})	(δ_{n9})	(δ_{n10})
0.61	1	0.87	0.7	0.87 or 0.73		0.87	0.61 or 0.78		0.9/1/1.5	1/1.5	1/1.5

Source: British Standards Institute. Permission to reproduce extracts from British Standards is granted by BSI. British Standards can be obtained from BSI Customer Services, 389 Chiswick High Road, London W4 4AL. Tel: +44 (0)20 8996 9001. email: cservices@bsi-global.com.

TABLE 19.5.5 Conversion Factor k_b Depending on the Thermal Properties of the Enclosure

$b = \sqrt{\rho c \lambda}$ $(J/m^2 sec^{1/2} K)$	k_b $(Min\text{-}m^2/MJ)$
$b > 2500$	0.04
$720 \le b \le 2500$	0.055
$b < 720$	0.07

Source: British Standards Institute. Permission to reproduce extracts from British Standards is granted by BSI. British Standards can be obtained from BSI Customer Services, 389 Chiswick High Road, London W4 4AL. Tel: +44 (0)20 8996 9001. email: cservices@bsi-global.com.

the standard time-temperature relationship. It is also important to note that they are based on specific compartment test data, rather than generalized heat balance solutions. They are therefore not entirely representative of natural temperature-time relationships, and, as such, are not independent of the standard fire resistance test formulation.

Drysdale describes a comparison Harmathy carried out where the Ingberg,[17] Pettersson,[18] and Harmathy equations for t_e were compared.[26] Drysdale rejects Ingberg's method as radiative heat flux T^4 makes simple scaling impossible when heat transfer is dominated by radiation. He concluded that Law and Harmathy provided more conservative solutions than the others. Note that Ingberg's method ignores ventilation, unlike the other methods presented here.

Law compared results using the time-equivalent relationships by Ingberg,[17] Kawagoe et al.[19] Pettersson, et al.,[18] Harmathy and Mehaffey,[27] plus the 1993 Eurocode formula[28] with experimental data from postflashover fires in full-scale compartments.[29] These consisted of small insulated compartments, 30 m^2 area, 2.5–3 m high, with brick or concrete enclosures and larger, deeper rooms 128 m^2 in area (depth to width ratio 4:1). Law concluded Pettersson, Harmathy, and Mehaffey were the most promising methods. See Figure 19.5.2 for Law's correlation compared with experimental data.

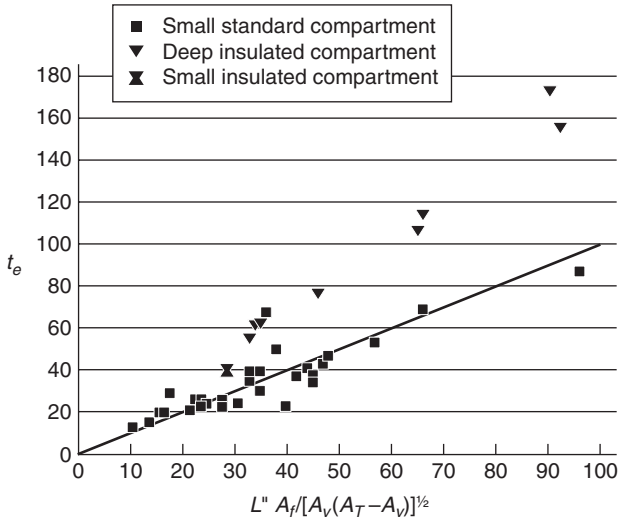


FIGURE 19.5.2 Law's Correlation Between Fire Resistance Requirements (t_e) and $L"A_f/(A_v(A_T - A_v)^{1/2}$ where
$L"$ = The fire load (kg/m^2)
A_f = The area of the floor
A_v = The area of the ventilation
A_T = The total internal surface area (m^2) of the compartment
(Courtesy of Margaret Law)

Limitations and Assumptions

There are several limitations, including the deep compartment* effect. Law examined deep compartments further, as all her derived time-equivalent formulae gave odd results when deep compartments were studied. Law also discovered that the 1993

*A deep compartment is defined by I. R. Thomas and I. D. Bennetts in *Fires in Enclosures with Single Ventilation Openings. Comparison of Long and Wide Enclosures,* 6th IAFSS Symposium, pp. 941–952, 1999 as the situation where the depth, *D,* is greater than the width, *W,* of the compartment.

Eurocode *t*-equivalent method gave poor correlation for both small and deep compartments. She concluded that the depth of the compartment has an effect on the time equivalent over and above that which can be allowed for by increase in insulation and in internal surface area A_t. Thomas and Heselden[20] had already shown that the ventilation-controlled rate of burning is affected by the compartment depth to width ratio. Recent research on this phenomenon has also resulted in the New Zealand codes recommending increased factors of safety to somehow account for this effect in their time-equivalent formula. Thomas and Bennetts[30] concluded that fire behavior and fuel mass loss rates in long and wide enclosures differ markedly if the width of the opening is less than the full width of the enclosures. However, it should be noted that they did not look at cross-ventilation. They demonstrated that mass loss in wide enclosures is greater than for deep enclosures that incorporate both full-width and partial-width openings. In their small-scale experiments the fire duration was double for deep compartments, relative to wide compartments with the same openings.

The Eurocode or BSEN formulae have caused considerable concern as Eurocode does not reference the source of the equation derivations, particularly regarding the ventilation factor, the correction factor to take account of cross section material types, as well as other factors of safety recommended for application to the calculated time-equivalent value. The Eurocode formula has also been extended to unprotected steelwork.

The k_c is defined for unprotected steel as 13.7 times the opening factor (O). Since $0.02 < O < 0.2$, this gives $0.27 < k_c < 2.7$ for unprotected steel. For small compartments $w_f = O^{-½}A_f/A_t$ and since $O = A_v h^{½}/A_t$, it can be written that the equivalent time for unprotected steel in small compartments is as follows:

$$t_e = 13.7\, q_{fd} \cdot k_b \cdot (A_v\, h^{1/2}/A_t)^{1/2} \cdot A_f/A_t$$

(fire load given as per unit floor area)

Pettersson calculated $t_e(h)$ for unprotected steel for values of opening factor ranging from 0.2 to 0.12 $m^{½}$ and various section factors (Tables 19.5.6 and 19.5.7). Law[31] compares Pettersson's time-equivalent formula with the Eurocode formula for $\varepsilon_r = 0.5$ for unprotected steel of various section factors in Table 19.5.8.

It can be seen that while the values of t_e tend to increase with increasing fuel load, they tend to decrease with ventilation factor. They are not independent of section factor. Yet when the Eurocode formula is used with $k_b = 0.055$ for Pettersson's compartment type A, for all sections, the following data is produced (Table 19.5.8).

The trends in the Eurocode are different and no explanation as to why has been provided. For unprotected steel, if the steel is assumed to be a perfectly stirred fluid, the postflashover fire temperatures are also perfectly stirred, and the temperature of the exposed surface is the same as the fire temperatures, which implies that the steel temperature is always the same as the fire temperature. Therefore, section factors of 100 m^{-1} or more would not be expected to survive a postflashover fire, but would survive a localized fire. Until suitable justification of such difference is made, it seems the original work of Pettersson or Law is best suited to this type of time-equivalent calculation.

Another limitation is that the *t*-equivalent methods do not address transient temperature gradients or associated load-bearing capacities. The ratings derived do not relate to actual frame performance in fire. These methods are quite simply refined versions of single element performance in fire, but only relative to the standard furnace test. They normally assume insulated structures only (protected steel or reinforced concrete). Although Pettersson's work does address uninsulated steel, these bare elements would not be expected to achieve a fire resistance of beyond 20 to 30 minutes.

A time-equivalent calculation does not apply if the preflashover calculations show that flashover will not occur—that is, the calculation is no longer relevant if flashover has not occurred. Then local heating effects are relevant, not temperatures in a uniformly heated compartment, as is assumed in time-equivalent analysis methods.

TABLE 19.5.6 Equivalent Time for Unprotected Steel with Section Factor = 50 m^{-1}

	$t_e(h)$			
	$A_v h^{1/2}/A_t (m^{1/2})$			
Q_{td} *(Fire Load)*	*0.02*	*0.04*	*0.08*	*0.12*
42	0.29	0.25	0.21	0.16
84	0.42	0.43	0.36	0.29
126	0.51	0.58	0.525	0.41

Source: Courtesy of Swedish Institute of Steel Construction.

TABLE 19.5.7 Equivalent Time for Unprotected Steel with Section Factor = 150 m^{-1}

	$t_e(h)$			
	$A_v h^{1/2}/A_t (m^{1/2})$			
Q_{td} *(Fire Load)*	*0.02*	*0.04*	*0.08*	*0.12*
42	0.21	0.23	0.19	0.16
84	0.27	0.37	0.38	0.30
126	0.30	NA	NA	NA

NA = Not available.
Source: Courtesy of Swedish Institute of Steel Construction.

TABLE 19.5.8 Equivalent Time for Unprotected Steel All Sections

	$t_e(h)$			
	$A_v h^{1/2}/A_t (m^{1/2})$			
Q_{td} *(Fire Load)*	*0.02*	*0.04*	*0.08*	*0.12*
42	0.07	0.11	0.15	0.18
84	0.15	0.21	0.30	0.37
126	0.22	0.32	0.45	0.55

Source: Arup.

In addition, *t*-equivalent methods are empirical formulae developed by regression analysis using a selected number of tests or calculations. Therefore, they have been developed for a certain range of structural steel sizes and thicknesses of insulation and so may not be appropriate outside this range. The methods are used for other materials, but beyond protected steel and reinforced concrete, very little is known of the accuracy in applying the methods to other materials. Note that all *t*-equivalent methods described here involve combustible solids only.

The time-equivalence method is a simple analytical method that is generally useful in the everyday design environment due to its relative ease of use and its time and cost efficiency. However, such methods are generally incapable of considering the numerous complex structural behavior issues and are highly dependent on the parameters and assumptions chosen by the designer.

Because of the limitations and uncertainties associated with time-equivalent methods, it is important that risk factors are considered in the analysis. Using a probabilistic model, the uncertainties in the concept of safety, fire, reliability of active and passive systems, structural stability, material behavior, and so on can be incorporated into a time-equivalent analysis to envelope the expected response. In this way, a numeric measure of risk can be assessed and compared to an accepted level of risk established by the governing codes.

The accepted level of risk varies from country to country and in many cases is not explicitly documented. In Europe, the acceptable level of risk is implicitly captured in the partial safety factors found in the National Annex for each country. Similar documents are also available in the U.S. codes, New Zealand codes, and other codes around the world. A discussion of risk assessment is given by Hall[32] and Baldwin.[33]

CASE STUDY: Outlining Use of the Time-Equivalent Method. This case study is based on a study of a 50 story high-rise office building in the United Kingdom, with a combination of several structural systems (a perimeter diagrid, a secondary bracing system, and internal columns). Based on the governing codes, the sprinklered building would be required to achieve a 120 minute fire resistance rating. However, an alternate rating was proposed for the design using the time-equivalent method for justification.

The main floor plate of the building consists of an open floor plan system as seen in Figure 19.5.3 (no subdivisions proposed). Because of this open floor layout, the entire floor was considered one single fire compartment. Due to the high variability in the building geometry/design and uncertainties in identifying a representative fire for the structure, a sensitivity study was conducted to provide a range of probable design fires.

Therefore, the factors forming the basis of the time-equivalent method—that is, the fire compartment geometry, the ventilation to the fire compartment, and the other significant fire parameters—were considered in a sensitivity analysis to determine a final equivalent time of fire resistance. In addition, several fire locations within the building itself were investigated in order to ensure that a reasonable worst-case fire scenario was determined. This was as an alternative to applying the code-required fire resistance ratings for individual structural elements.

The time-equivalent method described in the Eurocode[22] was used. Combining Equations 12 and 13, the equivalent time of fire exposure can be defined as:

$$t_{e,d} = mq_{f,k}\delta_{q1}\delta_{q2}\delta_{ni}w_f k_b k_c \quad \text{(min)} \tag{13}$$

Two floor levels (5th and 44th levels) were assessed to provide an upper and lower bound estimate for the equivalent time of fire exposure. This was because level 5 had the largest floor area of 1896 m^2 with the greatest amount of glazed facade, whereas level 44 had the smallest floor area of 694 m^2 and the least amount of glazed facade.

First, a sensitivity analysis was conducted to determine a range of possible design fire loads. The characteristic fuel load ($q_{f,k}$) was 511 MJ/m^2, the compartment floor area factor δ_{q1} was valued as 1.9, and the occupancy factor δ_{q2} was valued as 1.0, as recommended by the Eurocode for office buildings with compartment floor areas less than 2500 m^2. Assuming these values as constant, the combustion factor (m), the water extinguishing factor (δ_{ni}), the automatic detection factor (δ_{ni}), and the off-site fire brigade factor (δ_{ni}) were varied to determine their impact on resulting design fire loads:

$$q_{f,d} = mq_{f,k}\delta_{q1}\delta_{q2}\delta_{ni} \quad \text{(MJ/ m}^2\text{)} \tag{14}$$

Based on this sensitivity analysis a design fire load ranging from 270 to 971 MJ/m^2, as presented in Table 19.5.9, was obtained.

Next, a sensitivity analysis was conducted for each design fire load to determine a range of time-equivalent fire exposures based on the variation of the ventilation factor (w_f) in the following equation:

$$t_{e,d} = q_{f,d}w_f k_b k_c \quad \text{(min)} \tag{15}$$

The k_b and k_c terms were assumed constant at 0.07 min·m^2/MJ and 1.0, respectively.

Four different ventilation factors were determined by varying the area of ventilation openings in the facade from 25 percent to 100 percent. It was necessary to assess the lower levels of glazing failure (below 50%) due to the approving authority's concern with the concept of glazing breakage in fire and their lack of certainty that this would occur. The maximum openings for the 5th and 44th levels were 498 and 305 m^2, respectively. Note that there were no horizontal openings in the compartment.

The ventilation factor was calculated by the following equation taken from the Eurocode:

$$w_f = \left(\frac{6}{H}\right)^{0.3}\left[0.62 + \frac{90(0.4-\alpha_v)^4}{1 + b_v\alpha_h}\right] \geq 0.5 \tag{16}$$

Based on this sensitivity analysis, a range of 16 different equivalent times of fire exposure were determined and are presented in Table 19.5.10 and Figure 19.5.4 for levels 5 and 44 of the building investigated.

The results of the time-equivalent sensitivity study range from a fire resistance rating of 15 to 138 minutes. The sole value greater than 90 minutes was an equivalent time of 138 minutes. This value occurs when the reduction in risk of a flashover due to active fire protection methods is not incorporated, but only

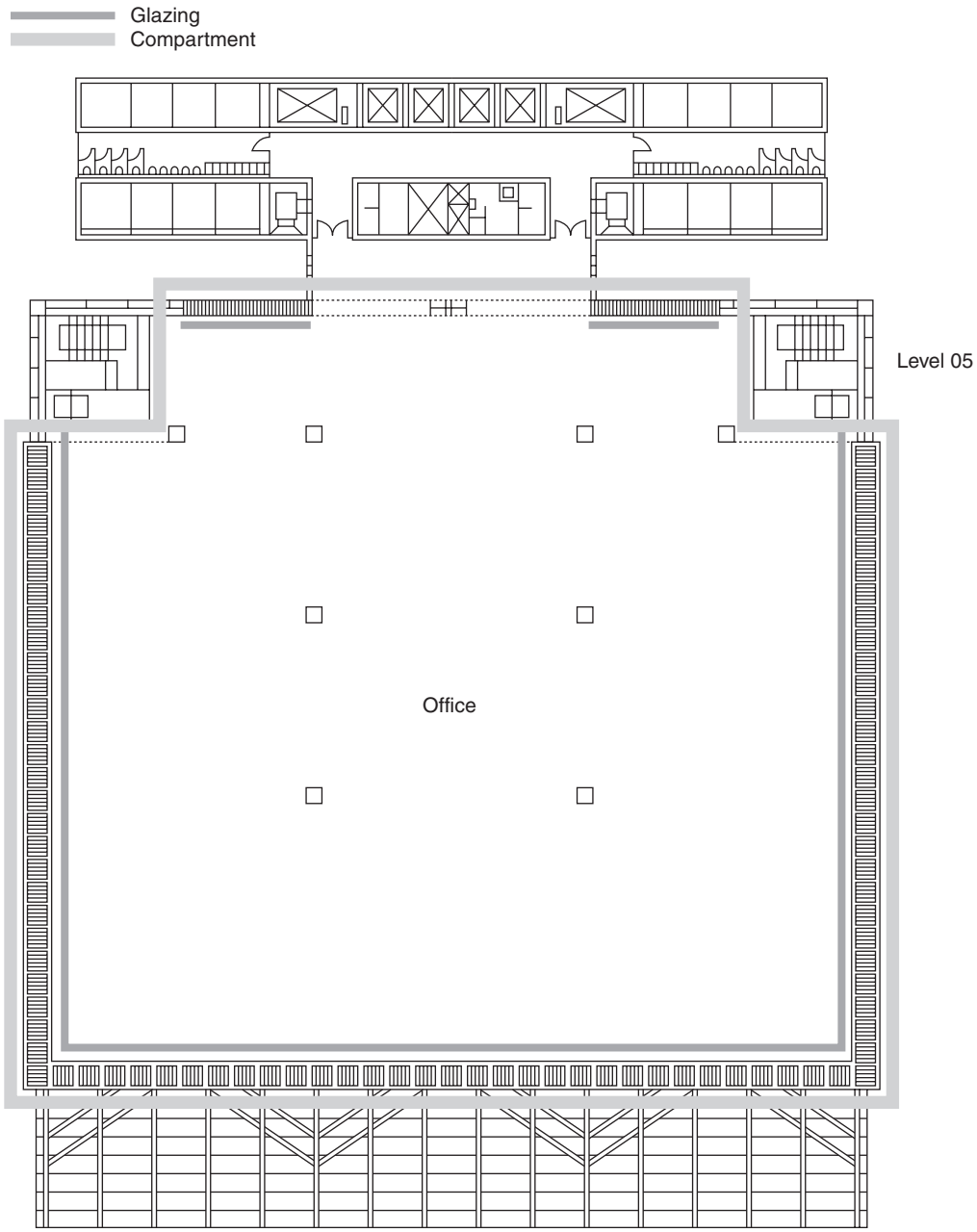


FIGURE 19.5.3 Level 5 Floor Plate, Compartmentation Arrangement, and Glazing (Source: Arup)

TABLE 19.5.9 Design Fire Loads for Sensitivity Study

	Characteristic Value	*Compartment Factor*	*Combustion Factor*	*Water Extinguishing Factor*	*Automatic Fire Detection*	*Off-Site Fire Brigade*	*Design Fire Load q_{fd} (MJ/m^2)*
Scenarios 1–4	511	1.9	0.8	0.61	0.73	0.78	270
Scenarios 5–8	511	1.9	1	1	1	1	971
Scenarios 9–12	511	1.9	1	0.61	1	1	593
Scenarios 13–16	511	1.9	1	0.61	0.73	0.78	338

Source: Arup.

TABLE 19.5.10 Sensitivity Study of Equivalent Time of Fire Exposure—Varying Fire Load, Ventilation, and Story for a Full Office Floor on Fire

	Level 5				Level 44				
	Design Fire Load q_{fd} *(MJ/m²)*	*Area of Ventilation Openings in Facade* *(m²)*	*Floor Area Compartment* (A_f) *(m²)*	$t_{e,d}$ *(min)*		*Design Fire Load* q_{fd} *(MJ/m²)*	*Area of Ventilation Openings in Facade* *(m²)*	*Floor Area Compartment (Af)* *(m²)*	$t_{e,d}$ *(min)*
Scenario 1	270	489	1896	15	Scenario 1	270	305	694	15
Scenario 2	270	367	1896	17	Scenario 2	270	229	694	15
Scenario 3	270	245	1896	24	Scenario 3	270	153	694	16
Scenario 4	270	122	1896	38	Scenario 4	270	76	694	28
Scenario 5	971	489	1896	52	Scenario 5	971	305	694	52
Scenario 6	971	367	1896	61	Scenario 6	971	229	694	52
Scenario 7	971	245	1896	86	Scenario 7	971	153	694	56
Scenario 8	971	122	1896	138	Scenario 8	971	76	694	99
Scenario 9	593	489	1896	32	Scenario 9	593	305	694	32
Scenario 10	593	367	1896	38	Scenario 10	593	229	694	32
Scenario 11	593	245	1896	53	Scenario 11	593	153	694	34
Scenario 12	593	122	1896	84	Scenario 12	593	76	694	60
Scenario 13	338	489	1896	18	Scenario 13	338	305	694	18
Scenario 14	338	367	1896	21	Scenario 14	338	229	694	18
Scenario 15	338	245	1896	30	Scenario 15	338	153	694	20
Scenario 16	338	122	1897	48	Scenario 16	338	76	694	34

Source: Arup.

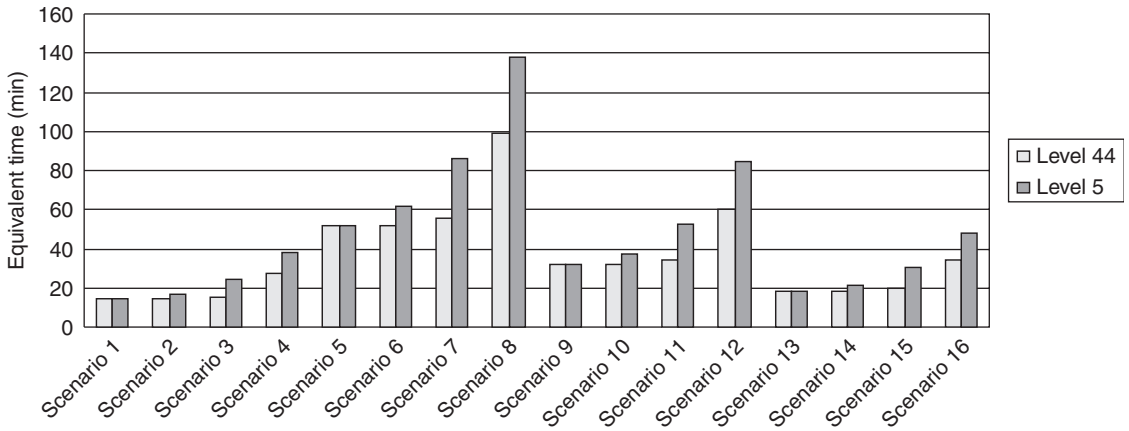


FIGURE 19.5.4 Graph of the Output Data from the Sensitivity Study (Source: Arup)

if a low glazing failure quantity is also assumed to occur. As it was agreed with the approving authorities that such a low level of glazing failure was not practically possible at the fire temperatures expected without active fire protection intervention, this value was deemed overly conservative.

The high variability in the upper and lower bound values illustrates the importance of performing such a sensitivity study, in order to appreciate the potential fire resistance ratings for a structure when using the time-equivalent method.

A reduction in the fire resistance of the building from 120 minutes to 90 minutes was proposed on the basis of this study, because the majority of cases fell well below this value.

DETERMINING A DESIGN FIRE FOR A STRUCTURAL ANALYSIS

Throughout the remainder of this chapter, as specific structural analysis techniques are presented, the important role of the heating regime on the structural element or elements is clear.

Specific references are provided to direct the reader to useful analytical models and formulae to represent fire.

Issues Involving Design of Fire Component

Before more detailed information is presented, it is useful to consider the issues involved with the fire component of a structural design. Unlike design basis fires for smoke control systems or as part of developing time to untenable conditions for purposes of egress, structures are usually most severely affected by postflashover fires. This is when the fire has moved beyond the incipient and growth phase to a point where it is consuming essentially all combustible contents of the enclosure. The resulting peak temperatures, duration, and overall fire severity are then a function of the available combustibles and the ventilation openings into the space. It is these postflashover fires that normally form the basis of a structural fire assessment.

When contemplating the occurrence of a postflashover fire, the sequence of events that must occur to allow such an event to take place is of importance. For example, in a fully sprinklered building, failure of the sprinkler system would have to be assumed to create a flashover condition. Another event is the effect of fire-fighting operations on the occurrence of flashover. Whatever assumptions are made, it is important to bear in mind the risks associated with such assumptions and the different consequences that may result depending on the building height, scale of occupancy, fuel content, use, and compartment extent. That is, the taller the building, the greater the consequence of failure of the structure, and so on.

Addressing Postflashover Events

Various methods are available to designers to address such a postflashover event, including the use of the standard temperature-time relationship on which the furnace tests are based; parametric temperature-time relationships derived from specific postflashover fire tests; or temperature-time relationships derived from resolving the heat balance system within a compartment.

The important question, then, is whether the temperature-time regime proposed represents (or even should represent) an absolute worst case or a reasonable worst-case scenario. In the Eurocodes, for example, designers are advised to use risk-based factors to apply to the fuel load content assumed in a compartment, such that the resulting heating regime is not absolute but also addresses the consequence of failure, the likelihood of occurrence of the fire, and the role of active fire safety systems (e.g., sprinklers) on the probability of a severe fire in a building.

There are concerns with the limitations of parametric fires specifically, as the equation now proposed, for example in the Eurocode, is in essence the result of a regression analysis of specific test data. How to justify the use of this outside the limits of the original test data remains an unresolved subject in the design domain. Although this is the case, engineers are relying on additional safety factors to ensure that design remains on a reasonably conservative side. The more theoretical approaches based on heat-balance relationships, such as Pettersson's, are less popular with code writers, but it may be prudent to revisit such approaches in order to resolve the design basis fire problem for structural fire engineering.

However, adopting a postflashover fire condition as a basis for design is not always the correct approach, as in the case, for example, of very large open spaces with specific pockets of fuel, such as in an airport terminal, where a postflashover fire is unlikely to occur. In such an arrangement, a severe localized fire may expose only one or two columns supporting a long-span structural roof system. For such design cases, specific formulae for local fire and smoke effects are available.[34–36]

Finally, if the structure in question is external to the building, the heating that results from internal and external flaming adjacent to the structural elements becomes the basis for design. Again guidance is provided in the following section on useful formulations to create temperature-time regimes for such events.

Once the design fire temperature-time regime is defined, the remaining steps in a structural fire assessment are possible. The following sections provide information on this. It is recommended that the authorities having jurisdiction are consulted and approve the design fire formulated prior to any time-consuming structural analysis.

SINGLE STRUCTURAL ELEMENT ANALYSIS

The analysis of a single structural element in isolation from the rest of the structural frame has formed the basis for structural fire engineering for many years, mainly because it is comparable with a standard furnace test and excludes calculations based on the nonlinear response of a whole frame or a significant subassembly to fire, both of which require extensive computations.

Single Element Analysis Defined

Single element analysis is useful as a first check of structural capacity at elevated temperature as a basis for design or before conducting a more complex analysis. It typically involves comparing the structural load that the member has to carry in the fire condition with the capacity of the member at elevated temperature. Axial force, bending, shear, and buckling, including lateral torsional buckling, all need to be considered as appropriate. The capacity of the associated connections also needs to be checked.

Single element analysis is a fast, effective technique that can bring substantial value to a design as it allows an understanding of the overcapacity or undercapacity of the member in the fire limit state. This can be used to formulate adequate fire resistance ratings and protection thicknesses for specific elements or to inform a change to the structural design to allow adequate capacity without any added fire protection. Using single element analysis is preferable for isolated structural element concerns in a building, rather than for forming a uniform design approach for all elements in a building. This is because single element checks cannot capture the full frame response, which can mean, in some construction forms, significant weaknesses in fire performance.

Specifically, it is not typical to consider thermal expansion in single element calculations; therefore, the forces experienced by the structural element in a fire when restrained by adjacent members in a structural frame are not adequately considered. However, in general, single element calculations can be assumed to be conservative because alternative load paths that can be present in a real frame during a fire are neglected.

Single element analysis techniques are codified in many countries worldwide. The approach is commonly applied to concrete, steel, and wood members. As with all structural fire engineering, single element analysis is generally based on a three-stage calculation process:

1. Definition of credible design fires
2. Heat transfer analysis to the structural member from the design fires
3. Structural analysis at the elevated member temperature calculated from the heat transfer

Design tools for heat transfer and structural analysis vary in complexity from empirical correlations, look-up tables, nomograms, and hand/spreadsheet calculations, to simple finite element analysis. The tools adopted by an engineer depend on the failure criteria to be identified. For example, a critical steel temperature of 1022°F (550°C) for column members may be sufficient as the basis of design; alternatively, determining the residual strength/stiffness could be more appropriate. However, a simple temperature comparison may not always be appropriate. In columns and beams that are unrestrained on their top flange, instability events such as buckling also need to be considered, because they occur at lower temperatures than the yield temperature of the constituent material. Guidance exists in several countries worldwide on how to approach this problem; several are identified in the following sections.

Design Fires

One approach to the design fire is to simply assume a heating regime in the compartment of interest identical to the standard temperature-time curve (e.g., ISO 834,[11] BS 476,[10] ASTM E119,[9] NFPA 251). Alternatively, a more rigorous approach to the heating regime from the design fire can be taken. The choice of design fire then depends on the location of the structure in relation to the fire compartment, available fuel load, available ventilation, compartment dimensions, and compartment enclosure material properties. Figure 19.5.5 produced for the One Stop Shop in Structural Fire Engineering website in the United Kingdom (MACE) highlights the range of design fires possible.

In addition, for countries outside the United States, it depends on whether failure of sprinklers must be assumed when calculating the fire for determining structural capacity of a single structural element. For example, external structures may only be exposed to flaming through specific window openings. In tall spaces with well-defined and specific locations for fire load, a local fuel-bed-controlled fire adjacent to a critical piece of structure might be appropriate as the basis of design. In areas of high fire load with ceiling heights of 3 to 4 m, a postflashover fire is likely to be the most appropriate fire case. Alternatively, the standard fire heating regime can be selected to carry out a comparative analysis of the structural element relative to code-based fire resistance recommendations.

Empirical equations and complex computer codes such as fire dynamics simulator (FDS) exist to calculate external fire exposures. A useful empirical approach is presented by Law and O'Brien.[37] Note this was also published in the United States by the AISC. FDS, which is well documented elsewhere,[38] can also be used to formulate, at a reasonably complex level, temperature changes with time for external flaming.

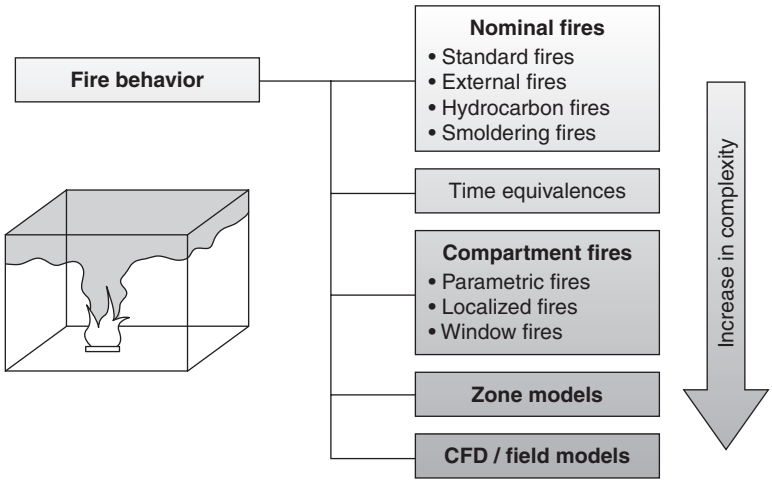
Empirical equations are available for considering local fire cases. In the United Kingdom, TM19[34] provides empirical correlations commonly used in the United Kingdom. The *SFPE Handbook of Fire Protection Engineering*[35] also describes correlations by many researchers, and these are used worldwide. The correlations generally enable the user to calculate flame heights, plume temperatures at various heights, and temperatures along ceiling jets. These data can then be used to calculate the heating effect to and through the structural element for the duration of the fire.

Many deterministic models of postflashover fires have been developed, starting in the 1960s. All postflashover models are based on the assumption that the gas temperature in the compartment is uniform. Walton and Thomas[39] provide a review of many of the available models in the *SFPE Handbook of Fire Protection Engineering.*

The models most often used in design internationally include the parametric temperature time curve given in Eurocode 1, Part 1.2[22] and the heat balance model developed by Magnusson and Thelandersson[21] (Figure 19.5.6). Note that in the United Kingdom, EC1-1-2 has been amended and adopted for use as BSEN1991-1-2:2002. Each country in Europe has similarly made various amendments based on local concerns and market, presented in National Application Documents (NAD) to the main Eurocode. This is true for each material type (steel, concrete, wood, aluminum) and for each calculation procedure or approach.

Computer zone models such as Ozone (University of Liege, Belgium) and CFAST (NIST) will also provide temperature-time curves for postflashover fires. All of the models developed to calculate postflashover fires are only strictly applicable for relatively small compartments, close to square in plan. They are not strictly applicable to large open plan spaces commonly found in real buildings, but they are the only tools available to engineers at the present time. For example, a typical commercial office floor in a tall building in London is approximately 1500 to 2000 m^2 per story, yet the EC1-1-2 limits compartment areas to 500 m^2. As such, the design theory continues to fall behind commercial design requirements and concerns.

The alternative is to use computational fluid dynamics (CFD) codes,[40] but these were originally developed for smoke movement studies and, therefore, consider small fuel-bed-controlled fires in large spaces. Work in defining realistic postflashover fires for use in large or rectangular spaces is ongoing and is considered urgent. Current CFD models will tend to overpredict compartment temperatures and must therefore be used with care when forming the basis of actual design. It is worth noting that NFPA's Technical Committee on Hazard



Fire Model	Nominal Fires	Time Equivalences	Compartment Fires		Zone Models		CFD / Field Models
			Parametric	Localized	One-Zone	Two-Zone	
Complexity	Simple	Intermediate			Advanced		
Fire Behavior	Postflashover fires			Preflashover fires	Postflashover fires	Preflashover/ localized fires	Complete temperature-time relationships
Temperature Distribution	Uniform in whole compartment			Nonuniform along plume	Uniform	Uniform in each layer	Time and space dependent
Input Parameters	Fire type No physical parameters	Fire load Ventilation conditions Thermal properties of boundary Compartment size		Fire load and size Height of ceiling	Fire load Ventilation conditions Thermal properties of boundary Compartment size Detailed input for heat and mass balance of the system		Detailed input for solving the fundamental equations of the fluid flow
Design Tools	BSEN1991-1-2				COMPF2 OZone SFIRE-4	CCFM CFAST OZone	FDS SMARTFIRE SOFIE
	PD7974-1		PD7974-1				
	Simple equations for hand calculations		Spreadsheet	Simple equations	Computer models		

FIGURE 19.5.5 Range of Design Fire Models (Courtesy of MACE One Stop Shop in Structural Fire Engineering, University of Manchester)

and Risk of Contents and Furnishings has recently initiated a project to better define fire loads for structural fire resistance calculations.

Heat Transfer

Once a temperature-time regime for the space containing the structural element or, in the case of a local fire or external fire, for the area immediately surrounding or adjacent to the structural element, the structural temperatures can be calculated using heat transfer equations. Various empirical and analytical equations exist in Europe; specifically, the lumped mass heat transfer equations to calculate average section temperatures in Eurocode 1, Part 1.2[22] and Eurocode 3, Part 1.2[41] or Law and O'Brien's[37] view factors to calculate radiative heat transfer to elements remote from a fire are typically used. All equations in codes and guidance documents are very similar because each one has to consider conduction, convection, and radiation in accordance with the principles of heat transfer.

For heat transfer analysis, the nonlinear values of conductivity, specific heat, density, and moisture content of the constituent materials are required to calculate heat transfer. Where available, these values should vary with increasing temperature to obtain an accurate result.

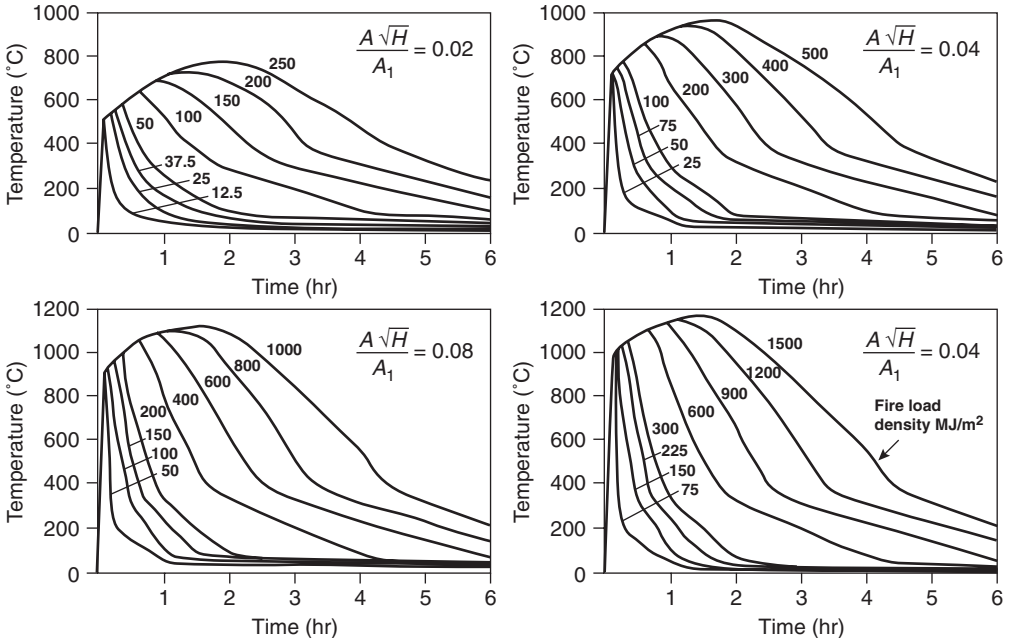


FIGURE 19.5.6 Postflashover Temperature-Time Curves (Courtesy of Swedish Institute of Steel Construction)

For single structural element analysis, some analytical design tools require the use of strength and stiffness properties at elevated temperatures. Where this is the case it is highlighted in the text in the following sections. Most international material codes provide values for stress-strain and Young's modulus with increasing temperature.

APPLICATION OF SINGLE STRUCTURAL ELEMENT ANALYSIS TO STEEL

There are numerous methods applicable to steel elements because the steel industry has spent many years of research optimizing steel design for fire. The main reason is that passive fire protection can significantly increase the cost of a steel frame solution. However, with modern fire protection materials, options for off-site application, particularly of intumescents, are on a rapid rise of use, mainly in Europe. These new approaches, which bring considerable time saving to a construction project and ensure a high quality of application and finish, along with performance-based design methods to optimize fire protection arrangements and thicknesses, mean steel frame solutions are cost effective and very popular in the United Kingdom, as well as in cities where high-rise construction is in demand internationally (e.g., Singapore, Beijing, Dubai).

Some steel-specific calculation methods follow.

Section Factor

The *Hp/A concept,* or *section factor,* is a key variable in single element analysis of steel members in fire. It provides a simple relationship between the surface area of the section exposed to fire and its cross-sectional area or thermal mass. The rate of temperature change in a steel section is a function of this relationship. Consequently, the concept is used by fire protection manufacturers as a factor in determining and specifying the necessary thickness of fire protection material for a particular member size. The value varies if the section is sprayed with fire protection or boxed, as shown in Figure 19.5.7.

Consider a unit length of a steel element where the end connections are ignored. A steel section with a larger surface area will receive more heat than one with a smaller surface area. Moreover, the greater the volume of the section, the greater is the heat sink. Typical values of section factor for structural steel members commonly used in building design are between 100 to 250 m^{-1}. At values of about 50 m^{-1}, a beam section can be assumed to have about 30 minutes inherent fire resistance[42] as a single element considering its thermal mass only.

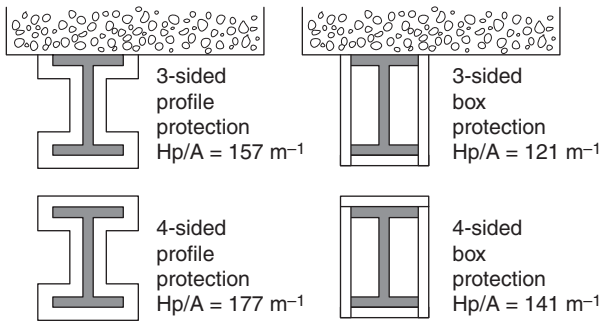


FIGURE 19.5.7 The Section Factor Concept (Courtesy of CORUS)

BS 5950-8[42] in the UK and Eurocode 3, Part 1.2[41] describe the Hp/A concept and how to calculate it for different steel sections and protection arrangements. Note that in the United States, the section factor is represented by the *W/D* (average weight/heated perimeter) *concept* where *W* is in pounds/ft and *D* is given in inches.

Section factors for common structural steel shapes are available from steel distributors worldwide, such as CORUS (the largest steel producer in Europe) and the Heavy Engineering Research Association (HERA), a nonprofit research organization dedicated to the needs of the metals-based industries in New Zealand. The American Institute of Steel Construction and various building codes provide reference to such information in the United States.

Once the section factor is known for a specific section, the average steel temperature development can then be evaluated using relatively simple lumped mass heat transfer formulae for protected and unprotected internal steelwork. The heat transfer analysis is based on the net heat flux to the surface of the member, including convection and radiation effects and conduction through the fire protection material and /or the steel. Equations are provided throughout the literature including the *SFPE Handbook of Fire Protection Engineering* and the following design codes: BS 5950-8,[42] EC 1-1-2,[22] and EC 3-1-2.[41] The lumped mass equations do not calculate temperature gradients through the depth of a steel section; they should, therefore, not be used when this is important for design—for example, if a protected column could fail as a result of thermal bowing. Heat transfer and structural stability have to be checked by finite element analysis or stability of the frame proven by showing the single element can be removed.

Note that the IBC[43] in the United States has many empirical correlations based on the *W/D* ratio to allow engineers to calculate the fire resistance of a particular steel section protected with different materials, including concrete, masonry, and type X gypsum board. It does not currently provide analytical methods for heat transfer analysis. *NFPA 5000®, Building Construction and Safety Code®,* allows for the use of analytical methods to determine the fire resistance of building assemblies. Specific reference is made to ASCE/SFPE 29, *Standard Calculation Methods for Structural Fire Protection,* and ACI 216.1/TMS 0216.1, *Standard Method for Determining Fire Resistance of Concrete and Masonry Assemblies.*

Fire Limit State Factors

Traditionally, single element analysis assumed failure of a steel member occurred at a temperature of 1022°F (550°C). This is because fire protection is typically applied to steel members to limit the temperature rise to 1022°F (550°C) for a prescribed fire resistance period and because steel has lost about 40 percent of its design strength at 1022°F (550°C). (Note that in more recent years in the United Kingdom, a limiting temperature of 620°C is now used for beams, with columns remaining at the traditional 550°C. It is important to ascertain for the specific fire protection being reviewed as part of the single element analysis what limiting temperatures have been assumed. For unprotected members, the limiting temperature should be clearly defined and used as the basis of the capacity checks.)

Often designers would not consider the load or structural actions on a steel member but simply assume failure at 1022°F (550°C). This was generally conservative, but analytical methods are now available to define critical steel temperatures more accurately, considering load, residual capacity of strength and stiffness, and structural failure mechanisms. What this means is that for some cases a higher limiting temperature is possible, but for others, a lower temperature should be assumed.

To determine the limiting steel temperature, load combinations for buildings exposed to fires must be considered. An important part of structural fire engineering is defining the applied load assumed to act on the structure during a fire event. It is common practice to assume that a fire is an unusual event, and, as such, that the safety factors applied to characteristic dead load, wind load, and live load can be reduced. (Dead load is a load of constant magnitude and position that acts permanently, including self-weight. Live load is load on a structure or member, other than wind load, produced by the external environment or the intended occupancy or use.) In general, dead load (DL) is multiplied by 1.0 and live load (LL) is multiplied by a factor ranging from 0.3 to 0.8, depending on the building occupancy type.[42]

Different countries adopt slightly different factors as discussed below. In the UK and Europe, partial safety factors for accidental loads in structural steel design are given by BS 5950-8[42] and Eurocode 0,[44] respectively, for the fire limit state. Table 19.5.11 shows the values for load factors at the fire limit state in BS 5950-8.[42]

The New Zealand Standard NZS 4203[45] adopts 1.0 DL + 0.6 LL or 1.0 DL + 0.4 LL for fire limit state. The live load factor 0.6 is used for storage occupancies and 0.4 for other

TABLE 19.5.11 Load Factors for γ_f at the Fire Limit State

Load	γ_f
Dead load	1.00
Imposed loads:	
a) Permanent:	
1) Those specifically allowed for in design, e.g., plant, machinery, and fixed partitions	1.00
2) In storage buildings or areas used for storage in other buildings (including libraries and designated filing areas)	1.00
b) Nonpermanent:	
1) In escape stairs and lobbies	1.00
2) In offices for general use	0.50
3) All other areas (imposed snow loads on roofs may be ignored)	0.80
Wind loads:	
a) Design for boundary conditions to control external fire spread	0.00
b) All other cases	0.33

Source: British Standards Institute. Permission to reproduce extracts from British Standards is granted by BSI. British Standards can be obtained from BSI Customer Services, 389 Chiswick High Road, London W4 4AL. Tel: +44 (0)20 8996 9001. email: cservices@bsi-global.com.

occupancies. The Australian Standard AS 1170[46] adopts the same factors as New Zealand for live load but a slightly higher factor (1.1) for dead load.

Ellingwood and Corotis[47] present a methodology for determining loads and load combinations for use in fire-resistant structural design in the United States. Loads and load combinations were found by using probabilistic load modeling techniques and modern load survey results. Since significant fires are rare, it was found that a reduced nominal live load combined with the structural action due to fire is appropriate for design. The load combination that they found is:

$$U_n = D_n + 0.5L_n + F \tag{17}$$

where D_n and L_n are the dead and live loads from the ANSI Standard A58.1[48] and F is the structural action due to fire.[47] ASCE 7-05, *Minimum Design Loads for Buildings and Other Structures,*[49] has adopted load combinations based on the work by Ellingwood and Corotis but applied a factor of 1.2 to dead load and a factor of 0.2 to wind load.

Single Element Calculation Methods Used in the United Kingdom and Europe

BS 5950-8[42] and the Eurocode series[22,41] are the main references for structural fire engineering of steel members. Both codes define methods for heat transfer analysis and single element structural analysis techniques. The codes also provide detailed information on the thermal and mechanical properties of steel at high temperatures necessary to conduct a single element calculation for a steel member.

A key factor in the introduction of BS 5950-8 was a series of loaded furnace tests conducted in the United Kingdom in the 1990s.[50] The tests showed that if a member was carrying less load than assumed in ambient design, then its failure temperature was shown to increase from the traditional 550°C typically assumed. As a result of these tests, BS 5950-8 was published and included the concept of the limiting temperature method. The limiting temperature method, also called the critical temperature method, relies on reduced dead and live loads in fire conditions (relative to the cold temperature design), as defined above, and allows the user to calculate a specific limiting temperature for the structural element on this basis, using the actual loads of the cold temperature structural design. Therefore, the resulting limiting temperature for the element is building-specific.

The limiting temperature method or critical temperature method therefore provides a simple way of relating the critical temperature to the load that the member actually supports in fire conditions. It does not require the engineer to consider reduced strength and stiffness properties at high temperature.

This approach has been commonly adopted in the United Kingdom, Europe, New Zealand, and Australia, where limit state design is used. In North America, however, working stress design is still preferred. This means that, in fire design, the structure's full dead and live design loads are assumed.

For beams under bending and having three or four sides fully exposed to the standard fire or to natural fires, BS 5950-8[42] defines the load ratio (R) as:

$$R = \frac{M_f}{M_c} \tag{18}$$

where M_f is the maximum bending moment under fire conditions (e.g., 1.0 DL + 0.5 LL in an office occupancy) and M_c is the bending moment capacity of the beams at ambient temperature.

If the beam fails by yielding of the steel, M_c is equal to the plastic bending moment capacity of the cross section of the beam. If lateral torsional buckling (LTB) governs design, M_c is the lateral torsional buckling capacity of the beam.

A similar equation is provided for columns or members in tension. For columns, axial load and bending in both directions is also considered.

All steel members lose strength in a similar manner, but because of aspects such as temperature gradients and instability effects (e.g., buckling) at elevated temperatures, it is not always appropriate to apply the same strength reduction to structural members as are applied to the steel itself. Therefore, BS 5950: Part 8 gives limiting temperatures for different types of member for a range of load ratios shown in Table 19.5.12.

The limiting temperature method is simple to use. However, if temperature distribution in a steel beam for the specific design fire is shown to be nonuniform and the beam is prevented from lateral torsional buckling, it may be more beneficial to use a more detailed method to calculate the bending capacity of the beam. Such calculations may be carried out using the bending moment capacity method in accordance with BS 5950–8.

For this approach the beam is divided into a number of sections (Figure 19.5.8) of approximately the same temperature. The number of elements will depend on the complexity of the member and its temperature gradient. The bending moment ca-

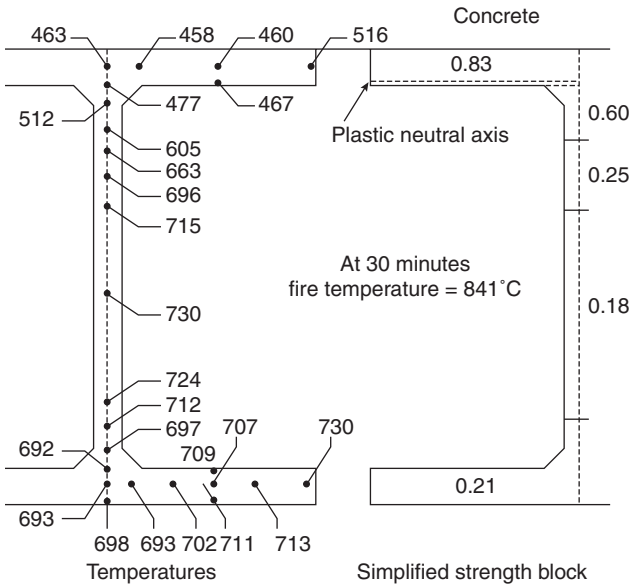


FIGURE 19.5.8 Example of Use of Moment Capacity for 838 × 292 × 194 UB (Courtesy of Steel Construction Institute, Silwood Park, Ascot, SL5 7QN, United Kingdom)

TABLE 19.5.12 Limiting Temperature for Design of Protected and Unprotected Hot Finished Members

	Limiting Temperature (°C) at a Load Ratio Of						
Description of Member	*0.7*	*0.6*	*0.5*	*0.4*	*0.3*	*0.2*	*0.1*
Members in compression, for a slenderness λ[a]:							
≤ 70	510	540	580	615	655	710	800
> 70 but ≤ 180	460	510	545	590	635	635	635
Noncomposite members in bending supporting concrete slabs or composite slabs:							
Unprotected members, or protected members complying with item (a) or (b) of 6.3[b]	590	620	650	680	725	780	880
Other protected members	540	585	625	655	700	745	800
Composite members in bending supporting concrete slabs or composite slabs:							
Unprotected members, or protected members complying with item (a) or (b) of 6.3[b]							
i) 100% degree of shear connection	550	580	610	645	685	470	840
ii) 40% degree of shear connection	575	600	635	665	700	760	865
Other protected members							
i) 100% degree of shear connection	495	530	570	610	650	705	785
ii) 40% degree of shear connection	530	560	595	630	675	725	795
Members in bending not supporting concrete slabs:							
Unprotected members, or protected members complying with item (a) or (b) of 6.3[b]	520	555	585	620	660	715	810
Other protected members	460	510	545	590	635	690	770
Members in tension: all cases	460	510	545	590	635	690	770

Note: For beams supporting a composite of slab the limiting temperatures only apply when the voids between the top of the beam and underside of the steel deck are filled with noncombustible void fillers. For guidance on limiting temperatures when void fillers are not used, see Association of Specialist Fire Protection (ASFP), *Fire Protection for Structural Steel in Buildings,* 3rd ed., ASFP and Steel Construction Institute, Hampshire, UK, June 2004.

[a]λ is the slenderness, i.e., the effective length divided by the radius of gyration.

[b]The 6.3 refers to the limiting strain level in the steel and the corresponding strain in any fire protection material. The following strains should not be exceeded: (a) composite members in bending that are unprotected or protected with fire protection materials that have demonstrated their ability to remain intact at a strain of 2.0 percent; (b) noncomposite members in bending that are unprotected or protected with fire protection materials that have demonstrated their ability to remain intact at a strain of 1.5 percent; (c) members not covered in (a) or (b) with a strain of 0.5.

Source: British Standards Institute. Permission to reproduce extracts from British Standards is granted by BSI. British Standards can be obtained from BSI Customer Services, 389 Chiswick High Road, London W4 4AL. Tel: +44 (0)20 8996 9001. email: cservices@bsi-global.com.

pacity of the cross section is calculated according to the reduced strength and stiffness of steel at the temperature of these sections. See Figure 19.5.7 and the SCI 080[51] for an example.

The bending moment capacity method requires more calculation work than the limiting temperature method. The benefit of using the more elaborate method is to explore possible benefits of the nonuniform temperature distribution in the cross section of the beam, particularly to optimize fire protection or to justify the use of unprotected steel.

EC3-1-2[41] gives two methods to calculate the bending capacity of a steel beam using reduced strength and stiffness properties for steel at high temperature. The first is identical to the bending moment capacity method in BS 5950-8,[42] which is described in the previous section.

Since this method requires many calculation steps, EC3 gives an alternative method that is simpler to use. In this simple method, the design bending moment resistance of the beam is given by

$$M_{fi,\theta,Rd} = \frac{k_{y,\theta} \cdot M_{Rd} \cdot \dfrac{\gamma_{m1}}{\gamma_{m,fi}}}{k_1 \cdot k_2} \tag{19}$$

where M_{Rd} is the bending moment capacity of the cross section ambient temperature and $k_{y,\theta}$ is the reduction factor in the effective yield strength of steel at the maximum temperature in the cross section. Adaptation factors k_1 and k_2 are used to account for nonuniform temperature distribution through the depth and along the length of the steel beam. γ_{m1} and $\gamma_{m,fi}$ are partial safety factors, which vary per country.

Although the bending resistance of a steel beam is usually controlled by the plastic bending capacity of the cross section, it is sometimes necessary to consider the lateral torsional buckling

(LTB) resistance of a steel beam in fire. In EC3, the lateral torsional buckling resistance of a steel beam is calculated the same way as at ambient temperature.

In EC3-1-2, calculations for the strength of a column in fire follow the procedure for design of cold columns in EC3, Part 1.1. An equation to calculate the column slenderness conditions under fire is given a buckling curve *c,* which is to be used to determine the reduced values for flexural stiffness. Although there are four column-buckling curves for column design at ambient temperature, for fire safety design in EC3-1-2, only column curve *c* is used regardless of the type of cross section and axis of buckling. Column buckling curve *c* gives relative conservative values of column buckling resistance. Reasons for using this low buckling curve in fire include the more severe influences of initial imperfections and additional bending moments in the fire case, due to possible nonuniform temperature distributions.[52] Application of BS 5950-8 for a postflashover design fire is presented in the following case study of the Rem Koolhaas CCTV Building in Beijing.

CASE STUDY: Rem Koolhaas CCTV Building, Beijing, China. At the request of the approving authorities in China, the fire resistance of the CCTV (Central China Television) building, Beijing, was calculated using performance-based engineering, despite the fact that that structure was proposed to be fully protected to code. This request was made because the structure was highly innovative, completely asymmetric, and, therefore, the approving authorities wanted to check that the performance was adequate in a real fire.

The CCTV building is a high-rise office building (Figure 19.5.9) with an internal structure consisting of a composite steel and concrete frame. The exterior structure consists of a lateral bracing system formed with tubular structural elements. This exterior lateral stability system comprises a series of axial members at many different orientations, forming a structural role as well as an architectural role. Each member is designed to carry load in axial compression and/or tension.

In collaboration with the structural engineer, the most highly loaded columns and bracing members were identified and checked against their respective failure criteria at the fire limit state using the limiting temperature method in BS 5950-8.[42] All of the steel members were to be protected to not exceed 540°C at the end of 2 or 3 hours heating, dependent on the prescriptive rating of the member in accordance with the local code.

In almost all cases the limiting temperature was shown to be greater than 540°C and therefore deemed to have passed the performance criterion. However, some members were considerably heavily loaded in compression, thereby lowering their limiting temperature to just below 540°C (see Table 19.5.13). A further check on stability was carried out by removing the critical member from the cold design structural model and assessing the performance of the rest of the frame. In all cases loads were able to redistribute to adjacent members without causing failure of adjacent members.

In order to carry out the analysis, credible postflashover design fires were proposed and calculated in accordance with

FIGURE 19.5.9 CCTV Building, Beijing, China (Source: Arup)

TABLE 19.5.13 Load Ratio Calculated for CCTV Building

Check Number	*Type*	*Load Type*	*Section*	*Load Ratio (R)*	*Limiting Temperature (°C)*	*Maximum Steel Temperature (°C)*	*Pass?*
C1	Steel column	Compression	EC5L-0.535	0.403290	615	540	Yes
C2	Steel column	Compression	EC6-0.106	0.311235	651	540	Yes
C3	Steel column	Compression	EC4-0.106	0.199308	710	540	Yes
C4	Steel column	Tension	EC6-0.093	0.147490	730	540	Yes
C5	Steel column	Compression	EC6-0.093	0.134998	773	540	Yes
C6	Steel column	Compression	EC6-0.093	0.342531	639	540	Yes
C7	Steel column	Compression	EC1-0.620	0.472994	590	540	Yes
C8	Steel column	Compression	EC1L-0.620	0.316175	647	540	Yes
C9	Steel column	Compression	EC3-0.323	0.587734	544	540	No
C10	Steel column	Compression	EC3-0.323	0.089909	800	540	Yes
BM1	Beam	Bending	EB1_ext	0.108341	794	540	Yes
BM2	Beam	Bending	EB1_ext	0.135486	778	540	Yes
BM5	Beam	Bending	EB5	0.067274	800	540	Yes
BR1	Brace	Compression	X3S60	0.374001	627	540	Yes
BR2	Brace	Compression	X35	0.374545	627	540	Yes
BR3	Brace	Compression	XH75Q	0.668774	519	540	No
BR4	Brace	Tension	X35Q	0.165109	714	540	Yes
BR5	Brace	Compression	X35	0.259566	677	540	Yes

Source: Arup.

the parametric equation in EC1-1-2, assuming no reduction of the fuel load as a result of sprinklers or other active systems (the parametric temperature-time curve and its limitations are discussed later in this chapter in the section "Use of Advanced Analysis in Global Structural Response to Fire"). The heat transfer from these design fires to the protected steel elements were then calculated using the lumped mass heat transfer equations in EC1-1-2 and EC3-1-2.

For the design fire case, all of the members passed their limiting temperature criterion because the design fires, although sometimes hotter than the standard fire, were of shorter duration than the standard fire resistance period required. The protected members, therefore, reached lower temperatures in response to the design fires than the 540°C at the end of the standard fire resistance test and also did not reach their limiting temperature.

Single Element Calculation Methods Used in Australia and New Zealand

Structural fire design is a rapidly developing subject in Australia and New Zealand. The New Zealand and the Australian standards are referenced in their building codes (AS 1170 and NZS 4203). The following fire engineering approach was developed in New Zealand and modified for Australia, but is still very similar. As with British and EC standards, the Australian and New Zealand standards determine a fire limit state load combination for fire emergency conditions.

Standards AS 4100[53] and NZS 3404[54] present a limiting temperature method. The simple design method is based on determining the limiting temperature of the steel member under consideration. The limiting steel temperature is the temperature at which the steel member would be expected to yield considering the strength of the steel and load ratio (load in fire/design capacity at ambient temperatures) of the member. The limiting temperature is directly related to the variation of material properties at elevated temperatures. The yield-stress ratio at elevated temperatures and Young's modulus degradation curve at elevated temperatures used in Australia and New Zealand is presented in Figure 19.5.10.

The standards specify the formula from European Convention for Constructional Steelwork[55] to predict the fire resistance time for protected and unprotected steel. Times are based on exposures to standard fire or on an equivalent time exposure.

Single Element Calculation Methods Used in the United States

ASCE/SFPE Standard 29-99, *Standard Calculation Methods for Structural Fire Protection,* provides calculation methods to find the fire resistance of selected structural member and barrier assemblies using structural steel, plain concrete, reinforced concrete, and wood. These methods are intended to produce fire resistance rating times equivalent to those found from ASTM E119, *Standard Test Methods for Fire Tests of Buildings Construction and Materials,* and to NFPA 251. Therefore, the results obtained from the calculations should be used in place of test results.

Chapter 5 of this standard covers the methods for determining the fire resistance of structural steel construction. It describes analytical procedures for determining the fire resistance rating of protected columns, beams, girders, and trusses.

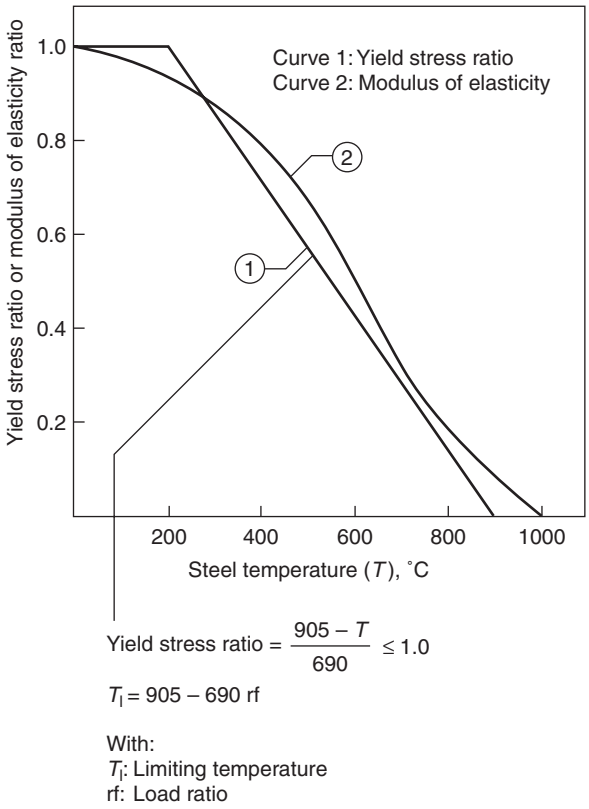


FIGURE 19.5.10 Australian and New Zealand Load Ratio and Limiting Temperatures Standards (Source: A. H. Buchanan, *Structural Design for Fire Safety.* Copyright John Wiley & Sons Limited, 2001. Reproduced with permission.)

The standard also provides calculation methods to find the fire resistance of structural steel beams and girders that differ in size from that specified in approved fire-resistant assemblies, as a function of the thickness of fire protection material and the weight (W) and heated perimeter (D) of the beam or girder. The W/D ratio is similar to the Hp/A concept used in the UK and Europe in that it is an indictor of heating rate.

The calculation methods apply to structural steel beams and girders protected with spray-applied cementitious or mineral fiber materials and a W/D ratio of 0.37 or greater (0.022 in SI units). In addition, the thickness of fire protection material is not to be less than ⅜ in. (9.5 mm). For beams and girder meeting these criteria, the thickness of fire protection material can be found using the following equation:

$$h_2 = \left(\frac{W_1/D_1 + 0.60}{W_2/D_2 + 0.60}\right) h_1 \qquad (20a)$$

where

h = Thickness of spray-applied fire protection material (in.)

W = Weight of the structural steel beam or girder (lbs per linear ft)

D = Heated perimeter of the structural steel beam or girder (in.)

In SI units:

$$h_2 = \left(\frac{W_1/D_1 + 0.036}{W_2/D_2 + 0.036}\right) h_1 \qquad (20b)$$

where

h = Thickness of spray-applied fire protection material (mm)

W = Weight of the structural steel beam or girder (kg per m)

D = Heated perimeter of the structural steel beam or girder (mm)

Subscript 1 refers to the beam and fire protection thickness in the approved assembly and subscript 2 refers to the substitute beam or girder and the required fire protection thickness.[56]

The ASCE standard also provides a method for dealing with structural steel trusses. Although analytical tools for steel fire design are not included in the codes and standards in the United States, the *SFPE Handbook of Fire Protection Engineering* includes a chapter dedicated to analytical methods for determining fire resistance of steel members. This chapter describes three types of calculation methods used to determine fire resistance of steel structural members. Empirical correlations are given based on the analysis of data from performing the standard test, heat transfer analyses to determine the time required for the structural member to attain a predetermined critical temperature or to provide input to a structural analyses, and structural analyses similar to those conducted for structural engineering purposes, except that the material properties are evaluated at elevated temperatures.[57] Methods developed by Lie and Stanzak to calculate the critical temperature of beam and column sections are presented. As with the methods described in other countries, the members are generally assumed to be simply supported and unrestrained.

Milke[57] provides examples throughout the description of each method to illustrate the procedure. The section also provides various methods of protection used for steel structural members.

Calculation Methods Applicable to Steel Elements Exposed to Local Heating

In general, the single element structural checks discussed in the previous section for steel members exposed to postflashover fires can also be applied to steel elements exposed to local heating. This equivalence is because once the temperature of the steel section has been established by heat transfer, the same structural checks considering load ratio and limiting temperature or the reduction in strength and stiffness of the constituent materials are conservative, unless temperature gradient is an issue for stability (e.g., columns).

In the case of local fires, the heat transfer calculation is slightly more sophisticated than the lumped mass heat transfer calculations used in a postflashover fire presented previously. Lower emissivity values and view factors need to be used to calculate heat transfer from radiation when the flames (external through a window or door) or fire are remote from the steel

member. For example, if a local fire is located under a floor slab supported by steel beams but the flames are not high enough to touch the steel, then the effects of convective and radiative heat transfer are reduced compared to a member in a compartment engulfed in a postflashover fire. In this case convective heat transfer to the steel member is a result of the temperature of the hot gases/smoke in the plume above the fire. Radiative heat transfer is largely dependent on the distance of the fire from the steel and is evaluated by using view factors.

Care should be taken when columns are likely to be exposed to a thermal gradient. In this instance the applicability of single element checks has not been validated. The gradient may result in significant thermal bowing and out-of-straightness that should be considered. For example, overall stability of the frame could be checked by removing the member from the ambient structural model that most structural engineers now generate for cold design and checking the resulting stability of the frame. The deflected shape of the structure is less important for fire limit state design, but the stresses generated in the rest of the frame, including the connections, should be shown as less than that required for failure. Once this assessment has been made, a single element approach is acceptable.

One form of local heating is external flaming from a compartment fire through openings or windows. Annex B of EC 1 gives thermal actions for external members. The equations and methodology in EC 1 are based on the external structural steel calculations originally developed by Law and O'Brien.[37]

The calculations consider the different fire exposure experienced by external structural members as compared to the same members in a fire compartment. The concept is shown in Figure 19.5.11. The calculations account for the following:

- The fire being within an adjacent compartment
- No heat buildup because the member is outside
- Cooling from surrounding air
- Heating based on flame size and position of member with respect to the facade
- Radiative heat flux from the fire compartment
- Radiative and convective heat flux from the external flames through the windows
- Radiative and convective heat loss from the steelwork to the ambient surroundings
- Size and location of the structural steelwork
- Through-draft conditions

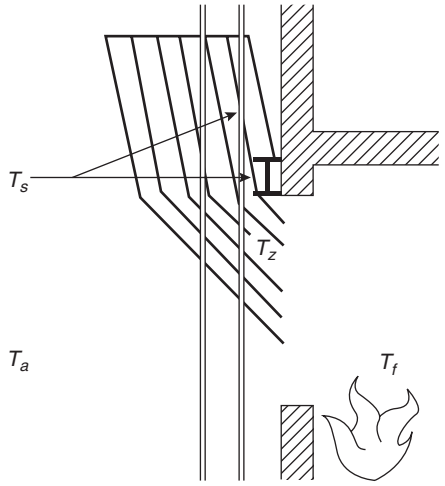


FIGURE 19.5.11 Concept of Thermal Actions on External Members (Courtesy of Steel Construction Institute, Silwood Park, Ascot, SL5 7QN, United Kingdom)

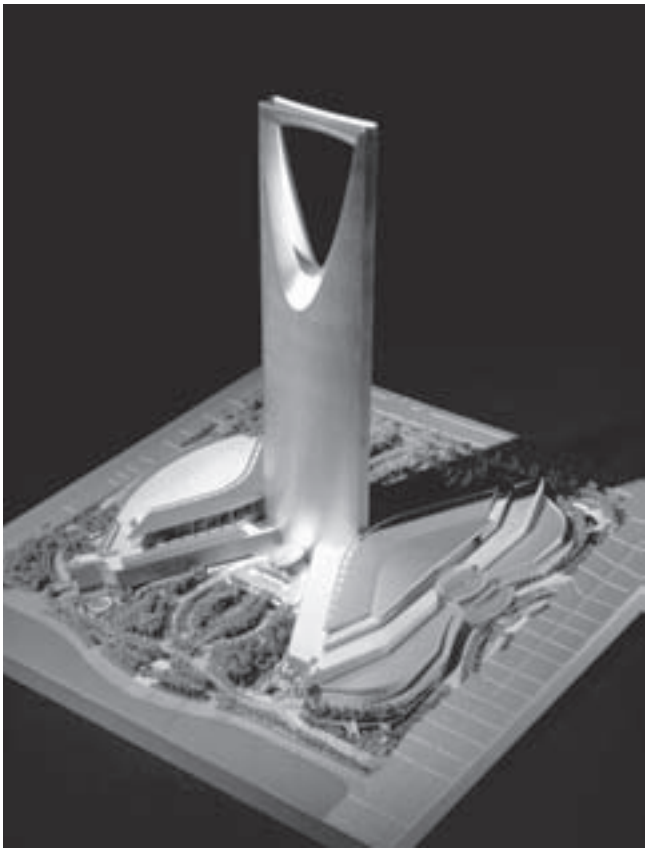


FIGURE 19.5.12 The Kingdom Centre, Riyadh, Saudi Arabia (Courtesy of Ellerbe Becket, Inc.)

CASE STUDY: Kingdom Centre, Riyadh, Saudi Arabia. The Kingdom Centre in Riyadh, Saudi Arabia, is an example of the application of Law and O'Brien's original external steel work calculations to an external flame–only design fire. The building is mainly office use with some retail and extends from grade to 180 m. At 180 m to 290 m, there is a raised observation deck (located at 290 m), a supporting structure containing lift/stair cores, and a steelwork "necklace." The observation deck, its supporting structure, and the nonstructural necklace are referred to as the "sculpture" (Figure 19.5.12 and 19.5.13).

The building structure was designed to meet the requirements of the Uniform Building Code, 1994. By code, it required a 3 hour rating, which meant the sculpture, which was not to contain any occupied floors other than the observation deck at the top, would be protected with passive fire protection. This passive fire protection requirement, however, had a negative impact

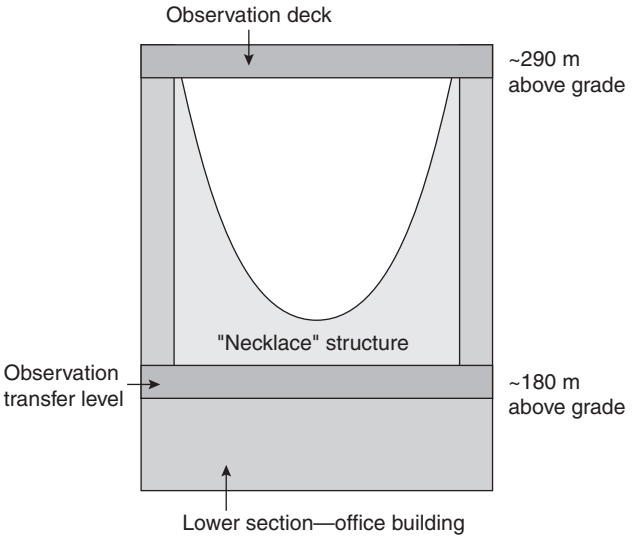


FIGURE 19.5.13 The Sculpture (Source: Arup)

on the aesthetic value of the sculpture and the construction program. In addition, the fire protection appeared to be redundant as it would be providing protection in an area of low fire load. A fire engineering study was, therefore, performed to reduce the areas of passive fire protection to the sculpture structure.

A number of fire scenarios were considered; failure was defined as a critical steel temperature of 550°C, when steel has lost about 40 percent of its ambient strength. This is conservative because it does not take advantage of the limiting temperature method presented previously, in which higher critical temperatures could have been calculated based on a reduced dead load, live load, and wind load at the fire limit state. For the sculpture this could have meant higher limiting temperatures of 600 to 700°C.

One of the fire scenarios considered for this project was the flame projection through the proposed windows and the resulting heating of the external steel members in proximity to the windows due to a postflashover fire on an office level. The flame projection (see Figure 19.5.14) from the office was determined for a range of ventilation conditions, and the heat transfer from the flames to the steel was calculated for the worst-case condition of flame length and temperature.

It was found by iteration that, at a vertical distances of greater than 10 m above the window opening, the heat flux from the flames would not heat the steel members to above 550°C, even after infinite exposure time. The steelwork immediately above the office floors was therefore protected for a height of 10 m, but the remainder of the structure above, including the observation desk, was unprotected. On the observation deck, credible local fires—for example, a large baggage fire—were investigated, assuming the same critical steel temperature of 550°C for failure criterion. Lower temperatures were shown as a result of heat transfer using the equations from the fire to the steel elements based on the work of Milke[57] from the *SFPE Handbook of Fire Protection Engineering.*

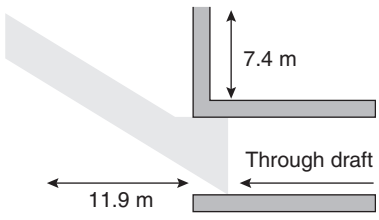


FIGURE 19.5.14 Summary of Flame Projection Calculations for the Office Level (Source: Arup)

Role of Connections in Single Element Design

Calculating the fire resistance of single members is only an acceptable design solution when the connections between the members are also considered. The fire resistance of connections in a steel frame is generally not well understood. The University of Sheffield in the United Kingdom has conducted some of the most significant research in this field.[58]

In addition, Scott, Lane, and Gibbons[59] discuss the behavior of connections in response to whole frame behavior and provide some insight into likely favorable and nonfavorable connection arrangements when considering the axial (compression and tension) forces placed on a connection as beams expand, pull, and push on connections in fire. Rotter et al.[60] state that connections should be designed for the tensile pulling force in the cooling phase of a fire when deflected steel beams try to contract to their original position but, because of plastic strains in the steel beam, cannot.

However, with respect to design recommendations in codes for single element analysis, it is generally assumed that a connection will be designed for ambient loads and then protected to the same standard as the adjoining member. If the adjoining member has been overdesigned so that it has more fire resistance, then the connection should also be overdesigned. This is always the approach when using the single element approach to design discussed in this chapter.

EC 3[41] and BS 5950-8[42] state that the fire resistance of a bolted or a welded connection may be assumed to be sufficient, as long as the fire protection on the connection provides the same thermal resistance to the joint as the fire protection on connecting members and the utilization of the joint is equal or less than the maximum value of the utilization of any of the connected members. BS 5950[42] further states that if the utilization of the connection is higher than the utilization of the connecting members, the protection to the connection should be increased to ensure that the connection does not fail first.

APPLICATION OF SINGLE STRUCTURAL ELEMENT ANALYSIS TO CONCRETE

The simplest and most common method of designing concrete structures in fire is to ascertain the required thickness and cover to reinforcement for the necessary fire resistance period, as spec-

ified in tabulated data in codes worldwide. When these tabulated data are applicable and are followed in the design of a concrete element, spalling prevention is generally assumed to heave been adequately addressed. There are a number of analytical methods to calculate the fire resistance of concrete members based on their capacity in fire, but the phenomenon of spalling must also be addressed when using these approaches.

Spalling

Detailed analysis of concrete members' response to fire, including the effect of spalling throughout the fire duration, is difficult due to the complexity of the factors that cause spalling and their nonlinear and unpredictable response to heat. Spalling prevention must therefore be demonstrated as provided prior to detailed analysis of concrete elements. Before the range of single element calculation methods available internationally for concrete are presented, a discussion of spalling and how it is treated by design codes in various countries is given.

Spalling is a complex process and, in general, not well understood, even by experts in the field. There are various different kinds of spalling (aggregate splitting, explosive, surface, corner separation, sloughing off, and cooling spalling). The most detrimental to a structural member in fire is explosive spalling. Explosive spalling (Figure 19.5.15) can occur at temperatures as low as 100°C and in some cases can fully expose the reinforcement to the full heat of a fire. Explosive spalling is thought to be primarily associated with evaporation of water in the concrete pores and the associated buildup of pore pressures. However, restraint to thermal expansion, the heating rate of the fire, the strength of the concrete, and the dimensions of the section also contribute.[61]

The risk of explosive spalling can be reduced by choice of aggregate, by limiting the concrete strength and moisture content where possible, and by the addition of polypropylene fibers. Arup Fire[61] conducted a research project to define the risk of spalling in normal weight-reinforced concrete exposed to hydrocarbon fires for the health and safety executive in the United Kingdom. Risk values (1 to 5) were assigned to all of the variables affecting spalling of concrete in a fire—for example, moisture content, restraint, and aggregate type. Risk categories associated with the combined or additive risk values for a particular concrete were assigned spalling rates defined by Arup Fire from evidence in the literature.

FIGURE 19.5.15 Example of Explosive Spalling of Concrete (Source: Arup)

Spalling Prevention Measures Used in the United Kingdom and Europe

BS 8110, Part 2[62] presents a tabulated approach to specifying cover and thickness of section required for different fire resistance periods for a range of concrete elements. Lennon[63] gives the background to these data and reports on spalling observed during standard fire tests and the adequacy of this guidance for cover to reinforcement given in the United Kingdom. Section 4 of BS 8110-2[62] gives additional measures necessary to reduce the risks of spalling at elevated temperatures. It is recommended that these additional measures also be implemented when the cover to reinforcement exceeds 40 to 50 mm.

The British standard discusses the key factors believed to influence spalling. It states that rapid rates of heating, large compressive stresses, or high moisture contents (over 5% by volume or 2% to 3% by mass of dense concrete) can lead to spalling of concrete cover at elevated temperatures, particularly for cover to reinforcement of thicknesses exceeding 40 to 50 mm. In addition it states that concretes made from limestone aggregates are less susceptible to spalling than concretes made from aggregates containing a higher proportion of silica, quartzites, and granites. Concrete made from manufactured lightweight aggregates are found to rarely spall.

Recommendations are given to designers to protect the concrete against spalling when the cover to reinforcement exceeds 40 to 50 mm. Acceptable measures are proposed as follows:

- An applied finish by hand or spray of plaster, vermiculite, and so forth
- The provision of a false ceiling as a fire barrier
- The use of lightweight aggregates
- The use of sacrificial tensile steel

The code states that welded steel fabric as supplementary reinforcement is sometimes used to prevent spalling; it is then placed within the cover at 20 mm from the concrete face.

General design rules concerning spalling are also mentioned in EC 2-1-2,[64] giving recommendations to limit explosive spalling and falling off of concrete. The main parameter considered by this design guidance is the moisture content. The code states that explosive spalling is unlikely to occur when the moisture content of the concrete is less than a certain amount with respect to the weight. This parameter is called k and is given as a percentage. The allowable percentage for each European nation is given by each individual National Annex. However, the recommended base value in EC 2-1-2[64] is 3 percent by weight of moisture content. (The United Kingdom has adopted 3%).

For normal-weight concrete, when using tabulated data to design section thickness and cover to reinforcement for the standard fire, the European code states that there is no further check required for spalling.

For beams, slabs, and tensile members, if the moisture content of the concrete is more than k percent by weight, the influence of explosive spalling on load-bearing function R may be assessed by assuming local loss of cover to one reinforcing bar or bundle of bars in the cross section and checking the reduced load–bearing capacity at the resulting high temperatures.

A specific section in the Eurocode addresses high strength concrete. For concrete grades C55/67 to C80/95 (where the two numerical values given after the C refer to the strengths measured in a cube and cylinder test), the rules as already described apply, provided that the maximum content of silica fume is less than 6 percent by weight of cement.

For higher contents of silica fume, further spalling prevention measures are proposed. For concrete grades $80/95 < C < 90/105$, spalling is deemed as likely in any situation for concrete exposed directly to the fire and at least one of the following methods should therefore be provided:

- *Method A.* A reinforcement mesh with a nominal cover of 15 mm. This mesh should have wires with a diameter greater than or equal to 2 mm with a pitch less than or equal to 50 × 50 mm. The nominal cover to the main reinforcement should be greater than or equal to 40 mm.
- *Method B.* A type of concrete for which it has been demonstrated (by local experience or by testing) that no spalling of concrete occurs under fire exposure
- *Method C.* Protective layers for which it is demonstrated that no spalling of concrete occurs under fire exposure
- *Method D.* Include in the concrete mix more than 2 kg/m³ of monofilament propylene fibers

Spalling Prevention Measures Used in New Zealand and Australia

The concrete code used in Australia is AS3600.[65] The existing code contains only a cautionary note about spalling, with no actual guidance; it reads as follows:

> SAA is not prepared at present to specify requirements for the prevention of spalling of concrete from beams or columns exposed to fire. However, reference may be made to Clauses 4.1.6 and 4.1.7 of BS8110 part 2, in relation to this matter.

The whole code is currently being redrafted. The reason for this exercise is to increase the maximum concrete grade addressed by the code and therefore more easily used in design from 65 MPa to 100 MPa. This further increases the risk of spalling. The current draft in circulation includes no guidance on spalling and the intention is to include some technical advice to prevent spalling, in the commentary only.

Spalling Prevention Measures Used in the United States

In the United States, the building codes and ACI Manual of Concrete Practice are silent on spalling prevention measures for fire other than specifying minimum levels of cover to reinforcement. In the *SFPE Handbook of Fire Protection Engineering,* Fleischmann and Buchanan[66] briefly discuss the merits of adding fine polypropylene fibers to the concrete mix but do not specify quantities for design.

Calculation Methods Applicable to Concrete Structures

In all the analytical methods presented here to determine the capacity of concrete elements in fire, engineers should also satisfy themselves that spalling has been adequately addressed by the design, through the meeting of tabulated code requirements for dimensions of section and cover or by prevention measures.

When designing concrete elements for fire protection, well-detailed reinforcement with adequate tying will generally perform well in that loads can be redistributed. It has been shown that continuity will enable redistribution of moments to hogging areas where steel is remote from the fire, enhancing the fire resistance of a slab or beam; if this is considered in design, however, then the detailing must allow for it.

Axial restraint will allow arch/membrane action to occur; some single element design methods take this into account to further increase the fire resistance that can be assumed to be achieved by a section in design, although it should be noted that this may also then increase the likelihood of spalling.

Calculation Methods for Concrete Used in the United Kingdom and Europe

The tabulated data in BS 8110 are based on furnace test data from the 1950s and are therefore relevant to design fire cases where a postflashover fire is assumed. Tables tend to be related to element type; tables for columns and beams, for example, are different. Similarly, separate tables exist for prestressed members as opposed to ordinary reinforced sections in BS 8110. The prestressed data are based on data for precast elements and their application, therefore, to modern posttensioned slabs is questionable, particularly bonded systems with very little passive reinforcement and the protection of anchorages in unbonded construction. Similar tables are available in Eurocode 2, Part 1.2, and these are also assumed to be applicable to the design fire case where flashover has occurred in the compartment containing the structural elements.

Both BS 8110-2 and EC2 give material properties for reinforcement, prestressing steel, and concrete at elevated temperature. These can be used for detailed analysis to determine the capacity of single concrete elements at elevated temperatures. Again a three-step process (design fire, heat transfer, capacity calculation) is required for concrete. When calculating heat transfer, there are no simple equations that can be used because the conductivity of concrete is low and concrete sections are thermally thick. Consequently, either predefined nomograms drawn for particular sections in response to the standard fire can be used, or a finite element heat transfer analysis is required to calculate the temperature gradient through the depth and/or along the length of a concrete section.

The most commonly applied design tool for concrete members in a compartment with a postflashover fire is the 932°F (500°C) isotherm method or reduced cross section method orig-

inally developed by Anderberg.[67] The approach is recognized by EC 2-1-2[64] and illustrated in Figure 19.5.16.

It is assumed that any concrete at a temperature greater than 500°C will not be able to support load in fire. Any concrete at a temperature less than 500°C can be assumed to have its full ambient design strength. These simple rules and the reduced strength of reinforcement are used to calculate the residual capacity of the section in response to fire. If this residual capacity is sufficient to carry the loads, factored for the fire limit state, the section is deemed to be acceptable.

Data are available in EC2 to predict the location of the 500°C isotherm in various sections at 30, 60, 90, and 120 minutes of the standard fire, usually in the form of nomograms. Alternatively, engineers can calculate a credible design fire and subsequent heat transfer through the particular concrete element to actually predict the isotherm. The methodology is generally applied to beams and columns, although it can also be applied to slabs, provided the section is not too thin that almost the entire section is at 500°C and, therefore, has to be ignored.

In addition to the 500°C isotherm method, Annex B of EC2-1-2 also provides the zone method for calculating the resistance to bending moments and axial forces. The zone method is recommended for use with small sections and slender columns fully engulfed in a postflashover fire, but is only valid when the standard fire is used as the design fire case.

The zone method requires more calculation but is of benefit to smaller sections because some strength in the concrete is considered even at high temperatures. The zone method splits the member into three or more zones of near equal temperature; then the material properties at elevated temperature are used to calculate that particular section capacity. A zone of damaged concrete at the surface is calculated and ignored in the capacity check. The capacity of the reduced section is then calculated by summing the capacity of each remaining zone.

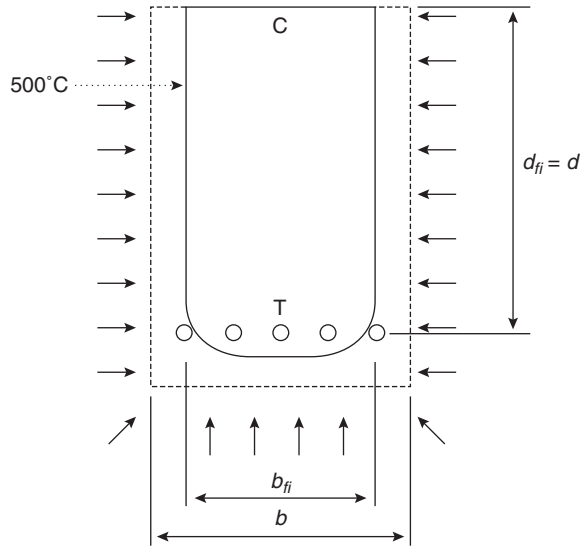


FIGURE 19.5.16 500°C Isotherm Method (Courtesy of British Standards Institute. Permission to reproduce extracts from British Standards is granted by BSI. British Standards can be obtained from BSI Customer Services, 389 Chiswick High Road, London W4 4AL. Tel: +44 (0)20 8996 9001. email: cservices@bsi-global.com.)

For shear, torsion, and anchorage, Annex D provides a simplified calculation method, although failure of concrete is rare in this respect. Shear can be a problem in precast, pretensioned slabs with narrow webs.[68]

Simplified methods for the design of beams and slabs where the loading is predominantly uniformly distributed and where the design at normal temperature is based on linear analysis are provided in Annex E of the Eurocode. A method for simply supported slabs and beams and a method considering redistribution of load for continuous members are also provided. When considering the redistribution of load in continuous members in fire, the curtailment length of the reinforcement over the supports should be checked because the point of contra-flexure will have changed. A formula to calculate the required length is given by EC2.

The Eurocode does not provide a simplified calculation method for the analysis of axially restrained slabs/beams, unlike methods presented in the *SFPE Handbook of Fire Protection Engineering*.[66] This is conservative as restraint induces thrust, which will enhance the members' fire resistance because the thrust acts as additional reinforcement.

Calculation Methods for Concrete Used in New Zealand and Australia

The Australian Concrete Design Code, AS 3600,[65] provides dimensions for concrete sections to achieve periods of fire resistance like all other codes, assumed as applicable for postflashover fire conditions. In Section 5.9 of the code it states that fire resistance may be predicted by methods of calculation provided the relevant properties of materials at elevated temperature are used. New Zealand's NZS 3101 has a similar approach.

Calculation Methods for Concrete Used in the United States

Tabulated data for cover and thickness of concrete elements are given in building regulations ACI 216.1-97 in the ACI *Manual of Concrete Practice*[69] and ASCE/SFPE 29-99.[56] The main differences between U.S. data and tabulated data elsewhere are that U.S. codes differentiate between aggregate type, recognizing that carbonate concretes spall less than siliceous concretes. Dimensions and cover are given for restrained and unrestrained slabs and beams as a consequence of the restrained furnace test in ASTM E119. The data for prestressed members differ from the data for ordinary reinforced members.

Fleischmann and Buchanan[66] present analytical methods for determining the fire resistance of concrete members in the *SFPE Handbook of Fire Protection Engineering*. The chapter presents temperature nomograms for slabs and beams in the standard fire and equations for calculating the fire resistance of simply supported slabs and beams, continuous unrestrained flexural members, and those restrained against thermal expansion.

Continuous unrestrained members have longer fire endurance than simply supported members because they can redistribute moments. Usually the redistribution of moment through the depth

of the member results in failure of the negative moment reinforcement over the supports. The chapter states that the American Concrete Institute warns against increasing this reinforcement as this could result in compression failure of the member, which is not desirable. Limitations are therefore placed on the negative reinforcement to ensure flexural failure in design. Equations to calculate the flexural strength at any point are given.

Equations are also given to account for the thermal thrust force that will occur in the axis of members heated from below and restrained from thermal expansion. The effect of the thermal thrust is the same as prestressing a concrete beam or slab. Therefore, the line of thrust can be considered a fictitious line of reinforcement in flexural design. To calculate the thrust moment, the midspan deflection must be calculated. Fleishmann gives an approximate equation for deflection.

Similar calculations to those presented by Fleischmann and Buchanan[66] are presented in ACI 216R-89, ACI *Manual of Concrete Practice.*[69]

Calculation Methods Applicable to Concrete Elements Exposed to Local Heating

As for steel design, local fires and external flaming can be considered as credible design fires to be resisted by the concrete element, in lieu of a standard fire or postflashover design fire, depending on the fuel load arrangement, quantity, and location (as outlined earlier, TM19[34] and Law[37] are useful references to determine such fire cases).

Heat transfer to concrete is more complex and will generally require a finite element computer code to calculate the temperature gradient through a concrete section.[68]

Spalling prevention measures should be addressed by the design if the concrete is exposed to direct flame impingement or if the concrete temperature in the cover to reinforcement exceeds 100°C. However, if overall frame stability can be shown when a single critical element is lost, then spalling prevention is not required. The capacity of the element in these local or external heating regimes can then be checked using the methods outlined from BS8110 Part 2 or EC2.

APPLICATION OF SINGLE STRUCTURAL ELEMENT ANALYSIS TO COMPOSITE STEEL AND CONCRETE MEMBERS

Composite steel and concrete members are generally concrete slabs connected to steel beams via shear studs, hollow steel sections filled with reinforced concrete, or hot rolled steel sections encased in concrete, all of which are designed at ambient temperature, taking into account composite action. In some cases steel hollow sections are filled with concrete to provide fire resistance, but the concrete fill is ignored by the ambient design. In this case there may be no composite action, and the concrete simply acts as heat sink, in which case there is a limit to the fire resistance that can be achieved (30 to 60 minutes maximum).

Composite steel frame construction generally has excellent fire resistance properties as a single member and as a whole frame. The main reason for this good performance is that when the steel member becomes hot and weak, there are alternative paths for the load into the colder concrete slab in a composite floor or the concrete core of a composite column.

As a consequence of the concrete, composite members experience large gradients through their depth; therefore, to obtain an accurate representation of this temperature gradient during a fire, a heat transfer analysis using a finite element method is usually required. A 2D analysis is sufficient if it is safe to assume there would be no gradient along the member.

For composite slabs it is reasonable to assume an average steel temperature from the fire for the entire protected or unprotected beam section, because it is the gradient between the steel beam and the concrete slab that tends to define performance. In this case, the simple lumped mass heat transfer equations can be used to calculate the average steel temperature. However, increased fire resistance could be achieved if the temperature gradient in the beam is also calculated.

As for all single element methods, the design fire must first be established (a standard fire; a postflashover fire calculated using, for example, a parametric equation; a local fire; or an external fire case). The heat transfer from this fire through the structural element can then be determined using a finite element analysis. Predefined nomograms based on standard furnace tests can also be used to obtain the temperature gradient. The capacity assessment methods, as follows, can then be used.

Composite Beams, Slabs, and Columns in the United Kingdom and Europe

The limiting temperature method discussed in the context of steel members previously can also be used for composite beams. The difference with the design methods for steel beams is that if the beam fails by yielding of the steel, M_c is equal to the plastic bending moment capacity of the cross section of the composite beam (steel and concrete). BS 5950-8[42] and Eurocode 4, Part 1.2,[70] therefore, give specific values for limiting temperature of composite steel beams.

An essential part of composite beams are the shear connectors or shear studs, which transfer the forces from steel beam into the concrete slab and vice versa. EC4-1-2[70] states that the design shear resistance in fire situation can be determined in accordance with the cold design in EC4-1-1,[71] except that in the fire circumstances, the variation of material properties with temperature and the different partial safety factor should also be taken into account. The temperature of the stud connector and concrete may be taken as 8 percent and 40 percent, respectively, of the temperature of the upper flange of the beam. Note BS 5950–8 does not consider the temperature of the shear stud.

However, both BS 5950-8 and EC4-1-2 differentiate between partial and full shear connection. Note that the limiting temperatures for partial shear connections are higher than for the 100 percent shear connection (Table 19.5.14) due to the fact that the partial shear connection determines the capacity of the beam. The shear connections remain relatively cold, because the studs are in the concrete slab. The limiting temperature for the rest of the cross section might therefore be higher. For the 100 percent shear connection, temperatures of the lower flange are determined to find the capacity of the composite beam in fire.

In addition to providing design methods for conventional composite beams, both design guides also present design meth-

TABLE 19.5.14 Limiting Temperature of Composite Beams

Description of Member		Limiting Temperature (°C) at a Ratio Of *0.7*	*0.6*	*0.5*	*0.4*	*0.3*	*0.2*
Unprotected, or protected with fire protection that can undergo large strains	100% shear connection	550	580	610	645	685	740
	40% shear connection	575	600	635	665	700	760
Other protected members	100% shear connection	505	540	575	620	660	715
	40% shear connection	535	565	605	640	675	736

Source: Arup.

ods to determine the capacity of partially encased composite beams (as would occur when shelf angle floor beams are used and some of the beam is embedded in the slab).

When calculating the load-bearing resistance of a composite slab in fire using a single element approach, it is often assumed that it is one-way spanning, being effective only in the direction of the concrete rib. This is in contrast to the much stronger mechanism that occurs in reality—tensile membrane action—discussed later in this chapter in the subsection "Analytical Methods to Quantify Tensile Membrane Action in Fire." Consequently, a single element approach will tend to be on the conservative side.

For a continuous slab, a plastic design method may be used as defined in EC 4.[70] In this method, plastic hinges are assumed at the support and locations of the maximum bending moment in the slab. In order to guarantee sufficient deformation capacity for continuous slabs, there are limitations on the minimum amount of reinforcement at supports and midspan.

In sagging bending, since the temperature rise on the unexposed side of the slab is generally required to be below 284°F (140°C) to fulfill the insulation requirement in standard fire resistance testing, the concrete in compression can be assumed to be cold. Its cold strength may be used when calculating the sagging bending moment capacity of the slab. Contributions from the steel decking are usually ignored because the decking will be unprotected and might debond when under direct fire attack. Reinforcement in the ribs generally provides the tension force in fire. (See Figure 19.5.17 for visualization of the design method.) To calculate this tension force, the temperature distribution through the composite slab is required and can be obtained from calculation using finite element heat transfer models or nomograms provided in Eurocode 4.

Under a negative bending moment (Figure 19.5.18) in a continuous slab, the compression face of a composite slab is exposed to fire where there is a steep temperature gradient. When calculating the negative moment capacity, the composite slab, including the concrete ribs, should be divided into a number of layers, each of approximately the same temperature. The contribution of each layer should be evaluated separately using the reduced strength and stiffness properties of the materials and then integrated to give the total slab resistance. To simplify this calculation, a ribbed or trapezoidal slab may be converted into a flat slab with an effective flat slab depth, with its corresponding temperature distribution. This temperature distribution can be calculated using nomograms for the standard fire or finite element analysis for any fire type.

Composite Beams, Slabs, and Columns in New Zealand and Australia

In New Zealand and Australia, the limiting temperature method is used for composite beam members. Performance-based design assuming reduced strength and stiffness of composite columns and other structural members can also be performed within the performance-based framework in both New Zealand and Australia.

Composite Beams, Slabs, and Columns in the United States

Fleishmann and Buchanan[66] briefly discuss composite steel–concrete construction in the *SFPE Handbook of Fire Protection Engineering* but simply cross-reference Eurocode 4 for detailed analysis. ASCE/SEI/SFPE 29-99[56] provides empirical correlations to calculate the benefit of increased thermal mass when steel sections are filled or encased with concrete.

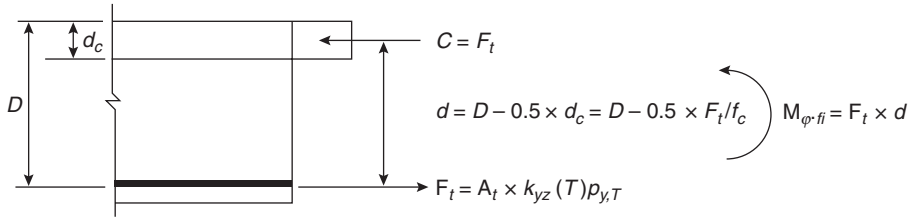


FIGURE 19.5.17 Calculation Method for Sagging Moment Capacity (Source: Arup)

$$\frac{1}{z} = \frac{1}{\sqrt{u_1}} + \frac{1}{\sqrt{u_2}} + \frac{1}{\sqrt{u_3}}$$

where u_1, u_2, u_3 are axial distances (mm) of the reinforcing bar to the profiled steel as specified in figure.

Additionally to the limitations given in the table, the use of this table is restricted to:

u_1 and $u_2 \geq 50$ mm

$u_3 \geq 35$ mm

Relation fire duration - temperature of the reinforcing steel

Standard Fire Resistance	*Temperature of Reinforcing Steel (°C)*
R 60	$\theta_z = 1175 - 350\ z \leq 810°C$ for $(z \leq 3{,}3)$
R 90	$\theta_z = 1285 - 350\ z \leq 880°C$ for $(z \leq 3{,}6)$
R 120	$\theta_z = 1370 - 350\ z \leq 930°C$ for $(z \leq 3{,}8)$
R 180	$\theta_z = 1490 - 350\ z \leq 1000°C$ for $(z \leq 4{,}0)$
R 240	$\theta_z = 1575 - 350\ z \leq 1500°C$ for $(z \leq 4{,}2)$

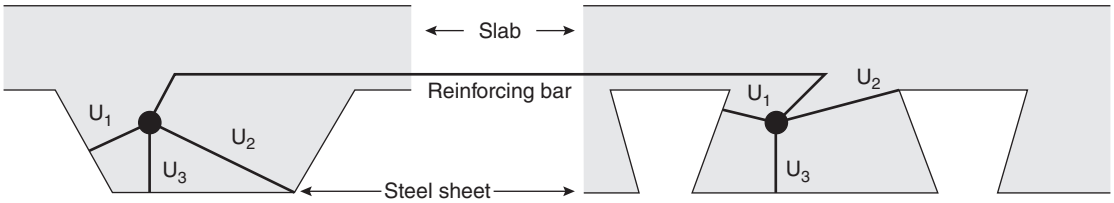


FIGURE 19.5.18 Calculation of the Negative Moment Resistance (Courtesy of British Standards Institute. Permission to reproduce extracts from British Standards is granted by BSI. British Standards can be obtained from BSI Customer Services, 389 Chiswick High Road, London W4 4AL. Tel: +44 (0)20 8996 9001. email: cservices@bsi-global.com.)

Calculation Methods for Concrete-Filled Hollow Steel Sections

Various existing calculation methods provide a cost-effective way to obtain columns with a high load-carrying capacity at ambient temperature and high fire resistance (Figure 19.5.19) without the addition of passive fire protection to the steel. When the column is designed as composite at ambient temperature and in fire the concrete filling has several beneficial effects. The concrete will act as a heat sink to slow the temperature rise of the steel column; the reinforced concrete can bear some or all of the axial load as the steel weakens; and the reinforced concrete fill can provide lateral stability to inhibit local buckling of the steel shell.

In some instances the hollow steel section is filled with concrete only and no benefit is taken from composite action in design, in which case the concrete simply acts as a heat sink. Low fire resistance periods of 30 to 60 minutes can be achieved.[72]

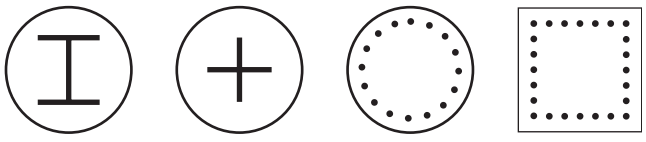


FIGURE 19.5.19 Example of Composite Column Sections (Source: F. Kettner, "Investigations on the Load Bearing Behavior of Composite Columns Under Fire Conditions," *1st International Ph.D. Workshop on Fire Protection Science and Engineering,* Hanover, Germany, 2005)

Composite Column Design Approaches

EC4-1-2 Design Approach. EC4-1-2 gives a more rigorous and detailed approach to composite column design than any other code worldwide. It introduces three design procedures for composite columns: (1) tabulated data, (2) simple calculation model, and (3) advanced calculation models.

The application of the tabulated approach is for a limited range of load ratios and steel section size and is only applicable to columns with a buckling length of less than 4.5 m. A more detailed calculation method is given in Annex H of EC4-1-2.[70] In this case the maximum buckling length permissible in order for the calculation to be valid is still 4.5 m as a consequence of the furnace tests the methodology is based on, but any section and any load ratio can theoretically be designed using this approach.

EC 4 also permits advanced analysis; a number of researchers have created software (Kettner,[73] CEC,[74] SCI,[51] and CORUS[72]) to calculate and extend the application of EC4-1-2 Annex H.[70] The software is still based on single element analysis but allows an accurate calculation of the through-depth thermal gradient and resulting differential strains in the steel casing, concrete, and reinforcement. Each code is based on an iterative process to obtain the squash load and rigidity of the composite column in fire. The calculation involves the determination of the temperature distribution in the cross section and the consequent residual rigidity (EI). The Steel Construction Institute (United Kingdom) and CORUS steel have produced software to make this calculation easy to use in design but this is also limited to a column buckling length of 4.5 m.[75]

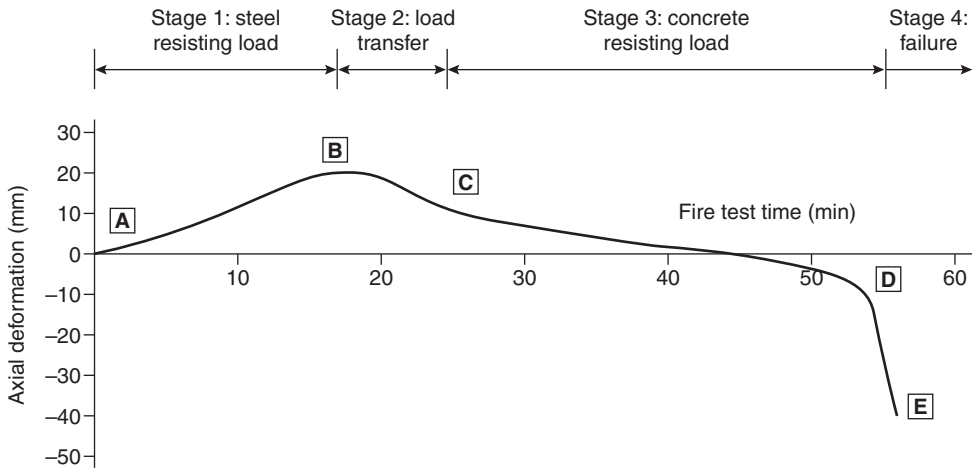


FIGURE 19.5.20 Axial Deformation Response as a Function of Time for a Typical Concrete-Filled Tube (Courtesy of V. K. R. Kodur and John C. Latour, National Research Council of Canada)

Canadian Fire Tests. In Canada a body of work exists on the response of concrete-filled steel sections. Over a number of years, the National Research Council of Canada (NRCC) carried out numerous fire tests on unprotected concrete-filled steel columns. The fire tests were carried out in a specially constructed fire testing furnace at the National Fire Laboratory.[76] The Canadian fire tests included different dimensions and thickness of circular and square hollow sections, a variety of concretes (plain, bar reinforced, high strength, and steel fiber reinforced with either siliceous or carbonate aggregates), and different levels of applied loads.[77–79] All the test columns were 3810 mm and the column ends were rotationally restrained at the ends. All fire tests were carried out with unprotected steel sections and fire exposure according to ASTM E119.[9]

Figure 19.5.20 shows a typical response of the recorded axial deformation-time relationship. It can be divided into four parts: (1) a phase of steady increase in the column expansion (A-B) is followed by (2) a sharp contraction (B-C) and (3) then gradual contraction (C-D) in the column axial deformation. (4) The columns experience another sharp contraction (D-E) before failure.

This type of behavior may be explained by considering the temperatures and resistances of the steel tube and concrete. Fire tests by others[74] on unprotected concrete-filled columns show similar results.

A design method for the calculation of the fire resistance of concrete-filled hollow steel columns was included in Appendix D of the National Building Code of Canada beginning with the 1995 edition and then later in a joint publication of the American Society of Civil Engineers and the Society of Fire Protection Engineers.[56]

CASE STUDY: Auditorium. The following case study demonstrates a single element analysis of unprotected circular hollow section (CHS) columns in a steel sway frame. The columns form part of the primary structural frame of an auditorium. The aim was to determine if the unprotected columns could achieve their necessary fire resistance rating as a result of composite action with reinforced concrete filling. The local code required a fire resistance rating of 2 hours, except where the columns support the roof, in which case a reduction to 1 hour was acceptable.

The simplified single element approach in Eurocode 4 for nonsway frames was deemed applicable for the sway frame of the auditorium because it was determined that the overall lateral stability could be provided by the global performance of the steel frame with four adjacent columns removed. Based on the fire load in the auditorium it was shown that only four columns are expected to be affected by fire simultaneously. Therefore, four adjacent columns were removed from the structural engineer's model and the stability of the frame in wind was shown to remain adequate. As global lateral stability was justified, the capacity of the columns under gravity loading in fire could be assessed individually.

The inherent fire resistance of the columns under axial load was checked in accordance with the simplified guidance in Eurocode 4 for single elements in a nonsway frame. The heating regime was assumed to be the standard temperature-time curve.[9] The calculations were performed using a combination of software developed by the steel producer CORUS[72] and spreadsheet calculations. The software assessed the temperature gradient in the section and then the capacity of the composite column using the properties of steel and concrete at elevated temperatures. It also considered the differential strains between the cool concrete and the hot steel casing. The resulting capacities were incorporated into a spreadsheet and compared to the demands.

The columns were analyzed with up to 6 percent reinforcement within the concrete fill with 1 in. (25.4 mm) cover throughout. The column capacities produced by the software were used to calculate the utilization (ratio of load to capacity) at 60 and 120 minutes of the standard fire for each column member. Failure was defined as a load ratio greater than one.

The effective length of the columns was assumed to be 1.0 and the safety factors applied to dead, snow, and live loads were taken as 1.0. These values are considered conservative because Eurocode 4 allows a reduction of 0.7 to 0.85 times the actual column length and a reduction in live load of 50 percent. These

reductions are permitted because a hot column will be restrained by the cold structure at its ends and the ambient design live load is unlikely to be achieved in reality. It was shown that all columns met the code required rating.

APPLICATION OF SINGLE STRUCTURAL ELEMENT ANALYSIS TO WOOD ELEMENTS

Pyrolysis Behavior of Wood

The pyrolysis behavior of wood (Figure 19.5.21) is that of a charring material that deposits residue as it burns. This residue helps prevent further pyrolysis; it does, however, result in some loss of section. The thermal and mechanical properties of wood vary with respect to heat flux/exposure, exposure time, moisture content, wood species, and density.

Wood performance in fire is complex to predict. Heat transfer through this material is affected by phase change of moisture as well as opening/cracking of the increasing char layers, which then generate new paths for heat transfer. The mechanical properties of wood are known to be dependent on creep, moisture, the direction of the grain, and the presence of knots and other discontinuities.

However, fire is a short-term event; therefore, creep is of less concern. Indeed, because fire is a short-term event, BS 5268, Part 4[80] and other design codes allow the long-term stress values used for ambient design to be increased when checking the cold residual section after charring in fire design—that is, the strength properties of the cold residual section are assumed to be better in fire than ambient because the member will only carry the load for a short time. Due to charring, design codes generally recommend the reduced cross section method to calculate the residual capacity in fire in order to determine available fire resistance.

As for steel and concrete, the design fire must be first ascertained (standard fire, postflashover design fire, local fire, or external fire). However, unlike steel and concrete, a heat transfer analysis to determine the wood section temperature for the fire duration is not always required because most design methods assume the charred material should be ignored and the rest of the section has its full ambient design strength. Specific capacity checks, assuming the same equations as used at ambient, as outlined in the following sections can then be utilized.

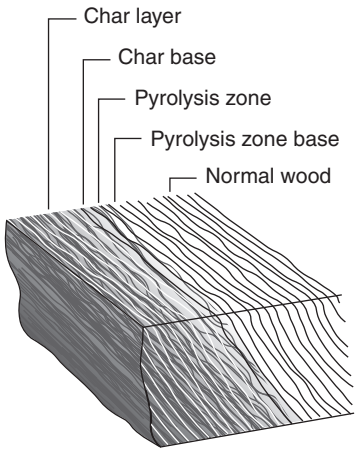


FIGURE 19.5.21 Charring of a Wood Section (Source: A. H. Buchanan, *Structural Design for Fire Safety.* Copyright John Wiley & Sons Limited, 2001. Reproduced with permission.)

Calculation Methods for Wood Used in the United Kingdom, Europe, Australia, and New Zealand

In the UK, BS 5268, Part 4[80] provides simple rules for designing wood members for fire. It treats solid members and glulams (glued laminated wood sections) in the same way, provided the glulam is laminated with certain phenolic and amnioplastic synthetic resin adhesives. Table 1 in the code lists charring rates to calculate the residual section of a wood member as a function of exposure of density. For example, the table has a higher char rate for western red cedar and a lower char rate for hardwoods with a density of 650 kg/m^3 or greater at 18 percent moisture content.

If wood sections are built up with metal fasteners, the charring rates given in BS 5268[80] can only be used on the whole section if the metal fasteners are fully protected against heat from the fire. Metal fasteners can be protected with passive fire protection or embedded in the wood so that they remain within the residual section (section not affected by charring).

To assess the fire resistance of a wood section, the following steps are proposed:

1. Calculate the residual cross section by subtracting the appropriate amount of lost wood, based on the defined charring rate for the fire resistance period under assessment. If the section has exposed corners, then rounding needs to be taken into account – that is, the corner will char more because it is exposed to heat on two sides.
2. Calculate the capacity of the resulting reduced section using cold design checks but assuming 2.25 × permissible long-term dry stresses.
3. For flexural, check that the deflection of the resulting reduced section does not exceed L/20 and does not impact the stability or integrity of other parts of the construction.
4. Check the stability in members subject to buckling, for example, columns or beams unrestrained by a slab.

Where connections are traditional wood joints, the same charring rates as for the main member can be adopted and its capacity in shear can be checked as it would be in ambient design.

The Hp/A of the wood section is important because fire-rated construction, for example, a ceiling, will shield wood sections and can have a significant impact on the resulting area of residual section for fire design. Figure 19.5.22 illustrates this concept. With shielding, considerably more area of residual section is possible, thereby increasing the fire resistance of the section.

Similar methods are given in Eurocode 5, Part 1.2[81] and design codes in Australia (SAA[82]) and New Zealand (NZS 3606[83]). The main difference is that BS 5628 and the methods in New Zealand ignore any reduction of wood strength below the char line (see Figure 19.5.21) whereas EC5 and SAA recommend considering it.

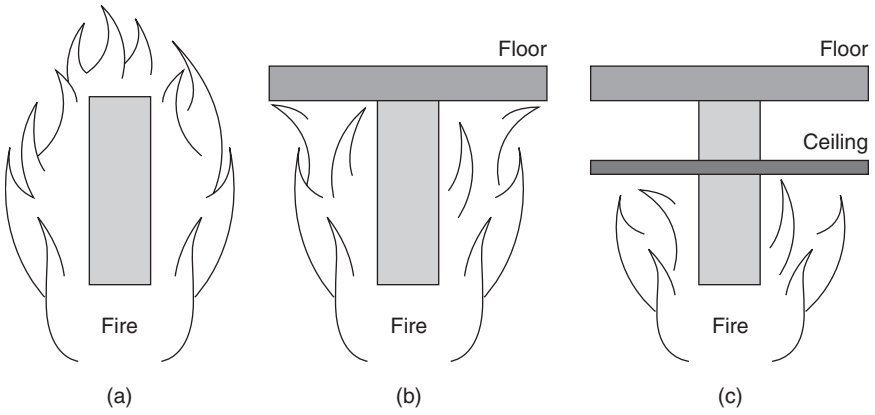


FIGURE 19.5.22 Heated Perimeter of a Wood Beam Shielded by a Fire-Rated Ceiling (Source: A. H. Buchanan, *Structural Design for Fire Safety.* Copyright John Wiley & Sons Limited, 2001. Reproduced with permission.)

Calculation Methods for Wood Used in the United States

White,[84] in Section 4, Chapter 11, of the *SFPE Handbook of Fire Protection Engineering,* discusses analytical methods for determining fire resistance of wood members. He reports on theoretical models for wood charring, many of which are based on the conservation of energy equation. The balance is between the heat stored in the wood, conduction away from or into the wood, and the fire and the energy absorbed when the wood undergoes pyrolysis. White also gives properties for wood at elevated temperatures and empirical models to calculate charring and the capacity of the residual cross sections.

For heavy wood members, ASCE/SFPE 29-99[56] provides analytical methods for calculating the fire resistance time (t) of beams and columns. The equations typically include load factor (z), initial dimensions of the section (b,d), and a constant (γ) with the units min/mm or min/in.

An example for beams exposed to fire on four sides is given in Equation 21.

$$t = \gamma z b \left[4 - 2\left(\frac{b}{d}\right)\right] \tag{21}$$

ASCE/SFPE 29-99[56] also presents values of fire resistance for various components of light frame wood construction. The additive method of calculation is proposed, which simply means adding together the fire resistance times assigned to each component as given in the code. For a stud wall, for example, the fire resistance time is equal to the total of all of the membrane elements on the fire exposed face plus the fire resistance time of the stud framing elements; the membrane on the unexposed face is ignored in the calculation.

Assessing Wood Connections in Fire

The collapse of traditional wood connections in fire scenarios is preceded by distinctive cracking and hissing noises due to the stresses in the wood. Visible deflections also become apparent before collapse, providing the fire services with notification that collapse is imminent.

New construction techniques involving steel connectors such as bolts or steel plates mean that the traditional bending and compressive forces in the wood joints have been largely replaced by localized shear forces surrounding the steel connectors.

Shear failure occurs when the lining within the wood section becomes heated and begins to act like a supercooled liquid. This change occurs at relatively low temperatures (~120°C) and causes the shear strength of the wood to change. This shear failure poses a catastrophic collapse mechanism during a fire because no prior warning of collapse is given under these circumstances. This area of fire engineering is being investigated by a number of researchers.[85,86] For now, metal connectors should be protected.

CASE STUDY: Residential Development, England. The following case study shows the application of single element calculation methods for wood using BS 5268 at a residential development in England. A structural assessment was undertaken of the existing wood beams within an old mill in the United Kingdom being converted to apartments. The structure required 60 minutes fire resistance according to the UK Building Regulations.

At ambient design, the wood members were being retrofitted with two steel plates, one on each side of the full length of the beam to resist bending. The beams were 190 mm wide by 390 mm deep plus partially shielded by a fire-rated ceiling 110 mm through its depth. The method in BS 5268[80] was used, assuming a total amount of charring of 40 mm for 60 minutes of the standard fire.

As an initial calculation, the residual section capacity after this section loss due to charring was calculated (Figure 19.5.23), assuming no benefit of the steel plates. This was done to determine if the steel plates might be left unprotected. The area of beam above the ceiling was assumed to not char because it is shielded from a fire. It was therefore assumed that the beam

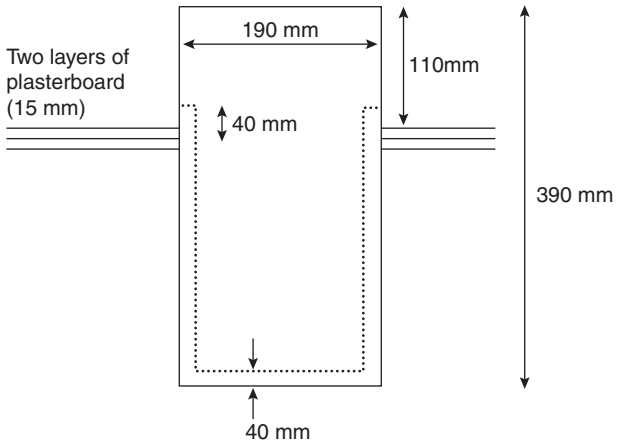


FIGURE 19.5.23 Residual Section After Char (Source: Arup)

would char on all three sides. The shear and bending capacity were checked, assuming the full strength of the residual cross section as permitted by BS 5268 [80].

From these assessments it was confirmed that the existing section would need additional provisions for 60 minutes fire resistance because the reduced section failed in bending. The following recommendations were therefore made:

- The wood section size to be extended to 430 mm deep from 390 mm, providing 40 mm sacrificial wood on the underside of the beam only (Figure 19.5.24)
- To provide two 280 mm × 12 mm S275 steel plates such that they extended the full depth of the exposed part of the beam, including the 40 mm additional depth proposed
- To protect the steel plates and bolt faces to a 60 minute applied fire protection, using a 550°C limiting temperature
- All connections exposed within the apartments to have 60 minutes applied fire protection because they are steel

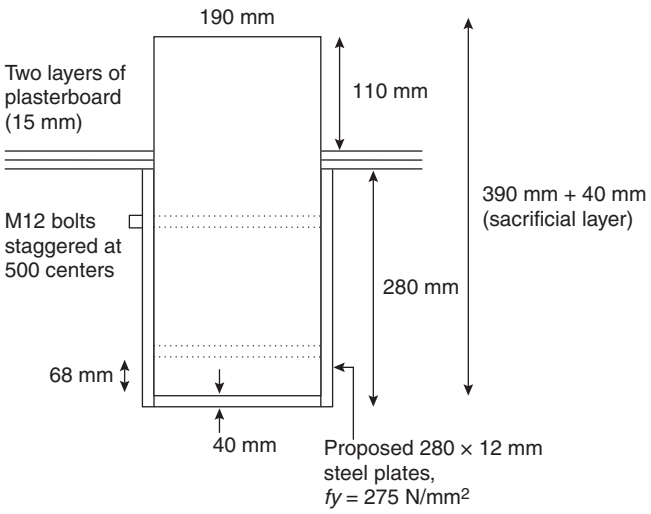


FIGURE 19.5.24 New Proposed Design Solution (Source: Arup)

The capacity of the new proposed section was shown to be adequate.

APPLICATION OF SINGLE STRUCTURAL ELEMENT ANALYSIS TO ALUMINUM

The sole design guidance available for the fire design of aluminum is Eurocode 9, Part 1.2, published in 2000.[87] In general the methods and principles are the same as for steel and the code looks very similar to EC3-1-2. Specific material properties (thermal and mechanical) at elevated temperatures are included.

USE OF ADVANCED ANALYSIS IN GLOBAL STRUCTURAL RESPONSE TO FIRE

Advanced Analysis Techniques

The current state of the art for structural fire assessments is to use advanced analysis techniques (Figure 19.5.25). These allow designers to quantify the global and local structural mechanisms throughout the duration of a fire. Therefore the stability of the structure in a severe fire can be determined, along with the quantification of the compartmentation response.

Such analysis can be used to assess a cold temperature structural design in specific fire events to determine if there are any particular areas of strength or, more importantly, weakness in the fire limit state. Fire-related responses are very different from any other form of cold temperature structural design concerns. So this form of analysis can prove a very useful tool to allow economical enhancements to be made to the areas of the structure underperforming in fire. For example, perhaps increasing the bottom flange thickness of a long span cellular beam is a more robust design measure in fire than applying thin-film intumescent paint.

Advanced analysis techniques also allow the development of refined passive fire protection strategies such that, in the case of steel structures, applied passive fire protection is proposed and installed in areas of the structure that require it, rather than providing "blanket" coverage, with its associated ongoing maintenance concerns throughout the lifetime of a structure. Of particular use is the ability, based on advanced analysis techniques, to quantify if compartmentation is being maintained, particularly at areas of concern, such as at egress stairs or fire fighter enclosures.

Advanced analysis models have undergone substantial validation for steel construction forms. Greater full-scale validation tests are now needed for other construction forms. Real-fire experience such as the Torre Windsor* in Madrid, Spain, on Feb-

*On the evening of Saturday, February 12, 2005, a fire broke out in the 32 story Windsor Tower, one of the tallest buildings in Madrid's commercial and banking center. The unsprinklered building had a concrete central core and a typical floor slab construction reinforced by bidirectional ribbed slabs spanning onto composite beams. Fire spread from the 21st floor, causing collapse of floors above the 17th, with significant deformation but no collapse of floors below the 17th.

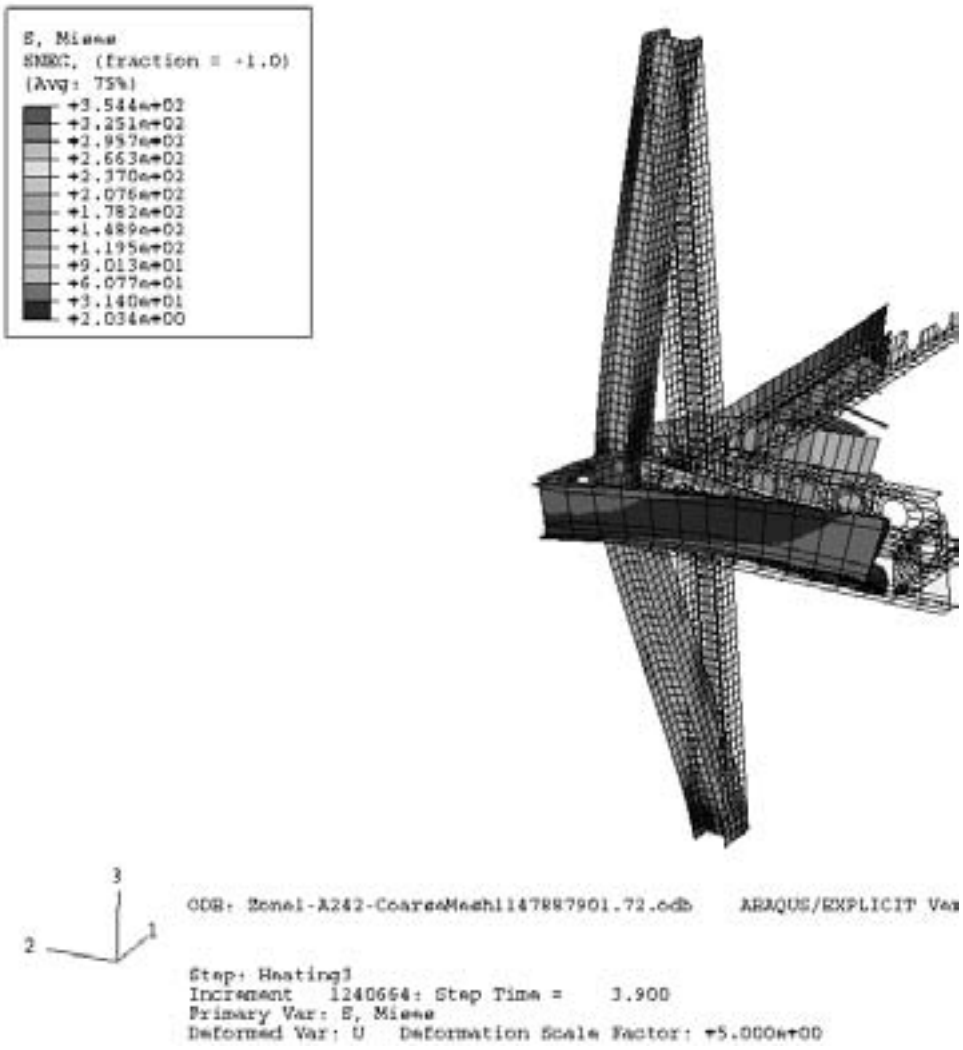


FIGURE 19.5.25 Example of Column Lateral Displacement from Advanced Analysis (Source: Arup)

ruary 12, 2005,[61] will provide substantial information on real performance of concrete structures. But a specific program of validation would be of great benefit for concrete, timber, and the increasingly popular long-span cellular beam construction forms.

This section addresses existing design methods, as well as a methodology for applying advanced finite element analysis techniques to real building design. This four-step technical process must always be accompanied by close consultation with the authorities having jurisdiction, and any other primary stakeholders, to ensure its real value is brought to a design.

Advanced analysis of steel/composite steel frames in fire was initiated in 2000. The Cardington experiments[6] and finite element modeling of the tests that followed[88–90] resulted in a number of design approaches for composite steel frame construction, taking advantage of tensile membrane action during high deflections in a fire. Two approaches are available: (1) design methods based on analytical methods derived from the Cardington data or (2) advanced thermomechanical analysis of the full structure using finite element analysis.

Analytical Methods to Quantify Tensile Membrane Action in Fire

In 2000, the Steel Construction Institute (SCI) in the United Kingdom produced relatively simple design guidance[91] based on work carried out by Bailey et al.,[92] as well as observations of the Cardington frame fire tests and similar building fire tests carried out in Australia and Europe. The guide is designed to allow secondary beams in composite steel-framed structures to be left unprotected, while achieving code-recommended fire resistances by capturing the strength enhancement of the composite slab in tensile membrane action. This occurs due to the high deflections in the slab during a fire.

Recommendations given in the new guide are restricted to structures that are similar to the Cardington eight-story

composite steel frame—that is, nonsway frames with composite steel decks. The slab should comprise steel decking, reinforcing mesh, and normal-weight or lightweight concrete. The profile of the slab can be trapezoidal or re-entrant. The floor beams should act compositely (including the edge beams) and be designed to BS 5950 Part 3 or EC 4.[70] This method, therefore, does not apply to fabricated beams or beams with large openings, precast concrete slabs, or slim-floor construction. Slim-floor construction is a proprietary product in the United Kingdom where the beams are partially embedded in the depth of the concrete slab to achieve fire resistance with reduced passive fire protection on the steel.

The design method, derived from the principles of yield line theory for slabs, is simplified into a set of look-up tables that state whether a particular design will pass or fail given a certain combination of variables of beam span, reinforcement mesh, slab profile, and load. The design data assume the standard fire exposure (Figure 19.5.26) only. However, the full theoretical model[92] can be implemented with natural fire curves if created specially on a spreadsheet-based tool.

The maximum fire resistance that can be achieved using the guide is restricted to 60 minutes. Rules and guidelines for maximum spans, layout configurations, allowable deflections, and construction details are based on providing a final solution that brings no increased threat to the life safety of the occupants or fire fighters. Property protection is not addressed by U.K. legislation.

Excessive deflections that can occur in a fire should, therefore, be limited to prevent compartmentation breach. This ensures that the fire would not be able to spread horizontally or vertically as a result of deflections imposed by the heating regime. The guidance for the detailing of the slab to achieve adequate tensile membrane action in the fire limit state is, therefore, on this basis.

The method requires the building floor to be split into square or rectangular design zones (see example in Figure 19.5.27) or panels with each panel incorporating a number of unprotected beams surrounded by a square or rectangle of fully protected beams. The spans are restricted to 9 m. The edges of each panel must be vertically supported for the duration of the fire. Catenary action of the beams is conservatively ignored, although a revised version has recently been published that includes catenary of the beams. As a result of the slab membrane forces, beams at the boundaries of the floor design zones receive additional loading due to forces transferred from the slab, thus increasing the load ratio. This increase is addressed in the final design guidance provided.

Failure is defined in terms of a maximum allowable vertical displacement (L/30) and limits mechanical strains by assuming a maximum allowable stress for the reinforcement of $0.5f_y$. The equation for allowable vertical displacements should always give conservative results because of the various assumptions made and the fact that there was no failure observed in any of the Cardington tests.[6]

The enhancement in load-carrying capacity as a result of tensile membrane action is restricted by this limit. It is impossible to know how overconservative this method is because failure was not observed in the tests to validate the failure criterion assumed by the analytical model. Global failure can be modeled by finite element analysis; therefore, overconservatism can be avoided using a finite element approach. The method also includes options to enhance the strength of the slab if the load capacity is determined to be less than the applied load in the fire limit state, for instance, by increasing the mesh size or slab depth.

In 2005 the method was extended to include orthotropic reinforcement, recognizing that structural bays are sometimes longer in one direction and therefore require an orthotropic reinforcement mesh. The new method also includes catenary action of the steel beams, which was conservatively ignored in the earlier approach.

Usmani and Cameron[93] also developed a new concept for determining the limit capacity of rectangular reinforced concrete slab panels subjected to fire in tensile membrane action. In the context of performance-based design, this additional capacity of composite decks or reinforced concrete slabs can be exploited for providing structural stability in fire, given that a quantitative estimate of this capacity can be reliably made.

The difference between Usmani and Cameron's approach compared with the Bailey method is that the deflected shape of

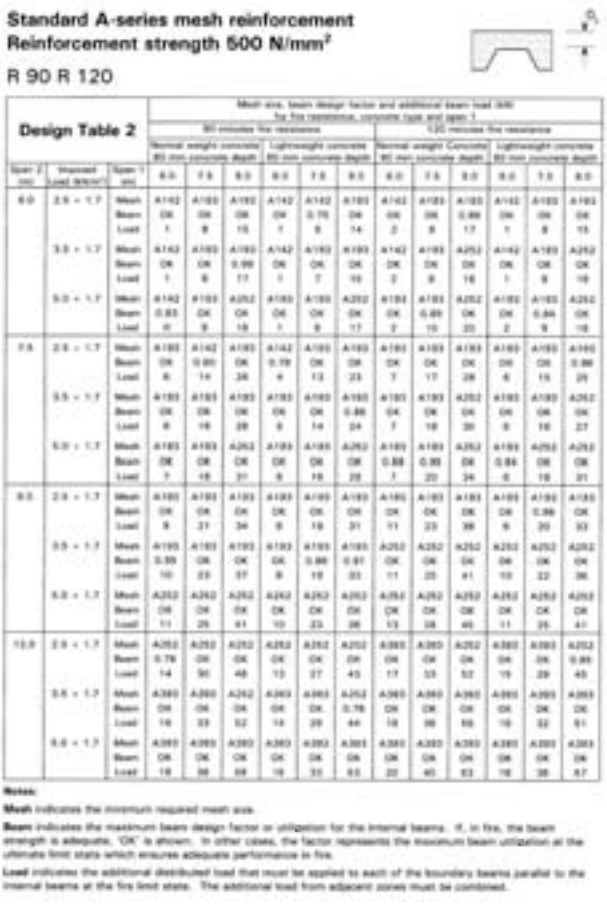
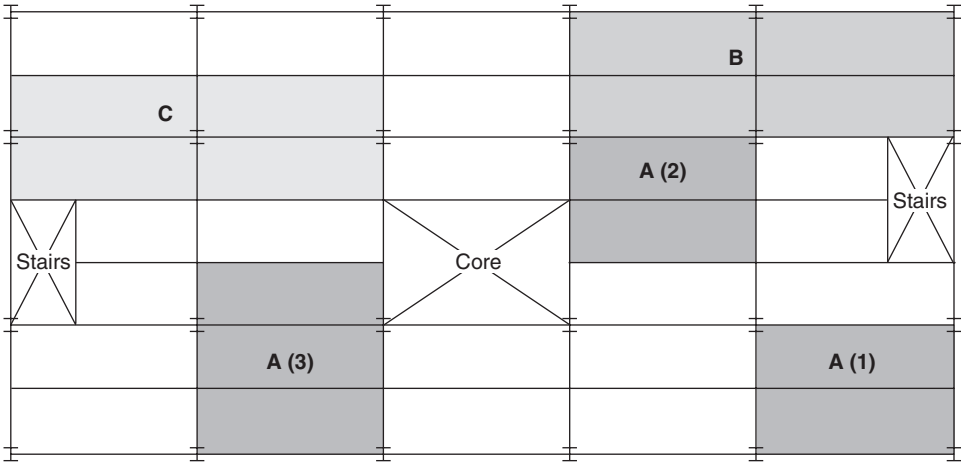

Standard A-series mesh reinforcement
Reinforcement strength 500 N/mm²
R 90 R 120
Design Table 2

FIGURE 19.5.26 Example of a Look-Up Table for the Bailey Method (Courtesy of Steel Construction Institute, Silwood Park, Ascot, SL5 7QN, United Kingdom)



Key to figure

A: Permitted area within scope of the guide
B: Permitted area outside scope of the guide
C: Not permitted—contains columns

FIGURE 19.5.27 Example of a Suitable Structural Zone for the Bailey Method (Courtesy of Steel Construction Institute, Silwood Park, Ascot, SL5 7QN, United Kingdom)

the reinforced concrete slab is estimated using a cubic function before a calculation of tensile membrane effects is carried out. Usmani and Cameron[93] propose a three-stage process. First, the temperature distribution over the depth of the slab is estimated for a given fire scenario. Then, the deflected shape of the reinforced concrete slab and its membrane stress state is determined using an analytical method. Finally, an energy-based method is used to determine the maximum load that the slab could carry based on the geometric form and stress state determined in the previous steps. Failure is defined as a rupture of the reinforcing mesh at a given mechanical strain. There is no limit placed on deflection.

Heavy Engineering Research Association (HERA), a nonprofit research organization dedicated to the needs of the metals-based industries in New Zealand, has also published a design procedure to capture tensile membrane action in fire.[94] The design approach predicts the strength re-enhancement required from tensile membrane action to support the load based on work by Wang.[95] As tensile membrane action is a function of the maximum deflection of the slab and the extent of strength re-enhancement required is known, this is used to determine the slab deflection at elevated temperatures associated with the required level of strength reenhancement. Limits are applied to prevent undesirable failure of the slab and secondary beams—for example, fracture of the reinforcement. The guide considers all aspects of the frame, including pulling in of the columns when the slab is at high deflections in tensile membrane action, which is not addressed by Bailey[92] or Usmani and Cameron.[93]

All of the analytical methods presented require primary and edge beams to be protected. The protection reduces the edge/primary beam deflections and will generally allow the frame to survive longer in a fire. If the edge beams are unprotected, the relative displacement of the floor slab between the outside edges and the middle of the compartment would be smaller, reducing the development of tensile membrane action. It is important to note, however, that in order to address long-span floor systems and the stability of the columns, a finite element approach is required.

CASE STUDY: No. 1 Bradford Interchange, United Kingdom. The following case study uses the Bailey method to optimize the passive fire protection layout at No. 1 Bradford Interchange, United Kingdom.[96] Two design options were calculated, both of which allow unprotected secondary steel beams but consider different solutions for the slab profile and size of mesh reinforcement.

The office use building is four stories high. The structure is a composite steel frame with two configurations for the structural bays. The first is a 9 m × 7.5 m bay. Secondary beams are 9 m with secondary beam centers at 3.75 m. The second configuration is a 6 m × 7.5 m bay. Secondary beams are 6 m with secondary beam centers at 3.75 m. A typical structural bay is illustrated in Figure 19.5.28.

The structural bays described in Figure 19.5.27 are appropriate floor design zones for assessment using Bailey's method because they are rectangular and bounded by beams on all sides. Each zone contains beams spanning in one direction only. The columns are on the boundary of the zone—not within the zone—and all the beams connected to the columns are protected to 60 minutes fire resistance.

The calculations were carried out using a spreadsheet based on the original theory by Bailey,[92] rather than the tabulated data presented in the SCI guide.[91] The results were compared with the look-up tables in the SCI guide for consistency; although the

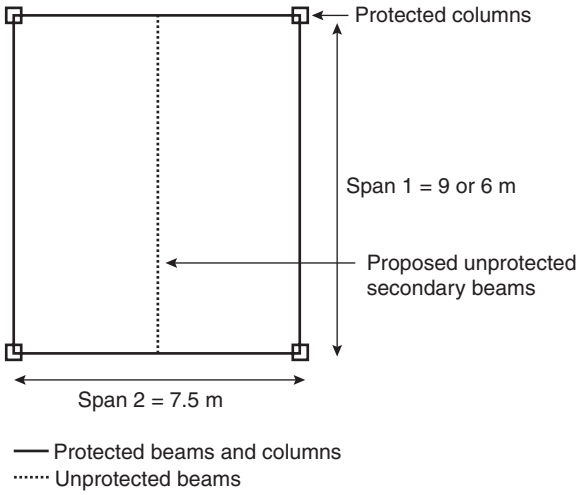


FIGURE 19.5.28 Schematic Plan View of a Structural Bay at Bradford Interchange (Source: Arup)

look-up tables are considered to be more conservative because the results are rounded up, they compared well.

The results of the design calculations for the 9 m span bay are given in Table 19.5.15. The use of re-entrant deck provides significantly better fire resistance because the ribs of the profile deck are bigger than in a trapezoidal deck, and therefore the reinforcement remains cooler. The reinforcing mesh required in a re-entrant deck slab is therefore less compared with the same design assuming a trapezoidal deck.

TABLE 19.5.15 Design options 9 m × 7.5 m Bays

	Option 1	*Option 2*
Span 1 (m)	9	9
Span 2 (m)	7.5	7.5
Unfactored dead load (kPa)	4	4
Unfactored live load (kPa)	4 + 1 = 5	4 + 1 = 5
Secondary beam spacing (m)	3.75	3.75
Mesh size	A393	A252
Slab profile	Trapezoid	Re-entrant
Reinforcement depth* (mm)	40–45	65
Concrete strength, f_{cu} (N/mm^2)	30	30
Concrete type	NWC	NWC
Secondary beam moment capacity (kNm)	640	640
Load ratio on edge beams parallel to secondary beams	0.33	0.32
Limiting temperature (Table 5 BS 5950 Part 8)	725	725
Resize edge beams for additional load?	No	No
Applied load at the fire limit state (kPa)	8	8
Capacity (kPa)	9.12	8.08
Capacity-load (kPa)	1.12	0.08

*The depth to reinforcement is measured from the top surface of the slab.
Source: Arup.

The location of the reinforcing mesh in the depth of the slab is critical to the design. Option 1 assumes a trapezoid deck with A393 mesh (a square mesh with 10 mm diameter bars at 200 mm pitch, providing an area of reinforcement equal to 393 mm^2/m); option 2 considers a re-entrant deck with A252 mesh (a square mesh with 8 mm diameter bars at 200 mm pitch, providing an area of reinforcement equal to 252 mm^2/m).

The additional load at the fire limit state on the edge beams parallel to the unprotected secondary beams is listed in Table 19.5.15 as a load ratio. The corresponding critical temperature in BS 5950, Part 8[42] is also listed. Where the critical temperature is less than 620°C (the normal assessment temperature for fire protection materials for beams), the beam must then be resized to incorporate a higher load-carrying capacity. In this case study, the critical temperatures for each beam size in each design option are all greater than 620°C; therefore, the beams did not need to be resized.

The method relies on good structural detailing; therefore, the following was written on the construction drawings:

1. All the steel beams should be composite with the slab through the use of shear studs.
2. The reinforcing mesh should be properly lapped and anchored in all areas of the slab as required for ambient design.
3. The location of the reinforcing mesh in the depth of the slab is critical to the design and should be marked on the construction drawings. For a trapezoid deck with A393 mesh, it should be 40 mm to 45 mm from the top surface of the slab. For a re-entrant deck with A252 mesh, it should be 65 mm from the top surface of the slab.
4. The mesh reinforcement should conform to the ductility limits of BS 4482[97] and BS EN 10080[98] for type B reinforcement. These limits are consistent with 12 percent elongation at failure.
5. Any cellular beams, including the beams immediately adjacent in the bay, are to be fire rated (i.e., no fire engineering).
6. All beams above a compartment wall (parallel or crossing the wall) should be fire protected to at least the same fire resistance standard as the compartment wall.

The use of Bailey's design method shows that unprotected steel secondary beams at Bradford Interchange were acceptable under the U.K. Building Regulations, which address life safety, while achieving structural stability for a 60 minute rating.

Design Methods Based on Finite Element Analysis

As a consequence of the Cardington Frame fire tests[6] and the savings that can be brought to a steel design project by using global structural analysis, composite steel frame structures are the most common construction form modeled using finite element techniques by design consultants. Performance-based

codes in the United Kingdom, Europe, Hong Kong, Australia, and New Zealand state that design considering credible design fires, thermal heat transfer, and structural analysis using advanced finite element methods is an acceptable approach to fire design. There is currently no such guidance document in the United States. However, organizations like SFPE, NFPA, NIST, and AISC are gradually funding research and drafting documents that will assist engineers in carrying out structural fire engineering using finite element analysis in the future. It is expected that this process will take a number of years to enter the design domain.

Since the collapse of the World Trade Center towers, the finite element analysis technique is being increasingly used as a design tool to bring greater robustness to the response of a structure to fire. This is the only method that allows the quantification of the strengths and weaknesses in a cold temperature structural design to be quantified and identified; it can provide invaluable information to the structural team to allow changes to be made to enhance the performance of the cold temperature structure in the fire limit state. Currently almost no data exist for concrete or wood structures at a level that exists for steel structures. Hence finite element methods remain underutilized with these forms of construction.

In general, structural fire design codes will not provide guidance on how to perform an advanced structural fire analysis using finite element methods. They do, however, set out the principles that should be followed. They tend to state that the structural performance of steel may be assessed using calculation models that consider the fire exposure, thermal response, and structural response, provided that the models are based on acknowledged principles and assumptions of the theory of heat transfer and structural mechanics. Further, they stipulate that the governing elevated temperature response of thermal expansion and geometric nonlinearity have to be included in a structural model.

When using finite element analysis, a four-step process is recommended:[99] (1) determine credible design fires, (2) calculate the heat transfer from these fires to the elements in a representative structural model, (3) quantify the mechanical response of these elements for the duration of the fire, and (4) determine strengths and weaknesses in the global response of the structure when considering stability and compartmentation.

Typically, stability is deemed to be maintained once the columns continue to carry their design load for the duration of the fire and runaway failure of the beams or slab does not occur.[99] Note that an alternative view to this is to simply design to prevent deflections beyond that allowed in the standard fire test (L/20 as an example in the United Kingdom[10]).

For compartmentation, an assessment of strain in the slab and adjacent to protected escape stairs or, in countries such as the United Kingdom, adjacent to fire-fighting cores is necessary to ensure severe cracking is not causing breach of integrity or insulation.

Various methods, such as Eurocode 1, Part 1.2[22] or those described in the *SFPE Handbook of Fire Protection Engineering,* exist to determine design fires. However, their limitation, due to the small-scale nature of the testing carried out, means realistic compartment sizes as used in real buildings have not yet been validated. For empirical methods, this remains a concern. It is essential that a factor of safety is introduced in the design fire to overcome this concern. Methods based on a theoretical heat-balance approach are, therefore, preferred for adoption in compartment sizes that exceed the limits of empirical methods (i.e., the parametric equation in the Eurocode, derived from specific experimental data sets from Franssen,[100] NFSC1,[15] and NFSC2[101]).

An alternative approach is to assume the heating regime follows the standard temperature-time relationship as would be utilized in a furnace. However, when this is used, no cooling phase is incorporated, and so the specific structural response in this phase is then ignored. This can in some cases result in a nonconservative design, especially of connections that can fail in cooling as contracting beams pull on the connections.

One example of a methodology when using a finite element method is outlined in Eurocode 3. It gives similar performance-based objectives to other codes but also specific details about what should be included in advanced calculation methods. For example, when conducting a calculation of mechanical response, it states the following requirements, among others:

- The effects of thermally induced strains and stresses, both due to temperature rise and due to temperature differentials, should be considered.
- The deformations at ultimate limit state implied by the calculation method should be limited to ensure that compatibility is maintained between all parts of the structure.
- The design should take into account the ultimate limit state beyond which the calculated deformations of the structure would cause failure due to the loss of adequate support to one of the members.

Eurocode 3 also explicitly asks for validation of the computer model being used for the assessment, with whole frame fire tests.

In the United Kingdom, a new guide is being produced by the Institute of Structural Engineers that will identify the best practice for creating and using finite element models, plus suggested failure criteria to assess structural and compartmentation response in fire.

In Australia, the performance-based design framework permits structural fire engineering analysis using advanced modeling techniques. This is as a result of a series of full-scale fire tests to determine which elements were critical to the stability of the Williams Street building in Melbourne, Australia, as well as those elements critical for ensuring adequate protection during egress and fire fighting—for example, detailing of connections at protected cores.[102]

In Hong Kong and China, the finite element approach is not specifically codified, but is possible via performance-based options for design in the building codes there. However, currently the approach is most widely used in the United Kingdom.

In the United States, performance-based design is also permitted as an alternate means to the prescriptive requirements of the building codes; therefore, a finite element approach is permitted if the basis for the design can be agreed with the approving authorities. The finite element approach is not codified in the United States.

An alternative approach to this quantitative method for assessing structural response to fire is to use a risk-based method, such as outlined by Fontana. The main objective of Fontana's work is to develop a fire risk assessment framework that takes into account both risks associated with property damage and risks associated with injuries and fatalities. A generic model is developed, taking into account fire relevant parameters such as fire load, ventilation, and so on. The causal interrelations are modeled with Bayesian networks. The generic model is used for the calibration of already existing fire risk assessment frameworks—for example, the Swiss SIA Documentation 81.[103]

CASE STUDY: Kings Place Building, London, England. The following case study outlines the key steps and major considerations for a whole frame analysis using finite element analysis. The Kings Place building in London, England, is a composite steel-framed structure with eight stories above ground and three basement levels. The composite floors are constructed using 130 mm deep composite slabs with profiled steel decking attached by shear connectors to steel beams with circular web penetrations. The columns are universal steel column sections with two changes in size (at floor 2 and floor 6). Steel beam spans are 9 m or 12 m.

A finite element analysis of the structure was proposed in order to determine the response of the structure to fire. The aim of this nonlinear finite element analysis was to determine an optimized fireproofing strategy, along with an understanding of the strengths and weaknesses in the cold temperature design. This would allow specific advice to be determined for the structural team to incorporate enhancements, if required, specifically for the fire limit state.

Specific aims of the nonlinear analysis were to investigate the required fire rating of the structural elements and to determine if secondary steel beams could be left unprotected when only the columns and primary structure (edge beams and beams connected to columns) are protected. Based on the life safety requirements of the building regulations in the United Kingdom, acceptance criteria for the data produced by the analysis were structural stability (columns maintain their load-carrying capacity throughout the fire duration and no runaway deflections in beams or floors), compartment integrity, and compartment insulation (assessment of strain in the slab and adjacent to fire-rated enclosures to prevent any cracking).

For addressing the fire ratings, all structures forming the fire-fighting shafts were considered to remain at the standard 120 minutes. The time-equivalent method, as defined in BSEN 1991-1-2,[22] was then used to determine an overall building rating, utilizing risk factors that address only compartment size, occupancy type, and sprinkler provision. This resulted in an equivalent fire resistance rating of 90 minutes, based on calculation for an assumed compartment area of 4081 m², with a compartment height of 3.68 m, and percentage glazing failure of 100 percent. A sensitivity study considering 100 percent or 50 percent of the glazing breaking as well as the influence of reducing the floor area of the compartment involved in the fire was studied to obtain the longest period of fire resistance. This rating was utilized as the basis of the first model run, when any protected elements proposed that did not form part of the fire-fighting shafts and all compartment floors were assumed to be protected to a 90 minute standard. Should the finite element analysis reveal any concerns with this rating assumption, alterations could then be made. This is necessary as time-equivalent methods do not incorporate any form of structural response; they are purely simple methods based on possible heating regimes in a compartment only.

As a first step in the structural fire analysis, an assessment of credible design fires was necessary. This resulted in two design fires, quantified using the parametric equation in BS EN 1991-1-2:[22]

- *Short/hot fire.* Assuming 100 percent glazing failure to allow ventilation in the postflashover fire state, with a flashover fire acting over the whole floor plate. The peak temperature is about 1200°C.
- *Standard fire.* A long/cool fire relative to the parametric temperature-time curve described above, as specified in BS 476.[10] This was at the request of the approving authorities.

A short/hot fire, which results when the fire is well ventilated, was considered because of its high peak temperatures and its short duration, which together are known to induce large thermal gradients within structural elements, and also because it includes a cooling phase. The standard fire was chosen to investigate the effects of a longer-lasting fire, with a constant increase in temperature—that is, no cooling phase. All other credible postflashover fire scenarios, based on possible ventilation provision to the specific compartment dimensions and boundaries, were considered to fall within the boundaries of the two cases adopted.

The next step was to calculate the heat transfer from these fires to the structural elements in the proposed representative structural model. Different approaches were followed with regard to the concrete and steel materials. The heat transfer for the concrete slab was modeled using a 1D heat transfer model in ABAQUS 6.5.4.[104] The slab is modeled as a flat slab of equivalent thickness, although ribs in the dovetail slab are ignored. The same assumption is used in the structural model. This reflects the approach given in Section 4.4 of EC 4, Part 1.2.[70] Input data to the heat transfer model complied with the recommendations for siliceous concrete material properties in EC 2.[64] Moisture content in the concrete was ignored.

The heat transfer calculations for the steelwork were conducted using the lumped mass heat transfer model in EC 1, Part 1.2[22] and EC 3, Part 1.2[41] for the unprotected steel beams and protected columns. Material properties for the protection material were provided by the manufacturer and for the steel the values of conductivity, specific heat, and density in EC3, Part 1.2, were assumed.

In order to create a representative structural model, that is, a model with enough elements within it that it represented the full building, various modeling assumptions were made. When considering a single-story fire, the third floor was deemed to be the worst-case floor scenario in the building due to the highest column load ratio occurring on this floor. Therefore, it was con-

sidered to be representative of the entire floor plate on any story from Level 1 to Level 8 (Figure 19.5.29).

Worst-case boundary conditions were assumed for the structural models of each zone (see Figure 19.5.29). This means the resulting structural fire responses observed are on the conservative side, as less reliance is placed on the overall floor continuity available in the model.

The boundary conditions assumed for Zone 1 makes the portion of the building weaker with respect to the real case. The edge beam condition on the north side does not take advantage of continuity of the floor plate. Furthermore, the two symmetry conditions discount the model from the beneficiary effect of the concrete core and the continuity of the floor plate on the south side.

The boundary conditions of Zone 2 make the model act as an infinitely long strip of structural bays. In reality it is six bays long, and three of these are connected to structure that wraps around the core.

Zone 3 does not have boundary conditions. It has been considered as a structure itself, neglecting the decks that connect it to the rest of the building.

BS 5950-8[42] has been used to determine the factored design loads for the structural elements in the fire limit state. The factored gravity (1.0) and live load (0.5) were applied to the model throughout the analysis, using the applied loads provided by the structural engineers.

The materials adopted to represent the steel and concrete of the composite frame were taken from the appropriate Eurocodes (Table 19.5.16). Thermal expansion and full degradation of the stress-strain curves with temperature are allowed.

All connections were modeled in such way that they could not fail. For this reason the connection forces were checked at key stages in the fire to determine if the connection was being pulled in tension by the beam. (The protected steel-steel and steel-concrete core connections will therefore be designed on site to resist a tensile pull force of 60 kN when at a temperature achieved at 90 minutes of the standard fire, when protected.)

The software used to perform the finite element analyses (FEA) was ABAQUS.[104] The software is used throughout the world for stress, heat transfer, and other types of analysis in mechanical, structural, civil, and related engineering applications.

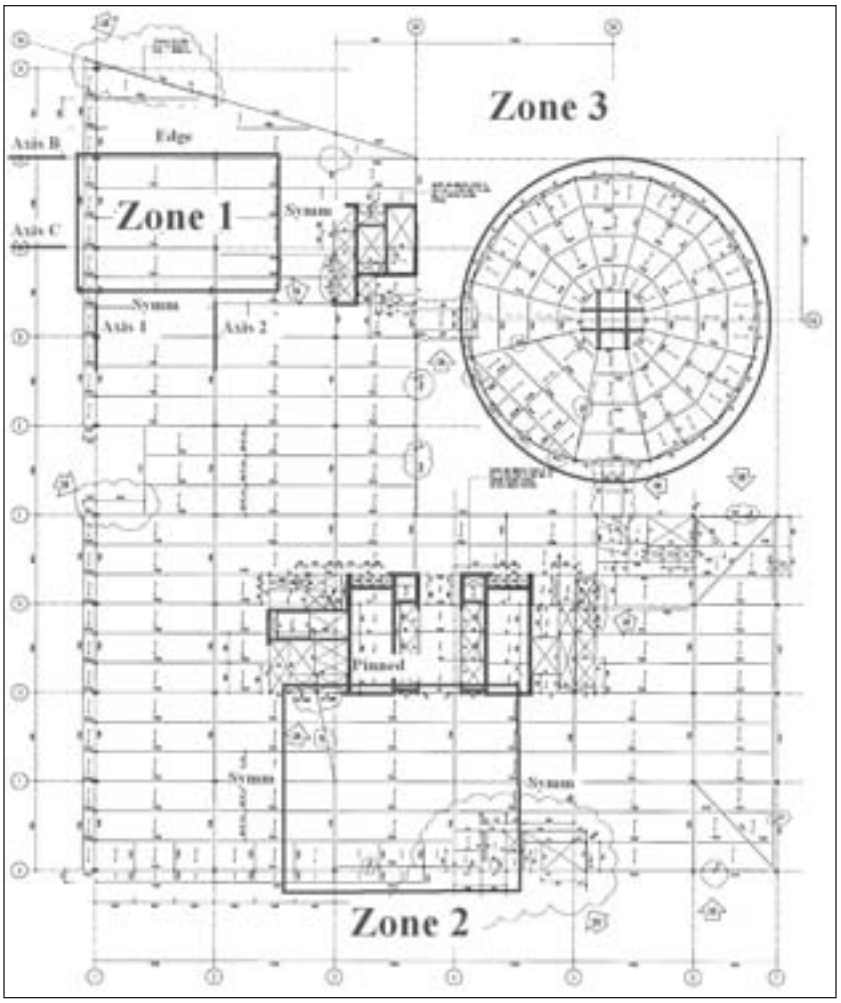


FIGURE 19.5.29 Third Floor Plan, Models Location, and Associated Boundary Conditions (Source: Arup)

TABLE 19.5.16 Material Properties

Material	*Grade*	*Model*
Steel (frame)	S355	Eurocode 3
Lightweight concrete (slab)	C35	Eurocode 2 with tensile strength equal to 5% of the compressive strength
Reinforcing mesh		A252, steel mat, 8 mm bars, spacing 200 mm

Source: Arup.

The code has been validated extensively for many engineering problems and in particular by University of Edinburgh[7] and British Steel (now CORUS)[5,6] to model composite steel and lightweight concrete structures in fire.

The performance of all the models under the effects of the short/hot fire was found to be acceptable; stability and compartmentation were maintained throughout the duration of the fire. For the standard fire, however, various issues with respect to the response arose, as described in the following sections.

The main differences between the two fires are the length of the heating phase, the maximum temperature, and the cooling phase. The standard fire does not have a cooling phase; therefore, the elements are heated up throughout the analysis, with a steep initial increase and a rather flat evolution for the rest of the time. Eventually, in the standard fire, the elements reach hotter temperatures than in the short/hot fire, and this results in larger deflections as a consequence of more thermal expansion and also weaker material strengths, therefore leading to reduced structural performance. This would also be true of a parametric fire with limited ventilation—for example, 25 percent glazing failure.

An important outcome of the study was the finding that the Zone 1 model failed when subjected to the standard fire. Structural failure is assumed because rapid downward vertical displacement of the columns was observed. After the initial downward movement due to the load given by the above floors, the columns began to elongate when heated. The displacement reached values of about 25 mm before inverting its trend. At about 80 minutes, all the columns showed vertical runaway with a rapid increase in the downward movement while the temperature was still rising (Figure 19.5.30).

The column capacity is undermined by the lateral movement of the elements at the floor level causing bending stresses and P-Delta moments. Due to large thermal elongation of the long-span beams connected to the columns, and consequently large displacements, the column elements were required to sustain loads and actions they were not designed for in cold temperature conditions. Additional stresses/strains, along with material degradation, therefore undermined the structural stability. The structural model was considered unsafe under the effects of fire, and therefore methods of increasing the robustness were investigated.

A number of options are available to increase the robustness of the structure, such as increasing the column size, increasing the strength of the slab by adding more reinforcement,

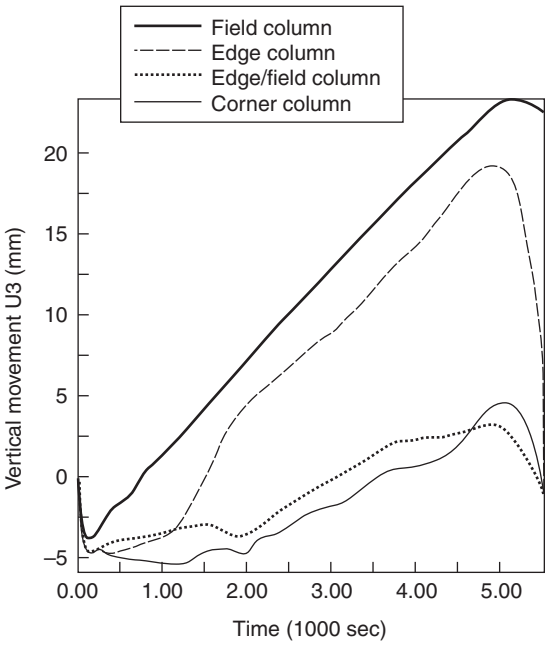


FIGURE 19.5.30 Vertical Displacement of Columns over Time During Standard Fire (Source: Arup)

keeping the 12 m span beams cooler with additional fire protection, or increasing their load-bearing capacity by increasing the member size. In this project the latter choice was adopted in order to reach the best performance/cost-effective solution. Therefore, the bottom flange of the 12 m span secondary protected beams connected to the columns was increased from 16 to 25 mm. This means less reliance on fire protection and greater reliance on the structural system itself. This is considered to be a more robust approach as it is not reliant on maintenance.

When the Zone 1 analysis was carried out to check that the improvements adopted in the model were significantly changing the response of the structure, it was determined that the change meant no column failure and therefore greater robustness in the building. Throughout the fire, the columns exhibited a steady elongation along with the increasing temperatures (Figure 19.5.31). No vertical runaway was recorded in this case, and therefore the columns can be expected to maintain their stability.

Figure 19.5.32 shows the deflection contour of the slab at the end of the fire. The maximum deflection is 1600 mm at the mid-span of the corner bay. The stability of the structure is maintained thanks to the tensile membrane action developing within each structural bay.

A thorough investigation was made with regard to the total strains exhibited by the model. The software itself does not model reinforcement rupture, and therefore identification of this failure mode had to be considered by plotting the plastic strains in the structure.

Due to the high value of deflection, relatively large total strains are observed across the protected secondary beams, axis

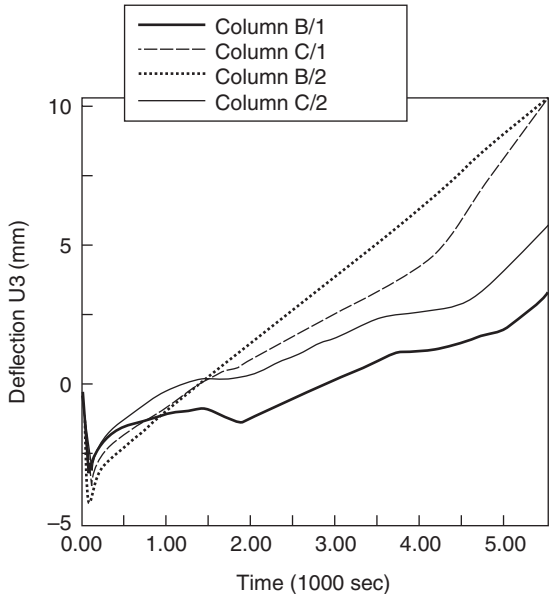


FIGURE 19.5.31 Vertical Displacement of the Column (Elongation) (Source: Arup)

C. The maximum observed strain is about 30 percent in the top of the slab and 25 percent in the reinforcement mesh (Figure 19.5.33).

It is assumed that these strains are likely to cause cracks at the top face of the composite slab. In addition, it is possible that the reinforcement may rupture locally over the support. To ensure stability is maintained, additional reinforcement was therefore proposed for the ribs of the dovetail profile over the protected primary beams.

For the Zone 2 model in the standard fire, there was generally better response than in Zone 1, mainly because Zone 1 represents the corner of the building and as such has two exterior edges, whereas Zone 2 represents an edge bay, which has more redundancies. However, as per the Zone 1 model, relatively large strains were observed at the core to slab interface. This has implications for compartmentation rather than stability. The connection between the concrete core and the dovetail slab was realized for this building using pull-out rebars that bond the core and the slab together. The concrete does not give continuity to the connection because it is poured in different stages, although a friction interaction might be assumed when the slab is heated and the edges are in close contact.

Given the aforementioned connection detail, the finite element model assumed a pinned connection between the concrete core and the slab. It is proposed that this assumption conservatively represents the connection at the early stages of the fire and better represents the behavior of the structure later in the analysis when the concrete slab may be cracked.

As highlighted in Figure 19.5.34, large strains up to a magnitude of 20 percent (neglecting the strains affected by the boundary conditions at the edges of the model) evolved at the concrete core, on the bottom side of the slab.

Initially, the underside of the slab will expand due to thermal elongation. Thus, high compressive strains will rise at the boundary with the slab pushing against the concrete core. Later, when the structural bays begin to deflect more, the edge of the slab will rotate significantly and concrete crushing is likely to occur on the lower portion and significant tension can be expected to develop in the rebars (Figure 19.5.35).

Compartmentation could be maintained due to geometrical rotation of the section, which is expected to tighten the lowermost portion of the concrete slab to the core. In addition, the rise in temperature throughout the extent of the fire will cause

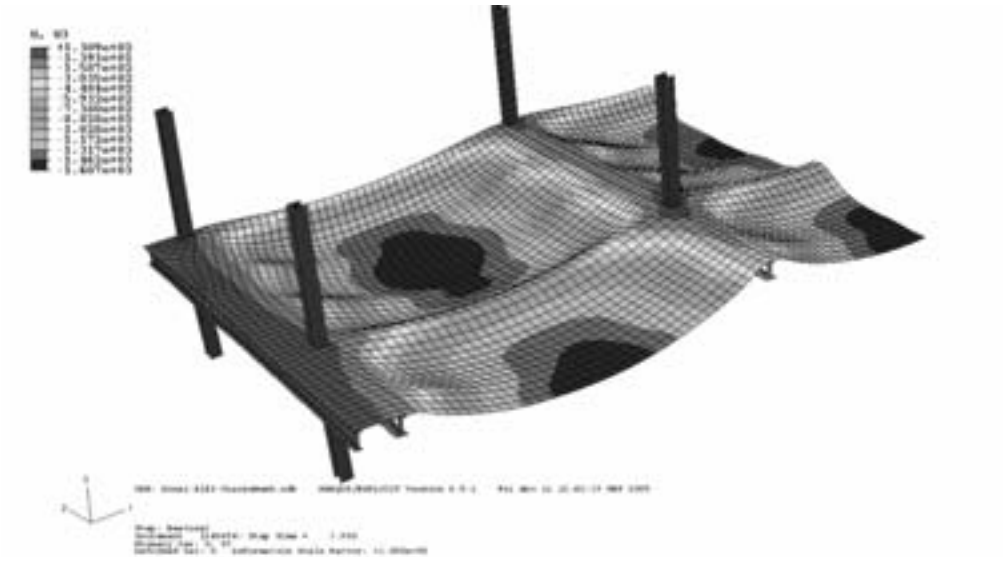


FIGURE 19.5.32 Deflection Contour at the End of the Fire (Source: Arup)

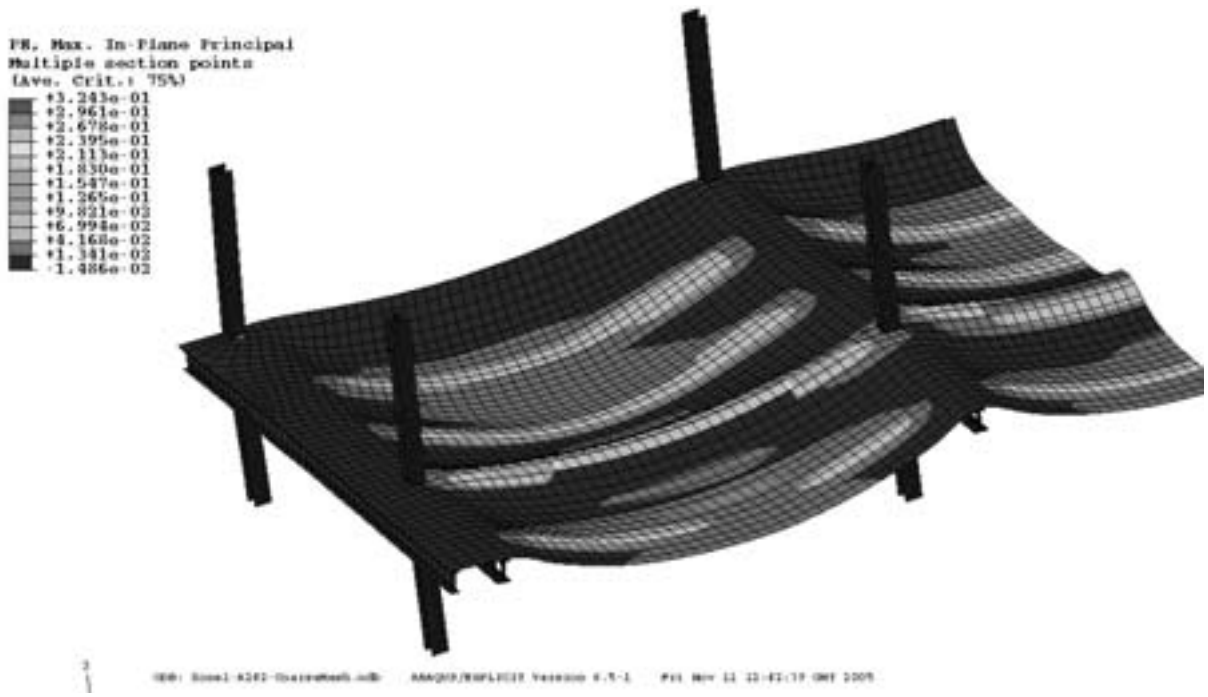


FIGURE 19.5.33 Maximum In-Plane Plastic Strains in the Reinforcement Mesh, Shorter Span Direction (Source: Arup)

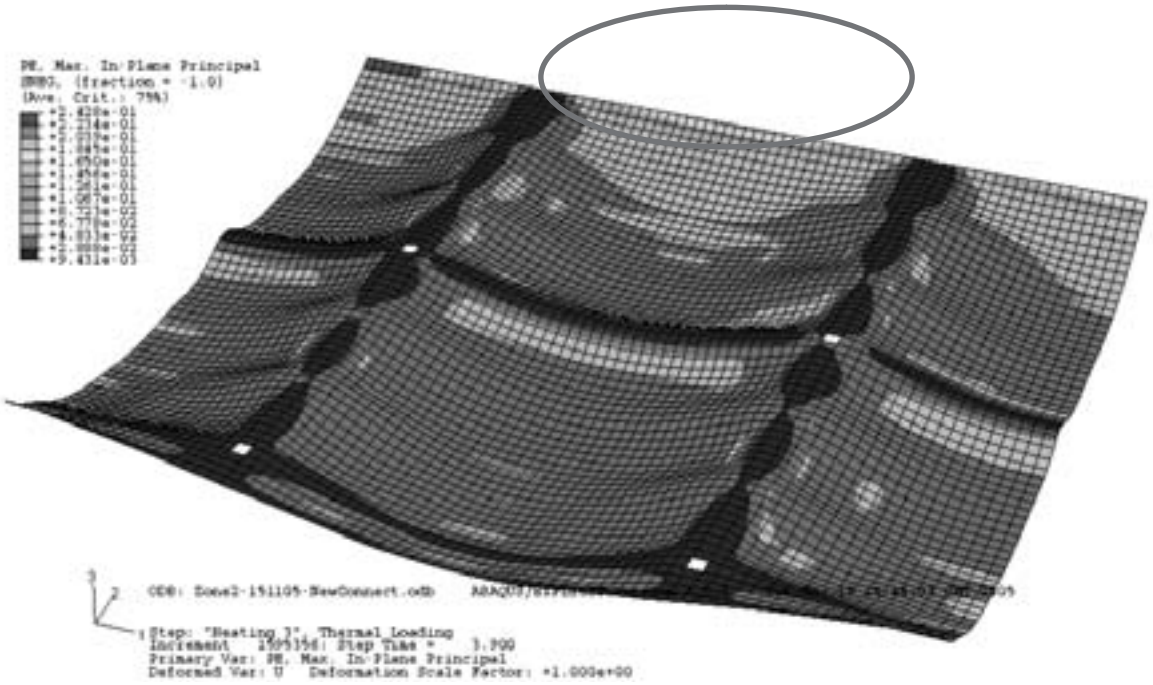


FIGURE 19.5.34 Maximum Resulting Plastic Strain on the Underside of the Slab at the End of the Fire (Source: Arup)

large elongation in the concrete, which will eventually help in closing the gap.

This interpretation of the matter is merely based on an understanding of the behavior of materials at high temperature and the likely structural response of an assembly in fire. Many factors, such as friction, concrete to steel bond, rebar anchorage, and temperature distribution are involved. Hence, a clear understanding of the phenomenon is not straightforward and to

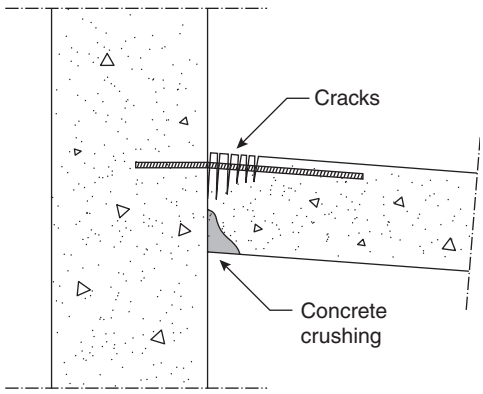


FIGURE 19.5.35 Likely Deformed Shape of the Structure at the Core Connection (Source: Arup)

obtain a more accurate understanding, specific detailed research is required. Detailing of connections and interfaces is becoming more and more important as the understanding of structures in fire evolves. It is important to note that this form of response is also true of fully protected structures.

Whether the current situation will cause a gap at the core to slab interface is highly debatable. On this subject, the approving authority has put forward a request for making further provisions to ensure compartmentation. To limit the effect of strains, a steel angle or similar vertical support was requested at the concrete core-to-floor interface to allow the slab to slide over the angle during a fire (Figure 19.5.36). The angle is fire protected and the length of the horizontal flange is at least 70 mm to accommodate an estimated horizontal displacement of the slab of 60 mm.

The analysis presented here was used to determine whether the structure could withstand an agreed set of credible design fires when secondary steel beams are left unprotected. This approach allowed a full quantification of the structural response of the building to fire.

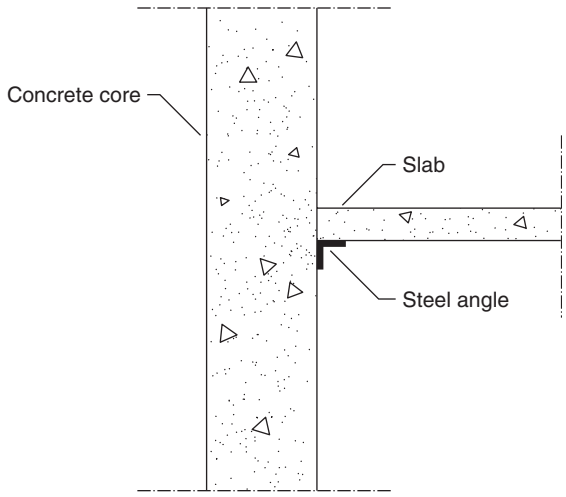


FIGURE 19.5.36 Detail of the Connection Between Slab and Concrete Core (Source: Arup)

The Kings Place case study has given rise to some important issues when considering stability and compartmentation of composite steel-framed buildings with long-span cellular beams. Leaving the secondary beams unprotected relies on secondary load-bearing mechanisms exhibited by the composite floor at the fire limit state. Minor mitigation measures were adopted to improve the structural performance in lieu of fire protection, including adding reinforcement locally and increasing the thickness of the lower flange of critical primary beams. Both are considered more robust than applied passive fire protection.

To improve compartmentation, a protected steel angle was proposed for the core walls to provide vertical support to the slab and allow the slab to slide over the angle during a fire. This provision is believed to avoid the fire breaching the floor-to-floor compartmentation of the building. The finite element analysis allowed such alterations to be determined.

This case study highlights the importance of checking that the cold temperature structural design has no intrinsic structural weaknesses in fire.

Advanced Analysis of Concrete Structures

Calculation of the whole frame response of concrete frames to fire is possible using finite element analysis. Eurocode 2 contains a method that specifically addresses concrete. However, none of the computer codes that currently exist and are used in fire design explicitly calculate spalling. Therefore the thickness of spalled material must be assumed and generally removed at the start of a structural or heat transfer analysis.

Most of the research in this field with regard to modeling concrete frames or sub-assemblies has been carried out in Europe, with some work in the United Kingdom after the full-scale Cardington frame fire test.[6] Most of the concrete finite element models in Europe have been validated against single element tests.[105,106]

Modeling tension cracking cannot be done without a code that includes fracture mechanics, which most do not because this calculation is labor intensive. In general, a smeared crack model is used to indicate areas of high tensile strain, which indicate that cracking will have occurred. Spalling is also an unknown; therefore, accurate concrete models are difficult to achieve.

The same four-step approach outlined for steel structures undergoing a finite element analysis can be used. Computer programs specifically written to quantify concrete frame response to fire include CONFIRE,[107] TCD,[108] FIRES-T3,[109] and SAFIR.[100]

As for any frame analysis in fire, concrete-specific codes must model nonlinear behavior of the structural elements and material properties, as well as include full degradation of material properties with temperature. An accurate representation of thermal gradients varying with time is particularly important for concrete elements as a consequence of concrete's poor conductivity. Nonlinear material properties of density, specific heat, and conductivity are required in a finite element model

of the concrete structural element's cross section to calculate through-depth temperature gradients. If moisture content is ignored this will give conservative results because there will be no thermal lag as a result of latent heat of evaporation at 100°C. A temperature-time curve representing the design fire and associated boundary conditions (convection coefficient and emissivity) can then be applied to the appropriate faces of the finite element model. Design fires can be determined, as outlined earlier in this chapter.

Calculating the whole frame response of concrete frames to fire is rarely carried out in design. The main reason for this is the lack of full-scale test data to validate the use of finite element methods with concrete materials.

Of particular interest in the United Kingdom currently is the performance of prestressed concrete frames in fire, as they may be more susceptible to fire because the slabs are thinner, the prestressed tendons tend to be weaker than ordinary reinforcement at elevated temperature, and thermal expansion may reduce prestress. This results in an overall reduced level of performance. However, this remains to be confirmed.

Tabulated data exist for the dimensions and cover to reinforcement for prestressed slabs exposed to the standard fire, but they are based on limited test data. Ideally, a full-scale fire test of a concrete frame comprised of prestressed slabs/beams is desirable to check the tabulated data when the slab is restrained as in the real case; more spalling may occur because of this restraint. The test should be designed to identify alternative load paths such as compressive and tensile membrane action, which may support the load if prestressing is reduced by the tendons expanding in a fire. The test should also measure the reduction in prestress, if any, during the fire.

Advanced Analysis of Wood Elements

Design of wood elements in fire is also generally achieved by single element analysis throughout the world. However, Eurocode 5, Part 1.2[81] acknowledges that advanced models can be used for heat transfer analysis and or mechanical response. The complex phenomena associated with wood response to fire, as highlighted when single element methods of design were discussed, are also an issue for whole frame response; the recommendations in EC5-1-2[81] for conducting advanced analysis recognize these. For instance, it states that the thermal response model should take into account the variation of the thermal properties of the material with temperature, including phenomena such as increased heat transfer due to mass transport (e.g. due to the vaporization of moisture) or increased heat transfer due to cracking, which causes heat transfer by convection and/or radiation.

In advanced calculation methods for the structural response EC5-1-2[81] states that the user should take into account the changes of mechanical properties with temperature and moisture. In particular, the effects of transient thermal creep and transient states of moisture should be taken into account. One way of doing this is to use the mechanical properties of wood given in Annex B of EC5-1-2,[81] which include the effects of thermal creep and transient states of moisture. As for the advanced analysis of any structural frame, EC5-1-2[81] states that the structural response model should take into account the effects of nonlinear material properties and nonlinear geometry.

SUMMARY

This chapter outlined some of the design techniques available to assess structural fire resistance, with a specific focus on international approaches. The initial emphasis on the heating regime, which resulted in alternative approaches to fire resistance, was summarized. These do not address structural performance; rather, they address only heating regimes in real compartments and their duration relative to the standard fire resistance heating regime.

The three different forms that fire can take when forming the basis of a structural design include postflashover fires, local fires, and external fires. Guidance was provided on when these very distinctive scenarios are appropriate. Although work remains to be done on addressing the fire scenario in a risk-based framework appropriate for structural design, several design options are available for real building performance. Determining a fire scenario for a structural analysis should, therefore, serve as a useful framework for understanding the issues surrounding the most important parameter in structural fire assessments.

Specific design methods allow single structural element response to elevated temperatures to be quantified. Single structural element analysis techniques provide useful understanding of single element strength in fires under the reduced loading conditions associated with the fire limit state. They do not, however, incorporate any thermal expansion effects, which is one of the most important parameters that govern full-frame structural response.

The chapter concludes with a discussion on methodologies for using advanced structural fire models, as well as some current design methods derived from full-scale testing available in the public domain. Such techniques allow quantification of structural mechanics in elevated temperatures, including significant parameters such as degradation of strength and the alteration in geometry that takes place in a fire. A formal process for design and approvals within a risk-based framework is suggested as a useful way forward for the profession, along with the creation and education of skilled structural fire engineering professionals trained to address this essential component of robust design for all structural forms.

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NFPA Codes, Standards, and Recommended Practices

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NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*

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SECTION 20

Protecting Occupancies

Gregory E. Harrington

20.1 Assessing Life Safety in Buildings
20.2 Board and Care Facilities
20.3 Hotels and University Housing
20.4 Apartment Buildings
20.5 Lodging or Rooming Houses
20.6 One- and Two-Family Dwellings
20.7 Manufactured Housing
20.8 High-Rise Buildings
20.9 Assembly Occupancies
20.10 Mercantile Occupancies
20.11 Business Occupancies
20.12 Educational Occupancies
20.13 Day-Care Occupancies
20.14 Detention and Correctional Occupancies
20.15 Health Care Occupancies
20.16 Storage Occupancies
20.17 Library and Museum Collections
20.18 Industrial Occupancies
20.19 Motion Picture and Television Studios and Soundstages
20.20 Occupancies in Special Structures

Section 20 of the *Fire Protection Handbook*® describes fire protection requirements and operating features for individual occupancies covered by NFPA *101*®*, Life Safety Code*®, and *NFPA 5000*®*, Building Construction and Safety Code*®. Many of the chapters also discuss the characteristics of the occupants typically found in the occupancies.

Chapter 1, "Assessing Life Safety in Buildings," sets the stage for the chapters that follow by previewing life safety concepts, goals, objectives, strategies, and tools such as the Fire Safety Concepts Tree and fire safety evaluation systems.

The next chapters deal with types of residential facilities. Chapter 2, "Board and Care Facilities," examines what makes alcohol and drug rehabilitation facilities, shelters, assisted living facilities, and other board and care facilities so susceptible to fire and loss of life and what must be done to improve the fire record. Chapter 3, "Hotels and University Housing," has undergone a major revision for the 20th edition. Chapter 4, "Apartment Buildings," also addresses residential condominiums. Chapter 5, "Lodging or Rooming Houses," provides information for facilities providing sleeping accommodations without separate cooking facilities for up to 16 persons who are capable of self-preservation.

The next two chapters also cover types of residences. Chapter 6, "One- and Two-Family Dwellings," concentrates on one- and two-family dwellings, defined as residential structures that contain not more than two dwelling units. Chapter 7, "Manufactured Housing," covers manufactured homes and their construction, fire safety features, installation, and associated utilities.

Chapter 8, "High-Rise Buildings," describes some of the code provisions and special features of the high-rise building, as well as presenting historical data on high-rise building fires.

Chapter 9, "Assembly Occupancies," addresses the fire safety issues of assembly occupancies, which generally can be defined as rooms, spaces, or structures in which groups of people gather for a purpose, such as deliberation, worship, entertainment, or to await transportation. Chapter 10, "Mercantile Occupancies," covers shopping malls and other shops and stores. Chapter 11, "Business Occupancies," includes a discussion of staged and total evacuation.

In previous editions of this handbook, information on educational occupancies and day-care occupancies were combined into a single chapter. In this edition, Chapter 12, "Educational Occupancies," addresses educational occupancies, which are generally defined as facilities in which six or more persons gather for purposes of formal or structured instruction through the twelfth grade. Chapter 13, "Day-Care Occupancies," addresses structures in which four or more clients receive care, maintenance, and supervision by other than their relatives or legal guardians for fewer than 24 hours per day.

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Chapter 14, "Detention and Correctional Occupancies," covers fire safety concerns in buildings and facilities in which persons are restrained for security purposes by locks they do not control.

Chapter 15, "Health Care Occupancies," describes fire protection needs in a variety of facilities that care for nonambulatory patients who are incapable of self-preservation.

Chapter 16, "Storage Occupancies," addresses fire protection for storage and warehouse operations, where intense fires can develop rapidly. Chapter 17, "Library and Museum Collections," summarizes the unique fire safety concerns, including damage limitation, in cultural properties such as historic buildings and sites.

Hazard assessment and prefire planning are among the topics considered in Chapter 18, "Industrial Occupancies." Chapter 19, "Motion Picture and Television Studios and Soundstages," includes a discussion of pyrotechnics before a proximate audience.

The section closes with Chapter 20, "Occupancies in Special Structures." For purposes of this chapter, special structures include limited access and underground structures, mall buildings, open parking structures, special amusement structures, piers and wharves, water-surrounded structures, membrane structures and tents, grandstands, towers, and open structures.

Chapter 1

Assessing Life Safety in Buildings

John M. Watts, Jr.

Chapter Contents

Life Safety Concepts
Life Safety Goals and Objectives
Characteristics of Occupants
Life Safety Strategies
Life Safety Assessment Tools

Key Terms

egress, evacuation capability, fire prevention, Fire Safety Concepts Tree, Fire Safety Evaluation Systems (FSES), fire scenario, life safety assessment, life safety concept, occupancy classification, occupant characteristics, occupant load, performance-based approach, travel distance, untenable condition

Assessment of life safety is the process of estimating the quality of security against fire and its effects. There is no universally accepted method of assessing life safety from fire in buildings. Life safety is a concept, and no formula can identify or guarantee that a building is safe from fire.

First of all, assessment requires an understanding of the fundamentals of the life safety concept. Life safety goals and objectives need to be reviewed and then an evaluation can be made of the parameters that create hazards to life and those that tend to offset or control a portion of the life hazard. A wide variety of tools have been devised to relate these parameters so as to assess life safety in buildings.

Every general type of fire safety practice and fire protection strategy discussed in this handbook may apply to life safety in buildings. Specific additional information that can be helpful in a life safety assessment is identified throughout this chapter.

See also Section 2, Chapter 1, "Physics and Chemistry of Fire"; Section 4, Chapter 1, "Human Behavior and Fire"; Section 4, Chapter 2, "Calculation Methods for Egress Prediction"; and Section 6, Chapter 2, "Combustion Products and Their Effects on Life Safety."

LIFE SAFETY CONCEPTS

Concern for life safety implies avoiding exposure to harmful levels of products of combustion. This goal is usually achieved by controlling the fire process or by separating endangered individuals from the harmful effects of fire by time, distance, or shielding. Thus, life safety is accomplished if endangered individuals can move away from potential danger or if harmful effects of fire can be delayed indefinitely from reaching people in the building.

Details of the fire's development, along with characteristics of exposed occupants, determine the magnitude of the hazard. In addition, specific safety measures may be employed to reduce the hazard. Understanding the interrelationships of these components is the first step in assessing life safety from fire in buildings.

Importance of Time

As a fire develops over time, smoke and heat build up to create an environment that is hazardous to life. The rate at which the environment deteriorates is difficult to predict, because a great many variables are involved. Figure 20.1.1 is a generalization of the way life hazard increases over time. At the time of ignition (lower left corner), the environment is normal. Most fires develop slowly, so the initial hazard is small. Eventually, fire intensity will increase more rapidly, building up the level of dangerous products of combustion.

After some period of time, the accumulation of products of combustion reaches a level at which the fire will be discovered by the occupants through sight or smell or by automatic fire detectors. The level of hazard at which discovery occurs corresponds to a specific time in the course

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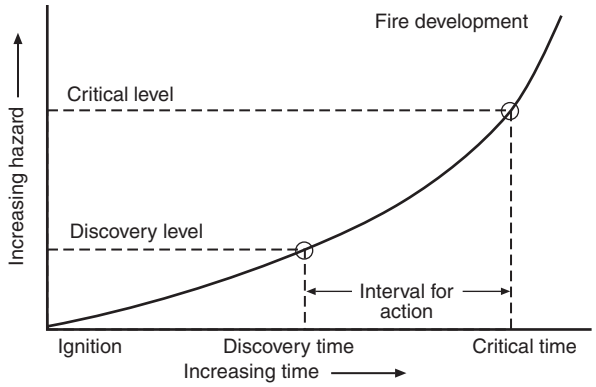

FIGURE 20.1.1 Representative Rate of Deterioration of the Environment as a Fire Progresses and the Interval of Time Available to Take Action to Prevent Death or Injury

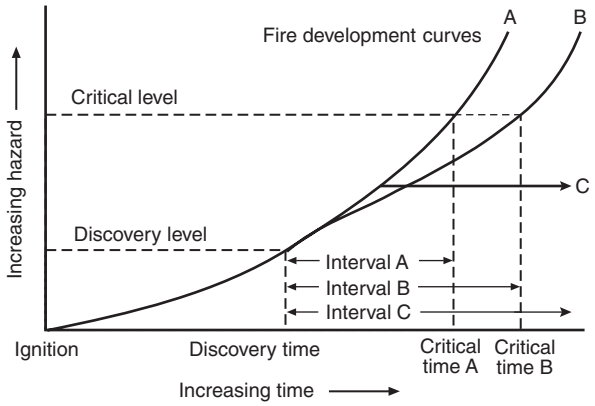

FIGURE 20.1.2 Difference in Deterioration Rates Between a Faster-Developing and a Slower-Developing Fire and Resulting Impact on the Interval for Action

of the fire. Figure 20.1.1 indicates a discovery level and a corresponding discovery time. If no actions are taken after discovery, eventually, the hazard will increase to a level that is lethal or incapacitating. In Figure 20.1.1 this is shown as the critical level and there is a corresponding critical time.

Fire Hazard

The critical time depends on the interaction of three sets of conditions: (1) elevated environmental temperatures, (2) toxic conditions resulting from pyrolysis or combustion products, and (3) preexisting or current psychophysiological attributes of the occupants. Elevated temperatures can cause burns or heat stress ranging from trivial to lethal. Specific chemical pyrolysis or combustion products, decreased oxygen concentration, or particulate smoke can cause toxic effects. The clinical consequences of these physical conditions also will reflect the psychophysiological conditions of the occupants. For example, preexisting heart disease has been established as a contributory factor in fire deaths.[1] Assessment of the variable interactions of these three sets of conditions is, obviously, extremely complicated.

Interval for Action

The interval between discovery and criticality is the time available to undertake action to prevent occupants from being exposed to the critical hazard level. This action may take various forms, such as activation of automatic equipment, evacuation of occupants, or both. Lowering the hazard level where discovery occurs, such as by automatic fire detection, will have a corresponding decrease in the time to discovery and, therefore, will increase the interval of time available for action. On the other hand, occupants with greater susceptibility and, hence, a lower personal critical level will have less time to react.

Fire growth and hazard are not the same in every fire. If conditions are insufficient to sustain a fast-spreading fire, the rate of deterioration of the environment is reduced, resulting in a decreased slope of the fire development curve. Figure 20.1.2 shows three different fire development curves. Curve A is the same fire as in Figure 20.1.1. Curve B represents a slower-developing fire than curve A. The curve starts at the same point of ignition but does not curve upward as quickly as curve A. This means it takes longer to reach the critical hazard level and, thus, has a resultant increase in the interval of time available for action. This could be affected by a decrease in the surface area or combustibility of interior finish materials.

Alternatively, curve C might represent the effect of a smoke control system or sprinkler system, which are two active systems that can stop or even reverse the developing severity of the fire. Curve C begins with ignition and then grows at the same rate as curve A, but at some point after discovery, the system is activated and it maintains the atmosphere below the critical level for an indefinite period of time.

LIFE SAFETY GOALS AND OBJECTIVES

Life safety goals and objectives identify what it is that we want to achieve. The primary difference between goals and objectives is that objectives are more specific to the problem being solved. Goals are always qualitative, whereas objectives may also be quantitative.

Life Safety Goals

A goal is a broad, qualitative expression of the overall, primary concern. Goals are nonspecific and are potentially measurable although only on a qualitative basis. They are stated in terms of conditions that are intrinsically desirable and do not rely on assumptions.

Goals relating to life safety are the most common and arguably the most important in fire and other emergency situations. The public trusts the built environment (that is, anyone involved in constructing buildings, structures, and other facilities—designers, engineers, code officials, and the like) to maintain some level of safety or protection from adverse conditions. Therefore, maintaining the health, safety, and welfare of building occupants is a basic goal.

NFPA *101*®, *Life Safety Code*®, has three stated goals to reduce the adverse impact of fire on people:

- Protection of occupants not in contact with the initial fire development
- Improvement of the survivability of occupants in contact with the initial fire development
- Provision of reasonably safe emergency crowd movement

Life Safety Objectives

A life safety objective is a requirement of the fire development, building, or occupants that needs to be accomplished in order to achieve a life safety goal. Objectives provide a greater level of qualitative detail than goals, are stated in more specific terms than goals, and are measured on a more quantitative rather than qualitative basis. In general, objectives define a series of actions necessary to make the achievement of a goal much more likely. If each life safety objective is accomplished for a building, then that building can be said to meet the life safety goals.

NFPA *101* has three objectives that address occupant protection, structural integrity, and system effectiveness:

- A structure shall be designed, constructed, and maintained to protect occupants who are not intimate with the initial fire development for the time needed to evacuate, relocate, or defend in place.
- Structural integrity shall be maintained for the time needed to evacuate, relocate, or defend in place occupants who are not intimate with the initial fire development.
- Systems utilized to achieve the goals shall be effective in mitigating the hazard or condition for which they are being used, shall be reliable, shall be maintained to the level at which they were designed to operate, and shall remain operational.

Life safety goals and objectives identify the fundamental purpose of assessing life safety in buildings. Meeting these goals and objectives is what the assessment is intended to help achieve.

CHARACTERISTICS OF OCCUPANTS

The most difficult component of life safety to evaluate is the population at risk (i.e., the occupants of the building). The difficulty is due to wide variations among building occupants. It is necessary to assess their susceptibility to fire and fire products and their ability to undertake and follow procedures necessary for their safety (i.e., anticipated response to a fire emergency). Indications of these abilities may be found in physical and mental characteristics of the occupants, as individuals and as a group. Four categories of occupant characteristics influence the ability to survive in a fire: (1) location, (2) response, (3) number, and (4) staff.[2]

Location

Assumptions generated by committees responsible for the development of NFPA *101* performance-based design option regarding the location of occupants dealt more with the density or concentration of people within a space rather than the actual location of individual occupants. However, the location of individual occupants may be inferred from the stated assumptions. For example, the Technical Committee on Board and Care Facilities assumed "full occupancy" and the Technical Committee on Residential Occupancies assumed "high-density (people per room) properties." These assumptions indicate that the maximum travel distance from any occupiable room or space within the building must be considered when designing and analyzing potential building designs.

The present prescriptive requirements in NFPA *101* and *NFPA 5000*®, *Building Construction and Safety Code*®, identify the location of occupants in regard to compliance with maximum allowable travel distances. Table 20.1.1 lists travel distance limits by type of occupancy and sprinkler protection as prescribed in NFPA *101* and *NFPA 5000.* These codes specify that the travel distance to an exit must be measured from the most remote point subject to occupancy. This has been interpreted as an assumption necessary for performance-based design as follows: "In every normally occupied room or area, at least one person shall be assumed to be located at the point most remote from the exit(s)." Although consistent with the prescriptive code, this is a conservative assumption and not necessarily representative of expected normal human behavior.

Another aspect of occupant location is the remoteness of exits when more than one is required. This is to ensure that multiple exits are not simultaneously blocked by a single fire. Current codes rely on a rule that says exits should be a straight-line distance apart not less than one-half the length of the maximum overall diagonal dimension of the building or area served. The rationale for this "one-half diagonal rule" is not obvious. There is no physical or logical reason to relate a building diagonal to the emergency egress of people. Furthermore, this approach permits configurations in which the exits might not intuitively be considered remote. For example, consider a space with a length of 100 ft (30.4 m) and a width of 60 ft (18.2 m) with both its exits at one of the narrow ends.

Remoteness of exits may be more logically a function of direction of travel than separation distance. A measure of this concept would be the angled distended between lines corresponding to routes from any point in a room or space to the exits or exit accesses. Figure 20.1.3 illustrates a situation where if the travel paths to two exits are different by at least 30°, the exits may be considered remote. That is, if the exits were closer together, the angle of remoteness would be less than 30°. There are also ways this concept can be adapted to include a common path of travel limitation.[3]

Response

In a performance evaluation of life safety, assumptions need to be made regarding the expected distribution of characteristics of a population appropriate to the use of the building. The four basic characteristics (i.e., sensibility, reactivity, mobility, and susceptibility) comprise a minimum, exhaustive set of mutually exclusive performance characteristics of people in buildings that can affect a fire safety system's ability to meet life

TABLE 20.1.1 Travel Distance Limits by Occupancy and Sprinkler Protection

Type of Occupancy	Travel Distance Limit			
	Unsprinklered		Sprinklered	
	ft	*m*	*ft*	*m*
Assembly				
New	200	61[a]	250	76[a]
Existing	200	61[a]	250	76[a]
Educational				
New	150	45	200	61
Existing	150	45	200	61
Day Care				
New	150	45[b]	200	61[b]
Existing	150	45[b]	200	61[b]
Health Care				
New	NA	NA	200	61[b]
Existing	150	45[b]	200	61[b]
Ambulatory Health Care				
New	150	45[b]	200	61[b]
Existing	150	45[b]	200	61[b]
Detention and Correctional				
New—use condition II, III, IV	150	45[b]	200	61[b]
New—use condition V	150	45[b]	200	61[b]
Existing—use condition II, III, IV, V	150	45[b]	200	61[b]
Residential				
One- and two-family dwellings	NR	NR	NR	NR
Lodging or rooming houses	NR	NR	NR	NR
Hotels and dormitories				
New	175	53[b,c]	325	99[b,c]
Existing	175	53[b,d]	325	99[b,d]
Apartments				
New	175	53[b,c]	325	99[b,c]
Existing	175	53[b,c]	325	99[b,c]
Residential *(continued)*				
Board and care				
Small, new and existing	NR	NR	NR	NR
Large, new	NA	NA	325	99[b,c]
Large, existing	175	53[b,c]	325	99[b,c]
Mercantile				
Class A, B, C				
New	150	45	250	76
Existing	150	45	250	76
Open air	NR	NR	NR	NR
Mall				
New	150	45	400	120[e]
Existing	150	45	400	120[e]
Business				
New	200	61	300	91
Existing	200	61	300	91
Industrial				
General	200	61[f]	250	75[g]
Special purpose	300	91	400	122
High hazard	0	0	75	23
Aircraft servicing hangars, ground floor	[f]	[f]	[f]	[f]
Aircraft servicing hangars, mezzanine floor	75	23	75	23
Storage				
Low hazard	NR	NR	NR	NR
Ordinary hazard	200	61	400	122
High hazard	75	23	100	30
Parking structures, open	300	91	400	122
Parking structures, enclosed	150	45	200	60
Aircraft storage hangars, ground floor	[f]	[f]	[f]	[f]
Aircraft servicing hangars, mezzanine floor	75	23	75	23
Underground spaces in grain elevators	200	61	400	122

[a]NFPA *101* has special considerations for smoke-protected assembly seating in arenas and stadia.
[b]This dimension is for the total travel distance, assuming incremental portions have fully utilized their permitted maximums. For travel distance within the room, and from the room exit access door to the exit, see the appropriate occupancy chapter.
[c]See the appropriate occupancy chapter in NFPA *101* for special travel distance considerations for exterior ways of exit access.
[d]See the appropriate occupancy chapter in NFPA *101* for requirements for second exit access based on room area.
[e]NFPA *101* has special travel distance considerations in covered malls considered to be pedestrian ways.
[f]NFPA *101* has special requirements on spacing of doors in aircraft hangars.
[g]NFPA *101* has industrial occupancy special travel distance considerations.
NR = No requirement; NA = Not applicable.
Source: Adapted from Table A.7.6, NFPA *101,* 2006 edition.

safety objectives. They are briefly described in Table 20.1.2. In application, as with the use of computer evacuation models, assumptions may address a larger number of factors that are components of these basic performance characteristics.

Furthermore, occupant response assumptions vary depending on the type of facility being analyzed. For example, the committee dealing with theaters, nightclubs, concert halls, sports arenas, and so on assumed that patrons may be intoxicated. This

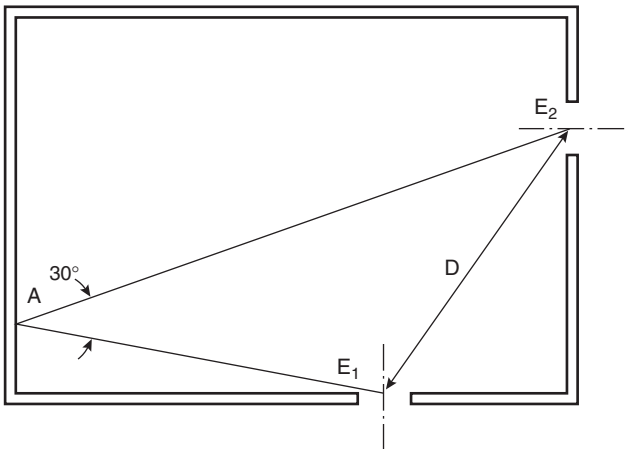

FIGURE 20.1.3 Travel Paths from Point A to Two Exits, E_1 and E_2, with 30° Difference (D = Safe separation distance)

assumption would affect the patrons' sensibility, reactivity, most likely their mobility, and possibly their susceptibility. Other occupancy committees made assumptions that fall into only one of the categories of Table 20.1.2: detention and correction facilities by their very purpose impair the mobility of the occupants; specific kinds of health care and board and care facilities may involve persons with limited sensibility, persons with limited reactivity, or persons having a wide range of susceptibility; and so on.

TABLE 20.1.2 Occupant Response Characteristics

Characteristic	*Description*
Sensibility	Sensibility to physical cues. Ability to sense the sounding of an alarm. May also include discernment and discrimination of visual and olfactory cues in addition to the sounds of the fire itself.
Reactivity	Reactivity is the ability to correctly interpret cues and take appropriate action. May be function of cognitive capacity, speed of instinctive reaction, or group dynamics. May need to consider reliability or likelihood of a wrong decision as in the influence of familiarity with the premises on wayfinding.
Mobility	Mobility is speed of movement. Determined by individual capabilities as well as crowding or congestion phenomena, such as "arching" at doorways.
Susceptibility	Susceptibility to products of combustion. Metabolism, lung capacity, pulmonary disease, allergies, or other physical limitations that may affect survivability in a fire environment.

There also may be a dynamic component to occupant response assumptions. Any facility in which occupants may be sleeping requires different sensibility and reactivity assumptions when occupants are expected to be awake than when occupants are expected to be sleeping.

One type of occupant response assumption that the occupancy committees made that is difficult to categorize has to do with an occupant's familiarity with the facility being analyzed. For example, occupants of an office building were assumed to have a high degree of familiarity with the building in which they work, whereas patrons in an assembly occupancy were assumed to be unfamiliar with their surroundings. Is "higher familiarity" manifested as greater mobility? Presumably, a higher degree of familiarity with a facility results in more correct decisions about the safest path to take to reach a place of safety and, therefore, an effectively higher degree of mobility. Certainly an argument may be made that those having less familiarity with a facility's exit locations and egress routes will have a lesser degree of mobility (i.e., take a longer time to evacuate). However, not enough is currently known to make an estimation of how much mobility should be degraded to account for poor decision making while evacuating a building.

Number

A critical factor in human behavior in fire is the number of occupants in a given space. NFPA *101* and *NFPA 5000* identify figures for the average maximum density of occupancy for the existing classifications. Table 20.1.3 shows occupant load factors for types of occupancies and functional spaces within the occupancies as prescribed in NFPA *101* and *NFPA 5000*. These figures represent acceptable estimates in the absence of preferable data.

Staff

When trained employees are explicitly or implicitly included as part of the fire safety system, assumptions regarding their capability need to be identified and documented. For example, in hospitals, staff characteristics such as number, location, quality, frequency of training, and so on should be considered. An aspect that is often overlooked is the potential effectiveness of staff in assembly occupancies such as art galleries and museums. Although staff may be present in a given occupancy, they often are not considered part of the fire safety system. A case in point is in most mercantile occupancies where staff are trained to aid customers in sales, not necessarily evacuation.

Additional information on human behavior in fire is found in Section 4, Chapter 1, "Human Behavior and Fire," and in the *SFPE Engineering Guide to Human Behavior in Fires.*[4]

NFPA 101A, *Guide on Alternative Approaches to Life Safety,* addresses some characteristics of occupants. The chapter on "Evacuation Capability Determination for Board and Care Occupancies" describes a method for determining evacuation capability for a specific type of occupancy. This method calculates an evacuation capability score using information on residents, staff, and vertical egress travel required. Rating of residents assesses several characteristics of occupants that are particularly important to board and care occupancies. Table 20.1.4

TABLE 20.1.3 Occupant Load Factor

Use	*(ft^2 per person)*[a]	*(m^2 per person)*[a]
Assembly Use		
Concentrated use, without fixed seating	7 net	0.65 net
Less concentrated use, without fixed seating	15 net	1.4 net
Bench-type seating	1 person/18 linear in.	1 person/455 linear mm
Fixed seating	Number of fixed seats	Number of fixed seats
Waiting spaces	See Sections 12.1.7.2 and 13.1.7.2 in NFPA *101*	See Sections 12.1.7.2 and 13.1.7.2 in NFPA *101*
Kitchens	100	9.3
Library stack areas	100	9.3
Library reading rooms	50 net	4.6 net
Swimming pools	50 (water surface)	4.6 (water surface)
Swimming pool decks	30	2.8
Exercise rooms with equipment	50	4.6
Exercise rooms without equipment	15	1.4
Stages	15 net	1.4 net
Lighting and access catwalks, galleries, gridirons	100 net	9.3 net
Casinos and similar gaming areas	11	1
Skating rinks	50	4.6
Educational Use		
Classrooms	20 net	1.9 net
Shops, laboratories, vocational rooms	50 net	4.6 net
Day-Care Use	35 net	3.3 net
Health Care Use		
Inpatient treatment departments	240	22.3
Sleeping departments	120	11.1
Ambulatory health care	100	9.3
Detention and Correctional Use	120	11.1
Residential Use		
Hotels and dormitories	200	18.6
Apartment buildings	200	18.6
Board and care, large	200	18.6
Industrial Use		
General and high-hazard industrial	100	9.3
Special-purpose industrial	NA	NA
Business Use	100	9.3
Storage Use		
In storage occupancies	NA	NA
In mercantile occupancies	300	27.9
In other than storage and mercantile occupancies	500	46.5
Mercantile Use		
Sales area on street floor[b,c]	30	2.8
Sales area on two or more street floors[c]	40	3.7
Sales area on floor below street floor[c]	30	2.8
Sales area on floors above street floor[c]	60	5.6
Floors or portions of floors used only for offices	See business use	See business use
Floors or portions of floors used only for storage, receiving, and shipping, and not open to general public	300	27.9
Mall buildings[d]	Per factors applicable to use of space[e]	Per factors applicable to use of space[e]

Note: The occupant load is the maximum probable number of occupants present at any time.

[a]All factors are expressed in gross area unless marked "net."

[b]For the purpose of determining occupant load in mercantile occupancies where, due to differences in grade of streets on different sides, two or more floors directly accessible from streets (not including alleys or similar back streets) exist, each such floor is permitted to be considered a street floor. The occupant load factor is one person for each 40 ft^2 (3.7 m^2) of gross floor area of sales space.

[c]For the purpose of determining occupant load in mercantile occupancies with no street floor, as defined in Section 3.3.239 of NFPA *101,* but with access directly from the street by stairs or escalators, the floor at the point of entrance to the mercantile occupancy is considered the street floor.

[d]For any food court or other assembly use areas located in the mall that are not included as a portion of the gross leasable area of the mall building, the occupant load is calculated based on the occupant load factor for that use as specified in this table. The remaining mall area is not required to be assigned an occupant load.

[e]The portions of the mall that are considered a pedestrian way and not used as gross leasable area are not required to be assessed an occupant load based on this table. However, means of egress from a mall pedestrian way are required to be provided for an occupant load determined by dividing the gross leasable area of the mall building (not including anchor stores) by the appropriate lowest whole number occupant load factor from Figure 7.3.1.2(a) or Figure 7.3.1.2(b) of NFPA *101.*

Each individual tenant space is required to have means of egress to the outside or to the mall based on occupant loads calculated by using the appropriate occupant load factor from this table.

Each individual anchor store is required to have means of egress independent of the mall.

NA = Not applicable.

Source: Table 7.3.1.2, NFPA *101,* 2006 edition.

summarizes these characteristics and illustrates that for some types of building use more detailed information on occupants is necessary.

Surrogate Descriptors

Occupant age is often used as a surrogate descriptor for characteristics that determine life safety risk. Relatively easy to identify, age is often directly associated with characteristics such as mobility, awareness, and knowledge. Statistics showing that the very young and the very old suffer higher fatality rates from fire indicate variation of life risk with age.

NFPA *101, NFPA 5000,* and other model building codes categorize building use or occupancy classifications to simplify the application of regulations governing construction, fire protection, and other life safety requirements. In application, occupancy class, once determined, becomes the basis for most code requirements. In effect, we use occupancy classification as a surrogate for life safety risk. This generalization is inadequate for more performance-based assessment of life safety in buildings. NFPA *101* and *NFPA 5000* categorize buildings using the following occupancy classifications:

- Assembly
- Educational
- Day care
- Health care
- Detention and correctional
- One- and two-family dwellings
- Lodging or rooming houses
- Hotels and dormitories
- Apartment buildings
- Residential board and care
- Mercantile
- Business
- Industrial
- Storage

NFPA *101* further classifies occupancies as either new or existing.

TABLE 20.1.4 Risk Factors for Rating Evacuation Capability of Residents in a Board and Care Occupancy (as addressed in NFPA 101A)

Risk Factor	*Description*
Risk of resistance	During an emergency evacuation, the resident might resist leaving the facility
Impaired mobility	Physical ability of the resident to leave the facility
Impaired consciousness	A resident could experience partial or total loss of consciousness in a fire emergency
Need for extra help	Possibility that more than one staff member might be needed to evacuate the resident
Response to instructions	Resident's ability to receive, comprehend, and follow simple instructions during a staff-directed evacuation
Waking response to alarm	Fire alarm might fail to awaken the resident

LIFE SAFETY STRATEGIES

Ideally, building design considers the risk factors associated with occupants and fire, and it includes safety features to mitigate the risks. The discussion in this chapter is intended as a synthesis of the various safety measures that may be applied to reduce the danger of fire to occupants. Major categories of safety strategies have been identified by NFPA 550, *Guide to the Fire Safety Concepts Tree,* as (1) prevent fire, (2) manage fire, and (3) manage exposed (occupants). A simplified portion of the Fire Safety Concepts Tree showing the relationships of these strategies is presented as Figure 20.1.4.

Fire Prevention

No harm can come from fire if no fire takes place. Fire prevention, therefore, has the potential to eliminate the need for other fire safety measures. However, no fire prevention strategy is ever totally effective, so it is not prudent to rely on fire prevention alone.

Fire prevention considerations relate to heat energy sources, fuels, and the mechanisms that bring them together. For example, major potential ignition energy sources, such as electrical power, can be controlled largely through regulation, such as by following the requirements of NFPA 1, *Uniform Fire Code™,* and NFPA 70, *National Electrical Code®*. In addition, some fuels, such as flammable liquids and interior finish, also may be addressed by codes and standards. However, not all energy sources or all fuels can be regulated. This is also true of people, the primary causal factor of ignition. Assessment of the probability of

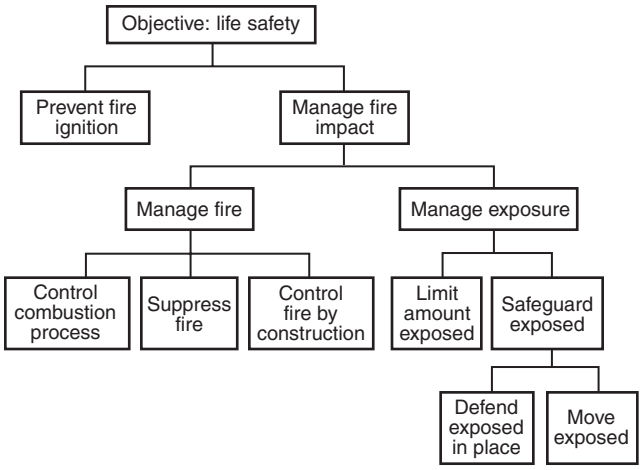

FIGURE 20.1.4 Simplified Portion of the Fire Safety Concepts Tree

fire occurrence involves analysis of ignition potential, especially in relation to the activities of building occupants, and of factors that will decrease the likelihood of ignition.

Fire Management

Since it is impossible to avoid all ignitions, managing fires that occur also is important. The strategies of fire management may be seen as reducing the slope of the fire development curves portrayed in Figures 20.1.1 and 20.1.2. These approaches strive to control the rate of smoke and heat production by altering fuel and/or the environment, controlling the combustion process by manual or automatic suppression, and controlling the products of combustion through venting and/or containment.

Objectives of the "manage fire" strategy are to reduce risks associated with fire growth and to reduce fire and smoke spread. Together, these reductions diminish the impact of a fire on building occupants.

Occupant Management

This life safety strategy (manage exposed) is the most complex, dealing with the risk factors of both fire and people. Occupant management involves undertaking emergency action appropriate to expected fire development and to characteristics of the occupants.

To initiate occupant management action, there first must be detection and alerting activities. Automatic equipment may perform these functions. Actions for managing exposed persons involve evacuation, refuge, or rescue. Evacuation is the most common approach when occupants are alert and mobile. In other cases, areas of refuge from fire and smoke within a building are employed, along with movement assisted by emergency personnel.

LIFE SAFETY ASSESSMENT TOOLS

The components of a generalized approach to assessment of life safety from fire in buildings are shown in Figure 20.1.5.

Step 1 is to identify the expected fire. This is depicted by the boxes to the left of the centerline in Figure 20.1.5. The expected fire is determined by the fire hazards that are present in the building, fire prevention measures implemented to prevent specific hazards from occurring, and fire management activities to control the severity of a fire if it does occur. The expected fire is input to step 2.

Step 2 is to the right of the centerline in Figure 20.1.5. The expected fire from step 1 is considered in conjunction with occupant risk factors and management of exposed occupants. This analysis produces a life safety assessment.

Step 3 is a return to the beginning to consider other expected fires or enhanced fire safety strategies. Thus, improving life safety in buildings is an iterative process of matching hazard and safety factors.

Specific techniques can be used in an assessment of life safety from fire in buildings including codes, exit analysis, fire safety evaluation systems (FSES), fire scenarios, evacuation models, and performance-based evaluation.

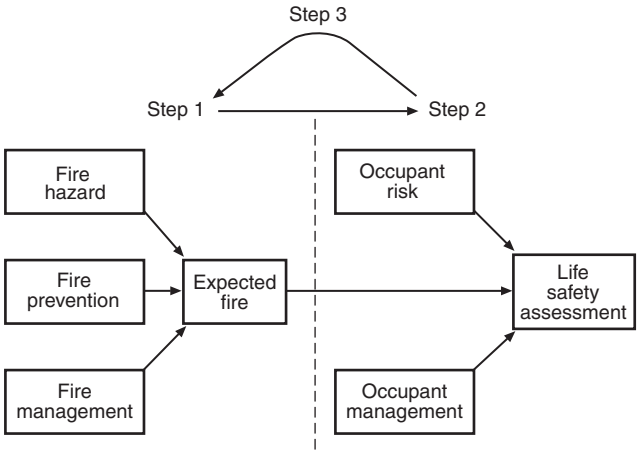

FIGURE 20.1.5 General Approach to Assessing Life Safety in Buildings

Codes

In the United States, NFPA *101* is the most widely used code for life safety from fire in buildings. The code has its origins in the 1912 *Exit Drills in Factories, Schools, Department Stores, and Theaters* that evolved as a result of the Triangle Shirtwaist factory fire in New York City that killed 146 workers in 1911. Requirements for factories and other occupancies were combined with specifications for building construction and automatic fire protection into the *Buildings Exit Code,* adopted and published in 1927. During the next 37 years, 18 revisions of this code were published, greatly expanding its content. In 1963, the document was reorganized and renamed the *Code for Safety to Life from Fire in Buildings and Structures,* or simply, the *Life Safety Code.* To date an additional thirteen editions have been published—the 2006 edition being the latest at the time this handbook was published.

NFPA *101* provides minimum requirements for the design, operation, and maintenance of buildings and other structures for safety to life from fire and similar emergencies. The code requires new and existing buildings to allow for "prompt escape" or to provide people with a reasonable degree of safety through other means.

The code meets its objectives by following two parallel approaches. First, it defines hazards, along with general requirements for the means of egress (a path of travel to a public way outside the building), fire protection features (such as fire doors), and building service and fire protection equipment (such as heating, ventilating, and air conditioning systems, sprinkler systems, and fire detection systems). Next, the code prescribes life safety requirements that vary with a building's use. Buildings used as one- and two-family dwellings, for example, have different life safety needs than hospitals and schools. Unique among fire safety codes, the provisions of the *Life Safety Code* depend on the type of occupancy and whether the occupancy is new or existing. The code can be used in conjunction with a building code or by itself in jurisdictions that have not adopted a building code.

NFPA *101* in particular and building codes in general are the predominant overall guides to life safety from fire in buildings in the United States. NFPA *101* identifies the following 10 fundamental requirements that are the basis for most of the specific provisions in the code. More information on these principles is found in Section 4, Chapter 3, "Concepts of Egress Design."

Multiple Safeguards. The design of every building or structure intended for human occupancy must be such that reliance for safety to life does not depend solely on any single safeguard. An additional safeguard(s) must be provided for life safety in case any single safeguard is ineffective due to inappropriate human actions or system failure.

Appropriateness of Safeguards. Every building or structure must be provided with means of egress and other safeguards of the kinds, numbers, locations, and capacities appropriate to the individual building or structure, with due regard to character of the occupancy, capabilities of the occupants, number of persons exposed, fire protection available, height and type of construction of the building or structure, and other factors necessary to provide occupants with a reasonable degree of safety.

Number of Means of Egress. Two means of egress, as a minimum, must be provided in every building or structure, section, and area where size, occupancy, and arrangement endanger occupants attempting to use a single means of egress that is blocked by fire or smoke. The two means of egress must be arranged to minimize the possibility that both might be rendered impassable by the same emergency condition.

Unobstructed Egress. In every occupied building or structure, means of egress from all parts of the building must be maintained free and unobstructed. No lock or fastening is permitted that prevents free escape from the inside of any building other than in health care occupancies and detention and correctional occupancies where staff are continually on duty and effective provisions are made to remove occupants in case of fire or other emergency. Means of egress must be accessible to the extent necessary to ensure reasonable safety for occupants having impaired mobility.

Awareness of Egress System. Every exit must be clearly visible, or the route to reach every exit must be conspicuously indicated. Each means of egress, in its entirety, must be arranged or marked so that the way to a place of safety is indicated in a clear manner.

Lighting. Where artificial illumination is needed in a building or structure, egress facilities must be included in the lighting design.

Occupant Notification. In every building or structure of such size, arrangement, or occupancy that a fire itself might not provide adequate occupant warning, fire alarm facilities must be provided where necessary to warn occupants of the existence of fire.

Vertical Openings. Every vertical opening between the floors of a building must be suitably enclosed or protected, as necessary, to afford reasonable safety to occupants while using the means of egress and to prevent spread of fire, smoke, or fumes through vertical openings from floor to floor before occupants have entered exits.

System Design/Installation. Any fire protection system, building service equipment, feature of protection, or safeguard provided for life safety must be designed, installed, and approved in accordance with applicable NFPA standards.

Maintenance. Whenever or wherever any device, equipment, system, condition, arrangement, level of protection, or any other feature is required for compliance with the provisions of the code, such device, equipment, system, condition, arrangement, level of protection, or other feature must thereafter be maintained unless the code exempts such maintenance.

Egress Analysis

Egress analysis is an important component of a life safety evaluation, as well as a tool for other forms of life safety assessment. The analysis uses anthropometric and biokinetic data on occupants, together with hydraulic flow analogies or other models, to calculate the time required to evacuate a building or space. The result can be compared to a calculated time for deterioration of the environment. Some basic engineering approaches to egress analysis have been developed and are presented in the *SFPE Handbook of Fire Protection Engineering*.[5,6] It is critical that results of egress analysis calculations, whether manual or computer, be examined with respect to the vagaries of human behavior that accompany an emergency.

Emergency egress systems should be assessed in terms of adequacy and reliability. Adequacy refers to structural components that determine the capacity to evacuate part or all of a building within a safe egress time span. Reliability considers how efficiently the egress capacity will be utilized. Factors of reliability include alerting messages and instructions, signage and emergency lighting, and protection of egress routes from fire, smoke, and toxic gases. Figure 20.1.6, a logic diagram, enumerates some features of egress adequacy and reliability.

Fire Safety Evaluation Systems (FSES)

NFPA 101A addresses fire safety evaluation systems (FSES). FSES is a fire risk indexing approach to determining equivalencies to NFPA *101* for certain occupancies. The FSES originally was created to provide a uniform method of evaluating health care facilities and to identify measures that would provide a level of fire safety equivalent to NFPA *101*.

Occupant Risk. Unlike NFPA *101,* the FSES for health care occupancies begins with a determination of relative risk derived from occupant characteristics. Variations of selected characteristics are assigned relative weights. Values were determined from the experienced judgment of a panel of fire safety professionals. Occupancy risk is then calculated as the

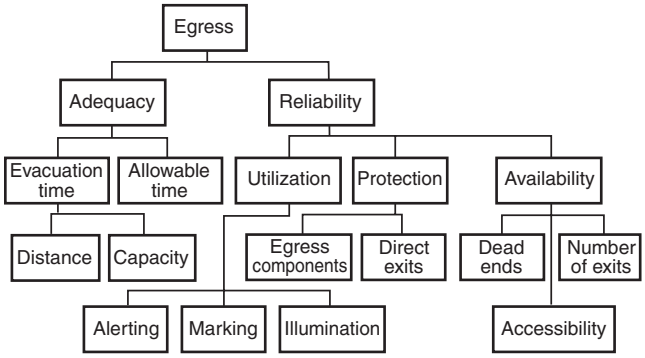

FIGURE 20.1.6 Logic Diagram of Egress Features

product of the risk factor values appropriate for the particular occupancy.

Safety Parameters. Safety features must offset this calculated risk. Thirteen possible safety parameters are considered. These parameters and their respective ranges of values for health care occupancies are based on opinions of the same expert panel.

Safety Strategies. An important concept of the FSES is reliability through redundancy by the simultaneous use of alternative safety strategies. Fire safety strategies considered in the FSES are containment, extinguishment, and people movement. Figure 20.1.7 indicates the expert panel's opinion of which safety parameters apply to each strategy. Values for a particular

Safety Parameters	Containment Safety (S_1)	Extinguishment Safety (S_2)	People Movement Safety (S_3)	General Safety (S_4)
1. Construction				
2. Interior Finish (Corr. and Exit)				
3. Interior Finish (Rooms)				
4. Corridor Partitions/Walls				
5. Doors to Corridor				
6. Zone Dimensions				
7. Vertical Openings				
8. Hazardous Areas				
9. Smoke Control				
10. Emergency Movement Routes				
11. Manual Fire Alarm				
12. Smoke Detection and Alarm				
13. Automatic Sprinklers			÷ 2 =	
Total Value	**S_1 =**	**S_2 =**	**S_3 =**	**S_4 =**

FIGURE 20.1.7 Individual Safety Evaluations for Fire Safety Evaluation of Health Care Occupancies. For use with NFPA 101A, *Guide on Alternative Approaches to Life Safety,* 2007, and NFPA *101®*, *Life Safety Code®*, 2006.

occupancy are entered in the appropriate places on Figure 20.1.7 and then added for each column. The resulting sums are compared to predetermined minimum values and to the occupancy risk previously calculated.

A method of minimizing the cost of retrofitting for compliance with the FSES for health care occupancies has been adapted for personal computers.[7] This approach is of practical interest to persons with fiscal responsibilities for health care facilities. The software includes the integrated code compliance optimizer, full-screen data editor, and file manager. ALARM 1.0 is available from the National Fire Protection Association (http://www.nfpa.org) through the One-Stop-Data-Shop. NFPA 101A includes FSESs for health care occupancies, correctional facilities, board and care facilities, business occupancies, and educational occupancies. One of the most widely used of these is Fire Safety Evaluation System for Business Occupancies. A PC-based computerized version has been developed. Fire risk indexing (FRI) models, such as the FSES, are powerful tools for assessing fire safety, especially in existing buildings. Designers can use FRI to determine the attributes needed to bring a building up to an acceptable level of fire safety. See the *SFPE Handbook of Fire Protection Engineering* for more information on this concept.

Fire Scenarios

In the theater, a scenario outlines the action of a play. Used in forecasting and political analysis, scenarios are sequences of events that lead to some specified circumstances. Scenarios are particularly suited to examining related conditions (such as building occupancy) and events (such as ignition). A fire scenario is a generalized, detailed description of an actual or hypothetical, but credible, fire incident. Such a scenario identifies a chain of events leading to deaths and other fire losses.

Each fire scenario includes all details relevant to a fire's development and the subsequent behavior of people and protection mechanisms. A properly developed fire scenario describes all essential elements of a fire incident. Scenario development is one of the most useful devices for anticipating a largely uncertain future. Fire protection engineering evaluation of a building or facility involves creating and analyzing fire scenarios. In the simplest form, a fire protection engineer hypothesizes plausible fire scenarios using professional experience and scientific principles of fire dynamics. A more sophisticated form uses computer models to predict fire scenario events.

Fire scenarios are particularly useful in assessing life safety in buildings. By considering various fire scenarios, it often is possible to identify and evaluate the potential for life loss. Plausible fire scenarios are an essential component of some other techniques of life safety assessment, such as the performance-based approach.

Evacuation Models

Computer models for the assessment of life safety in buildings are developing rapidly, concurrent with technical knowledge and hardware capability. These advances occur internationally in acknowledgment of their potential effect on reducing loss of life from fire.

Computer simulation is the process of representing item by item and step by step a system's essential features and then predicting what is likely to happen by running the model case by case. A great advantage of computer simulation is that by using computer-generated random numbers, the model can represent with desired precision processes for which satisfactory analytical approximations do not exist. A system that is not well enough understood to permit mathematical relations between variables to be formalized may often be modeled as a simulation. In studying behavioral systems, the need for simulation becomes acute. When objective data are very difficult to obtain, most predictions must be derived from vague, tentative, and intuitive conjectures. Such ill-defined structures and laborious analyses make computers indispensable tools.

The flexibility of simulation modeling and the complexity of the evacuation problem have resulted in numerous applications. These models differ in complexity, input requirements, underlying assumptions, specific application areas, and validation. Computer simulations of emergency egress range from simple travel time models to detailed representations of human decision making.

Performance-Based Approach

Most building codes maintain only an assumed, implicit relationship between fire safety requirements and fire safety objectives. For example, the number of exits has an intuitively positive correlation with life safety but no explicit relationship and no functional association for determining costs or benefits.

Performance-based evaluation focuses on fire safety objectives. This implies an examination of how all materials, products, components, and assemblies in a building work together as a system to meet fire safety objectives. For example, in determining adequacy of egress routes, it is desirable to consider the overall effect of number, size, length, and reliability of use, as well as the interdependencies among fire growth, fire resistance, and fire suppression.

The performance-based approach establishes fire safety objectives and leaves means for achieving objectives to the design professional. Carrying out this significant departure from traditional code practice requires the capability to determine whether fire safety objectives are being met.

NFPA *101* provides requirements for the evaluation of a performance-based life safety design. The evaluation process is summarized in Figure 20.1.8. On the left-hand side of Figure 20.1.8 is input from the code, life safety goals, the objectives necessary to achieve these goals, and the measures that are to be used to determine whether the objectives have been met.

At the top of Figure 20.1.8 is the input necessary to evaluate a life safety design. The design specifications are to include certain retained prescriptive requirements as specified in the code. All assumptions about the life safety design and the response of the building and its occupants to a fire need to be clearly stated. Fire scenarios are used to assess the adequacy of the design.

Appropriate methods for assessing performance are to be used and safety factors are to be applied to account for uncertainties in the assessment. If the resulting predicted outcome of the scenarios is bounded by the performance criteria, then the

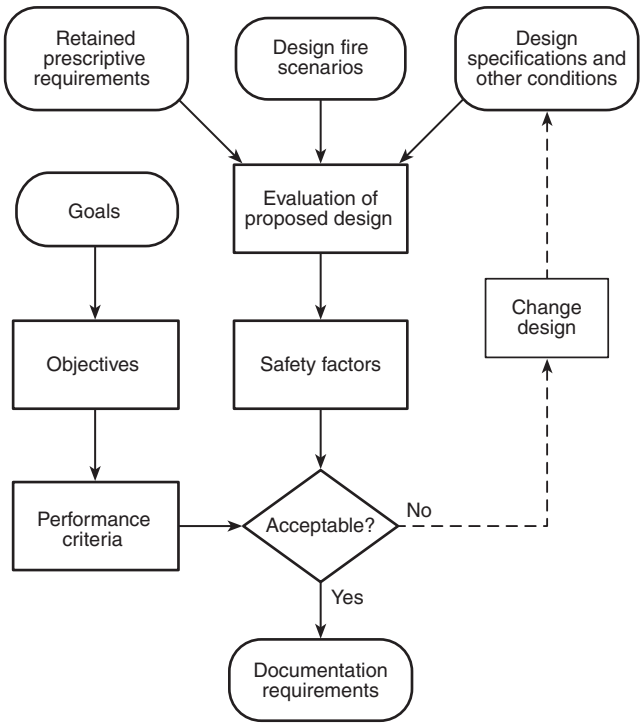

FIGURE 20.1.8 Performance-Based Life Safety Evaluation Process

objectives have been met and the life safety design is considered to be in compliance with the code. A design that fails to comply can be changed and reassessed as indicated on the right-hand side of Figure 20.1.8.

Although the performance option of this code contains goals, objectives, and performance criteria necessary to provide an acceptable level of risk to occupants, it does not describe how to meet the goals, objectives, and performance criteria. Professional design and engineering are needed to develop solutions that meet the performance provisions. Additional information on performance-based fire codes and standards is found in Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety," and the *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings.*[8]

SUMMARY

The main goals of life safety are to prevent fire, control fire if it happens, and to evacuate occupants. Many factors need to be evaluated when assessing life safety in buildings. The qualified evaluator must, therefore, have a good understanding of a range of concepts, including ignition potential, fire hazards, fire detection, fire suppression, emergency notification, building construction, occupant behavior, exit systems, and emergency management. Tools that can be used in the assessment process include fire code requirements, egress analysis, fire safety evaluation systems, fire scenarios, computer evacuation models, and the performance-based approach.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on assessing life safety in buildings discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™*
NFPA 70, *National Electrical Code®*
NFPA *101®, Life Safety Code®*
NFPA 101A, *Guide on Alternative Approaches to Life Safety*
NFPA 550, *Guide to the Fire Safety Concepts Tree*
NFPA 5000®, Building Construction and Safety Code®

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Chapter 2

Board and Care Facilities

Philip R. Jose

Chapter Contents

Definition
Code Requirements for New Board and Care Facilities
Classifying Board and Care Facilities
Occupancy Characteristics
Fire Problems
Fire Protection Strategies

Key Terms

egress, evacuation capability, fuel control, ignition control, occupant characteristics, personal care, residential board and care occupancy, special hazards

Although it has been with us for more than a century, the residential board and care home has been a phenomenon in the United States since the 1970s. Reasons for the growth of this type of occupancy are numerous. The population of state hospitals was reduced sharply in the 10-year period from 1969 to 1979. Social, judicial, economic, and therapeutic pressures to remove patients from the restrictive environments of psychiatric hospitals, nursing homes, state schools, and other institutional settings helped create a need for board and care facilities. This occupancy provides the deinstitutionalized person with a more normal setting to live in and furnishes the support services the resident needs to cope with life's daily requirements.

Today's older adults often live alone, even after they are unable to care for all their own needs. They might need to be in a setting where someone can look after their nutrition, personal hygiene, and so on. In recent decades, the rapid growth of assisted living facilities has driven the overall growth in board and care facilities, a trend that will continue to accelerate due to the aging baby boom population.

Alcohol and drug rehabilitation programs often use the halfway house concept, in which the individual is somewhat sheltered from the pressures of returning too quickly to society for independent living. Shelters for battered persons, unwed mothers, and homeless children have also become more common.

The fire experience in what NFPA statistical analysts call board and care homes was striking during 1979–1983 and remains a concern today (Table 20.2.1). Many of the multiple-death fires reported in Table 20.2.1 killed over half the residents, and it is not unusual for the largest fires to totally destroy facilities. At the same time, these fires are becoming less frequent. Fires involving 10 or more fatalities in particular are declining, and this is a hopeful development.

This chapter examines what makes board and care facilities so susceptible to fire and loss of life and what must be done to improve the fire record.

See also Section 5, Chapter 5, "Reaching High-Risk Groups"; and Section 20, Chapter 1, "Assessing Life Safety in Buildings."

DEFINITION

A residential board and care occupancy is defined in NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®, as a building or portion thereof that is used for lodging and boarding of four or more residents, not related by blood or marriage to the owners or operators, for the purpose of providing personal care services. The characteristic of providing personal care services distinguishes a board and care facility from a rooming house or dormitory.

In fire incident databases, a board and care facility is defined by its occupants' needs. It is important to keep the distinction between the code and database definitions in mind, because there is no guarantee that the occupants' needs match the care the facility provides. In particular, the care needs of occupants that qualify a property as a board and care facility for fire-reporting purposes will often be greater than the care delivered by a facility legitimately classified as a board and care facility under NFPA *101* and *NFPA 5000.* Therefore, Table 20.2.1 might not properly describe

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TABLE 20.2.1 North American Board and Care Home Fires Causing Five or More Deaths (1971–2005)

Date	*Occupancy**	*Civilians Killed*
1/73	Pleasantville, NJ	10
4/79	Farmington, MO	25
4/79	Washington, DC	10
4/79	Connellsville, PA	10
11/79	Pioneer, OH	14
7/80	Bradley Beach, NJ	24
11/80	Detroit, MI	5
1/81	Keansburg, NJ	31
10/82	Pittsburgh, PA	5
2/83	Eau Claire, WI	6
3/83	Gladstone, MI	5
4/83	Worcester, MA	7
8/83	Lawrenceville, GA	8
12/83	Cincinnati, OH	7
11/84	Lexington, KY	5
3/91	Colorado Springs, CO	10
9/91	St. Isidore, Quebec	5
6/92	Detroit, MI	10
10/94	Mobile, AL	6
12/94	Fort Lauderdale, FL	6
3/95	Mississauga, Ontario	7
3/96	Laurinburg, NC	8
8/96	Sainte Genevieve, Quebec	7
5/97	Harveys Lake, PA	10
4/98	Arlington, WA	8
1/04	Maryville, TN	5

*The classification as a board and care home is based on the needs of the occupants, specifically the presence of tenants who were over age 65 or had chronic mental illness. The classification is not based on the level of care the facility offered or the level of care it claimed to offer.

Source: NFPA Fire Incident Data Organization.

the fire experience of facilities that NFPA *101* and *NFPA 5000* would have classified as board and care homes or that claimed to be board and care homes.

The NFPA *101* and *NFPA 5000* definition could easily describe a hospital or a nursing home. The primary difference is in the definition of personal care. The care given in a hospital or a nursing home is certainly personal, but its primary purpose is to meet the medical needs of patients. In the board and care facility, the care provided is not medical in nature, nor does it require the services of doctors and nurses. It is generally a kind of assistance that can be rendered by laypersons who help residents cope with the rigors of daily living. This care might include looking after residents' personal hygiene, cleaning their living quarters, helping those who are physically handicapped to move around, preparing meals, looking after residents' financial matters, seeing that appointments are kept, reminding residents to take their medications, and numerous other tasks.

As this discussion implies, NFPA *101* and *NFPA 5000* seek to identify distinct populations in terms of needed levels of care and then define distinct categories of facilities that are established to provide the level of care required by a group of potential residents. A separate problem must be solved; making sure that residents are not put in facilities that are unable to or will not serve all their needs. This problem, implicit in most of the fires in Table 20.2.1, is one for enforcement authorities and probably the most important key to fire safety for all populations needing care.

Few board and care facilities call themselves by that name. Some facilities that fit into the definition of this occupancy include the following:

- Assisted living facilities
- Group homes for mentally retarded persons
- Group homes for released psychiatric patients
- Rest homes for older adults
- Foster care homes
- Orphanages
- Shelters for battered persons
- Shelters for unwed mothers
- Halfway houses for rehabilitated alcoholics
- Halfway houses for rehabilitated drug abusers
- Halfway houses for prison parolees
- Shelters for runaways
- Rescue missions with overnight accommodations

Whatever their names, a common thread ties these facilities together. They provide residents with more than just food and shelter. The residents usually are furnished some form of assistance, support, or care that is not of a medical nature.

The technical committee responsible for developing the board and care chapters of NFPA *101* and *NFPA 5000* has worked very hard to balance the need for a high level of fire safety with the financial constraints imposed on the owners and operators of the facilities. Many new small board and care facilities are existing residential structures that have been converted to this new occupancy. The owners and operators of these facilities are filling a significant need for this type of housing. The cost of upgrading these homes to meet board and care requirements is a major issue. The committee has allowed for certain code modifications to meet this concern. One such, often controversial, modification is the sprinkler exemption for conversions of existing buildings with a prompt evacuation capability and eight or fewer residents. It is important to note that by definition, a facility with a prompt rating houses a group of people with "the ability to move reliably to a point of safety in a timely manner that is equivalent to the capacity of a household in the general population." The committee feels with that restriction and the many other fire safety features required for this occupancy, a reasonable level of fire safety is provided.

CODE REQUIREMENTS FOR NEW BOARD AND CARE FACILITIES

Starting with the 2003 editions of NFPA *101* and *NFPA 5000,* the requirements for new board and care facilities are not dependent on the evacuation capability of the residents. For new facilities, one set of requirements applies, regardless of the evacuation capability. This new approach provides one level of safety for all

new facilities. Not only does this simplify the application of code requirements for new facilities, it resolves the ongoing compliance problem presented by an aging resident population.

The code has always required that facilities upgrade to meet the requirements for new construction whenever the evacuation capability of the residents changed to a slower classification. This routinely occurs as residents grow older and less able to evacuate at the same rate. Owners can be faced with costly modifications, which might include the installation of automatic sprinklers. Possible alternatives are moving selected residents to other facilities or hiring additional staff. Now that new facilities are governed by one set of requirements, this issue needs to be addressed only in existing facilities.

This same approach is not realistically viable for existing board and care facilities, as nearly all structures would require significant costly modifications to meet the code requirements to provide a level of safety appropriate for all evacuation-capability classifications. The existing approach of providing increased levels of protection, dependent on the evacuation capability of the residents as a group, continues to be valid and reasonable for existing facilities.

CLASSIFYING BOARD AND CARE FACILITIES

Classifying a board and care facility is an extremely important first task when conducting an inspection or evaluating a facility for compliance with NFPA *101* or *NFPA 5000.* If a mistake is made here, most of the inspection or evaluation that follows will be invalid. Answers to three questions determine building requirements for board and care facilities:

- Is the facility new or existing?
- Is the facility large or small?
- If existing, what is the facility's evacuation capability?

New or Existing

If the structure is built new or if it is a conversion from another occupancy type other than health care, the requirements for new board and care facilities in NFPA *101* must be met. If not, the requirements for existing facilities apply.

Large or Small

Simply counting the number of available beds for residents determines the size of the facility. Staff or family members are not counted when making this determination. By definition, a resident is a person who is receiving personal care and resides in the board and care facility. It is only the total number of residents in the facility that determines if it is large or small. Small facilities are those that provide sleeping accommodations for not more than 16 residents. Large facilities are those that provide sleeping accommodations for 17 or more residents.

Evacuation Capability in Existing Facilities

All *occupants* of the building, as a group, are evaluated when determining the evacuation capability. *Everyone* in the structure is included when making this determination, not just the residents. Assistance by staff, if provided, is a key part of the evaluation. A group of residents who might otherwise be classified slow could be considered prompt when well-trained staff assist in the evacuation process. Remember, however, if staff assistance is used to enhance the rating, they must always be present in the facility to provide that assistance when needed.

There are three classifications of evacuation capability: prompt, slow, and impractical. The rating may be arrived at in one of three ways—using the definitions to come up with a subjective determination; using NFPA 101A, *Guide on Alternative Approaches to Life Safety;* or using a program of timed exit drills.

NFPA *101* requires that facility management furnish to the authority having jurisdiction (AHJ), on request, an evacuation capability determination using a procedure acceptable to the AHJ. If such documentation is not furnished, the evacuation capability is classified as impractical.

If timed drills are used to determine evacuation capability, NFPA *101* recommends that evacuation times of 3 minutes or less be used for classifying a facility as prompt, 3 minutes to 13 minutes slow, and greater than 13 minutes impractical. The slowest time should be used for classification. Evacuation time is measured from the time of alarm to the time the last occupant arrives at a *point of safety* as defined in NFPA *101.*

NFPA *101* requires that six fire drills be performed each year in all board and care facilities, with a minimum of two drills conducted at night when residents are sleeping. It is at this point in the evaluation process that judgment becomes critical. Common sense and experience must be used to look at the residents and staff as a group and determine if the recorded times for drills performed during the last year are realistic. To aid in the determination of evacuation capability, the AHJ might ask the facility owner to conduct a fire drill while he or she is present. Occupants' performance during the day can be observed and compared against the recorded times for night drills when residents are sleeping. Clearly, if the group is unable to evacuate the home within the previously recorded time frames during waking hours, night drills indicating equal or faster times may have been falsified.

Construction and egress arrangement requirements become more strict as evacuation capability decreases. For instance, windows may not be used for the secondary means of escape in a small facility with a slow evacuation rating. Classification of a board and care facility is the most important step in the evaluation process. Taking the necessary time to get it right is critical to the safety of the residents.

OCCUPANCY CHARACTERISTICS

Characteristics of Buildings

The contents of a board and care facility typically fall into the ordinary hazard category by the methods of evaluation under NFPA *101.* There are rarely any large concentrations of combustible materials and usually no use of flammable liquids or gases. No processes pose "special hazards." Ignition sources are typical of those found in residential occupancies, and fuel loads

are generally light. The most significant fire threat in this occupancy is the enormous potential for loss of life.

Structural characteristics of buildings that house residential board and care facilities vary significantly. They range from single-family dwellings, in which a family takes in a few boarders, to high-rise, reinforced-concrete apartment buildings for the elderly operated by religious organizations, to commercial rest homes built for the purpose. Construction can be practically any type.

Characteristics of Residents

A description of the characteristics of the "typical" resident of a board and care facility is just as elusive as a description of a "typical" construction type. Residents of board and care facilities do not fit a stereotype—they may be children or elderly, physically impaired or physically sound, mentally handicapped or fully functioning. They may be capable of self-preservation or totally dependent on others to provide for their safety. No one description fits the residents of all board and care facilities. Variations that exist in the buildings and the range of residents' capabilities in these facilities pose the most significant challenge to fire protection professionals.

FIRE PROBLEMS

Problems of board and care facilities generally fall into two categories: structural and behavioral.

Structural Problems

Many board and care facilities are single-family dwellings or single-family dwellings to which space has been added to accommodate a number of boarders. Consequently, it is probable that many facilities are in structures built to standards intended for housing a "typical" family with normal abilities to detect, respond to, and escape from a fire. What follows are some of the specific fire safety characteristics for those kinds of facilities.

Building Construction. Board and care facilities that are converted dwellings reflect construction preferences for dwellings. Hence, many facilities are housed in one-, two-, and three-story wood-frame structures. In older buildings, balloon construction and unprotected wood structural members are common structural hazards. Under the best circumstances, wood-frame construction can offer some measure of protection, but fire endurance is limited and the combustible structure will eventually contribute fuel to a fire.

Egress Facilities. In converted dwellings, there is generally only a single route that occupants can use from any given room to get to safety outdoors. In converted two-story dwellings, this escape route typically includes an unenclosed stairway that might take escaping residents through the area of the house that is on fire. Often, the only alternate escape route is through a window, which in the case of a three-story building, may be more than 20 ft (6 m) above the ground. Typical of single-family dwellings, exit doors often are equipped with locking devices that impede egress, particularly for those unfamiliar with the locks or incapable of operating them.

Compartmentation. Separation of rooms from corridors and rooms from each other is sometimes nonexistent or of construction that provides little or no resistance to the passage of fire and smoke. If so, a fire in any room can quickly fill the entire building with smoke and toxic combustion products, limiting visibility and making the environment intolerable for human survival.

Vertical Openings. As with many multistory dwellings, the stairway, which also serves as the primary means of escape, normally is not enclosed. Stairs are usually open to the corridor on the upper floors and living spaces on the first floor. The spread of fire and smoke from one floor to the next can occur rapidly.

Interior Finishes. Walls and ceilings may be finished with paneling and acoustical ceiling tiles, without any thought to the combustibility of these materials. The facility owner, trying to improve the environment in which the residents live by providing attractive decor, may be placing them in jeopardy without knowing it. Highly combustible wall paneling and ceiling tiles can contribute to rapid horizontal and vertical fire spread and can be a major factor contributing to flashover. They can also contribute to the speed with which egress pathways become untenable.

Electrical Wiring and Appliances. Wiring is generally typical of the converted building's original use, which as noted is often that of a single-family dwelling. In older buildings, circuits may be inadequate in number and capacity, insulation may be old and deteriorating, fuses may be the wrong size for the circuits they protect, and wiring modifications, if any, may have been made by unqualified people. Use of extension cords, space heaters, and other residential-type electrical appliances may be common and contribute to the risk of fire.

Furnishings. The fire hazard posed by furniture and furnishings varies widely. Often, residents are permitted to bring an unlimited quantity of personal furnishings into the facility. Practically all such products can contribute fuel to a fire, with some, of course, being worse than others. Furniture that burns fiercely or gives off inordinately large quantities of smoke or toxic combustion products is a major hazard.

Behavioral Problems

Much concern over life safety in board and care facilities arises from the fact that they house a number of people who, in many cases, have diminished physical and/or mental capacity. Although this is not true of all facilities, or all residents of a given facility, the very fact that impaired people are residents of a facility that assists them in coping with daily life suggests that they may have problems fending for themselves in an emergency.

The impact that behavioral problems create generally falls into two categories: evacuation capability and safety consciousness.

Evacuation Capability. Because populations housed in board and care facilities differ widely, a broad statement describing evacuation capability in all such facilities cannot be made.

In the case of homes for older adults, some residents may be slow and unsteady, and unable to manage stairs, to see well, or to remember procedures to be followed in a fire. Some may be so incapacitated that they cannot be evacuated without a great deal of assistance. Residents of some facilities may be physically handicapped to such an extent that self-evacuation is not possible.

Evacuation capability can be affected by the facility's staff. In a facility housing deaf residents, for example, the presence of one staff member who can awaken and alert the residents to the emergency might be sufficient to normalize the evacuation capability of the group. In facilities housing more debilitated handicapped persons, a large staff might still be incapable of effecting a prompt evacuation.

Safety Consciousness. One risk factor that this occupancy has to a greater degree than other residential occupancies is that more of the residents tend to be unaware of or unconcerned with the dangers of their actions. This heightened risk applies to all the behaviors where errors lead to fires in ordinary homes, including smoking, use of space heaters, cooking, supervision of children who might play with fire, handling of appliances and electrical equipment, and even deliberate fire-setting.

FIRE PROTECTION STRATEGIES

With respect to life safety, the fire problems in board and care facilities can be addressed by ignition control, fuel control, occupant protection, detection and suppression equipment, and planning and training operations. The systems approach to fire safety in correctional facilities can be modified to apply to board and care facilities as well. (See Section 20, Chapter 14, "Detention and Correctional Occupancies.")

Ignition Control

Smoking materials start many fatal fires in board and care facilities. Every facility must have a smoking policy to address such issues as where smoking is permitted and the proper disposal of smoking materials. Clearly, the policy should attempt to prevent ignitions that occupants cause by falling asleep while smoking or improperly disposing of smoking materials. Noncombustible safety-type ashtrays should be provided in areas where smoking is permitted. In those facilities that permit smoking, designated smoking areas that are supervised or in which an occupant is rarely alone can work well.

Other ignition sources, such as space heaters, cooking and other heat-producing appliances, and electrical equipment must be controlled and maintained properly. The use of such equipment should be limited to those who are capable of operating the appliance properly or to those who are being trained under supervision. Sufficient numbers of electrical outlets should be provided to eliminate the use of extension cords.

Fuel Control

In many board and care facilities, residents are permitted to bring their own furnishings into their sleeping rooms. Most of these furnishings have not been subjected to any type of test to indicate their ease of ignition or heat release rates. New drapes, curtains, upholstered furniture, and mattresses must meet specific NFPA test criteria. An exception is made for upholstered furniture and mattresses belonging to residents when placed in their sleeping room, provided a smoke alarm is installed in the room.

In facilities with existing furnishings that do not meet the referenced NFPA flammability criteria, other protection features, such as early detection, suppression, and compartmentation, should be evaluated to ensure that an acceptable level of protection is provided. Other fuel sources, such as interior finish materials, should also be evaluated with respect to their potential to spread fire.

Occupant Protection

Setting minimum criteria for the protection of life from fire in board and care occupancies is not simple. As indicated, this is not a homogeneous occupancy. Minimum protection in one facility may be overprotection or inadequate protection in another. In few, if any, other types of occupancies is it so difficult to ensure over time that there is a proper match between the care residents need and the care provided to them by the facility.

Evacuation capability is the most significant factor in determining the fire protection features needed to achieve an acceptable level of life safety. A facility that houses a group with a normal ability to respond may need little protection beyond that of other residential occupancies. In buildings housing people who respond slowly, a protection system that provides extra time to react and evacuate may be adequate. Groups that cannot be expected to evacuate to safety unaided may need a defend-in-place protection system.

One might suspect that, over a period of time, all facilities may house residents who are incapable of evacuation, so that protection for the worst situation should be provided. This approach is valid in the instance of homes for the aged, where deteriorating physical and mental conditions are predictable. However, many types of board and care facilities, because of their size and the nature of the services they provide, never deal with people incapable of self-preservation.

For a population with a relatively normal evacuation capability, the most basic system of protection consists of the following:

- Controls to prevent ignition
- Prompt detection
- Means to alert the residents
- Possibly a means of automatically suppressing the fire
- At least two routes of escape
- Prohibiting highly combustible interior finish materials (limiting the rate of fire spread and minimizing the risk of flashover)
- Enclosing vertical openings (limiting the vertical spread of fire and smoke)

For a population that is able to evacuate, but does so slowly or with difficulty, a reasonable system of protection would include all the items listed above, plus the following:

- Stricter controls to prevent ignition
- Early detection and alarm
- A greater need for automatically suppressing the fire
- Exits that are easier to use than those that might be adequate for a more capable population
- Stricter controls on the combustibility of interior finishes
- A greater degree of fire endurance to maintain building integrity during a longer evacuation period
- Compartmentation to confine fire and smoke, thus keeping egress pathways usable during the longer evacuation period
- Greater resistance to the vertical spread of fire and smoke

For a population that is not capable of evacuation, a defend-in-place protection concept would include all the features listed previously, plus the following:

- Sufficient structural fire endurance to allow the building and the internal compartmentation to outlast the fire
- A means of automatically suppressing the fire before it seriously threatens the structure and the compartmentation
- Strict control on furnishings

Note that the code requirements for new board and care facilities are predicated on the assumption that a facility's evacuation capability is impractical.

Fire Detection and Suppression

The means by which ignition and fuel controls are implemented, as well as the occupants' evacuation capability, are critical factors in determining the appropriate level of detection and suppression necessary. Residential sprinklers are the most effective means of increasing life safety. In accordance with NFPA *101* and *NFPA 5000,* a sprinkler system in accordance with one of the following standards may be used in board and care facilities, depending on the size of the facility and, for existing facilities, the evacuation capability of the occupants:

- NFPA 13, *Standard for the Installation of Sprinkler Systems*
- NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*
- NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*

With respect to NFPA 13D, it should be recognized that the water supply duration depends on the evacuation capability rating of the facility and that domestic water demand is not necessarily included. Other exceptions permit sprinklers to be omitted from certain areas such as small closets, bathrooms, attics, and other areas in which fire loss data indicates that fatal fires are less likely to originate. NFPA 13 now mandates the use of either quick response or residential sprinklers for these and all other light-hazard occupancies.

Insurance carriers and applicable codes should be consulted before selecting detection and suppression systems. Preventive maintenance requirements for each type of system should also be considered during the selection and design process. Once installed, inspection, and testing and maintenance of these systems in accordance with applicable NFPA standards is mandatory.

Planning and Training Operations

The facility management must develop an emergency plan that addresses various emergencies or disasters, including fires. The plan should be realistic and capable of being implemented with the minimum resources that may be available, typically during the night. The plan should be coordinated with the local fire department to ensure that their expectations and those of the facility are consistent. The emergency plan must be amended or revised whenever a resident with special needs is admitted to the facility. All staff must understand their responsibilities in the plan and should formally review those responsibilities at least every 2 months.

Capable residents must participate in the training and drills. As discussed above, residents need to be familiar and comfortable with various egress paths available to them. Escape routes used by residents should be routinely alternated during drills so they become familiar with all ways out of the building. Residents should demonstrate the ability to use all egress routes. If windows are used as a secondary means of escape, residents must demonstrate the ability to open them unless staff or other residents are specifically assigned to assist. If assistance is needed, those so assigned must always be present when those needing assistance are present in the building. Local fire departments, fire training schools, and fire marshals' offices may have personnel and audiovisual materials that can assist in staff and resident training. It is important that the training be specific to the facility. This is one area in which board and care facilities have an advantage over other residential occupancies. There can be significantly better control over occupants in these facilities. When properly trained, board and care residents can perform above average during fire drills.

SUMMARY

The number of residential board and care facilities is steadily increasing. The move during the last half century toward reducing populations in psychiatric hospitals, nursing homes, and other types of institutional environments has created a greater need for board and care facilities. Hazards typical of board and care occupancies include structural problems, such as building construction and egress facilities, as well as behavioral problems. Fire protection strategies used in these facilities include ignition control, fuel control, occupant protection, detection and suppression activities, and planning and training operations.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on board and care facilities discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*
NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA *101®*, *Life Safety Code®*
NFPA 101A, *Guide on Alternative Approaches to Life Safety*
NFPA 5000®, *Building Construction and Safety Code®*

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Chapter 3

Hotels and University Housing

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Key Terms

active fire protection systems, automatic sprinkler system, dormitory, false alarm, fire containment, fire-safe cigarette, Greek housing, hotel, Hotel and Motel Safety Act, lodging occupancy, nuisance alarm, occupancy characteristics, occupant characteristics, residence hall, smoke control system, university housing, unwanted alarm

In NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®, requirements for hotels and dormitories are located in the same chapters. NFPA *101* and *NFPA 5000* definitions for hotel and dormitory are as follows:

Hotel—A building or groups of buildings under the same management in which there are sleeping accommodations for more than 16 persons and primarily used by transients for lodging with or without meals

The definition of *hotel* is further refined in NFPA *101* and *NFPA 5000* to include hotel, inn, club, motel, bed-and-breakfast, or any other structure meeting the foregoing definition of hotel.

Dormitory—A building or a space in a building in which group sleeping accommodations are provided for more than 16 persons who are not members of the same family in one room or a series of closely associated rooms under joint occupancy and single management, with or without meals, but without individual cooking facilities.

It is important to note that the definition for dormitory that is used by the National Fire Incident Reporting System (NFIRS) includes occupancies other than just the typical dormitory found on campuses across the country. It includes military barracks, monasteries, and nursing quarters. For this reason, the statistics generated since 2000 for "dormitories" are no longer only applicable to university housing.

As used in this chapter, *university housing* includes dormitories or residence halls and Greek housing (whether on or off campus) in addition to apartments and houses.

See also Section 20, Chapter 1, "Assessing Life Safety in Buildings"; and Section 20, Chapter 4, "Apartment Buildings."

FIRE SAFETY IN HOTELS

Hotel Fire Record

The May 1981 issue of *Fire Journal,* NFPA's membership publication now titled *NFPA Journal,* provided a bleak summary of multiple-fatality hotel fires in the United States reported to NFPA since 1934. The article also contained an analysis of the fire scenarios involved in 170 fatal hotel fires experienced in the previous decade.

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The *Fire Journal* article followed these four landmark hotel fire incidents in North America that occurred between November 1980 and February 1981:

- MGM Grand Hotel (Las Vegas, Nevada, November 1980)
- Stouffers Inn (Harrison, New York, December 1980)
- Inn on the Park (North York, Ontario, Canada, January 1981)
- Hilton Hotel (Las Vegas, Nevada, February 1981)

These four hotel fires resulted in 125 civilian deaths as well as injuries to hundreds of civilians and scores of fire fighters.

As shown in Table 20.3.1, fire deaths of this magnitude, within such a short period of time, had not occurred in North American hotels in almost four decades. Previously, between June 1946 and December 1946, nearly 200 fatalities were recorded in three notorious fatal hotel fires, including the LaSalle Hotel in Chicago and the Winecoff Hotel in Atlanta.

The large scale of the fire incidents in the early 1980s shook public confidence in the lodging industry and prompted industry experts and regulatory authorities to reconsider the life safety strategies used for hotel occupancies.

The review of fire scenarios clearly showed the need to emphasize protection of the sleeping-room areas of hotels. Smoking materials and intentionally set fires were the leading ignition factors in the data set of fires reviewed.

Unlike the period following the 1946 incidents, fire suppression and detection technology had evolved by the early 1980s to provide tools to effectively protect building occupants in the incipient stages of a fire. These technologies, complemented by cooperative fire safety research into industry-specific solutions, coupled with public expectations regarding fire safety, resulted in significant changes to building and fire safety codes in the United States, as applied to hotels.

Evolution of Life Safety Strategies for Hotels

Prior to the landmark fires of the early 1980s, little emphasis was placed on the use of automatic sprinklers in hotels. Reliable, commercially viable, early-warning fire detection technology did not exist until the latter part of the twentieth century. Further, although fire research had been ongoing for decades, application to residential settings was limited.

TABLE 20.3.1 Summary of Fire Incidents, Hotel Fires in the United States, as Reported to NFPA, with Ten or More Fatalities, 1934–2005

City	*Hotel*	*Date*	*Deaths*
Lansing, MI	Kerns Hotel	December 1934	32
Atlanta, GA	Terminal Hotel	May 1938	35
Minneapolis, MN	Marlborough Hotel	January 1940	19
Houston, TX	Gulf Motel	September 1943	54
Chicago, IL	LaSalle Hotel	June 1946	61
Dubuque, IA	Canfield Hotel	June 1946	19
Atlanta, GA	Winecoff Hotel	December 1946	119
Chicago, IL	Barton Hotel	February 1955	29
Atlantic City, NJ	Surfside Hotel	November 1963	25
Jacksonville, FL	Hotel Roosevelt	December 1963	22
St. Paul, MN	Hotel Carlton	January 1966	11
Boston, MA	Paramount Hotel	January 1966	11
Anchorage, AK	Lane Hotel	September 1966	14
Seattle, WA	Ozark Hotel	March 1970	20
Los Angeles, CA	Ponet Square Hotel	September 1970	19
Tucson, AZ	Pioneer International	December 1970	28
Tyrone, PA	Pennsylvania House Hotel	January 1972	12
Berkely Springs, WV	Washington House	August 1974	12
Portland, OR	Pomona Hotel	July 1975	11
Fremont, NE	Pathfinder Hotel	January 1976	20
Breckenridge, MN	Stratford Hotel	January 1977	17
Bay City, MI	Wenonah Park Hotel	December 1977	10
Kansas City, MO	Coates House Hotel	January 1978	20
Honesdale, PA	Allen Motor Inn	November 1978	12
Greece, NY	Holiday Inn	November 1978	10
Cambridge, OH	Holiday Inn	July 1979	10
Las Vegas, NV	MGM Grand Hotel	November 1980	85
Harrison, NY	Stouffers Inn	December 1980	26
Houston, TX	Hilton Hotel	March 1982	12
San Juan, PR	Dupont Plaza	December 1986	97

Source: NFPA's archive files, *The1984 Fire Almanac,* and NFPA's Fire Incident Data Organization database.

The January 1930 issue of *NFPA Quarterly* provided a summary of numerous hotel fires experienced within the United States during the prior 30-year period. Based on this experience, several hotel fire safety requisites were summarized by the *Quarterly,* including the need for fire-resistive construction, the provision of proper exits, the protection of vertical openings, the use of fire walls, and the provision of fire alarm facilities.

The article summarized nearly 100 hotel fire incidents that occurred between 1910 and 1928 where automatic sprinklers were present. Despite a significant success rate for control and suppression of fires (72 of 76 incidents where sprinklers activated were extinguished with not more than four sprinklers), sprinkler installation was listed below construction features in the summary of hotel fire safety requisites.

Automatic sprinklers were recommended for the entire building "where possible," but otherwise, complete coverage was only considered mandatory for buildings of combustible construction or in limited hazardous areas such as kitchens and basements.

By the mid-1980s the effectiveness of automatic sprinkler protection was recognized. In testimony provided to a science subcommittee of the U.S. House of Representatives in 1988, Rolf Jensen, in his capacity as president of the Society of Fire Protection Engineers, observed that the twentieth-century history of fatal fire incidents in hotels involved "fast fires," killing "large numbers of people in a single incident." Mr. Jensen's testimony detailed the progress that had been made to develop sprinkler technology that could be effectively applied to hotels as well as other residential structures.

Code and Legislative Developments Related to Sprinkler Systems in Hotels

The 1976 edition of NFPA *101* reflected the decades-old protective philosophy discussed previously and contained no specific requirement for automatic sprinklers in hotels. Requirements for smoke detection systems were limited to corridors in new facilities.

NFPA *101* was amended in 1988 to require the installation of automatic sprinklers in new and existing high-rise hotels. By 1990, each of the United States model building codes also required this level of protection, with the Uniform Building Code requiring new hotels with 20 or more sleeping rooms, regardless of height, to be protected with automatic sprinklers.

Three decades following the publication of the 1976 edition of NFPA *101*, the 2006 edition emphasizes the use of active fire protection systems, notably automatic sprinklers, in hotels. With limited exceptions for smaller properties or those hotels with guest-room entrances leading directly to the exterior, NFPA *101* and *NFPA 5000* require full sprinkler protection for new hotels.

Several states, including large tourism states such as Nevada and Florida, legislated retroactive fire protection requirements for certain existing lodging establishments, generally high-rise hotels. In the 1980s, the states of Alaska, California, and New Jersey exempted fire protection system installations from taxation by virtue of either a tax credit (Alaska) or a property tax exemption (California and New Jersey), thus easing the financial cost of such improvements in existing buildings including hotels.

In 1989, NFPA issued a new sprinkler standard, NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height,* aimed at making sprinkler protection more affordable for low-rise, residential-use buildings. NFPA 13R, combined with the development and listing of chlorinated polyvinyl chloride (CPVC) and polybutylene (PB) sprinkler pipe, reduced the cost of sprinkler installation, especially in existing hotels.

In 1990, Congress enacted the Hotel and Motel Fire Safety Act of 1990 (Public Law 101-391). This statute brought the power of the federal government's purse to bear on the lodging fire safety issue by limiting meetings in lodging establishments by federal agencies to hotels and motels that met the fire safety requirements outlined in the act. Individual federal employees on official travel were also limited, after a phase-in period, to staying only in lodging facilities that also met these requirements.

Industry Response to Hotel Fires

In addition to code and legislative changes, the hotel industry responded to the fire challenge experienced in the early 1980s. In 1987, in cooperation with leading hotel firms, NFPA formed the Lodging Industry Membership Section to provide a forum and focus within the association for the industry's voice and needs.

The automatic sprinkler industry developed equipment specifically devised for life safety protection. As new "quick-response" sprinkler technology and fire detection capability were developed, many hotel owners and operators voluntarily retrofitted new protective systems into existing buildings as well as new construction projects.

By 1988, and noted in the first large-scale study of fire safety in the lodging industry conducted by the American Hotel and Motel Association, now the American Hotel and Lodging Association, almost universal usage of smoke alarms within hotel guest rooms was reported. The study also noted that about half of all hotel rooms were equipped with automatic sprinklers, with the number rising to about two-thirds when only high-rise hotels were considered.[1]

As evidenced by Table 20.3.2 covering the years 1980 to 2002, there was a downward trend in reported lodging industry fire incidents, losses, and most importantly, casualty figures.

The effectiveness of automatic sprinklers in hotels can be seen in Table 20.3.3. For the years 1994 to 1998, estimates show a 100 percent reduction in fatalities per 1000 fires with automatic fire suppression systems present.

Improvements to fire loss statistics have occurred despite an unparalleled building boom in the 1990s when thousands of new hotels were constructed. (See *Lodging Profile.*[1])

Recent Lodging Industry Fire Experience

For the years 1999 to 2002, data developed by NFPA suggest that three factors—cooking equipment, smoking materials, and arson—are today's leading causes of fatal fires in hotels and motels. See Tables 20.3.4 and 20.3.5.

TABLE 20.3.2 Structure Fires in Hotels and Motels, by Year: 1980–2002

Year	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage (in Millions of Dollars) As Reported	Direct Property Damage (in Millions of Dollars) In 2002 Dollars
1980	12,530	80	752	63.7	139.2
1981	12,880	148	719	69.5	137.3
1982	10,240	52	587	42.2	78.6
1983	9,550	73	562	103.2	186.2
1984	9,670	34	538	65.6	113.4
1985	9,310	85	412	74.0	123.5
1986	8,790	57	416	74.4	122.2
1987	8,210	54	430	70.6	111.7
1988	8,230	35	382	85.1	129.5
1989	7,710	24	333	68.2	99.0
1990	7,090	54	496	70.3	96.9
1991	6,610	22	372	84.8	111.9
1992	6,530	26	395	63.5	81.4
1993	6,140	62	456	63.9	79.5
1994	5,890	28	349	59.3	72.0
1995	5,460	36	299	71.5	84.4
1996	5,610	43	332	110.6	126.9
1997	5,010	21	284	81.6	91.4
1998	4,750	24	257	55.3	61.1
1999	4,610	24	249	124.6	134.4
2000	4,830	11	170	82.8	86.6
2001	4,590	12	217	59.3	60.2
2002	4,180	16	138	77.1	77.1

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten; civilian deaths and injuries are rounded to the nearest one; and direct property damage is rounded to the nearest hundred thousand dollars.

Source: NFIRS and NFPA survey. Inflation adjustments were based on U.S. Census Bureau's *Statistical Abstract of the United States: 2006,* "Table 705, Purchasing Power of the Dollar."

TABLE 20.3.3 Automatic Suppression Systems in Hotel and Motel Fires Reported to Public Fire Departments: 1994–1998 Annual Averages

Percentage of fires in buildings with automatic suppression system	34%
Deaths per 1000 fires with automatic suppression system	0.0
Deaths per 1000 fires with no automatic suppression system present	7.7
Reduction in deaths per 1000 fires when automatic suppression systems were present	100%
Average loss per fire when automatic suppression system was present	$7,160
Average loss per fire with no automatic suppression system	$15,320
Reduction in loss per fire when automatic suppression systems were present	53%

Source: National estimates based on NFIRS and NFPA survey. 1998 is the most current data available.

Cooking Equipment. Changes to cooking equipment and oils have led to the development of more effective means to control cooking fires, notably advances in wet chemical fixed extinguishing systems. As with any commercial kitchen, hotel kitchens require the installation of fire suppression equipment effective for the hazard present.

Smoking Materials. For smoking, research[2] authorized by Congress pursuant to the 1990 Fire Safe Cigarette Act and undertaken by the National Institute of Standards and Technology (NIST) concluded that the commercial production of a relatively fire-safe cigarette was feasible. Although regulation at the federal level has not passed legislation, several states have introduced requirements limiting the sale of cigarettes to only those cigarettes that were deemed fire safe effective in January 2003.

Faced with the possibility of having to produce different cigarettes for different states, the nation's largest producer of cigarettes, the Altria Corporation (formerly Philip Morris) took the position that all such cigarettes should be fire safe.[3] With that

TABLE 20.3.4 Leading Causes of Structure Fires in Hotels and Motels: 1999–2002 Annual Averages

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Cooking equipment fire	1060	(23%)	0	(0%)	37	(19%)	14.0	(16%)
Identified cooking equipment	770	(17%)	0	(0%)	35	(18%)	10.2	(12%)
Confined cooking fire	290	(6%)	0	(0%)	2	(1%)	3.7	(4%)
Smoking materials	710	(16%)	9	(56%)	45	(23%)	7.0	(8%)
Intentional	530	(12%)	6	(37%)	35	(18%)	24.7	(29%)
Heating equipment	440	(10%)	3	(17%)	14	(7%)	4.1	(5%)
Identified heating equipment	380	(8%)	3	(17%)	13	(7%)	4.0	(5%)
Confined chimney or flue fire	30	(1%)	0	(0%)	0	(0%)	0.0	(0%)
Confined fuel burner or boiler malfunction or fire	30	(1%)	0	(0%)	1	(0%)	0.1	(0%)
Clothes dryer or washer	430	(9%)	0	(0%)	21	(11%)	1.9	(2%)
Electrical distribution or lighting equipment	360	(8%)	1	(7%)	15	(8%)	9.3	(11%)
Candle	120	(3%)	0	(0%)	10	(5%)	1.8	(2%)
Torch, burner, or soldering iron	80	(2%)	0	(0%)	6	(3%)	3.0	(3%)
Exposure to other fire	80	(2%)	0	(0%)	0	(0%)	4.7	(6%)
Contained trash fire	100	(2%)	0	(0%)	0	(0%)	0.0	(0%)

Note: These are the leading causes, obtained from the following list: intentional (from the NFIRS field "cause"); playing with fire (from factor contributing to ignition); confined heating (including confined chimney and confined fuel burner or boiler fires), confined cooking, and contained trash or rubbish (from incident type); identified heating, identified cooking, clothes dryer or washer, torch (including burner and soldering iron), electrical distribution and lighting equipment, medical equipment, and electronic, office, or entertainment equipment (from equipment involved in ignition); smoking materials, candles, lightning, and spontaneous combustion or chemical reaction (from heat source); and mobile property involved (from mobile property involved in ignition). Exposure fires include fires with an exposure number greater than zero, as well as fires identified by heat source or factor contributing to ignition when no equipment was involved in ignition that were not intentionally set. The same fire can be listed under multiple causes, based on multiple data elements.

These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten; civilian deaths and injuries are rounded to the nearest one; and direct property damage is rounded to the nearest hundred thousand dollars. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey.

change in position and with additional research by NIST,[4] new legislation[5] was introduced in April 2002 by Senators Richard Durbin (D-Ill.) and Sam Brownback (R-Kan.) and Rep. Edward Markey (D-Mass.) to effect such change. For current information about the changing status of legislation to require fire-safe cigarettes, see http://firesafecigarettes.org.

Arson. As for arson, its traditional rationales include arson for profit, revenge, and emotional disturbance. The 1990s saw a new dimension: arson as a weapon in domestic terrorism. Although yet to strike the hotel industry, arson as a means to express a political philosophy adds a new rationale for ensuring the reliability of fire protection equipment and systems and for a stronger hotel emergency team to ensure the security of lodging occupants and establishments. Arson is a difficult crime to prevent. Typically, the industry steps up its security measures in times of difficult labor relations, political unrest, when controversial individuals or groups meet or stay at a particular hotel, and so forth. Properties will add cameras to their perimeter surveillance systems and increase security patrols during such times.

ACTIVE FIRE PROTECTION SYSTEMS AND EQUIPMENT IN HOTELS

Industry experience, for nearly a century, underscores the need for the installation of adequately designed and maintained active fire protection systems and equipment in hotels. These systems can include fire alarm systems, automatic sprinkler systems, and smoke control systems, as well as smoke alarms and kitchen fire suppression systems. This chapter will briefly discuss fire alarm systems, automatic sprinkler systems, and smoke control systems for use in hotels. For information on smoke alarms, see Section 14. Also see Section 17, Chapter 2, "Chemical Extinguishing Agents and Application Systems."

Selection of the proper system or systems will depend in large measure on the size and configuration of the property.

Fire Alarm Systems

A fundamental design parameter for fire alarm systems in lodging occupancies is that most building occupants are transient

TABLE 20.3.5 Structure Fires in Hotels and Motels by Equipment Involved in Ignition: 1999–2002 Annual Averages

Equipment Involved	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
No equipment involved	1780	(39%)	12	(76%)	88	(45%)	49	(58%)
Clothes dryer or washer	430	(9%)	0	(0%)	21	(11%)	2	(2%)
Range or cooking surface	430	(9%)	0	(0%)	16	(8%)	2	(2%)
Confined cooking fire	290	(6%)	0	(0%)	2	(1%)	4	(4%)
Lamp, bulb, or lighting	120	(3%)	0	(0%)	1	(0%)	2	(2%)
Wiring, switch, or outlet	120	(3%)	1	(7%)	3	(2%)	5	(6%)
Fixed area heater	120	(3%)	0	(0%)	4	(2%)	1	(1%)
Unclassified kitchen or cooking equipment	100	(2%)	0	(0%)	5	(3%)	4	(5%)
Contained trash or rubbish fire	100	(2%)	0	(0%)	0	(0%)	0	(0%)
Portable cooking or warming equipment	90	(2%)	0	(0%)	6	(3%)	0	(0%)
Torch, burner, or soldering iron	80	(2%)	0	(0%)	6	(3%)	3	(3%)
Oven or rotisserie	80	(2%)	0	(0%)	5	(2%)	0	(1%)
Unclassified heating, ventilating and air conditioning, other	80	(2%)	0	(0%)	5	(2%)	0	(1%)
Air conditioner	80	(2%)	0	(0%)	3	(1%)	0	(1%)
Unclassified equipment involved in ignition	60	(1%)	0	(0%)	3	(2%)	0	(1%)
Central heat or boiler	60	(1%)	0	(0%)	0	(0%)	0	(1%)
Water heater	60	(1%)	3	(17%)	4	(2%)	1	(1%)
Cord or plug	50	(1%)	0	(0%)	9	(5%)	1	(1%)
Fireplace or chimney	50	(1%)	0	(0%)	0	(0%)	0	(0%)
Confined chimney fire	30	(1%)	0	(0%)	0	(0%)	0	(0%)
Confined fuel burner or boiler fire or malfunction	30	(1%)	0	(0%)	1	(0%)	0	(0%)
Elevator or lift	30	(1%)	0	(0%)	0	(0%)	0	(0%)
Unclassified portable appliance designed to produce heat	20	(1%)	0	(0%)	1	(0%)	0	(0%)
Steam table or warming drawer or table	20	(1%)	0	(0%)	0	(0%)	0	(0%)
Other known equipment	230	(5%)	0	(0%)	14	(7%)	9	(10%)
Other confined fire	10	(0%)	0	(0%)	0	(0%)	0	(0%)
Total	4550	(100%)	16	(100%)	194	(100%)	86	(100%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten; civilian deaths and injuries are rounded to the nearest one; and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation.

Nonconfined fires in which the equipment involved in ignition was unknown or not reported have been allocated proportionally among fires with known equipment involved. Sums may not equal totals due to rounding errors.

Source: NFIRS and NFPA survey.

users of the buildings. Little detailed knowledge of the building should be assumed, as numerous guests use a given hotel for as little as a single night. In numerous labor markets within the United States, employee turnover rates can be significant, thereby also limiting the number of individuals within a hotel with detailed knowledge of the building.

High-rise hotels and large campus-type properties will require the use of addressable technology and voice technology to efficiently pinpoint fire incidents and effectively notify guests and employees of an emergency.

The installation of fire alarm systems in hotels will typically be subject to the requirements of *NFPA 72®*, *National Fire Alarm Code®*, which is widely referenced by model building codes. Notification devices, both audible and visual, must account for the fact that occupants may need to be alerted to a fire emergency from a deep-sleep condition.

Automatic Sprinkler Protection

With few exceptions, the installation of sprinkler protection throughout all portions of newly constructed hotels, regardless of their height, has become a general requirement in most building codes. Of particular importance for the protection of smaller hotels and dormitories is NFPA 13R, which may provide for more economical design and installation of automatic sprinkler systems in low-rise residential occupancies.

Once installed, automatic sprinkler protection should be inspected, tested, and maintained in strict accordance with NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems.* As automatic sprinkler systems age, it is imperative that piping, valves, and related hardware be maintained in working order, that fire pumps and water supplies remain within design tolerance, and that as modifications are made to the underlying building, sprinkler protection changes reflect these changes.

Smoke Control Systems

For high-rise and atrium hotels, smoke control concepts, including stairway pressurization and smoke exhaust, play an important role in mitigating initial smoke production from fires until sprinklers activate and make any staged evacuation tenable. NFPA *101* and *NFPA 5000* permit atria in hotels and dormitories, provided that they meet certain conditions. Included in these conditions are the requirements for properly designed automatic sprinkler protection and either an engineering analysis to show that the building is designed to keep the smoke layer interface above the highest unprotected opening to adjoining spaces, or 6 ft (183 cm) above the highest floor level of exit access open to the atrium, or that it has an engineered smoke control system that will do the same. The design parameters for smoke control systems and the engineering methods used for the analysis can be found in NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences,* and NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces.*

FIRE SAFETY IN UNIVERSITY HOUSING

Overview of University Housing

As used in this chapter, *university housing* includes dormitories (more accurately known as *residence halls*), university-owned apartments and houses (whether located on or off campus), and on- and off-campus Greek housing (whether owned by the university, fraternity, or sorority). For the purposes of this chapter, colleges and universities are generically referred to as "universities."

On-campus university housing consists of dormitories/residence halls, university-owned apartments, and houses. Some Greek houses are university owned, whereas others are owned by the fraternity or sorority. In some cases, the building may be privately owned and is rented by the local chapter. The capacity of residence halls at these institutions is approximately 15 percent of the 17 million students enrolled.[6]

According to the U.S. Department of Education, there were more than 4000 degree-granting colleges and universities in the United States[6] and it was projected that more than 17 million students enrolled in 2- and 4-year institutions in the fall of 2006.[7] For many of these students, this was their first time living away from home, meeting new friends, and having new experiences.

Fire Deaths in the University Environment

Unfortunately, over the years we have seen that tragedy can strike these students. According to information compiled by Campus Firewatch from January 2000 to April 2007, at least 109 people died in student housing fires. Over 80 percent of the fire deaths occurred in off-campus houses and apartments and the remainder occurred either in residence halls or fraternity houses (i.e., in Greek housing). Clearly, the predominant fire-death risk is in the off-campus environment (Table 20.3.6).

Occupancy and Occupant Characteristics

University years are a period when young adults have a sense of invulnerability. A number of factors come together in campus environments that create a potentially high-risk environment.

Close Quarters. There is a greater density of people living in close proximity to one another, both on and off campus. This creates a situation in which the actions of one person can potentially endanger a greater number of people than would otherwise be expected.

Risky Behavior. Young adults tend to engage in risky behaviors, such as drinking, that contribute to the incidence of fire. Alcohol consumption has long been connected with college campuses. Although the recent trend is toward educating students in more responsible behavior, the problem still exists. The connection between alcohol consumption, student behavior, and the incidence of fires in student housing, both on and off campus, is a serious concern.

Currently, there is no known research that definitively connects impaired judgment from alcohol consumption to fire risk in the student demographic. However, in speaking with fire chiefs across the country in college communities, there is no question that there is a definite correlation between the two. In a number of the incidents identified by Campus Firewatch, alcohol has played a factor. This is further reinforced in a study conducted by *USA TODAY* for an article on campus-related fires.[8]

Level of Scrutiny. Although on-campus housing facilities tend to be more regulated and monitored, off-campus housing facilities are subject to a lower level of scrutiny and a potentially lower level of fire safety.

Dormitories/Residence Halls

Note that in NFIRS, the classification "dormitories" includes school, college, and university dormitories; nurses' quarters;

TABLE 20.3.6 Summary of Fire Deaths in the University Environment

City	*University*	*Date*	*Type of Housing*	*Deaths*
East Orange, NJ	Seton Hall University	1/19/00	Residence hall	3 students
Bloomsburg, PA	Bloomsburg University	3/19/00	Fraternity	3 students
Cambridge, MA	Massachusetts Institute of Technology	4/10/00	Residence hall	1 student
Decatur, IL	Millikin University	6/8/00	Fraternity	1 student
Berkeley, CA	University of California	8/20/00	Off-campus	1 student and her 2 parents
Pittsburgh, PA	University of Pittsburgh	9/29/00	Off-campus	1 student
Baytown, TX	Lee College	11/16/00	Off-campus	1 student
New York, NY	New York University	11/22/00	Off-campus	1 student
Dayton, OH	University of Dayton	12/10/00	Residence hall	1 student
Morgantown, WV	West Virginia University	1/1/01	Off-campus	1 student
Athens, GA	University of Georgia Law School	1/19/01	Off-campus	1 student
Berkeley, CA	University of California	1/30/01	Off-campus	1 student
Binghamton, NY	Binghamton University	2/26/01	Off-campus	1 student
Austin, TX	University of Texas	5/1/01	Off-campus	1 student
Cleveland Heights, OH	John Carroll University	5/19/01	Off-campus	1 student
Athens, OH	Ohio University	5/19/01	Off-campus	1 student and 1 guest
Emporia, KS	Emporia State University	7/29/01	Off-campus	1 student and her son
Morgantown, WV	University of West Virginia	8/18/01	Off-campus	1 student
Anderson, IN	Anderson University	8/30/01	Off-campus	1 student
Lexington, KY	University of Kentucky	9/1/01	Off-campus	1 student
Fort Wayne, IN	Ivy Tech State College	9/30/01	Off-campus	1 student and her son
Salisbury, NC	Catawba College	10/28/01	Residence hall	1 student
Richmond, VA	Virginia Commonwealth University	11/2/01	Off-campus	1 student and her 2 children
Greensboro, NC	University of North Carolina–Greensboro	2/15/02	Off-campus	4 students
Narragansett, RI	University of Rhode Island	7/17/02	Off-campus	1 student
Houghton, MI	Michigan Tech University	8/13/02	Fraternity	1 student
Bloomington, IN	Indiana University	12/3/02	Off-campus	1 student
Medford, MA	Tufts University	1/18/03	Off-campus	1 student
Greenville, NC	Eastern Carolina University	2/18/03	Off-campus	2 students
Meadville, PA	Allegheny College	2/22/03	Off-campus	1 student
Cape Girardeau, MO	Southeast Missouri State University	3/11/03	Off-campus	1 student
Amherst, MA	University of Massachusetts	4/5/03	Off-campus	1 student
Columbus, OH	Ohio State University and Ohio University	4/13/03	Off-campus	5 students
Bowling Green, KY	Western Kentucky University	5/4/03	Residence hall	1 student
Minneapolis, MN	University of Minnesota–Twin Cities	9/20/03	Off-campus	3 students
Undetermined[a]	West Virginia University	9/22/03	Off-campus	1 student
Baton Rouge, LA	Louisiana State University	10/18/03	Off-campus	1 student
Ames, IA	Iowa State University	3/8/04	Off-campus	1 student
Bloomington, IN	Indiana University	5/22/04	Off-campus	3 students
College Station, TX	Texas A&M University	7/31/04	Residence hall (married student housing)	A student's daughter and mother
Savannah, GA	Savannah College of Art and Design	8/19/04	Off-campus	1 student
Oxford, MS	University of Mississippi	8/27/04	Fraternity	3 students
Washington, DC	Georgetown University	10/17/04	Off-campus	1 student
Oxford, OH	Miami University	4/10/05	Off-campus	3 students
State College, PA	Penn State	4/24/05	Off-campus	1 student
Collegedale, TN	Southern Adventist University	4/26/05	Residence hall	1 student

TABLE 20.3.6 Continued

City	*University*	*Date*	*Type of Housing*	*Deaths*
College Park, MD	University of Maryland	4/30/05	Off-campus	1 student
Chicago, IL	Conservatory of Recording Arts and Sciences (NOTE: The students were on an internship in Chicago.)	6/7/05	Off-campus	3 students
Raleigh, NC	North Carolina State University	10/7/05	Off-campus	2 students
Lawrence, KS	University of Kansas	10/7/05	Off-campus	1 student
College Park, MD	University of Maryland	1/24/06	Off-campus	1 student
Pittsburg, KS	Pittsburg State University	2/11/06	Off-campus	2 guests
Lincoln, NE	University of Nebraska–Lincoln	2/15/06	Off-campus	1 student and her child[b]
Anchorage, AK	University of Alaska	2/26/06	Off-campus	1 student and 1 nonstudent
Coos Bay, OR	Southwestern Oregon Community College	4/26/06	Academic building	1 student
Ithaca, NY	Cornell University	5/13/06	Off-campus	1 student
Stillwater, OK	Oklahoma State University	7/30/06	Off-campus	1 student
Pittsburgh, PA	University of Pittsburgh	11/4/06	Off-campus	1 student
Lincoln, NE	Nebraska Wesleyan University	11/17/06	Fraternity	1 student
St. Louis, MO	University of Missouri–St. Louis	11/29/06	Fraternity	1 student
Huntington, WV	Marshall University	1/13/07	Off-campus	3 students and 2 siblings who were visiting a student
Linwood, MS	University of Mississippi–Meridian	2/3/07	Off-campus	1 student, her husband, and her daughter
Weldon, NC	Halifax Community College	2/12/07	Off-campus	1 student
Boston, MA	Boston University	2/24/07	Off-campus	2 students
Farmville, VA	Longwood University	3/3/07	Off-campus	2 students
Boston, MA	Boston University	3/16/07	Off-campus	1 student[c]
Cincinnati, OH	Cincinnati State	4/21/07	Off-campus	1 student[d]

[a]The city where the death occurred could not be determined. The student was living in a trailer.
[b]The woman was scheduled to deliver her child three hours after the fire occurred. Since the fetus was full-term, the Lincoln Fire Department classified this as two fire deaths.
[c]The victim was from Bloomsburg University and was visiting two BU students when the fire occurred.
[d]The victim had been enrolled at Cincinnati State until the semester before the fire. He was reportedly taking this semester off and he stayed in Cincinnati, living in off-campus student housing.

convent, monastery, and other religious dormitories; and bunkhouses and workers' barracks. For this reason, statistics are not available specific to the occurrence of fires in university residence halls.

The types of dormitories/residence halls that are found on campuses can range from wood-frame renovated houses to noncombustible high-rise buildings. More schools are building third-party residence halls as a solution to providing housing. Third-party residence halls are buildings that are built and owned by a private developer but function as residence halls. One vendor, who has buildings on 39 campuses, estimates that there are approximately 30 companies building privately run residence halls.

Fires in residence halls pose a special risk because of the higher concentration of people who live in these buildings—one fire can quickly endanger a large number of occupants.

Residence halls tend to be occupied by younger students, such as freshmen and sophomores. Because housing is limited on a number of campuses, and as they get older, students tend to move off campus into Greek housing or rented houses and apartments.

Since residence halls are under the control of the university, it is possible to impose conditions that can dramatically improve the level of fire safety in these buildings as opposed to off-campus residential occupancies. These can include the following:

- Regulating the combustibility of contents such as furniture, wall, and floor finishings
- Regulating appliances such as microwaves, refrigerators, and so on
- Regulating the use of open flames, including candles, incense, and smoking

Many residence halls have staff assigned to them to help the students, often referred to as resident assistants, or RAs. This staff is generally made up of older students who live in the building and have received training in a variety of different areas. RAs can serve a vital role in fire safety since they are living in the

building and can identify any potential hazards and assist in ensuring that students understand the importance of fire safety and the dangers of tampering with fire protection equipment.

The residence hall physical plant can be maintained to a consistent level of fire safety by the university as opposed to off-campus housing in the community. Dangerous conditions can be corrected properly.

Students who live in residence halls are subject to stricter behavior guidelines than off-campus students. When students move into a residence hall, they are often provided with information regarding expected behavior, what comprises a violation, and the penalties that can follow. Because of the presence of university staff in these buildings, it is more likely that violators can be identified and either counseled or penalized as necessary. If a student's actions are serious enough, the student can be removed from the residence hall altogether.

Apartments and Houses

Because of the lack of existing on-campus dormitory space, some institutions are either building or purchasing off-campus apartment complexes to provide student housing. In other cases, the school may be buying private houses to serve the same function. Although these structures may be "off campus," since the institution owns them, they should be provided the same fire protection as dormitories/residence halls.

Greek Housing

In the Greek system, the fire-death problem clearly lies within the fraternity community rather than the sororities. From 1990 to May 2006, there has been only 1 fire fatality in a sorority versus 27 within fraternities, according to information compiled by NFPA and Campus Firewatch.

Because of the recognized problem with fires in Greek occupancies, a number of communities, as well as the state of New Jersey, have passed ordinances and laws requiring that they be equipped with automatic fire sprinklers. Some fraternal organizations are taking it upon themselves to install sprinklers in their properties nationwide, recognizing the importance and value of these systems.

"Circle of Life" Approach to University Fire Safety

A comprehensive approach to fire safety for students living in residence halls and Greek housing is needed. As part of this approach, it is important to remember that the education and training that are provided will also give students the fire safety tools they need to protect them when they move off campus, where almost 80 percent of the fire fatalities do occur.

The solutions to fire safety problems in universities often are not unique. What is unique is the environment in which they must be employed. An approach developed by Campus Firewatch involves the four following components that are collectively known as the "Circle of Life" and includes:

- Prevention
- Detection
- Containment
- Suppression

FIRE PREVENTION ISSUES IN UNIVERSITY HOUSING

For general information on fire prevention, see Section 1, Chapter 5, "Fire Prevention and Code Enforcement."

There is a unique challenge in the campus environment to educate and train the students. People of this age have a sense of invulnerability that can be difficult to overcome and convince them of the risk they face from fire. For this reason and other reasons, it is important to ensure that the environment around them is as fire safe as possible, so if they should involve themselves in risk-taking behavior, or if a fire should occur, the effects of it can be minimized. For example, there should be sufficient exits that are properly marked and illuminated. If there are fire safety design features, such as fire doors that are routinely propped open for convenience, then the university or landlord should evaluate strategies to stop this practice from occurring.

The basic fire prevention strategies in university housing are to do the following:

- Reduce fuel load
- Reduce ignition sources
- Enforce good housekeeping
- Educate students about the fire protection features of their housing

Reducing Fuel Load

The fuel load in a fire comprises the structure, its interior finish materials, and the contents that are placed inside of the structure.

Structure. Many residence halls that are built today are made up of noncombustible materials. This construction helps to reduce the fire load significantly and also helps to compartmentalize the building, limiting fire spread. However, there are many older buildings, either built as residence halls or converted into residence halls, which are constructed of combustible materials. Reduced ignition sources, good housekeeping practices, and student fire safety education are particularly important in these combustible structures.

Interior Finish. For a general discussion of interior finish, see Section 18, Chapter 2, "Interior Finish."

Interior finish can, and has, played a significant role in the spread of fires in university housing. At the Chapel Hill fraternity fire, the wood paneling on the walls was identified as a significant contributing factor to the spread of the fire from the basement to the second floor. Universities and landlords should be cognizant of the materials used inside of the buildings and how they may contribute to the fire spread.

Contents. Furniture represents much of the fuel load in student housing. In an environment where it is possible to control the type of furniture, such as residence halls, appropriate flamma-

bility and combustibility criteria should be followed. Personal contents such as clothes and books that students bring cannot be regulated and should be considered a part of the normal fuel load in any student housing occupancy.

Students may personalize or decorate areas using combustible materials. This situation can especially be a problem during holidays. For example, at the Providence College fire in 1977 where 10 students were killed, the combustible decorations on the corridor walls were identified as a significant factor in the fire spread. A Halloween decorating contest at Seton Hall, months after the fatal fire at that university, was stopped by the fire department because of the accumulation of combustible materials, including hay, in the corridor.

Reducing Ignition Sources

In the university housing environment, control of smoking hazards, electrical hazards, and cooking hazards can be particularly helpful in reducing ignition sources.

Smoking. Many universities have implemented no-smoking policies in their residence halls, often in response to public health concerns. The fire safety professional should be concerned with students attempting to circumvent no-smoking regulations, especially during colder weather when people are more reluctant to go outside to smoke. In order to smoke in their rooms, students sometimes disable smoke detectors or find alternative locations to smoke within the building. This can lead to a fire breaking out in areas that may not normally be inhabited, such as stairwells or utility closets.

Electrical. Electrical equipment represents a significant concern in the university housing environment. Many residence halls and Greek houses were built prior to the advent of computers, microwaves, stereos, televisions, and other electrical equipment that students commonly possess. Two problems arise because of increased electrical needs.

First, a room, house, or facility may not have sufficient electrical capacity to provide the required power, which may cause the electrical system to overload. If circuit breakers continually trip, the occupants may try to circumvent such safety features to ensure that power is not interrupted. For example, occupants may run extension cords from other areas into their living space to power the equipment, leading to problems such as worn or frayed cords or overloaded circuits in another area.

Second, if there are not enough outlets, occupants are likely to use extension cords and power taps (commonly known as "power strips"). The use of such devices creates problems, such as the following:

- Overheated electrical cords that may be coiled or bunched up, creating a potential ignition source
- Physical damage—electrical cords that are run under carpet and around furniture in such a way that they can become damaged or worn, exposing bare conductors
- Overloading—even though occupants may use power strips equipped with individual circuit breakers, the circuit is not necessarily adequately protected

Halogen torchiere lamps have been a concern in residence halls and Greek housing because of the high temperature of the bulb. In recent years, manufacturers have implemented design changes to prevent combustible materials from contacting the bulb, helping to reduce the potential for ignition. Nonetheless, the use of torchiere lamps is discouraged by a number of universities, not only because of the fire hazard but also because of their high power demand.

Cooking. Cooking should be permitted only in specifically designated cooking areas. The use of hotplates and other cooking devices should be restricted or prohibited to minimize the potential for a fire. To regulate the size of microwaves and refrigerators in residence halls, some institutions specify a vendor to provide this equipment to the students and only use of specified equipment is permitted.

Enforcing Good Housekeeping

For general information, see Section 11, Chapter 2, "Housekeeping Practices."

Maintaining an environment that is relatively clean and orderly helps to reduce the amount of combustible fuel load that can potentially be ignited or serve as a fuel load to a fire. The 1996 fire in Chapel Hill was fueled in its initial stages by trash that had not been discarded following a party the evening before.

Recycling has created a challenge to good housekeeping. Recycling containers for paper and cardboard placed in buildings create two concerns. The first is that a container with a concentrated combustible fuel load may either be ignited (accidentally or deliberately) or may serve as a fuel package for an external fire. It is, therefore, important that recycling containers be emptied on a regular basis and that their placement be regulated with consideration given to fire safety.

The second concern is that recycling containers might be placed in a means of egress. The philosophy is that corridors and stairways should be kept clear of any such fuel loads because they may impact the safety and integrity of the escape route if they should become ignited. Also, these containers may serve as an obstruction along the egress route. Placement of these containers should be carefully monitored and controlled.

Educating Students About Fire Protection Features

A key component of any fire safety education program is ensuring that the occupants understand the importance of fire safety and how their actions can have a direct impact on the level of fire safety in their residence hall, fraternity, sorority, apartment, or house.

Students often are not fully aware of the fire protection features in the buildings they occupy and may inadvertently bypass them by, for example, propping open fire doors to facilitate pedestrian traffic flow. Students should understand the importance of fire protection systems, such as sprinkler and fire alarm systems, and the results of tampering with them. During an inspection at one university, audible notification appliances in some

of the rooms were found to have been disabled by the students. In several fatal fires, smoke detectors were found to have been either disabled or removed entirely. The risks and penalties for tampering with fire protection systems should be communicated to every student and enforced.

Fire safety education and training for university students can be difficult to accomplish because of the regular turnover of students. Furthermore, any fire safety education program must compete for the attention of the student audience. The fire safety professional may have to be creative and tailor the message to appeal to the students.

Sample strategies include the following:

- *Audience-appropriate videos.* The U.S. Fire Administration's video "Get Out and Stay Alive" is one such program, among others.
- *Live fire training.* Students and/or staff can be given live fire training, such as fire extinguisher training that includes propane-fueled fires.
- *Fire academies.* The Boulder Fire Department and the University of Colorado, among a number of schools across the nation, hold annual fire academies for the resident assistants and the Greek leadership. Such intensive training programs stress the importance of student actions in fire safety. Training programs also motivate the students to look at their living areas with a more critical eye for fire safety dangers.

FIRE DETECTION ISSUES IN UNIVERSITY HOUSING

For general information on detection technology, see Section 14, "Detection and Alarm."

Unquestionably, smoke detection plays a critical role in any fire safety program. Properly installed, operating smoke detection systems or smoke alarms can literally make the difference between the occupants being able to escape from a fire and being trapped by the smoke and flames.

Unfortunately, in the university environment, smoke alarms are sometimes disabled. In a number of fatal fires, especially off campus, the batteries were removed from smoke alarms. In some cases, smoke alarms could not even be located following the fires. Steps should be taken to ensure that such fire protection features are properly maintained.

False or Unwanted Alarms

False or unwanted alarms are a particular problem in the university setting. Students can activate the fire alarm system as a prank, which causes the residents to become desensitized to the alarms and to not react when needed. The problem with unnecessary activation of the fire alarm system is it creates apathy among the students. The occupants will become "numb" to the sound of the fire alarm system and will begin to ignore it, which could have tragic consequences. For example, there had been a number of false alarms in the weeks leading up to the Seton Hall fire in January 2000. Because of this, several of the occupants of the building did not evacuate when the fire alarm system went into alarm on the night of January 19, 2000. This time, there really was a fire.

A *false alarm* is a situation in which someone has deliberately activated the fire alarm system, knowing that there is no danger. For example, a student activating a manual pull station when there is no fire would be classified as a *malicious false alarm.* An *unwanted alarm* or *nuisance alarm* is one when the fire alarm system is activated but not under conditions where a fire exists. For example, a smoke alarm placed in or near a shower and activated by the shower steam would be considered an unwanted or nuisance alarm.

In addition to creating apathy among the students, false or unwanted alarms place undue stress on the local responders. If they are continually responding to false or unwanted alarms at a building, they may develop a "cry wolf" syndrome. In addition, a false alarm takes these units out of service to respond to other emergencies.

The solution that some schools adopt to avoid overloading the local responders is to have the alarms investigated, often by security, before notifying the local fire department. This is a very dangerous procedure since it may allow a fire to grow to a point where it can be fatal. This was the case at Catawba College where a student was killed in a fire that occurred after a series of other smaller fires and false alarms. A clear distinction must be made between false alarms and unwanted alarms.

Engineering, Education, and Enforcement Strategies

Engineering, enforcement, and education are three strategies that can be employed to help reduce the number of false and unwanted alarms.

Engineering. Maintenance of the smoke detectors is critically important. By having an ongoing program of inspection and maintenance, the number of alarms caused by dirty smoke detectors can be reduced.

Using devices that cover the manual fire alarm boxes (pull stations) is an engineering solution to false alarms. When the device is lifted, a local alarm sounds, alerting people in the area. Such covers do not restrict access to the pull station, which can be activated if necessary.

The use of addressable fire alarm systems is beneficial in helping to identify problem areas. Detectors that are improperly located or are continuing to cause unwanted alarms can be identified and corrected.

Education. Educating the occupants and enforcing proper behavior are also important components when it comes to reducing the number of alarms. At one university, postings were put up in the buildings after every alarm advising students as to the cause of the alarm. If the alarm activation was accidental, they provided information on how to avoid future activations. If the alarm was malicious, then information about the incident as well as a reward was offered.

Enforcement. Universities may impose sanctions on resident students up to and including dismissal for maliciously activating

a fire alarm. One university offers rewards to find offenders and has installed CCTV cameras to record violators in the act.

A particularly vexing problem is that of off-campus houses and apartments where the smoke alarms are not part of a fire alarm system that can monitor the condition of the devices. Disabled or missing smoke alarms can contribute substantially to the risk of fatality in a fire in any residential occupancy. Strategies include the following:

- Severe penalties for students who are caught activating the fire alarm needlessly
- Financial penalties being imposed on the floor or building where there is an ongoing problem of false alarms, leading to peer pressure to help reduce the problem

FIRE CONTAINMENT AND SUPPRESSION ISSUES IN UNIVERSITY HOUSING

Fire Containment

For general information, see Section 18, "Confining Fires."

A common violation of the principle of fire containment in university housing occurs when doors are propped open in corridors and stairwells. Even if they aren't designed to protect openings in a fire or smoke barrier, they will serve to stop the spread of the smoke, reduce the number of people who may be endangered, and also limit the amount of damage that may be caused by fire or smoke. Doors that are supposed to be kept closed to limit the spread of smoke and fire are frequently propped open simply for convenience. Educating the students and maintenance and cleaning staff about the importance of ensuring that barrier doors are kept closed can help to alleviate this problem.

Fire Suppression

Two types of fire suppression can be used: manual (by portable fire extinguishers or the fire department using hoselines) and automatic.

Fire Extinguishers. Fire extinguishers can play a valuable role in ensuring that the fire remains in the incipient stage. However, there are certain considerations, as discussed more extensively in Section 17, Chapter 5, "Fire Extinguisher Use and Maintenance."

First, the fire extinguisher should be matched to the probable hazard that will be encountered. Many of the fires that would be encountered in student housing would probably involve Class A combustibles such as wood, paper, and so on. A water-based fire extinguisher would probably be the best type to use in this environment. However, the occupants must be knowledgeable in the steps to take if a fire should occur. Training and education must be conducted prior to an incident to ensure that the occupants know what actions to take. This can be a time-consuming, yet important, responsibility of the university.

Fire extinguishers, especially those that are water based, can be inappropriately discharged as a "squirt gun" and then placed back on the wall. When such misuse occurs, the extinguisher is no longer operational. Constant vigilance by staff is necessary to ensure that the fire extinguishers are not tampered with and that they are promptly recharged when necessary.

Because of the need for ongoing occupant training and education in the use of fire extinguishers, one university has taken the step of removing them from all residence halls. This was done, however, only in fully sprinklered, noncombustible buildings.

Fire Department Response. When a fire does occur, time is critically important. The sooner the occupants of the building are alerted to the fire, the better their chances are of escape and survival. Also, the sooner that the fire department is notified of the fire, the faster it will be able to respond, suppress the fire, and rescue any trapped occupants. For this reason, it is important that procedures are in place to notify the fire department promptly whenever a fire alarm is sounding.

Automatic Sprinklers

Based on the occupancy and occupant characteristics (particularly in the residence halls and Greek environment), the need for sprinklers is paramount. For this reason, NFPA *101* requires automatic suppression systems for new construction.

Recognizing the importance of automatic fire sprinklers in life safety, a number of schools across the country are voluntarily installing these systems in their residence halls. Fire sprinklers provide a significant level of safety when used in concert with fire alarm systems and student education, especially given the risk presented by student behavior, actions, and lifestyle. In addition to protecting lives, sprinklers will minimize the property damage and the amount of time that students will be displaced. Often, they can re-enter the building almost immediately, except for the areas directly affected by the fire and water discharge.

In the wake of the Seton Hall fatal fire, legislation was introduced across the country calling for the installation of sprinkler systems in residence halls and Greek housing. The most sweeping legislation was enacted in 2000 by the State of New Jersey, which called for sprinkler systems to be installed within 4 years. All of the schools met this deadline, greatly increasing the level of fire safety for students across the state.

INSTITUTIONS AND ORGANIZATIONS INVOLVED IN UNIVERSITY HOUSING FIRE SAFETY

University and Fire Department Interaction

The university should work closely with the local fire department in all areas of fire protection. This effort should include not only the academic and support buildings and residence halls but also the off-campus Greek and private student housing. Especially in off-campus housing, the fire department is a critical component in helping to provide a fire-safe environment for the school's students.

Universities should not completely rely on the fire department for all fire safety needs. For example, fire prevention is ultimately the responsibility of the institution. The fire department

cannot be expected to inspect the residence halls and other buildings for fire hazards as frequently as the university staff.

Depending on whether it is a public or private university, the fire department may or may not be legally required to conduct plan reviews. However, it is a good idea to always involve the fire department in any plan reviews of new construction or renovations. This coordination helps to build a stronger relationship between the university and the fire department; the university can gain valuable information on fire-safe design and the fire department can improve its familiarity with the different occupancies on campus.

Organizations Involved in University Housing Fire Safety

A number of organizations are active in various facets of campus fire safety. They are as follows:

Campus Firewatch
P.O. Box 1046
Belchertown, MA 01007
http://www.campus-firewatch.com

Campus Safety Health and Environmental Management Association
c/o National Safety Council
1121 Spring Lake Drive
Itasca, IL 60143
http://www.cshema.org

Center for Campus Fire Safety
P.O. Box 2358
Amherst, MA 01004
http://www.campusfire.org

National Association of State Fire Marshals (NASFM)
P.O. Box 8778
Albany, NY 12208-0778
http://www.firemarshals.org

National Fire Protection Association (NFPA)
One Batterymarch Park
Quincy, MA 02269
http://www.nfpa.org

National Fire Sprinkler Association (NFSA)
Robin Hill Corporate Park
Route 22
P.O. Box 1000
Patterson, NY 12563
http://www.nfsa.org

United States Fire Administration (USFA)
16825 S. Seton Avenue
Emmitsburg, MD 21727
http://www.usfa.fema.gov

SUMMARY

Since the late 1980s, building and fire codes have changed to require fire protection systems and equipment for lodging establishments. More recently, similar awareness and action have taken place in the area of university housing.

In both lodging and university housing, occupants have unique characteristics. For example, hotel occupants are in an unfamiliar environment. Students can be very familiar with their housing but engage in risky behavior. Hotels and university housing both feature high population density.

These occupant characteristics lead to the need for an effective emergency organization, automatic sprinklers, compartmentation, effective egress design, and detection and alarm systems. Regular fire drills will enhance survivability. Continued improvements in fire protection technology and related areas, such as fire-safe cigarettes, are expected to contribute to further decline in fires in hotels and university housing.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on hotels and university housing discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA 72®, National Fire Alarm Code®
NFPA *101®, Life Safety Code®*
NFPA 5000®, Building Construction and Safety Code®

Chapter 4

Apartment Buildings

Kenneth Bush

Chapter Contents

Occupancy Characteristics
Occupancy Hazards
Life Safety Concepts

Key Terms

apartment building, condominium, hazard classification, means of egress, occupancy characteristic, occupancy hazard, public fire and life safety education, residential occupancy

Apartment buildings are those structures containing three or more living units with independent cooking and bathroom facilities, whether designated as apartment houses, tenements, condominiums, or garden apartments. Apartments differ from multi-unit residential occupancies that are not considered homes, such as hotels and boarding homes, by the provision of individual cooking facilities, the number of sleeping rooms, and the less transient nature of the occupants.

The adequate protection of residential buildings and their occupants from the effects of fire has historically been a major concern of fire protection professionals. The construction of multiple dwelling units makes this job more complex. Such construction not only adds to building size and occupant numbers but also adds major complexity due to building design, construction, and fire protection features.

See also Section 20, Chapter 2, "Board and Care Facilities"; Section 20, Chapter 3, "Hotels and University Housing"; Section 20, Chapter 5, "Lodging or Rooming Houses"; and Section 20, Chapter 6, "One- and Two-Family Dwellings."

OCCUPANCY CHARACTERISTICS

According to statistics compiled from the U.S. Census Bureau, there were an estimated 109,902,090 occupied housing units in the United States in 2004. Of that number, 21,136,883 units, or approximately 21 percent of the total number of such units, consisted of three or more units, meeting the definition of "apartment building" in NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®. The breakdown of all housing units both occupied and vacant by size was 5,739,277 in structures with 3 or 4 units; 6,088,586 in structures with 5 to 9 units; 5,521,813 in structures with 10 to 19 units; and 9,526,484 in structures with 20 or more units.[1,2]

The U.S. population is aging. In 2000, approximately 12.4 percent of the U.S. population was age 65 or over, with an additional 22.1 percent of the population age 45 to 64. Projections from the U.S. Census Bureau indicate that by the year 2050, these figures will increase to 20.7 percent for the group of persons age 65 or over, including 5 percent age 85 or over, and an additional 22.2 percent of the population from 45 to 64 years of age. Coupled with these statistics comes an increasing need for housing units that are compact, economical, and require less individual maintenance. As land values continue to increase, there is little wonder why the design, construction, and occupancy of multi-unit buildings has become a popular issue with the U.S. public.

During 2004, approximately 1,550,500 fires were attended by public fire departments in the United States. Of that number, 526,000 fires occurred in structures, of which 410,500, a significant 78 percent of all structure fires, occurred in residential properties. Of these residential structure fires, 301,500, or 57.3 percent of all structural fires, occurred in one- and two-family dwellings and another 94,000 occurred in apartment buildings, accounting for 17.8 percent of all structural fires. This figure represents an increase of 2.7 percent of fires reported in apartments compared to 2003. This means that a fire occurred in a structure at the rate of one every 60 seconds, and in particular, a residential fire occurred every 77 seconds.[2]

For the period 1977 to 2004, the number of structure fires was at its peak in 1977 when 1,098,000 structure fires occurred. The number of structure fires then decreased quite steadily,

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particularly in the 1980s, to 688,000 by the end of 1989, for an overall decrease of 37.3 percent from 1977. The number of structure fires continued to decrease at a steady rate following 1989 by an overall figure or 24.7 percent to 517,500 incidents by the end of 1998 and has remained in the vicinity of 526,000 fires per year from 1998 to 2004.

OCCUPANCY HAZARDS

The occupancy hazards of apartment buildings include all risk factors that may arise in particular segments of the population. Preschoolers and older adults, if present, have a higher risk of dying in fires because of the mental or physical limitations associated with their age. Older children and younger adults may be at risk if they are physically or mentally handicapped or as a result of drug or alcohol use. Fatal fires are more common at night when people are asleep.

Another important consideration for the protection of apartment buildings is the difference in causes attributed to fire incidents between this property classification and one- and two-family dwellings (Figure 20.4.1). This difference is most likely due to the centralized design and installation of systems typically found in most apartment buildings. Equipment fires are usually the result of poor maintenance or misuse; such equipment tends to have closer supervision in apartment buildings. The number of fires and related casualties caused by occupants, especially from cooking operations, remains high in all types of residential structures. This demonstrates the need to properly apply all required code provisions to these occupancy types, and it also demonstrates the importance of public education regarding the causes, prevention, and control of home fires.

There were 3900 civilian fire deaths in 2004 with almost 82 percent, or 3225 of these deaths occurring in a residential setting. Of these deaths, 510 occurred in apartment fires, a substantial increase of 24.4 percent from 2003. Home fire deaths were at their peak in 1978 when 6015 fire deaths occurred. These numbers slightly decreased during the period of 1979 to 1982, except for 1981, and further decreased a substantial 20 percent during the period to 4820 by the end of 1982. For the next six years, the number of home fire deaths remained consistent in the area of 4655 to 4955 deaths, except for 1984 when 4075 deaths occurred.

In addition, during 1984 there were 17,785 civilian fire injuries, with 14,175 injuries, or nearly 80 percent occurring in residential occupancies. Of the number of persons injured in residential properties, 3200 such injuries occurred in apartments. For the period from 1977 to 2003, the number of civilian injuries ranged from a high of 31,275 in 1983 to a low of 17,785 in 2004 for an overall decrease of 43 percent. It is recognized that these statistics may not represent the actual number of total injuries, as many such injuries occur at small fires where no fire department response is made, or where the responding fire department may not be aware of injured persons that do not require medical attention or are transported for treatment by private means (Table 20.4.1).

During 2004, fire caused an estimated $9.8 billion in property damage, with $5.9 billion attributed to fires in residential occupancies. The $5.9 billion residential property fire loss in 2004 represented a slight increase of 2.1 percent from 2003. The actual property loss from fires in apartments during 2004 totaled $885 million, a decrease of 1.3 percent from 2003. Fires in structures resulted in $8.3 billion in property damage, a moderate decrease of 5.3 percent. The average loss per structure fire

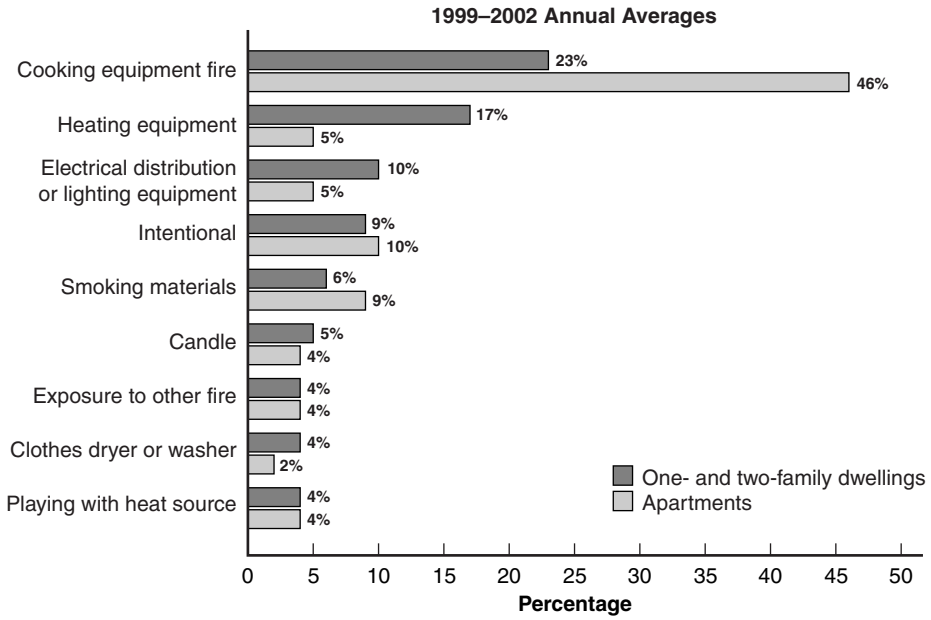

FIGURE 20.4.1 Leading Causes of Structure Fires in One- and Two-Family Dwellings and Apartments (Source: *U.S. Fires in Selected Occupancies,* NFPA, Mar. 2006)

TABLE 20.4.1 Estimates of 2005 Civilian Fire Deaths and Injuries by Property Use

	Civilian Deaths			Civilian Injuries		
Property Use	*Estimate*	*Percentage Change from 2004*	*Percentage of All Civilian Deaths*	*Estimate*	*Percentage Change from 2004*	*Percentage of All Civilian Injuries*
Residential (total)	3,055	–5.3	83.1	13,825	–2.5	77.1
One- and two-family dwellings[a]	2,570	–4.1	69.9	10,300	–1.9	57.5
Apartments	460	–9.8	12.5	3,000	–6.3	16.7
Other residential[b]	25	–28.6	0.7	525	+10.5	2.9
Nonresidential structures[c]	50	–37.5	1.4	1,500	+11.1	8.4
Highway vehicles	500	–3.8	13.6	1,450	+11.5	8.1
Other vehicles[d]	20	–33.3	0.5	200	0.0	1.1
All other[e]	50	+11.1	1.4	950	+11.8	5.3
Total	3,675	–5.8		17,925	+0.3	

Note: Estimates are based on data reported to the NFPA by fire departments that responded to the 2005 National Fire Experience Survey. Note that most changes were not statistically significant; considerable year-to-year fluctuation is to be expected for many of these totals because of their small size.

[a]This includes manufactured homes.

[b]Includes hotels and motels, college dormitories, boarding houses, etc.

[c]This includes public assembly, educational, institutional, store and office, industry, utility, storage, and special structure properties.

[d]This includes trains, boats, ships, farm vehicles, and construction vehicles.

[e]This includes outside properties with value, as well as brush, rubbish, and other outside locations.

Source: *Fire Loss in the United States During 2005,* Table 3, NFPA, Sept. 2006.

was $15,806, a decrease of 4.2 percent. During the reporting period of 1997 to 2004, the average loss per structure fire ranged from a low of $3757 to a high of $17,016 in 2001 for an overall increase of 353 percent. The increase in the average structure loss between 1977 and 2001 was 56 percent when adjusted for inflation. It should be noted that this overall property loss statistic represented a significant 20.5 percent decrease in the totals from the previous year, much of which was attributed to losses incurred by wildfires in Southern California during 2003 (Table 20.4.2).

Citing the number of fires and fire casualties that continue to dominate fire loss statistics, and considering the increased interest in multiple-unit building design, particularly among a growing elderly U.S. population, a number of fire safety initiatives targeted at the residential fire problem remain key to any reductions in these numbers. Currently, five major strategies exist to further reduce the numbers of fire incidents, contain property losses, and control the number of home fire deaths and injuries. First, more widespread public safety education is needed on how to prevent fires and how to avoid serious injury or death should a fire occur. A primary message of any such education must contain information on the common causes of fatal and significant loss fires.

Second, the use, including proper installation and maintenance, of smoke alarms, and the development and practice of home escape plans play another significant role in the control of overall fire losses. Third, accompanying this use of early warning devices comes a need for the aggressive pursuit of the installation and maintenance of approved residential sprinkler systems.

Fourth, additional means to improve the safety of household products should be sought. Recent regulations on the production of child-resistant lighters and research on self-extinguishing cigarettes are two excellent examples of such safe product initiatives. Acceptance of the manufacture, purchase, and use of upholstered furniture and mattresses that are more resistant to cigarette ignition, and to the use of decorations that have been made, or specially treated, to resist ignition represents another change that has already produced positive results and will continue to influence fire safety trends in the future. Lastly, there has to be special considerations for the fire safety needs of high-risk populations, especially very young children, older adults, and the poor.[3]

Smoke detectors and smoke alarms have been a great success in apartment buildings, as well as in private homes. Use of smoke alarms continues to grow, but more slowly since 1982. In 1995, 93 percent of all homes had at least one smoke alarm, and there was evidence that their use in apartments was higher still, probably because state and local laws requiring smoke alarms often have stronger requirements for apartments. However, NFPA studies indicate that when fire occurs, roughly one-third of apartment smoke alarms are not operational, the same share as for one- and two-family dwellings. These studies also indicate that smoke alarms cut the risk of dying in a home fire by roughly 40 percent. However, the estimated reduction is only 16 percent in apartments, townhouses, and condominiums based on fires that occurred between 1985 and 1994. Although available data do not lead to definite conclusions, it appears that the difference in effectiveness levels may be due to the fewer number or longer distance in apartment building escape routes, more success in early detection to prevent fires from growing large enough to report, or the delayed reaction of apartment dwellers to alarms outside of their unit.

TABLE 20.4.2 Estimates of 2005 Structure Fires and Property Loss by Property Use

	Structure Fires		Property Loss[a]	
Property Use	*Estimate*	*Percentage Change from 2004*	*Estimate*	*Percentage Change from 2004*
Public assembly	13,500	+3.9	$320,000,000	+1.3
Educational	6,000	–14.3	67,000,000	–1.5
Institutional	7,500	+15.4	40,000,000	+60.0**
Residential (total)	396,000	–3.5	6,875,000,000	+15.6**
One- and two-family dwellings[b]	287,000	–4.8*	5,781,000,000	+16.8**
Apartments	94,000	0.0	948,000,000	+7.1
Other residential[c]	15,000	0.0	146,000,000	+27.0*
Stores and offices	23,000	–2.1	687,000,000	+17.2*
Industry, utility, defense[d]	11,500	–4.2	376,000,000	–11.1
Storage in structures	30,000	–6.3	590,000,000	–21.1**
Special structures	23,500	+9.3	238,000,000	+19.0
Total	511,000	–2.9	$9,193,000,000	+10.6**

Note: The estimates are based on data reported to the NFPA by fire departments that responded to the 2005 National Fire Experience Survey.
[a]This includes overall direct property loss to contents, structure, a vehicle, machinery, vegetation, or anything else involved in a fire. It does not include indirect losses, e.g., business interruption or temporary shelter costs. No adjustment was made for inflation in the year-to-year comparison.
[b]This includes manufactured homes.
[c]Includes hotels and motels, college dormitories, boarding houses, etc.
[d]Incidents handled only by private fire brigades or fixed suppression systems are not included in the figures shown here.
*Change was statistically significant at the .05 level.
**Change was statistically significant at the .01 level.
Source: *Fire Loss in the United States During 2005,* Table 4, NFPA, Sept. 2006.

Once a potentially serious fire starts, apartment buildings can pose special problems to fire department suppression forces. The variety of these types of residences, as well as the architectural desire to make buildings aesthetically pleasing yet functional, creates an interesting combination of fire protection demands. Building designs, space considerations, and parking arrangements can create major access problems, particularly for fire-fighting apparatus (Figure 20.4.2). Long hose lays and blocked roadway access can create problems for fire-fighting operations in addition to existing problems, such as weather, personnel deficiencies, and hampered water supplies (Figure 20.4.3). Architectural designs may use false partitioning and veneered construction, giving an unrealistic impression of the type and magnitude of the actual building construction (Figure 20.4.4). Although NFPA *101* makes no special requirements for the construction of these buildings, many such requirements are found and enforced through model building codes, such as *NFPA 5000,* as well as through many local codes and ordinances currently in effect. Sometimes the location and construction of apartment buildings make egress for residents and access by fire fighters very difficult (Figure 20.4.5).

Apartment buildings are typically a collection of more than two self-contained dwelling units with independent living and cooking facilities. Model building codes, such as *NFPA 5000,* establish the criteria for separation between dwelling units in order for them to be classified as other occupancy types, most likely one- and two-family dwellings. These substantial separation requirements are intended to protect dwelling units from a fire in a neighboring unit, even if the fire severity causes collapse of the unit involved in fire. Residents of these buildings are typically less transient in nature and are more familiar with the building construction and arrangement, especially exiting patterns and levels of protection afforded such as the installation of smoke detection, fire alarms, and automatic sprinkler systems.

FIGURE 20.4.2 Apartment Building Designs and Parking Arrangements Creating Major Access Problems and Hindering Fire-Fighting Operations

FIGURE 20.4.3 Location and Lack of Access Routes for Many New Apartment Buildings Creating Major Fire Apparatus Placement and Fire-Fighting Operations Problems

FIGURE 20.4.4 Architectural Designs Using False Partitioning and Veneered Construction

The levels of protection required by most model codes take this level of familiarity into consideration when establishing reasonable levels of protection.

Whenever apartment units are utilized for other purposes, such as day-care homes, residential board and care facilities, or even business offices, the levels of protection and design considerations must be adjusted accordingly. Such modifications may affect only one or a limited number of apartment units, or may involve modification to the entire building. Earlier editions of NFPA *101* made some adjustments to its requirements based upon the advanced ages of building residents; however, that distinction no longer exists in more recent code editions. Many times, local statutes, such as zoning codes or license requirements, restrict the nature of occupancy, and the number and abilities of persons who may reside in an apartment building.

FIGURE 20.4.5 Limited Fire Department Access Due to Proximity of Waterway

Another important consideration to remember is that the term "condominium" refers to ownership, not occupancy. Therefore, the occupancy classification for residential occupancies is not dependent on property lines or ownership arrangements.

An additional problem arises in the location and combination of apartments with other occupancy types, particularly those above and behind mercantile and business occupancies (Figure 20.4.6). Where multiple occupancy classes occur in the same building and are so intermingled that separate safeguards are impractical, means of egress facilities, construction, protection, and other safeguards must comply with the most restrictive code requirements for the occupancies involved.

LIFE SAFETY CONCEPTS

The apartment fire death and injury problem is very complex, and several strategies must be presented to help solve it. The installation and proper maintenance of smoke alarms and quick-response residential sprinklers in sleeping areas provide an effective, low-cost, and widely available method of early warning so that evacuation, containment, and suppression can begin during the incipient stages of a fire.

FIGURE 20.4.6 Combination of Apartments with Other Occupancy Types

Public Education

The general public must be taught to protect themselves and others occupying the residential unit from fire through the safe use and installation of alternative heating devices, the proper storage and handling of flammable liquids, and the identification and correction of home fire hazards. In addition, stringent flammability standards for upholstered furniture, such as those previously issued by the U.S. Consumer Product Safety Commission (CPSC) for children's sleepwear and mattresses, will provide long-term fire safety benefits. Specially designed systems that are effective in terms of life safety should be installed to provide a high level of protection to occupants, particularly where large numbers of persons are present, such as in a high-rise apartment building, or where the occupants' ability to escape is hampered, such as in apartments for the elderly.

Design Considerations

Although such fire safety precautions are not always practical, particularly within an individual dwelling unit, a more concentrated effort must be made to confine the fire and its effects to a well-defined, limited area of the structure. This task is accomplished through the adoption of accepted fire safety and building construction codes, such as NFPA *101* and *NFPA 5000.* Since many current laws and regulations prevent fire inspection authorities from entering individual living units, adequate fire protection features must be designed and constructed during the initial phases of the project. The regulation of interior furnishings provides only a partial solution to the fire safety problem, although such consumer items are generally in use for many years before they are replaced. Futhermore, the individual habits and attitudes of building occupants can never be regulated and are difficult to change.

Additional requirements of *NFPA 5000* address fire safety requirements intended to promote property protection and to enhance the safety of fire fighters and other emergency personnel who must enter the building under varying degrees of fire conditions. Such levels of protection include detailed requirements for building construction and other structural features and the installation of standpipes and alarm and communication systems for fire service use. Although these requirements have been modeled from those recognized by NFPA *101* for occupant protection, *NFPA 5000* is intended to address other issues concerning property protection and emergency operation procedures.

One of the most important, yet sometimes most complicated considerations of adequate protection is the proper classification of occupancy. All residential occupancies, including apartment buildings, require occupancy by persons for more than 24 hours. However, the number and abilities of building occupants, particularly to be able to escape a fire without assistance, play vital roles in the classification of an occupancy, and hence, directly affect the design, construction, and arrangement of the building and associated levels of protection.

All occupants of an apartment building are expected to have the ability to recognize a direct fire threat, or the warning from a building alarm system, and be able to physically exit the building without obstruction, including locked egress doors. Where these criteria are not met, classification of the building as a different occupancy type, such as a health care facility, residential board and care facility, or detention and correctional occupancy, may be warranted. Even though it is recognized that reaction to a fire may be delayed while residents are asleep, it is assumed that they will be able to take appropriate actions for self-preservation when warned of potential danger.

Because apartment buildings are so diverse in size, configuration, and resident population, many regulatory codes pay particular attention to construction designs and fire protection features. NFPA *101* covers the presence of hazards such as cooking and heating equipment, as well as the occupant's degree of familiarity with his or her living space. NFPA *101* and *NFPA 5000* require most new apartment buildings to be protected by automatic sprinklers. However, sprinkler protection is not required where each apartment has a door directly to the outside at ground level, such as in townhouse-style apartments, or is served by an interior stair totally enclosed by fire-rated construction, or where an outside stair serves a maximum of two units located on the same level (Figure 20.4.7). NFPA *101* has a unique method of regulating the construction and design of existing apartment buildings based on the type and extent of automatic fire detection and/or fire suppression equipment provided. Recognizing equivalency provisions found elsewhere in NFPA *101,* the

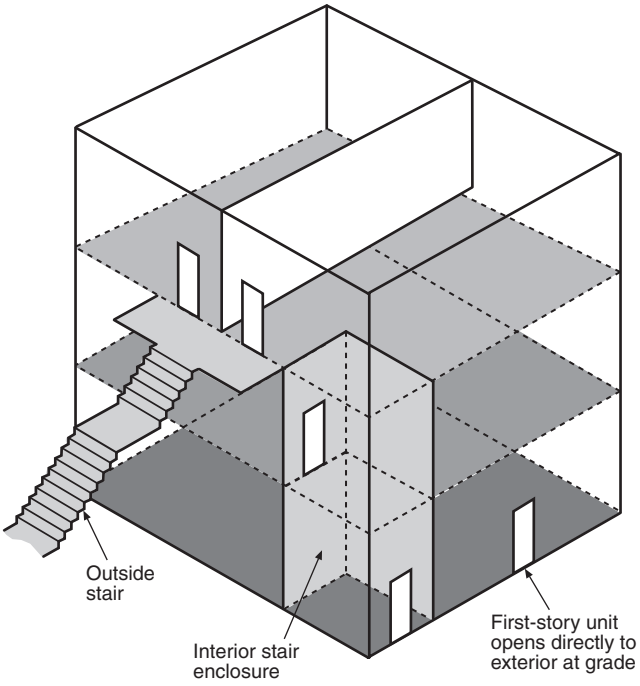

FIGURE 20.4.7 Required Exiting Arrangements for New Apartment Buildings Without Sprinkler Protection

technical committee on residential occupancies established four equivalent schemes to provide a high degree of flexibility. These designs provide a minimum level of life safety for apartments. Some systems have additional protective capability, permitting greater building heights and larger building areas.

This overall approach provides one of the first system design attempts to be codified. Whereas a total system would have many design approaches, this more limited system offers only four different approaches. Yet an evaluator can identify an appropriate method from the four approaches based on the building size, height, and arrangement. This allows the person evaluating the existing building to formulate a safety approach that best fits the building, rather than fitting the building to a single codified design criterion.

The contents of living units in residential occupancies fall into the ordinary-hazard classification as defined by NFPA *101* and *NFPA 5000*. Characteristics of these hazards include moderately rapid burning and considerable smoke generation (Figure 20.4.8). Under normal conditions, no unduly dangerous exposure should develop during the period necessary to escape from the fire area given prompt occupant notification of the fire. Generally, this classification represents conditions found in most buildings. Even with the introduction of plastics, foam materials, and other combustible materials in furnishings, the amount and configuration of such materials present a lower hazard than in other occupancies where they may be sold, stored, or displayed. NFPA 13, *Standard for the Installation of Sprinkler Systems,* classifies the contents of apartment buildings as "light hazard" for the design of extinguishing systems. This classification difference is based on the threat to life safety assumed in

FIGURE 20.4.8 Exits from Apartments Discharging to a Public Way, Protected from Fires in Exposure Occupancies, Particularly Parking Areas

the ordinary classification versus that assumed where the extinguishing capability of the automatic sprinkler system results in the light-hazard classification.

Means of Egress

In designating the number and types of exits required for apartment buildings, NFPA *101* and *NFPA 5000* determine the occupant load on the basis of 1 person/200 ft^2 (18.6 m^2) of gross floor area, or the maximum probable population of any room or section under consideration, whichever is greater. Many buildings, such as dormitories, may produce a greater occupant load. However, even though some portions of these buildings are densely populated, the whole building may not necessarily exceed 1 person/200 ft^2 (18.6 m^2) of gross area, owing to the space taken for toilet facilities, hallways, closets, and living rooms. These requirements do not preclude the need for providing adequate exit capacities from concentrated use and sleeping areas based on the maximum probable population, rather than on the design figure. The capacities of required exits are as specified in NFPA *101* and *NFPA 5000.*

Travel within the individual dwelling unit need not comply with the requirements for means of egress, but must be arranged as means of escape. The differences between means of escape and means of egress have an impact on the size and type of escape components, especially doors and headroom of some occupiable spaces. Most of these requirements apply to the unit only, and not necessarily to the entire building.

Although seemingly contrary to the basic code requirements of two distinct, remote means of egress from all locations, several exceptions to this rule are found within the requirements for apartment occupancies. Whereas the traditional interior exit corridor arrangement commonly found in larger apartment buildings and condominiums requires two remote exits, several other options in apartment building configurations permit other arrangements. The common townhouse arrangement, which provides an exit directly to the street or yard at ground level or

by way of an outside or enclosed stairway serving that apartment only, permits the front door to be the only required exit. Therefore, a rear door, which is often provided, would not be required and could be a sliding door to a porch or patio.

Another exit arrangement unique to apartment buildings permits an exception to the typical requirement for remoteness of exits from nonlooped exit access corridors in apartment buildings that have corridor doors from dwelling units arranged so that exits are located in opposite directions from such doors. In addition, a provision was introduced into the code to limit travel distances from areas of apartment buildings, other than those within living units, to a maximum of 200 ft (61 m) in unsprinklered buildings and a maximum of 250 ft (76 m) in sprinklered buildings.

In apartment buildings, travel distance does not typically include the means of escape within the dwelling unit; only the path of travel in the means of egress is considered. Likewise, common paths of travel are only considered outside the dwelling unit. Travel distance in nonsprinklered buildings is tacitly regulated by limiting any floor level of an individual dwelling unit to no more than one level above or below the entrance floor. In the event of multiple levels within a single dwelling unit, consideration must be given to the limitation of no more than two levels within a dwelling unit to be open to each other. Where a third level exists, it must be separated from the other two levels as required by other code provisions.

Another exception is a basic design approach for garden apartments where the apartment entrances are enclosed around a single protected stairway. This single stairway usually is open to the exterior or is glass enclosed. It must be separated from the building by construction of at least 1-hour fire resistance rating. The doors should be treated similarly. Note that this exception for a single exit is limited to buildings having four or fewer stories with not more than four living units per story and protected throughout by an approved, supervised automatic sprinkler system, and to existing buildings of three stories or less. Interestingly, the basic design of a typical garden-style apartment has influenced other chapters of NFPA *101*. Previous editions of NFPA *101* required that all exit stairways continuing beyond the floor of discharge be interrupted at that level by partitions, doors, or other effective means to make clear the direction of egress to the street. However, an exception to this requirement allows these stairways to continue one-half story beyond the level of discharge without such physical interruption. This exit arrangement is typically found in garden-style apartments that have apartments or service areas on the ground floor or terrace level. Based on this exception, stairways serving these levels need not be interrupted at the floor of exit discharge for fire safety reasons. Recently, fire escape ladders and alternating tread devices have been added as recognized means of egress components from apartment buildings. It must be recognized, however, that these types of means of egress components are acceptable in a very limited number of circumstances, such as from areas having low occupant loads of persons physically capable of using such devices.

In addition to the number and types of required exits, the arrangement and travel distance to these exits are regulated by the general requirements of NFPA *101* and *NFPA 5000,* with due consideration to the levels of fire protection features within the building. As in other occupancies, all exits must terminate directly at a public way or at an approved exit discharge (see Figure 20.4.8), unless certain additional protection features, such as automatic sprinkler protection and vestibule separation and/or enclosures, are provided to permit 50 percent of the required exit capacity to discharge through areas on the level of discharge. NFPA *101* and *NFPA 5000* also recognize the use of areas of refuge, particularly for spaces accessible to persons with severe mobility impairments. Because of the high level of satisfactory performance and response to fire conditions by supervised automatic sprinkler systems, any story of an apartment building equipped with this level of protection may be considered an area of refuge even if an occupant does not have access to any of the apartment units. Because locked apartment unit doors create inaccessibility to spaces other than the corridor, the corridor maintains its tenability due to the effectiveness of the automatic sprinklers and serves as the area of refuge. This does not preclude the demonstration of the corridor to maintain tenable conditions, especially if the aggregate area of the corrider is less than 1000 ft^2.

Minimum levels of illumination must be provided for public spaces, hallways, stairways, and other means of egress. Emergency lighting is required for apartment buildings that have more than 12 living units or are more than three stories high, except in buildings where every living unit has a direct exit to the outside at grade, such as in townhouses. Approved exit signs are required in all apartment buildings with more than one required exit. However, discretion should be used in placing such signs where exits are obvious or where all occupants are familiar with the building.

Because a higher degree of transient occupancy in some apartments is a definite possibility, special exiting considerations are made within the individual living units, in addition to those found in the public access spaces. All individual living units with two or more rooms must comply with the minimum provisions for operable exterior openings to be used as a secondary means of escape or with the specialized separation or protection requirements of NFPA *101* and *NFPA 5000*. Not only must these openings be of a minimum size, but they also must be accessible and easy to operate. In addition, every dwelling unit greater than 2000 ft^2 (180 m^2) or having a travel distance to the primary means of escape greater than 75 ft (22.5 m) must have two primary means of escape remote from each other, or it must be protected by an approved supervised automatic sprinkler system. Special multilevel units, such as penthouses, are permitted to have regular, curved, or spiral stairways that connect to one level above or below the entrance to the apartment.

Additional requirements prohibit any door in an apartment building, including individual unit doors, from being locked against egress while the building is occupied. This means that a door may be locked so that it can be opened from within the building but not from the outside. Ordinarily, dead bolts, double-cylinder locks, and chain locks would not meet these provisions. Multiple-death fires may occur if a key cannot be found to unlock the door or the chain is not removed. A concept that sets apartment buildings apart from other residential occupancies is a unique arrangement where a nontransient population

is required to escape the building utilizing a common corridor egress system. In recognition of heightened security concerns, one additional operation is permitted to operate locks installed on doors between public spaces and individual dwelling units. This operation may include a sliding chain and catch or bolt, or any similar device such that no key or special knowledge or effort is necessary. Additional locks or latches may be installed provided that no more than two operations are required to open the door. In that case, one action must operate more than one locking or latching device. Note that in existing residential occupancies, NFPA *101* permits two additional releasing operations, for a total of three. The use of delayed egress locks, however, is permitted in apartment buildings protected throughout by automatic sprinkler systems or fire detection systems. The limitation of one such locking device in any one egress path and the 15- or 30-second delayed release provides the security needed for infrequently used doors but at the same time ensures that the door remains available for emergency use.

Another feature unique to apartment buildings permits stairway doors to be locked to prohibit building re-entry when such stairs are arranged as smokeproof enclosures. This requirement differs slightly from other occupancy types for which a number of restrictions exist to permit locking of doors from the exit stair to prevent re-entry onto a floor of the building (Figure 20.4.9).

In apartment buildings, the protection of vertical openings, such as stairways, elevator shafts, and atria, follows the requirements found in NFPA *101* and *NFPA 5000*. Smokeproof enclosures are required in existing high-rise apartment buildings except those that are totally sprinklered. This limits the possibility of smoke contamination of exits and ensures a safe, protected means of egress. The protection from hazards, as well as the classification of interior finishes, is also based on the levels of fire detection and/or protection within the building.

The recognition of the limited fire hazard and fuel loading in apartment buildings permits a unique reduction for the fire resistance requirements for vertical openings. In apartment buildings protected throughout by automatic sprinklers, vertical openings are permitted to be enclosed by construction having a fire resistance rating of 1 hour regardless of the number of stories connected by the opening unless the building is a high-rise.

A relatively new provision of the model codes prohibits unenclosed vertical openings of any kind within new buildings or fire sections of new buildings served by a single exit. In addition, any new building with unprotected vertical openings is required to be protected throughout by an approved supervised automatic sprinkler system. However, convenience openings, which meet the special requirements found in other chapters of NFPA *101* and *NFPA 5000* are permitted without exception in apartment buildings.

A highly effective form of fire protection in a residential occupancy is early warning. All living units in an apartment building must be equipped with approved smoke alarms. These smoke alarms are usually located in hallways that have access to the sleeping areas although new unsprinklered apartment buildings must also be equipped with smoke alarms in every sleeping room. In multiple-level units, a smoke alarm also should be located at the tops of stairways. Detection systems must be

FIGURE 20.4.9 Locked Stairway Doors Served by Smokeproof Enclosure

installed in accordance with basic engineering practices. Special consideration should be given to room configuration, air movement, and stagnant air pockets that would reduce detector efficiency, and to cooking areas, fireplaces, or other normally smoke-producing appliances that cause an excess of nuisance alarms. All smoke alarms required for installation in multiple-dwelling units must be powered by the building's electrical system. In order to reduce the possibilities of unnecessary alarms due to ambient conditions, or where incipient incidents can be controlled without total building evacuation, smoke alarms within individual units are not required to sound the building fire alarm. This permits rapid notification of those persons most intimate with the fire without unnecessary evacuation of areas of the building not immediately affected by the incident. Secondary power sources are not required for single-station smoke alarms in existing buildings only. In addition, where a single apartment needs more than one smoke alarm, there is no requirement to interconnect multiple smoke alarms within a single unit. However, the audibility requirements of *NFPA 72®*, *National Fire Alarm Code®*, almost always require multiple smoke alarms within a single dwelling unit to be electrically interconnected

such that when one detects smoke, all smoke alarms within the dwelling unit sound their audible (and visible, where applicable) alarms. Note that this type of detection system is required in addition to the requirements for any other detection or suppression system.

Manual fire alarm systems are required in apartment buildings according to the building's size and height. As building designs become higher and more complex, additional special features are required, such as annunciator panels, visible alarm signals, voice communications systems, and automatic transmission of building fire alarms to the fire department. Voice communications systems are often used as part of a multifaceted system that allows the fire department to provide verbal instructions to building occupants during a fire. Where levels of protection, such as automatic sprinkler protection or exit access directly to the exterior of the building, particularly at ground level, are suitable to maintain a safe egress system for a longer period of time, other fire protection features, such as fire alarm systems, are not required to be installed. This is in recognition of the benefits associated with a properly designed, installed, and maintained automatic sprinkler system in a type of occupancy in which fire casualties remain at a high level.

As mentioned before, NFPA *101* and *NFPA 5000* require almost all new apartment buildings to be protected by automatic sprinklers. In existing apartment buildings, the extent of automatic sprinkler protection is again governed by the building's size and height, as well as by the four protection options discussed in NFPA *101*. To the extent permitted by the applicable sprinkler system installation standard, the use of residential or quick-response sprinklers is required for new installations of sprinkler systems in dwelling units, apartments, and hotel guest rooms. The increased technology, cost-effectiveness, and appearance of these systems have provided numerous additional incentives for mandating this protection option. An exception permits the elimination of the draftstops and closely spaced sprinklers as required by NFPA 13 for convenience openings within dwelling units.

Continuing efforts have been made by the technical committees of the model building codes, NFPA *101,* and the sprinkler standards to coordinate the requirements for automatic sprinkler protection in buildings housing residential occupancies. Two examples are the levels of protection necessary for closets within individual dwelling units and for open parking structures in buildings protected by systems designed in accordance with NFPA 13.

Caution should be exercised when designing automatic sprinkler protection in buildings where residential and other occupancies are located. Often mercantile or business uses occupy the lower floors of a building, with residential units located on upper floors. These nonresidential spaces might pose an additional threat of a fire during nonbusiness hours, having the potential of affecting the tenability of egress routes from residential areas above. These buildings might be classified as mixed-use buildings, and do not fall within the scope of NFPA 13R, *Standard for* the *Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height,* for the design and installation of automatic sprinkler protection. Therefore, the sprinkler design for these types of structures must conform to the requirements of NFPA 13.

Designers of sprinkler systems for apartment buildings must pay particular attention to details, because residential and quick-response sprinklers cannot always be installed in a system that could normally be designed with standard sprinklers. There may also be other situations, such as vaulted ceilings or areas with special ambient temperature considerations, where residential sprinklers or quick-response sprinklers might not be listed for use. In all cases, the intent to obtain the quick response afforded by these types of sprinklers, as well as the high spray provided by residential sprinklers, serves to maintain tenability within the room of fire origin.

NFPA *101* requires portable fire extinguishers to be located in hazardous areas only, not throughout the entire building. Many building owners place these extinguishers in individual living units, under the direct responsibility of the occupant. In addition, a provision of NFPA *101* eliminates the need for portable fire extinguishers in buildings protected throughout by an approved supervised automatic sprinkler system. The possible ineffective use of such devices by persons not routinely trained in their operation, as well as the expense and effort to install and maintain portable extinguishers, especially in unsecured areas, is addressed by using early warning and suppression operations of smoke alarms and automatic sprinklers, especially those systems utilizing fast-response or residential sprinklers, to adequately notify building occupants and to control fires without the need for occupant intervention. It should be noted, however, that some fire prevention codes, including NFPA 1, *Uniform Fire Code*™, require the installation of portable fire extinguishers throughout apartment buildings. The requirements of NFPA 1 and NFPA *101* differ because the two codes have differing scopes, goals, and objectives.

The design, installation, and maintenance of all such fire detection and protection systems are based on referenced fire protection standards, as well as on sound engineering judgment. For residential occupancies of four or fewer stories, see NFPA 13R.

When fires cannot be confined to the area of origin, the means of egress must be sufficiently protected to allow all building occupants enough time for safe evacuation. This basic concern for providing safety for the occupant in a room during a fire led to a minimum corridor wall construction to keep fire in a corridor from entering a room or to keep fire in a room from entering the corridor. Doors protecting openings in these enclosures must provide a level of protection commensurate with the expected fuel load in the room and with the fire resistance of the corridor wall construction. Contrary to the general rule for door assembly considerations, the requirements for doors in residential occupancies apply to the leaf only, with a 1¾ in. (45 mm) solid, bonded, wood-core door considered equivalent to a door with a 20-minute fire protection rating. The door rating requirement establishes a minimum quality of construction and does not require a complete listed fire door assembly. However, the requirement that doors between apartments and corridors be self-closing reduces the risk of fire fatalities. Fire spread can occur mainly due to the door being left open as the occupant flees the fire. People may die after opening the door to a fully involved room, or after causing a room to become fully involved by opening a door and introducing oxygen to the fire. Under

both circumstances, a door equipped with spring-loaded hinges or a door closer would prevent smoke or fire from spreading down the corridor and exposing other occupants. Since a fire and its effects can be adequately and quickly contained in spaces that are protected by residential or quick-response sprinklers, the installation of those styles of sprinklers now permits the elimination of corridor walls and doors separating exit access corridors from spaces not used as dwelling units or hazardous areas. Such spaces may include meeting rooms, lobbies, gift shops, offices, and other ancillary spaces found in a number of apartment buildings. Spaces where a higher fuel load, or where sources of ignition may exist, such as workshops, storage rooms, and laundries, are not permitted to use this corridor wall exception.

During a fire, the evacuation of all residents from a large apartment building is at best a time-consuming process. This problem is compounded by the introduction of larger and taller structures, complex and intricate building designs, and a larger population of residents who are incapable of rapid evacuation, especially by stairways. For these reasons, the most expedient movement of a sizable number of residents may be horizontally. The introduction of required areas of refuge serves three purposes fundamental to the protection of building occupants by (1) limiting the spread of fire and fire-produced contaminants, (2) limiting the number of occupants exposed to a single fire, and (3) providing for horizontal evacuation by creating safe and tenable space on the same level.

Accessible means of egress and associated areas of refuge are required in new apartment buildings based on the evacuation capabilities of the building's occupants and on the construction and design characteristics of the building and levels of fire protection features. Since the majority of apartment residents are assumed to be capable of vertical evacuation using stairways, the location of stairways provides both the required area of refuge as well as the required means of egress. Where travel time to stairways increases due to excessive horizontal distances and/or where a majority of residents have reduced mobility, specialized areas are required on the same floor level.

Typically, all building service equipment and utilities in apartment buildings are required to be designed and installed in accordance with sound engineering practices and all applicable NFPA standards. The use of a public corridor as part of the supply, return, or exhaust air system is not permitted in accordance with NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems.* In fact, in certain apartment building designs, these corridors must be pressurized against smoke movement. The standard requirements for the reliability of the means of egress and fire retardancy for interior furnishings and decorations, as well as the proper maintenance and testing of fire protection equipment also apply equally to apartment occupancies. With the advent of new innovations in gas heater technology and design, including automatic fuel shutoffs and oxygen-depletion alarms, the use of approved gas space heaters is now permitted under certain conditions commensurate with the listing of the heater.

Occupants of each living unit must be given emergency instructions on a yearly basis, indicating the location of alarms, exiting paths, and actions to be taken in response to a fire in the living unit and in response to the sounding of an alarm. However, other operating features, such as specialized fire safety training and fire exit drills, have been deleted due to the nontransient nature of most building occupants.

SUMMARY

The statistical data previously cited provide clear evidence that the fire problem in apartment buildings and in residential occupancies as a whole is complex, significant, and not easily solved. The increasing demand for adequate, yet low-cost, functional and aesthetically pleasing housing has led to an increasing demand for adequate, safe, and economical fire protection. The problem intensifies with the demand for higher and larger buildings with a higher density of occupants and with the demand for more personal services for building occupants. Although the solution to these fire problems undoubtedly requires much future study, the obvious short-term solution of effective code formulation, adoption, and enforcement is the immediate responsibility of every fire safety professional.

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3. Karter, M. J., Jr., *Fire Loss in the United States During 2004,* National Fire Protection Association, Quincy, MA, Sept. 2005.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on apartment buildings discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA 72®, National Fire Alarm Code®
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA *101®, Life Safety Code®*
NFPA 5000®, Building Construction and Safety Code®

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Chapter 5

Lodging or Rooming Houses

Revised by
Richard R. Anderson

Chapter Contents

Occupant and Occupancy Characteristics
Fire Safety
Means of Escape
Passive Fire Protection
Active Fire Protection Systems and Equipment

Key Terms

bed-and-breakfast, occupancy characteristic, occupant characteristic, rooming house, self-preservation, university housing

Lodging or rooming houses are defined by NFPA *101®, Life Safety Code®,* and *NFPA 5000®, Building Construction and Safety Code®,* as those buildings in which separate sleeping rooms are rented and sleeping accommodations are provided for 16 or fewer persons on either a transient or a permanent basis, with or without meals, but without separate cooking facilities for individual occupants.

Facilities with sleeping accommodations for more than 16 persons are classified as hotels and dormitories, and those with individual cooking facilities are classified as apartment buildings. Occupants must be capable of self-preservation. The presence of four or more occupants who are incapable of self-preservation reclassifies the facility as a health care, or possibly, a board and care facility. Based on these restrictions, the classification "lodging or rooming house" is effectively limited to facilities providing sleeping accommodations without separate cooking facilities for up to 16 persons who are capable of self-preservation.

Lodging or rooming houses can be in buildings of any construction type permitted by local building codes. NFPA *101* does not identify any minimum construction requirements for occupant life safety purposes. Because most lodging or rooming houses are located in converted dwellings or share space with mercantile operations, construction is generally found to be Type III or V, as defined by NFPA 220, *Standard on Types of Building Construction,* and *NFPA 5000*. The hazard of the contents is considered "ordinary," a trait consistent with most residential occupancies.

For related topics, see the following chapters in Section 20: Chapter 1, "Assessing Life Safety in Buildings"; Chapter 2, "Board and Care Facilities"; Chapter 3, "Hotels and University Housing"; Chapter 4, "Apartment Buildings"; and Chapter 6, "One- and Two-Family Dwellings."

OCCUPANT AND OCCUPANCY CHARACTERISTICS

How familiar occupants of lodging and rooming houses are with the layout of the houses they live in varies considerably. Permanent occupants of a rooming house have the advantage of being familiar with the layout of the building. Occupants of a campus lodging house, better known as a fraternity or sorority house, are not permanent; however, over the course of a semester they can become increasingly familiar with the layout of the building. Bed-and-breakfast guests, like hotel guests, are typically transient in nature.

Mixed occupancies generally are not encountered in lodging and rooming houses, except in cases in which mercantile-use spaces are located on the lower floor or floors and sleeping rooms are located above. Neither NFPA *101* nor *NFPA 5000* permits such an arrangement without specific protection requirements.

Rooming Houses

In the 1970s and 1980s, several new markets spurred a growth in the number and nature of lodging and rooming houses, which were once considered budget-conscious alternatives to expensive hotels. Landmark court decisions required that psychiatric patients capable of living in less

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restrictive environments than psychiatric hospitals be released to live in the general population. Although many deinstitutionalized people do not require the assistance of support staff, such as might be found in residential board and care facilities, they prefer not to assume all the responsibilities of independent living, meal preparation, and the like and choose to live in rooming houses.

Due to the limited number of sleeping accommodations and the lack of separate cooking facilities for individual occupants, lodging or rooming houses are viewed, from a life safety standpoint, as falling above one- and two-family dwellings and below dormitories, hotels, and apartment buildings.

NFPA *101* and *NFPA 5000* requirements for lodging and rooming houses center on four key elements essential to life safety: means of escape, detection and alarm systems, separation of sleeping rooms, and automatic sprinkler protection. These four elements are covered in the sections that follow.

Bed-and-Breakfast Properties

Bed-and-breakfast properties are typically distinctly different from rooming houses, dormitories, or fraternity and sorority houses. They are typically owner-occupied, well kept, and often upscale accommodations. Bed-and-breakfasts and country inns have become increasingly popular in the United States as alternative travel accommodations to hotels. Many facilities known as bed-and-breakfasts meet the definition of hotel because they provide sleeping accommodations for more than 16 guests.

Fraternity/Sorority or University Housing

Fraternity houses, sorority houses, and university housing in converted dwellings are found on and around university campuses. These properties pose many of the same life safety hazards posed by rooming houses. In most cases, these properties are occupied by young adults who might be prone to risky behavior—for example, smoking, consuming alcohol, and using controlled substances—which can serve to increase the life safety hazard.

FIRE SAFETY

Because most fires involve behaviors and transitory hazards that may not be identified in an annual inspection, the property owner should be well versed in understanding fire hazards.

Inherent Hazards

The leading causes of fires in lodging and rooming houses during the 4-year period from 1999 to 2002 were cooking equipment (42%), smoking materials (16%), and arson (10%). Whereas cooking equipment was involved in 42 percent of all fires in rooming and boarding houses, 25 percent were confined to the cooking equipment.[1] Smoking in the guest rooms and common areas of bed-and-breakfast properties can be prohibited, and enforcement of a no-smoking policy can eliminate one of the leading causes of fires in these occupancies. However, smoking is typically allowed in rooming, fraternity, and sorority houses. Fire-retardant textiles, furniture, and mattresses can help slow the spread of fires caused by smoking materials.

Electrical Equipment

The original design of the electrical systems for homes converted to or used as bed-and-breakfast occupancies did not consider the use of modern-day appliances, such as 2000 watt hair dryers, 900 watt space heaters, coffee makers, and the like. If a property has undergone renovations to facilitate its use as a bed-and-breakfast, the electrical system might have been updated. However, if there were no renovations, electrical systems may be prone to improper use of extension cords and outlet strips due to the lack of sufficient receptacles. The use of extension cords and outlet strips should be limited due to the potential of overloading circuits. Where used, such devices should be listed, approved, and used according to the manufacturer's recommendations. From 1992 to 2002, electrical equipment represented the cause of 5 percent of structural fires in lodging and boarding houses.[1]

Building Systems

Due to the limited size of lodging or rooming house occupancies, building systems are typically not very sophisticated; however, it is not uncommon for them to have a central air and heating system. These systems might be required to be equipped with smoke dampers to isolate the air-handling equipment from the remainder of the system or smoke detectors in the ducts arranged to automatically shut down the system upon detection of smoke. See NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems,* for detailed requirements for such systems.

Heating and cooling systems should be installed by qualified installers and maintained in accordance with the manufacturer's recommendations. Inadequate heating can lead to the use of supplemental heating devices, such as portable electric, kerosene, or fixed-space heaters. Each represents a specific hazard and has its own accompanying set of requirements.

Appliances

Appliances in a lodging or rooming house occupancy include appliances similar to those found in a residence. However, the frequent use of clothes dryers to do laundry for up to 16 guests can lead to a dangerous buildup of lint that could result in a fire. In rooming houses some tenants may be permanent and are, therefore, likely to accumulate more electrical appliances than transient tenants, such as those in a bed-and-breakfast facility.

Open Flames

Sources of open flames in lodging or rooming houses include candles and fireplaces. The National Candle Association recommends that candles never be left unattended. Many bed-and-breakfast owners have instituted policies that prohibit the use of candles in the guest rooms or have replaced them with battery-operated candles. Battery-operated candles can actually flicker and appear very realistic, thus providing the desired ambiance without the danger.

Cooking Equipment

The presence of individual cooking facilities changes the type of occupancy, typically to an apartment building. However, a central kitchen is sometimes found in lodging or rooming house occupancies. The leading cause of fire incidents in U.S. lodging and room houses from 1999 to 2002 was cooking equipment, which resulted in 16 civilian injuries and $0.9 million in direct property damage.[1] Central kitchens are typically only accessible to staff. Cooking equipment in such central kitchens should be protected in accordance with NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations.*

Fireplaces

Wood-burning fireplaces are common in bed-and-breakfast properties and are typically used more often than in private residences. Annual cleaning and inspection of the flue can prevent the buildup of flammable creosote and reveal defects in the flue or blockage, such as a nest.

Occupancy Conversion or Remodeling

Fire hazards may be inadvertently created during conversion or remodeling. Existing wall and ceiling finishes might be removed, exposing combustible structural components. Concealed combustible spaces may be created by installing drop ceilings and new wall finishes. Concealed combustible spaces can permit rapid fire development and spread and limit accessibility for fire fighting. The wall and ceiling finishes in new facilities are limited to Class A, B, or C as defined in NFPA *101* and *NFPA 5000*; however, wall and ceiling finish materials can exceed these limitations and significantly increase fire spread and smoke generation in existing buildings.

MEANS OF ESCAPE

In lodging or rooming houses, the egress system consists of means of escape, which, by definition, is a way out of a building or structure that does not conform to the strict definition of means of egress but does provide a safe way out.

Sleeping rooms and living areas above and below grade are required to have a primary and secondary means of escape, one of which must be either an enclosed interior stairway, an exterior stairway, a horizontal exit, or an existing fire escape. The primary means of escape must provide a safe path of travel from the building, one that does not expose occupants to an unprotected vertical opening, except in completely sprinklered buildings of three stories or fewer (Figures 20.5.1, 20.5.2, and 20.5.3). In buildings protected throughout by automatic sprinklers, secondary means of escape are not required.

The example in Figure 20.5.1 shows an enclosed interior stairway that discharges directly outside. Access to the interior stairway is by an interior corridor that is not exposed to an unprotected vertical opening. The secondary means of escape could be through windows of sufficient size to provide egress. The bottom of the stairway can be enclosed several ways; this is only one example. In the example of means of escape shown

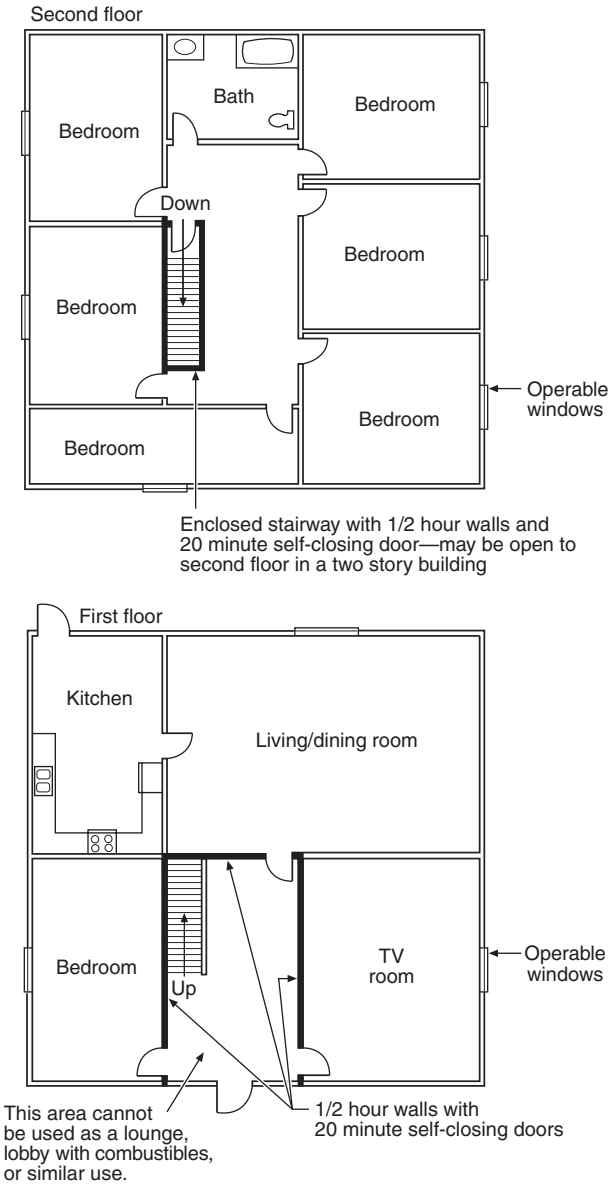

FIGURE 20.5.1 Means of Escape from a Lodging or Rooming House Using an Interior Stairway

in Figure 20.5.2, the tenants reach the exterior stairway via an interior corridor that is not exposed to an unprotected vertical opening. The secondary means of escape is through windows.

In the example shown in Figure 20.5.3, access is not through an interior corridor, and the secondary means of escape is through the open interior stairway.

The specified means of escape should meet the requirements of NFPA *101* and *NFPA 5000*. Detailed requirements for secondary means of escape are provided in NFPA *101* and *NFPA 5000*; they include either a door or stairway that provides unobstructed travel to the outside of the building at street or ground level or an outside operable window located not more than 20 ft (6.1 m) above the ground. Note that a secondary means of escape is not required where the room has a door leading directly

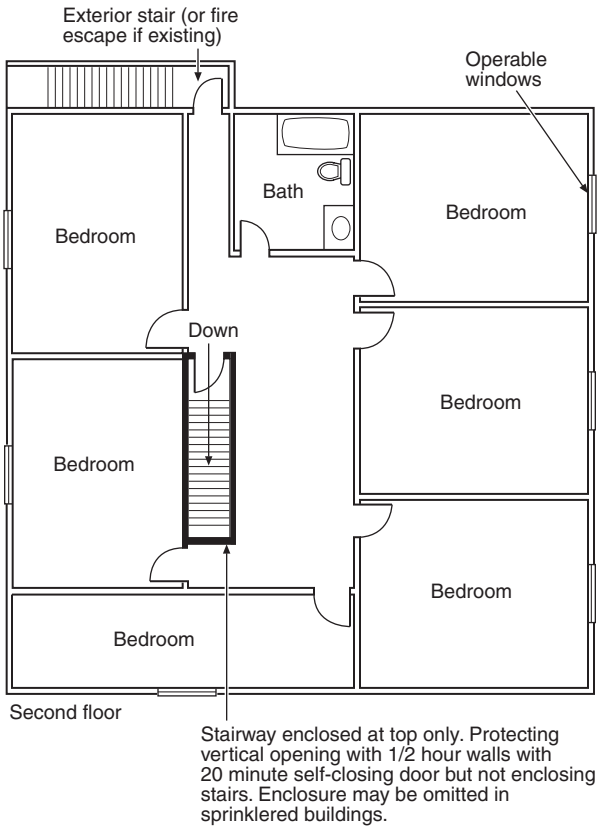

FIGURE 20.5.2 Means of Escape from a Lodging or Rooming House Using an Exterior Stairway

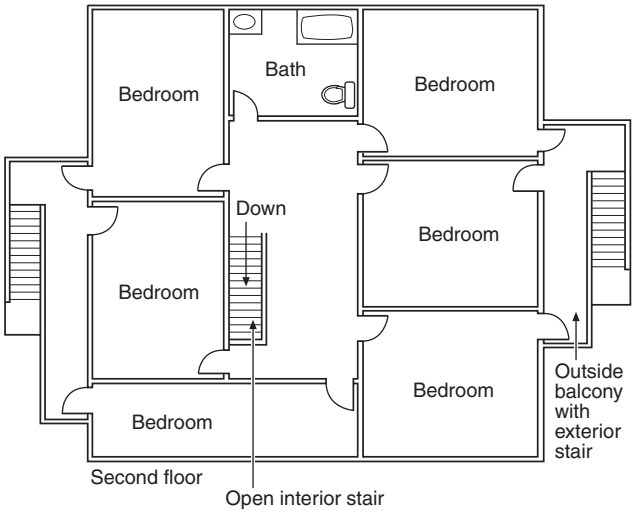

FIGURE 20.5.3 Means of Escape from a Lodging or Rooming House Using an Outside Stairway with Exterior Exit Access

outside at grade level or to an approved outside stair. No required means of escape may be routed through an area that is not under the control of the occupant who is leaving the building or be routed through a door that may be locked.

PASSIVE FIRE PROTECTION

Fire Doors

The installation of automatic or self-closing doors is an effective, relatively low-cost, and easy-to-maintain life safety feature. Fire-rated doors can help to confine a fire to the room of origin. Fire doors must not be blocked or otherwise secured in the open position, and they must positively latch when closed. See NFPA 80, *Standard for Fire Doors and Other Opening Protectives,* for details on the installation of fire doors.

Lack of Fire Blocking

Many older buildings lack fire blocking in walls and ceilings due to the lack of a building code or its enforcement at the time of construction. Such a lack of fire blocking, sometimes referred to as "balloon construction," can accommodate rapid, undetected spread of fire and smoke.

Separation of Sleeping Rooms

Sleeping rooms should be separated from corridors by smoke-resistant walls and self-closing doors. This feature helps prevent smoke from compromising the egress corridors in case of a fire in a room. In addition, if the corridor becomes smoke-logged before all occupants can escape, the smoke-resistant separation will allow occupants to remain within the room for a limited period of time.

Vertical Openings

Vertical openings, or "holes" in the floor that connect two or more contiguous stories, are not limited to stairs. They include shafts, floor penetrations for air ducts, heat grates, and other old floor openings that were never covered. Each represents a path for vertical fire and smoke spread. Unprotected vertical openings have been identified as significant contributing factors in many fatal fires.

CASE STUDY: Small Inn Fire. The fire that broke out on July 17, 2001, in a small inn in Allentown, New Hampshire, demonstrates how the lack of some of the passive fire protection measures mentioned in this section can result in tragedy. A three-alarm fire killed the innkeeper and destroyed the historic building that dated from 1760. Of the six guests who were occupying the premises, all survived, three by climbing to the roof of a portico. The NFPA fire investigation and analysis[2] revealed that the following played a significant role in the incident:

- There was only a single path of escape from the attic bedroom.

- No fire alarms or smoke detectors were functioning.
- There were unprotected vertical openings.

ACTIVE FIRE PROTECTION SYSTEMS AND EQUIPMENT

Detection and Alarm Systems

Detection and alarm systems in lodging or rooming houses play a critical role in the early warning and evacuation of occupants. A manual fire alarm system should be installed in accordance with *NFPA 72®, National Fire Alarm Code®*.

Smoke alarms installed in accordance with *NFPA 72* and powered by the building electrical service are required on each floor, including basements, but excluding crawl spaces and unfinished attics. When activated, the smoke alarms should be audible in all areas. This requirement can be satisfied by interconnecting smoke alarms with the manual fire alarm system. In addition to smoke alarms in the corridors on each level, a single-station smoke alarm powered by the building electrical system is required in each sleeping room to alert the occupant to a fire or smoke in the room. It is critical that the fire alarm system be audible in all sleeping rooms.

Automatic Sprinkler Protection

Automatic sprinkler systems are designed to operate during the early stages of fire development and minimize the fire's overall impact. If the room of fire origin is provided with a sprinkler system, flashover should be prevented, thus improving the opportunity to escape or be rescued and minimizing property damage. NFPA *101* and *NFPA 5000* require most new lodging or rooming houses to be protected by automatic sprinklers. Modifications to other requirements are permitted where sprinklers have been installed. In existing buildings, where automatic sprinkler protection is provided, the following code modifications are permitted:

- The lodging or rooming house is permitted to be located above another occupancy type.
- No secondary means of escape is required.
- It may be permissible for the primary escape stairway to remain unenclosed if each bedroom and living area has a secondary means of escape.

NFPA *101* and *NFPA 5000* recognize three standards for the installation of automatic sprinkler systems in lodging or rooming houses. For small, one- and two-family residences in which boarders are housed and rooming houses that are not part of a mixed occupancy, NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes,* permits a simple, lower-cost system. For larger buildings of up to four stories in height, NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height,* may be used. For large buildings, especially those housing multiple occupancies, NFPA 13, *Standard for the Installation of Sprinkler Systems,* is the appropriate installation standard. Successful testing of water mist suppression systems in residential properties may offer a desirable protection strategy to owners of historic bed-and-breakfast occupancies containing irreplaceable antique contents and furnishings.

Staff Emergency Training

By combining the recognition of individual responsibilities to report fire-related hazards and how to initiate the appropriate actions should a fire occur, the risks to employees and the workplace can be reduced. Staff should be familiar with their responsibilities in the event of a fire including guiding guests or tenants in proper evacuation. NFPA *101* fire drill requirements for dormitories call for them to take place often enough so that the occupants are familiar with the emergency procedures, evacuation routes, alarm operation, and tone. In hotels, where guests are transient and may only be there for one night, the staff must be trained and prepared to assist the guests in the event of an incident. Although these code requirements do not directly apply to lodging or rooming house occupancies, the concepts can be readily applied to them to enhance a facility's life safety program.

SUMMARY

Lodging or rooming houses are defined as facilities providing sleeping accommodations without separate cooking facilities for up to 16 persons who are capable of self-preservation. Fire spread in these occupancies can be rapid due to lack of firestopping, unprotected vertical openings, storage of combustible materials, and the lack of automatic sprinkler protection. Primary fire hazards include electrical and other building service equipment, supplemental heating devices, smoking, and cooking.

Fire and life safety protection involves providing adequate means of escape, detection and alarm systems, bedrooms that are separated from corridors by smoke-resistant walls and self-closing doors, and automatic sprinkler systems.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on lodging or rooming houses discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*

NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*
NFPA 72®, National Fire Alarm Code®
NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations*
NFPA *101®, Life Safety Code®*
NFPA 220, *Standard on Types of Building Construction*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 5000®, Building Construction and Safety Code®

Chapter 6

One- and Two-Family Dwellings

James K. Lathrop

Chapter Contents

Importance of Evacuation
Fire and Life Safety Hazards
Prevention of Fire Ignition

Key Terms

dwelling, evacuation, fire prevention, heating equipment, residential sprinkler system, smoking materials

One- and two-family dwellings are defined as residential structures in which not more than two families reside. These dwelling units may be attached to or detached from one another, and typical styles include detached single-family dwellings, townhouses, and duplexes. There are many different designs, such as the one-story ranch, two-story colonial, split-level, and three-level townhouse. Wood frame and masonry are the most common construction types.

In 2003, 70 percent of all housing units occupied year-round were single-family detached or attached units, and another 6 percent were manufactured housing. The figures for seasonal housing were comparable at 63 percent and 23 percent. Two-family houses were not tabulated separately, but housing units in buildings with two to four housing units accounted for another 8 percent of the total year-round housing and 3 percent of the total seasonal housing. Therefore, one- and two-family housing accounts for 75 to 84 percent of all housing in the United States. This total has not changed since the last edition of the *Fire Protection Handbook.*

Each year, the majority of all U.S. fire deaths occur in one- and two-family dwellings. During 1999–2002, 94 percent of the civilian structure fire deaths occurred in the home and 83 percent of those occurred in one- and two-family dwellings, a share comparable to their share of all housing units. Thus, it is important to consider every element of fire safety for its potential value in this setting. Unless otherwise indicated, all data contained in this chapter come from *Selections from U.S. Fires in Selected Occupancies—Homes,* by Marty Ahrens, NFPA Fire Analysis and Research Division, NFPA, March 2006.

NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®, include requirements for one- and two-family dwellings. In particular, NFPA *101* addresses the need for two means of escape from every room for occupant evacuation; the selection of interior finish materials to prevent rapid early fire growth and spread and to protect occupant evacuation routes; and smoke alarms to provide early warning. Beginning with the 2006 edition of NFPA *101,* all new one- and two-family dwellings require sprinkler protection.

See also Section 4, Chapter 5, "Strategies for Occupant Evacuation during Emergencies"; Section 14, Chapter 6, "Household Fire Warning Equipment"; and Section 16, Chapter 6, "Residential Sprinkler Systems."

IMPORTANCE OF EVACUATION

The philosophy of life safety and fire protection for one- and two-family dwellings is based on evacuation of the building in the event of a fire. The defend-in-place concept used in other types of occupancies, which relies on fixed fire protection systems and fire-resistant construction, does not lend itself to one- and two-family dwellings. To allow residents time to evacuate, they must be alerted to a fire that has been detected at the incipient stage, they must know what action to take, and they must have adequate means of escape. Even with residential sprinkler systems, ocupants need to evacuate. NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family*

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Dwellings and Manufactured Homes, permits a limited water supply, so defending in place is not an option in most cases.

Proper installation and use of smoke alarms can accomplish early warning. *NFPA 72®, National Fire Alarm Code®*, recommends smoke alarms be installed in all sleeping rooms, outside of each separate sleeping area, in the immediate vicinity of the sleeping rooms, and on each additional story of the dwelling including basements. Additional information on smoke alarms can be found in Section 14, Chapter 6, "Household Fire Warning Equipment."

Means of Escape

After the occupants have been alerted, they must promptly evacuate. A written fire escape plan should be made for each dwelling, showing two means of escape from every habitable room, especially the bedrooms, and this plan should be practiced by the entire family. Programs such as NFPA's Exit Drills in The Home (EDITH) explain how to write and practice a home fire escape plan.

Adequate means of escape from each room should be provided in accordance with the requirements of NFPA *101* and *NFPA 5000.* Two means of escape are required from each room. One must be a door or stairway, and the second way can be an operable window. Figure 20.6.1 illustrates means of escape from a three-bedroom single-family home. The bedroom in the upper left has no window, but it has a door directly to the outside. The alternate means of escape from the other bedroom is through windows and must comply with the requirements of NFPA *101* and *NFPA 5000.* Figure 20.6.2 shows the minimum

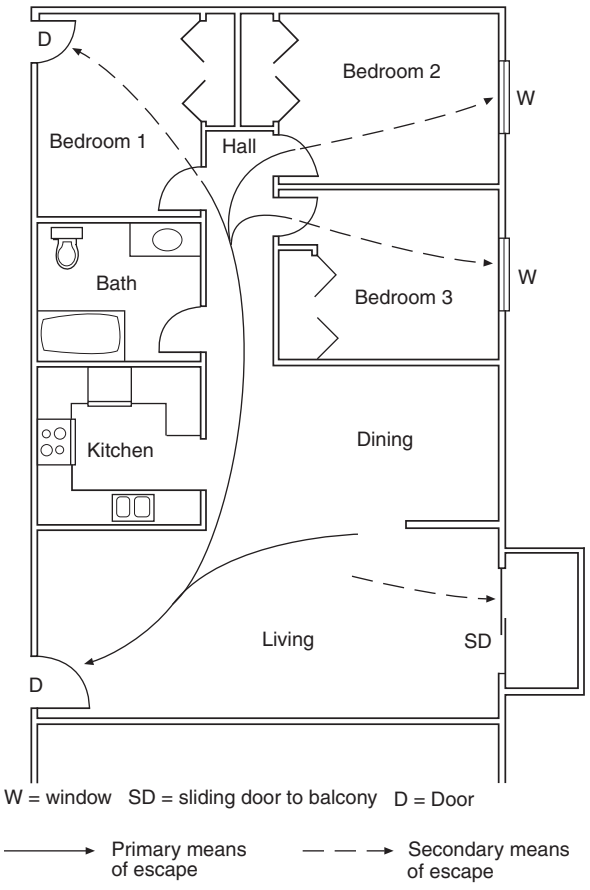

FIGURE 20.6.1 Means of Escape from Single-Family Home

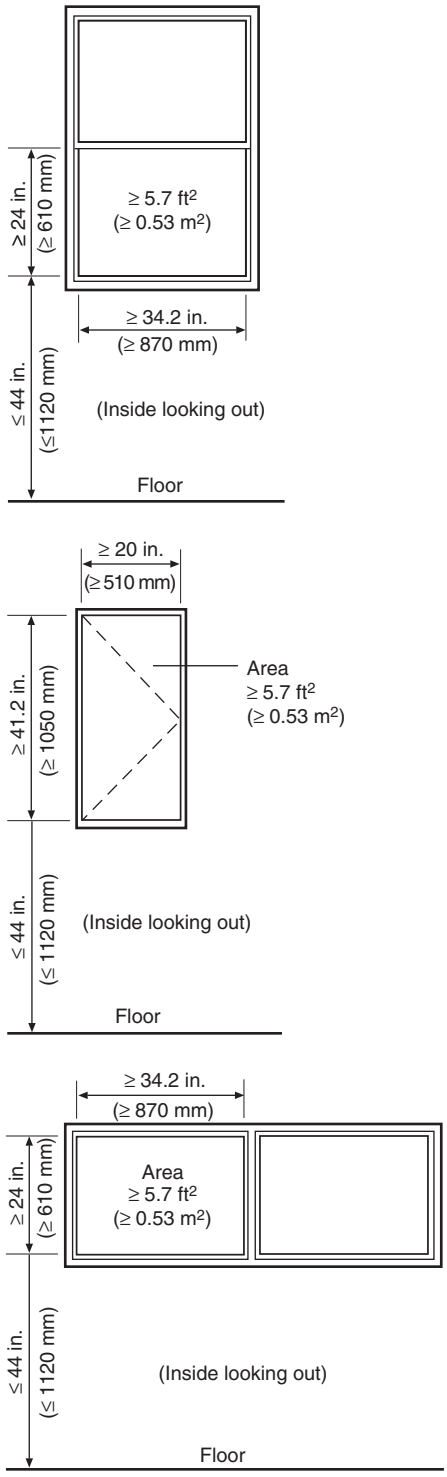

FIGURE 20.6.2 Escape Window Minimum Opening Dimensions

size and dimensions of outside windows used as a second means of escape.

Adequate means of escape also involves eliminating obstacles created by some security provisions. Escape may be slowed—possibly more than safe escape allows—by security measures like double-cylinder locks, which require a key to open from inside. Escape may be totally obstructed by security measures, either designed (such as burglar bars) or makeshift (such as nailing windows shut).

Residential Sprinklers

Residential-type automatic sprinkler systems provide a high degree of protection for one- and two-family dwellings. A growing number of communities require sprinklers in all new dwellings, as does the 2006 edition of the *Life Safety Code*. Even where they are not required, sprinklers are a valuable and effective fire safety choice. In any property, sprinklers reduce the chances of dying if fire occurs and the average property loss per fire by one-half to two-thirds. From 1994 through 1998 automatic suppression systems, usually sprinklers, were present in 1 percent of one- and two-family dwelling fires, 7 percent of the apartment fires, and in 2 percent of reported home fires overall. The fire death rate per 1000 fires was 77 percent lower and the average loss per fire was 85 percent lower in fires in which this equipment was present. Additional information on sprinkler systems in one- and two-family dwellings can be found in Section 16, Chapter 6, "Residential Sprinkler Systems."

FIRE AND LIFE SAFETY HAZARDS

Many other fire protection strategies are under discussion, but they have not yet been reduced to codes or regulations. These address the contribution of various types of contents, furnishings, and construction elements to fire growth, smoke and gas generation, and confinement after a fire begins.

Most fire fatalities in one- and two-family dwellings are a result of smoke inhalation, not burns, and most victims die in a room that is not the room of fire origin. In other words, they die as a result of a fire that has produced enough smoke to spread beyond the room in which the fire began. Prevention and early action are needed to control the development of these lethal conditions.

When studying fire data in one- and two-family dwellings, it is very important to understand that the statistics are significantly different between numbers of fires and numbers of fatal fires. For example the leading cause of fires in one- and two-family dwellings is cooking equipment, but by far the leading cause of fatal fires in dwellings is smoking materials. Table 20.6.1 demonstrates these differences.

TABLE 20.6.1 Leading Causes of Structure Fires in One- and Two-Family Dwellings, 1999–2002 Annual Averages

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Cooking equipment fire	63,400	(23%)	220	(9%)	2570	(24%)	357	(8%)
Identified cooking equipment	45,800	(16%)	220	(9%)	2300	(22%)	350	(8%)
Confined cooking fire	17,600	(6%)	0	(0%)	280	(3%)	7	(0%)
Heating equipment	48,900	(17%)	300	(12%)	1090	(10%)	571	(13%)
Identified heating equipment	36,100	(13%)	300	(12%)	1060	(10%)	563	(13%)
Confined chimney or flue fire	10,400	(4%)	0	(0%)	10	(0%)	7	(0%)
Confined fuel burner or boiler malfunction or fire	2,500	(1%)	0	(0%)	10	(0%)	1	(0%)
Electrical distribution or lighting equipment	27,900	(10%)	200	(8%)	770	(7%)	577	(14%)
Intentional	25,500	(9%)	410	(17%)	850	(8%)	515	(12%)
Smoking material	16,400	(6%)	640	(26%)	1150	(11%)	307	(7%)
Candle	14,400	(5%)	130	(5%)	1230	(12%)	304	(7%)
Exposure to other fire	11,800	(4%)	20	(1%)	70	(1%)	161	(4%)
Clothes dryer or washer	11,200	(4%)	10	(1%)	240	(2%)	90	(2%)
Playing with heat source	10,200	(4%)	180	(7%)	940	(9%)	175	(4%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest ten, and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey.

PREVENTION OF FIRE IGNITION

Leading Causes of Fire Fatalities

The leading cause of fire deaths in one- and two-family dwellings is smoking materials or lighted tobacco products (Tables 20.6.2 and 20.6.3). Fatal smoking material fires most often involve the ignition of upholstered furniture, mattresses, or bedding, which also rank highest as combustible items first ignited in all kinds of fatal fires. Because it is not unusual for a fire to smolder for hours before it progresses to open burning, many of these fatal fires occur at night when everyone is asleep. Although smoking material is the leading cause of fatal one- and two-family dwelling fires, it is fifth in list of causes of the total number of fires in one- and two-family dwellings.

A major change from the last edition of the *Fire Protection Handbook* is that intentional fires have moved to the second leading cause of fatal fires in one- and two-family dwellings. These fires previously ranked third. Intentional fires rank fourth as the cause of all fires in one- and two-family dwellings.

The third-ranking cause of fire deaths in one- and two-family homes is heating equipment. Heating equipment was also the second leading cause of fires. Heating equipment includes fixed or portable space heaters, chimneys, central heating units, fireplaces, and water heaters. Each type of heating appliance has its own rules for safe installation, maintenance, and use. NFPA 211, *Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances,* in particular, covers solid-fueled appliances. Maintaining adequate clearance to combustibles, whether fixed (e.g., walls and structural members) or moveable (e.g., furniture, bedding, and clothing), is a common problem for all types of portable and area heating equipment. Safe fueling practices are especially important for liquid-fueled units, as is adequate venting for gas-fueled units and regular inspection and cleaning for solid-fueled units.

Electrical distribution equipment ranked a very close fifth as a cause of fire deaths. Many people mistakenly believe that electrical system fires represent a larger share of fires, but the widespread and long-term use of NFPA 70, *National Electrical Code®*, has reduced them to a lower-order problem, usually involving some kind of failure to observe the code. Electrical distribution equipment fires can take many forms. Damaged components, such as frayed cords, broken switches, or plugs; bypassed protection systems, such as oversized fuses or pennies in place of fuses; overloaded cords, circuits, or outlets; and cords run through traffic areas or pinned by furniture, are all potential problems. Knowledgeable, experienced people should always perform repairs and modifications in strict accordance with applicable codes.

Cooking equipment ranked fifth as a cause of fire deaths but first in fires and fire injuries. Such equipment also accounts for a majority of unreported fires, which injure tens of thousands. Unattended cooking is a principal cause. Others include combustibles, such as rags, pot holders, or bags, placed too close to heat; failure to clean stove tops and ovens; and overhanging curtains, drapes, or clothing.

The sixth leading cause of fire deaths in one- and two-family dwellings was "playing with heat source, usually matches or

TABLE 20.6.2 Leading Causes of Structure Fires Resulting in Civilian Fire Deaths in One- and Two-Family Dwellings, 1999–2002 Annual Averages

Cause	*Fires*		*Civilian Deaths*	
Smoking material	16,400	(6%)	640	(26%)
Intentional	25,500	(9%)	410	(17%)
Heating equipment	48,900	(17%)	300	(12%)
Identified heating equipment	36,100	(13%)	300	(12%)
Confined chimney or flue fire	10,400	(4%)	0	(0%)
Confined fuel burner or boiler malfunction or fire	2,500	(1%)	0	(0%)
Cooking equipment fire	63,400	(23%)	220	(9%)
Identified cooking equipment	45,800	(16%)	220	(9%)
Confined cooking fire	17,600	(6%)	0	(0%)
Electrical distribution or lighting equipment	27,900	(10%)	200	(8%)
Playing with heat source	10,200	(4%)	180	(7%)
Candle	14,400	(5%)	130	(5%)
Exposure to other fire	11,800	(4%)	20	(1%)
Clothes dryer or washer	11,200	(4%)	10	(1%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred and civilian deaths are rounded to the nearest ten.

Source: NFIRS and NFPA survey.

TABLE 20.6.3 Leading Causes of Civilian Injuries and Direct Property Damage in Structure Fires in One- and Two-Family Dwellings, 1999–2002 Annual Averages

Cause	*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Cooking equipment fire	2570	(24%)	357	(8%)
Identified cooking equipment	2300	(22%)	350	(8%)
Confined cooking fire	280	(3%)	7	(0%)
Candle	1230	(12%)	304	(7%)
Smoking material	1150	(11%)	307	(7%)
Heating equipment	1090	(10%)	571	(13%)
Identified heating equipment	1060	(10%)	563	(13%)
Confined chimney or flue fire	10	(0%)	7	(0%)
Confined fuel burner or boiler malfunction or fire	10	(0%)	1	(0%)
Playing with heat source	940	(9%)	175	(4%)
Intentional	850	(8%)	515	(12%)
Electrical distribution or lighting equipment	770	(7%)	577	(14%)
Clothes dryer or washer	240	(2%)	90	(2%)
Exposure to other fire	70	(1%)	161	(4%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Civilian injuries are rounded to the nearest ten and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey.

TABLE 20.6.4 Structure Fires in One- and Two-Family Dwellings by Area of Origin, 1999–2002 Annual Averages

Area of Origin	*Civilian Deaths*		*Fires*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Common room, living room, family room, lounge, or den	730	(30%)	18,900	(7%)	1,340	(13%)	481	(11%)
Bedroom	590	(24%)	34,800	(12%)	2,700	(25%)	702	(16%)
Kitchen or cooking area	390	(16%)	59,200	(21%)	2,850	(27%)	561	(13%)
Unclassified function area	100	(4%)	3,600	(1%)	240	(2%)	87	(2%)
Unclassified structural area	70	(3%)	4,600	(2%)	140	(1%)	106	(2%)
Garage or vehicle storage area	40	(2%)	9,600	(3%)	330	(3%)	304	(7%)
Crawl space or substructure space	40	(2%)	7,800	(3%)	240	(2%)	186	(4%)
Unclassified	40	(2%)	4,000	(1%)	110	(1%)	125	(3%)
Dining room, bar, or beverage area	40	(2%)	2,000	(1%)	120	(1%)	48	(1%)
Other known area	410	(15%)	137,100	(49%)	2,530	(25%)	1667	(41%)
Total	2450	(100%)	281,600	(100%)	10,600	(100%)	4267	(100%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest ten, and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation. Nonconfined and noncontained structure fires in which the area of origin was unknown or not reported have been allocated proportionally among fires with known area of origin. Totals may not equal sums due to rounding errors.

Source: NFIRS and NFPA survey.

lighters." Children playing with fire also is the leading cause of fire deaths for children under age 6. Children must be monitored closely and taught at an early age that matches and lighters are tools for adults, not toys. These fire deaths have dropped sharply since the Consumer Product Safety Commission adopted regulations requiring butane lighters manufactured in the United States to be child-resistant in mid-1994. Matches and lighters must be kept out of the reach and sight of young children.

Location of Fire Fatalities

Nearly three-fourths of all fatal fires in one- and two-family dwellings begin in living rooms, family rooms, or dens; bedrooms; or kitchens (Table 20.6.4). These areas are also the leading areas for fires, injuries, and direct property damage. The number of one- and two-family dwelling fires has decreased over the last couple of decades as has the number of civilian deaths. This is seen in Table 20.6.5. However, the decrease appears to be leveling off, which indicates that we cannot sit back, but must be aggressive in attacking this problem

SUMMARY

The majority of U.S. fire deaths occur in one- and two-family dwellings, the most common form of housing in the United

TABLE 20.6.5 Structure Fires in One- and Two-Family Dwellings, by Year, 1980–2002

				Direct Property Damage (in Millions of Dollars)	
Year	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*As Reported*	*In 2002 Dollars*
1980	595,800	4222	14,245	2457	5369
1981	573,500	4329	13,978	2338	4619
1982	545,700	3858	14,806	2732	5086
1983	518,600	3850	15,020	2644	4770
1984	494,000	3277	13,031	2714	4690
1985	483,800	3897	13,285	3026	5050
1986	448,400	3777	12,637	2758	4529
1987	421,600	3643	13,635	2831	4480
1988	421,800	3977	15,155	3024	4601
1989	386,000	3365	13,702	2953	4286
1990	346,700	3184	13,327	3221	4438
1991	357,400	2783	14,106	4262	5626
1992	347,900	2923	13,834	3006	3854
1993	347,700	2996	14,568	3827	4764
1994	334,500	2746	12,908	3291	3996
1995	317,300	2926	12,702	3368	3974
1996	316,900	3336	12,714	3854	4422
1997	299,600	2652	11,558	3512	3935
1998	282,600	2673	11,337	3471	3833
1999	274,300	2359	10,688	3839	4143
2000	274,600	2857	11,579	4328	4522
2001	288,600	2459	10,476	4264	4333
2002	288,900	2112	9,670	4635	4635

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest million dollars.

Source: NFIRS and NFPA survey. Inflation adjustments were based on U.S. Census Bureau, *Statistical Abstract of the United States: 2006,* "Table 705, Purchasing Power of the Dollar."

States. Fatalities are most often the result of smoke inhalation rather than burns. The requirements for one- and two-family dwellings are covered by NFPA *101* and *NFPA 5000*, which address the need for two means of escape from every room for occupant evacuation; the selection of interior finish materials to prevent rapid early fire growth and spread and to protect occupant evacuation routes; and smoke alarms to provide early warning. In new construction sprinkler protection must be installed, and it is also encouraged in existing homes. A written evacuation plan, adequate means of escape, and properly installed and functioning smoke alarms are critical to life safety. In recent years, residential-type automatic sprinkler systems have proved an effective means of fire suppression. Fire prevention measures should be taken to avoid ignition in the home. The most common sources of ignition of fatal fires in one- and two-family dwellings are smoking material, arson, heating equipment, cooking equipment, electrical equipment, children playing with heat sources, and candles.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on one- and two-family dwellings discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*

NFPA 13R, *Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height*

NFPA 70, *National Electrical Code®*

NFPA 72®, National Fire Alarm Code®

NFPA *101®, Life Safety Code®*

NFPA 211, *Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances*

NFPA 5000®, Building Construction and Safety Code®

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Chapter 7

Manufactured Housing

Kirsten M. Paoletti

Chapter Contents

Background on Manufactured Housing
Manufactured Housing Standards
HUD Code Requirements
NFPA Requirements

Key Terms

HUD *Manufactured Home Construction and Safety Standards,* manufactured home, manufactured home construction, manufactured home safety, manufactured home site, manufactured housing, oil-burning equipment, residential fire sprinkler systems, smoke alarms

Manufactured homes represent an important and affordable housing option for over 22 million people in the United States. By 2000 an estimated 10.5 million units made up the manufactured housing inventory, including those used year-round, either occupied or vacant, and used seasonally.[1] (The U.S. Census Bureau reported a lower figure of 8.9 million total units and a lower population served, apparently because of differences in definitions and labeling rules.[2]) During 2000, newly placed manufactured homes accounted for almost 23 percent (280,900 units) of the combined total of new privately owned (site-built) one-family houses completed and manufactured homes placed for residential use (1,242,000 total combined units). This share for manufactured homes represented an increase of over 17 percent in 1990, a recent low point in manufactured home placements, and roughly the same as 20 percent in 1980.[3]

Manufactured homes are getting larger. In 2000, some 70 percent of the 250,419 manufactured homes shipped were multisection units, and the remaining 30 percent were smaller single-section homes. The share of multisection units was just under 50 percent in 1991. Further, on an average square foot basis, multisection manufactured homes are becoming comparable in size to site-built homes. For example, in 2001 the average square footage of a multisection home was 1695 ft^2 (157.5 m^2), which was 74 percent of the average site-built home at 2282 ft^2 (212.0 m^2).[1,4]

Most new manufactured homes (68 percent) are located on private property with the remainder located in manufactured home communities. Manufactured homes are predominantly located in rural areas with a concentration in the southern regions of the United States. In 1997, 44 percent of manufactured homes were located in rural areas compared to 20 percent of detached single-family dwellings. Also, during 1997, over one-half of all occupied manufactured homes were located in the South compared to 37 percent of occupied single-family dwellings. During 1993, the five states receiving the greatest percentage of new manufactured homes were North Carolina, Texas, Florida, Georgia, and South Carolina.[5–8]

This chapter covers manufactured homes and their construction, fire safety features, installation, and associated utilities. The development of the HUD *Manufactured Home Construction and Safety Standards, 24 CFR, Part 3280* (HUD Code), which governs manufactured home construction in the United States, is discussed. The recent developments of NFPA standards, such as NFPA 501, *Standard on Manufactured Housing,* and NFPA 225, *Model Manufactured Home Installation Standard,* are addressed. Related manufactured home fire experience is also addressed.

See also Section 20, Chapter 6, "One- and Two-Family Dwellings."

BACKGROUND ON MANUFACTURED HOUSING

Manufactured Home Defined

Amendments made in 1980 to the National Manufactured Housing Construction and Safety Standards Act of 1974 changed the definition of manufactured homes from "mobile" to "manufactured." Manufactured homes in the United States are built in accordance with the federal HUD Code,

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which preempts state and local building codes. Manufactured homes are factory-assembled structures that can be transported in one or more sections. Sections are typically 8 ft (2.5 m) or more wide and 40 to 80 ft (12.2 to 24.4 m) long, each built on a permanent chassis. When assembled on site for occupancy as a dwelling, manufactured homes are connected to required utilities and placed on stabilizing devices, which may be piers and footings, or a permanent foundation. Manufactured homes are constructed in sections. A single-wide home is one that is made up of a single, transportable section. A multiwide home is one that is made up of two or more transportable sections, typically referred to as double-wide and triple-wide (Figure 20.7.1). The length of a manufactured home is the home's largest overall dimension in the traveling mode including cabinets and other projections that contain interior space. The final length, in terms of the outside dimensions of the living space, is typically 4 ft less than the traveling mode length. Although predominantly single-story structures, the single most important advancement since the late 1990s has been the development of two-story models. With recent innovations in chassis and transportation systems as well as improved architectural compatibility with existing homes in urban/suburban surroundings, multistory models, although still a small percentage of the overall housing market, have gained tremendous consumer interest and will likely translate into increased availability by manufacturers.[9] Figure 20.7.2 illustrates a multistory manufactured home.

HUD Code manufactured homes are not to be confused with modular homes. A modular home is built in a factory in units and transported to a site where the units are joined together on a permanent foundation. It is designed and constructed in accordance with a building code that has been adopted, administered, and enforced by a state or local regulatory agency. Further, some non–HUD Code factory-built, commercial modular units are used as temporary classrooms, construction site offices, or for business uses such as banks or fast-food restaurants. Depending on the application and local authorities having jurisdiction (AHJs), such structures typically must comply with state or local building codes.

FIGURE 20.7.1 Installed Double-Section Manufactured Home

FIGURE 20.7.2 Installed Multistory Manufactured Home (Source: Manufactured Housing Institute)

Manufactured Home Construction

HUD Code manufactured homes consist of four major components or subassemblies: the chassis, floor system, wall system, and roof system.

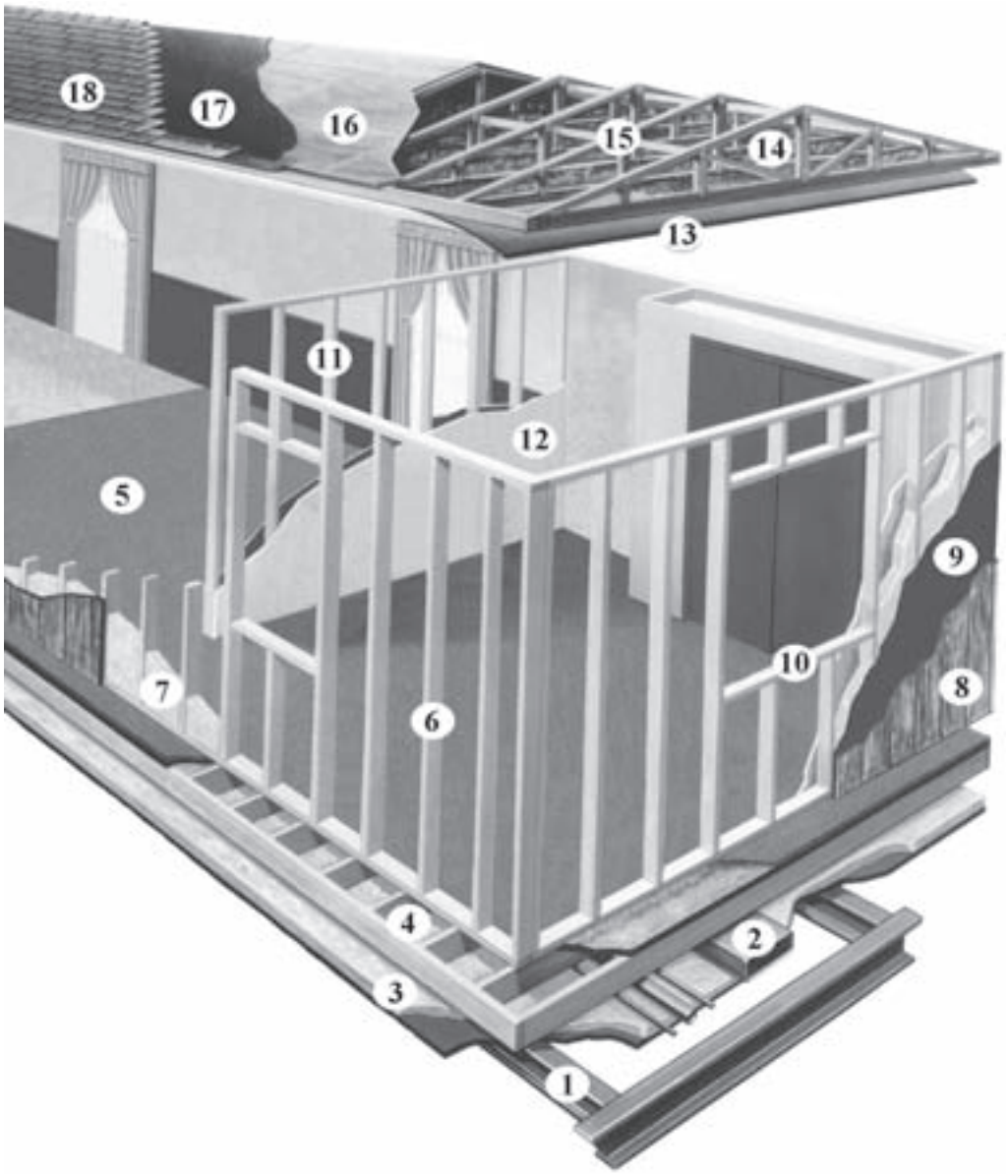
Chassis System. The chassis is the structural base of the manufactured home, which receives all of the vertical loads from the walls, roof, and floor and transfers them to stability devices, which may be piers, footings, or a permanent foundation. The chassis generally consists of two longitudinal steel beams braced by steel cross members. Steel outriggers extending from the outsides of the main beams bring the width of the chassis to the approximate overall width of the superstructure.

Floor System. The floor system consists of its framing members with sheet decking of particleboard, oriented strand board (OSB), or plywood, glued and nailed to the joists; glass fiber insulation blankets or cellulose insulation installed between the joists; and a bottom board material sealing the bottom of the floor. Trunk ducts and piping are often installed longitudinally within the floor system. The floor finish is generally carpeting, resilient flooring, linoleum, or tile.

Wall System. The exterior wall system consists of vinyl, wood, cement board, hardboard, or sometimes metal on wood studs applied over laminated fiberboard, insulative fiberboard, or OSB sheathing. The interior surfaces of exterior walls are most often constructed of gypsum wallboard, and fiberglass insulation blankets provide exterior wall insulation. Interior partitions are most often constructed of gypsum wallboard attached to wood studs.

Roof System. The roof system consists of either the framed wood roof rafter and ceiling joist system or a wood truss system. This roof decking generally consists of oriented strand

board (OSB) or plywood attached to the top of the roof rafters or trusses. The finished roofing is most often composition shingles and infrequently metal without decking. Blown rockwool or cellulose insulation or fiberglass insulation blankets provide the roof insulation. The interior ceiling finish, which consists of gypsum wallboard, is attached directly to the bottom chords of trusses or joists. Steel strapping or brackets are used to reinforce connections between the walls and floor systems and between the walls and roof to make a complete transportable section (Figure 20.7.3).



1. Steel chassis.
2. Heating ducts in floor cavities, normally sized for central air conditioning.
3. Fiberglass or cellulose insulation under the entire floor covered by a bottom board material that acts like a vapor barrier.
4. 2 in. × 6 in. (51 mm × 152 mm) wood floor joists spaced every 16 in. to 24 in. (406 mm to 610 mm). Joists are normally positioned and secured transverse to steel I-beams.
5. Decking of particleboard, oriented strand board (OSB), or plywood, under carpeting or vinyl rolled goods.
6. 2 in. × 6 in. (51 mm × 152 mm) or 2 in. × 4 in. (51 mm × 102 mm) wood studs spaced every 16 in. or 24 in. (406 mm or 610 mm) in exterior walls.
7. Fiberglass insulation in all exterior walls, plus a vapor barrier.
8. Vinyl, wood, hardboard, cement board, or metal exterior siding.
9. Laminated Kraft fiberboard, insulative fiberboard, or OSB.
10. Glass windows with screens. At least one egress window in each bedroom.
11. 2 in. × 4 in. (51 mm × 102 mm) or 2 in. × 3 in. (51 mm × 76 mm) wood studs in the interior walls.
12. Gypsum wallboard for interior wall paneling. Flame spread index shall not exceed 200, except for walls enclosing a furnace or water heater shall not exceed 25.
13. Gypsum wallboard on either cathedral or flat ceilings, flame spread index shall not exceed 75.
14. Fiberglass or cellulose roof insulation, plus a ceiling-area vapor barrier.
15. Load-tested, wood roof-rafter system normally 2 in. × 3 in. (51 mm × 76 mm) chords, for structural strength against wind and snow loads.
16. Plywood or OSB roof decking.
17. Roofing underlayment between shingles and roof decking.
18. Shingled pitched roof.

FIGURE 20.7.3 Typical Manufactured Home Construction Systems and Materials (Source: Champion Home Builders Co.)

HUD Code Manufactured Home Fire Experience

Post–HUD Code homes have much lower fire losses per fire incident compared to pre–HUD Code homes.* From 1989 to 1998, manufactured homes built after 1976 averaged 1.2 civilian fire deaths per 100 fires compared to 2.6 civilian fire deaths per 100 fires for manufactured homes built before 1976. The 54 percent lower fire death rate per 100 fires in post-1976 units was also strengthened by a significantly lower rate of reported fires per 1000 units, although precise calculations are not possible because the census reporting on year of manufacture breaks at 1974–1975 and not at 1976. Manufactured homes built after 1976 also averaged 4.3 civilian fire injuries per 100 fires, 22 percent lower than the 5.5 civilian fire injuries per 100 fires for manufactured homes built before 1976.[10]

Post–HUD Code manufactured home fire incident, death, and injury rates are roughly the same as rates for other one- and two-family, stick-built dwellings relative to the number of occupied units.† Annual average statistics for the 1999–2002 period show that the fire death rate per 100 fires in HUD Code homes was 1.7 compared to 0.8 for one- and two-family dwellings. The fire injury rate was 3.9 per 100 fires in HUD Code homes and 3.8 in one- and two-family dwellings. There were 2.0 fires per 1000 housing units in HUD Code units, lower than the 3.2–3.5 fires per 1000 units in one- and two-family dwellings. HUD Code homes had 3.3 deaths per 100,000 housing units, a slightly higher rate, compared to 2.7–3.0 deaths for one- and two-family stick-built homes. The statistics for deaths and injury rates in pre–HUD Code manufactured homes are significantly higher than one- and two-family dwellings, 2.6 deaths per 100 fires and 5.5 injuries per 100 fires, respectively.[11]

Table 20.7.1, which compares pre– and post–HUD Code fire causes from 1999 to 2002, shows a continued downward shift in the share of electrical distribution and heating system fires in post–HUD Code manufactured homes when compared with statistics from 1989 to 1998. Electrical and heating systems must meet the installation and testing requirements of the HUD Code. Further, furnace and water heater compartments must meet the flame spread and combustibility construction requirements. In both pre– and post–HUD Code homes, occupant-related fire causes comprise a significant share of the total fire causes. These include incendiary or suspicious fires, caused by cooking, smoking materials, children playing, and open flame.

The dramatic difference in the injury and death rates is directly attributable to HUD's uniformly applying and enforcing the fire safety provisions of the HUD Code. Both the mandatory smoke alarm provision and the restrictions on flame spread ratings, throughout the unit and especially around heating and cooking equipment, are major contributors to the effects of the HUD Code. From 1999 to 2002, 45 percent of post-standard manufactured home fires were reported as having no smoke alarms present, a higher percentage than in 1997 and 1998. As noted in the NFPA report *Manufactured Home Fires in the U.S.,* "Because all post-standard manufactured homes are required to be sold with smoke alarms installed, this implies a disturbingly high rate of smoke alarm removal by occupants."[12]

When smoke alarms are not present in post–HUD Code homes, the fire death rate is significantly higher than in HUD Code homes where smoke alarms were recorded as present (1.3 deaths per 100 fires compared to 0.9 deaths per 100 fires). Every HUD Code home must have installed and tested smoke alarms, which are verified at the plant by approved quality control procedures. One study of manufactured home smoke alarm installation and testing practices found that nearly 100 percent of smoke alarms were installed, tested, and left in place at the factory. In a few cases, for special transportation-related reasons, smoke alarms were removed after testing, and reinstallation instructions were provided for those responsible for the setup of the home. In fire incident reports, a home recorded as not having smoke alarms most likely involves the removal of them by some party following the manufacturing process, or the devices were possibly not

TABLE 20.7.1 Structure Fires Reported to U.S. Fire Departments: Pre-Standard and Post-Standard Manufactured Home Fires, by Cause, 1999–2002

Cause	*Pre-Standard Percentage (Pre-1976)*	*Post-Standard Percentage (Post-1976)*
Electrical distribution	17	10
Heating	16	8
Intentional	13	10
Exposure (to other hostile fire)	10	16
Other equipment	9	21
Cooking	9	9
Open flame, candle, or torch	7	7
Appliance, tool, or air conditioning	7	5
Smoking material (i.e., lighted tobacco product)	4	5
Child playing	4	4
Other heat source	3	4
Natural causes	1	1
Total	100	100

Note: These are percentages of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Only percentages are shown because so few fires have unitage coded after 1998. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Totals may not equal sums because of rounding.

Changes in coding and analysis rules produced some shifts in shares by major cause, beginning in 1999 and growing thereafter. Major changes include (1) movement of unknown-equipment fires from "other equipment" to "unknown," where they are then statistically allocated; and (2) movement of playing fires where firestarter age is not recorded from "child playing" to the category for the heat source, primarily "open flame."

Source: NFIRS and NFPA survey.

*For statistical purposes, post–HUD Code homes refer to manufactured homes built after the year 1976. Pre–HUD Code refers to homes built before 1976.

†For statistical reasons in this data set only, post–HUD Code homes are those built in 1975 and later, and pre–HUD Code homes are those built before 1975.

found during a fire investigation. Nonworking smoke alarms are a concern in manufactured homes and other dwellings. The issue of nonworking smoke alarms was addressed in the Consumer Product Safety Commission's (CPSC) National Smoke Detector Project, which found that power supplies (batteries or ac power) were too often disconnected. The project found that the leading reason for nonoperability of home smoke alarms, when it occurs, is frustration over nuisance alarms, leading to occupants disabling the offending smoke alarms. Home manufacturers typically provide homeowners with the smoke alarm manufacturer's literature, which includes instructions for the inspection and testing of smoke alarms. Some manufacturers also provide additional fire safety information in their homeowner's manuals.[13–16]

The installation of smoke alarms alone is not enough. To ensure reasonable fire safety, homeowners need to practice fire prevention, periodically test and maintain smoke alarms, and develop and practice home escape plans. Clearly, with working smoke alarms and these fire safety practices, the manufactured home fire experience could be further improved.

MANUFACTURED HOUSING STANDARDS

HUD Code Development

Manufactured housing in the United States is built in accordance with the preemptive federal standard, *Manufactured Housing Construction and Safety Standards, 24 CFR, Part 3280* (HUD Code), which is administered by the U.S. Department of Housing and Urban Development (HUD). Effective mid-1976, the HUD Code was based on NFPA 501B, *Standard for Mobile Homes* (ANSI No. A119.1), which was the result of a cooperative NFPA and industry committee project developed under the NFPA consensus codes and standards-making process. In 1979, NFPA 501B was withdrawn following the federal legislation that established the HUD Code. Unique among built structures, the federal preemptive status sets a single construction and performance specification for all manufactured homes that are built in the United States. Neither state nor local jurisdictions can reduce or increase on the federal standards without a great deal of effort to amend the requirements.

In 1997, NFPA reinstituted the standard for manufactured housing as NFPA 501, based in part on the 1977 edition of NFPA 501B and the HUD Code, and it was updated to include current technology. The 1999 edition of NFPA 501 contained significant revisions to the smoke alarm requirements, and it was developed through the NFPA Manufactured Housing project consisting of the Technical Correlating Committee on Manufactured Housing and the six technical committees involved with specific areas of responsibility including administration, electrical, fire safety, mechanical, plumbing, and structural. The current edition of NFPA 501 incorporates significant revisions concerning the installation of smoke alarms; residential sprinkler installation requirements; updated electrical provisions; new heating, cooling, and fuel-burning system requirements; updated plumbing provisions; revised load testing for trusses; and updated referenced standards.

In 1998 HUD selected NFPA to develop proposals for revisions to the HUD Code, and NFPA submitted a proposal to HUD for the revision of smoke alarm requirements to reflect current state-of-the-art smoke alarm technology and installation practices. A notice of the proposed rulemaking, for HUD Code smoke alarm revisions, was published in the May 2000 *Federal Register* and the final rule was published in the March 2002 *Federal Register.* In addition, NFPA has submitted recommendations to HUD for changes to the HUD Code based on the 1997, 1999, 2000, and 2003 editions of NFPA 501.[17]

NFPA 501A, *Standard for Fire Safety Criteria for Manufactured Home Installations, Sites, and Communities,* was prepared by the same technical committees involved with the NFPA Manufactured Housing project. NFPA 501A provides state and local AHJs with the requirements for fire safety at manufactured home sites, including accessory buildings, structures, and communities.

NCSBCS/ANSI A225.1, *American National Standard, Manufactured Home Installations,* was published by the National Conference of States on Building Codes and Standards, Inc. (NCSBCS). In 2001, an agreement was reached between NCSBCS and NFPA that allowed transfer of the ANSI A225.1 standard to NFPA. The 1994 edition of NCSBCS/ANSI A225.1 formed the basis for the first edition of NFPA 225, *Model Manufactured Home Installation Standard*. This document was not only developed to pick up where the previous NCSBCS document left off, but it also became an integral part of providing another option, along with other state-sponsored installation standards, that could potentially be considered by HUD, the ultimate overseer of manufactured homes. NFPA 225, *Model Manufactured Home Installation Standard,* covers the installation of manufactured homes at sites or communities whenever the manufacturer's installation instructions are not available. This document is applicable to new installations of single-section and multisection homes, regardless of whether they are at new or existing manufactured housing sites. The criteria in NFPA 225 are intended to be adopted and enforced by the authority having jurisdiction when an alternative state standard does not exist. In addition to covering the basic administrative criteria, provisions are included for site preparation work, foundations, and procedures during on-site installation/erection, as well as management of appliances and utility connections. Requirements reflecting current design loads and practices associated with seismic, wind, and flood events have been included.

HUD Code and Regulatory Enforcement Program

NFPA standards activity regarding manufactured homes began in 1937 with publication of the first standard in 1940, and the documents have evolved over the years. The 1969 edition of NFPA 501B, ANSI A119.1 and its revisions through 1977, had become the guiding industry construction standard for manufactured homes. For example, the Mobile Home Manufacturers Association (MHMA), which became the Manufactured Housing Institute (MHI), required that its members meet NFPA 501B before the HUD Code became effective in June 1976. NFPA 501B was the basis for the HUD Code. It addressed the unique construction characteristics, or the body and frame design; plumbing systems; heating, cooling, and fuel-burning systems; and electrical systems of transportable homes. By the early 1970s, almost all states adopted the NFPA 501B standard for manufactured homes, and concerned federal agencies, such as

the Federal Housing Administration and the Veterans Administration, used it in connection with home purchases under loan programs they administered.

However, both the manufactured housing industry and the federal government were concerned about the lack of enforcement by states, counties, and cities. To ensure a safe, low-cost form of housing of uniform quality throughout the United States, Congress passed the National Manufactured Housing (formerly Mobile Home) Construction and Safety Standards Act of 1974 (Title VI of the Housing and Community Development Act of 1974). This act established HUD as the sole source of standards governing the construction of these homes in the United States. It gave HUD the authority to establish procedural and enforcement regulations necessary to ensure that makers of manufactured homes uniformly met the construction standards.

HUD fully implemented the act in June 1976, substantially adopting NFPA 501B as the construction standard and naming the NCSBCS as the contract agent for ensuring uniform enforcement. The HUD manufactured housing program requires that manufacturers participate in a system of design approvals and inspections to ensure that a home complies with the HUD Code. The enforcement system includes preproduction design approval, production inspections, and postproduction consumer complaint handling. An independent, third-party design approval primary inspection agency (DAPIA) reviews and approves home designs and the manufacturer's quality assurance manuals. An independent, third-party production inspection primary inspection agency (IPIA) ensures that homes in the plant comply with the design, quality assurance manuals, and the HUD Code. Before production begins, the IPIA conducts a plant certification inspection, and during production, each home is inspected in at least one stage of its construction. During a plant visit, to assure quality control, the IPIA inspects each visible part of each home on the production line. A state with an approved state administrative agency (SAA) may act as the DAPIA or IPIA in that state.[18]

All transportable sections of each manufactured home sold in the United States must bear a HUD certification label, which certifies that the home has been inspected, has passed all of the quality assurance checks, and is in compliance with the HUD Code. These metal labels are attached to the exterior siding of the transportable sections of each home and bear a unique IPIA identification number for each section.

In 1984, some of the HUD Code fire safety provisions were revised following research on means of egress and fire growth and spread issues, conducted by the Center for Fire Research, National Bureau of Standards (NBS), now the National Institute of Standards and Technology (NIST). However, the HUD Code has not kept up with developing fire safety technology. In December 2000, the Manufactured Housing Improvement Act was passed, which provides for a more timely process of establishing new standards, updating the existing standards, and providing comments to HUD on related programs for consumer protection, regulatory enforcement, and similar programs that affect the industry. The act established a federal advisory committee that mostly conducts its business in accordance with ANSI procedures. Since its inception, the advisory committee, generally referred to as the Manufactured Housing Consensus Committee (MHCC), has made numerous recommendations to HUD on ways to keep the HUD Code up-to-date. The act provides a mechanism for HUD adoption and adaptation of requirements from private-sector, consensus standards such as NFPA 501. Also under the act, each state will be required to establish an installation program and a dispute resolution program. The MHCC has provided base guidelines to HUD that can be adopted by each state. Conversely, a state can establish its own program but the criteria must be at least as stringent as the federal criteria.[19]

Approximately 6.6 million manufactured homes have been built under the act. The infusion of safer new manufactured homes into the U.S. housing stock has dramatically affected life safety and fire incidents in manufactured homes built after June 1976.[20]

HUD CODE REQUIREMENTS

HUD Code Fire Safety Provisions

Since 1976, the HUD Code has required that the interior finish be regulated for flame spread characteristics and, in certain areas of the home, for combustibility. Fire blocking is required in concealed wall and partition spaces. At least two exterior doors are required, and they must be arranged to provide a means of unobstructed travel to the outside. The minimum width of doors is specified, as is the ability to operate locking mechanisms without a key from inside to facilitate egress. Each room designed expressly for sleeping, unless it has a door to the outside, must have at least one outside window large enough to permit emergency egress. The window must meet size and location specifications and must be able to be opened without the use of special tools or special knowledge.

In 1979 the Center for Fire Research, National Bureau of Standards (NBS), now NIST, issued a report following four years of fire tests in manufactured homes. The purpose was to provide experimental data on the potential growth and spread of fire in manufactured homes and recommend upgrades in the level of fire protection for kitchen areas and flame spread ratings for interior finishes.* The Center for Fire Research also conducted research and issued reports on emergency egress from manufactured homes. Following these reports, HUD issued the first update to its standard in 1984. HUD lowered the maximum height above the floor of the egress window latch from 60 to 54 in. (1.5 to 1.4 m). More importantly, HUD issued a stricter limit on ceiling interior finish flame spread—to a flame spread index of 75 from 200—and expanded its criteria on kitchen cabinet protection. Other minor changes included further clarification of fire-blocking construction techniques in concealed wall, ceiling, and floor construction; recognition of $^{5}/_{16}$-in. (8-mm) thick gypsum wallboard as fire-blocking material; and clarification of smoke alarm placement instructions.[21–24]

The HUD Code also specifies the minimum construction requirement, thickness, and gauge of the metal ventilating hood

*These NBS (NIST) fire tests of over 25 years ago focused on major fire growth factors understood during the 1970s such as room geometry and combustible interior finish. Based on further NIST research during the 1980s, the role of combustible contents, including heat release rates, was also identified as having a significant influence on the rate of compartment fire growth leading to flashover.

to be installed over a kitchen range. In addition, the HUD Code limits the flame spread of the wall and cabinet finishes in the immediate vicinity of the kitchen range. This combination of requirements effectively negates or minimizes the direct exposure of the wall and cabinet surfaces nearest the kitchen range in the event of a cooking surface fire. Fire experience statistics show that these provisions produce smaller cooking and heating fires in post-1976 manufactured homes and that a much smaller share of such fires spread beyond the room of origin than in pre-1976 units.

HUD Code Utility Provisions

Manufactured homes requiring fuel-gas are required to be equipped with a natural gas piping system that is acceptable for LP-gas. The gas piping system must be designed for a pressure no more than 14 in. (3.4 kPa) water column and no less than 7 in. (1.7 kPa), and manufacturers are required to provide written instructions regarding the design pressure limitations for safe and effective operation. The HUD Code regulates piping materials, routing, sizing, joints, and anchoring. Tubing for gas piping systems cannot be run inside walls, floors, partitions, or roofs, and listed appliance connectors, when used, cannot run through walls, floors, ceilings, or partitions except cabinetry. Shutoff valves must be installed in the gas piping at appliances upstream of unions or connectors. Piping systems are to be tested at specified pressures before and after connection of gas appliances. Gas supply connections cannot be located beneath an exit door. Manufacturers are required to affix a permanent label on the outside of the home at the gas supply connection, providing supply requirements and precautions for installers. For fuel-gas systems the HUD Code references ANSI Z223.1/NFPA 54, *National Fuel Gas Code,* and NFPA 58, *Liquefied Petroleum Gas Code.*

Where oil is used as the heating fuel, there are specific requirements for oil tanks, fill and vent pipes, liquid level gauges, and shutoff valves. Materials for oil piping systems are specified as to size, type of joints, couplings, grading, hangers, and leakage tests. For oil-burning equipment the HUD Code references NFPA 31, *Standard for the Installation of Oil-Burning Equipment.*

A unique feature of the HUD Code concerns the installation of heat-producing appliances. Especially noteworthy is the requirement that all fuel-burning appliances except ranges, ovens, illuminating appliances, clothes dryers, solid fuel-burning fireplaces, and solid fuel-burning fireplace stoves be installed so that the combustion system is completely separate from the home's interior. Combustion air inlets and flue gas outlets must be listed or certified components of the appliance. The required separation may be obtained by installing direct vent systems (sealed combustion systems) or by installing the appliance within an enclosure so its appliance combustion and venting systems are separated from the manufactured home's interior.

No forced-air appliance, or its air return system, can allow the creation of a negative pressure that will affect either its combustion air supply or that of any other appliance, nor can the systems act to mix products of combustion with circulating air. Other requirements for heat-producing appliances include special provisions relating to solid fuel-burning fireplaces or fireplace stoves. The size and air tightness of circulating air duct materials are specified, and the design and combustibility of duct materials are regulated. Special provisions are included for registers and grills and ducts in expandable or multiple transportable section connections.

The HUD Code includes specific requirements for electrical installations. It concentrates on those provisions that differ from provisions applicable to all buildings under NFPA 70, *National Electrical Code®*. Some special features relate to the fact that manufactured homes are factory assembled, to the underchassis wiring requirements, to the wiring of expandable units with multiple transportable sections, to the need to bond metal parts, and to the grounding of services and appliances. For example, regarding electrical hookups at the site, manufacturer's installation instructions typically require a four-conductor service entrance (two hot conductors, a neutral, and a ground conductor); a grounding conductor must also be run from the electrical distribution panel to a grounding rod, and on the distribution side of the electrical system, the neutral bus in the electrical panel must be isolated from the grounding system. The HUD Code and approved quality control procedures require that at the factory the manufactured home electrical system be subjected to a continuity test to ensure metallic parts are properly bonded, an operational test to ensure that appliances are connected and working, and a polarity check to determine if connections have been properly made. Also, a dielectric strength test is conducted at 900 to 1079 V for 1 minute or alternatively at 1080 to 1250 V for 1 second to detect and correct electrical current leakage or short circuits.[25]

NFPA REQUIREMENTS

NFPA 501 Fire Safety Provisions

As discussed previously, NFPA 501 contains provisions impacting fire safety and reflecting state-of-the-art concepts and technology. Of particular note are the sections addressing the installation of smoke alarms and residential sprinklers. The Technical Committee on Fire Safety for Manufactured Housing had previously updated the smoke alarm requirements based on a 1998 research report, *Smoke Alarms in Manufactured Housing,* from the NIST Building and Fire Research Laboratory. These requirements are in harmony with other NFPA codes and standards, including *NFPA 72®, National Fire Alarm Code®,* and NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes.*[26]

Smoke Alarms. Smoke alarms must be ac powered or powered by a nonreplaceable, 10 year battery, and they are permitted to be installed on flat ceilings, sloping ceilings, or walls, with specific requirements for each arrangement. Regarding location, smoke alarms are required in all sleeping rooms, outside each sleeping area, and on each additional story of the home. If installed within a 20 ft (6.1 m) horizontal path of a cooking appliance, they must have an alarm-silencing means or be of a photoelectric type. If stairs lead to other occupied levels, smoke alarms must be installed near the top of each stair. Smoke alarms are required to be interconnected so that the operation of one will sound all of the smoke alarms in the home. There are additional requirements for visual notification appliances if they are provided.

Following their installation at the manufactured home factory, smoke alarms must be functionally tested. Recognizing that smoke alarm testing is also a critical responsibility of others after the home leaves the factory, NFPA 501 requires that the home manufacturer provide testing instructions for the setup crews or other installers to use at the site and for the homeowner for periodic testing and maintenance. Further, the home manufacturer is to provide the homeowner with instructions to replace alarms if they fail to respond during tests and to replace smoke alarms after 10 years of service.

Residential Fire Sprinkler Systems. NFPA 501 contains minimum requirements for residential fire sprinkler systems if installed by the home manufacturer. The requirements are voluntary unless the AHJ requires fire sprinklers in all detached one- and two-family dwellings. When fire sprinkler systems are to be provided in the manufactured home, they are to be designed, installed, and tested in accordance with NFPA 13D, and the home manufacturer must affix a certificate adjacent to the home data plate. The certificate is to include information on the residential sprinkler system, such as sprinkler specifications, minimum water supply required, and control valves. The home manufacturer is required to provide setup crews or other installers with instructions for inspection and testing of the system. Further, when the system is connected at the home site, the water supply must be verified and tested, and those data added to the system certificate. The home manufacturer is also required to provide the homeowner with information about the automatic fire sprinkler system's operation, testing, and maintenance.

There are several other important fire safety provisions in NFPA 501, including definitions on interior finish and limited-combustible materials and requirements on the application of foam plastics. Means of egress provisions include design requirements for exterior doors, egress windows from sleeping rooms, and interior passage and room requirements.

NFPA 501 Utility Provisions

NFPA 501 addresses heating, cooling, and fuel-burning equipment installed within or external to a manufactured home and contains specific requirements for the various systems. The following NFPA codes and standards are referenced: ANSI Z223.1/NFPA 54, NFPA 58, NFPA 90B, *Standard for the Installation of Warm Air Heating and Air-Conditioning Systems,* and NFPA 31. Additionally, NFPA 501 contains requirements for electrical conductors and equipment installed within the home and service entrance equipment that connect the home to an electrical supply. In addition to NFPA 501 requirements, NFPA 70 applies to manufactured home electrical systems. It further states that service entrance equipment must be installed in accordance with NFPA 70 and that bonding and grounding of the service must meet NFPA 70 requirements.

NFPA 501A Provisions for Manufactured Home Installations, Sites, and Communities

NFPA 501A covers fire safety requirements for manufactured home installation, home sites, accessory buildings, structures, and communities. A manufactured home site is a parcel of land for one home and its supplemental structures. A manufactured home accessory building or structure is a supplemental structure such as an awning, cabana, garage, carport, or storage building. A community building is a nonresidential building used for manufactured home community purposes.

Fuel storage and supply systems for manufactured home sites and communities must meet the requirements of the referenced NFPA or federal standards, including ANSI Z223.1/NFPA 54, NFPA 58, and NFPA 31. The same requirements also apply to manufactured home community buildings. Electrical service equipment and installations must meet the applicable provisions of NFPA 70.

NFPA 501A includes manufactured home separation requirements for fire safety and requires that fire separation distances comply with local regulations. However, the fire separation distances mandated by *NFPA 5000®*, *Building Construction and Safety Code®*, must be used where local rules or regulations do not exist. Manufactured home installations must follow the printed instructions provided by home manufacturers, including the installation of the support system and utility connections.

NFPA 501A includes fire safety requirements for manufactured home community buildings, including construction, control of outdoor hazards, fire detection and alarm systems, and water supplies for fire protection. The posting of emergency information in conspicuous places is required for manufactured home communities. The standard also contains setback requirements for accessory buildings and exit requirements as well. The appendices of NFPA 501A provide manufactured home community management and manufactured home residents advisory material on fire safety responsibilities and procedures.

SUMMARY

In the United States, manufactured homes, which are factory-assembled structures that can be transported in one or more sections, are built in accordance with the federal HUD Code and NFPA codes and standards. These codes and standards cover many aspects of design, construction, and installations, including body and frame design; plumbing systems; heating, cooling, and fuel-burning systems; electrical systems; and smoke alarms. NFPA 501, *Standard on Manufactured Housing,* contains provisions impacting fire safety and reflecting state-of-the-art concepts and technology.

NFPA 225, *Model Manufactured Home Installation Standard,* addresses provisions for the installation of manufactured homes used as dwelling units. The criteria established by NFPA 225 govern single-section as well as multisection homes and provide requirements for everything from interconnection criteria for multisection homes to anchor provisions to restrict movement from wind loads, seismic events, and floods.

NFPA 501A, *Standard for Fire Safety Criteria for Manufactured Home Installations, Sites, and Communities,* covers fire safety requirements for manufactured home installation, home sites, accessory buildings, structures, and communities. To ensure fire safety, occupants must also practice fire preven-

tion, periodically test and maintain smoke alarms, and develop and practice home escape plans.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on manufactured housing discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*
NFPA 31, *Standard for the Installation of Oil-Burning Equipment*
NFPA 54, *National Fuel Gas Code*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 70, *National Electrical Code®*
NFPA 90B, *Standard for the Installation of Warm Air Heating and Air Conditioning Systems*
NFPA 225, *Model Manufactured Home Installation Standard*
NFPA 501, *Standard on Manufactured Housing*
NFPA 501A, *Standard for Fire Safety Criteria for Manufactured Home Installations, Sites, and Communities*
NFPA 5000®, Building Construction and Safety Code®

Chapter 8

High-Rise Buildings

James R. Quiter

Chapter Contents

Definition and Background
Fire Loss History
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Key Terms

egress, fire department access, fire resistance, high-rise building, National Institute of Standards and Technology (NIST), NFPA High-Rise Building Safety Advisory Committee, performance-based codes, smoke movement, stack effect, World Trade Center

The high-rise building has garnered significant attention in the fire safety world over the years, but perhaps never more so than since 2001. The public; the code bodies; the local, regional and federal governments; and the design, build, and ownership communities are all reviewing high-rise building safety and developing positions regarding the need (or lack of need) for additional protection in those buildings. This chapter describes some of the code provisions and special features of the high-rise building, as well as presenting historical data on high-rise building fires.

See also Section 1, Chapter 7, "Protecting Against Extreme Events"; Section 20, Chapter 1, "Assessing Life Safety in Buildings"; and Section 20, Chapter 3, "Hotels and University Housing."

DEFINITION AND BACKGROUND

High-Rise Building Defined

NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®, define a high-rise building as a building where the floor of an occupiable story is greater than 75 ft (23 m) above the lowest level of fire department vehicle access. This definition is consistent with most U.S.-based model building codes but is not consistent around the world. Many local authorities having jurisdiction also use varying heights and measurement criteria to determine whether a building is a high-rise, with heights ranging from 40 ft (12 m) to as high as 150 ft (45 m). When evaluating whether a code requires a building to be treated as a high-rise, it is important to review the code, as well as any local amendments, to determine the method of measuring building height and what height threshold is used to define a high-rise.

Code application to high-rise buildings is also inconsistent. For many years, most of the U.S. model building codes limited high-rise provisions to business and residential buildings. NFPA *101* contained provisions for high-rise buildings that varied by occupancy. In 2006, most U.S. codes for high-rise apply to all high-rise buildings except open parking garages and some special use structures. Open parking garages are excluded because of the minimal risk imposed by the open structure.

Background

The original intent of the high-rise building provisions was to provide greater protection in buildings where rescue of occupants via ladders was no longer practicable. The 75 ft (23 m) threshold and the measurement of level of fire department vehicle access to the top occupied floor were intended to track with the maximum height that fire department ladders could reach. Many of the jurisdictions that lowered the threshold did so because their equipment was incapable of reaching such heights.

Extensive high-rise provisions first appeared in U.S. codes in the early 1970s. These provisions contained an option to either sprinkler the building or to separate each floor into 2-hour compartments. If the sprinkler option was chosen, several "construction modifications" were permitted.

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Over time, most codes have been changed to require automatic sprinklers, yet still allow some of the original "modifications" that were originally permitted.

Many codes outside the United States also address high-rise buildings, and many apply high-rise provisions at a building height of about 75 ft (23 m). Provisions similar to those found in U.S. codes apply in other countries. Codes from outside the United States may include more restrictive criteria, including the number and location of fire fighter lifts (elevators); the number, width, and travel distance to escape stairs; compartmentation requirements; and structural fire resistance. In parts of Asia, buildings over a certain height (often in the 15- to 30-story range) also require one or more open-air refuge floors.

In recent years in the United States, two problematic areas have gradually begun to be addressed. The first is that building codes typically apply to new buildings, yet there is a huge stock of existing buildings, particularly in older cities, to which building code requirements do not apply. Retrofit sprinkler ordinances have been passed in many U.S. cities, often after a local disaster. These retrofit laws are not consistent in the level of protection they require, in the types of buildings to which they apply (that is, office, hotel, apartment, condominium), or in the time allowed to complete the retrofit. NFPA *101* has gradually added to the types of existing high-rise buildings required to have automatic sprinklers, but it is not necessarily applied to all existing buildings. Therefore, the public has no easy way of knowing the level of protection they will be afforded in a high-rise building, particularly as they travel from city to city.

Another series of code changes has occurred more recently. Some codes require additional protection measures in some buildings as they get higher. Few people, when they walk into a 7- to 10-story building, picture that building as a high-rise. Yet the level of protection traditionally required is the same as that required in a 50- or 100-story building down the street. Similarities between two such buildings are that exterior rescue above 75 ft (23 m) is difficult if not impossible (depending on local fire department apparatus and access to the building). However, the dynamics of air movement (and therefore smoke movement), the viability of total evacuation versus staged evacuation, and the level of information needed by occupants and the fire service are clearly different in a very tall building compared to a mid-level (but still "high-rise" building). These ideas are beginning to be addressed in a piecemeal fashion in the codes but often with little technical analysis or evaluation of risk. NFPA has established a High-Rise Building Safety Advisory Committee to try to coordinate and guide the NFPA codes as they adapt to the new high-rise performance expectations of society.

FIRE LOSS HISTORY

The NFPA Fire Analysis and Research Division publishes an annual statistical report on high-rise fire incidents.[1] Table 20.8.1 is shown in five parts and is taken from the 2005 edition of the annual survey, with statistics through 2002. It shows, by year, the number of fires, deaths and injuries, property damage, and percentage of high-rise fires to total fires. Separate parts of Table 20.8.1 show results for apartment buildings, hotels, health care occupancies, offices, and all structures. The tables seem to show that there has been a general trend of improvement in all categories.

Table 20.8.1 reflects fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires are rounded to the nearest hundred, civilian injuries are rounded to the nearest ten, and direct property damage is rounded to the nearest million dollars; civilian deaths are not rounded. Property damage has been adjusted for inflation, using the Consumer Price Index, to 2002 dollars.

Significant High-Rise Fires

Throughout history, there have been many significant high-rise fires. Table 20.8.2 contains a summary of fires occurring from 1911 to 2004 that have resulted in 10 or more deaths. These fire incident reports include only those submitted to and documented by NFPA. Since not all fires are reported to NFPA, the information should not be considered complete.

Since 2000, several events have caused the fire protection community to refocus on whether we are adequately addressing high-rise protection, through mechanisms such as the NFPA High-Rise Building Safety Advisory Committee. Similar committees have been formed by government entities and professional associations around the world.

One of the recent events that has inspired this rethinking was the World Trade Center disaster of September 11, 2001. However, several other significant fires have also occurred.

Recent Events

Cook County Office Building. Chicago had two significant fires in existing high-rise buildings in the early 2000s. The first occurred at 69 West Washington Street in the Cook County office building on October 17, 2003. In this incident, the fire started in a storage room on the 12th floor of a nonsprinklered building. It was able to spread through the suite of origin, and because corridor walls were not full height, it also spread hot smoke and gases into the corridor system. A stair enclosure with a vestibule was located almost directly across the corridor from the area of fire origin. When the fire department responded and opened the doors from the corridor into the stairs, hot smoke and gases flowed into the stairwell. In this building, stairwell doors were locked from the stair side for security purposes, and no automatic or remote unlocking capability was provided. Six occupants, all who were trapped above the 12th floor, died in the stairwell. Those were the only fatalities in this event. The postfire analysis concluded that, if the stair doors had not been locked from the stair side, there would likely have been no fatalities. Similarly, if the building had been sprinklered, it is unlikely that the smoke and gases would have been as hot, as buoyant, or in the same quantities. Therefore, the fatalities (and much of the damage) could have been avoided by the presence of sprinklers. Perhaps the only lesson learned from this fire is that we ought to apply the knowledge that we already know. Sprinklers greatly increase the safety of buildings, and locked stairwells, even from the stair side, create a hazard.

TABLE 20.8.1 High-Rise Building Fire Experience for Selected Property Classes, by Year, 1985–2002 Structure Fires

Year	*Fires*	*Civilian Deaths*	*Civilian Injuries*	Direct Property Damage (in Millions of Dollars) *Current Dollars*	Direct Property Damage (in Millions of Dollars) *2002 Dollars*	*What Percentage of All Apartment Fires Were High-Rise?*
A. Apartment Buildings						
1985	11,700	54	470	15	26	10
1986	10,300	32	380	21	35	9
1987	8,900	46	520	22	34	8
1988	10,300	83	640	48	63	9
1989	11,000	97	610	30	44	10
1990	9,400	76	460	22	31	9
1991	9,900	23	590	129[a]	170[a]	9
1992	10,300	31	640	19	25	9
1993	9,600	43	600	41	51	9
1994	8,900	51	830	36	44	9
1995	7,700	53	530	31	36	8
1996	9,600	56	650	33	38	10
1997	9,200	27	480	30	33	10
1998	8,100	35	570	23	25	9
1999	9,900	27	430	42	46	10
2000	8,600	83	480	25	26	9
2001	7,400	23	320	24	24	8
2002	5,900	15	280	21	21	7
Adjusted Estimates[b]						
1999	10,200	25	430	44	47	11
2000	9,200	85	520	26	27	10
2001	9,800	32	330	19	19	11
2002	8,700	26	350	19	19	10
B. Hotels						
1985	1,800	0	70	2	3	21
1986	1,600	0	50	2	3	20
1987	1,500	5	40	6	10	20
1988	1,800	8	60	20	30	24
1989	1,600	5	60	4	6	22
1990	1,300	7	120	6	8	24
1991	1,300	0	90	6	8	21
1992	1,000	0	80	4	5	21
1993	900	0	60	6	8	17
1994	1,000	0	70	4	5	17
1995	1,100	0	70	5	6	20
1996	800	8	100	17	20	21
1997	800	6	40	9	10	18
1998	800	0	20	11	12	19
1999	900	0	30	19	21	18
2000	900	0	20	3	3	19
2001	900	0	10	13	13	21
2002	700	0	10	1	1	17
Adjusted Estimates						
1999	800	0	30	25	27	18
2000	1,000	0	30	4	4	21
2001	1,300	0	20	24	24	29
2002	1,200	0	40	5	5	28

(continued)

TABLE 20.8.1 Continued

Year	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage (in Millions of Dollars)		What Percentage of All Apartment Fires Were High-Rise?
				Current Dollars	2002 Dollars	
C. Hospitals and Other Facilities That Care for the Sick						
1985	2,400	11	120	2	3	38
1986	2,000	3	30	1	2	37
1987	1,700	0	70	1	2	32
1988	1,500	2	70	1	2	35
1989	1,400	9	110	3	4	34
1990	1,300	0	40	4	6	37
1991	1,100	0	50	4	5	36
1992	1,100	2	30	3	4	32
1993	1,000	0	30	3	4	32
1994	900	6	30	4	5	31
1995	800	2[c]	40	1	1	31
1996	900	0[c]	30	3	3	35
1997	800	0	20	1	1	29
1998	600	2	80	4	5	29
1999	700	0	20	1	1	24
2000	600	0	10	1	1	23
2001	500	0	10	1	1	23
2002	400	0	10	1	1	23
Adjusted Estimates						
1999	700	0	20	1	1	24
2000	600	0	10	1	1	23
2001	500	0	10	2	2	26
2002	500	0	20	2	2	30
D. Office Buildings						
1985	1,300	1	10	6	10	13
1986	1,100	1	80	28	28	12
1987	900	4	10	11	11	10
1988	1,000	0	20	50	50	13
1989	900	0	20	30	30	12
1990	900	0	10	22	22	14
1991	800	0	10	15	15	12
1992	1,000	1	80	62	62	12
1993	800	0	20	14	14	12
1994	700	0	20	18	18	10
1995	500	0	60	8	8	9
1996	500	0	20	18	18	9
1997	600	0	10	4	4	10
1998	500	0	10	4	4	9
1999	600	0	10	7	7	11
2000	500	0	10	3	3	10
2001	300	0	10	7	7	8
2002	300	0	0	3	3	7
Adjusted Estimates						
1999	600	0	10	7	7	12
2000	500	0	10	3	3	11
2001	600	0	10	19	20	13
2002	500	0	0	5	5	12

TABLE 20.8.1 Continued

Year	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage (in Millions of Dollars) Current Dollars	Direct Property Damage (in Millions of Dollars) 2002 Dollars
E. Four Property Classes Combined					
1985	17,200	66	670	25	41
1986	15,000	37	550	41	68
1987	13,000	54	640	36	36
1988	14,600	94	780	102	102
1989	14,800	111	800	58	58
1990	13,300	84	620	48	48
1991	13,100	23	750	150	150
1992	13,600	34	830	75	75
1993	12,400	43	700	61	61
1994	11,500	57	950	59	59
1995	10,000	55	690	45	45
1996	12,100	64	790	69	69
1997	11,400	33	560	43	43
1998	10,000	37	680	41	41
1999	12,100	27	500	68	68
2000	10,600	83	520	32	32
2001	9,200	23	350	44	44
2002	7,300	15	300	26	26
Adjusted Estimates					
1999	12,400	25	490	76	82
2000	11,300	85	560	34	35
2001	12,300	32	360	64	65
2002	10,900	26	410	31	31

Note: Property damage figures for office buildings are underestimated in several years due to problems in handling some large-loss fires, such as the $325 million One Meridian Plaza fire in Pennsylvania in 1991 and the $230 million World Trade Center incident in 1993, whose more than 1000 injuries also are not properly reflected in national estimates. The events of September 11, 2001, are not reflected in these figures.

[a]Property damage figures for apartments in 1991 are inflated by problems in handling the Oakland wildfire in the estimates.

[b]The "Adjusted Estimates" are calculated using only NFIRS Version 4.1 data to estimate the percent of fires (and losses) that occurred in high-rise buildings. Use Adjusted Estimates for trend analysis, as they are more comparable in approach to pre-1999 data, but for any single year, use the main estimates, which are considered more accurate.

[c]Based on high-rise share of fires in 1995 and 1996, because all deaths were in buildings with unknown height.

Source: *High-Rise Building Fires,* NFPA Fire Analysis and Research Division, p. 5, August 2005. Original data from NFIRS and NFPA survey.

For a discussion of the evacuation from the Cook County office building, see Section 4, Chapter 1, "Human Behavior and Fire."

La Salle Bank Building. The second Chicago fire, on December 6, 2004, occurred at the La Salle Bank Building and had better results. Again it was a fire in a nonsprinklered high-rise building. This building had operable windows, and several occupants went to windows for fresh air. There were no fatalities in this fire although there were 37 injuries. The fire was notable nationally because it closely followed the 69 West Washington Street fire, making it the second significant high-rise fire in the same city in a short period of time. As with 69 West Washington, sprinklers in the building would have greatly reduced the amount of smoke and heat generated and therefore would probably not have required occupants to rely on operable windows for fresh air.

Chicago has since passed a retroactive high-rise sprinkler ordinance and has also outlawed door locks on stairwells, unless there is automatic and remote release.

Parque Central Building. In October 2004, a fire began on the 34th floor of the Parque Central Building in Caracas, Venezuela. This building was a 56-story government office building. The fire did more than $250 million (U.S.) in damage, burning the structure's contents from the 34th to the 50th floor. The building was fully sprinklered; however, the sprinkler system was inoperable. Postfire analysis indicated that had the sprinkler system been active, the fire would have been limited to the floor of

TABLE 20.8.2 International Listing of Fatal High-Rise Structure Fires, 1911–2004 (10 or More Deaths)

Date	*Building*	*Location*	*Number of Deaths*	*Floor of Origin*	*Height in Stories*
March 1911	Clothing manufacturer	New York	146	8	10
July 1945	Office building	New York	11	79	102
June 1946	Hotel (transient hotel)	Illinois	61	1	22
December 1946	Hotel (transient hotel)	Georgia	119	3	15
December 1961	Hospital	Connecticut	16	9	13
December 1963	Hotel	Florida	22	1	14
January 1966	Hotel (transient hotel)	Massachusetts	11	Basement	11
February 1967	Restaurant/apartment building	Alabama	25	11	11
December 1970	Hotel	Arizona	28	4	11
December 1971	Hotel	Korea	163	2	21
February 1972	Andraus building	Brazil	16	5	31
November 1972	Elderly apartments	Georgia	10	7	11
February 1974	Bank building	Brazil	179	12	25
June 1977	Detention center (jail)	New Brunswick, Canada	21	Sublevel	16
November 1980	Hotel	Nevada	85	1	23
March 1981	Office building	Chile	11 (1 FF)	12	15
February 1982	Hotel	Japan	32	9	10
March 1982	Hotel	Texas	12	4	13
January 1984	Hotel	Korea	38	4	10
October 1984	Hotel	New Jersey	15	3	9
November 1984	Hotel	Philippines	10	17	16
February 1986	Office building	Brazil	23	Unknown	13
September 1986	Hotel	Norway	14	1	13
December 1986	Hotel	Puerto Rico	96	1	20
October 1989	Plastic manufacturing plant	Texas	23	Unknown	20
April 1995	Office building	Oklahoma	168	Outside	9
November 1996	Office building	Hong Kong	40 (1 FF)	Basement	16
July 1997	Hotel	Thailand	90	1	17
March 2001	Oil rig	Brazil	10	Unknown	40
September 2001	Office building	New York	2791 (340 FF)	Bldg. 1: 94–98 Bldg. 2: 78–84	Bldg. 1: 110 Bldg. 2: 110
August 2003	Apartment building	Taiwan	13	Unknown	8
January 2004	Apartment building	Egypt	14 (8 FF)	Unknown	12

FF = fire fighter.

Source: *International Listing of Fatal High-Rise Structure Fires, 1911–2004,* National Fire Protection Association, 2005, http://www.nfpa.org.

origin. The lesson learned from this fire is that the systems that are provided in buildings should be maintained.

Madrid Office Building. On February 12, 2005, a nighttime fire in a Madrid office building resulted in significant fire and structural damage to the building, but no fatalities. Again, the fire was in a nonsprinklered building, and the results would likely have been very different in a sprinklered building. Therefore, although we may learn from the structural response to this fire, from a life safety point of view, sprinkler protection was likely the first and best protective measure that could have been provided.

Lessons Learned. The lessons learned from these fires are simple. The satisfactory protection of the structure, maintaining the integrity of the egress systems, and the compartmentation of high-rise buildings must be ensured. That is not enough, however. All high-rise buildings should be protected by automatic sprinklers; if they were, they would be significantly safer. It is recognized that there is no simple means of sprinklering existing high-rise buildings. Therefore, means to encourage sprinkler protection in those buildings, such as tax incentives on capital improvements and extended times for installation, need to be factored into the process of requiring automatic sprinklers. However, until such sprinklers are required, there is the risk of significant fire and risk to life safety in our stock of nonsprinklered high-rise buildings.

The World Trade Center

Much has been written and discussed about the World Trade Center (WTC) events of September 11, 2001. This chapter can-

not address the event in any level of depth, given that the National Institute of Standards and Technology (NIST) has written reports totaling over 10,000 pages for WTC 1 and 2 and will have more to say about WTC 7. Neither of the NIST reports addresses all the fire protection design issues that must be considered. Before discussing the NIST recommendations, there are a couple of thoughts or concepts that bear serious consideration.

The first question is whether the incident involving WTC 1 and 2 is an event that should be considered in high-rise building design. Other questions include whether all buildings, or a subset of landmark buildings, are going to be designed to defend against terrorist threats and hostile acts. If so, which threats? What will this design cost, and can society afford it? Also, if buildings are designed to protect against these extreme events, will day-to-day life become more difficult, or will our reaction to more typical or equally severe but unusual threats become more hazardous? For instance, if we decide to fully evacuate all high-rise buildings for all events, will we end up with more injuries and deaths than we save?

For example, one common recommendation that has been heard coming out of the event is the need to harden stairwells. What does this mean? How hard should they be made? If they are hardened, what are the results? For instance, if a bomb were detonated in a hardened stairwell, is it better or worse than the traditional stairwell? The bottom line is we cannot react to a single event without understanding that there may be negative implications in the building's response to other events—the theory of unintended consequences. It is a difficult task to apply rigor to our thinking as we respond to events such as security threats that may be very unlikely, impossible to predict, and subject to emotion. If we do not, however, the overall performance of a building may be worsened rather than improved.

A second big question coming out of the WTC disaster is whether we, as a society, are comfortable with the performance of the rest of the WTC complex. There was significant damage to several of the buildings, including the collapse of WTC 7, a 47 story building. Although the ignition was due to the attacks on WTC 1 and 2 and the lack of water for both automatic sprinkler systems and manual fire-fighting efforts was also due to that event, the fuel and fire causing the collapse were all within the WTC 7 building. There may well be lessons to be learned from this event that can extend to typical high-rise buildings.

The NIST Recommendations

In 2005, NIST issued a series of recommendations on the collapse of the World Trade Center Towers.[2] The report included 30 recommendations in eight general groups. This paper does not attempt to address each of those recommendations. However, to gain a feel for the recommendations, the groupings are described as follows:

Group I: Increase Structural Integrity
Group II: Enhanced Fire Resistance of Structures
Group III: New Methods for Fire Resistance Design of Structures
Group IV: Improved Active Fire Protection
Group V: Improved Building Evacuation
Group VI: Improved Emergency Response
Group VII: Improved Procedure and Practices
Group VIII: Education and Training

These recommendations were issued in draft form and many organizations have responded with comments. Many of the recommendations were logical outgrowths of the event, but some others could lead to substantial changes in building design. NIST has offered to work with model code groups in developing code language to respond to these recommendations. Some of the far-reaching recommendations are considered controversial because they may not necessarily spring from the World Trade Center events or because the recommendation seems to stem from an event that occurred only because of the method of attack. Others will lead to long-term improvements in buildings or building operations, or perhaps will spur industry to develop new products. Still other recommendations can be accomplished quite easily with changes in operations or methods.

The NIST reports can be found on the NIST website (http://www.nist.gov or http://wtc.nist.gov). This includes all of the research reports that have led up to the recommendations, as well as the recommendations themselves.

HIGH-RISE FIRE RISK

Why do high-rise buildings require more protection than other buildings? Simply put, the risk of a significant hazardous event is greater than that associated with a non–high-rise building. This is because the number of people exposed is likely greater than normal; the building's floor area is likely greater than normal; the impact of an event is more likely to impact other floors and more people than an event in a large low-rise building; evacuation via building systems will take longer; the dynamics of smoke spread will encourage spread to upper floors; external evacuation is not practical; and a localized structural collapse could impact other portions of the building or of adjacent buildings. While codes do not explicitly define these risks, many of the code provisions do address them. For the designer, it is important that these risks be considered, rather than just assuming that the code has adequately covered them for any specific building.

UNIQUE FEATURES OF A HIGH-RISE

Some of the major issues that make high-rise buildings different from other buildings include fire department access, egress, smoke movement, and fire control.

Fire Department Access

Fire department accessibility, a major issue, takes several forms:

- The limitations of present-day fire apparatus in reaching upper floors from the exterior of the building
- The height of the fire and the number of personnel required to deliver adequate types and amounts of equipment to the fire area. (Due to the possible height of the fire area, equipment transport and force deployment efforts

could exact an exhaustive toll on fire-fighting forces before they can even mount a fire attack. This has a significant impact when available fire fighters and equipment are limited. This condition can also occur in a large low-rise building with the same distance problems as a high-rise, although the elevation difference in a high-rise exaggerates the problem.)

- Inherent delays in deploying equipment. (Delays in deploying equipment and fire fighters can indirectly affect fire growth, thereby resulting in a fire of greater magnitude by the time manual forces are in place to attack.)
- The height and location of a building. (The height and location of a building can further restrict the fire department's ability to approach the area of origin from more advantageous directions. As a result, the fire department may only be able to approach a fire area from below. In many cases where the area of origin has no automatic suppression and compartmentalization, the area of origin may not be approachable at all, resulting in a defensive approach that depends on fuel consumption for control and extinguishment. This approach typically results in a large or unacceptable loss.)
- Communication issues. (Fire department as well as other first responder radio transmitters struggle to work or do not work at all in the confines of a high-rise building. Delays in reporting real-time fire conditions, summoning more help to upper floors, or learning of imminent threats can jeopardize the fireground safety parameters.)

Egress

Egress and people movement systems within a high-rise building also make the building unique. In a low-rise building, it is typical to assume that total evacuation of the building can occur in a relatively short time. In a high-rise, however, full evacuation may take more than an hour. Also, because all occupants are using the same stairs, full evacuation in many circumstances may lead to slower evacuation of those most affected by the event. In addition, competition for stair use by first responders can further slow evacuation travel times. Because of these differences, a high-rise requires a well-conceived and delivered evacuation system which revolves around education and information. Therefore, written emergency plans, fire drills, and training are important factors regarding safety in a high-rise. Notification to occupants is typically provided by zone via voice communication, which allows those most directly affected to evacuate or relocate first and gives emergency responders the opportunity to communicate with others in the building, perhaps to initiate a full and orderly evacuation.

In tall buildings, relocation to other areas is often the first mode of evacuation. This may be by horizontal exit or relocation to other floors. Most events do not necessitate full evacuation of a building, and initial relocation to nearby areas may prevent slips and falls or exhaustion-related injuries. From the area of relocation, the authorities can decide whether evacuees should remain in place, use the elevators, or continue down the stairs in an organized manner.

Smoke Movement

The high-rise building often has natural forces affecting fire and smoke movement that are not normally significant in lower buildings. Stack effect and the impact of exterior winds can be very significant, and very different, in high-rise buildings.

Stack Effect. Stack effect results from the temperature differences between two areas, usually the inside and outside temperatures, which create a pressure difference that results in natural air movements within a building. In a high-rise building, this effect is increased due to the height of the building. Many high-rise buildings have a significant stack effect, capable of moving large volumes of heat and smoke through the building.

No manual fire-fighting techniques are known to counter stack effect or to mitigate its effect during a fire. Stack effect cannot be eliminated because of the temperature differences and building height. As a result, potential stack effect will exist and may vary with climatic conditions. The only way to mitigate the potential of stack effect is to design and construct the building to minimize the effect. A thorough review of available resources on the subject will enhance design and construction. Basic concepts include the following:

- Compartmentalization from floor to floor and wall to wall, which involves sealing penetrations and exterior building tightness
- Limiting continuous shaft heights or constructing vestibules on stairs, elevators, and other vertical shafts
- Use of vestibules and gasketing on exterior doors at both the bottom and top of a building
- Eliminating naturally ventilated shafts and floors that could contribute to stack effect during a fire (elevator shafts with normally open vents, which are commonly utilized, can significantly enhance stack effect)
- Zoning, compartmentalization, and control of mechanical systems, which could contribute to, or be affected by, stack effect

Winds. Winds can profoundly affect fire and smoke movement within a building. Wind patterns around high-rise buildings have been the subject of study due to their effect on structural issues, but very little has been studied with regard to fire protection. In high-rise buildings, winds can vary radically in intensity and direction at different floor levels or sections. It is known that wind velocity and direction can be very different at the street level than at upper sections of the structure, and there is no known method of predicting or preliminarily measuring their effects.

The primary design approach to mitigate the effect of wind on smoke movement is to make the exterior walls of a building as airtight as possible. This approach is highly dependent on the design criteria, materials chosen, and integrity of workmanship. The result should be that wind direction and velocity will have a reduced impact on air movement within the structure, thereby allowing conventional smoke management systems to overcome the effects of wind to some degree. It is noted that the degree of the smoke management system's ability to overcome the wind effect is based on many variables, including system

design, system power, tightness of the building, wind velocity, and wind direction.

It is reasonable to assume that, if wind is not taken into consideration in the design and construction of the high-rise building and the exterior of the building is not reasonably tight, any fire may be significantly affected by wind velocity and direction. Wind direction can complicate the accessibility and preferred direction of fire attack and can increase fire and smoke impingement on areas of refuge, possibly exceeding their design criteria.

Even when heating, ventilating, and air conditioning (HVAC) systems are zoned and compartmentalized, they can share common exhaust shafts and fresh-air intake shafts. Such shafts and duct runs often penetrate multiple fire zones, requiring special attention to design and protection. Many high-rise buildings integrate smoke management systems with conventional HVAC systems. Although this is acceptable, and in many cases preferred, it requires special design considerations, including fail-safe devices and adequate controls, acceptance testing, and ongoing maintenance. See NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*, and NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*, for additional information on the design of smoke management systems.

Fire Control

Of special importance in a high-rise building is the ability to control a fire. With large numbers of people in a building, many of whom may be above the fire location, fire control is both a life safety and property protection issue. Fire control affects many of the features of the building including its overall fire resistance, compartmentation, automatic and manual suppression, and control of contents.

Most new high-rise buildings around the world are now required to have automatic sprinklers. This is a significant first step in fire control but may not be enough by itself. Codes require manual suppression capabilities in the form of standpipes and portable extinguishers. All of this may be inadequate, however, if the contents in the building become significantly more hazardous than were originally assumed for the building.

CODE REQUIRED FEATURES

NFPA *101* and *NFPA 5000* contain general high-rise building protection criteria in Chapters 11 and 33, respectively. The occupancy chapters use these as base criteria and add or subtract as deemed necessary for the particular occupancy. In Chapter 33 of *NFPA 5000,* the following criteria are addressed:

- Construction types and construction modifications
- Voice communication for fire alarm
- Two-way fire department communication systems
- Automatic sprinkler protection
- Smoke-proof exit enclosures
- Emergency lighting
- Standby power
- Emergency command center

These features are intended to address many of the unique features of a high-rise building. Over the past several years, code requirements such as these have caused the active protection of existing high-rise buildings to gradually improve. Tables 20.8.3 and 20.8.4 show the levels of automatic sprinkler, fire detection, and fire-resistive construction in hotel and office buildings from 1985 to 1998.

HIGH-RISE ISSUES TO CONSIDER

Areas to which the design and code community should give serious consideration with respect to high-rise buildings include risk evaluations, thresholds, and structural fire resistance.

Risk Evaluations

Very large buildings should not be designed using a "cookbook" approach. Rather, an integrated, holistic, and rational engineering approach should be used. Although there are not enough events in high-rise buildings to do statistical analysis of the risks, there are many ways to look at risk in relation to high-rise buildings. As a building gets taller, the number of occupants increases, and the potential for disaster increases. Engineering decisions should be based on such factors as potential occupant load; whether a building may be a target; potential contents and businesses within the building; the capability and effectiveness of built-in systems such as automatic sprinklers, emergency power, and other systems to protect the occupants and the structure; and supplemental, unique features in the building. Without such analysis, the rigor that the building demands and the public deserves will not be included in the design process. This rigor should lead to an informed, well-documented design, so that the thought process on which the design is based can be followed in the future. Only then will high-rise buildings be engineered rather than pieced together. Application of current codes to very or extremely tall buildings is worthy of scrutiny and discussion. Criteria that are virtually identical for a 10 story building and a 100 story building should be adjusted for the taller structures; the only question is how. Such an approach exists today in the form of performance-based codes, but their use in high-rise buildings has been limited, particularly in the United States.

Thresholds

Although codes are gradually grappling with the concept that not all high-rise buildings are the same, it may make sense to develop some thresholds of protection. For instance, high-rise requirements may start at 75 ft (23 m), or 7 or 8 stories, based on the reach of fire department apparatus. The next threshold may occur at about 20 stories, where full-building evacuation becomes unwieldy, and where stack effect can significantly affect smoke movement. Subsequent thresholds may be at 40, 60, or 100 stories, where the time to evacuate may exceed the fire resistance of a structure, where elevators may need to be considered in building evacuation, where special provisions for fire fighter access may be needed, where mechanical systems alone may not be able to overcome stack effect, and where people

TABLE 20.8.3 Fire Protection in Hotels and Motels, High-Rise Versus Other Buildings, 1985–1998 Structure Fires

Year of Fire	*Percentage of High-Rise Buildings*	*Percentage of Buildings That Are Not High-Rise*	*Percentage of All Buildings of Known Height*
A. Automatic Extinguishing Systems[a]			
1985	51	11	19
1986	61	15	24
1987	59	16	25
1988	63	19	30
1989	63	22	32
1990	69	22	34
1991	66	22	32
1992	72	22	32
1993	75	25	34
1994	69	25	33
1995	72	23	33
1996	76	24	35
1997	67	27	34
1998	77	32	41
B. Fire Detection Equipment[b]			
1985	74	54	58
1986	82	60	64
1987	82	63	67
1988	85	65	70
1989	87	70	74
1990	86	69	73
1991	86	74	76
1992	91	73	77
1993	90	73	76
1994	92	76	79
1995	87	74	77
1996	89	76	79
1997	91	78	80
1998	87	76	78
C. Fire-Resistive Construction			
1985	57	13	22
1986	63	14	24
1987	52	15	22
1988	59	12	24
1989	54	14	23
1990	55	13	23
1991	48	13	21
1992	48	10	18
1993	52	12	19
1994	49	12	18
1995	43	11	17
1996	46	11	19
1997	51	13	20
1998	54	9	18

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. "High-rise" means seven or more stories in height.

[a]Analysis limited to buildings of known height (number of stories), so statistics do not agree exactly with statistics for all buildings, including buildings with unreported height, as shown in Kimberly D. Rohr, *U.S. Experience with Sprinklers,* NFPA Fire Analysis & Research Division, Quincy, MA, Sept. 2001.

[b]Analysis limited to buildings of known height (number of stories), so statistics do not agree exactly with statistics for all buildings, including buildings with unreported height, as shown in Marty Ahrens, *U.S. Experience with Smoke Alarms,* NFPA Fire Analysis & Research Division, Quincy, MA, Sept. 2001.

Source: *High-Rise Building Fires,* NFPA Fire Analysis and Research Division, p. 23, August 2005. Original data from NFIRS and NFPA survey.

movement and psychology may have to be factored into how messages are transmitted and received. At one of these thresholds, it may well be that prescriptive codes no longer apply and that a performance-based approach using engineered systems is the only allowed alternative. Once this analysis is done, it may also be that requirements can be relaxed somewhat in the 7- to 20-story building range. As an example, in China, buildings over 820 ft (250 m) are considered as super-high-rise buildings, and approval involves the central government authorities.

Structural Fire Resistance

Although the current code methods of evaluating structural fire resistance are archaic, they still provide a very accurate and con-

TABLE 20.8.4 Fire Protection in Facilities That Care for the Sick, High-Rise Versus Other Buildings, 1985–1998 Reported Fires

Year of Fire	*Percentage of High-Rise Buildings*	*Percentage of Buildings That Are Not High-Rise*	*Percentage of All Buildings of Known Height*
A. Automatic Extinguishing Systems[a]			
1985	61	61	61
1986	60	61	60
1987	64	63	63
1988	62	58	60
1989	64	60	61
1990	69	62	65
1991	57	64	62
1992	74	67	70
1993	76	69	71
1994	67	66	67
1995	78	67	70
1996	82	69	74
1997	80	69	72
1998	80	70	73
B. Fire Detection Equipment[b]			
1985	85	80	82
1986	88	86	87
1987	89	85	86
1988	90	85	87
1989	90	85	87
1990	92	87	89
1991	87	87	87
1992	91	88	89
1993	93	86	88
1994	94	88	90
1995	96	88	90
1996	94	89	91
1997	96	89	91
1998	92	89	90
C. Fire-Resistive Construction			
1985	73	58	64
1986	67	54	59
1987	66	48	54
1988	66	49	55
1989	57	47	51
1990	54	46	49
1991	53	43	47
1992	55	42	46
1993	57	42	46
1994	53	34	40
1995	48	36	40
1996	49	33	39
1997	51	38	42
1998	49	33	38

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. "High-rise" means seven or more stories in height.

[a]Analysis limited to buildings of known height (number of stories), so statistics do not agree exactly with statistics for all buildings, including buildings with unreported height, as shown in Kimberly D. Rohr, *U.S. Experience with Sprinklers,* NFPA Fire Analysis & Research Division, Quincy, MA, Sept. 2001.

[b]Analysis limited to buildings of known height (number of stories), so statistics do not agree exactly with statistics for all buildings, including buildings with unreported height, as shown in Marty Ahrens, *U.S. Experience with Smoke Alarms,* NFPA Fire Analysis & Research Division, Quincy, MA, Sept. 2001.

Source: *High-Rise Building Fires,* NFPA Fire Analysis and Research Division, p. 25, August 2005. Original data from NFIRS and NFPA survey.

sistent model of expected performance. Simulation techniques are available that can reveal much more about a building's potential behavior than a 1-, 2-, or 3-hour rating. In the automotive industry, physical crashes and crash simulations are used on new car models to determine how a vehicle will respond to a series of events. Those same models can be used (and are starting to be used) in the building industry to judge structural and fire performance.

Another aspect of structural fire resistance in tall buildings is the need for a building to withstand an event for long periods of time. In a medium-height building, the current building codes reasonably match full evacuation time with structural fire resistance. As we get into very tall buildings, however, should we consider a change in fire resistance? If so, how much (given that fires will only burn a finite amount of time)? A balance on

this item that has not yet emerged and needs to be found. Costs and acceptable end-points if sprinklers fail also need to be discussed. Surely, total building collapse is unacceptable, but is localized collapse or deflection over small areas acceptable in the rare event of a fire and sprinkler failure? With more stringent provisions come more costs.

SUMMARY

The high-rise building presents several challenges not found in traditional low-rise buildings. Those involved with the design and construction of high-rise buildings should recognize those challenges and address them accordingly. Although codes provide a basis for dealing with a high-rise, each building should be considered individually. Items to consider include height, occupancy, occupant load, unusual uses, availability of fire service, and the expectations of society.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on high-rise buildings discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*

NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*

NFPA *101®, Life Safety Code®*

NFPA 5000®, Building Construction and Safety Code®

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Chapter 9

Assembly Occupancies

Revised by
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Chapter Contents

Occupancy Characteristics
Special Considerations
Occupancy Hazards
Life Safety Concepts for Assembly Occupancies
Main Entrance/Exit Criteria
Life Safety Evaluation

Key Terms

aisle accessway, assembly occupancies, continental seating, crowd management, dead-end aisles, festival seating, fire exit hardware, fixed seating, legitimate stage, life safety evaluation, normal seating, panic hardware, Station Nightclub fire

Assembly occupancies generally can be defined as rooms, spaces, or structures in which groups of people gather for a purpose, such as deliberation, worship, entertainment, or to await transportation. Examples of assembly occupancies are large meeting rooms, restaurants, nightclubs, dance halls, bars, cocktail lounges, auditoriums with fixed or loose chair seating, libraries, concert halls, theaters, cinemas, multipurpose rooms, exhibition halls, convention centers, sports facilities, field houses, places of worship, and passenger terminals for air or surface transportation.

Because the safety and hazards of large numbers of people gathered in one place are a specific concern with this type of occupancy, a minimum number of occupants must be reached to establish whether a room, space, or structure constitutes an assembly occupancy. Although this minimum number of occupants can vary between codes, NFPA *5000*®, *Building Construction and Safety Code*® and NFPA *101*®, *Life Safety Code*®, set the threshold at 50 persons. Occupancies with similar uses but having occupant loads less than 50 would be incidental within other occupancy classifications. An example might be a small meeting room in an office building (incidental assembly use in a business occupancy). NFPA *101* and *NFPA 5000* recommend, via annex notes, classifying small restaurants and drinking establishments with occupant loads of less than 50 as mercantile occupancies.

See also Section 4, Chapter 2, "Calculation Methods for Egress Prediction"; Section 4, Chapter 4, "Techniques of Crowd Management"; Section 4, Chapter 5, "Strategies for Occupant Evacuation During Emergencies"; and Section 20, Chapter 1, "Assessing Life Safety in Buildings."

OCCUPANCY CHARACTERISTICS

The density of the occupant population presents a unique concern for safety in assembly occupancies. No other occupancy experiences occupant loads of such density. The occupant load is dependent upon how the space is being used. Typically, one person per 15 ft^2 (1.4 m^2) of net area would be expected in less concentrated spaces, 7 ft^2 (0.65 m^2) of net area in concentrated spaces, and 5 ft^2 (0.46 m^2) of net area in very concentrated spaces.

Assembly occupancies are usually inhabited by persons who do not use the building frequently and, therefore, might not be familiar with exit locations, egress paths, or other safeguards present. In addition, many assembly occupancies, such as theaters, concert halls, nightclubs, lounges, and some restaurants, are used in conditions of low lighting levels. Such high occupant densities under these conditions impact physical movement and the behavior of people. The capacity and maintenance of the means of egress elements, fire resistance of building construction and interior finish materials, fire suppression systems, crowd management, and the method of alerting occupants of an emergency require proper attention.

All of these factors—high occupant density, unfamiliarity with the building, and low lighting levels—are common to the many and varied forms of assembly occupancies. Provisions must be made to deal with all of these factors to avoid panic and facilitate orderly egress when an emergency occurs. Despite these factors, sprinklered assembly occupancies have had a remarkably good fire

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record. A fire on February 20, 2003, at the nonsprinklered Station Nightclub in West Warwick, Rhode Island, resulted in the loss of 100 lives (Figure 20.9.1).

Tables 20.9.1 and 20.9.2 provide data on structure fires in assembly occupancies.[1]

SPECIAL CONSIDERATIONS

Restaurants and Nightclubs

Both restaurants and nightclubs share common concerns, such as aisles that do not provide adequate access to exits. Adding tables in an effort to increase the number of occupants may simply be uncomfortable under normal conditions but can be disastrous in an emergency. Although nightclubs share this concern with restaurants, it is more acute with nightclubs due to increased consumption of alcohol.

Proper aisle access and aisles must be maintained to facilitate egress. Aisles should be wide enough to accommodate the movement of people, taking into consideration the position of chairs during normal use and during emergencies. Proper aisle access and aisle widths also provide more comfort and make table service easier and more efficient in restaurants. Nightclubs differ from restaurants in that there can be less focus on ease and efficiency in table service and the occupant load is more concentrated. Certain techniques, such as using small, round tables rather than larger, square tables, help achieve maximum patron capacity.

In both restaurants and nightclubs, the decor can be elaborate and thematic. Care and attention are required to assure that decor does not obstruct or obscure exits, exit markings, emergency lighting, automatic sprinkler systems, and other safety features. Absence of effective, well-understood procedures for alerting patrons to an emergency and notifying the fire department can have disastrous outcomes in these occupancies. Delayed notification shortens the available evacuation time in case of an emergency and delays fire department response. Reluctance to notify patrons and the fire department of an emergency before the last possible minute significantly reduces the likelihood of safe egress.

Fixed Seating

Occupancies that use fixed seating present the usual challenges, such as exit marking, emergency illumination, and occupant notification; however, there are some added unique considerations. Fixed seating arrangements have very concentrated occupant densities in a confined environment where there is limited ability to move. People exiting from their seats must move through the space between the rows of seats (called an *aisle accessway* in *NFPA 5000* and NFPA *101*) to reach an aisle, and then tra-

FIGURE 20.9.1 Overhead View of Smoldering Remains of Station Nightclub (Source: AP Photo by Tom Gilbert)

TABLE 20.9.1 Structure Fires in Eating and Drinking Establishments, 1999–2002 Annual Averages

Occupancy	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
Restaurant or cafeteria	7670	3	108	153
Bar or nightclub	1270	1	13	41
Unclassified or unknown-type eating or drinking place	960	1	12	20
Total	9910	4	133	214

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest million dollars.

Source: National estimates based on NFIRS and NFPA survey.

TABLE 20.9.2 Structure Fires in Public Assembly Properties, Excluding Eating and Drinking Establishments and Religious and Funeral Properties, 1999–2002 Annual Averages

Occupancy	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
Fixed use amusement or recreation	710	0	6	15.2
Variable use amusement or recreation	930	1	6	11.9
Club	950	1	17	31.4
Library, museum, or courtroom	450	0	5	11.2
Passenger terminal	220	0	2	0.7
Theater or studio	270	0	6	3.2
Unclassified or unknown-type public assembly property	360	0	2	8.2
Total	3890	2	43	81.8

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest hundred thousand dollars.

Source: National estimates based on NFIRS and NFPA survey.

verse the aisle to a cross-aisle, vomitory, vestibule, concourse, or corridor, and continue to an exit. Proper design of each exit access component for the fixed seating area is critical for safe egress of all occupants during an emergency.

Prior to the 1988 edition, NFPA *101* classified fixed seating into two types: (1) normal and (2) continental (Figures 20.9.2 and 20.9.3).

Normal seating is characterized by a limited number of seats, with cross-aisles limiting dead-end aisles. Continental seating is characterized by long rows of chairs discharging into side aisles, which, in turn, connect directly to exits from the room. In 1988, NFPA *101* was the first model code to adopt concepts for all seating in new assembly occupancies rather than dividing seating into two categories. These concepts can now be found in other model codes. This approach recognizes the advantages of continental seating, such as reduced egress time, and applies those principles comprehensively to all seating. Since the inception of this new approach, the requirements for

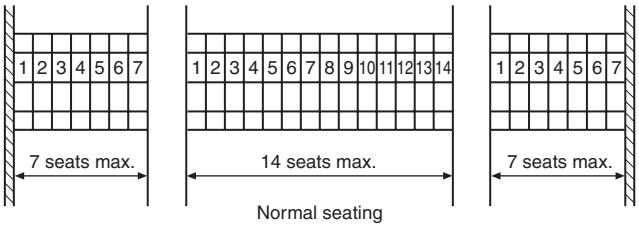

FIGURE 20.9.2 Arrangement of Seats and Aisles in an Assembly Occupancy with Normal Seating

assembly seating have been refined through the code development process.

NFPA 5000 and NFPA *101* utilize one approach for all assembly seating arrangements. Egress capacity factors are used to calculate minimum required clearances. Alternative factors

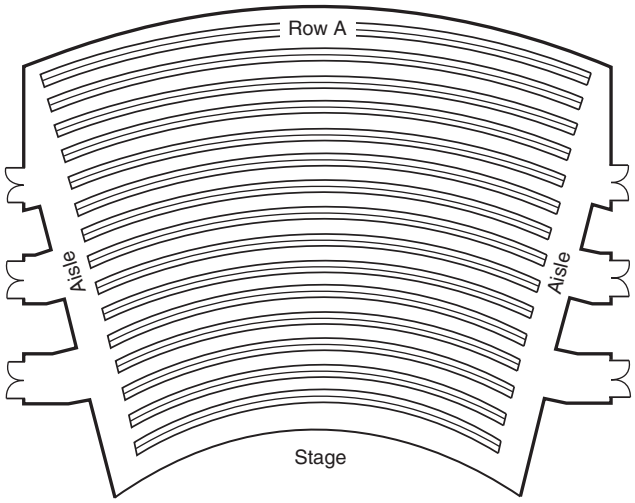

FIGURE 20.9.3 Arrangement of Seats and Aisles with Continental Seating

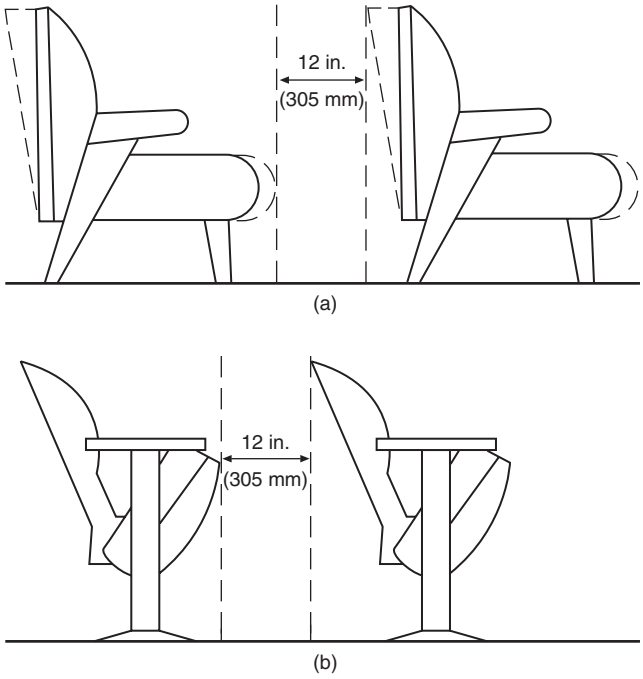

FIGURE 20.9.4 Correct Measurement of Minimum Spacing Between Rows of Seats (Aisle Accessway Width) (a) Without Self-Rising Seats and (b) With Self-Rising Seats

are utilized where the assembly seating is protected from smoke since more time to egress would be provided by such protection. However, an overall evaluation of life safety is necessary to support such modifications. Assembly seating requirements are summarized as follows:

1. Rows of seats are permitted to extend to 100 seats between aisles provided there is sufficient clearance between rows. However, rows would typically have fewer seats between aisles due to practical considerations.

2. The minimum clear width between rows of seats, called the *aisle accessway,* is determined by starting with 12 in. (355 mm) for an allocated number of seats, which is then increased proportionately for the number of additional seats up to a maximum width of 22 in. (560 mm) (Figure 20.9.4).

3. The length of *dead-end aisles,* an aisle exiting in only one direction, is limited unless the assembly seating is protected from smoke. However, the length of dead-end aisles in a smoke-protected assembly would be limited by the number of seats served by the aisle and the width of the aisle along with practical considerations.

4. The minimum width of aisles is determined by the greater of either a specified minimum width or a formula based on egress capacity factors, which take into account the riser height of the steps in a stepped aisle, the slope of a ramped aisle, and the locations of handrails.

5. The travel distance to an exit from assembly seating areas is limited to 200 ft (61 m) or 250 ft (76 m) if the occupancy is protected by an approved, supervised automatic sprinkler system. Greater distances are permitted where the occupancy is protected from smoke; it is permitted to be unlimited where the occupancy is smoke protected, the seating facility is of Type I or Type II construction as defined in *NFPA 5000,* and all portions of the means of egress are open to the outside.

Smoke-protected assembly seating is defined by NFPA *101* and *NFPA 5000* as seating served by a means of egress that is not subject to smoke accumulation within or under the structure. Smoke-protected assembly seating is typically achieved in indoor venues by providing an engineered smoke control system. NFPA *101* establishes conditions that must be assessed as part of a life safety evaluation when considering provisions for smoke-protected assembly seating. See the end of this chapter for a brief discussion of life safety evaluation. Where loose chairs are used in lieu of fixed seating, care must be taken to keep the chairs from being moved into a haphazard arrangement that could impair exit access. Generally, loose chairs must be arranged in a manner similar to fixed seating to maintain required aisle accessway and aisle widths. To prevent chair movement during use, most codes require loose chairs to be fastened together in groups to make them difficult to reposition in order to maintain egress paths. Many chair manufacturers produce chairs with interlocking features to meet this requirement. These features usually require no tools to join or separate the chairs, which can also be stacked for storage.

Festival Seating

A concept called *festival seating* is popular for certain entertainment events, particularly concerts. Festival seating is an audience or spectator accommodation in which no seating, other than the floor or ground surface, is provided for the audience gathered to observe a performance. This type of seating has the potential to result in overcrowding and high audience density that may compromise occupant safety. Also notable is the po-

tential for injury prior to the actual event as patrons rush into the venue seeking the best locations. Festival seating should be used with caution. NFPA *101* requires the completion of a life safety evaluation for festival seating for more than 250 occupants; in addition, trained crowd managers are required for all assembly occupancies. See the end of this chapter for a discussion of a life safety evaluation.

Multipurpose Rooms

Ballrooms, meeting rooms, cafeterias, and gymnasiums are usually multipurpose rooms and may be used for dining, dancing, sporting events, exhibits, meetings, receptions, or other uses. In general, local codes contain requirements for each use. Overall, the key to occupant safety is adequate exiting. If movable walls or partitions subdivide large areas, each subdivision must have proper exit access and exits. Care must be taken to ensure that proper means of egress is designed into the arrangement.

Exhibit Halls

Exhibit halls are large assembly areas that are multipurpose in nature. Special diligence regarding control of display and chair arrangement must be exercised to ensure unimpeded egress and to maintain the proper travel distances to exits. Therefore, a permit process for the authority having jurisdiction's approval of display and seating layouts is recommended prior to each trade show or exhibition.

Exhibit halls might have excessive quantities of combustible materials unless provisions are made for remotely storing the packing materials needed to transport the displays and for surplus quantities of literature. The importance of this cannot be overemphasized, since failure to remove this heavy fuel load to proper storage areas, remote from the exhibit hall, can result in large, rapidly spreading fires. The McCormick Place fire of January 1967, in Chicago, Illinois, is an example of the fire potential of this type of occupancy.[2] Special attention must be paid to the travel distance within a larger exhibit booth or display to the aisle; this distance should be limited to 50 ft (15 m). Multilevel exhibit booths present problems with regard to both egress and fire protection. This type of booth, as well as large exhibit booths with ceilings, can shield the booth's contents from the building's automatic sprinkler system. In these cases, consideration should be given to providing sprinkler protection for the booth itself. In all cases, booths should be constructed of noncombustible, limited combustible, or fire-retardant-treated materials. NFPA *101* and *NFPA 5000* contain special requirements for exhibit halls. Because of the fuel load and the large number of occupants, moderate and larger size exhibit halls should be provided with automatic sprinkler systems in accordance with NFPA 13, *Standard for the Installation of Sprinkler Systems.*

Sports Facilities

Sports arenas, stadiums, ballparks, and field houses usually have fixed seating for large numbers of spectators, as well as large areas. It is not uncommon for such occupancies to hold more than 10,000 people. Smoke development during a fire can present a major threat to life safety when large numbers of people are evacuating a sports facility. Proper clearances between rows of seats, aisle width, and travel distances require proper care during the planning stage. Protecting the assembly seating and exit path from smoke provides more time for people to evacuate, thereby allowing adjustment in clearances and travel distances where smoke protected.

On the positive side, these occupancies usually include very large open areas, permitting smoke to be diluted or held above exiting occupants' heads in the early stages of a fire, keeping them reasonably safe for egress. Engineered smoke control systems can be designed to keep enclosed facilities protected from smoke similar to outdoor facilities. If they are used for exhibitions, the special considerations for exhibit halls must also be followed. Requirements for the design of smoke-control systems are provided in NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences,* and NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces.*

Care must be taken to prevent the accumulation of combustible waste under seating areas; such trash accumulation, along with combustible construction, contributed to the Bradford, England, soccer stadium fire of 1985, in which 56 spectators died.

Passenger Terminals

Passenger terminals require special consideration for fire safety because only general rules can be written for their regulation. Dense populations are localized, especially at departure and arrival gates. NFPA *101* and *NFPA 5000,* via annex notes, recommend special occupant load factors for airport terminals. As in most assembly occupancies, the occupants of passenger terminals are generally unfamiliar with the building, its egress routes, and its protection features. Proper marking of exits and egress routes and limiting travel distances to exits are particularly important.

The potential for significant loss of life from fire in passenger terminals that are not sprinklered has been tragically realized in recent years. On November 18, 1987, a fire originated within an escalator at the King's Cross Station—a subway station in London, England—leading to the deaths of 30 occupants and one fire fighter.[3] On April 11, 1996, workers using cutting torches inadvertently started a fire in a combustible concealed space in the ceiling of a terminal building at the airport in Düsseldorf, Germany. The ensuing fire spread rapidly and undetected in the void space. By the time it was noticed, a significant portion of the ceiling void was involved in fire. Delays in occupant notification resulted in numerous people trapped in spaces adjoining the main terminal area, such as airline clubrooms and lounges. Because these mezzanine areas were only provided with means of egress back through the main terminal area, and inadequate occupant notification was provided, 17 occupants lost their lives and 62 were injured.[4]

Passenger terminals must have their projected occupant loads carefully analyzed based on projected passenger operations; capacity of aircraft, vehicles, and trains utilized; and peak scheduling and possible delays, which involve embarking and disembarking passengers. A study of embarking and

disembarking passengers with safety factors for delays should be performed. In addition certain sterile or secure areas and the people who must use these areas in a given time frame need to be analyzed. Unlike most other assembly facilities, the projected occupant load does not increase proportionally with increased floor area.

Special Amusement Buildings

Special amusement buildings are temporary, permanent, or mobile structures that contain a device or system conveying passengers, space for viewing a display, a walkway course in any direction, or any combination for the purposes of amusement. These structures are of particular concern because the egress path might not be readily apparent due to low lighting levels, visual or audio distractions, and intentionally confounded paths of travel. In addition, amusement displays can involve a large amount of combustibles. The Haunted Castle fire at the Great Adventure Amusement Park in Jackson Township, New Jersey, on May 11, 1984, is an example of all of these concerns that was not equipped with an automatic sprinkler system. Eight teenagers, ranging in age from 15 to 19 years, died in that fire.[5] Special amusement buildings require unique protection provisions. Consideration should be given to automatic sprinkler protection, special controls to increase lighting levels and turn off confusing or confounding sounds and visual displays when smoke is detected, the strategic placement of exit signs, and control of interior finish materials. NFPA *101* and *NFPA 5000* contain provisions for special amusement buildings that address all the above considerations.

Requirements for special amusement buildings in NFPA *101* and *NFPA 5000* include multilevel play structures, such as those found in children's play areas in fast-food restaurants. It is important to note that NFPA *101* and *NFPA 5000* classify special amusement buildings as assembly occupancies even when the occupant load is less than 50 persons; other assembly uses must meet the 50-occupant load threshold before they are classified as assembly occupancies.

OCCUPANCY HAZARDS

Cooking and Open Flames

Cooking is often associated with the use of assembly occupancies (Tables 20.9.3 and 20.9.4).[1] The hazards associated with cooking in traditional kitchens can be handled by automatic extinguishing systems and proper vapor removal, as outlined in NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations.* The widespread use

TABLE 20.9.3 Leading Causes of Structure Fires in Eating and Drinking Establishments, 1999–2002 Annual Averages

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Cooking equipment fires	4500	(45%)	1	(27%)	68	(51%)	30	(14%)
Identified cooking equipment	3300	(33%)	1	(27%)	56	(42%)	28	(13%)
Confined cooking fire	1210	(12%)	0	(0%)	12	(9%)	2	(1%)
Electrical distribution and lighting equipment	1050	(11%)	0	(0%)	5	(4%)	42	(20%)
Heating equipment fires	790	(8%)	0	(11%)	8	(6%)	12	(6%)
Identified heating equipment fire	510	(5%)	0	(11%)	7	(5%)	12	(5%)
Confined heating equipment	280	(3%)	0	(0%)	2	(1%)	0	(0%)
Smoking materials	820	(8%)	4	(82%)	8	(6%)	19	(9%)
Intentional	760	(8%)	2	(54%)	12	(9%)	42	(20%)
Exposure to other fire	150	(2%)	0	(0%)	0	(0%)	6	(3%)
Contained trash or rubbish fire	180	(2%)	0	(0%)	1	(1%)	0	(0%)

Note: These are the leading causes, obtained from the following list: intentional (from the NFIRS field "cause"); playing with fire (from factor contributing to ignition); confined heating (including confined chimney and confined fuel burner or boiler fires), confined cooking, and contained trash or rubbish (from incident type); identified heating, identified cooking, clothes dryer or washer, torch (including burner and soldering iron), electrical distribution and lighting equipment, medical equipment, and electronic, office, or entertainment equipment (from equipment involved in ignition); smoking materials, candles, lightning, and spontaneous combustion or chemical reaction (from heat source); and mobile property involved (from mobile property involved in ignition). Exposure fires include fires with an exposure number greater than zero, as well as fires identified by heat source or factor contributing to ignition when no equipment was involved in ignition that were not intentionally set. The same fire can be listed under multiple causes, based on multiple data elements.

These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest million. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey.

TABLE 20.9.4 Structure Fires in Eating and Drinking Establishments by Area of Origin, 1999–2002 Annual Averages

Area of Origin	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Kitchen or cooking area	4080	(41%)	1	(33%)	70	(52%)	57	(27%)
Confined cooking fire	1210	(12%)	0	(0%)	12	(9%)	2	(1%)
Exterior wall surface	450	(5%)	0	(0%)	1	(1%)	5	(2%)
Exterior roof surface	370	(4%)	0	(0%)	4	(3%)	4	(2%)
Attic or ceiling/roof assembly or concealed space	360	(4%)	0	(0%)	4	(3%)	19	(9%)
Lavatory, bathroom, locker room, or check room	270	(3%)	0	(0%)	5	(3%)	2	(1%)
Dining room, bar or beverage area, cafeteria	230	(2%)	1	(22%)	4	(3%)	12	(6%)
Heating equipment room	210	(2%)	0	(0%)	4	(3%)	3	(2%)
Wall assembly or concealed space	190	(2%)	0	(0%)	0	(0%)	3	(1%)
Storage of supplies or tools or dead storage	190	(2%)	0	(0%)	4	(3%)	7	(3%)
Duct for HVAC, cable, exhaust, heating, or air conditioning	130	(1%)	0	(0%)	1	(1%)	3	(1%)
Office	110	(1%)	1	(22%)	3	(2%)	5	(3%)
Confined chimney fire	100	(1%)	0	(0%)	1	(0%)	0	(0%)
Storage room, area, tank, or bin	90	(1%)	0	(0%)	1	(1%)	4	(2%)
Ceiling/floor assembly or concealed space	90	(1%)	0	(0%)	0	(0%)	6	(3%)
Unclassified	90	(1%)	0	(0%)	0	(0%)	2	(1%)
Crawl space or substructure space	90	(1%)	0	(0%)	0	(0%)	20	(9%)
Small assembly area, less than 100-person capacity	90	(1%)	1	(12%)	4	(3%)	4	(2%)
Common room, living room, family room, lounge, or den	80	(1%)	0	(0%)	2	(1%)	6	(3%)
Laundry room or area	80	(1%)	0	(0%)	3	(2%)	1	(1%)
Lobby or entrance way	80	(1%)	0	(0%)	1	(0%)	3	(1%)
Confined fuel burner or boiler fire	80	(1%)	0	(0%)	2	(1%)	0	(0%)
Unclassified equipment or service area	80	(1%)	0	(0%)	2	(1%)	2	(1%)
Trash or rubbish chute, area, or container	70	(1%)	0	(0%)	0	(0%)	1	(1%)
Awning	60	(1%)	0	(0%)	0	(0%)	1	(0%)
Unclassified storage area	60	(1%)	0	(0%)	1	(0%)	3	(2%)
Unclassified structural area	50	(1%)	0	(0%)	0	(0%)	4	(2%)
Chimney	50	(1%)	0	(0%)	0	(0%)	1	(0%)
Other known service or equipment area	110	(1%)	0	(0%)	1	(0%)	3	(1%)
Other known means of egress	90	(1%)	0	(0%)	1	(1%)	3	(1%)
Other known assembly or sales area	90	(1%)	0	(0%)	0	(0%)	3	(1%)

of "display cooking" presents new problems in vapor removal and in protecting the cooking surfaces and humans in case of fire. However, display cooking on properly designed and fixed equipment can be made reasonably safe with fixed systems, proper means of egress, and trained staff.

The use of portable cooking equipment must be carefully evaluated before it is permitted. Cooking equipment that uses LP-gas is common; however, large LP-gas cylinders, such as those commonly found on outdoor gas grills, must never be used indoors. A failure of the valve or connecting hose or other event could result in propane leakage and potentially result in a vapor cloud explosion. Such an event in an indoor assembly occupancy would obviously be catastrophic. Small LP-gas cylinders, similar in appearance to aerosol spray cans, can be used safely indoors with properly listed equipment. Details on the use of such equipment are found in NFPA 58, *Liquefied Petroleum Gas Code.*

The use of open-flame devices in tableside and flambé cooking should be carefully reviewed before it is permitted. Specially designed equipment and properly trained staff are necessary to ensure safety. The use of candles and other open flames requires the same degree of awareness as tableside

cooking. Several commercial devices are available that make open-flame lighting safe, even in the event of a tip-over. Coordination between facility operators and the fire department can help maintain an acceptable level of safety.

Theatrical Stages

The distinctive fire hazards of theaters tend to revolve around the stage area. The 1903 Iroquois Theater fire in Chicago, Illinois, is probably the most vivid example of a stage fire and its tragic consequences.[6] The Iroquois Theater was not protected with automatic sprinklers and did not have many of today's code-required safeguards.

Traditional proscenium stages have scenery and lighting "flown" above the stage and scenery on the back and sides of the stage; shops along the back and sides of the stage; and storage, props, trap doors, and stage lifts under the stage floor. The potential for maximum fire severity is great with this combination of fuel and potential ignition sources. Since the Iroquois Theater fire, many safeguards have been required to control these hazards, including the following:

- Automatic sprinklers at the ceiling level, below the gridiron, in usable spaces under the stage, and in all auxiliary spaces surrounding the stage
- Ventilation over the stage, operable manually or automatically by fusible links
- An automatically closing fire-resistant curtain to cut off the stage from the audience chamber

All of these features are necessary with a full theatrical stage, defined in NFPA *101* and *NFPA 5000* as a *legitimate stage.*

Modern stages are generally modified versions of the classic theatrical stage. More scenery is now moved horizontally, eliminating the need for the high scene loft or fly space. Modern stages also tend to be variations of the traditional proscenium stage, thrusting the stage farther out into the audience or having it open to the audience on three sides, as in an arena theater—often called "theater in the round."

Whatever the arrangement of scenery on the stage, scenery handling equipment and allied shops need to be protected to prevent a large stage fire from threatening the audience, either directly or indirectly during evacuation.

Projection Booths

Projection booths refer to any booth housing equipment for the transmission of light onto a screen, curtain, or stage. The hazard is not with the projection of motion pictures or slides made on flammable film, as is commonly assumed, but with the mechanism used to project light. Electric arc, zenon, and other light sources generate hazardous gases, dust, or radiation and can fail with explosive force under certain circumstances. Where these light sources are used, a booth around the projection equipment is required to protect the audience. Proper ventilation also is required. Incandescent light sources do not produce the same hazard and, therefore, need not have the same enclosure. The enclosure of projection rooms in modern motion picture theaters is for sound control, not fire protection purposes.

Modern motion pictures and slides use safety film, which does not introduce the hazards of nitrocellulose found in early movies. Therefore, modern projection rooms are not designed for, and cannot safely project, non–safety film.

Storage

Improper storage practices present a hazard for fire and life safety in assembly occupancies, as in many other occupancies. Storage of tables and chairs, scenery, or supplies in aisles, exit access paths, or exits compromises not only life safety of a large number of occupants trying to evacuate but also fire department response. It is essential that space be allocated for proper storage of materials, supplies, props, tables, chairs, and other items associated with assembly occupancies to avoid the creation of unnecessary hazards.

LIFE SAFETY CONCEPTS FOR ASSEMBLY OCCUPANCIES

Many life safety features contribute to the protection of assembly occupancies, including construction, fire suppression, alarm systems, interior finish, and employee training (Tables 20.9.5 and 20.9.6).[1]

Construction

Assembly occupancies have a high occupant density under variable conditions, which, to one degree or another, makes alerting and evacuating the occupants more difficult than in other occupancies. Because of this, building construction is an important element in the life safety system.

In general, the building should be constructed to allow the structure to remain intact under fire conditions and not contribute significantly to the fire development for at least the time necessary for evacuation. Obviously, for a one-story building, this is relatively easy to accomplish when occupant loads are moderate in size (under 1000). But even a one-story building with proper exits may require structural protection and/or fire-resistant finish materials to ensure everyone's safety. The roof height and the required evacuation time, type of construction, finish materials, fire suppression, and means of egress need to be analyzed and considered specifically to the type of assembly occupancy.

As building heights increase, the level of construction and protection must increase accordingly to permit large assembly occupancies on higher stories. NFPA *101* and *NFPA 5000* specify sizes of assembly occupancies permitted in buildings based on construction, height of the assembly occupancy above the level of exit discharge, and fire protection provided (such as the presence of automatic sprinkler systems). Whereas *NFPA 5000* is generally limited to new construction, NFPA *101* applies to both new and existing assembly occupancies.

Alarm Systems

Prompt notification of occupants of an emergency cannot be overemphasized. However, the sounding of a fire alarm without

TABLE 20.9.5 Automatic Suppression Systems in Public Assembly Property Structure Fires Reported to Public Fire Departments Excluding Fires in Eating and Drinking Establishments and in Religious and Funeral Properties, 1994–1998 Annual Averages

Percentage of fires in buildings with automatic suppression system	26%
Deaths per 1000 fires with automatic suppression system present	0.0
Deaths per 1000 fires with no automatic suppression system present	1.1
Reduction in deaths per 1000 fires when automatic suppression systems were present	100%
Average loss per fire when automatic suppression system was present	$6,320
Average loss per fire with no automatic suppression system	$30,490
Reduction in loss per fire when automatic suppression systems were present	79%

Source: National estimates based on NFIRS and NFPA survey.

TABLE 20.9.6 Automatic Suppression Systems in Fires in Eating and Drinking Establishments Reported to Public Fire Departments, 1994–1998 Annual Averages

Percentage of fires in buildings with automatic suppression system	29%
Average loss per fire when automatic suppression system was present	$6,500
Average loss per fire with no automatic suppression system	$18,800
Reduction in loss per fire when automatic suppression systems were present	65%

Source: National estimates based on NFIRS and NFPA survey.

accompanying verbal instructions might introduce the threat of panic, or alternatively, delay in occupant response. To overcome these possibilities, an appropriate alarm system—perhaps one using prerecorded or electronically synthesized voice messages—can be installed. Such voice-evacuation systems are required by NFPA *101* and *NFPA 5000* in assembly occupancies that have occupant loads greater than 300 persons.

Panic Hardware or Fire Exit Hardware

Because of the threat of a large group of occupants rushing to an exit, leaning together on the door, and making use of traditional knob-activated latching devices difficult or impossible, assembly occupancies usually require panic hardware or fire exit hardware. Panic hardware and fire exit hardware consist of a door-latching assembly incorporating a wide barlike or push padlike device that releases the latch on application of force in the direction of egress travel. Security-conscious owners in the past have objected to panic hardware or fire exit hardware because of the potential for slipping the latch from the outside for purposes of gaining unauthorized entry. However, modern panic and fire exit hardware designs provide for both life safety and security.

There is no excuse for chained or padlocked doors, given the availability of secure exit hardware. Outdoor facilities using gates offer different challenges. Although panic devices or fire exit hardware can be installed on gates, they cannot be made secure due to practical considerations without potentially compromising the hardware's ability to reliably open under crowd pressures. Therefore, other means to secure gates are often taken regardless of whether gates are provided with secure exit hardware or not. Any measures to secure exit gates must be removed prior to occupancy when such outdoor facilities are opened to the public so that such gates will open on contact.

Interior Finish

Interior finish is a key element in providing fire control and life safety. Materials used in assembly occupancies must limit the rate of flame spread and smoke production. Generally, materials are limited to flame spreads of 75 or less (Class A or B), when tested in accordance with NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials,* for all but the smallest assembly uses. Drapes, hangings, tapestries, and other decorative materials must be fire retardant when tested in accordance with NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films,* if they constitute a significant part of the decor or if they would provide a continuous path for fire travel. Ignition of such materials without fire retardant can lead to very rapid fire growth and spread, with the potential for a high death toll in densely occupied spaces, such as the 1942 Cocoanut Grove nightclub fire in Boston, Massachusetts, in which 492 people perished. Proper treatment to make materials fire retardant is necessary to avoid disaster.[7] For additional information on interior finish, see Section 18, Chapter 2, "Interior Finish."

The fire at the Station Nightclub in West Warwick, Rhode Island, on February 20, 2003, was ignited by the improper use of indoor pyrotechnics. It is believed that foam sound insulation surrounding the stage area that did not limit the rate of flame spread and smoke production contributed to the rapid spread of this deadly fire.

Employee Training

Employees of assembly occupancies are critically important to the life safety of patrons. If staff members are trained properly, they can prevent serious injury or death to many patrons. The Beverly Hills Supper Club fire in 1977 at Southgate, Kentucky, showed the importance of staff assistance in fire survival.[8] Although the building lacked proper exits and had no automatic fire sprinkler protection, staff members saved hundreds of lives by leading patrons to means of escape unknown to the patrons.

The management of every assembly occupancy should devise an emergency plan in conjunction with the local fire department, deal with the many contingencies associated with fires, and properly train staff members in safe emergency procedures.

Assembly occupancies can be safely occupied when the following conditions are avoided:

- Overcrowding
- Blocked or impaired exits or means of exit access
- Chained or locked exits
- Storage of combustibles in improper locations
- Improper use or insufficient control of open flames
- Disregard for fire characteristics of materials and decorations

Crowd Management

The 2006 edition of NFPA *101* requires "trained crowd managers" for all assembly occupancies regardless of occupant load. This is a significant revision compared to the prior (2003) edition of the code, which set the occupant load threshold at 1000 occupants before crowd managers were required. Where the occupant load exceeds 250, an additional trained crowd manager or supervisor is required for every 250 occupants. Assembly occupancies used exclusively for religious worship with an occupant load not exceeding 2000 are exempt from the requirement for crowd managers. For additional information, see Section 4, Chapter 4, "Techniques of Crowd Management."

Sprinkler Protection

In response to the tragic Station Nightclub fire, the 2006 editions of NFPA *101* and *NFPA 5000* require automatic sprinkler protection for all of the following new assembly occupancies regardless of occupant load:

- Bars with live entertainment
- Dance halls
- Discotheques
- Nightclubs
- Assembly occupancies with festival seating

In addition, NFPA *101* now requires those same existing assembly occupancies with an occupant load of greater than 100 to be protected with a supervised automatic sprinkler system. This new provision requires retrofitting such existing assembly occupancies with automatic sprinkler protection.

Other new assembly occupancies are required by NFPA *101* and *NFPA 5000* to be protected by automatic sprinklers where the occupant load is 300 or greater or where necessary based on the building's construction type.

MAIN ENTRANCE/EXIT CRITERIA

The 2006 edition of NFPA *101* requires the following new assembly occupancies main entrance/exit on each level to accommodate two-thirds of the occupant load of such levels:

- Bars with live entertainment
- Dance halls
- Discotheques
- Nightclubs
- Assembly occupancies with festival seating

As in the requirement for automatic sprinkler protection, the increase of accommodating two-thirds of the occupants from the previous one-half the occupant load at the main entrance was in reaction to the Station Nightclub fire in Warwick, Rhode Island, in 2003.

LIFE SAFETY EVALUATION

A *life safety evaluation* is a comprehensive report on the planned safety measures considering such things as the nature of the assembly event and participants, crowd management, medical emergencies, fire hazards, structural systems (e.g., temporary stages, rigging, etc.), severe weather, earthquakes, civil disturbances, and hazardous materials. It also considers the relationships between facility management, event participants, emergency responders, and others. When required, a life safety evaluation must be prepared by persons having experience with the conditions described and must be approved by the authority having jurisdiction.

A life safety evaluation is an ongoing exercise that requires periodic confirmation at appropriate times depending on the facility and/or events being held. A change in the type of events, operational practices, or the built environment would warrant an evaluation of life safety. Operational practices may not be fully known when an application for a building permit is submitted. Therefore, consideration should be given to those contingent items needing confirmation prior to issuance of a certificate of occupancy.

Detailed guidance on the development of life safety evaluations is included in NFPA *101*.

SUMMARY

Assembly occupancies, by their nature, pose unique life safety challenges. Typical characteristics include large numbers of people with a high occupant density and an emotional or raucous environment (such as during a sporting event or rock concert). Because of the large number of occupants, evacuation of the building can take longer when compared to other occupancies. To ensure rapid evacuation, sufficient means of egress systems must be provided and maintained. Prompt notification must be made to the occupants and clear directions provided. This requires a well-documented emergency plan, trained staff, and facility management who must not hesitate in implementing the emergency plan. Fire-resistive construction, automatic fire suppression systems, adequate means of egress, alarm and communications systems, and trained staff all contribute to the safety of assembly occupants.

Lessons learned from the tragedies described in this chapter have been incorporated into codes, such as NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®. Codes alone, however, are not the entire solution—they must be enforced. In other words, incorporation of lessons learned into the codes and even code adoption do not ensure occupant safety. Codes must be enforced for the entire life of the facility. Facility management must commit to life safety by maintaining fire protection systems and conducting

frequent staff training. An open line of communications with the local fire department and other emergency response agencies (police, emergency medical services, etc.) will help to keep assembly events safe. Every assembly event poses unique hazards and each should be evaluated carefully and mitigated.

NFPA members can download at no cost a number of investigation reports on public assembly fires from NFPA's website at http://www.nfpa.org. Nonmembers may order investigation reports through the NFPA library.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on assembly occupancies discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*
NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations*
NFPA *101®*, *Life Safety Code®*
NFPA 101A, *Guide on Alternative Approaches to Life Safety*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*
NFPA 5000®, *Building Construction and Safety Code®*

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Chapter 10

Mercantile Occupancies

Ed Schultz

Chapter Contents

Mercantile Occupancy Classifications
Occupant and Fire Loads
Mall Buildings
General Life Safety Factors Applying to Mercantile Occupancies

Key Terms

accessory occupancy, exit, mall building, means of egress, mercantile occupancy, occupant load factor, smoke management, sprinkler system

This chapter addresses mercantile occupancies, from small stores operated by families to large shopping malls and multiuse projects. It also describes changes in building codes in response to the increased complexities of megaprojects.

Because in many instances a mercantile use may be an ancillary or accessory use in a building with a different occupancy classification, this chapter covers only those facilities whose primary occupancy classification is mercantile.

See also Section 20, Chapter 1, "Assessing Life Safety in Buildings."

MERCANTILE OCCUPANCY CLASSIFICATIONS

Mercantile occupancies are facilities in which a wide variety of goods and services are displayed and sold. Examples of such goods and services include clothing and footwear; jewelry; beauty, health, and fitness products; home furnishings; luggage, books, cards, and stationery; music, electronic equipment, and photography supplies; sport specialties; toys, hobbies, and pets; drugs, varieties, and tobacco; food and food specialties; and hardware.

Many items displayed in mercantile occupancies are combustible and spread over the available floor where customers circulate to view and purchase the items. Many mercantile occupants are in an unfamiliar environment that may be conducive to rapid fire development after a fire begins. This condition raises various levels of concern because the size of the mercantile occupancy and the number of occupants vary greatly. Therefore, it is important to categorize mercantile stores by size.

Small Mercantile Occupancies

In the past, smaller shops were constructed principally in cities and towns, along business thoroughfares, next to each other, often with basements for stock, and sometimes with an office or dwelling unit immediately above them. Many such stores still exist today, especially in older business sections of cities; they are sometimes called "ma and pa" stores because their proprietors often live in the dwelling units directly above them. However, this type of store is slowly fading out of existence.

Because of more restrictive zoning regulations, larger stores are now constructed without other occupancies above them, unless the mercantile occupancy serves an ancillary or accessory use such as a retail shop in a hotel lobby. In addition, basement space, even for stock space, is being phased out because stock space on the same level as the sales area is more efficient and functional. Also the retail merchandising concepts have changed to that of displaying as much of the available merchandise on the sales floor as possible. This decreases the amount of inventory held in stockrooms.

Originally, these stores were constructed primarily of wood- or masonry-bearing walls with wood joists, floors, and roofs. Subsequent establishment of fire districts in urban areas, plus the adoption of more stringent building code requirements, led to construction with noncombustible materials, such as masonry walls, load bearing or nonload bearing; steel joists; concrete floors; and metal roof decks.

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Until recently, these small stores were seldom sprinklered. NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®, currently require sprinkler protection based on height and area and, in certain instances, whether the stores are located below the level of exit discharge.

Medium Mercantile Occupancies

Medium-size mercantile occupancy stores, such as supermarkets and discount drugstores, did not become numerous until the mid- to late 1940s. In many areas, they replaced the neighborhood grocer and the corner druggist, who could not compete with high-volume chains.

Medium mercantile occupancy stores generally range in size from 10,000 to 40,000 ft^2 (2800 to 3700 m^2), are usually one story with mezzanine management offices, and are usually constructed of noncombustible unprotected construction. Until the mid-1970s sprinklers were not required in these stores.

These stores are generally freestanding buildings, unless they are part of a shopping center complex, and they may have relatively large contiguous parking areas surrounding them.

Medium-size mercantile occupancy stores usually have at least two principal areas: (1) the stock space or "back of the house" employee area and (2) the sales space or customer area. Approximately one-tenth to one-third of the total area is apportioned to stock and the remainder to sales. These stores typically include nonmercantile accessory uses, such as management offices, that occupy a small area in relation to sales and stock space. From a retailer's viewpoint, the distinction between retail stock space and storage space is important. Employees enter the retail stock areas frequently during the day to bring merchandise onto the sales floor. Storage areas, on the other hand, are less frequently accessed because goods are set aside in these areas for extended time periods. Today, if one corporation operates many stores, its storage areas are generally in a separate location, essentially a distribution warehouse. Again the new retail marketing concepts are reducing the amount of area used for stock and storage areas in favor of enlarging the sales area to display more merchandise.

Large Mercantile Occupancies

The multiple-category merchandise store, such as a department store and bulk merchandising retail buildings, is as common as other types of mercantile occupancies. Generally from one to three stories high, their area normally exceeds 40,000 ft^2 (3700 m^2).

Earlier department stores were constructed exclusively in business and retail districts in cities. Stores were typically either of exterior masonry-bearing wall construction with protected wood joists and floors or of reinforced concrete. Many had no sprinkler protection. Today, most newly or recently constructed department stores are of protected and unprotected noncombustible construction and are protected by complete automatic sprinkler systems.

As their name implies, department stores are divided into departments or sections for different kinds of merchandise, with or without partition walls. Departments are laid out in a particular way to influence customer movement patterns vertically and horizontally through the store according to a preconceived merchandising plan. Vertical movement in multistory stores is most effectively accomplished using escalators and stairs in open wells in highly visible and accessible areas.

At one time basements were quite commonly used as either sales or stock areas. This practice generally is no longer followed because basement space is not as desirable as the same area constructed at or above ground level.

Unlike the vast majority of small and medium mercantile occupancies where stock space is located in the rear of the store, stock space in large mercantile occupancies is often distributed throughout the store in many small stockrooms. These stockrooms often represent 10 to 15 percent of the total floor area, with the remaining area used for retail sales.

Another example of a large mercantile store is the discount store, which grew out of the well-known "five-and-dime" variety store. It is usually one story high and laid out like a retail food supermarket, with shopping carts, self-service, and checkout counters. However, the same sectioning of merchandise occurs as in a department store.

Over the last 20 years, bulk merchandising retail stores have come into existence. These facilities are a blend of warehouse operation and retail sales store. Typically, pallet or rack storage is used in a large portion of the building with other areas of the building designed in the more traditional retail display using fixtures and low-level racks or shelves to display merchandise. A large portion of the facility typically has shelving and rack storage that can extend to a height of 20 ft (6 m) or more. The retail merchandise is displayed on the lower portion of the rack and the stock is located directly above. This arrangement eliminates the separate stock areas that are typical to retail department stores.

Bulk merchandising retail stores generally have very limited interior finishes and are typically constructed as warehouse facilities with exposed concrete floors, masonry exterior walls, and unprotected steel columns and roof structures. These stores function as self-service facilities with shopping carts and they have checkout counters near the main entry of the facility.

Since this type of retail operation displays and sells a variety of commodities, many of the design standards that must be used are those used for storage (warehouse) facilities. See the chapters on new and existing mercantile occupancies that are listed in NFPA *101* for a listing of some of these design standards. These properties are sufficiently challenging in size and fuel load that they may require a specific engineering analysis to design, and confirm the adequacy of, built-in fire protection. See, for example, several research reports from the Fire Protection Research Foundation dealing with flammable and combustible liquid storage in wholesale/retail occupancies.

Accessory Occupancies

To round out the full range of goods and services a customer needs and expects, mercantile occupancies sometimes include accessory or ancillary occupancies, in addition to administrative office areas. Examples are restaurants, beauty shops, travel agencies, banks, and optometry services.

OCCUPANT AND FIRE LOADS

Occupant Load

Actual occupant load varies with the seasons, generally being higher before school begins, around holidays, and during occasional clearance sales. NFPA *101* and *NFPA 5000* take these primary merchandising seasons into account in establishing the occupant load factor for calculating egress requirements. The model construction codes, including NFPA *101* and *NFPA 5000,* require that occupant load for mercantile occupancies be calculated on the basis of a factor of one occupant per 30 ft^2 (2.8 m^2) of street floor or basement sales areas, and a factor of one occupant per 60 ft^2 (5.6 m^2) of other upper sales floors. These factors for occupant load vary based on the expected flow of customers into and out of these large stores. An increase in occupant load is also created by the retailer merchandising concepts of placing the higher-volume sales items on the main level to accommodate and benefit from the higher customer flow.

These factors have been recognized by some of the codes by addressing building designs that have main entrances on more than one floor level. In these design concepts, the customer flow (occupant load) is projected to be less than a single main floor design but more than a second-level sales floor. Therefore, the occupant load factor assumed for this type of design concept is one occupant per 40 ft^2 (3.7 m^2) for both of the floor levels having main entrances. The occupant load for stock or storage space that is not open to the public and other accessory occupancies is calculated using different factors, depending on the particular use.

Fire Load

As in most other occupancies, contents represent the major potential hazard. Sprinklers have proven effective as a means of combating fires in mercantile occupancies. In terms of life safety, NFPA *101* reflects cost-benefit considerations in the use of sprinklers. Its requirements for sprinklers, based on height and area limits, let many small shops be unsprinklered (unless they are accessory uses to an occupancy requiring sprinklers), while requiring medium and large mercantile occupancies to be protected with automatic sprinklers. In recent years, recognition has been given to the variety of contents of mercantile occupancies. The building and fire codes have now addressed the amounts of select contents that could be classified as hazardous that may be stored or displayed in areas of a mercantile occupancy. The maximum quantities permitted are generally limited to control area; this provides for separation of materials that are considered as presenting a physical hazard such that a single fire or other type of condition would only affect the materials in one control area.

MALL BUILDINGS

A mall is commonly defined as a covered or roofed interior area used as a pedestrian way, which connects buildings or portions of a building housing single and/or multiple tenants. Mall buildings became very popular in a relatively short time period, and today most large shopping centers either planned or under construction are of this type. In addition, many mall buildings are now being built in urban areas as multiuse projects in conjunction with parking decks, office buildings, hotels, recreational facilities, and public or private transit systems.

The mall may be considered as either (1) a way of exit access from the connected buildings or (2) a pedestrian way permitting an increase in the distance of travel from each of the tenant stores to a mall exit.

The first instance treats the entire complex as one building or one compartmented retail facility; the mall is simply an extension of the sales space. In terms of exit access, the mall is an aisle common to the various tenant stores that extends (continues) exit access aisles of tenant stores to mall exits. This treatment, in terms of NFPA *101* and *NFPA 5000,* leads to the strict application of all design factors as though the shopping center were a large single mercantile occupancy or department store.

The second instance employs a systems approach. The mall is considered to offer a higher degree of safety than a typical aisle serving as an exit access if certain minimum conditions and systems are provided. The mall should be of at least sufficient clear width to accommodate egress requirements for all mercantile tenants, but in no case less than 20 ft (6 m) wide at its narrowest dimension. The minimum width dimension of 20 ft (6 m) is particularly significant in terms of protecting occupants from direct exposure to a fire within a tenant store while those occupants utilize the exit access paths within the mall. Newly constructed malls with floor openings connecting more than two levels must be provided with an engineered smoke control system.

Design

The mall building is generally designed as one building connecting several sizable department stores and composed of numerous smaller specialty stores (mall tenant shops), all interconnected by a covered, climate-controlled, pedestrian way. The complex may also include ancillary occupancies, such as movie theaters, bowling lanes, ice arenas, food courts, project management offices, and other customer service areas accessed from the mall. Some even contain enclosed amusement parks.

The mall building may be designed as a single- or multilevel structure, depending on such factors as topography, size of the land parcel, and number and size of department stores and retail shops.

When a mall has two levels, the parking areas surrounding it usually are shaped to provide grade access to each level of the department stores and the small shops. This permits each level to serve as an entrance/exit, thus providing stores on all levels increased and equalized customer traffic as customers enter and leave the building (Figure 20.10.1). The two-level shopping center differs from the two-story shopping center in this important respect. When department stores are part of a two-level mall building, they are designed and merchandised in a similar manner.

Building codes have recognized that the construction of mall buildings up to a maximum of three stories high with floor openings within the pedestrian way (the mall) complying with the code mall provisions should not be considered atriums based on the special code provisions that address mall buildings.

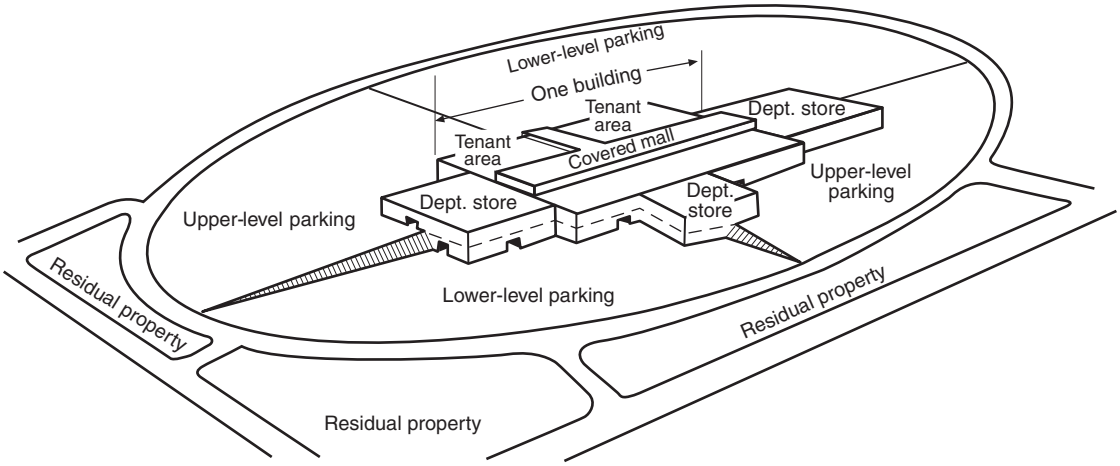

FIGURE 20.10.1 Two-Level Mall Building with Equal Distribution of Customer Traffic on All Levels

Exiting Concept. The mall proper is designed primarily to meet requirements for occupant flow and egress. Storefronts along the pedestrian way (the mall) must be designed to encourage unrestricted customer flow and traffic control from the mall to individual shops and to any connected department stores. This system of customer traffic flow and traffic control reflects the merchandising concept of mall buildings and the exiting concept of the codes. The exit concept is that the mall is an inherently safe space with controlled uses, adequate width, large volume, and high ceiling space that may also have smoke venting, and is protected with automatic sprinklers. This then allows egress capacity design to be based on the assumption that 100 percent of the occupants in the mall building will exit via the mall proper. This allows the back exit system for tenant shops to be sized for the most restrictive of the following:

1. The code-stated minimum dimension
2. The exit width required for the largest single tenant occupant flow exiting into the back exit system
3. The exit width required for occupants exiting from the mall, if the exit passageway also serves as a mall exit

This is the case even if the mall uses the same exit passageway that is used for a second exit by several mall tenant shops. Again this concept is based on the fact that occupants tend to exit the way they entered a store, via the mall itself. Therefore, the back exit system is truly a secondary exit system, and the mall is the primary egress path for mall building occupants.

Open storefronts between the mall and tenant mall shops are critical because swinging doors, whether glass or solid, not only make exiting more difficult but also promote what the retail industry calls "threshold resistance"—that is, customers' reluctance to push, pull, or slide doors to enter. The storefront closures ideally suited for maintaining after hours security are those that can be fully recessed, such as rolling overhead grilles, side-coiling grilles, and horizontal sliding doors. Because the ambient temperature in the mall and the tenant space is the same, the storefront closure only needs to satisfy a security requirement when the store is unoccupied.

Occupant Allowance Requirements. Mall buildings are constructed before tenants are known. When construction begins, the ultimate ratio of sales space to storage space for tenant stores and what changes may occur in the life of the building are also unknown. The use of each tenant space—for example, retail or assembly—is also typically unknown at the time of construction. Hence, occupant load must be projected to determine the required egress width well before negotiations with prospective tenants.

Egress width from the mall need only satisfy the calculated occupant load based on all connected tenant occupancies. It is not necessary to provide egress width from the mall commensurate with the minimum mall width. Doing so would unnecessarily result in wall-to-wall doors.

The occupant load factor used to determine egress width for the mall proper varies with the aggregate area of the connected stores. This sliding scale of occupant load factors reflects the relationship between an increase in a shopping center's size and an increase in its occupant load, which is not linear but parabolic, as Figure 20.10.2 shows. Once determined, the occupant load factor is applied to the gross leasable area (GLA) to calculate the covered mall building total occupant load for egress design. Again, this factor is not applied to gross building area. However, in mall buildings with large seating areas within the mall concourse that are part of a food court concept, the number of occupants for whom seating is provided is normally added to the occupant load that is calculated using the GLA of the mall building to establish the required egress width. Other types of assembly tenant spaces, such as restaurants with seating included within the tenant space, are considered as typical tenant spaces that are a portion of building's GLA.

Systems Approach

In most cases, two- or three-level covered malls are designed for visual communication among levels through openings in the floor of the upper level(s). Wherever practicable, visual com-

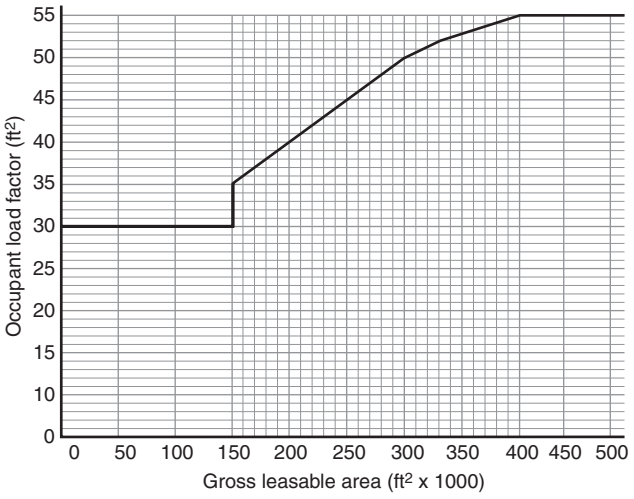

FIGURE 20.10.2 Relationship of an Increase in the Size of a Covered Mall to an Increase in the Occupant Load

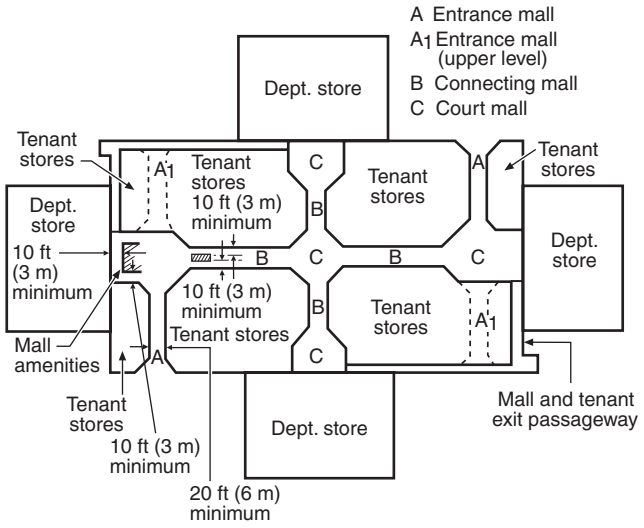

FIGURE 20.10.3 Typical Two-Level Shopping Center (Lower Level)

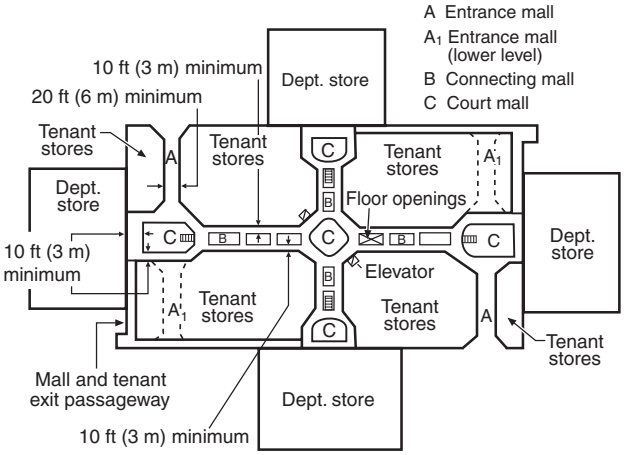

FIGURE 20.10.4 Typical Two-Level Shopping Center (Upper Level)

munication between levels is important in maximizing exposure of storefronts and merchandise to customer traffic. The floor areas between openings in the upper level(s) serve as bridges that promote cross-mall shopping convenience for the customer (Figures 20.10.3 and 20.10.4).

When construction starts, not everything about the shopping center is known, even to the developer. Mechanical, electrical, and fire protection systems are designed for main distribution only in the tenant store areas, with branch distribution added to the construction documents as lease agreements define tenant space.

The mall proper may contain other amenities for sales promotion, customer service, and convenience, such as seating areas, art objects, planting areas, food court seating areas, pools, specialty retail kiosks, directories, openings in upper levels of multilevel structures, and areas designed for promotional activities. Care must be exercised in locating these amenities so they do not interfere with, or encroach upon, required exit access. However, the width of the covered mall connecting courts at entrances to department stores generally is found well in excess of the 20 ft (6 m) minimum to provide for these amenities and at the same time provide for an aggregate of 20 ft (6 m) of exit access width (see Figure 20.10.3).

Stores located on either side of entrance malls and not along the direct path to department stores (commonly called "anchor stores" or "magnet stores" because of their greater customer attraction) do not enjoy as much customer exposure as those located along connecting malls. To compensate and maximize convenient cross-mall customer shopping, stores on opposite sides of the entrance mall are brought closer together by eliminating mall amenities that by themselves are not likely to generate traffic. The minimum mall width of 20 ft (6 m) is entirely compatible with this merchandising concept and does not impose an unreasonable burden on developers or merchants. This minimum width requirement has been applied successfully in shopping centers throughout the United States.

The mall should have an unobstructed exit access of not less than 10 ft (3 m) clear width on each side of the mall floor area, parallel and adjacent to the mall storefronts. The exit access should lead to an exit having a minimum of 66 in. (168 cm) of width. The purpose of requiring 10 ft (3 m) of clear exit access is to provide a higher degree of safety in the covered mall commensurate with its use as a continuation of exit access from the tenant stores. Safe, continuous, and unobstructed exit access from each tenant store is provided, while the owners' merchandising and operational requirements for mall amenities are recognized.

The minimum requirement of 10 ft (3 m) of clear exit access parallel and adjacent to the mall storefronts relates directly to the minimum mall width of 20 ft (6 m). None of the mall amenities mentioned earlier should encroach on this minimum

dimension of 10 ft (3 m). In effect, this requirement precludes the installation of mall amenities in areas of the covered mall that are the minimum 20 ft (6 m) width. In life safety terms, this requirement has proven reasonable and workable and has the added advantage of not being unduly restrictive or burdensome to developers.

Sprinkler Protection

The mall and all its connected buildings must be provided with an electrically supervised automatic sprinkler system throughout. This has proven the most effective way to protect life and property from fire. Sprinklers allow the replacement of many passive long-standing code requirements by active systems in combination with specified design requirements. See NFPA 13, *Standard for the Installation of Sprinkler Systems,* for details on the design and installation of sprinkler systems.

Separation of Mall Tenant Stores

Walls dividing mall building stores from each other can extend from the floor to the underside of the roof deck or floor deck above or to the underside of a noncombustible ceiling. The purpose of this requirement is to help limit fire and smoke spread to its area of origin. No separation is required between a store and the covered mall. The engineering of a smoke-control system may require deletion of the tenant partitions above the ceilings so the system operates effectively to prevent smoke accumulation. Tenant separation walls are usually constructed of metal studs and gypsum board.

Any requirement for separation at the storefront would defeat the merchandising purpose of the mall: to optimize unrestricted customer flow between the mall and the tenant store. This form of compartmentation, in concert with an electrically supervised automatic sprinkler system, eliminates the need for any fire separation wall requirements at the mall storefronts. In shopping centers, additional fire separation is unnecessary and, in fact, burdensome from an operational standpoint. In the leasing and subsequent re-leasing of shopping centers, maximum flexibility to rearrange space is important to continued success.

Smoke Management

Smoke management has been evaluated over the 30 years that mall buildings have existed and several approaches to smoke management are used in these buildings. One approach is a method to remove smoke from the mall when smoke migrates into it, since the mall is a primary component of the means of egress system.

Another approach is to design an engineered smoke management system for both the mall and the tenant spaces. This approach reacts to smoke that develops in a tenant space to limit smoke migration to the mall.

A third approach is to use the expansive volume of the mall building space, including the volume of the mall proper, to act as a reservoir for the accumulation of combustion products. With this method, even if smoke develops and migrates into the mall area, it will represent little threat to life safety since the building is sprinklered throughout, and the smoke and combustion gases entering a large-volume space, such as an atrium or mall, can be expected to be maintained at the higher elevations of the mall, which are typically well above the occupants who are evacuating. Since the mall is typically a large open space, people can see the smoke developing from a distance and use one of the multiple egress paths available to evacuate the mall building, while moving away from the developing fire condition.

Construction codes recognize that active smoke removal or venting may not be necessary in one- or two-level mall buildings. Thus, the type of smoke management system used can vary depending on project design from active mechanical systems to that of a passive design concept. See NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences,* and NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces,* for details on smoke control system design.

General Requirements

In addition to the special code provisions, certain means of egress conditions should be present in all mall buildings:

1. Every floor and every store of a mall building, except those less than 100 ft (30 m) deep, should have at least two exits remotely located from each other. The two required exits may both be through the mall concourse if the exits from the tenant space are remotely located as required by the code.
2. Every mall should have unobstructed 10-ft (3-m) wide exit access parallel and adjacent to the connected tenant spaces. The exit access should extend to the mall exits.
3. Exits from the mall should be arranged so that travel distance from any mall storefront entrance to an exit is no more than 200 ft (61 m).

GENERAL LIFE SAFETY FACTORS APPLYING TO MERCANTILE OCCUPANCIES

A number of factors related to life safety are common to all types of mercantile facilities.

Prompt discovery is one of the most important factors associated with minimizing loss due to fire. This is especially important during nonbusiness hours, from late night to very early morning. Many fires occur in stock areas, as opposed to sales areas. Poor housekeeping and smoking are two significant concerns in stock areas. For example, workers may remove merchandise from cartons for display on the sales floor and not properly dispose of the cartons and packaging, thus increasing the hazard.

Properly engineered sprinkler systems can be expected to respond to a fire to control its development, if not extinguish it entirely. The exit concepts for all large mercantile occupancies, including bulk merchandising stores, require careful design to achieve the operational needs of the facility while ensuring safe evacuation of the occupants in the event of a fire or other emergency.

Some items to consider follow:

1. If the main entrances are in one wall of the store, the code may require 50 percent or more of the required egress capacity to be provided in the same exterior wall. If high racks or fixtures are used, occupants must be able to readily identify the direction to this main exit wall.
2. Do egress paths of travel conflict with merchandise and stock movement? Such could be the case if exit access passes through shipping and receiving areas without defined egress paths identified by floor markings or physical barriers.
3. Does exit access require travel through other use areas in which the egress path is not clear and direct? Exit access through stockrooms, back-of-house or employee areas, or exterior garden departments can be used effectively if a clear and defined egress path is available.

The need to renovate existing facilities as a result of new trends in fashion or store design may arise in mercantile facilities as may the need to reconstruct existing facilities when releasing space, especially in shopping centers. Extra care should be taken to mitigate the potential problem of fire during these times, since reconstruction and renovation are very likely to increase the hazard. See NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations,* for more information.

Certain accessory uses, such as food preparation areas in restaurants, often found in mercantile facilities and more particularly in department stores and shopping centers, warrant special attention. Such areas should be segregated with appropriate construction, if not sprinklered, and appropriate fire suppression systems should be installed in food preparation equipment. See NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations,* for more information.

SUMMARY

An important purpose of this chapter on the nature of mercantile occupancy is to form a basis for considering or reconsidering code requirements that let the mercantile trade function optimally and yet provide the necessary degree of life safety for the facilities' occupants.

All requirement-related items discussed in this chapter have been practically applied in many stores and mall buildings throughout the United States. They have answered the need for life safety without imposing burdensome or unreasonable restrictions on either the developers or the merchandising needs of the mall buildings.

In addition to NFPA *101* and *NFPA 5000,* other model codes address the issues presented in this chapter in an effort to achieve codification of requirements for mall buildings. This effort's success will depend on how successfully the life safety concern is addressed in harmony with the retail merchandising purpose of the mall building.

Overreaction in the formulation of code requirements is possible if the fire record is not reviewed and used as a guide to the need for additional requirements. This is especially important when operational needs of the building type being considered are not fully understood. Therefore, code revisions should be tested to see if they are unreasonably restrictive or unfounded in terms of any real threat to life safety, compared to practicability in application and in terms of costs and benefits.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on mercantile occupancies discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*
NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations*
NFPA *101®, Life Safety Code®*
NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations*
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Chapter 11

Business Occupancies

Brian L. Marburger

Chapter Contents

Building Construction
Occupancy Characteristics
Potential Fire Scenarios
Means of Egress
Exit Lighting
Automatic Sprinklers
Existing Buildings

Key Terms

defend in place, Fire Safety Evaluation System, fire scenario, means of egress, occupancy characteristic, relocation, staged evacuation, total evacuation

As the service side of the economy continues to grow, more and more of us have become part of the many industries that deal in information. For example, based on U.S. Census statistics, the seasonally adjusted annual rate of the value of construction put in place for "Offices" grew 4.2 percent from January 2005 to January 2006. This indicates a continued growth in the development and construction of office space. Record keeping, data processing, and information management are central to businesses that are physically located in office buildings, and office buildings are the prototype for the class of properties defined as business occupancies in NFPA *101®*, *Life Safety Code®*, and *NFPA 5000®*, *Building Construction and Safety Code®*.

Most of the fires each year in business occupancies occur specifically in general business offices (Tables 20.11.1 and 20.11.2). Large numbers of business occupancy fire problems also occur in college classroom and administrative buildings, medical offices, and bank buildings. Other examples of this occupancy class include city or town halls, courthouses, laboratories not involving hazardous chemicals, and some ambulatory outpatient clinics. In each of these properties, information storage has dominated the building's distinctive fuel load. However, in recent decades the increased use of desktop computers and peripheral equipment has added to the overall fuel load.

The business occupancy has long been considered a low-hazard occupancy and, therefore, not worthy of serious protection consideration. However, this is not the case, as this chapter will show. It examines building construction, occupancy characteristics, potential fire scenarios, means of egress, effects of sprinklers, effects of detection systems, and special cases of existing buildings.

Rather than recite requirements available for reference in codes and standards, this chapter approaches the subject of protecting life in a business occupancy from a more philosophical standpoint. It challenges the reader to look beyond the codes and to observe, measure, and understand the impact that building and occupancy conditions actually have on persons in them.

During the 1999–2002 period, the 4900 fires in office properties accounted for 0.9 percent of the 517,130 structure fires, 0.1 percent of the 3140 civilian structure fire deaths, 0.3 percent of the 17,730 civilian structure fire injuries, and 1.6 percent of the $8.6 billion in direct property loss. (The events of September 11, 2001, are excluded from these statistics.)[1]

In addition, fires in office properties fell 60 percent from 10,570 in 1980 to 4200 in 2002 (see Table 20.11.2). From 2001 to 2002, structure fires in these occupancies fell 14 percent. In comparison, structure fires of all types declined 51 percent from 1980 to 1999.[1]

What's driving the reduction in fires? Most industry experts attribute the loss reduction to a combination of improved application of safety codes and standards, increased public fire prevention and awareness, and increased effectiveness of life safety measures.

Office buildings have been terrorist targets in recent years. On February 23, 1993, a terrorist attack at the World Trade Center in New York City claimed six lives. On April 19, 1995, an explosion at a federal office building in Oklahoma City killed 168 people. On September 11, 2001, terrorist attacks on the twin towers of the World Trade Center in New York City and at the Pentagon in Virginia caused thousands of deaths.

NFPA members can download a number of investigation reports on office building fires, including the 1995 attack in Oklahoma City, the first World Trade Center attack in 1993, Philadelphia's One Meridien Plaza, Boston's Prudential Office Building, New York City's Rockefeller Center, and

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TABLE 20.11.1 Structure Fires in Office Properties, 1999–2002 Annual Averages*

Occupancy	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
Business office	4060	4	42	114
Research or veterinary office	420	0	4	10
Bank	320	0	3	14
Post office or mailing firm	100	0	1	3
Total	4900	4	51	141

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation.

*Excluding the events of September 11, 2001.

Source: NFIRS and NFPA survey.

TABLE 20.11.2 Structure Fires in Office Properties, by Year 1980–2002

				Direct Property Damage (in Millions of Dollars)	
Year	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*As Reported*	*In 2002 Dollars*
1980	10,570	0	103	89	195
1981	11,330	3	142	141	278
1982	10,220	8	176	310	578
1983	9,040	14	157	121	218
1984	9,270	9	140	99	171
1985	9,830	8	93	150	250
1986	9,170	8	195	158	259
1987	8,680	4	107	109	172
1988	8,170	4	128	272	414
1989	7,330	2	82	114	166
1990	6,970	8	68	154	213
1991	7,030	2	99	134	177
1992	8,070	4	148	456	585
1993	6,430	3	113	127	158
1994	6,500	2	93	155	188
1995	5,390	0	90	83	98
1996	6,200	1	86	186	213
1997	5,760	0	73	106	119
1998	5,130	2	59	118	131
1999	5,530	5	62	116	125
2000	4,960	9	91	159	166
2001*	4,910	2	31	191	194
2002	4,200	0	19	100	100

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest million dollars.

*Excluding the events of September 11, 2001.

Source: NFIRS and NFPA survey. Inflation adjustments were based on U.S. Census Bureau's *Statistical Abstract of the United States: 2006,* "Table 705, Purchasing Power of the Dollar."

Los Angeles's First Interstate Bank and Union Bank Building, at no cost from http://www.nfpa.org. Nonmembers may order these reports from the NFPA library.

A discussion of the terrorist threat to office buildings is provided here only as a point of reference to the changing landscape of risks in America. This chapter does not address the specific risks associated with terrorism.

To be aware of the concept of risk is to begin to understand the fire problem. The business occupancy is certainly of a lower hazard class than many industrial or hazardous materials handling operations. But when more people occupy a single building than reside in a small town, as is often the case in the modern high-rise, the magnitude of the challenge faced in protecting the building, its contents, and, most importantly, its occupants, is realized.

This chapter examines how the contents and the building itself affect fire growth and severity, how growth and severity affect notification and egress time of occupants, and how the conditions of occupants affect their abilities to escape. A format and issues for analysis are presented.

Additional information on determining necessary levels of protection can be found in Section 3, "Information and Analysis for Fire Protection." More information on fire-safe building design can be found in Section 1, Chapter 9, "Systems Approach to Fire-Safe Building Design." Information on interior finish can be found in Section 18, Chapter 2, "Interior Finish." Other relevant information can be found in Section 4, Chapter 5, "Strategies for Occupant Evacuation During Emergencies."

BUILDING CONSTRUCTION

Construction Type

Business occupancies can be found in a variety of building types. Although a two- or three-story noncombustible structure or a fire-resistant high-rise may be most familiar, many business occupancies are housed in ordinary wood frame, joisted masonry, and even heavy timber buildings.

Each construction type affects the business occupancy differently because fires behave differently in each. This discussion and its examples are confined to noncombustible and fire-resistive construction because it is most prevalent. The reader must understand that, in other construction types, the availability of fuel from the structure itself can increase fire severity, thereby decreasing potential structural integrity much more quickly.

Noncombustible Construction. In noncombustible construction, construction materials do not burn, thereby providing a measure of increased occupant safety. In reviewing the life safety needs of a business occupancy in a building of noncombustible construction, the designer or reviewing official can be primarily concerned with fuel load from the contents, furnishings, and interior finish, and with the means of egress. Although the potential fire's effect on the structure also must be assessed, this is usually simpler to do than it is in the case of combustible construction materials.

Fire-Resistive Construction. Fire-resistive structures are similar to noncombustible structures except that the material or combinations of materials used inherently resist failure due to fire or to the spread of fire. These characteristics help ensure sufficient time for persons to egress and/or receive other forms of assistance.

Interior Finish

Interior finish comprises the various aesthetic treatments to the structure that make it more comfortable to work in and more pleasing to the eye. Interior finish includes the materials used to cover walls, ceilings, and floors, such as paint, wallpaper, vinyl and textile wallcoverings, paneling, acoustic panels, hardwood floors, vinyl tile, terrazzo, and carpet.

The main fire performance measure of an interior wall or ceiling finish material is flame spread. This is the ability of the material to propagate a flame front across its surface. Wall and ceiling materials are ranked by relative ratings based on a value of 100 given for a specially prepared sample of red oak. Floor finishes are rated by the amount of heat energy imparted to the surface from an external source that is necessary to sustain combustion; this is called critical radiant flux. The better the flame-spread characteristics—that is, the lower the rating for wall and ceiling material, and the higher critical radiant flux for floor coverings—the more occupant protection can be assumed.

It is important to note that flame-spread ratings are based on tests of materials under controlled conditions and with specific backing materials. A wallcovering mounted on gypsum wallboard would be expected to perform differently than a wallcovering installed over brick or concrete block.

A most important but often overlooked point is that interior finish materials are also fuels. When materials are relatively thin—two coats of paint or one layer of vinyl wallcovering, for example—the additional fuel may be insignificant. In general, wallcovering materials with a thickness of 1/28 in. (0.91 mm) or less are typically exempt from testing on the actual substrate material. If they achieve a Class A rating when tested using fiber cement board as the substrate, they are not subject to the interior finish requirements of NFPA *101* and *NFPA 5000*. But when several layers of wallcovering, carpet, floor coverings, or other materials are present, the hazard and risk change dramatically. It should not be assumed that a low flame-spread rating alone results in a significant risk reduction. It is important to understand the impact this additional fuel has on the entire environment.

Furnishings and Contents

Furnishings and contents make up the bulk of the potential fuel load in a business occupancy. Furnishings, for the purpose of this discussion, include desks, chairs, sofas, and files.

Over the past decades, there have been many changes in the furnishings put into buildings. At one time, desks and chairs were routinely wood. Then metal became popular. Now, any combination of wood, metal, thermoplastics, and foamed plastics can be found. In addition, the increased use of computers has added to the fuel load.

Business occupancies are considered lower hazard than industrial or other occupancies handling hazardous materials. However, this perception sometimes confuses familiarity with safety. The quantity of combustible fuel in business occupancies can be a source of significant hazard, even if hazardous materials

are not involved. In addition, some relatively benign materials may have burning characteristics—such as peak intensity of heat when fully involved in fire—comparable to some hazardous materials.

The designer and code official must be aware of the characteristics of the materials in a building, such as construction materials, interior finish materials, and furnishings. Each provides a degree of protection and a degree of hazard; their combined effect influences risk. Without understanding the potential fire behavior in a business occupancy, one cannot begin to understand its potential effect on people.

OCCUPANCY CHARACTERISTICS

Business occupants are generally characterized as awake, alert, and familiar with their surroundings. Although this is true of most offices, designers and code officials must assess the actual characteristics of a particular business occupancy, such as a doctor's office or an outpatient clinic, in which a minority of the occupants are familiar with the surroundings. In business occupancies, generalities do not always apply. The following three examples of different occupancy conditions emphasize the need for designers and code officials to evaluate the actual occupant conditions.

Support Services

Support services often are found within business occupancies. Each provides a challenge in the analysis of potential fire impact because these service areas present their own special hazards (Table 20.11.3). Examples include cafeterias, auditoriums, print shops, storage areas, parking facilities, small retail outlets,

TABLE 20.11.3 Structure Fires in Office Properties, by Area of Origin, 1999–2002 Annual Averages*

Area of Origin	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Office	750	(15%)	3	(68%)	17	(33%)	43	(30%)
Kitchen or cooking area	290	(6%)	1	(21%)	2	(4%)	1	(1%)
Exterior wall surface	260	(5%)	0	(0%)	0	(0%)	4	(2%)
Attic or ceiling/roof assembly or concealed space	220	(4%)	0	(0%)	1	(1%)	15	(10%)
Exterior roof surface	210	(4%)	0	(0%)	1	(1%)	3	(2%)
Lavatory, bathroom, locker room, or check room	190	(4%)	0	(0%)	0	(0%)	2	(1%)
Confined cooking fire	190	(4%)	0	(0%)	0	(0%)	0	(0%)
Heating equipment room	190	(4%)	0	(0%)	6	(11%)	3	(2%)
Machinery room or area or elevator machinery room	170	(3%)	0	(0%)	0	(0%)	9	(6%)
Storage of supplies or tools or dead storage	130	(3%)	0	(0%)	0	(0%)	6	(4%)
Computer room, control room, or center	110	(2%)	0	(0%)	1	(2%)	1	(1%)
Lobby or entrance way	110	(2%)	0	(0%)	1	(2%)	4	(3%)
Hallway, corridor, or mall	110	(2%)	0	(0%)	2	(5%)	1	(0%)
Wall assembly or concealed space	100	(2%)	0	(0%)	0	(0%)	2	(1%)
Crawl space or substructure space	80	(2%)	0	(0%)	2	(3%)	5	(4%)
Ceiling/floor assembly or concealed space	80	(2%)	0	(0%)	1	(1%)	3	(2%)
Trash or rubbish chute, area, or container	80	(2%)	0	(0%)	1	(2%)	1	(1%)
Switchgear area or transformer vault	70	(1%)	0	(0%)	3	(6%)	3	(2%)
Dining room, bar or beverage area, cafeteria	70	(1%)	0	(0%)	1	(1%)	0	(0%)
Unclassified	60	(1%)	0	(0%)	1	(1%)	5	(3%)
Unclassified equipment or service area	60	(1%)	0	(0%)	0	(0%)	1	(1%)
Unclassified structural area	60	(1%)	0	(0%)	0	(0%)	3	(2%)
Duct for HVAC, cable, exhaust, heating, or air conditioning	60	(1%)	0	(0%)	2	(5%)	0	(0%)
Common room, living room, family room, lounge, or den	60	(1%)	0	(0%)	1	(1%)	2	(1%)
Closet	50	(1%)	0	(0%)	1	(1%)	0	(0%)
Confined fuel burner or boiler fire	50	(1%)	0	(0%)	0	(0%)	0	(0%)
Records storage room or vault	50	(1%)	0	(0%)	1	(2%)	1	(1%)
Unclassified storage area	50	(1%)	0	(0%)	0	(0%)	2	(2%)
Storage room, area, tank, or bin	50	(1%)	0	(0%)	2	(4%)	4	(3%)

*Excluding the events of September 11, 2001.

Source: NFIRS and NFPA survey.

and banks or credit unions. People usually gather in these areas during certain times, often in large concentrations relative to the general occupant load for the entire building. Many service areas increase the potential for fire ignition because of their operation; one example is a cafeteria kitchen.

Child-Care Center

Another growing service area in business occupancies is the child-care center. With more families having both parents, or the only parent, working, employer-provided child care or contract day care is becoming more common. This poses special concerns: the occupants' ages, their lack of familiarity with their surroundings, mobility, and the fact that they sleep in the space from time to time. Special protection must be considered for child-care centers, including smoke detection, sprinkler protection, fire-resistive enclosures, location at grade level with direct access to the outside, and sufficient adult supervision.

Disabilities

Another high-risk segment of the population in business occupancies are people with disabilities. There are special requirements for access and acommodations for disabled people, as well as increasing awareness of the large number of people with ability limitations of some kind to some degree that could affect their response to fire. Disabilities cover a wide range, including sight, hearing, and mobility impairments. A disability also can be temporary or transient, such as a broken leg. Disabilities can increase the time needed to alert individuals or the time necessary to safely egress an area or the building. Designers and code officials must consider the presence of persons with known or hidden disabilities when evaluating a life safety system for a business occupancy.

POTENTIAL FIRE SCENARIOS

Fire safety design for a particular property must begin with a consideration of characteristics of most likely fires and the most serious fire the occupancy might encounter (Table 20.11.4). This may be done by defining potential fire scenarios to use as a basis for analysis.

Ignition Sources

Leading sources of heat for unintentional ignition include electrical distribution systems, portable and fixed space heating

TABLE 20.11.4 Leading Causes of Structure Fires in Office Properties, 1999–2002 Annual Averages*

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Electrical distribution and lighting equipment	930	(19%)	0	(0%)	22	(44%)	23	(16%)
Intentional	650	(13%)	0	(0%)	6	(12%)	41	(29%)
Heating equipment fires	520	(11%)	1	(33%)	5	(10%)	6	(4%)
Identified heating equipment	460	(9%)	1	(33%)	5	(10%)	6	(4%)
Confined heating equipment fire	60	(1%)	0	(0%)	0	(0%)	0	(0%)
Cooking equipment fires	500	(10%)	1	(33%)	4	(7%)	2	(1%)
Identified cooking equipment	310	(6%)	1	(33%)	4	(7%)	2	(1%)
Confined cooking fire	190	(4%)	0	(0%)	0	(0%)	0	(0%)
Smoking materials	490	(10%)	1	(25%)	1	(3%)	13	(9%)
Exposure to other fire	250	(5%)	0	(0%)	1	(1%)	10	(7%)
Torch (including burner or soldering iron)	240	(5%)	0	(0%)	4	(9%)	5	(3%)
Candle	120	(2%)	0	(0%)	1	(1%)	3	(2%)
Contained trash or rubbish fire	130	(3%)	0	(0%)	0	(0%)	0	(0%)

Note: These are the leading causes, obtained from the following list: intentional (from the NFIRS field "cause"); playing with fire (from factor contributing to ignition); confined heating (including confined chimney and confined fuel burner or boiler fires), confined cooking, and contained trash or rubbish (from incident type); identified heating, identified cooking, clothes dryer or washer, torch (including burner and soldering iron), electrical distribution and lighting equipment, medical equipment, and electronic, office, or entertainment equipment (from equipment involved in ignition); smoking materials, candles, lightning, and spontaneous combustion or chemical reaction (from heat source); and mobile property involved (from mobile property involved in ignition). Exposure fires include fires with an exposure number greater than zero, as well as fires identified by heat source or factor contributing to ignition when no equipment was involved in ignition that were not intentionally set. The same fire can be listed under multiple causes, based on multiple data elements.

These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation.

*Excluding the events of September 11, 2001.

Source: NFIRS and NFPA survey.

equipment, other appliances, torch and other maintenance operations, matches and lighters, and smoking materials. The design professional and code official must know where potential ignition sources are and where they expose potential fuels.

Arson

One of the leading causes of fire in business occupancies is not unintentional, however; it is arson. Arson prevention is partly a matter of understanding the business and those who might wish to harm it, such as competitors, disgruntled employees, angry customers, or economically strapped owners. But arson more often occurs as a result of less direct motives, such as emotional disturbance, so it is important to emphasize security controls and arrangements, such as housekeeping, that will reduce the range of attractive and easy targets for potential arsonists. Also, the importance of arson underscores the limits of fire prevention as a strategy, so postignition fire protection provisions are needed, too.

The value at risk from a fire in a business occupancy can easily be underestimated, with the increase in regular use of computers, facsimile machines, copy machines, printers, and similar equipment, and the purchase of telephone systems for offices and buildings. The value of loss of business and other interruption costs, including the occupancy of temporary space and reduced employee productivity during space restoration, also must be considered.

The designer and code official must look carefully at the business occupancy for available fuels and potential ignition sources. The impact of fire on the occupancy and occupants can then be predicted. Computer models and other engineering tools can translate the occupancy's physical and occupant characteristics into a timeline of fire development and its effects on people and property.

MEANS OF EGRESS

In analyzing the potential fire scenario and choosing strategies to deal with the results of the analysis, it is useful to think in terms of major groups of fire protection provisions. Means of egress will be the first discussed here. Before the means of egress needs can be assessed, however, an objective must first be established: every occupant should be able to reach a safe location from anywhere in the building without incurring serious harm from fire, smoke, or other products of combustion along the way.

For a long time, this objective was fulfilled by evacuating building occupants when fire was discovered. As buildings get larger and taller, this came to be less practical. Some high-rise building populations are the size of a small town; total evacuation may take hours. Nor does it make sense to move people from the 40th floor of a building in response to a small trash fire on the 60th floor, especially if the fire is being controlled or extinguished by an automatic sprinkler system. Persons with severe mobility impairments may not have this option available without assistance.

One method of establishing an acceptable level of protection for persons from fire is the application of NFPA *101* or *NFPA 5000*. They provide requirements for determining occupant loads, arrangement of means of egress, capacity of means of egress, and exit travel distances, as well as requirements for the design of doors, stairs, and interior finish materials. NFPA *101* recognizes differences in existing buildings and new construction, and it provides different requirements for each. In fact, all codes and standards have equivalency clauses so as not to exclude sound engineering approaches that accomplish the same or similar results. The code official must be aware of the application of these equivalency clauses.

Total Evacuation

In a total evacuation, persons should be able to leave the building before conditions become untenable. Fire growth, temperature rise, and the production of toxic combustion products must be estimated. Then the time needed to evacuate the building must be estimated. The difference between the evacuation time and the time to untenable conditions is the time allowed for fire detection, notification of occupants, and occupant reaction.

The alarm system, either manual or automatic, must be chosen based on the time available to notify occupants. In most business occupancies, a manual alarm system is sufficient, but the designer and code official must be aware of conditions that warrant the use of an automatic detection and alarm system. If automatic sprinkler protection is provided, the designer should take advantage of its presence and use it as an alarm-initiating device.

Alternatives to Total Evacuation

If total evacuation is not practical, it is still necessary to ensure that occupants can get to an area of relative safety before conditions become untenable. This is commonly accomplished by a combination of four approaches.

Relocation. Fire conditions and necessary egress time must be estimated. The area of relative safety must then be chosen. This may be a trial-and-error design process because estimated fire conditions and the structure's ability to resist fire affect where the safer areas will most likely be. Furthermore, persons must be able to reach those areas in a reasonable time.

Other egress or occupant protection strategies are similar to relocation and include defend in place, staged evacuation, and use of horizontal exits.

Defend in Place. Defend-in-place strategies are generally used in health care occupancies where patients cannot be readily moved. Although not preferred for business occupancies, the existence of such strategies should be noted and understood.

Staged Evacuation. Staged evacuation can take several forms. One is staged total evacuation where the fire floor occupants are notified, and, after a determined time period, other occupants are notified. This allows those on the fire floor the first opportunity to escape. Persons in areas farther from the fire start to evacuate a bit later.

Another method of staged evacuation is the use of "hardened" areas, or areas of refuge, where persons may seek tem-

porary refuge until they are able to egress. These staging areas pose several questions:

1. How should the area be hardened? Fire resistance is not enough. Ventilation and pressurization are critical to maintaining a tenable environment when the area is exposed to postflashover conditions or smoke migration.
2. How many people will use the area? These areas have been suggested for use by people with disabilities. With the population of mobility-impaired occupants growing in many business occupancies, a minimum number of such occupants must be able to be safely protected in such areas. NFPA *101* and *NFPA 5000* provide guidance on this topic.
3. How will people use these areas? Practice is the only answer. If provided, these areas must be addressed in the fire evacuation plan for the building. This fact would suggest that these staging areas have only limited impact on persons who are not familiar with the building.
4. How will persons eventually leave the building? These areas must not be considered as a place to wait until the fire is extinguished. Persons generally must leave the fire floor. These areas, if provided, should be adjacent to stairs or elevators so that fire department personnel or building fire wardens can assist persons in these areas to other areas of relative safety.

The use of this type of staging area takes much planning, practice, maintenance, and coordination. Unfortunately, it is of little benefit to persons unfamiliar with the building and its features. Therefore, a preferred method would be to establish a way to protect the occupants with little or no special instructions.

In potential impact and effectiveness of staging areas for occupants with disabilities, complete automatic sprinkler protection (properly designed, installed, and maintained) afforded occupants sufficient safety without actually needing to egress the floor (Table 20.11.5). If the sprinkler system uses quick-response sprinklers, there will likely be no perception of risk on the part of building occupants.

Horizontal Exit. Another method of staged evacuation is through horizontal exits. Horizontal exits can be provided by subdividing a building with specially designed fire barriers. Persons passing through doors in these walls move to an area of relative safety. In some cases, the horizontal exit alone may provide enough egress protection. In others, the horizontal exit may be used to provide enough protection to stage occupants, thereby allowing more time for total evacuation or assisted evacuation, as in the case of persons with disabilities.

In either relocation or staged evacuation, fire control is important. To ensure the success of the egress or occupant protection strategy, fire growth and combustion products must be held to a minimum. This can be done in several ways. Fuel can be limited, room geometry can be controlled, and ventilation of fire areas can be limited. A proven effective method of controlling fire growth and smoke production is through the use of automatic sprinklers. Therefore, where occupant relocation or staging is an intended strategy, the building should be protected with automatic sprinklers, although individual conditions dictate the actual protection necessary.

TABLE 20.11.5 Fire Protection Features in Office Property Structure Fires Reported to Public Fire Departments, 1994–1998 Annual Averages

Percent of fires in buildings with smoke or other fire alarms present	53.7%
Percent of fires in buildings having smoke or other fire alarms in which devices were operational	74.3%
Percent of fires in buildings with operational smoke or other fire alarms (product of first two statistics)	39.9%
Percent of fires in buildings with automatic suppression system	25.4%
Deaths per 1000 fires with automatic suppression system present	0.0
Deaths per 1000 fires with no automatic suppression system present	0.3
Reduction in deaths per 1000 fires when automatic suppression systems were present	100.0%
Average loss per fire when automatic suppression system was present	$11,311
Average loss per fire with no automatic suppression system	$28,091
Reduction in loss per fire when automatic suppression systems were present	59.7%

Source: National estimates based on NFIRS and NFPA survey; Marty Ahrens, *The U.S. Fire Problem Overview Report,* NFPA Fire Analysis and Research Division, Quincy, MA, June 2001.

EXIT LIGHTING

The means of egress should be continuously illuminated by a reliable lighting system. This usually means spacing lighting fixtures and providing primary and emergency power to ensure a lighting level of at least 1 footcandle (10 lux), measured at the floor level.

Emergency power can be provided in many ways: batteries, inverters, generators, separate building substations with automatic transfer switches, and power distribution system network grids. The concept behind emergency power for egress lighting is to ensure that the exit path is illuminated if a fire in the building disrupts the primary power source. Because a complete power failure at the utility would rarely occur at the same time a fire in the building would, it is sufficient to have only one of the recommended emergency power sources. However, other design arrangements may be necessary, depending on specific local conditions and utility reliability.

AUTOMATIC SPRINKLERS

As discussed, automatic sprinkler protection can increase the level of fire safety in a business occupancy. From the life safety standpoint, sprinklers limit fire growth and the production of smoke, thereby increasing the time available for persons to egress. If designed to do so, automatic sprinklers can even keep conditions in close proximity to the fire in a tenable range.

Another reason sprinklers should be considered is property protection. Fire department suppression capabilities may

be limited by staffing issues, water supplies, or height of the fire above ground level. If fire fighters must rescue occupants, their fire suppression capability decreases. As property values and mission criticality increase, the typical business cannot afford this potential exposure.

The average loss per fire was cut almost in half when automatic suppression systems were present. Automatic suppression systems were present in only 25 percent of these fires from 1994 to 1998. The average estimated direct property damage was almost twice as high when no automatic suppression system was present. Because a code for undetermined system presence was not included in Version 5.0 of NFIRS until 2004, data on number of fires and loss rates cannot be confidently updated (Table 20.11.6).

Sprinkler protection automatically detects a fire and starts suppression actions, providing additional time for occupants to exit. The sprinkler system can even notify occupants of the fire when arranged to activate the fire alarm. Sprinklers also limit fire and water damage, thereby decreasing business interruption. With the expanded use of quick-response sprinklers, these occupant protection factors and property protection features can be expected to increase.

Retrofitting sprinkler systems is becoming easier with the use of special materials such as lightweight steel pipe, copper tube, and plastic pipe. In addition, sprinklers can be safely installed in buildings with sprayed-on asbestos containing fireproofing through a process of local encapsulation and control. See the additional readings for this chapter for more information on this subject.

EXISTING BUILDINGS

Business occupancies in existing buildings pose several concerns from a life safety standpoint. Many do not meet the requirements of codes, standards, or design practices for new construction. The question should not be, "Do they comply?" Rather, we should ask, "Is the occupant protection objective fulfilled?" In this case, occupant protection should be no different than that previously discussed. The objective is to get people to an area of relative safety before conditions become untenable.

TABLE 20.11.6 Automatic Suppression Systems in Office Property Structure Fires Reported to Public Fire Departments, 1994–1998 Annual Averages

Percent of fires in buildings with automatic suppression system	25%
Average loss per fire when automatic suppression system was present	$11,300
Average loss per fire with no automatic suppression system	$28,100
Reduction in loss per fire when automatic suppression systems were present	60%

Source: National estimates based on NFIRS and NFPA survey.

The difference is that an existing building constrains the protection strategy. Several resources can be used to help find solutions to egress problems in existing buildings.

NFPA *101* has a separate chapter for existing business occupancies. Requirements in that chapter are similar to those for new buildings, but they reflect the necessity of accepting those things that cannot be economically changed, provided a reasonable degree of safety is present.

Another good reference is NFPA 101A, *Guide on Alternative Approaches to Life Safety,* which includes a chapter on a Fire Safety Evaluation System (FSES) for business occupancies. FSES is a measuring system. It compares the level of safety provided by an arrangement of safeguards that differs from those specified in NFPA *101* to the level of safety provided in a building that conforms with the details of the code.

Other analytical methods exist that may be beneficial in evaluating the risk to life in an existing business occupancy. These include hand calculations and computer-based predictive fire models. (See Section 3, "Information and Analysis for Fire Protection.") In any event, the process is the same—determine the fire exposure, the time available for safe egress, and the time needed to egress.

A special category of existing buildings must be mentioned: historic or architecturally significant buildings. Society puts additional constraint on these structures as to the way alterations must be done. Here, historic preservation and life safety objectives must be carefully outlined and communicated. These objectives are not necessarily at cross purposes. Innovative design techniques and engineered performance-based solutions, rather than code compliance, are usually called for. A reference on the process and design tips is included in the list of additional readings following this chapter. Also see Section 20, Chapter 17, "Library and Museum Collections."

SUMMARY

Business occupancies comprise a large segment of the communities protected, and they can be found in a variety of building types. Construction type, occupancy characteristics, potential fire scenarios, means of egress, the effect of sprinklers, and existing conditions all affect the ability to protect occupants from the effects of fire. An objective has been set for protecting these occupants by keeping them in a tenable environment or by allowing them to escape to an area of relative safety before untenable conditions are reached. This area may be outside the building, on another floor, or through a horizontal exit.

The designer and code official must look deeper than codes and standards alone to understand actual conditions and measure exposures. They will then be able to recommend ways of fulfilling the objective of protecting occupants.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on business occupancies discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA *101®, Life Safety Code®*
NFPA 101A, *Guide on Alternative Approaches to Life Safety*
NFPA 5000®, Building Construction and Safety Code®

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Chapter 12

Educational Occupancies

Revised by
Alex L. Szachnowicz

Chapter Contents

Fire Problem in Educational Occupancies
Occupant Characteristics
Design Considerations
Occupancy Hazards
Life Safety Concepts

Key Terms

educational occupancy, exit hardware, fire exit drills, means of egress, occupant characteristic, occupant load, open plan design, windows

This chapter addresses *educational occupancies,* which are generally defined as new or existing facilities in which six or more persons gather for purposes of formal or structured instruction. This chapter describes the nature of educational occupants as well as the hazards and life safety concepts relevant to this type of occupancy.

Examples of educational occupancies include public, private, and parochial schools, academies, kindergartens, and other facilities whose purpose is primarily educational, even though their students may be of preschool age. Educational occupancies are typically defined as places where students are present for formalized instruction for more than 4 hours per day, or more than 12 hours per week, through the twelfth grade. This is differentiated from day-care occupancies, which are generally defined as those facilities in which four or more clients receive care, maintenance, and supervision by other than their relatives or legal guardian for less than 24 hours per day. Colleges, universities, and postsecondary trade schools are typically excluded from educational occupancies as well. Furthermore, the definition of an educational occupancy excludes facilities in which instruction is incidental to some other occupancy. In such cases, the requirements of the predominant occupancy shall apply. Examples of excluded facilities include the following:

- Rooms located within places of worship used for purposes of religious education while services are being held in the building
- Rooms used for extracurricular purposes such as piano instruction, dance instruction, martial arts classes, or sport activities
- Classrooms and laboratories located within business or industrial occupancies

See also Section 20, Chapter 13, "Day-Care Occupancies."

FIRE PROBLEM IN EDUCATIONAL OCCUPANCIES

The U.S. fire problem in educational occupancies is outlined in Tables 20.12.1 through 20.12.4. As one can see, between 1999 and 2002, there was an annualized average of approximately 7070 structure fires in educational properties. These fires contributed to an average of 113 civilian injuries and $112 million in direct property damage per year during that period. Although educational occupancy fires can start in a variety of locations, the data indicate that the leading areas of origin tend to be in lavatories or locker rooms, with rubbish, trash, magazines, papers, and other waste products often the first items to be ignited. Almost half of the fires in educational occupancies were intentionally set or the result of fireplay. It is for this reason that traditional fire safety education messages should be augmented with juvenile firesetter programs in educational occupancies. It is important to note that these data are derived from the National Fire Incident Reporting System (NFIRS) and from information gleaned from an annual survey conducted by NFPA. As such, this information does contain some imbedded data garnered from day-care occupancies, colleges, universities, and other adult learner properties.

Table 20.12.5 presents the benefits of automatic suppression systems in educational properties. Note that automatic suppression systems were present in only 24 percent of the fires in educational

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TABLE 20.12.1 Structural Fires in Educational Properties, 1999–2002 Annual Averages

Occupancy	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
Nursery school through high school	5320	0	88	74
Preschool	210	0	1	1
Elementary school, including kindergarten	1380	0	13	27
High school, junior high, or middle school	3020	0	62	33
Unclassified nonadult school	700	0	12	13
Adult education center or college classroom	980	0	17	30
Day care	440	0	4	4
Unclassified educational	330	0	3	5
Total	7070	0	113	112

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires are rounded to the nearest ten, deaths and injuries to the nearest one, and direct property damage to the nearest million dollars. Sums may not equal totals due to rounding errors. Damage has not been adjusted for inflation.

Source: *U.S. Fires in Selected Occupancies,* National Fire Protection Association, March 2006. National estimates based on NFIRS and NFPA survey.

properties, and the average estimated direct property damage was almost five times higher when no automatic suppression system was present.

OCCUPANT CHARACTERISTICS

People in educational occupancies vary in their ability to deal with an emergency condition, depending on their age, mental and physical conditions, as well as the facility's physical characteristics. Generally, regulations concerning educational occupancies are based on the abilities of children in the third through eighth grades, with special provisions made for younger children. High school occupants gain an extra measure of protection because the fire safety design package is based on younger children's capabilities.

Children younger than those in the third grade require special consideration because of their limited ability to traverse

TABLE 20.12.2 Leading Causes of Structure Fires in Educational Occupancies: 1999–2002 Annual Averages

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Intentional	2650	(38%)	*	(*%)	27	(24%)	51.2	(46%)
Cooking equipment fires	930	(13%)	*	(*%)	8	(7%)	1.7	(2%)
Identified cooking equipment	570	(8%)	*	(*%)	6	(6%)	1.7	(2%)
Confined cooking fire	350	(5%)	*	(*%)	2	(2%)	0.0	(0%)
Electrical	550	(8%)	*	(*%)	23	(20%)	12.0	(11%)
Heating equipment fires	530	(8%)	*	(*%)	4	(3%)	6.6	(6%)
Identified heating equipment	450	(6%)	*	(*%)	4	(3%)	6.5	(6%)
Confined heating equipment fire	80	(1%)	*	(*%)	0	(0%)	0.1	(0%)
Playing with fire	520	(7%)	*	(*%)	0	(0%)	4.0	(4%)
Smoking materials	350	(5%)	*	(*%)	6	(6%)	3.5	(3%)
Torch (including burner or soldering iron)	220	(3%)	*	(*%)	10	(9%)	4.7	(4%)
Clothes dryer or washer	200	(3%)	*	(*%)	3	(3%)	0.5	(0%)
Contained trash or rubbish fire	550	(8%)	*	(*%)	4	(4%)	0.3	(0%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest hundred thousand dollars. Property damage has not been adjusted for inflation.

*The cause of all the fatalities during this period was unknown or not reported.

Source: *U.S. Fires in Selected Occupancies,* Table 5, National Fire Protection Association, March 2006. Based on NFIRS and NFPA survey.

TABLE 20.12.3 Structure Fires in Educational Properties, by Area of Origin, 1999–2002 Annual Averages

Area of Origin	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Lavatory, bathroom, locker room, or check room	1330	(19%)	0	(0%)	23	(21%)	1	(1%)
Kitchen or cooking area	630	(9%)	0	(0%)	8	(7%)	15	(14%)
Hallway, corridor, or mall	440	(6%)	0	(0%)	2	(1%)	3	(3%)
Small assembly area, less than 100-person capacity	440	(6%)	0	(0%)	11	(10%)	15	(14%)
Confined cooking fire	350	(5%)	0	(0%)	2	(2%)	0	(0%)
Heating equipment room	200	(3%)	0	(0%)	1	(1%)	1	(1%)
Exterior wall surface	160	(2%)	0	(0%)	0	(0%)	2	(2%)
Laundry room or area	150	(2%)	0	(0%)	4	(4%)	1	(1%)
Exterior roof surface	150	(2%)	0	(0%)	2	(1%)	6	(5%)
Attic or ceiling/roof assembly or concealed space	130	(2%)	0	(0%)	2	(2%)	5	(4%)
Storage of supplies or tools or dead storage	130	(2%)	0	(0%)	1	(0%)	5	(5%)
Office	120	(2%)	0	(0%)	3	(3%)	7	(6%)
Unclassified	110	(2%)	0	(0%)	0	(0%)	5	(4%)
Trash or rubbish chute, area, or container	110	(2%)	0	(0%)	2	(1%)	0	(0%)
Bedroom	110	(1%)	1	(100%)	6	(6%)	1	(0%)
Laboratory	100	(1%)	0	(0%)	9	(8%)	2	(2%)
Large open room without fixed seats	90	(1%)	0	(0%)	1	(0%)	2	(2%)
Machinery room or area or elevator machinery room	80	(1%)	0	(0%)	1	(1%)	1	(1%)
Wall assembly or concealed space	80	(1%)	0	(0%)	1	(1%)	1	(1%)
Closet	70	(1%)	0	(0%)	1	(0%)	0	(0%)
Interior stairway or ramp	70	(1%)	0	(0%)	0	(0%)	0	(0%)
Unclassified storage area	70	(1%)	0	(0%)	1	(1%)	1	(1%)
Dining room, bar or beverage area, cafeteria	70	(1%)	0	(0%)	1	(1%)	1	(1%)
Common room, living room, family room, lounge, or den	70	(1%)	0	(0%)	0	(0%)	1	(1%)
Lobby or entrance way	70	(1%)	0	(0%)	1	(0%)	0	(0%)
Confined fuel burner or boiler fire	70	(1%)	0	(0%)	0	(0%)	0	(0%)
Large assembly area with fixed seats	60	(1%)	0	(0%)	0	(0%)	4	(4%)
Unclassified technical processing area	60	(1%)	0	(0%)	1	(1%)	0	(0%)
Duct for HVAC, cable, exhaust, heating, or air conditioning	60	(1%)	0	(0%)	1	(1%)	1	(1%)
Crawl space or substructure space	50	(1%)	0	(0%)	1	(1%)	0	(0%)
Unclassified equipment or service area	50	(1%)	0	(0%)	1	(1%)	1	(1%)
Ceiling/floor assembly or concealed space	50	(1%)	0	(0%)	0	(0%)	1	(0%)
Computer room, control room, or center	50	(1%)	0	(0%)	1	(1%)	4	(4%)
Maintenance or paint shop or area	50	(1%)	0	(0%)	2	(1%)	1	(1%)
Unclassified structural area	40	(1%)	0	(0%)	0	(0%)	1	(1%)
Unclassified function area	40	(1%)	0	(0%)	1	(1%)	1	(1%)
Storage room, area, tank, or bin	40	(1%)	0	(0%)	1	(0%)	3	(2%)
Multiple areas of origin	40	(1%)	0	(0%)	0	(0%)	6	(5%)
Exterior stairway, ramp, or fire escape	40	(1%)	0	(0%)	1	(1%)	0	(0%)
Switchgear area or transformer vault	40	(1%)	0	(0%)	8	(7%)	1	(1%)
Other known service or equipment area	90	(1%)	0	(0%)	3	(3%)	0	(0%)
Other known outside area	80	(1%)	0	(0%)	0	(0%)	1	(1%)
Other known technical processing area	60	(1%)	0	(0%)	6	(5%)	1	(1%)
Other known assembly or sales area	60	(1%)	0	(0%)	1	(0%)	5	(5%)
Other known area	140	(2%)	0	(0%)	2	(2%)	2	(2%)
Contained trash fire	550	(8%)	0	(0%)	4	(4%)	0	(0%)
Other confined fire	40	(1%)	0	(0%)	0	(0%)	0	(0%)
Total	7070	(100%)	1	(100%)	113	(100%)	112	(100%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation. Nonconfined and noncontained structure fires in which the area of origin was unknown or not reported have been allocated proportionally among fires with known area of origin. Totals may not equal sums due to rounding errors.

Source: *U.S. Fires in Selected Occupancies,* Table 8, National Fire Protection Association, March 2006. Based on NFIRS and NFPA survey.

TABLE 20.12.4 Structure Fires in Educational Properties, by First Item Ignited: 1999–2002 Annual Averages

Item First Ignited	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Rubbish, trash, or waste	870	(12%)	0	(0%)	5	(4%)	3	(3%)
Unclassified	600	(9%)	0	(0%)	11	(10%)	9	(8%)
Electrical wire or cable insulation	600	(8%)	0	(0%)	15	(13%)	5	(5%)
Magazine, newspaper, or writing paper	570	(8%)	0	(0%)	3	(3%)	2	(2%)
Contained trash or rubbish fire	550	(8%)	0	(0%)	4	(4%)	0	(0%)
Cooking materials, including food	440	(6%)	0	(0%)	3	(3%)	1	(1%)
Confined cooking fire	350	(5%)	0	(0%)	2	(2%)	0	(0%)
Flammable or combustible liquid or gas, filter, or piping	190	(3%)	0	(0%)	11	(10%)	12	(11%)
Structural member or framing	180	(3%)	0	(0%)	1	(1%)	10	(9%)
Unclassified storage supplies	180	(2%)	0	(0%)	6	(5%)	1	(1%)
Multiple items first ignited	170	(2%)	0	(0%)	1	(1%)	17	(15%)
Rolled or wound material	170	(2%)	0	(0%)	8	(7%)	1	(1%)
Box, carton, bag, basket, or barrel	160	(2%)	0	(0%)	1	(1%)	1	(1%)
Clothing	150	(2%)	0	(0%)	4	(4%)	1	(1%)
Exterior roof covering or finish	130	(2%)	0	(0%)	2	(2%)	6	(5%)
Household utensils	120	(2%)	0	(0%)	4	(3%)	1	(1%)
Exterior wall covering or finish	110	(2%)	0	(0%)	1	(1%)	3	(3%)
Linen other than bedding	100	(1%)	0	(0%)	1	(1%)	2	(2%)
Appliance housing or casing	90	(1%)	0	(0%)	8	(7%)	1	(1%)
Interior wall covering, excluding drapes	80	(1%)	0	(0%)	1	(1%)	2	(2%)
Unclassified structural component or finish	80	(1%)	0	(0%)	2	(2%)	2	(2%)
Insulation within structural area	80	(1%)	0	(0%)	0	(0%)	2	(2%)
Dust, fiber, lint, sawdust, or excelsior	70	(1%)	0	(0%)	3	(3%)	0	(0%)
Confined fuel burner or boiler fire or malfunction	70	(1%)	0	(0%)	0	(0%)	0	(0%)
Cabinetry, including built-in	60	(1%)	0	(0%)	3	(3%)	3	(3%)
Book	60	(1%)	0	(0%)	1	(1%)	1	(1%)
Floor covering, rug, carpet, or mat	60	(1%)	0	(0%)	0	(0%)	0	(0%)
Transformer or transformer fluids	60	(1%)	0	(0%)	1	(1%)	0	(0%)
Interior ceiling cover or finish	50	(1%)	0	(0%)	0	(0%)	2	(2%)
Unclassified adornment, recreational material, or sign	50	(1%)	0	(0%)	1	(1%)	0	(0%)
Unclassified furniture or utensils	50	(1%)	0	(0%)	1	(1%)	1	(1%)
Upholstered furniture or vehicle seat	40	(1%)	0	(0%)	0	(0%)	1	(1%)
Exterior trim, including doors	40	(1%)	0	(0%)	0	(0%)	0	(0%)
Unclassified soft goods or wearing apparel	40	(1%)	0	(0%)	1	(1%)	0	(0%)
Mattress or bedding	40	(1%)	1	(100%)	4	(3%)	0	(0%)
Decoration	40	(1%)	0	(0%)	0	(0%)	0	(0%)
Agricultural crop, including fruits and vegetables	40	(1%)	0	(0%)	1	(1%)	0	(0%)
Other known item	280	(4%)	0	(0%)	7	(6%)	19	(17%)
Other confined fire	40	(1%)	0	(0%)	0	(0%)	0	(0%)
Total	7070	(100%)	1	(100%)	113	(100%)	112	(100%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation. Nonconfined and noncontained structure fires in which the area of origin was unknown or not reported have been allocated proportionally among fires with known area of origin. Totals may not equal sums due to rounding errors.

Source: *U.S. Fires in Selected Occupancies,* Table 9, National Fire Protection Association, March 2006. Based on NFIRS and NFPA survey.

TABLE 20.12.5 Automatic Suppression Systems in Educational Property Structure Fires Reported to Public Fire Departments: 1994–1998 Annual Averages

Percentage of fires in buildings with automatic suppression system	24%
Average loss per fire when automatic suppression system was present	$2800
Average loss per fire with no automatic suppression system	$12,900
Reduction in loss per fire when automatic suppression systems were present	78%

Note: Because a code for undetermined system presence was not included in Version 5.0 of NFIRS until 2004, data on number of fires and fire loss rates cannot be confidently updated.

Source: National estimates based on NFIRS and NFPA survey.

stairs or evacuate effectively in an emergency. Because there is a potential for younger children to be overrun by older students and adults on stairs, most codes require that preschool, kindergarten, and first-grade students be located on a level of exit discharge to facilitate egress. Second-grade students are usually limited to one level above a level of exit discharge in recognition of their limited movement ability. NFPA *101* and *NFPA 5000* permit students younger than the third grade to use rooms or areas located on floor levels higher than the first or second level where provided with independent means of egress dedicated for use by the younger children. The codes recognize that these younger students, with the help of teachers and staff, can use stairs and ramps effectively if they do not have to compete with older, larger, and faster students.

DESIGN CONSIDERATIONS

Schools of only one story, with each room having a direct exit to the outside, represent the most conservative design for life safety. However, economics, site restrictions, or programmatic requirements often dictate other design considerations that can be accommodated and made safe by adhering to certain design principles noted elsewhere within this chapter, in NFPA *101,* and in *NFPA 5000.*

The need to accommodate physically and mentally challenged students within the general school population also affects school designs. Access and egress must be considered for these students by providing facilities such as elevators, ramps, horizontal exits, and areas of refuge in multiple-story buildings. Provisions must be made for using elevators or other special facilities to shelter and evacuate these students. It is important that local fire departments be aware of any special arrangements for evacuating physically disabled students and preplan for such scenarios, as their approach to rescue efforts might be affected by such arrangements.

Flexible and Open Plan Designs

Flexible and open plan design concepts used in some schools differ from conventional designs in that the walls may be demountable or easily moved without major reconstruction efforts. The ability to easily rearrange walls to suit changing programmatic or educational needs is valuable, but proper consideration to egress requirements and fire safety must be included in the planning process.

Open plan buildings delineate spaces and corridors by using movable fixtures and low-height partitions (usually maximum height of 5 ft [1.5 m]). Although this design provides greater flexibility, it diminishes the building's overall fire safety level by omitting features that could confine fire and smoke to a single, smaller compartment long enough to permit orderly evacuation. The compensating factor is the occupants' ability to observe the entire area over the low-height partitions and presumably detect any fire in its incipient stage. Because occupants are presumably awake and alert, their natural faculties can serve as fire and smoke detectors. Such early detection should make prompt evacuation and emergency forces notification possible.

Flexible and open plan buildings should be evaluated while all folding walls are extended and in use, as well as when they are in the retracted position. Flexible and open plan buildings shall also be permitted to periodically rearrange their walls and partitions if revised plans have been thoroughly reviewed and approved by the authority having jurisdiction.

Day-Care Occupancies

Requirements for educational occupancies are not applicable to most child, adult, or home day-care occupancies. As occupants of day-care facilities may not always be considered as being capable of self-preservation actions, a higher level of active and passive life safety measures is often prescribed for day-care occupancies. For more information on child, adult, and home day-care occupancies, see Section 20, Chapter 13, "Day-Care Occupancies."

College and Universities

Requirements for educational occupancies are not applicable to colleges, universities, postsecondary trade schools, or other forms of education beyond grade 12. Students at these levels are generally presumed to be capable of adult behavior because of their age and maturity levels. For more information on colleges and universities, see Section 20, Chapter 3, "Hotels and University Housing," and Section 20, Chapter 11, "Business Occupancies."

OCCUPANCY HAZARDS

Multiple Occupancies

Often more than one type of occupancy exists within or adjacent to an educational facility. Typical scenarios often include assembly and business occupancies as well as dormitories.

In multiple-occupancy situations where the occupancies are mixed as described in NFPA *101* and *NFPA 5000,* care must be taken to ensure that the fire and life safety provisions for all occupancies are met. It is important to provide sufficient protection to prevent the educational occupancy from being exposed to

any hazards associated with other occupancies located within or adjacent to the educational facility.

Hazardous Areas and Arrangements

Areas such as laboratories, shops, kitchens, storage areas, janitor closets, laundries, mechanical rooms, and stages may often be separated from educational occupancies or otherwise protected. Usually, fire-rated walls and doors provide the necessary degree of protection unless the hazard is severe, in which case, automatic suppression systems may also be required. Kitchens should also be protected in accordance with NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations.*

Clothing, personal effects, and other combustible materials should not be stored in corridors. However, if automatic smoke detection or suppression systems protect the corridors, or if metal lockers are used, clothing and personal effects can be stored in corridors. Metal lockers should not, however, reduce the required egress width.

Child-prepared artwork and teaching materials attached directly to walls should not cover more than 20 percent of the wall area in nonsprinklered buildings or more than 50 percent of the wall area in sprinklered buildings. It is advantageous to not only limit the quantity of artwork and teaching materials displayed but also to avoid placing such materials near a room's exit access doors. Because the artwork's combustibility cannot be effectively controlled, the quantity, in terms of the percentage of the overall wall area covered, is regulated to avoid creating a continuous combustible surface that will spread flames across the room. Hanging banners in rooms and corridors should also be avoided unless they meet the requirements for flame resistance as prescribed in NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films.* Because banners can frequently obstruct exit signs, emergency lights, and sprinklers, consideration should be given to problems associated with hanging such banners before allowing their use.

LIFE SAFETY CONCEPTS

Occupant Load

The occupant load, in terms of the number of persons for whom means of egress provisions are to be provided, is typically determined on the basis of the occupant load factors prescribed by NFPA *101* and *NFPA 5000*. The occupant load factors utilized should take into consideration the characteristics or actual use of the space being analyzed. NFPA *101* and *NFPA 5000* prescribe an occupant load factor of 20 net ft^2 (1.9 net m^2) per person for typical classrooms in educational occupancies. Shops, laboratories, and vocational rooms should utilize an occupant load factor of 50 net ft^2 (4.6 net m^2) per person. Areas for assembly uses and spaces utilized for business, storage, kitchens, and so on should utilize the occupant load factors appropriate to that specific function.

Means of Egress

There are no substitutes for properly designed and protected exit access paths, exits, and exit discharges. The total capacity of the means of egress for any story, level, or occupied area must be sufficient for the occupant load thereof. Travel distance requirements and dead-end restrictions are especially important in educational occupancies because of the age and nature of the occupants. Every room or space larger than 1000 ft^2 (93 m^2), or with an occupant load of more than 50 persons, must be provided with a minimum of two exit access doors. It is also important that no less than two separate and remote exits be provided and made accessible on every story, level, or mezzanine.

Proper exit and vertical opening enclosures are important to prevent smoke and heat contamination. Precautions must also be taken to prevent corridors from becoming untenable. The use of fire-rated corridor construction, generally with a fire resistance rating of 1 hour, is common practice in nonsprinklered educational occupancies. If the corridor ceiling is an assembly that has a 1-hour fire resistance rating (when tested as a wall), the corridor walls are normally permitted to terminate at the corridor ceiling. NFPA *101* and *NFPA 5000* do not require lavatories to be separated from corridors in educational occupancies, provided the building is protected throughout by an approved, supervised automatic sprinkler system, or the lavatories are separated from all other spaces by walls having a fire resistance rating of not less than 1 hour as shown in Figure 20.12.1. Proper door controls are also necessary to protect corridors, exits, and vertical openings. Although many codes require self-closing doors in these locations, operational necessities make them impractical in many schools. Therefore, integrated magnetic door hold-open devices and staff training are necessary to ensure doors are properly closed at the appropriate times, such as during emergency evacuation scenarios.

Additionally, exit access corridors may not be not less than 6 ft (1830 mm) wide, regardless of the required egress capacity. The intent of the 6 ft (1830 mm) corridor is to permit two files of students to move simultaneously with sufficient room for teachers or monitors to supervise. Short corridors serving only one or two rooms might warrant consideration for some reduction in required width. NFPA *101* and *NFPA 5000* are very exacting about limiting projections, such as drinking fountains, furniture, or lockers into these corridors.

Windows for Rescue

NFPA *101* and *NFPA 5000* require the installation of specially sized windows for fire department use for rescue (Figure

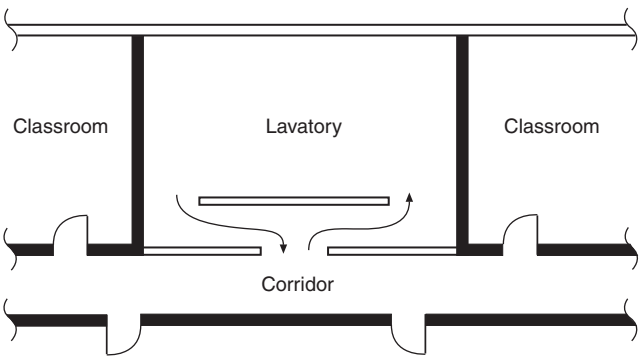

FIGURE 20.12.1 Lavatory Permitted to Be Open to Corridor

20.12.2). One such window is required in any room larger than 250 ft^2 (23.2 m^2) that is normally subject to occupancy by students, unless the building is protected by a supervised automatic sprinkler system. The minimum dimension requirement allows students to escape through the window and fire fighters wearing self-contained breathing apparatus to enter the room for rescue or fire suppression purposes. These windows must be accessible to fire department personnel but are not required on floors above the third story as fire department ground ladders cannot reliably reach these windows. Such taller structures are often protected throughout with automatic sprinklers, which eliminate the need for rescue windows. The requirement for such rescue windows does not apply to any room or space that has a door leading directly to the outside of the building.

Exit Hardware

All exit facilities should be inspected on a daily basis to ensure that they remain unobstructed and function properly. As we become increasingly attuned to safety and security considerations, additional care must be taken with respect to access-control devices and special locking arrangements. Any such locking devices must be approved by the authority having jurisdiction, listed for their intended use, and integrated with the overall life safety and fire protection plan for the building. In no instance are chains or padlocks permitted on exit doors when the building is occupied. If such security devices are used when the building is unoccupied, provisions for their removal must be made to the satisfaction of the local authorities. Any condition likely to interfere with safe egress should be reported to the proper authorities and corrected immediately.

In new educational occupancies, any door in a required means of egress from an area having an occupant load of 100 or more persons is permitted to be provided with a latch or lock only if it is outfitted with approved panic hardware or fire exit hardware. In existing educational occupancies, panic hardware or fire exit hardware is only mandated on required exit doors that are capable of locking or latching if the door's required egress capacity is 100 or more persons.

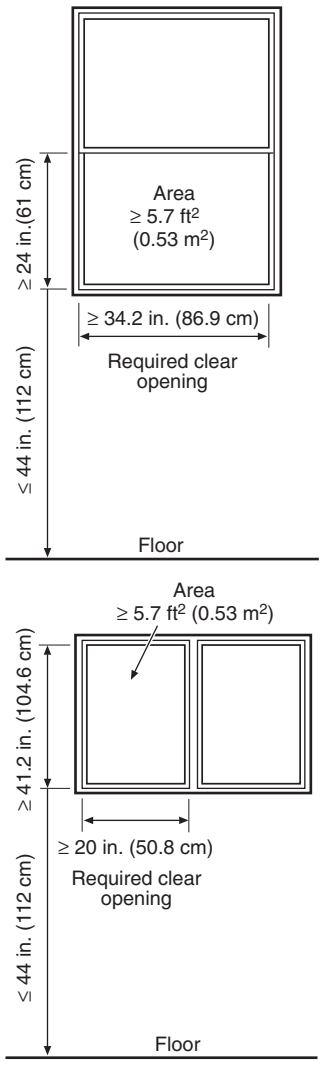

FIGURE 20.12.2 Minimum Dimensional Criteria for Rescue and Ventilation

Means of Egress Illumination and Marking

The means of egress must be properly illuminated any time that the conditions of occupancy require that the means of egress be available for use. Stairways should be provided with a minimum illumination level of 10 ft-candle (108 lux) when measured at the floor. Other walking surfaces along the means of egress route should be provided with a minimum illumination level of 1 ft-candle (10.8 lux) when measured at the floor. Suitable emergency lighting provisions must be provided to automatically illuminate the means of egress system in the event of any interruptions to the normal electrical power supply or building lighting circuitry. Exits should be marked with approved signs that are readily visible from any direction of exit access travel. The access paths leading to the exits should also be marked with approved signage where the route to reach the exit is not readily apparent to the occupants.

Alarm Systems

In general, schools require a manual fire alarm system as a minimum. Because of vandalism, fire alarm systems have sometimes been inappropriately turned off or otherwise disabled in order to prevent malicious or false alarms from disrupting the learning process. Recent changes in some codes permit the deletion of manual fire alarm boxes if the building is protected throughout by an approved automatic fire detection system or supervised automatic sprinkler system, and there is a continuously staffed central location where an evacuation signal can be manually activated. Emergency forces notification must also be provided to alert the fire department of any fire or other hazardous condition.

In school structures not over 1000 ft^2 (93 m^2) and that contain only a single classroom, fire alarm systems are not usually required. As with flexible and open plan design areas, the entire area can be readily observed and, therefore, a fire would likely be easily detected in its incipient state. A minimum separation distance of 30 ft (9.2 m) between the single classroom building and any other structure should be maintained.

Emergency Plans and Fire Exit Drills

Operators of educational occupancies should develop emergency plans in conjunction with the local fire department. The emergency plans should reflect procedures for the reporting of emergencies as well as the occupant and staff response to such emergencies. The local fire department needs to be made aware of the school's plan regarding evacuation of any students with disabilities or staff who might be incapable of self-preservation. Areas of refuge (as required by NFPA *101, NFPA 5000,* or other accessibility laws) should be easily identifiable from the exterior so that fire department personnel can readily access these areas. Emergency plans should be reviewed and updated periodically to reflect any new information or changes in condition.

Frequent fire exit drills are critical in achieving the proper response by occupants during an emergency. Fire exit drills should include the assignment of staff or more mature students to hold doors open in the line of march and to close doors where necessary to prevent the spread of fire or smoke; to search lavatories or other ancillary rooms; to properly account for all occupants; and to achieve a prompt, quiet, and orderly evacuation of the building or relocation to designated areas of refuge. Occupants should not be allowed to retrieve clothing or book bags after the alarm sounds due to the confusion that would result in forming lines, student accountability, and the danger of tripping over dragging apparel.

Fire exit drills should be held not less than once per month when the building is open for occupancy. In climates where winter weather is severe, additional drills should be run before bad weather starts. Everyone within the building should participate in such drills as this ensures that all staff and students understand the fire exit drill procedure. Drills should be unannounced and held at different hours of the day, during changing of classes, when the school is at assembly, and during recess or gym periods. As drills simulate an actual fire or emergency condition, the fire alarm signaling devices should be used so that occupants recognize the signal and respond appropriately. A separate and distinct recall signal should be developed to prevent a premature return to the building. Repetitive training in fire drills will also benefit the student later in life or when he or she is within another occupancy type.

Unfortunately, several high-profile school tragedies have given school officials pause with respect to conducting traditional fire exit drills. Schools should not be dissuaded from conducting these vital drills since delayed egress can lead to tragic consequences. However, some adjustments to previously established emergency evacuation and relocation drills may be advisable. One such alteration may be to involve law enforcement agents to supplement the role traditionally played by the fire service. School-based personnel may also be assigned to scan the school grounds and create a safety perimeter until the proper recall signal is sounded. Where building geometries and fire-resistive design features permit, consideration may also be given to utilizing horizontal exiting strategies and phased emergency evacuation scenarios to relocate students to predetermined safe locations in lieu of evacuating in the traditional sense. It is critical that any such adjustments be documented in the building's emergency plan, practiced frequently, and communicated to the appropriate first responders.

SUMMARY

Because of the nature of their occupants, educational facilities require specific life safety considerations. Educational occupancies can generally be characterized as public, private, and parochial schools for students from kindergarten through grade 12. Examples of educational occupancies include conventional schools, academies, kindergartens, and other facilities whose purpose is primarily educational, even though their students may be of preschool age. Fire protection measures should focus on building design principles, means of egress provisions, exit hardware, fire alarm systems, and emergency planning, staff training, and exit drills. Fire protection strategies must take into consideration the fact that the occupants may vary in their ability to cope with emergency situations. Hazardous areas such as laboratories, shops, kitchens, storage areas, janitor closets, laundries, mechanical rooms, and stages must often be separated from educational occupancies by fire-resistant construction or otherwise protected. In addition, special care must be taken to avoid hazardous arrangements such as the improper storage of clothing and the display of child artwork. In multiple-occupancy situations where the occupancies are mixed, care must be taken to ensure that the fire and life safety provisions for all occupancies are met.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on educational occupancies discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals*
NFPA 54, *National Fuel Gas Code*
NFPA 72®, *National Fire Alarm Code®*
NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations*
NFPA *101®*, *Life Safety Code®*
NFPA 101A, *Guide on Alternative Approaches to Life Safety*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*
NFPA 5000®, *Building Construction and Safety Code®*

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Chapter 13

Day-Care Occupancies

Catherine L. Stashak

Chapter Contents

Occupant Characteristics
Construction Requirements
Occupancy Hazards
Life Safety Concepts
Day-Care Homes

Key Terms

capable of self-preservation, day-care home, day-care occupancy, hazardous area, lockup, means of egress, occupant characteristics

This chapter addresses day-care occupancies, which are generally defined as structures in which four or more clients receive care, maintenance, and supervision, by other than their relatives or legal guardians for less than 24 hours per day. This chapter describes the nature of day-care occupants as well as the hazards and life safety concepts pursuant to the occupancy.

Examples of day-care occupancies include adult day-care occupancies, except where part of a health care occupancy; child day-care occupancies; day-care homes; and nursery schools. In areas where local schools offer half-day kindergarten programs only, many child day-care occupancies offer state-approved kindergarten classes for children who need full-day care. As these classes are normally incidental to the day-care occupancy, the requirements applicable to the day-care occupancy should be followed. The definition of day-care occupancy also excludes day-care occupancies that are incidental to some other occupancy. In such cases, the requirements of the predominant occupancy apply. Examples of excluded facilities include the following:

- Rooms located within places of worship used as nurseries or for supervision of children or religious education while services are being held in the building
- Rooms used for temporary child care during short-term recreational activities of the child's relative or guardian, such as within a health club

Table 20.13.1 summarizes structure fire loss in day-care occupancies.

See also Section 5, Chapter 5, "Reaching High-Risk Groups"; and Section 20, Chapter 1, "Assessing Life Safety in Buildings."

OCCUPANT CHARACTERISTICS

Day-care facilities have traditionally been associated with child care and have thus been historically considered as educational occupancies. Changes in society have indicated a need to expand the definition of day-care facilities to include facilities that care for older people. Because physical limitations that apply to children can also apply to older adults, this approach seems logical from fire protection and life safety standpoints. Design criteria for these facilities should focus less on age-group classifications and more on clients' ability to evacuate and staff members' ability to evacuate clients.

Capability of Self-Preservation

NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®, use the term *capable of self-preservation,* which is defined as the ability of a client to evacuate a day-care occupancy without direct intervention by a staff member, in the chapters that address day-care occupancies. It is the intent of NFPA *101* and *NFPA 5000* to classify children under the age of 24 months as incapable of self-preservation. Children older than 24 months should be capable of navigating stairs without dropping to their knees and will also follow directions. Other examples of incapability of self-preservation for children and adults might be confinement to a wheelchair

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TABLE 20.13.1 Structure Fires in Day-Care Occupancies, 1999–2002 Annual Averages

Occupancy	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
Day-care	440	0	4	4

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires are rounded to the nearest ten, deaths and injuries to the nearest one, and direct property damage to the nearest million dollars. Damage has not been adjusted for inflation.

Source: *U.S. Fires in Selected Occupancies,* March 2006. National estimates based on NFIRS and NFPA survey.

or other physical disability and clients who are unable to follow directions or a group to the outside due to mental or behavioral disorders. Examples of direct intervention by staff members include carrying a client, pushing a client in a wheelchair, and guiding a client by direct hand-holding or continued bodily contact. Another common method of evacuation used with infants is to place several infants in one crib and roll the crib out of the facility. If clients are unable to exit the building by themselves, with minimal intervention from staff members, such as verbal orders, classification as incapable of self-preservation should be considered. Client mobility is an important consideration in developing life safety requirements.

It should be recognized that some day-care facilities operate 24 hours per day to care for dependents of people who work at night. These facilities present the greatest hazard because their occupants will most likely be asleep when a fire starts. Therefore, day-care facilities that operate at night require special considerations. No matter what time of day, day-care staff members are required to be awake and alert at all times; however during a nap period it is possible that some staff may be asleep when an emergency occurs.

Lockups

It is possible that a day-care facility might have an area where clients are restrained, and such occupants are considered as incapable of self-preservation because of security measures not under the occupant's control. If this arrangement exists, these areas must comply with the requirements for lockups in NFPA *101* and *NFPA 5000*, which are located in the chapters that address detention and correctional occupancies.

CONSTRUCTION REQUIREMENTS

NFPA *101* prescribes location and construction type limitations for both new and existing day-care occupancies. The types of construction listed in Tables 20.13.2 and 20.13.3 are defined in NFPA 220, *Standard on Types of Building Construction,* and *NFPA 5000*. The types of construction permitted by the code depend on the location of the day-care occupancy in the building relative to the level of exit discharge (LED).

TABLE 20.13.2 Location and Construction Type Limitations for New Day-Care Occupancies

Location of Day-Care Occupancy	*Sprinklered Building*	*Construction Type*
1 story below LED	Yes	I (442), I (332), II (222), II (111), II (000), III (211), IV (2HH), V (111)
	No	NP
Level of exit discharge	Yes	Any type
	No	Any type
1 story above LED	Yes	Any type
	No	I (442), I (332), II (222)
2 or 3 stories above LED	Yes	I (442), I (332), II (222), II (111), II (000), III (211), V (111)
	No	NP
More than 3 stories above LED but not high-rise	Yes	I (442), I (332), II (222), II (111)
	No	NP
High-rise	Yes	I (442), I (332), or II (222)
	No	NP

LED = Level of exit discharge.
NP = Not permitted.

Source: NFPA *101,* 2006 edition, Table 16.1.6.1.

OCCUPANCY HAZARDS

Multiple Occupancy

Sometimes more than one type of occupancy exists in conjunction with a day-care facility. Where a day-care facility serves not more than 12 clients in an apartment building, it could be considered a day-care home; a corporate day-care center that serves more than 12 clients could be located within an office building, which is classified as a business occupancy. Where multiple occupancies are mixed, as described in NFPA *101* and *NFPA 5000*, care must be taken to ensure that the fire and life safety provisions for all occupancies are met. It is important to provide sufficient protection to prevent the day-care occupancy from being exposed to hazards of other occupancies in the structure. To be considered separate occupancies, the day-care occupancy must be separated from the other uses by fire barriers, and the occupancies must be provided with independent exit access.

TABLE 20.13.3 Location and Construction Type Limitations for Existing Day-Care Occupancies

Location of Day-Care Occupancy	*Sprinklered Building*	*Construction Type*
1 story below LED	Yes	I (442), I (332), II (222), II (111), II (000), III (211), IV (2HH), V (111)
	No	I (442), I (332), II (222), II (111), III (211), IV (2HH), V (111)
Level of exit discharge	Yes	Any type
	No	Any type
1 story above LED	Yes	Any type
	No	I (442), I (332), II (222)
	No	II (111)*, III (211)*, V (111)*
2 or 3 stories above LED	Yes	I (442), I (332), II (222)
	Yes	II (111)*, III (211)*, V (111)*
	No	I (442), I (332), II (222)
At or above 3 stories above LED but not high-rise	Yes	I (442), I (332), II (222)
	Yes	II (111)*
	No	I (442), I (332), II (222)
High-rise	Yes	I (442), I (332), II (222)
	No	NP

LED = Level of exit discharge.
NP = Not permitted.
*Permitted only if clients are capable of self-preservation.
Source: NFPA *101,* 2006 edition, Table 17.1.1.

Hazardous Areas and Arrangements

Areas such as storage areas and boiler and furnace rooms must be separated from day-care occupancies. Usually, fire-rated walls and doors provide the necessary degree of protection unless the hazard is severe, in which case automatic suppression systems may also be required. In some cases, the fire resistance rating is eliminated if the building is protected throughout with automatic sprinklers.

Clothing, personal effects and other combustible materials should not be stored in corridors. If automatic detection or suppression systems are provided in the corridors, or if metal lockers are used, clothing and personal effects can be stored in corridors. Metal lockers should not, however, reduce the required egress width.

Child-prepared artwork and teaching materials attached directly to walls should not cover more than 20 percent of the wall area in a building that is not protected throughout by an approved, supervised automatic sprinkler system. In a building that is protected throughout by an approved, supervised automatic sprinkler system, child-prepared artwork and teaching materials attached directly to walls should not cover more than 50 percent of the wall. It is advantageous not only to limit the quantity of child-prepared materials displayed but also to avoid placing such materials near a room's exit access doors. Because the artwork's combustibility cannot be effectively controlled, the quantity, in terms of percentage of the overall wall area covered, is regulated to avoid creating a continuous combustible surface that will allow flames to spread across the room.

Draperies, curtains, hanging banners, and other similar furnishings and decorations should meet the requirements for flame resistance when tested per NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films.* Care should be taken when installing hanging banners so that exit signs and automatic sprinklers are not obstructed.

LIFE SAFETY CONCEPTS

Means of Egress

There are no substitutes for properly designed exit access paths, exits, and exit discharges. Travel distance requirements and dead-end limits are especially important in day-care occupancies because of the nature of the occupants and the slower rate at which evacuation is completed. Proper exit enclosures are important to prevent contamination by smoke and heat. Means of egress requirements for day-care occupancies do not differ much from those for educational occupancies, except that 6 ft (1.8 m) corridors, which are required in educational occupancies, are not required in day-care occupancies.

NFPA *101* and *NFPA 5000* require the installation of specially sized windows for fire department use for rescue as shown in Figure 20.13.1. One such window is required in any room normally subject to client occupancy, other than bathrooms. These windows are not required if the building is protected by a supervised automatic sprinkler system or if the room or space has a door leading directly to the outside of the building or on floors above the third story. The minimum dimension requirement allows clients to escape through the window and fire fighters wearing self-contained breathing apparatus to enter the room for rescue or fire suppression purposes. These windows must be accessible to fire department personnel, so they are not required on floors above the third story as fire department ground ladders do not normally reach such windows.

Although the ability of staff to assist and participate in evacuation is part of the life safety package for day-care occupancies,

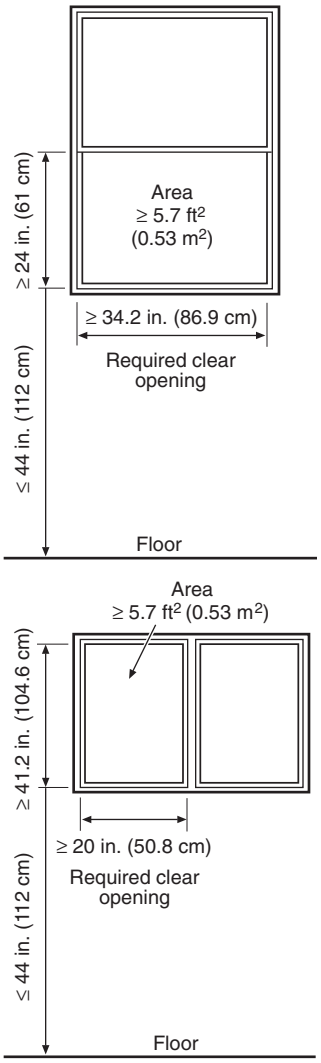

FIGURE 20.13.1 Minimum Dimensional Criteria for Rescue and Ventilation

neither NFPA *101* nor *NFPA 5000* mandates staff-to-client ratios because, from the standpoint of the local authority, ratios are very difficult to enforce. Most state licensing requirements include staff-to-client ratios; additional requirements are considered duplicate effort.

Precautions must be taken to prevent corridors from becoming untenable. The use of fire-rated corridor construction, generally with a rating of one hour, is common practice. If the corridor ceiling is an assembly that also has a 1-hour fire resistance rating (when tested as a wall assembly), the corridor walls are normally permitted to terminate at the corridor ceiling. This requirement is reduced if the building is protected throughout with automatic sprinklers or if rooms occupied by clients have a direct exit to the outside. Neither NFPA *101* nor *NFPA 5000* requires lavatories to be separated from corridors, provided the lavatories are separated from all other spaces by walls having a fire resistance of not less than one hour as shown in Figure 20.13.2.

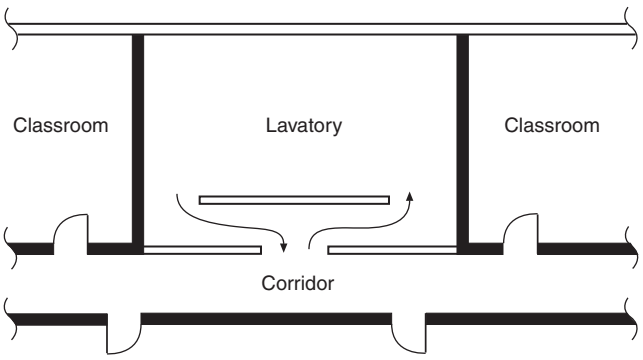

FIGURE 20.13.2 Lavatory Permitted to Be Open to Corridor

Exit Hardware

Any door within a required means of egress from an area having an occupant load of 100 or more should have panic hardware or fire exit hardware if equipped with a lock or latch. It should be noted that the requirement for panic hardware or fire exit hardware is based on the total occupant load of the area served and not the required capacity of the door. In no instance are chains or padlocks permitted on egress doors when the building is occupied.

Closet and Bathroom Doors

Closet Doors. Closet doors should be designed so that clients can open the door from inside the closet. The purpose of this requirement is to prevent arrangements where a client can be trapped in a closet. It is intended that this provision be broadly interpreted to include equipment such as refrigerators and freezers.

Bathroom Doors. Bathroom doors should be designed to allow the door to be unlocked from the outside by an opening device that is readily accessible to the staff. The purpose of this requirement is to permit access to a client in the bathroom should they become injured or sick.

Fire Alarm Systems

Fire alarm requirements for day-care occupancies are more stringent than those for most occupancies because it takes longer for day-care clients to evacuate—they could be asleep or they could be incapable of self-preservation. In day-care centers housed in more than one room, smoke detection is required so as to provide early warning for clients and staff not located in the room of fire origin. This early notification is especially important in centers that have clients incapable of self-preservation or clients that are asleep.

In day-care centers that are housed in one room, fire alarm systems are not usually required. The entire area can be observed; therefore, a fire can be easily detected in its incipient stage. An important part of a day-care occupancy's life safety plan is notification of the local fire department. The sooner fire department personnel arrive on the scene, the sooner they can assist with evacuation of clients.

Staff Training and Emergency Egress and Relocation Drills

Day-care occupancies should develop emergency plans in conjunction with the local fire department. The local fire department needs to be made aware of the day-care facility's plan regarding evacuation of clients who are incapable of self-preservation. Areas of refuge, as required by NFPA *101, NFPA 5000*, or any other accessibility laws, need to be identifiable from the exterior so fire department personnel can readily access these areas.

Frequent fire exit drills are critical in achieving proper response by occupants during an emergency. Fire exit drills should include assignment of staff to close doors where necessary to prevent spread of fire or smoke; to search the lavatories or other rooms; to account for all occupants; and to achieve a prompt, quiet, and orderly evacuation of the building or relocation to areas of refuge. Fire exit drills should be held not less than once per month when the building is open for occupancy. In climates where winter weather is severe, most drills should be run before bad weather starts. This ensures that staff and clients understand fire exit drill procedures.

Drills should be held at expected and unexpected times and at varying times that the day-care center is open, including during outdoor play time and even during nap periods. As drills simulate an actual fire condition, the fire alarm signaling devices should be activated so that occupants recognize the signal and respond appropriately. Repetitive training in fire drills will benefit the client when he or she is within another occupancy type. When a fire alarm is activated within the other occupancy, the day-care client should recognize the signal and respond appropriately.

DAY-CARE HOMES

Day-Care Home Defined

NFPA *101* and *NFPA 5000* provide requirements for smaller day-care occupancies. A *day-care home* is defined as a day-care occupancy that has not more than 12 clients. Day-care homes are further subdivided into family day-care homes that have 4 to 6 clients and group day-care homes that have 7 to 12 clients. NFPA *101* and *NFPA 5000* specify that the caregiver's own children or relatives under the age of six are to be included in the specified staff-to-client ratios for these day-care occupancies. The provisions found in NFPA *101* and *NFPA 5000* recognize that a typical day-care home is usually located in a residential setting. Because of this, it is difficult to mandate fire protection features that are as stringent as in a "full-size" day-care occupancy, such as one serving more than 12 clients.

Means of Escape in Day-Care Homes

In day-care homes, means of escape are permitted as the egress system. The concept of means of escape is well developed in the chapters that address one- and two-family dwellings in NFPA *101* and *NFPA 5000*. However NFPA *101* and *NFPA 5000* require that every room used for sleeping, living, or dining meet the following provisions:

- At least two means of escape must be provided, one of which needs to be a door or stairway providing travel to the outside of the building at street or ground level.
- The second means of escape is permitted to be a window under certain circumstances.
- No room or space that is accessible only by a ladder, folding stair, or through a trapdoor is permitted to be occupied for living or sleeping purposes.
- In group day-care homes, spaces used by clients on any story above the level of exit discharge must have access to at least one means of escape that discharges directly to the outside; the second means of escape can be a window under certain circumstances.
- Spaces used by clients below the level of exit discharge must be provided with not less than one means of escape that discharges directly to the outside, with vertical travel not more than 96 inches to the ground level; the second means of escape can be a window under certain circumstances (Figure 20.13.3).

Staff-to-Client Ratio

It is important that the staff-to-client ratios mandated by NFPA *101* and *NFPA 5000* for day-care homes be followed. Table 20.13.4 addresses the staff-to-client ratios mandated by NFPA *101* and *NFPA 5000* for day-care homes.

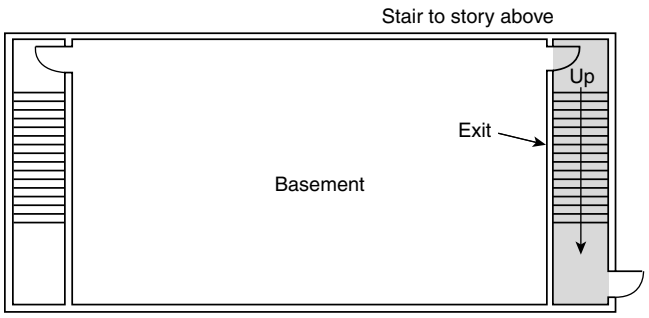

FIGURE 20.13.3 Egress Requirements from Group Day-Care Home Occupying Basement (Source: *Life Safety Code® Handbook,* NFPA, 2006 edition)

TABLE 20.13.4 Required Staff-to-Client Ratios in Day-Care Homes

Day-Care Home Type	*Staff-to-Client Ratios (Including Caregivers' Children)*	*Maximum Number of Clients Incapable of Self-Preservation*
Family day-care homes	1 staff for up to 6 clients	2
Group day-care homes	2 staff for up to 12 clients*	3

*Staff-to-client ratio is permitted to be modified by the authority having jurisdiction (AHJ) where safeguards in addition to those specified by code are provided.

Local authorities may not have knowledge of the full number of day-care homes within their jurisdictions. Parents who wish to earn money while staying home with their own children may simply advertise by word of mouth that they are willing to watch children. No notification may be given to the fire department, which will have to deal with multiple young children when the home is involved in fire. Local authorities may only find out about the day-care home if the owner obtains a license from the state.

SUMMARY

Because of the nature of their occupants, day-care facilities require specific life safety considerations. Day-care occupancies include both child and adult day-care occupancies, day-care homes, and nursery schools. Fire protection measures should focus on building design, means of egress, exit hardware, fire alarm systems, staff training, and emergency egress and relocation drills. The fact that the occupants, whether children, infants, the elderly, or disabled, vary in their abilities to cope with emergency situations should be taken into consideration. Hazardous areas such as janitor's closets, kitchens, storage areas, and furnace rooms should be separated from day-care occupancies or protected with automatic sprinklers. In addition, special care must be taken to avoid hazardous arrangements such as the improper storage of clothing or excessive display of child-prepared artwork.

BIBLIOGRAPHY

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on day-care occupancies discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA *101®*, *Life Safety Code®*
NFPA 220, *Standard on Types of Building Construction*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*
NFPA 5000®, *Building Construction and Safety Code®*

References

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Chapter 14

Detention and Correctional Occupancies

Thomas W. Jaeger

Chapter Contents

Occupancy Characteristics
The Fire Problem in Detention and Correctional Facilities
Systems Approach to Fire Safety in Detention and Correctional Facilities
Lockups

Key Terms

area of refuge, defend-in-place, detection, drills, emergency procedures, evacuation, fire emergency plan, fuel control, ignition control, lockup, occupant protection, suppression

Detention and correctional occupancies include buildings and facilities in which persons are restrained by locks they do not control. Such occupancies include adult correctional institutions, adult local detention facilities, adult community residential centers, juvenile detention facilities, juvenile training schools, juvenile community residential centers, adult and juvenile work camps, and adult and juvenile substance abuse centers. Some psychiatric and acute care hospitals may have similar security provisions, but this chapter addresses only facilities where controlled movements are not based entirely on health care considerations. Security is a major operational consideration in these facilities and must be included in the fire protection design process.

Lockups facilities in occupancies other than detention and correctional facilities are areas where building occupants are restrained for less then 24 hours and occupants are incapable of self preservation because of security measures not under their control. Lockups can be found in courthouses, police stations, international airports, sports arenas and stadiums, shopping malls, and other occupancies where it might be necessary to detain occupants for security purposes. Lockups are now specifically addressed in provisions that are new to the 2006 editions of NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®.

Large correctional facilities may contain other occupancies, including industrial occupancies such as vocational shops; business occupancies such as classrooms and offices; assembly occupancies such as dining halls, auditoriums, and gymnasiums; and storage occupancies such as warehouses. The principal concern of Chapters 22 and 23 of NFPA *101* and Chapter 21 of *NFPA 5000* is the residential portion of correctional facilities. Except for the locking of doors, other uses within the detention and correctional occupancy must comply with the appropriate occupancy chapters of NFPA *101* and *NFPA 5000*. If locking of doors in these occupancies is required, Chapters 22 and 23 of NFPA *101* or Chapter 21 of *NFPA 5000* should be reviewed for guidance. These chapters of NFPA *101* do permit locking of doors in other use areas if staff is available to unlock the egress doors.

Additional information relevant to fire safety in correctional institutions can be found in Section 18, Chapter 2, "Interior Finish"; Section 18, Chapter 3, "Smoke Movement in Buildings"; and the discussion on portable fire extinguishers in Section 17, Chapter 5, "Fire Extinguisher Use and Maintenance."

OCCUPANCY CHARACTERISTICS

The major difference between detention and correctional occupancies and other residential occupancies is that the occupants are not capable of significant self-preservation actions until staff unlocks the doors. However, the occupants are capable of such actions when the doors are unlocked.

The degree of locking can have a significant impact on the risk to the occupants. For example, a facility with only two locks that can be remotely released to allow the occupants out of the building into a controlled exercise yard generally would present less risk to the occupants than

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one that required 15 locks to be unlocked manually with 10 different keys. Although the number of locks and the method of unlocking have an impact on the level of risk to the occupants, operations have even a greater impact. Because of the nature of the occupancy, there is a natural reluctance for staff to quickly unlock doors until adequate staff and security are present. This operational feature results in a delay in initiating the unlocking of doors and initiating evacuation or relocation.

Five types of restraint or locking systems are generally found in detention and correctional occupancies. These different locking conditions, referred to as "Use Conditions" by NFPA *101* and *NFPA 5000,* are illustrated in Figure 20.14.1 and defined below.

Use Condition I—Free Egress

In Use Condition I, free movement is allowed from sleeping areas and other spaces where access or occupancy is permitted to the exterior through means of egress meeting the requirements of NFPA *101* and *NFPA 5000.* For example, a work release center, where the doors are not locked, would be considered Use Condition I. Use Condition I facilities are permitted to comply with the requirements for Use Condition II facilities or with the requirements for the appropriate residential occupancy in NFPA *101* or *NFPA 5000.* Since a Use Condition I facility has no locks on doors in the means of egress, this type of facility can be treated as a residential occupancy.

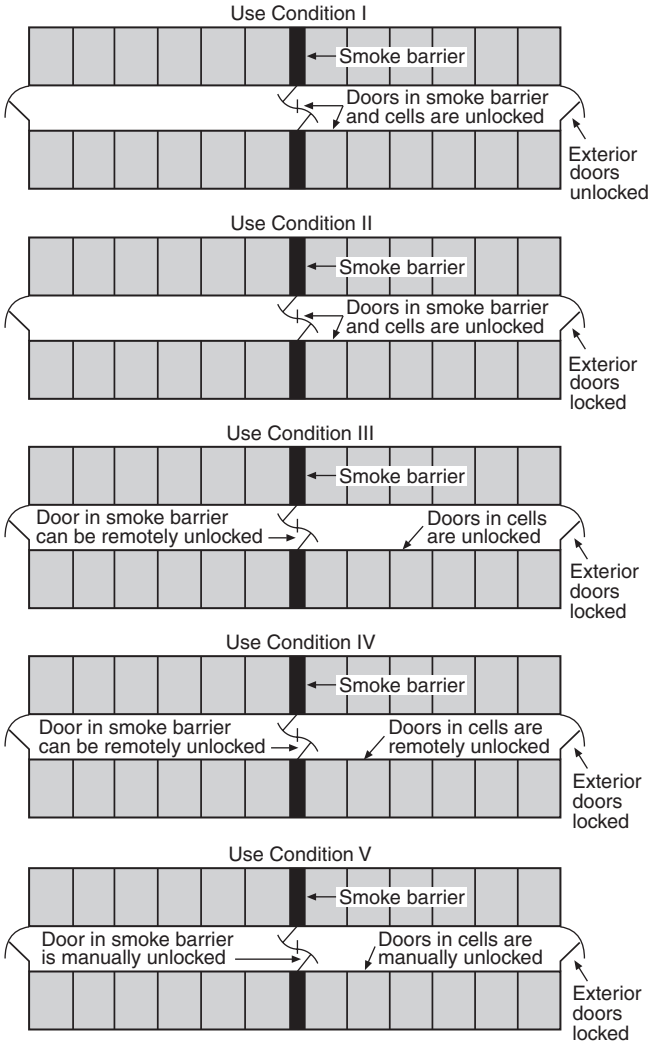

FIGURE 20.14.1 Classes of Restraint: Use Conditions I, II, III, IV, and V

Use Condition II—Zoned Egress

In Use Condition II, free movement is allowed from sleeping areas and any other occupied smoke compartments to other smoke compartments, but the exterior doors are locked.

The individual cell door may be locked from the inside by the occupant and can be unlocked by the occupant. Also, the individual cell door may be locked by the occupant when leaving the cell. This is sometimes done to provide security for the occupants' property while occupants are out of their cells.

Use Condition III—Zoned Impeded Egress

In Use Condition III, free movement is allowed within individual smoke compartments—for example, within a residential unit composed of individual sleeping rooms and within group activity space—with egress from that smoke compartment to another smoke compartment provided by the remote-control unlocking of doors. The exterior doors may be manually locked. Again, the individual cell doors may be locked by the occupant as noted in the Use Condition II section.

Use Condition IV—Impeded Egress

In Use Condition IV, free movement is restricted from an occupied space. Remote-control release is provided to permit movement from all sleeping rooms, activity spaces, and other occupied areas within the smoke compartment to other smoke compartment(s). Exterior doors may be manually locked. NFPA *101* and *NFPA 5000* allow up to a maximum of 10 manual release locks to be unlocked to relocate all occupants from one smoke compartment to an area of refuge for Use Condition IV. Unlocking of the manual release locks cannot require more than two separate keys, and the unlocking must occur as promptly as would occur if remote-control unlocking was used.

Use Condition V—Contained

In Use Condition V, free movement is restricted from an occupied space. Staff-controlled manual release at each door is provided to permit movement from all sleeping rooms, activity spaces, and other occupied areas within the smoke compartment to other smoke compartments.

When evaluating the degree of locking for determination of Use Condition, any operable locks, even those not normally used, need to be considered lockable.

The higher level of security provided, the more demanding the code requirements are for life safety because higher levels

of security result in longer evacuation times, a more difficult population to evacuate, or a combination thereof.

THE FIRE PROBLEM IN DETENTION AND CORRECTIONAL FACILITIES

Each year NFPA statistically analyzes the fire problem in detention and correctional facilities.[1] The expanded version of this analysis, which appears in Tables 20.14.1, 20.14.2, and 20.14.3, identifies the significant common characteristics of correctional facility fires and groups them into several categories.

Most fires in detention and correctional facilities are incendiary or suspicious in nature. Motives can include the following:

- Increased chances of escape
- Malicious damage as a protest against conditions
- Show of force during a riot
- Suicide attempt
- Divert attention from other activities
- Weapon

In nearly all intentionally set fires for which the ignition source could be identified, the source was a match, smoking materials, or a cigarette lighter. These are the ignition sources most readily available to inmates. The typical correctional facility fire is incendiary in origin, starts in a cell, and involves bedding, trash, or papers.

Reported prison and jail fires fell 79 percent from 4180 in 1980 to 860 in 2002. It is encouraging to see that the fire data show both a reduction in the number of fires and the number of civilian deaths in detention and correctional occupancies in recent years even though the population of this occupancy has significantly increased during this same period. It should be pointed out that various detention and correctional agencies

TABLE 20.14.1 Structure Fires in Prisons and Jails by Year, 1980–2004, Structure Fires Reported to U.S. Municipal Fire Departments

Year	*Fires*	*Civilian Deaths*	*Civilian Injuries*	Direct Property Damage (in Millions of Dollars)	
				As Reported	*In 2004 Dollars*
1980	4200	0	190	4.6	10.6
1981	3900	5	420	14.9	30.8
1982	3600	8	210	4.4	8.6
1983	3000	0	260	5.8	11.1
1984	3000	0	140	4.3	7.8
1985	3300	2	80	2.6	4.5
1986	3200	0	110	3.2	5.5
1987	3200	2	70	5.0	8.3
1988	2900	0	180	5.6	8.9
1989	3100	5	210	15.7	23.9
1990	2500	0	140	7.1	10.3
1991	2600	0	210	29.2	40.4
1992	2300	1	150	8.1	10.8
1993	2200	1	190	8.3	10.8
1994	2300	0	200	3.5	4.5
1995	1900	0	70	2.2	2.8
1996	2100	0	70	1.2	1.5
1997	2400	0	50	6.9	8.2
1998	2200	0	50	6.9	7.9
1999*	1900	0	10	5.4	6.1
2000	1500	0	20	1.7	1.8
2001	1200	0	30	11.4	12.1
2002	900	0	20	0.8	0.8
2003	700	0	10	3.1	3.1
2004	700	0	60	1.1	1.1

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, direct property damage is rounded to the nearest hundred thousand dollars, and civilian deaths and injuries are not rounded. Confined fires are analyzed separately.

*From 1999, based on only fires reported in NFIRS Version 5.0.

Source: NFIRS and NFPA survey. Inflation adjustments were based on the consumer price indexes in the U.S. Census Bureau's *Statistical Abstract of the United States: 2006*, Table 705.

TABLE 20.14.2 Structure Fires in Prisons and Jails, by Area of Origin, Annual Average of 2000–2004 U.S. Structure Fires Reported to Municipal Fire Departments*

Area of Origin	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Bedroom	220	(26%)	0	(NA)	16	(58%)	0.8	(22%)
Laundry area	160	(19%)	0	(NA)	4	(16%)	0.5	(14%)
Kitchen	50	(5%)	0	(NA)	0	(2%)	0.0	(1%)
Duct	30	(3%)	0	(NA)	0	(0%)	0.0	(1%)
Unclassified equipment or service area	30	(3%)	0	(NA)	0	(0%)	0.0	(1%)
Unclassified area of origin	30	(3%)	0	(NA)	0	(0%)	0.0	(0%)
Unclassified function area	20	(3%)	0	(NA)	2	(7%)	0.0	(0%)
Office	20	(3%)	0	(NA)	0	(0%)	0.3	(7%)
Bathroom	20	(2%)	0	(NA)	0	(0%)	0.0	(0%)
Corridor	20	(2%)	0	(NA)	1	(2%)	0.0	(0%)
Wall assembly	20	(2%)	0	(NA)	0	(0%)	0.0	(1%)
Cell (intended to be test cell; possibly miscoded)	20	(2%)	0	(NA)	2	(8%)	0.0	(1%)
Attic or crawl space above top story	20	(2%)	0	(NA)	0	(0%)	0.0	(1%)
Lounge, living room, family room, or den	20	(2%)	0	(NA)	0	(0%)	0.2	(5%)
Unclassified service facility	10	(2%)	0	(NA)	0	(0%)	0.0	(0%)
Heating room or area	10	(2%)	0	(NA)	0	(0%)	1.0	(29%)
Exterior roof surface	10	(2%)	0	(NA)	0	(0%)	0.0	(1%)
Maintenance shop or area	10	(1%)	0	(NA)	0	(0%)	0.3	(8%)
Tool or supply storage room or area	10	(1%)	0	(NA)	0	(0%)	0.0	(1%)
Storage room, area, tank, or bin	10	(1%)	0	(NA)	0	(0%)	0.0	(0%)
Exterior wall surface	10	(1%)	0	(NA)	0	(0%)	0.0	(0%)
Entrance way or lobby	10	(1%)	0	(NA)	0	(0%)	0.0	(0%)
Other known area of origin	120	(14%)	0	(NA)	2	(7%)	0.2	(7%)
Total	860	(100%)	0	(NA)	27	(100%)	3.6	(100%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, direct property damage is rounded to the nearest hundred thousand dollars, and civilian deaths and injuries are rounded to the nearest one. Prison and jail fires with area of origin unknown are proportionally allocated.

*Based on only fires reported in NFIRS Version 5.0, excluding fires reported as confined fires.

NA = Not applicable because total is zero.

Source: NFIRS and NFPA survey.

indicate "off-the-record" that a significant number of fires, up to 75 percent, in prisons and jails are small fires that go unreported to local fire departments due to security concerns.

SYSTEMS APPROACH TO FIRE SAFETY IN DETENTION AND CORRECTIONAL FACILITIES

To deal with the fire safety problem in correctional facilities, two concerns need to be addressed continually: security for the public and safety from fire for the inmates. Fire safety and security are not contradictory concepts, and there need not be an imbalance of emphasis for either in detention and correctional facilities. Neither absolute fire safety nor absolute security is attainable when considered independently, let alone when considered together. The systems approach seeks to guide the analysis and planning of correction toward achieving an economically feasible program that will attain an acceptable level of protection within the intent of the applicable codes and standards and good engineering practices and that is commensurate with the level of security provided.

The systems approach to fire safety helps to achieve these two objectives through a systematic analysis of each problem area and application of available technologies. Fire safety should be an integrated subsystem of building design, construction, and operation. This method of designing fire safety is known as the systems approach or systems concept of fire-safe building design. A system organizes interacting components in such a way that, working together, they perform a predetermined function or reach a specified objective. The use of the systems approach first requires that fire safety goals be clearly identified. These goals should describe the amount of protection a building should provide its occupants, contents, and operations. These goals should be quantified wherever possible. Once these fire safety goals are established, the methods used to achieve them should work collectively to achieve and maintain the prescribed level of fire safety.

TABLE 20.14.3 Structure Fires in Prisons and Jails, by Leading Major Cause, Annual Average of 2000–2004 U.S. Structure Fires Reported to Municipal Fire Departments*

Major Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Intentional	350	(36%)	0	(NA)	22	(80%)	1.7	(48%)
Clothes dryer or washer	170	(17%)	0	(NA)	5	(19%)	0.2	(5%)
Cooking equipment fire	100	(10%)	0	(NA)	1	(3%)	0.0	(1%)
Identified cooking equipment	30	(3%)	0	(NA)	0	(0%)	0.0	(1%)
Confined cooking fire	70	(7%)	0	(NA)	1	(3%)	0.0	(0%)
Electrical distribution or lighting equipment	50	(5%)	0	(NA)	1	(4%)	0.1	(3%)
Smoking materials	50	(5%)	0	(NA)	0	(0%)	0.1	(3%)
Heating equipment	40	(4%)	0	(NA)	0	(0%)	0.2	(5%)
Identified heating equipment	20	(2%)	0	(NA)	0	(0%)	0.2	(5%)
Confined chimney or flue fire	0	(0%)	0	(NA)	0	(0%)	0.0	(0%)
Confined fuel burner or boiler fire	10	(1%)	0	(NA)	0	(0%)	0.0	(0%)
Playing with fire	40	(4%)	0	(NA)	0	(0%)	0.2	(5%)
Air conditioning or fan	20	(2%)	0	(NA)	0	(0%)	0.0	(0%)
Contained trash fire	40	(4%)	0	(NA)	0	(0%)	0.0	(0%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, direct property damage is rounded to the nearest hundred thousand dollars, and civilian deaths and injuries are rounded to the nearest one. Candidate causes are examined separately; confined fires are analyzed separately. Major causes are defined by groupings from the data elements of cause, factor contributing to ignition, heat source, and equipment involved in ignition. Major causes are shown only if they accounted for at least 2 percent of fires.

*Based on only fires reported in NFIRS Version 5.0.

NA = Not applicable because total is zero.

Source: NFIRS and NFPA survey.

Goals of a Simplified Fire Safety System

The systems approach can be illustrated by the simplified fire safety system for correctional facilities. The box at the top of Figure 20.14.2 shows the four goals of the simplified fire safety system.

Life Safety. The protection of life is paramount in any fire. Occupants can be protected by providing a safe area of refuge from the fire within the building or by providing a safe and readily available path of travel to an outside secured area.

Property Protection. The protection of property is also of concern, particularly with today's higher replacement costs. Some areas may be considered more important than others—for example, a control room versus a storage room—and therefore require more protection.

Continuity of Operations. This involves providing protection to limit fire damage so an area can be returned to use quickly. This is a critical issue since there are generally no adequate alternative facilities available to house and provide services to displaced occupants.

Security. The primary function of a detention and correctional facility is to maintain a secure perimeter and protect the public from the occupants. Fire safety must be compatible with this function.

Objectives of a Simplified Fire Safety System

These goals are achieved through a series of objectives:

- Ignition control
- Fuel control
- Occupant protection
- Detection and suppression
- Planning and training

Success in meeting the overall goals depends on the degree of success in meeting these five objectives, and the relationships between goal success and objective success may be mathematically complex. In practical terms, however, no one objective is likely to be sufficient by itself to meet the goals, so it is safest to assume that all five objectives must be addressed. Some methods to attain each objective are listed beneath the objectives shown in Figure 20.14.2. For the objective of ignition control, for example, the methods available to reduce ignitions include the following:

- Controlling smoking materials
- Controlling electrical ignition sources
- Controlling occupant population mix to reduce intentionally set fires

When certain methods for achieving the objective are not practical or not particularly effective, other parts of the system may have to be enhanced to compensate. For example, when ignition sources cannot be effectively reduced, fuel control

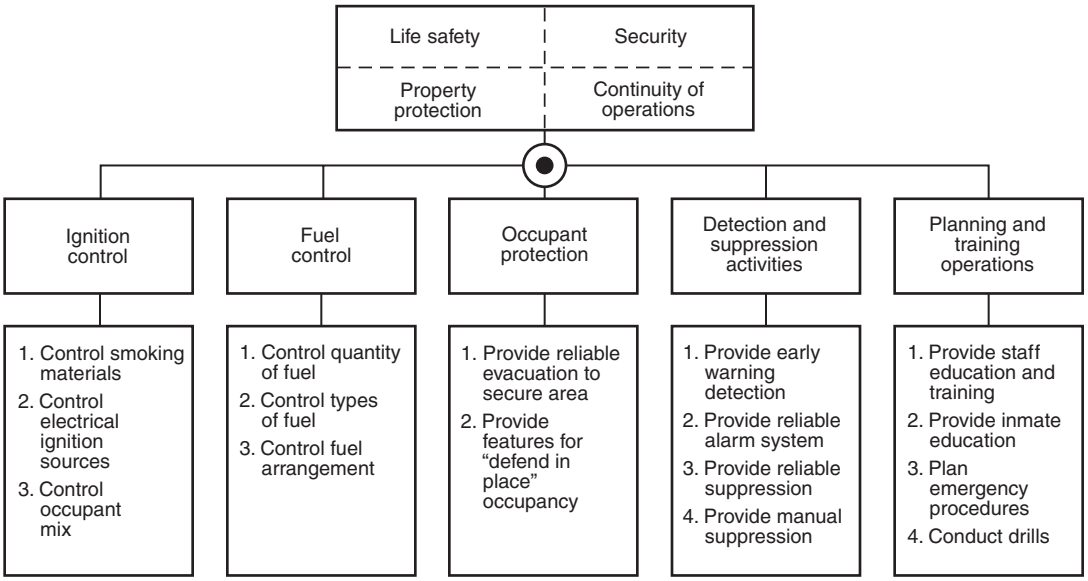

FIGURE 20.14.2 Simplified Fire Safety System for Detention and Correctional Facilities

becomes more important, or when the quantity of combustible materials cannot be effectively controlled, sprinklers may offset the hazard.

Because different objectives do not have an equal impact on the ultimate level of fire protection, the concept of equivalent protection, also known as tradeoffs, may be necessary. For example, under certain conditions, NFPA *101* and *NFPA 5000* permit the use of higher flame spread materials as interior finish if automatic sprinklers are provided. The systems approach provides for analysis of the interacting components of the fire safety system so that alternate means of protection can be evaluated. This evaluation may include initial costs, operational and maintenance costs, and impact on operations.

Ignition Control

Ignition control means greater and more dependable protection of heat sources and separation from fuel sources. In a property where most fires are deliberately set, this primarily means eliminating unnecessary heat sources. Unfortunately, total ignition control is nearly impossible to maintain and may therefore be the least effective fire defense measure. Sources of ignition are nearly always available because cigarettes and matches are, in most cases, available to inmates, and electrical appliances are generally allowed in cells. However, an effort must be made to control unwanted or unnecessary ignition sources. Some jails and prisons prohibit smoking for health reasons. This, of course, will also reduce smoking materials as an ignition source. If smoking is permitted, the types of lighters or matches can be specified. The overall use of electrical power must be carefully supervised. The number and type of heat-producing appliances, such as toasters, hot plates, and space heaters, must be controlled by the facility administrator to prevent overloading circuits. If electrical devices are allowed in cells, adequate electrical outlets should be provided to discourage the use of extension cords.

Fuel Control

Fuel control means controlling the type, arrangement, and burning characteristics of potential fuels. These fuels may include the building structural system, interior finish materials, and combustible contents, such as furnishings and inmates' personal property. Assuming that heat sources will be available, the likelihood of fire and the rate of fire growth can be controlled by limiting the type, quantity, and arrangement of the fuels available. Limiting the speed at which fire develops and spreads reduces its impact on life safety.

Achieving the goal of fuel control means keeping fuel quantity at a minimum, controlling the type of fuel, eliminating those fuels that are easy to ignite or result in fast fires, and separating fuels from readily available ignition sources. One part of fuel control is to eliminate highly combustible furnishings. Since mattresses and bedding are the fuel sources most readily available to inmates, they are most frequently involved in fires. Certain types of polyurethane foam mattresses can be a significant fuel source in prison fires because they can support fast fire development, high heat release, and heavy smoke production.

Mattresses can be made to resist ignition from cigarettes, which are a low-heat ignition source. The federal *Flammability Standard for Mattresses*[2] requires that mattresses resist ignition by cigarettes placed at 18 specified locations. This test does not include sheets or blankets on the mattress and does not indicate the resistance to ignition from open flames or the intensity of the resulting fire. A series of tests of mattresses by the U.S. Department of Agriculture[3] concluded that "the data show that mattresses containing polyurethane foam easily comply with the federal standard[2] where cigarettes are the igniting source; however, such mattresses present a significant hazard where the igniting source is an open flame. Mattresses containing 100 percent polyurethane foam usually burn vigorously until little char

remains. Burning in such cases is accompanied by the release of copious amounts of black smoke."

In 1977, the National Bureau of Standards (now the National Institute of Standards and Technology) conducted fire tests of mattresses and issued a report,[4] which categorized mattresses into four groups in order of safety (Table 20.14.4).

These tests indicate that the best mattresses for use in correctional facilities are those with padding material of cotton treated with boric acid. Mattresses of cotton treated with boric acid pass the federal standard[2] and perform well when exposed to open-flame ignition sources. Such mattresses will burn but at a much slower rate than urethane foam mattresses.[5] Some other materials are entering the market for mattress padding, including treated neoprene. Because occupants of detention and correctional facilities frequently intentionally damage mattresses, operators of these facilities are reluctant to purchase expensive mattresses. Therefore, the most common mattresses found are fire-retardant-covered foam or cotton-treated mattresses.

Inmate possessions and furnishings in the cell must be controlled in order to limit the size of fire that can be expected. Books, clothing, and other combustible personal property allowed in cells should be stored in closable metal lockers or fire-resistant containers. Combustible decorations should be prohibited unless they have been treated with flame retardants. Although rarely used, draperies, curtains, or other decorative and acoustical materials should be noncombustible or rendered and maintained flame resistant according to NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films.* There is no maximum limit of combustibles permitted in NFPA *101* or *NFPA 5000.* The codes do, however, provide a cautionary statement for management to control the combustibles.

TABLE 20.14.4 Mattress Safety Categories

Group	*Safety Criteria*
A	Mattresses that did not exceed any of the tenability criteria for the duration of the 30 minute test. This group included two treated, cotton-batting mattresses.
B	Mattresses that only exceeded the smoke obscuration criterion. Two neoprene mattresses were in this category.
C	Mattresses that exceeded all tenability criteria, but did not cause full room involvement. This group included three polyurethane foam-core mattresses and one of mixed fiber construction. The best-performing polyurethane mattress was of the type associated with a multiple-life-loss prison fire.
D	Mattresses that exceeded all criteria. Included were one styrene-butadiene latex foam core and one polyurethane foam-core mattress. The latex mattress was of the type associated with a multiple-life-loss fire in a health care institution.

Interior finish materials can contribute fuel to a fire, they may accelerate room flashover, and they can result in rapid fire spread. Materials that have high flame spread rates or produce hazardous concentrations of smoke or noxious gases should not be used. This includes plastic wall finish material, fiberboard, thin paneling, and untreated plywood. Interior finish alternatives with good fire characteristics include paneling treated to provide Class A interior finish rating with a flame spread of 25 or less, painted steel, gypsum board, or masonry block.

Occupant Protection

Occupant protection means providing life safety to building occupants in case of fire. This may be accomplished either by evacuating them to a secure area or by defending them in place. This objective is the most controversial in the fire safety system for correctional facilities because "evacuation" is often interpreted by administrators and staff to mean "escape." Although this assumption is not valid, means of egress does directly affect security.

With reference to the evacuation of inmates, most detention and correctional facilities can be grouped into two general types, based on their physical arrangement. In the first group are larger institutions that have an outdoor secure area such as an outdoor exercise yard or courtyard. It is possible to evacuate inmates rapidly from the fire area to this outside area and still maintain security. In the second category are the inner city high rise facilities and the smaller city or county facilities where there are no separate, secure outdoor areas. In these facilities, which have no enclosed courtyards or other areas to evacuate inmates and still maintain security, it becomes necessary to defend the inmates in place from fire. Evacuating inmates outside the secured perimeter of a facility is as much a safety hazard to the general public as the fire itself.

Defend-in-Place Strategy. The defend-in-place protection strategy is a workable and accepted means of providing fire safety for building occupants and is commonly used to protect persons in hospitals and nursing homes. The technology exists to defend inmates in place so that only a few cells need to be evacuated—possibly only the cell of fire origin. A defend-in-place occupancy, as well as an occupancy using evacuation to a secure area of refuge, needs a reliable means of egress. Unique to detention and correctional facilities, because some occupant populations cannot be mixed with the general population for security reasons, there is often a need for multiple and separate areas of refuge for both inside and outside secured areas. Although means for defending the occupants in place are provided, it is always considered necessary to provide reliable exits. According to NFPA *101* and *NFPA 5000,* this means that two distinct paths of travel must be provided from each cell block or area. The exits should be remote from each other so that a single fire cannot readily block both. In addition, travel distances must not exceed those specified by NFPA *101* and *NFPA 5000.* The travel distance can be increased if the building is sprinklered. The exit access needs to be free and unobstructed, and it should not be circuitous. An exit access that requires travel through a room or an area containing a fire hazard higher than usual for

the occupancy violates the principles of safe egress. Dead-end corridors are not good practice because a fire in a dead end between an exit and an occupant can prevent the occupant from reaching the exit. Means of egress need to be illuminated continuously, and emergency lighting must be provided. Exits and the paths to them should be clearly marked. However, NFPA *101* and *NFPA* 5000 permit the elimination of exit signs in inmate housing areas where no visitors are permitted. The rationale for this is that the inmates cannot leave until someone unlocks the doors and security staff, who are familiar with the locations of exits, direct the evacuation of inmates.

Compartmentation. Compartmentation is an important aspect of occupant protection, whether inmates are evacuated or defended in place. Compartmentation limits the number of persons exposed to a single fire. The walls, ceilings, and floors of fire compartment boundaries must be fire resistant. Openings must be protected with self-closing, fire-rated doors. The degree of fire protection these elements provide depends on the degree of hazard the occupancy presents, or its fuel loading, and the type of building construction—for example, fire resistive versus combustible—and the function served, such as a load-bearing or nonload-bearing wall. For more information on compartmentation, see Section 18, Chapter 1, "Confinement of Fire in Buildings."

Smoke Control. Controlling smoke means controlling the type and quantity of materials used in the building construction and building contents and providing a means of restricting smoke movement within the building. Dilution, which is reducing smoke concentration by introducing massive quantities of uncontaminated air into a building, is not always satisfactory when used alone. Smoke may be generated in such quantities that adequate dilution may not be obtained. Prudent use and placement of automatically opening vents can provide some relief from smoke and combustion products in small, one-story buildings or multitiered cell blocks. However, smoke confinement can best be achieved by providing a physical barrier, such as a wall with self-closing doors and dampers that restrict smoke movement, and by using pressure differences across the physical barrier to prevent smoke from entering the nonfire area. The building's heating, ventilating, and air-conditioning (HVAC) system can be designed to provide this pressurization. Physical barriers alone usually are not effective in controlling smoke movement because they have many penetrations, and the fire, the building HVAC, and/or the weather conditions create uncontrolled pressures. NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences,* provides requirements for the design and installation of smoke-control systems. For more information on smoke control, see Section 18, Chapter 3, "Smoke Movement in Buildings."

Locking Systems. Since the primary objective of detention and correction facilities is security, reliable locking systems are essential. However, the inability to unlock doors has played a major role in some of the deadliest correctional fire tragedies. Whatever the type of locking system, the system must function reliably in emergencies, whether a facility is designed to evacuate its inmates or to defend them in place. Individual key locks are the most unreliable for several reasons, including the time required to unlock each door, the loss of keys or the breaking of a key in a lock during an emergency, heat and smoke prohibiting entry into the cell block, and confusion due to the number of keys required to release the inmates.

It is important that the number of keys needed to evacuate the occupants to the outside or to an area of refuge be limited to reduce the confusion. Also, all keys needed for evacuation should be marked by sight and touch for quick identification in an emergency.

CASE STUDY: Jail Fires. In two deadly jail fires, a major factor was the loss, early in the incident, of the only set of keys to the fire-involved area, combined with the lack of a secure area of refuge to which prisoners could be evacuated. Both facilities lacked sprinklers; at least one of the two facilities lacked detectors as well. In both facilities, exit problems were cited (in one, the two means of egress were too close together; in the other, the means of egress were blocked and inadequate in number). In one incident, the storage of urethane foam mattresses in an unsecured room was cited as a contributing factor.[6]

Detection and Suppression Activities

Detection and suppression activities deal directly with the fire—detecting its presence, sounding an alarm to alert occupants, and inhibiting fire growth by active fire suppression. To achieve this objective, the following must be provided: an early warning fire detection system, a reliable alarm system, and a reliable fire suppression system. All automatic detection and suppression systems and manual equipment need to be inspected and tested regularly. See NFPA 10, *Standard for Portable Fire Extinguishers*, NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*, and *NFPA 72®*, *National Fire Alarm Code®*.

There are three separate stages of detection and suppression activities, each of which can be performed automatically or manually (Table 20.14.5). Automatic and manual systems can

TABLE 20.14.5 Stages of Detection and Suppression

Stage	*Manual*	*Automatic*
Detection	Inmate or guard detects fire	Smoke detectors or sprinklers detect fire
Alarm	Guard verbally transmits information to other guards	Fire alarm system activates audible and visible alarms
Suppression	Guards use extinguishers to suppress fire	Sprinklers begin extinguishing immediately

also be combined. For example, detection can be provided by smoke detectors installed throughout the facility with manual fire fighting by fire brigade personnel using a standpipe hose. However, any system needing manual intervention requires that someone make a decision, requires time for human action, and requires trained personnel with the necessary equipment to do the job. The human element is generally the most unreliable part of a fire safety system.

The effectiveness of fire detection and suppression systems depends on the rate of fire growth and the time from ignition until detection and, eventually, suppression activities begin. If the fuel available is capable of producing a fast fire, as it is in padded cells, the extinguishing agent, usually water, must be applied to the fire very quickly after ignition. This is very difficult to do with manual fire suppression even if early warning fire detection, such as automatic smoke detectors, is available. Automatic sprinklers provide reliable fire detection and suppression, and they need no human intervention. With an automatic sprinkler system, the extinguishment phase begins almost simultaneously with detection and alarm, a response difficult to achieve with manual suppression.

Detection and Alarm Activities. NFPA *101* and *NFPA 5000* require smoke detectors in the sleeping areas of detention and correctional occupancies. Smoke detectors may cause needless or nonfire emergency alarms. Therefore, in housing areas, they may alarm at a constantly attended location, such as a control room, and are not required to sound a general evacuation alarm or call the fire department. A manual fire alarm system is also required. NFPA *101* and *NFPA 5000* permit the manual fire alarm boxes to be locked, provided staff has keys. In addition, the alarm systems should be arranged to automatically notify the local fire department. Manual suppression ability should include portable fire extinguishers of the proper type and number, readily accessible fire hose stations for use by correctional officers, and a means to stretch fire hoses through double security gates, or sallyports, so the gates can be closed and security maintained.

Suppression Activities. Sprinklers have been, and are being, installed quite successfully in detention and correctional facilities throughout the United States and Canada. Contrary to some schools of thought, vandalism of sprinklers by inmates, especially in long-term facilities, is very low. It is recommended that institutional type sprinkler heads be used in areas occupied by and within easy reach of inmates. Sprinklers control fire development, thereby reducing the production of heat and smoke. They also give fire service personnel a better opportunity to begin rescue and extinguishment operations. Automatic sprinklers can reduce property loss and limit downtime. In addition, they offer several economic advantages:

- Insurance premiums may be reduced with the installation of sprinkler protection.
- Many building codes offer tradeoffs when sprinklers are used, thereby reducing building costs.
- Sprinklers may also result in fewer persons being evacuated and reduce the burden for manual fire fighting—in effect, increasing security.

NFPA *101* and *NFPA 5000* require the installation of automatic sprinkler systems in all new detention and correctional occupancies, other than those classified as Use Condition I. Prior to the 1997 edition of NFPA *101*, requirements for automatic sprinklers depended on the facility's construction type, number of stories, and use condition.

Planning and Training Operations

Planning and training mean conducting training activities among inmates and staff and planning emergency operating procedures. To achieve this objective, the following methods are used: staff education and training, inmate education, planning emergency procedures, and conducting drills. Planning and training require little capital investment in equipment, but they will make a big difference in reducing the impact of a potentially disastrous fire. In addition, planning and training are important to maintain a high level of security during a fire.

Because fire safety should be everyone's concern, both staff and inmates should be involved in a fire safety program. Each shift should practice the fire emergency plan at least quarterly, and new employees should be briefed routinely on the fire emergency plan. Inmates should be instructed in emergency procedures. Safety information can also be included in an inmate information booklet.

The fire safety program should be designed to meet the needs of the facility. The size and age of the facility and the security classification of the occupants, as well as its proximity to municipal fire departments, should be considered. All training programs should include a short description of the background and evolution of the problem; how to recognize, prevent, and reduce fire hazards; information on the fire protection technology available for application at the facility; hands-on training for staff and inmate fire brigades; emergency operating procedures; and identification of potential problems that affect fire safety.

Fire brigades should be equipped and trained to deal effectively with a fire emergency. Brigade responsibility and functions will vary with the size of the facility and the size and location of the nearest fire department, but they should include calling the fire department, safeguarding lives, providing manual suppression to control the fire until the fire department arrives, and protecting equipment. Fire department access into detention and correctional facilities will usually be delayed because of security.

Each building in a detention or correctional facility should have a written fire emergency response plan detailing staff action during a fire emergency. The plan provides a guide for evaluating the particular problems and coordinating the response of the fire brigade, fire department, staff, and inmates. Emergency response plans should be simple yet comprehensive, specific, flexible, and workable. Preparing the plan can be accomplished in these five steps:

- Define the potential fire protection problems in the particular detention and correctional facility.
- Determine the security needs of the facility.
- Set objectives for what can be accomplished with the plan in an emergency.

- Determine the facility's capability for controlling an emergency.
- Define the roles of the responding agencies, especially the fire department and fire brigade.
- Put the information in written form.

The local fire department should be involved in formulating the fire emergency plan and briefed on building conditions, contents, and fire-fighting equipment within the complex. Fire departments with correctional facilities within their jurisdictions should conduct site surveys and have their own prefire plans for each building.

LOCKUPS

For many years building officials, fire officials, and designers have looked for guidance in codes on how to treat and protect "lockup" areas of buildings. Lockups are holding areas for not more than 50 detainees, where individuals are detained for less than 24 hours. A lockup that has a holding area for more than 50 detainees or detains individuals for 24 hours or more is classified as a detention and correctional occupancy or health care occupancy. Lockups are commonly found in courthouses, international airports, sports arenas and stadiums, shopping malls and police stations. The 2006 editions of NFPA *101* and *NFPA 5000* contain, for the first time, requirements for such lockups.

The only real difference between a lockup area and a detention and correctional facility is that an occupant in a lockup area is detained for less than a 24 hour period and generally sleeping facilities are not provided in lockup areas. Occupants in lockups, like detention and correctional occupancies, are generally prevented from taking actions for self-preservation because of security measures not under the occupants' control.

Because occupants in lockups are generally incapable of self-preservation, the lockup areas require a higher level of life safety than other portions of the same building. Codes require that the lockup areas comply with the requirements of the predominant occupancy plus staff must be present to release locks and/or restraints within two minutes of the onset of a fire or similar emergency or the lockup areas must be provided with a complete smoke detection system and automatically notify the staff and the fire department.

SUMMARY

Providing balanced fire protection and security in detention and correctional facilities can be challenging and has two goals: security for the public and safety from fire for the inmates. The systems approach to fire safety helps to achieve these two goals through meeting a series of objectives, including ignition control, fuel control, occupant protection, detection and suppression, and planning and training. Ignition control involves greater and more dependable protection of heat sources and separation from fuel sources. Fuel control means controlling the type, arrangement, and burning characteristics of potential fuels. Occupant protection can be accomplished either by evacuating inmates to a secure area or by defending them in place. Detection and suppression of fire require an early warning fire detection system, a reliable alarm system, and a reliable fire suppression system. Planning and training include staff education and training, inmate education, emergency procedure planning, and emergency drills. When certain of these objectives cannot be met, other parts of the system may have to be enhanced to compensate. The fire safety program should be designed to meet the particular needs of the facility and should involve the participation of the local fire department.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on detention and correctional facilities discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™*
NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 72®, National Fire Alarm Code®
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA *101®, Life Safety Code®*
NFPA 204, *Standard for Smoke and Heat Venting*
NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*
NFPA 5000®, Building Construction and Safety Code®

Chapter 15

Health Care Occupancies

Daniel J. O'Connor

Chapter Contents

Occupancy Characteristics
Ignition Sources
Fire Loads
Fire Severity
Building Construction
Fire Suppression Equipment
Protection of Hazardous Areas
Operating Features
Emergency Planning
Fire Safety Evaluation System
Ambulatory Health Care

Key Terms

automatic sprinkler system, disposable equipment and supplies, exit illumination, exit marking, interior finish, means of egress, portable fire extinguisher, smoke control, vertical openings

In today's business environment, health care, medical care, and personal care services have evolved such that there is a wide variety of facilities and business operations delivering health care to the general population. As a result, there are varying levels of risk among the facilities that offer health care and medical services. Within NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®, there are several types of occupancies where people may receive some form of health care, medical, or personal care service. These include the following:

- Health care occupancies
- Ambulatory health care occupancies
- Residential board and care occupancies
- Business occupancies

The focus of this chapter is on those facilities that pose greater risks due to the impairment of occupants and/or lack of ambulatory capabilities of the occupants. Specifically, this chapter addresses health care occupancies and ambulatory health care occupancies; however, some brief discussion of residential board and care and business occupancies is warranted, as there are important distinctions that should be understood and considered when applying the requirements of NFPA *101* and *NFPA 5000*.

Health care facilities are used for the treatment or care of persons suffering from physical or mental illness, disease, or infirmity, and for the care of infants, convalescents, or aged persons. These facilities provide sleeping accommodations for occupants who may be incapable of self-preservation because of physical or mental disability or age. Some buildings that house health care occupants have security measures that limit freedom of movement.

In recent years, facilities—sometimes called ambulatory health care facilities—have been developed to provide medical treatment on an outpatient basis. Although patients might be placed under general anesthesia or other treatment that would render them incapable of self-preservation, they are not housed overnight. Occupants exhibit some characteristics of people in business occupancies and some characteristics typical of people in health care facilities.

Tremendous growth has occurred in recent years in residential board and care facilities. These facilities are commonly called assisted living facilities, personal care facilities, and so on. Residential board and care facilities provide personal care to occupants in a residential setting. The residents' abilities to respond to a fire threat differ greatly from patients in health care facilities. The safeguards appropriate for health care facilities should be applied only when a facility meets the definition in NFPA *101* and *NFPA 5000* of a health care facility.

In many facilities the presence of doctors providing diagnosis and treatment for patients may suggest that the facility is a health care occupancy. This may not be the case, as most doctor's offices and birthing centers are classified as business occupancies when meeting the definitions and criteria defined in NFPA *101* and *NFPA 5000*. Where doctor's offices solely provide outpatient care and are physically separated from facilities housing inpatient treatment and care areas, such offices can be classified as business occupancies, although associated with the operations and management of a health care occupancy.

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Additionally, in recent years there has been a significant growth in facilities known as birth centers. These facilities do not pose the risks associated with health care occupancies as they are intended for low-volume service for healthy, childbearing women and their families, who are capable of evacuating in the event of a fire. Such facilities should meet the definitions for birth center and business occupancy given in NFPA *101* and *NFPA 5000;* otherwise the facility may be a health care occupancy.

This chapter describes the characteristics and fire hazards of health care facilities. It specifically discusses the characteristics of the health care occupant and the fire safety features that all health care facilities should provide.

Additional information relating to health care facilities can be found in Section 8, Chapter 6, "Protection of Electronic Equipment"; Section 18, Chapter 1, "Confinement of Fire in Buildings"; Section 18, Chapter 2, "Interior Finish"; and Section 20, Chapter 2, "Board and Care Facilities."

OCCUPANCY CHARACTERISTICS

Occupants of health care facilities are generally presumed to be incapable of self-preservation. A significant percentage of occupants in hospitals and nursing homes are incapable of self-evacuation or are ambulatory but incapable of perceiving a fire threat and choosing a rational response.

There are three types of care in most modern hospitals: (1) ambulatory, (2) general, and (3) intensive care. Given proper directions, unless smoke or heat is intense, ambulatory patients can make their own way to safety. General care patients may be transported on stretchers or in wheelchairs with some difficulty; horizontal and even some vertical movement is generally possible, although independent evacuation is not. Patients in intensive care are likely to be connected to various life support devices, making movement for even short distances very difficult and evacuation almost impossible without further endangering these patients' lives.

Occupants of nursing homes vary from geriatric residents who are capable of evacuation with limited assistance to residents who are comatose and require close supervision with evacuation being very difficult. Today's nursing home resident is less ambulatory and requires more medical care than a resident of even 10 years ago. The significant increase in the number of assisted living facilities has made the typical intermediate care nursing home resident of yesterday an assisted living resident today.

Because some occupants are incapable of movement or slow to evacuate, a health care facility resembles a ship at sea: it is better to keep the fire from the patient than to remove the patient from the fire. Thus, occupants must be defended in place. As a result, health care facility design and operation must incorporate methods by which a fire can be detected early, contained, and fought rapidly and successfully. Accomplishing this requires careful planning of the health care facility and its day-to-day operation.

NFPA *101,* widely used to establish minimum requirements for life safety from fire within health care facilities, sets forth criteria based on the following general principles:

- Fire-resistive construction
- Subdivision of spaces, known as compartmentation
- Protection of vertical openings
- Provision of adequate means of egress
- Provision of exit marking, exit illumination, and emergency power
- Limits on the use of interior finish materials
- Fire alerting facilities
- Control of smoke movement
- Protection of hazardous areas
- Adequate protection of building service equipment
- Control of fuel loads
- Operational features

Total building fire protection for life safety is more necessary in health care facilities than in other occupancies because of the nature of the occupants. At the same time, exits are slightly less important. The first principle of designing a fire-safe health care facility is that safety must not depend wholly on any single safeguard.

IGNITION SOURCES

In the 1994–1998 period, smoking materials, both lighted tobacco products and implements used to light them, and incendiary and suspicious acts accounted for 75 percent of deaths and 45 percent of injuries in facilities that care for the sick and for 54 percent of deaths and 33 percent of injuries in facilities that care for older adults. These causes totally dominate the ignition side of the life safety problem in these properties, although other causes, notably failures in electrical distribution systems, appliances, and other equipment, are also important in property damage (Tables 20.15.1 through 20.15.4).

More and more health care facilities are establishing smoke-free environment policies. In addition, the Joint Commission on Accreditation of Healthcare Organizations (JCAHO) requires facilities to establish a no-smoking policy. As the result of prohibiting or controlling smoking in health care facilities, a new phenomenon has developed: visitors giving smoking materials to patients and residents without the health care staff's knowledge.

Most fatalities in health care fires are so close to the point of origin that their locations are coded as "intimate with ignition" (Table 20.15.5). Most fatalities that occur in the room where a fire begins turn out to have been intimate with ignition. Most intimate-with-ignition fire deaths begin on the victims' clothing or in the mattress, bedding, or upholstered furniture on which they were lying when the fire began.

FIRE LOADS

Studies show relatively low fuel loads within most spaces in health care facilities. Fire duration varies from approximately 20 minutes for patient areas to several hours, depending on the space involved.

A study by the National Bureau of Standards (now the National Institute of Standards and Technology [NIST]) conducted in 1942 involving three hospitals revealed an average fuel load

TABLE 20.15.1 Causes of Fires and Direct Property Damage, Structure Fires in Facilities That Care for the Sick, 1994–1998 Annual Averages (Unknown-Cause Fires Allocated Proportionally)

Cause	*Fires*		*Property Damage (in Millions of Dollars)*	
Other equipment	500	(20.2%)	1.8	(19.2%)
Electronic equipment	100	(3.6%)	0.4	(3.9%)
Separate motor or generator	100	(2.5%)	0.1	(1.0%)
Cooking equipment	500	(18.0%)	0.3	(2.9%)
Stove	100	(5.1%)	0.1	(1.5%)
Portable cooking or warming unit	100	(5.1%)	0.1	(0.6%)
Oven	100	(2.4%)	0.0	(0.3%)
Appliance, tool, or air conditioning	400	(15.6%)	1.4	(15.1%)
Dryer	200	(6.1%)	0.4	(4.7%)
Electrical distribution	300	(12.1%)	1.4	(15.4%)
Light fixture, lamp holder, ballast, or sign	100	(3.9%)	0.1	(0.7%)
Incendiary or suspicious	300	(10.5%)	2.1	(22.7%)
Smoking materials	200	(7.6%)	0.2	(2.6%)
Open flame, ember, or torch	200	(7.4%)	1.2	(12.6%)
Torch	100	(4.5%)	0.7	(8.1%)
Heating equipment	100	(5.1%)	0.4	(4.3%)
Other heat source	0	(1.3%)	0.2	(1.9%)
Natural causes	0	(1.2%)	0.2	(1.8%)
Exposure (to other hostile fire)	0	(0.7%)	0.1	(1.5%)
Child playing	0	(0.4%)	0.0	(0.0%)
Total	2600	(100.0%)	9.2	(100.0%)

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires are expressed to the nearest hundred and property damage is rounded to the nearest hundred thousand dollars. Property damage figures have not been adjusted for inflation. The 12 major cause categories are based on a hierarchy developed by the U.S. Fire Administration. Sums may not equal totals due to rounding errors.

Source: National estimates based on NFIRS and NFPA survey.

TABLE 20.15.2 Causes of Civilian Deaths and Injuries, Structure Fires in Facilities That Care for the Sick, 1994–1998 Annual Averages (Unknown-Cause Fires Allocated Proportionally)

Cause	*Civilian Deaths*		*Civilian Injuries*	
Open flame, ember, or torch	3	(55.9%)	14	(13.4%)
Match	2	(35.0%)	5	(4.9%)
Lighter	1	(20.0%)	8	(7.5%)
Other equipment	1	(24.6%)	16	(15.3%)
Biomedical equipment or device	1	(12.5%)	5	(4.3%)
Incendiary or suspicious	1	(14.2%)	26	(24.3%)
Smoking materials	0	(5.3%)	9	(8.0%)
Cooking equipment	0	(0.0%)	12	(11.5%)
Electrical distribution	0	(0.0%)	9	(8.4%)
Appliance, tool, or air conditioning	0	(0.0%)	8	(7.3%)
Natural causes	0	(0.0%)	6	(5.5%)
Heating equipment	0	(0.0%)	5	(4.6%)
Other heat source	0	(0.0%)	2	(1.7%)
Total	5	(100.0%)	107	(100.0%)

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Civilian deaths and injuries are rounded to the nearest one. The 10 major cause categories are based on a hierarchy developed by the U.S. Fire Administration. Sums may not equal totals due to rounding errors.

Source: National estimates based on NFIRS and NFPA survey.

TABLE 20.15.3 Causes of Fires and Direct Property Damage, Structure Fires in Facilities That Care for the Aged, 1994–1998 Annual Averages (Unknown-Cause Fires Allocated Proportionally)

Cause	*Fires*		*Property Damage (in Millions of Dollars)*	
Appliance, tool, or air conditioning	900	(30.5%)	1.3	(19.7%)
Dryer	600	(20.3%)	0.9	(14.0%)
Fixed area air conditioner	100	(2.1%)	0.1	(0.9%)
Cooking equipment	600	(19.3%)	0.9	(13.1%)
Stove	300	(8.9%)	0.7	(10.2%)
Portable cooking or warming unit	100	(3.3%)	0.0	(0.3%)
Oven	100	(3.0%)	0.1	(1.1%)
Heating equipment	300	(10.0%)	0.3	(4.9%)
Fixed area heater	100	(4.8%)	0.2	(2.3%)
Central heating unit	100	(2.1%)	0.1	(1.5%)
Smoking materials	300	(10.0%)	0.6	(8.9%)
Electrical distribution	300	(9.7%)	0.8	(12.1%)
Light fixture, lamp holder, ballast, or sign	100	(2.6%)	0.1	(0.8%)
Fixed wiring	100	(1.7%)	0.4	(5.5%)
Other equipment	300	(9.0%)	0.7	(10.6%)
Incendiary or suspicious	100	(4.8%)	0.8	(12.3%)
Open flame, ember, or torch	100	(2.8%)	0.9	(12.7%)
Natural causes	100	(1.9%)	0.1	(1.3%)
Other heat source	0	(1.3%)	0.2	(2.7%)
Exposure (to other hostile fire)	0	(0.5%)	0.1	(1.2%)
Child playing	0	(0.1%)	0.0	(0.5%)
Total	3000	(100.0%)	6.8	(100.0%)

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires are expressed to the nearest hundred and property damage is rounded to the nearest hundred thousand dollars. Property damage figures have not been adjusted for inflation. The 12 major cause categories are based on a hierarchy developed by the U.S. Fire Administration. Sums may not equal totals due to rounding errors.

Source: National estimates based on NFIRS and NFPA survey.

TABLE 20.15.4 Causes of Civilian Deaths and Injuries, Structure Fires in Facilities That Care for the Aged, 1994–1998 Annual Averages (Unknown-Cause Fires Allocated Proportionally)

Cause	*Civilian Deaths*		*Civilian Injuries*	
Smoking materials	5	(39.5%)	54	(22.6%)
Other equipment	3	(24.7%)	25	(10.3%)
Biomedical equipment or device	2	(18.0%)	2	(1.0%)
Unclassified special equipment	1	(6.0%)	5	(2.1%)
Open flame, ember, or torch	2	(18.7%)	12	(4.9%)
Lighter	1	(8.0%)	5	(1.9%)
Incendiary or suspicious	1	(6.9%)	21	(8.9%)
Cooking equipment	1	(6.1%)	11	(4.5%)
Stove	1	(6.1%)	6	(2.3%)
Other heat source	0	(4.1%)	2	(0.6%)
Appliance, tool, or air conditioning	0	(0.0%)	65	(27.1%)
Heating equipment	0	(0.0%)	29	(12.2%)
Electrical distribution	0	(0.0%)	20	(8.3%)
Child playing	0	(0.0%)	1	(0.5%)
Exposure (to other hostile fire)	0	(0.0%)	0	(0.2%)
Total	12	(100.0%)	241	(100.0%)

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Civilian deaths and injuries are rounded to the nearest one. The 11 major cause categories are based on a hierarchy developed by the U.S. Fire Administration. Sums may not equal totals due to rounding errors.

Source: National estimates based on NFIRS and NFPA survey.

TABLE 20.15.5 Locations of Victims of Fatal Health Care Facility Fires

Property Class	*Intimate with Ignition*	*Same Room as Fire but Not Intimate*	*Not Same Room as Fire*
Facilities that care for the sick	76%	6%	18%
Hospitals	75	5	20
Other or unknown type	86	14	0
Facilities that care for older adults	53	19	28
With nursing staff	60	15	25
Other or unknown type	39	27	33
All facilities combined	60	15	25

Source: NFPA analysis of data from 1980–1998 NFIRS and NFPA survey.

TABLE 20.15.6 Fuel Loads in Typical Health Care Facilities

Location	Average Combustible Contents (per ft^2) *Movable Property*	*Exposed Woodwork and Floors*[a]	*Total*
Rooms (single)	0.5	3.2	3.7
Corridors	0.0	2.6	2.6
Waiting rooms	1.7	1.5	3.2
Janitors' closets and supplies	3.1	3.4	6.5
Doctors' offices	5.7	2.9	8.6
Nurses' offices and rooms	3.1	1.9	5.0
Nurses' infirmary	0.8	2.2	3.0
Diet kitchens and dining rooms	1.2	2.4	3.6
Laundries	4.4	0.6	5.0
Laundries and clothes storage	12.5	0.6	13.1
Dormitories	0.8	2.0	2.8
Pharmacy, dispensary, and stores	5.8	1.9	7.7
Lockers, toilets, and barber shops	0.2	1.2	1.4
Approximate average for entire usable floor area of three hospital buildings surveyed			5.7[b]

[a]Combustible floor finish, where present, was ¼ in. (6.35 mm) linoleum; it was assumed to be the equivalent of 1 lb (0.37 kg) of combustible material, such as wood, per ft^2 of floor area (4.88 kg/m^2). Doors, windows, trim, moldings, baseboards, and so on are included.

[b]This approximate average weight was computed from Table 16 on page 25 of the Bureau Report BMS 921. The value is somewhat high because the highest weight in each bracket of combustible contents was used in figuring it, that is, in the bracket "0 to 4.9 lb/ft^2 (23.9 kg/m^2)," the value 4.9 lb (2.22 kg) was applied to the indicated area, and so on.

of 5.7 lb/ft^2 (30 kg/m^2).[1] Fuel loads for typical spaces are indicated in Table 20.15.6. A 1980 study of fuel loads in a U.S. Navy hospital confirms the relatively low fuel loads for general hospital areas but indicates that higher fuel loads may be anticipated in some spaces such as medical libraries, X-ray file rooms, linen storage, and general storage rooms. Further, the increased use of disposables and modern medical record storage practices are likely to result in above average fuel loads. These areas may contain fuel loads sufficient for fires from 1- to 3-hour duration. However, such spaces represent a small percentage of total floor area.

A major portion of the floor area of health care facilities is used for patient sleeping or treatment rooms. Fuel loads for such spaces are low. For example, fuel loads in nursing homes have been estimated at 2.5 to 3 lb/ft^2 (10 to 15 kg/m^2).[2] NIST surveys indicate that fuel loads for hospital patient rooms approximate 4 lb/ft^2 (20 kg/m^2) and that the combustible load in patient sleeping areas ranges from approximately 3 to 4.5 lb/ft^2 (15 to 23 kg/m^2). A study of a Navy hospital indicates fuel loads for sleeping rooms average 1 lb/ft^2 (5 kg/m^2) or less. Assuming standard time/temperature conditions, fire duration for patient areas and a majority of other occupied spaces would be less than 30 minutes.

Disposables

The use of combustible disposable equipment and supplies is common in health care facilities. Disposables include bedding, gowns, gloves, drapes, collection bags, tubing, dishes, glasses, syringes, needles, and many diagnostic and therapeutic instruments. All such items require packaging, which can add to the combustible load both before and after use.

Data Processing and Medical Records

Used to satisfy general business needs as well as to store patient records, data processing centers contain quantities of combustibles. These combustibles could expose high-value equipment, result in loss of vital records, and produce a fire that threatens occupants outside the data processing areas. Special protection should be considered for data processing centers.

Health care facilities generate and store medical files in considerable quantity. Files stored in closed steel cabinets do not represent any significant increase in hazard over that typical of most areas. However, files stored on open shelving create a serious fire hazard. Large quantities of open-file storage should be treated as a severe hazard and should be separated by fire-rated construction and protected by automatic sprinklers.

FIRE SEVERITY

Determining relative fire hazard involves considerations beyond total fuel loads. The arrangement of combustibles, their chemical makeup, and their physical state are all factors to be

evaluated in addition to room geometry, ventilation rates, fire compartment size, and fire protection facilities. Generally, the faster a fire develops, the greater its threat.

Although the total fuel load in patient rooms remains low, the nature of the combustibles is important. Foam plastic decubitus pads, upholstered furniture, and polyurethane foam mattresses may not affect the length of time a fire will burn, but such items have affected the rate of fire growth. These types of products can cause fire to grow to a large size quickly.

Fires that reach flashover produce acutely lethal atmospheres generating thousands of cubic feet of smoke per minute. Such fires threaten fire-rated barriers and produce enough energy to drive smoke to remote areas. A fire that grows to full room size in a health care facility represents an unacceptable level of risk; there is a high likelihood that such a fire will result in injuries or fatalities if its origin is in the patient sleeping area. Therefore, every effort should be made to recognize and eliminate or adequately protect fuel arrangements that might produce such fires.

Fire tests and actual fire experience have shown that certain common arrangements and types of fuels in patient rooms create especially hazardous situations because they are able to produce large fires in short time periods. In January 1976, for example, multiple-death fires in both the Wincrest and Cermak House nursing homes involved wooden wardrobes within patient sleeping rooms.[3,4] Tests show that combustible wardrobe fires can result in acutely hazardous environments in as little as 120 seconds.[5]

A 1989 fire in a Norfolk nursing home resulting in 12 deaths originated in a foam plastic decubitus pad on a mattress in a patient sleeping room. The fire grew to flashover in less than 5 minutes.[6] A 1985 fire in a Michigan hospice initially involved an upholstered chair. The fire caused eight deaths.[7] Analysis of this fire established that flashover could have occurred in the room of origin in under 4 minutes. See Figure 20.15.1 for documentation of the analysis for the hospice fire.

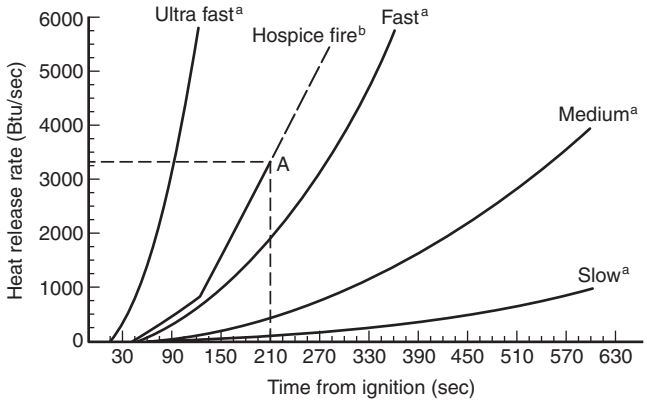

FIGURE 20.15.1 Comparison of the Hospice Fire to *NFPA 72®, National Fire Alarm Code®* Growth Curves. [a]From *NFPA 72®, National Fire Alarm Code®*. [b]From NFPA study of the hospice fire, Southfield, Michigan, December 1985 and CFR/NBS fire model analysis. A = Room flashover

Any combination of finishes, combustible building materials, or contents and furnishings that could result in full room involvement or flashover in 5 minutes or less represents a severe fire hazard in a health care facility. Such spaces should always be protected by automatic sprinklers and separated by fire-rated construction.

Computer fire models developed at NIST have been used to establish the rate of heat release required to produce flashover in a typical patient sleeping room. Under the "worst" circumstances—where the room door is partially open—a 1 MW fire can cause flashover. When the room door is fully open, approximately a 2 MW fire is necessary to cause flashover. NFPA *101* suggests that upholstered furniture, mattresses, and wardrobes be constructed to produce a maximum rate of heat release of 250 kW. It also has been determined that when a fire grows beyond 250 kW in size, hazard thresholds are exceeded, and patients must be removed from sleeping rooms.

Furnishings are frequently major contributors to fire growth. Recent developments make it possible to determine whether furnishings in a given environment can produce sufficient energy to cause full room involvement.

A simplified equation for estimating the rate of heat release required for flashover to occur in a room[8] is given by the expression

$$\dot{Q} \geq 750A\sqrt{h}$$

where

$\dot{Q}$ = Rate of heat release (kW)

A = Ventilation opening area (ft^2 [m^2])

h = The height of the opening (ft [m])

Once the heat release rate required to produce flashover is known for a typical room geometry, such information can be compared to actual heat release rates for typical furnishings, as determined by tests conducted in a calorimeter such as the NIST furniture calorimeter[9] or by Underwriters Laboratories (UL) Subject 1056, "Outline of Investigation for Upholstered Furniture." Figures 20.15.2 and 20.15.3 are idealized curves developed by NIST that illustrate the rate of heat release for typical furnishings as a function of time. Such information can be used to establish the probability of flashover; it also allows estimation of the time required to reach critical fire size.

Interior Finish

A successful fire protection strategy requires fires to remain small. Any large fire in a confined space creates a potentially lethal atmosphere. A fire's initial growth may be affected significantly by the interior finish of walls, ceilings, and floors. Interior finishes, therefore, deserve special attention. Combustible wall and ceiling finishes can act as a fuse, causing a fire to spread to objects remote from the fire origin. Wall and ceiling finishes also provide a large continuous surface over which fire may spread. Thus, an interior finish may, by releasing energy, cause a fire that would otherwise have remained small to become large.

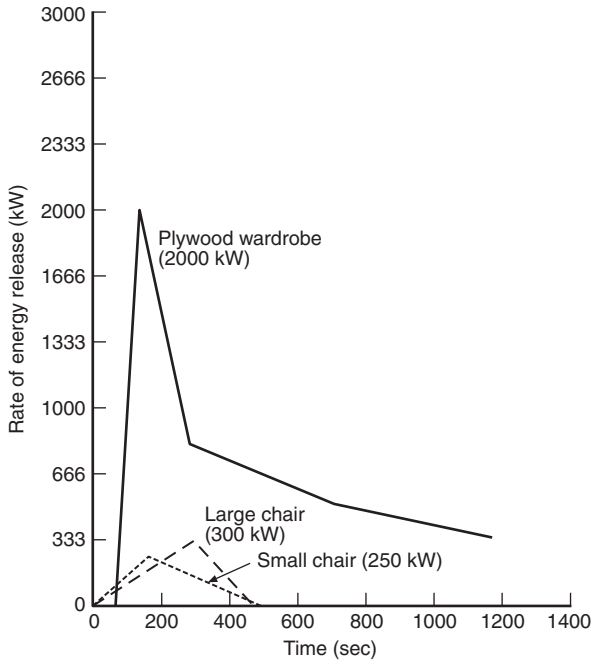

FIGURE 20.15.2 Heat Release Rates for Miscellaneous Furniture

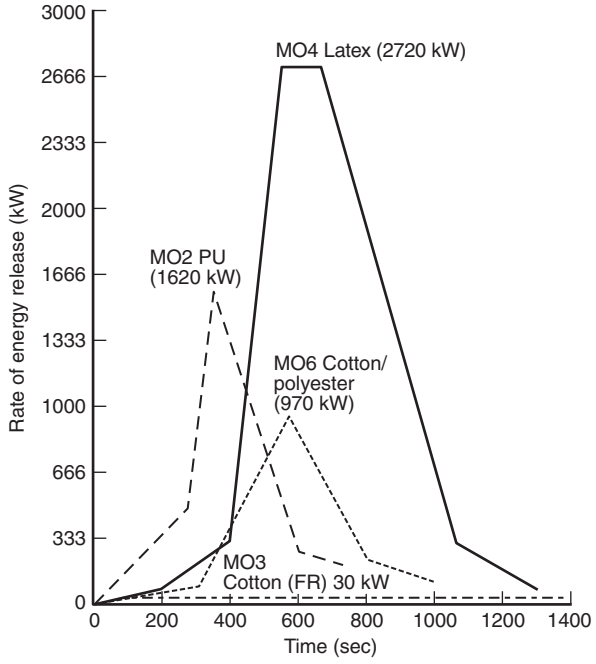

FIGURE 20.15.3 Heat Release Rates for Beds

The relative hazard of an interior finish is usually determined by a test conducted in accordance with NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials,* commonly called the "tunnel test."

Interior finish on walls and ceilings within the means of egress and any room should be limited to Class A materials, which have a flame-spread rating of 25 or less. Class B materials, or those with a flame-spread rating of 25 to 75, are considered tolerable, but they should be limited to small rooms. Full-scale experiments show that automatic sprinklers can limit fire growth in rooms with Class C wall and Class D ceiling finishes.[2,5] Accordingly, in buildings with automatic sprinkler protection, it has been judged acceptable practice to allow the use of materials having higher flame-spread classifications than would otherwise be permitted. For example, Class B materials are sometimes used where Class A is normally specified and Class C materials where Class B is normally required. In new health care facilities, higher flame-spread classifications are permitted based on the mandatory requirement for sprinklers.

Further, it has been shown that the performance of interior finishes also is related to location.[10] Finishes on the upper portions of walls and ceilings contribute more significantly to flame propagation than finishes on the floor or on the lower half of a wall. Therefore, where finishes are limited to the lower half of a wall and are less than 4 ft (1.2 m) above floor level, materials having a higher flame-spread rating than would otherwise be allowed might be used without significantly affecting fire growth. For example, where Class A materials are judged necessary, a Class B material might be allowed on the lower portion of a wall.

In the past, floor finish materials were excluded from requirements for interior finishes, based on favorable experience and the assumption that limited exposure exists at the floor level during an actual fire. However, a fire on January 9, 1970, in the Harmer House Convalescent Home in Marietta, Ohio, significantly changed this attitude.[11] Thirty-two persons died in this fire. Carpeting with foam-rubber backing was judged to have played a significant role.

Interior floor finishes in the corridors of nonsprinklered health care facilities should be limited to Class A materials or those with a minimum critical radiant flux of 0.45 W/cm^2. Where automatic sprinklers are provided, interior floor finishes need not be regulated beyond the federal flammability standard.

BUILDING CONSTRUCTION

Because occupants of health care facilities must be defended in place, construction is an important factor, especially in multistory buildings. Buildings preferably should be constructed of noncombustible materials that resist the effects of fire and maintain structural integrity.

Buildings of two or more stories should be constructed of noncombustible materials with major structural members having at least a 2 hour fire resistance. Materials that either burn or support combustion, although less desirable, are considered acceptable if special precautions are taken. An automatic sprinkler system is an essential part of the total fire defense system for combusitble buildings.

Any evaluation of building materials should include consideration of their smoke-generating capabilities. In addition, plastic construction materials, which are becoming more

common, are sometimes capable of generating large quantities of smoke.

Subdivision of Building Spaces

Mixed and Separated Occupancies. There are basically two ways to handle multiple occupancies in a building that houses a health care facility and other uses. One alternative is to separate the different occupancies. The second alternative is to treat the entire facility as a mixed occupancy and comply with the provisions that are the most stringent of the occupancies involved. When using the mixed occupancy design alternative, there are no specific fire-rated separation requirements. Fire-rated separation requirements, however, do apply in addition to other restrictions when adjacent occupancies are separated from health care occupancies. The health care occupancy chapters and the ambulatory health care occupancy chapters stipulate the fire-resistance separation requirements (2 and 1 hours, respectively) and other provisions when the health care facility is intended to be separated from adjacent occupancies.

Figure 20.15.4 shows health care and other occupancy areas intermingled without fire separations as a mixed occupancy facility. Figure 20.15.5 shows a health care occupancy (hospital) separated from an adjacent business occupancy and ambulatory health care occupancy. In this case, 2 hour fire-resistive separa-

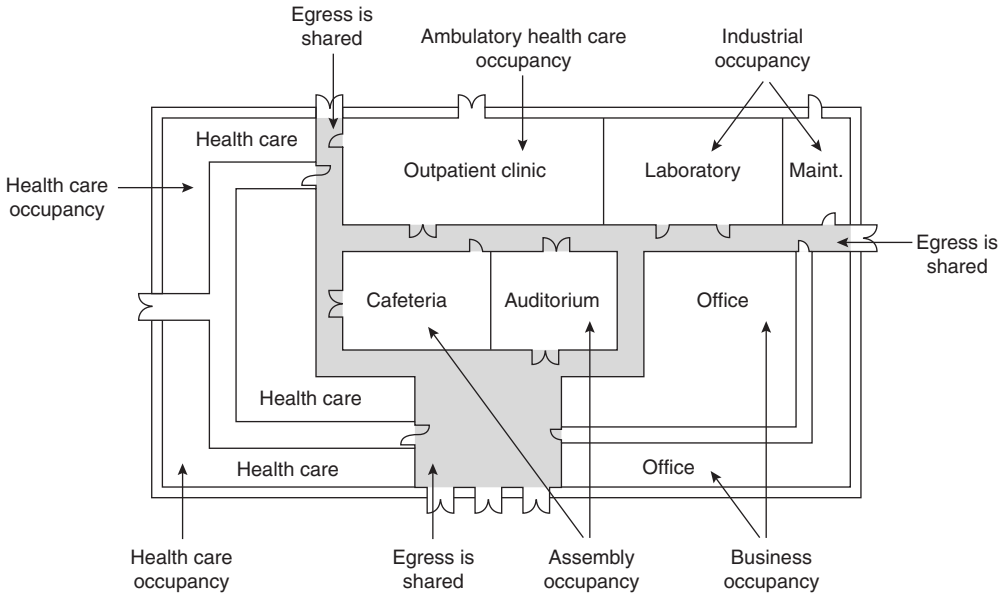

FIGURE 20.15.4 Multiple Occupancy with Mixed Uses

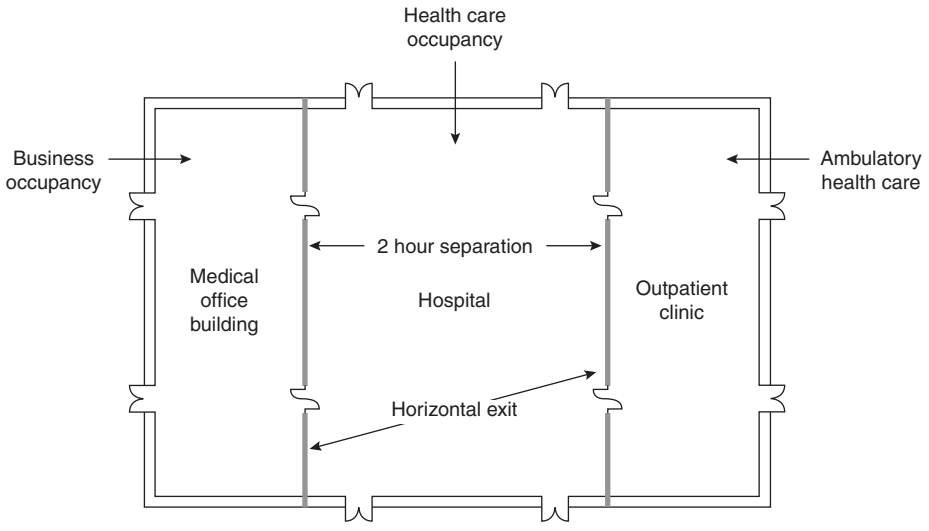

FIGURE 20.15.5 Multiple Occupancy with Separated Uses

tions are used to qualify the hospital, business, and ambulatory health care areas as separate occupancies.

Separation of Patient Sleeping Rooms. Because it may not be possible to remove occupants during a fire, sleeping rooms other than the room of fire origin sometimes must serve as temporary areas of refuge. Therefore, sleeping rooms should be isolated from all other building spaces by fire-rated construction. Partitions should be continuous from the floor slab to the floor or roof above through any concealed spaces, such as those above suspended ceilings. If the building is protected by sprinklers, NFPA *101* and *NFPA 5000* allow these walls to be nonrated, provided the walls resist the passage of smoke, and they are permitted to terminate at the ceiling, provided the ceiling resists the passage of smoke (see Figure 20.15.6 for typical floor plan for a health care facility).

There has been much discussion in the past about the operational considerations versus the fire safety considerations of equipping patient room doors with door closers. NFPA *101* and *NFPA 5000* do not require door-closing devices on patient room doors. The current opinion is that a health care facility's functional needs prevail, and other fire safety and operational features a health care facility provides are adequate alternatives to door-closing devices.

Any penetration of fire barriers by building service equipment should be protected in order to maintain the required fire resistance rating. All spaces around piping and duct penetrations should be sealed tightly with a noncombustible material having adequate fire resistance and capable of retarding the transfer of smoke. Transfer grills should not be used within such doors or partitions.

Smoke Barriers. Every floor used by inpatients should be subdivided into at least two compartments by smoke barriers that also have a 1-hour fire resistance rating. A horizontal exit, when constructed to satisfy the additional criteria imposed on construction of smoke barriers, is a desirable alternative. Smoke barriers and smoke compartments play a very important fire safety role in health care facilities. Subdividing each floor minimizes the number of occupants exposed to a single fire. More importantly, the barriers allow for horizontal evacuation of occupants to an area of refuge on the same floor. In a protect-in-place occupancy where evacuation is difficult, having the capability to evacuate horizontally is extremely important.

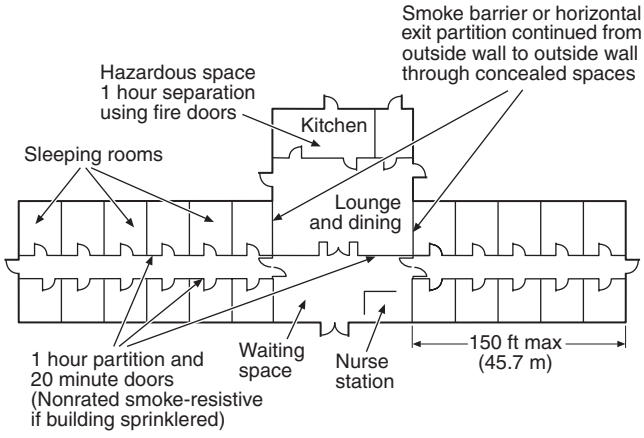

FIGURE 20.15.6 Typical Floor Plan for a Health Care Facility

In new health care construction, smoke barriers are generally required to subdivide into at least two compartments every story used for inpatient sleeping and treatment and any story in the building, regardless of occupancy, that has an occupant load of greater than 50 people. In existing facilities, subdividing a space with a smoke barrier is required only on stories with patient sleeping areas that can accommodate more than 30 patients. Several exceptions to the general requirement for smoke barriers in new health care construction are found in NFPA *101* and *NFPA 5000.*

For stories that must be subdivided, there are two limitations on how large the smoke compartment formed can be related to area and travel distance from any point to a door in a smoke barrier. No smoke compartment can exceed 22,500 ft^2 (2100 m^2) nor can the travel distance from any part of a smoke compartment to the door in a smoke barrier exceed 200 ft (60 m). One exception for existing health care occupancies is that the travel distance to reach the smoke barrier door need not be limited where neither the length nor width of the smoke compartment exceeds 150 ft (45 m). Figures 20.15.7 and 20.15.8 illustrate the basic dimensional criteria and features that constitute an appropriate smoke compartment arrangement for new and existing health care facilities. In addition to the features shown in Figures 20.15.7 and 20.15.8, accumulation space must be provided on both sides of a smoke barrier to accommodate a certain number of people in an emergency based on factors that range from 30 net ft^2 (2.8 m^2) per patient for hospitals and nursing homes to as low as 3 net ft^2 (2.8 m^2) per person on floors with non–health care spaces.

Protection of Vertical Openings

Fire, smoke, and other toxic products of combustion tend to spread vertically within a building. Special effort is required to prevent fire on one level from threatening the occupants above; this is especially important in health care facilities.

All shafts should be provided with fire-rated enclosures. Vertical openings connecting not more than three floors should be enclosed with fire barriers having a minimum 1-hour fire resistance rating. Two-hour rated enclosures should be provided for vertical openings connecting more than three floors. Openings to shafts should be limited to those necessary, and such openings must be protected.

When designing partitions to enclose vertical shafts, consideration should be given to the varying durability of materials. In spaces where partitions may be subject to mechanical injury, materials used to provide floor-to-floor separation should be able to resist damage in order to maintain the required fire resistance.

Means of Egress Design

Exits in health care facilities should be limited to doors leading directly outside of the building, interior stairs and smokeproof

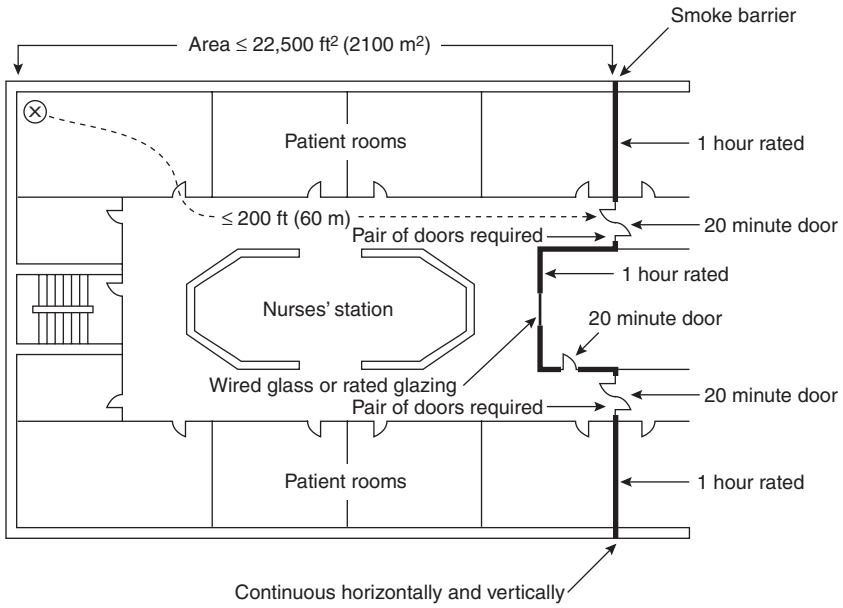

FIGURE 20.15.7 Smoke Compartment in a New Health Care Facility

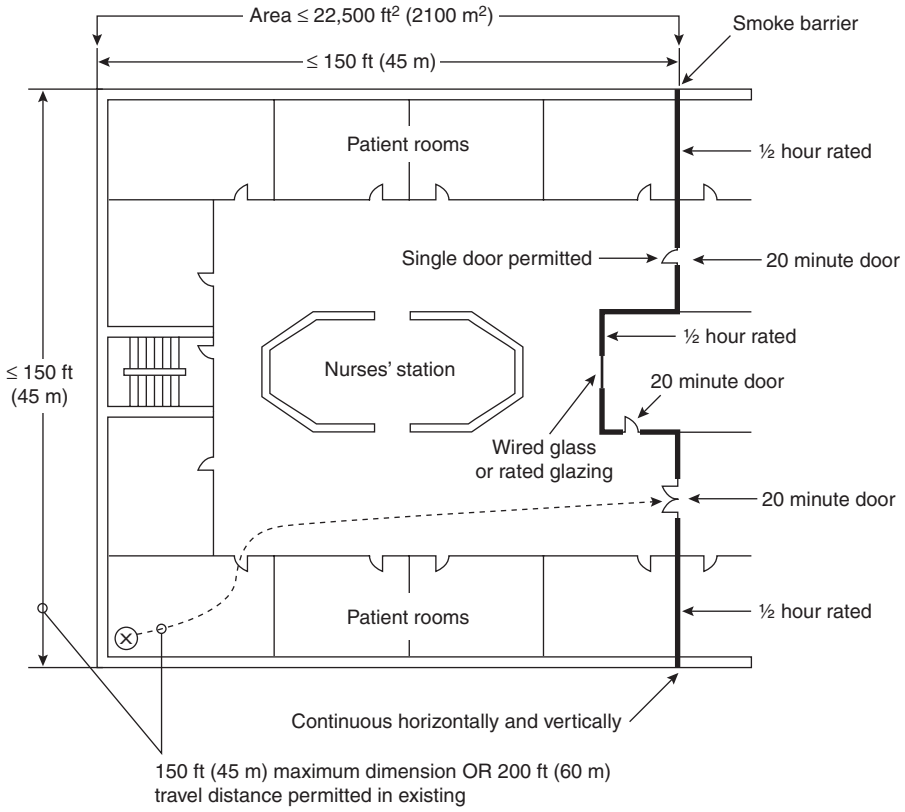

FIGURE 20.15.8 Smoke Compartment in an Existing Health Care Facility

enclosures, ramps, horizontal exits, outside stairs, and exit passageways.

Vertical evacuation of occupants within a health care facility is, at best, difficult and time consuming. Therefore, horizontal movement of patients is of primary importance.

Horizontal passageways and doors opening into corridors and rooms used for sleeping or treatment should be wide enough to allow the horizontal movement of occupants, even those in beds or on gurneys. Relocation of patients is a slow process, even under favorable staff-to-patient ratios. Because of the time required to move patients, exit access routes should be protected against fire effects. Spaces open to the corridor should not be used for patient sleeping or treatment rooms, nor should hazardous contents or activities be permitted within them. NFPA *101* and *NFPA 5000* provide detailed requirements for spaces open to corridors. Such requirements include the installation of smoke detection systems, quick-response sprinklers, direct visual supervision of the open space by staff, or a combination thereof.

Horizontal Exits. Horizontal exits are common in health care facilities. Partitions used as horizontal exits and smoke barriers should provide the fire resistance required for exits and, in addition, should satisfy the criteria for smoke barriers when appropriate. If possible, door openings should be limited to corridors, lobbies, or public spaces. The most desirable arrangement of mechanical systems is one in which the partitions forming the horizontal exit are not penetrated. If penetration by utilities or piping occurs, the space around the piping should be filled tightly with noncombustible materials and maintain the barrier's required fire resistance. If ducts penetrate partitions intended to be smoke barriers, combination fire/smoke dampers that close if smoke detectors within the duct activate should be provided.

Two-hour fire barrier walls must be used to create horizontal exits. Such barriers must be vertically continuous and must penetrate any ceiling and continue to the floor or roof deck above. NFPA *101* and *NFPA 5000* require such barriers to be continuous to the ground. The fire barrier is allowed to be omitted on any story below, provided the floor below the lowest level on which the barrier exists and all supporting members are of a 2 hour fire-resistive construction. Figure 20.15.9 illustrates the vertical continuity of walls forming horizontal exits.

Because a horizontal exit implies that occupants will be transferred from one side of a partition to the other (horizontal evacuation), adequate space must be available to house occupants after movement. In hospitals, at least 30 net ft^2 (2.79 m^2) per patient should be available on each side of the horizontal exit, allowing for accumulation of the total number of patients in adjoining compartments.

Interior Stairs. Exit stairs should be designed to satisfy the criteria for interior stairs. Stairs should be enclosed with fire barriers, and openings into stair enclosures should be limited to those necessary for access and discharge purposes. Stairs must be properly protected from the effects of fire.

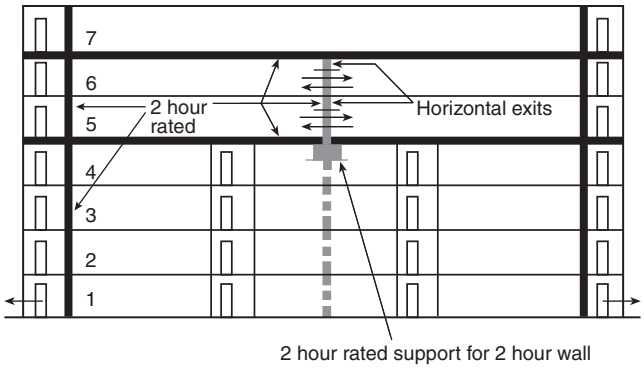

FIGURE 20.15.9 Building with Horizontal Exits on Some Floors

Exit Features

Life safety from fire in health care facilities relies on a "defend-in-place" principle. Horizontal exits or smoke barriers are required to subdivide each story of a health care facility to provide an area of refuge on each floor.

The original concept for the design of exits for health care facilities was derived from studies conducted in the early 1900s. A practice evolved of using exit stair enclosures as areas of refuge. Exit capacity for health care facilities was set conservatively to offset slow travel rates and to create space within exit enclosures for "storing" patients on litters and in wheelchairs.

Means for horizontal evacuation are provided for each story, using either a smoke barrier or a horizontal exit. A barrier subdivides each story to provide an area of refuge for patients without traversing stairs. Furthermore, it is common—indeed, it is required since the 1991 edition of NFPA *101*—to install automatic sprinklers throughout all new health care facilities. Automatic sprinklers limit fire size and complement the defend-in-place strategy currently in use.

Egress capacity in nonsprinklered health care facilities is set at 0.6 in. (15.24 mm) per person for travel over stairs, whereas the capacity through doors and level passageways is calculated at 0.5 in. (12.7 mm) per person. Where automatic sprinklers are provided throughout a building, exit capacity is increased to 0.3 in. (7.62 mm) per person for travel over stairs and 0.2 in. (5.08 mm) per person for travel over level passageways.

Capacity is calculated using a "flow rate" principle. Flow rates assumed are for able-bodied persons because it is presumed that evacuation over stairs will involve only staff, visitors, and ambulatory patients. Nonambulatory occupants are expected to remain in the building under the defend-in-place concept, with those patients on the floor of fire origin being moved horizontally to an adjoining smoke or fire compartment.

Limits on travel distance reflect anticipated slow movement. Travel distance normally should not exceed the following:

1. 100 ft (30 m) between an exit and any room door intended for use as an exit access
2. 150 ft (46 m) between an exit and any point in a room

3. 50 ft (15 m) between any point in a sleeping room or suite of sleeping rooms and the exit access door of that room

Increases in corridor travel distance are permitted in sprinklered buildings.

Because smoke barriers and areas of refuge play such an important role in fire safety, travel distances to smoke barriers is also restricted in NFPA *101*. Travel distance from any point on a floor to reach a door in a smoke barrier is limited to 200 ft (61 m).

Elevators are not permitted to serve as required exits in health care occupancies because they possess numerous shortcomings that may prevent their use during a fire. In the cases of critically ill patients, patients in body casts or balkan frames, and others who would be difficult to move, however, elevators provide the only practical evacuation method from upper stories of the facility. If separate banks of elevators are located in separate smoke compartments, and if the staff are well trained, it may be possible to devise a plan in which using elevators during fires is safe.

Suites

The design of suites has been addressed by NFPA *101* for many years. These requirements, however, were previously dispersed among several topic areas in the code. In the 2006 editions of NFPA *101* and *NFPA 5000,* the terms "suite," "non-sleeping suite," and "sleeping suite," were defined in the context of health care occupancies, and their requirements were consolidated under the provisions for means of egress arrangement.

The suite concept permits groups of rooms in health care occupancies to be treated as one large "room" subject to specified limitations. Normally, rooms in health care occupancies must be provided with direct access to a corridor without traveling through an intervening room. Rooms within suites are not subject to the usual corridor separation requirements, and the circulation spaces within suites are not subject to the strict use limitations imposed on corridors. The creation of suites has long been a cost-effective solution to address the needs of groups of patients having similar health issues or needing similar levels of staff monitoring and care. Suite configurations are often used for specialty care patient sleeping units, such as intensive care, cardiac care, or pediatric care units. Suites can also be used effectively for treatment areas such as a radiology department or operating room suite. In prior editions of NFPA *101* and *NFPA 5000,* sleeping suites were limited in size to 5000 ft^2 (460 m^2) and required direct visual supervision by staff.

Some facility designers and architects have attempted to create sleeping suites larger than 5000 ft^2 using alternative measures (equivalency) to substitute for the requirement of "direct visual supervision by staff" and as a means of providing a cost-effective environment for patients. Based on the prevalence of the suite size limitation issue, the 2006 editions of NFPA *101* and *NFPA 5000* have increased the sleeping suite area limitation from 5000 ft^2 (460 m^2) to 7500 ft^2 (700 m^2) if the suite is provided with smoke detection, sprinkler protection, and direct visual patient supervision by staff. Direct supervision is typically provided from a normally attended staff location. Separation by glass walls is permitted provided that staff can visually see into the patient sleeping room. The use of cubical curtains at patient beds is also permitted; solid walls and doors would not facilitate the required direct visual supervision.

The Technical Committee on Health Care Occupancies recognized that there are practical safety concerns pertaining to how good visual supervision is for patient sleeping rooms within suites. In sleeping suites that do not exceed 5000 ft^2 (460 m^2), any room that lacks direct visual supervision can be used for patient sleeping only where such room is provided with automatic smoke detection arranged to activate the fire alarm. This option only applies to suites that are 5000 ft^2 (460 m^2) or less. Sleeping suites exceeding 5000 ft^2 (460 m^2) are required to provide a total coverage automatic smoke detection system throughout the sleeping suite and provide direct visual patient supervision. It is important to note that although smoke detection can substitute for direct visual supervision in smaller sleeping suites, it is intended that staff are constantly present in the suite.

Several other revisions to the requirements for suites in NFPA *101* and *NFPA 5000* allow for design flexibility without compromising occupant safety. Where two means of egress from a suite are required because of its size, at least one must lead directly to a corridor. The second means of egress is permitted to lead through another suite. See NFPA *101* and *NFPA 5000* for additional details on suite arrangments.

Exit Marking and Exit Illumination

Readily visible signs should mark all exits. Where access to exits is not immediately visible, access routes also should be marked.

The entire means of egress must be continuously illuminated whenever the building is occupied. In some cases, normal street lighting is adequate for illumination of exit discharge. However, consideration should be given to the conditions that would result from a power failure.

Emergency power is also required to illuminate the means of egress and exit marking. In hospitals, this power should be supplied by the life safety branch of the hospitals' essential electrical system. Luminescent, fluorescent, or reflective material should not be substituted for required lighting.

Emergency power supplies should maintain illumination automatically in the event of a power failure without any appreciable interruption during the changeover from normal to emergency power. Where a generator is provided, the delay should not be more than 10 seconds. Where emergency power is supplied by a central system with an engine-driven generator, the design should minimize the probability of any single emergency simultaneously interrupting both normal and emergency power supplies. The switch(es) that transfers power from normal to emergency circuits is one place where normal and emergency circuits are required to merge. If this switch(es) is exposed to fire, it could simultaneously interrupt power to both normal and emergency circuits. The transfer switch and other electrical distribution panels and switch gear should be separated from the generator, as well as from the remainder of the building. See NFPA 99, *Standard for Health Care Facilities,* NFPA *101,* NFPA 110, *Standard for Emergency and Standby Power Systems,* and *NFPA 5000* for additional details on emergency power for health care occupancies.

Fire Alarms

Every health care facility should be equipped with a fire alarm system. When actuated, the system should sound alarms that can be heard above ambient noise levels throughout the facility. Visible alarm indicating devices are permitted in critical patient care areas in lieu of audible alarm devices. The fire alarm should also transmit automatically to the fire department. Any fire detection or fire suppression system that activates should automatically activate the building alarm system.

Alarm systems, including detection devices, should be provided with an emergency power supply and designed according to *NFPA 72®*.

The activation of any sprinkler system, manual fire alarm box, or detection device should provide automatically an alarm for staff and/or occupants within the affected zones initially. Means to notify staff and occupants in other zones as needed should be provided. In sprinklered health care facilities, positive alarm sequence in accordance with *NFPA 72* is permitted. Although the use of a general evacuation alarm is permitted, it may be more appropriate to use the private operating mode as described in *NFPA 72* because occupants may be incapable of evacuating without assistance. The private operating mode recognizes that health care facility staff will perform and direct evacuation procedures within patient areas affected by the fire. The private operating mode requires that the notification method for staff provide a means to identify the zone, area, floor, or building in need of evacuation.

FIRE SUPPRESSION EQUIPMENT

Automatic Sprinkler Systems

A proven effective, practical, and reliable approach to life safety in health care facilities is to use automatic fire suppression—in particular, automatic sprinkler systems. Although persons in the area of origin may still be seriously threatened, those in adjoining spaces—and, in a number of cases, in the same room—are protected.[2,3,7,12] NFPA *101* and *NFPA 5000* require all new health care facilities to be protected by automatic sprinklers.

The 1991 edition of NFPA *101* was the first to require sprinkler protection for all new health care facilities. Two multiple death nursing home fires occurred within seven months of each other in 2003—one in Hartford, Connecticut, on February 26, 2003, that resulted in 16 deaths, and another in Nashville, Tennessee, on September 25, 2003, that resulted in 15 deaths. These fires resulted in calls to require automatic sprinkler protection in all existing nursing homes. As a result, the 2006 edition of NFPA *101* became the first edition to retroactively require that all buildings containing nursing homes be protected throughout with electrically supervised automatic sprinkler systems.

Full sprinkler protection obviously increases the level of fire protection and life safety in nursing homes; however, the impact on scarce health care funding must also be addressed. Although the design, installation, and maintenance of sprinkler systems in nursing homes will have a measurable cost (which can be affected by the availability of an adequate water supply), there are associated savings, including the following:

- Some buildings of noncompliant construction types could "become" compliant, negating the need for equivalencies, other alternate means of protection, or waivers.
- Increased allowable travel distances permitted in sprinklered facilities could solve existing egress problems and/or facilitate building additions.
- Hazardous area enclosures would change from 1 hour fire barriers to smoke partitions—facilities might save money because firestopping of penetrations above the ceiling would no longer be necessary.
- Some areas would be allowed to be open to the corridor.
- Corridor walls would be required to be smoke resistant rather than fire rated—facilities might save money because firestopping of corridor wall penetrations above the ceiling would no longer be necessary.
- The requirement for smoke dampers in duct penetrations of smoke barriers in fully ducted HVAC systems would be eliminated—facilities could disconnect existing dampers, fix them in the open position, and save money on future testing and maintenance.
- Newly introduced upholstered furniture and mattresses could be less expensive because they would be exempted from ignition resistance and heat release rate standards.

The ability of automatic sprinklers to provide a survivable environment for building occupants has been debated at length. Full-scale tests have shown that standard sprinklers can extinguish many fires while maintaining a survivable atmosphere outside the room of fire origin.[2,5] In addition, sprinklers have been shown to be effective in limiting carbon monoxide to nonlethal levels outside the room. Tests have also shown that privacy curtains may interfere with sprinkler discharge.[13] To obtain full sprinkler effectiveness, the influence of any building design feature or furnishing that would impair sprinkler discharge should be evaluated carefully.

The quick-response or fast-response sprinkler has been shown in most instances to maintain a survivable atmosphere within the room of fire origin. Full-scale tests at NIST have documented this performance.[13]

Where fire defenses are based on automatic sprinkler systems, fast-response sprinklers should be considered for the entire building. At a minimum, fast-response sprinklers should be used throughout compartments having sleeping rooms. This is required for new health care facilities by NFPA *101*.

Automatic sprinkler systems should comply with NFPA 13, *Standard for the Installation of Sprinkler Systems.* Sprinkler operation should sound the building fire alarm automatically. The sprinkler system and components should be electrically supervised to ensure reliable operation and should include valve tamper switches with a local alarm at a constantly attended location when the valve is closed. If pressure tanks are the primary source of water, air pressure, water level, and temperature should be supervised. If fire pumps are provided, electrical supervision should monitor the fire pump in accordance with NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection.*

Portable Fire Extinguishers

Portable fire extinguishers should be placed in all buildings, as they may provide an opportunity to control a fire during its early stages. In all cases, however, the fire department should be notified before or at the same time that occupants are attempting to fight the fire. Delayed alarms have allowed fires to grow to large scale and, in turn, threaten occupants before fire department notification and arrival.

Smoke Control

Although operable windows were required in every patient sleeping room for many years, neither NFPA *101* nor *NFPA 5000* requires them. Outside windows are required but need not be operable. Windows in atrium walls are considered to be equivalent to outside windows in health care facilities.

Special forced-air systems or, in some cases, the adaptation of conventional building air-handling systems can permit venting of products of combustion early in the fire. Such systems may also make it possible to create a pressure difference across physical barriers, such as floors or partitions, and prevent smoke transfer. The effectiveness of fire partitions often improves significantly by the use of such systems.

Where adaptation of the building air-handling system is contemplated for smoke removal, its design should be in accordance with NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences.* Consideration should be given to alternative power supplies and electrical supervision of critical system components.

PROTECTION OF HAZARDOUS AREAS

Areas with contents more hazardous than those normally found in health care facilities should be arranged to minimize occupant exposure if a fire occurs. NFPA *101* and *NFPA 5000* address hazardous areas in general and also address hazardous areas in the specific occupancy chapters. The general provisions require one of the following:

1. Enclose the hazardous area with fire barriers having a 1-hour fire resistance rating and without windows.
2. Protect the area with an automatic extinguishing system.
3. Apply the protection of both (1) and (2) where the hazard is severe or where otherwise specified by the occupancy chapters.

When the 1 hour enclosure is used, the doors must be ¾ hour fire rated, self-closing, and positive-latching doors. Typically, in new construction and in any health care occupancy, when a hazardous area is sprinkler protected without having a fire resistance rated enclosure, the area must be protected with at least a smoke-resisting enclosure equipped with smoke-resisting self- or automatic-closing doors. In health care facilities, corridor doors are normally required to latch. Doors in hazardous areas are typically required to be self- or automatic-closing doors and self-latching.

The health care occupancy chapters of NFPA *101* and *NFPA 5000* detail the specific areas that must be addressed as hazardous areas; however, the listed areas are not intended to be all-inclusive, and the general provisions must be met if an area poses unusual fire hazards in the health care facility.

There are provisions related to other hazardous areas, including gift shops, laundry and trash chutes, cooking facilities, and laboratories. Gift shops must be protected as hazardous areas when they are used for storing or displaying combustibles in quantities considered hazardous. Trash chutes and linen chutes can pose significant fire risks for health care occupancies. These areas should comply with NFPA 82, *Standard on Incinerators and Waste and Linen Handling Systems and Equipment.* Laboratories, anesthetizing locations, and medical gas systems should comply with the provisions of NFPA 99, which relate to the protection of hazardous areas. New heliports must comply with NFPA 418, *Standard for Heliports.* Cooking facilities are required to be protected in accordance with NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations.*

Building Service Equipment

Building service equipment should be installed and maintained in accordance with appropriate NFPA standards. Special consideration should be given to the design and installation of heating and air-conditioning systems.

Portable heating devices are unsafe in patient-occupied portions of health care facilities. All heating devices should be designed and installed to prevent ignition of combustible materials. Approved suspended unit heaters may be used, except in means of egress and patient sleeping areas, if they are high enough to be out of the reach of persons using the area.

Air for combustion and ventilation in boilers, incinerators, or heater rooms should be taken directly from, and discharged directly to, the outside of the buildings.

OPERATING FEATURES

Smokers cause many fires in health care facilities. Adoption and enforcement of suitable smoking regulations are essential.[7] Smoking should be prohibited in any room, ward, or compartment where flammable liquids, combustible gases, or oxygen is used or stored. Such areas should be posted with no-smoking signs. Smoking by patients who are under sedation or who are not considered responsible should be prohibited. Smoking should be permitted in a sleeping room only when authorized by medical staff and then only under direct staff supervision. Metal containers with self-closing covers should be available for disposal of smoking materials in all areas where smoking is allowed.

Most hospitals and many nursing homes have established no-smoking policies. JCAHO requires hospitals to be smoke free. Nursing homes are becoming smoke free on a voluntary basis. These are very positive steps in improving the level of fire safety in health care facilities.

Visitors sometimes give patients smoking materials without the staff's knowledge. Health care facilities need to address this serious issue. In 1989, 12 residents died in a Norfolk, Vir-

ginia, nursing home fire attributed to a visitor giving a resident smoking materials.

Window draperies and curtains should be made of noncombustible material or material that has been rendered and maintained flame retardant. These window hangings should be capable of passing NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films.* Furnishings, decorations, and other objects should not obstruct exits or exit access routes. Combustible decorations should be prohibited.

Exits and mechanical devices provided to control or limit fire should be maintained to ensure reliable operation. Inspections and tests should be performed, as required, to verify satisfactory performance.

In facilities with locked exits, adequate staff should always be present to release occupants and direct them away from the fire area to a place of safety during an emergency.

Care should be exercised during construction and repair operations to ensure that such activities do not reduce life safety.

EMERGENCY PLANNING

In no occupancy are staff training and emergency planning more important than a protect-in-place occupancy housing a significant number of occupants incapable of self-preservation. Every health care facility must have a fire and evacuation plan, including a disaster plan, with which all personnel must be familiar. NFPA 99 provides guidance for both internal and external disasters that affect health care facilities. In addition, personnel should be trained to use fire extinguishers and hose cabinet lines if provided. They must also know how to sound an alarm, move or evacuate patients, and contain the fire.

Each facility should have a safety officer whose primary responsibility is to recognize hazards, act as liaison with the fire service, and arrange for training personnel. While training health care personnel is straightforward and can be accomplished on the job, orienting members of the fire service to health care facility problems is more difficult.

Copies of the fire and evacuation plan should be available to all personnel. The plan should contain specific instructions for key—that is, supervisory—personnel if there is a fire. A copy of the plan also should be posted for reference. All employees should be periodically trained to ensure readiness.

Emergency drills should include transmission of a fire alarm signal and simulation of emergency conditions insofar as possible without jeopardizing occupants. Drills should be conducted on each shift at least quarterly, with at least 12 drills held every year. The drills should be varied to test the alertness of all shifts and, if possible, should be unannounced. Use of the building alarm during drills also verifies its normal operation.

The fire and evacuation plan should include the following fundamentals:

- Training personnel to use the alarm and alarm equipment
- Transmission of alarm to the fire department
- Details of the fire location
- Evacuation practices for all areas
- Preparation of building spaces for evacuation
- Fire extinguishment

During drills, emphasis should be on immediate notification of the fire department; many fires have spread because of delayed alarms.

FIRE SAFETY EVALUATION SYSTEM

NFPA codes contain the fundamental statement of the "equivalency concept," which provides for the use of alternatives to the methods, materials, devices, systems, and so on that are prescribed and/or specifically detailed by the codes. Key to the concept of equivalency is the submission of technical documentation acceptable to the authority having jurisdiction. One method of providing technical documentation for health care facilities is to appropriately apply and utilize the *Fire Safety Evaluation System for Health Care Occupancies (FSES),* which provides a formalized equivalency methodology specific to health care occupancies. The documentation and procedure for the use of this fire safety evaluation system are found in NFPA 101A, *Guide on Alternative Approaches to Life Safety.*

The *FSES for Health Care Occupancies* has, since the 1981 edition of NFPA *101,* provided a basis for developing alternatives that achieve a level of safety equivalent to that mandated by the *Life Safety Code.* The *FSES* was developed to provide a rational basis for achieving the level of safety intended by the *Life Safety Code* without necessarily meeting all of its prescriptive requirements. This can be especially important for existing buildings in which physical conditions may not allow strict compliance or where retroactive compliance may present an economic hardship.

The *FSES* involves the evaluation and comparison of the risk factors and safety features present or proposed for a health care occupancy. The *FSES* methodology for health care occupancies is based on the evaluation of individual "zones," which are generally the spaces separated by floors, horizontal exit barriers, or smoke barriers. The risks of a zone consider the number of people affected by a given fire, the density of the people in the zone, the mobility of the patients, the age of patients, the location of the zone, and the ratio of patients to staff in the given zone.

In addition to the risk aspects of the *FSES,* each zone must consider the ability of the building and its fire protection features to provide measures of safety commensurate with the risk. Safety parameters that are evaluated include building construction fire resistance, interior finish, corridor partitions/walls, corridor doors, zone dimensions, vertical openings, hazardous areas, smoke control, egress routes, fire alarms, fire detection, and automatic sprinklers. Redundancy of the safety features is an important aspect of the *FSES.* By evaluating the redundancy of safety features, the methodology intends to ensure that the failure of a single protection feature or device will not result in major failure of the entire system.

The approach is quantitative in that the *FSES* awards positive point values for strong life safety and fire protection features and negative point values for lesser conditions. With appropriated selection of alternative features a number of both positive and negative factors can be balanced in a manner that results in establishing a level of life safety equivalent to NFPA *101* without complying with all of its prescribed requirements.

The *FSES* methodology has a long and proven track record, but it is not the only approach available for establishing equivalency. NFPA *101* formally recognizes performance-based options for the design and analysis of alternatives to the prescriptive requirements of the code. Additional discussion of the performance-based option can be found in Section 3, Chapter 10, "Performance-Based Codes and Standards for Fire Safety."

AMBULATORY HEALTH CARE

The provisions for ambulatory health care facilities intend to fulfill the needs of facilities that do not pose the risks of 24 hour health care facilities such as hospitals but do pose a greater risk than medical office buildings (business occupancy) that provide for routine doctor visits.

The definition of an ambulatory health care occupancy has three key elements:

1. An ambulatory health care occupancy is a building or portion of a building used to provide services or treatment simultaneously to four or more patients.
2. The services or treatment provided is done solely on an outpatient basis and renders the patients incapable of taking action for self-preservation under emergency conditions without the assistance of others.
3. Anesthesia is provided solely on an outpatient basis and renders the patients incapable of taking action for self-preservation under emergency conditions without the assistance of others.

The distinguishing features of an ambulatory health care occupancy are that 24 hour sleeping accommodations are not provided and services are rendered solely on an outpatient basis. This effectively means that patients walk in and walk out of the facility but may be subject to treatment or anesthesia that temporarily renders them incapable of self-preservation, including postoperative recovery in a bed.

The life safety and fire protection features specified in NFPA *101* and *NFPA 5000* for ambulatory health care occupancies are a blend of those used for both health care occupancies and business occupancies. In fact, many of the provisions for ambulatory health care facilities are simply addressed by references to the provisions for business occupancies. Construction type requirements are less restrictive than those required for health care occupancies but more restrictive than allowed for business occupancies. Several egress requirements are more restrictive than those permitted for business occupancies. Also, there are specific provisions for mixed occupancies, smoke compartments, and fire alarm features that will affect the design of an ambulatory health care occupancy.

SUMMARY

Total building fire protection for life safety is more necessary in health care facilities than in other occupancies because of the nature of the occupants. A significant percentage of occupants in hospitals and nursing homes are incapable of self-evacuation or are ambulatory but incapable of perceiving a fire threat and choosing a rational response. Therefore, fire protection is based on a "defend-in-place" principle and cannot depend on any one safeguard. As a result, health care facility design and operation must incorporate methods by which a fire can be detected early, contained, and fought rapidly and successfully. Fire safety requirements include fire-resistive construction, compartmentation, fire-alerting facilities, and control of smoke movement. In addition, it is critical that every health care facility have a fire and evacuation plan, including a disaster plan, with which all personnel are familiar. Personnel should be trained in emergency procedures, including how to sound an alarm, move or evacuate patients, and contain the fire. Emergency drills should be conducted on each shift at least quarterly, with at least 12 drills held every year.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on health care facilities discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 20, *Standard for Installation of Stationary Pumps for Fire Protection*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 55, *Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks*

NFPA 72®, National Fire Alarm Code®
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA 96, *Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations*
NFPA 99, *Standard for Health Care Facilities*
NFPA *101®, Life Safety Code®*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*
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Chapter 16

Storage Occupancies

Revised by
Jeffrey Moore

Chapter Contents

NFPA Storage Standards
Occupancy Characteristics
Hazards Associated with Occupancy
Operational Hazards and Fire Prevention Practices
Life Safety Considerations
Building Construction Affecting Hazardous Conditions
Automatic Sprinkler Protection
Supplemental Fire Protection
Special Storage Facilities
Warehouse Fire-Fighting Operations and Pre-Incident Planning
Outdoor Storage

Key Terms

aircraft hangar, automatic sprinkler system, bulk storage, characteristics of materials, cold storage warehouse, commodity, fire-fighting operations, flammable liquid, mixed storage, outdoor storage, pallet storage, parking garage, pier, portable fire extinguisher, pre-incident planning, private fire service main, rack storage, smoke venting, storage occupancy, warehouse

This chapter addresses fire protection for storage and warehouse operations. Due to the nature, quantity, and arrangement of inventory in these occupancies, intense fires can develop rapidly. Developing and implementing a comprehensive fire protection plan are essential to minimize the potential for significant fire loss and disruption of operations.

Modern storage practices aim to maximize storage efficiency by piling products high and leaving minimal aisle space between storage piles or racks. As a result, enormous volumes of combustible material are often located in a single fire area or building. In addition, many warehouses contain large quantities of plastics as both products in storage and as packing materials. Most plastics burn rapidly, have a high rate of heat release, and generate copious amounts of smoke, soot, and toxic products of combustion.

Most facilities have some sort of storage or warehousing area to store raw stock, in-process goods, or finished products. The area may be called a storeroom, parts crib, or central sterile supply, depending on the type of facility and the materials in storage. Fortunately, the incidence of fires in storage areas is relatively low compared to other occupancies. Unfortunately, when storage and warehousing fires do occur, they tend to be severe.

This chapter reviews basic fire protection principles for the protection of warehousing and storage areas. It presents an overview of the fire protection features that a comprehensive fire protection program needs and highlights materials and storage occupancies that pose unusual fire protection challenges.

See also Section 6, "Characteristics of Materials and Products"; Section 7, "Storage and Handling of Materials"; Section 9, Chapter 7, "Storage and Handling of Grain Mill Products"; and Section 18, Chapter 4, "Venting Practices."

NFPA STORAGE STANDARDS

NFPA has developed standards that provide an effective means of preparing fire protection plans for various types of storage occupancies. Design requirements for sprinkler system protection of general indoor storage, rack storage, rubber tires, roll paper, baled cotton, and other commodities have been consolidated into NFPA 13, *Standard for the Installation of Sprinkler Systems*.

The fire protection for commercial warehousing and storage occupancies depends on the type of storage and the methods of storage. In most cases, the protection standards contemplate dedicated storage areas with storage heights exceeding 12 ft (3.7 m). NFPA 13 addresses fire protection for miscellaneous storage not meeting this criteria, as well as the protection requirements for dedicated warehousing and storage areas of most commodities.

Miscellaneous storage typically does not exceed 12 ft (3.7 m) in height and is incidental to the primary operations in a facility. For example, small areas used for parts storage along an assembly line would generally be considered incidental storage. A storeroom in a business occupancy would also usually be considered incidental storage. NFPA 13 describes the various types of storage and the design of automatic sprinkler protection for each type and configuration of storage.

The requirements contained within NFPA standards, such as NFPA 13, are based on full-scale fire tests and past fire experience. The standards do not address storage arrangements where

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test data are not available or where valid conclusions could not be drawn from the extrapolation of available data, judgment, or experience. For storage arrangements beyond the scope of a specific NFPA document, engineering judgment and other sources should be utilized. In some cases this may require actual fire testing of the materials and configurations encountered or contemplated.

OCCUPANCY CHARACTERISTICS

A study of warehouse fires conducted by NFPA and several major property insurers showed that over a 4 year period, warehouse and storage fires comprised only 14 percent of the reported fires, but these fires caused nearly 40 percent of the damage incurred. The study further determined that, on average, a warehouse fire occurs every 22 hours, and that a warehouse fire that results in a loss of over $500,000 occurs every 11 days.[1]

Storage occupancies are buildings, or portions of a building, used to store or shelter goods, merchandise, products, vehicles, or animals. Storage facilities can be separate and distinct facilities or part of a multiple-use occupancy. Storage occupancies pose a wide range of fire protection challenges, including large open fire areas, high values concentrated in a relatively small area, limited access for fire suppression operations, and fuels arranged in arrays conducive to rapid fire development and spread. Examples of storage occupancies are warehouses, freight terminals, parking garages, aircraft hangars, grain elevators, and outdoor storage areas. Table 20.16.1 shows the estimated frequency of fires in various warehousing and storage occupancies.

NFPA 13 classifies storage occupancies as light-, ordinary-, or extra-hazard, or a combination of these where mixed commodities are stored together without separation. NFPA *101®*, *Life Safety Code®*, and *NFPA 5000®, Building Construction and Safety Code®*, divide storage occupancies into low-, ordinary- and extra-hazard. Factors affecting the hazard classification are burning characteristics of the material stored, combustibility of packaging, method of storage and packaging, and the quantity stored.

Current material handling technology permits storage in automated storage and retrieval systems to heights exceeding 100 ft (30 m). Computer-controlled stacker cranes are now being used to move and place commodities in rack storage areas. Distribution warehouses may cover several acres under one roof and may contain multilevel mezzanines. These large, open areas pose a major fire threat. Fortunately, storage occupancies usually have a limited number of occupants in relation to total floor area. The presence of fewer people generally translates into a lower incidence of fire. Although some warehouses with automatic storage and retrieval systems are fully automated, the workflow in most warehouses usually requires employees to move materials through the facility using industrial lift trucks.

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The contents of storage occupancies may consist of raw materials, goods in an intermediate stage of production, or finished products. These materials may be found in bulk storage, solid piling, palletized storage, or rack storage arrangements. Bins and narrow shelves are also used, usually in stockrooms and small storage areas. The major difference between these storage arrangements is the exposed surface area of the storage. As the exposed surface area of the storage increases, the speed at which a fire develops increases. Other storage occupancies, such as parking garages, grain elevators, and aircraft hangars create other problems due to the nature of operations in the building. The problems posed by these and other storage operations are addressed later in this chapter.

Mini-Storage Facilities

Mini-storage facilities for rental to the general public consist of several small rental spaces ranging from 40 to 400 ft^2 (3.7 to 37 m^2) in one building or several adjacent buildings. These facilities pose some unique fire problems of their own. There is little control over the type and amount of materials that may be stored in rental areas because they are accessible to renters on a 24 hour basis. Automatic sprinklers are typically not installed in these buildings and fire-resistance-rated walls or barriers do not usually separate the individual rental spaces from each other.

HAZARDS ASSOCIATED WITH OCCUPANCY

Contents

In determining the hazard classification of storage, consideration should be given to the product, product container, and packaging materials. The fire hazard of a warehouse or storage occupancy is a function of the commodity or material in storage, the method of packaging, and the storage arrangement. Fire development in a storage area depends on the material, ease of ignition, flame spread rate, and the rate of heat release. All too often a judgment concerning the hazard of the storage is based on the commodity with little thought given to the methods of packaging and the storage arrangement. For example, a metal part stored on a wooden pallet poses a low threat of fire. However, if the same part is packaged inside a multilayer cardboard carton with expanded polystyrene foam packing material, the fire hazard is greatly increased. Plastics are increasingly used as part of the product as well as the packaging.

Package Commodity Storage. A packaged commodity must be considered as a whole—that is, the way it burns. For example, bottled beer would be considered a low hazard, but when stored in cardboard or wood containers, it becomes an ordinary-hazard commodity. Washing machines have very few combustible components. However, they can burn rapidly and produce large volumes of smoke where packaged in cardboard boxes and surrounded with plastic packing materials.

Mixed Storage. In areas with mixed storage, the hazard classification should be based on the most hazardous storage. This mixed condition is common in most warehouses supplying department stores, hardware stores, and automotive parts stores. High-hazard materials or materials that require special consideration can sometimes be segregated from other storage to keep

TABLE 20.16.1 Reported U.S. Structure Fires in Warehouse-Type Storage Properties, 1994–1998 Annual Averages

Type of Storage Facility	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Loss (in Millions of Dollars)*
WAREHOUSE (excluding refrigerated storage)	5489	3	73	237.2
General item storage (excluding wharf or pier, ice storage)	2893	2	37	103.3
General warehouse	1338	1	25	77.3
Freight terminal	75	0	1	2.5
Coal or coke briquette or charcoal storage	13	0	0	0.5
Packaged mineral products storage	8	0	0	0.5
Other military or national defense storage	7	0	0	0.2
Bagged mineral products storage	6	0	0	0.0
Unclassified general item storage	885	0	6	11.1
Unknown-type general item storage	562	1	4	11.2
Agricultural products storage (containerized)	820	0	9	19.7
Agricultural supply storage	650	0	8	14.5
Boxed, crated, or packaged agricultural products storage	82	0	1	3.4
Loose or bagged agricultural products storage	57	0	0	1.1
Loose or baled tobacco storage	30	0	0	0.7
Wood or paper products storage (excluding timber or wood fuel)	663	1	12	35.7
Lumberyard or building materials storage	180	0	2	15.6
Paper or paper products storage	163	0	4	10.0
Wood products or furniture storage	112	0	3	2.8
Fiber products storage	27	0	0	1.2
Rolled paper storage	13	0	0	0.2
Unclassified wood or paper products storage	57	0	0	2.6
Unknown-type wood or paper products storage	110	0	2	3.3
Metal or metal products storage (excluding scrap yards)	498	0	3	18.3
Machinery storage	142	0	1	4.8
Hardware storage	110	0	0	4.3
Electrical appliance or supply storage	44	0	0	1.1
Basic metal form storage	39	0	0	1.9
Metal parts storage	38	0	1	1.9
Finished metal products storage	21	0	0	0.4
Unclassified metal or metal products storage	37	0	0	0.9
Unknown-type metal or metal products storage	66	0	0	3.1
Chemical or plastic or related products storage	270	1	8	49.2
Plastic or plastic product storage	43	0	0	4.1
Industrial chemical storage	42	0	2	31.7
Paint or varnish storage	38	0	1	2.3
Rubber or rubber products storage	35	0	1	2.2
Hazardous chemical storage	34	0	4	2.7
Fertilizer storage	15	0	0	0.3
Drug, cosmetic, or pharmaceutical storage	14	0	0	0.2
Photographic film storage	6	0	0	0.0
Unclassified chemical or plastic or related products storage	14	0	0	2.2
Unknown-type chemical or plastic or related products storage	29	0	0	3.4
Processed food or tobacco storage (not refrigerated)	172	0	3	4.0
Packaged foodstuff storage	76	0	1	1.8
Canned or bottled food or soft drink storage	29	0	1	0.7
Loose or bagged processed food storage	26	0	1	0.6
Packaged tobacco product storage	3	0	0	0.0
Bulk sugar storage	1	0	0	0.0
Bulk flour or starch storage	1	0	0	0.0
Unclassified processed food or tobacco storage	12	0	0	0.2
Unknown-type processed food or tobacco storage	24	0	0	0.6

continued

TABLE 20.16.1 Continued

Type of Storage Facility	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Loss (in Millions of Dollars)*
Textile storage	140	0	1	5.6
Clothing or finished textile storage	47	0	0	0.6
Baled cotton storage	22	0	0	0.9
Cloth or yarn storage	12	0	0	0.2
Baled jute, flax, or mixed fiber storage	7	0	0	0.3
Leather or leather products storage	5	0	0	0.0
Baled silk or synthetic fiber storage	4	0	0	0.6
Fur, skin, or hair products storage	3	0	0	0.0
Baled wool or worsted storage	0	0	0	0.0
Unclassified textile storage	18	0	0	1.6
Unknown-type textile storage	22	0	0	1.3
Flammable or combustible gas or liquid storage (containerized)	34	0	0	1.4
Alcoholic beverage storage	18	0	0	0.5
Packaged petroleum products storage	16	0	0	0.9
REFRIGERATED STORAGE	63	0	0	3.6
Cold storage	46	0	0	2.0
Food locker plants	9	0	0	1.5
Ice storage	8	0	0	0.1
Total of warehouse-type properties	5552	3	73	240.8

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires, deaths, and injuries are estimated and direct property damage rounded to the nearest hundred thousand dollars. Sums may not equal totals due to rounding errors. Damage has not been adjusted for inflation.

Source: National estimates based on NFIRS and NFPA survey.

them from influencing the overall hazard classification. Examples of high-hazard materials are rubber tires, plastic products, combustible fibers, paper and paper products, hanging garments, carpeting, pesticides, flammable liquids and gases, and reactive chemicals. NFPA 13 details the specific sprinkler requirements for areas containing such commodities.

Flammable Aerosol Products. Flammable aerosol products pose an extreme hazard. When heated in a fire, the containers rupture, produce fireballs, and can rocket throughout the storage area. This results in the ignition of multiple fires that can quickly overwhelm the automatic sprinklers. Bulk storage of aerosols should meet the requirements of NFPA 30B, *Code for the Manufacture and Storage of Aerosol Products.* Smaller quantities of flammable aerosol storage should be segregated in a specially protected room or in flammable liquid storage cabinets.

A 1982 fire in a K-Mart distribution warehouse, located in Falls Township, Pennsylvania, vividly illustrated this hazard. The fire started in palletized storage of petroleum-liquid-based aerosol containers. Exploding aerosol cans quickly overwhelmed the automatic sprinklers and destroyed the 1.2 million ft^2 (111,500 m^2) distribution center.[2] The rapid spread of the fire was due in great part to rocketing aerosol cans that spread the fire throughout adjoining areas.

The 1982 K-Mart distribution warehouse fire is just one of many similar incidents that illustrates the need for proper segregation and protection of flammable aerosols. A single pallet of flammable aerosols is sufficient to burn a general storage warehouse to the ground. Such materials need to be stored in a special area with fire protection features designed in accordance with NFPA 30B.

Storage Arrangement

The arrangement of stored materials impacts the potential for fire spread. It also affects the efficiency of materials handling in the warehouse, and, unfortunately, this is where fire protection and materials-handling efficiency generally conflict with each other. Each feature that is desirable to enhance fire safety usually has a negative impact on the operating efficiency of the warehouse.

Aisles are required in storage areas to permit access by materials-handling equipment. For maximum storage efficiency, these aisles are normally as narrow as possible and spaced as far apart as possible. These same aisles provide access to the area for manual fire suppression operations during a fire and act as fire breaks between storage piles or racks. From a fire safety standpoint, wide aisles spaced at short intervals are preferred. Such arrangement permits maximum access to the area while decreasing the probability of fire spread across an aisle due to radiant heat or from a pile collapse. See Figure 20.16.1 for an example of a typical rack storage arrangement. Note that aisles

FIGURE 20.16.1 Typical Rack Storage Arrangement (Courtesy of Jeffrey Moore)

provide access for materials-handling equipment as well as acting as fire breaks between the storage racks.

Horizontal air spaces formed by the pallets in palletized storage create open channels that feed air into the center of the storage and serve as pathways for fire spread throughout the pile. Rack storage compounds this problem by exposing multiple surfaces of the storage, permitting them to burn simultaneously.

Storage height is another area where fire protection and materials-handling efficiency clash. In general, the higher the storage is stacked, the greater the fire control challenge. Higher storage means more surface area exposed to burning and a greater total quantity of fuel available. The rate of heat release will also be greater as the height of the storage is increased.

As storage expands and available warehouse space decreases, the trend is to increase the storage height. This can be done safely as long as the automatic sprinkler protection is designed to meet the additional challenge posed by the higher storage. Even one extra tier of storage can be enough to burn a warehouse to the ground if that extra tier increases the storage height beyond the protection capabilities of the sprinklers.

OPERATIONAL HAZARDS AND FIRE PREVENTION PRACTICES

Storage occupancies often encompass large open spaces occupied by only a few people. With few occupants in the area, fires in the incipient stage may go undetected for an extended time period, particularly in spaces not protected by automatic fire detection or suppression systems.

Common hazards and ignition sources generally associated with storage occupancies are incendiarism, hot work operations, failure of electrical equipment, careless disposal of smoking materials, and ignition from materials-handling equipment.

Incendiarism

Storage occupancies are vulnerable to incendiary acts because they often present an inviting target for those who wish to cause a great deal of damage and disruption. Often an arsonist can enter and start a fire without being detected. Even where security personnel are present but access is not tightly controlled, arsonists may ignite a fire in a location beyond their sight. Such fires can grow to disastrous proportions before detection, particularly if multiple fires are set.

Hot Work Operations

Hot work operations, such as cutting, welding, and grinding, should be prohibited in storage areas unless there is no other method of accomplishing the work. If hot work is conducted in a storage occupancy, extraordinary precautions must be taken to prevent ignition of the stored materials. Such operations should not begin until all combustible materials have been removed from the area or covered with a fire-retardant cover. Portable fire extinguishers or small hose lines should be ready for use before the operation begins. A fire watch must be present at all times during operation and for at least 30 minutes after its completion. Consideration should be given to using mechanical fastening devices and saws when repairing or replacing steel racks to avoid cutting or welding. All cutting and welding must be conducted in accordance with NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work.*

Lighting and Heating Appliances

Sufficient clearance must be provided between storage and any lighting fixtures or heating appliances in the area. The appropriate NFPA standards, such as NFPA 70, *National Electrical Code*®, should be consulted to determine the minimum required distances from electrical equipment. Special care is needed when using temporary or portable lighting or heating appliances. Relevant NFPA codes and standards must be strictly observed for all types of heating and electrical distribution system equipment in storage areas.

Smoking

Smoking should be prohibited in storage areas. Effective implementation of a smoking control program requires facility management to conscientiously enforce the smoking prohibition and also provide a safe area for employees to smoke. Such areas should be confined to specific areas set aside from storage. The areas must be kept clean and appropriate disposal containers must be provided.

Housekeeping Practices

Proper housekeeping practices prevent the accumulation of combustible waste that can serve as the point of origin for a fire. Packing or unpacking operations generally result in the generation of significant quantities of loose packing materials such as paper, cardboard, and polystyrene beads or cocoons. Procedures must be in implemented to remove excess materials from the building before they pose a significant hazard.

Idle Pallet Storage

Piles of empty wooden pallets are an ideal configuration for rapid development of a fire. The pile is essentially multiple layers of combustible fuel each separated by a layer of air. The built-in flues provide a means for fire to spread throughout the pile and for air to carry oxygen to the layers of burning fuel. Their large surface area to mass ratio also makes the pallets easy to ignite. Plastic pallets and shipping containers present similar hazards. Empty pallet storage poses a severe threat of a fast-developing fire. Even where stored in areas protected by automatic sprinklers, idle pallet fires can cause extensive damage. Pallet pile sizes should be limited, and the pallets should preferably be stored outside, away from any buildings (Figure 20.16.2). If pallets must be stored inside the building, they should be in a segregated area with automatic sprinklers designed for such storage. NFPA 13 contains special provisions for the design of sprinklers to protect idle pallet storage.

Industrial (Lift) Trucks

Industrial trucks, also called lift trucks or forklifts, are an integral part of most storage occupancies. The trucks are usually electric or propane powered, although some may use other fuels. Misuse of the trucks can result in their being an ignition source.

FIGURE 20.16.2 Idle Pallet Storage Should Be Away from Buildings. Here the pallet storage poses a severe threat to the building. (Courtesy of Jeffrey Moore)

There have been many multimillion dollar losses caused by the improper use or application of industrial lift trucks.

The general hazards associated with the use of lift trucks are refueling operations, maintenance, and storage when not in use. Refueling operations should be conducted outside or in a segregated area of the storage building or warehouse. Fuel leakage during refueling operations has been the cause of many fires. Storage and dispensing of the fuel must comply with applicable NFPA codes and standards. Lift trucks used in areas where flammable or combustible liquids are stored must be specifically listed for use in such areas. NFPA 505, *Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operations,* designates the type of truck that can be used in a hazardous area.

LIFE SAFETY CONSIDERATIONS

The life safety hazard in a storage occupancy depends on a number of factors. These include the materials stored, the storage configuration, construction of the building, the type and design of the fire protection systems provided, and the number, arrangement, and location of the exits provided. Fire in a storage area can develop and spread rapidly. Although the occupant load is generally light in a storage occupancy, the means of emergency egress is a concern. In single-story buildings with high ceilings, smoke and heat may have a place to accumulate before descending to a level that obscures or obstructs the means of egress. In buildings with low ceilings, the opposite occurs. In multilevel buildings, smoke and heat from fires below can rapidly block a means of egress on an upper level. (The thermal gradient normally causes the smoke and products of combustion to rise to the ceiling.) In buildings protected by automatic sprinklers, operation of the sprinklers may contain the spread of fire, but it also usually upsets the thermal gradient in the space. This can cause smoke to hang close to the floor, disrupting egress from the area.

In older multiple-floor warehouses, unprotected vertical openings for freight elevators and other materials-handling systems are common. These permit rapid smoke and heat spread to upper floors.

Egress Design

NFPA *101®*, *Life Safety Code®*, and *NFPA 5000®*, *Building Construction and Safety Code®,* address life safety from fire and similar emergencies. They detail the features required to provide the minimum level of fire safety to occupants of a storage or warehouse occupancy, including the number of exits required and the arrangement of the means of egress.

NFPA *101* and *NFPA 5000* classify the materials stored in a warehouse or storage occupancy as low-, ordinary-, or high-hazard based on the expected speed of fire development. The codes contain significantly different requirements for different hazard classifications. For example, the maximum travel distance to an exit in a warehouse with low-hazard contents is essentially unlimited, whereas the maximum travel distance to an exit in a warehouse with high-hazard contents is 100 ft (30 m) where

sprinklers are provided, and 75 ft (23 m) where the building is nonsprinklered. Where a warehouse or storage area contains storage of different classifications in the same area, the requirements for the most hazardous classification apply. Sound judgment must be used when determining the hazard classification of the contents. NFPA *101* and *NFPA 5000* use ordinary-hazard as the basis for general requirements; most storage occupancies fall into this classification. Only rarely does storage fall into the low- or high-hazard classifications.

The requirements for the means of egress in storage occupancies are similar to other occupancies. The principal difference is that storage occupancies typically require fewer exits than other occupancies. Since storage areas and warehouses generally have few occupants, neither NFPA *101* nor *NFPA 5000* assigns occupant load factors to such uses. Rather, occupant load is based on the maximum probable number of occupants present at any time. NFPA *101* or *NFPA 5000* should be consulted to determine the specific arrangement of the means of egress.

Exit doors must remain unlocked from the egress side of the door when the building is occupied. In areas of low- and ordinary-hazard contents, special-listed delayed-egress locks are permitted if an approved automatic fire detection or supervised sprinkler system protects the entire building. Access controlled egress doors are permitted, provided they meet specific requirements in NFPA *101* and *NFPA 5000.* Egress doors from areas of high-hazard contents must swing in the direction of egress travel.

The continual movement of stock within a storage occupancy demands special attention to prevent blocking required means of egress aisles and doors.

Exit Identification

All required exits must be marked as required by NFPA *101* and *NFPA 5000*. The signs must identify the means of egress, exit locations, and be readily visible where the direction of exit access is not obvious. In areas with high-piled storage, exit identification can be a problem. In addition to signage, other means of egress marking may be necessary, such as painting egress travel paths on the floor.

Illumination of the means of egress is also required. This is particularly important in windowless buildings where natural light is not available during all occupied times. Emergency lights must be installed to provide illumination of required egress stairs, aisles, corridors, ramps, and passageways. NFPA *101* and *NFPA 5000* detail the specific requirements for means of egress illumination.

Vertical Openings

Vertical openings, such as conveyor openings in multistory buildings, must be provided with automatically closing fire doors, fire shutters, or fire dampers on each opening. Convenience openings are permitted provided they connect not more than two stories (they pierce only one floor), are separated by a fire barrier from unprotected vertical openings serving other floors, are separated from corridors, and do not serve as a required exit.

Fire Alarm Systems

Although a fire alarm system is often provided in a warehouse or storage occupancy due to property protection concerns, a fire alarm system is not generally required in warehouses to meet the requirements of NFPA *101* or *NFPA 5000,* unless the warehouse stores high-hazard commodities or exceeds 100,000 ft^2 (9300 m^2). However, due to the large areas and the limited number of employees that may be working in widely scattered areas of the building, a fire alarm system should be considered to alert all occupants in the event of a fire. A fire alarm system provides timely notification of building occupants who can then initiate emergency action and notify the fire department or private fire brigade.

Fire alarm systems for occupant notification must include audible and visible notification appliances installed in accordance with *NFPA 72®*, *National Fire Alarm Code ®*. Fire alarm system actuation may be manual, through the use of manual fire alarm boxes, or automatic, through the use of fire detectors or sprinkler waterflow alarms. Fire alarm systems must be installed, tested, and maintained in accordance with *NFPA 72*. The fire alarm signal must be separate and distinct from any other audible signals used in the facility. All new fire alarm systems must use the American National Standard evacuation signal to initiate evacuation as required by *NFPA 72*, unless otherwise permitted by the authority having jurisdiction.

BUILDING CONSTRUCTION AFFECTING HAZARDOUS CONDITIONS

Most construction types are suitable for a storage occupancy, although the use of noncombustible construction is preferred. Combustible construction, although permitted by most building codes, adds to the fire load and may contain combustible concealed spaces that contribute to rapid fire spread.

Materials

The combustibility, flame spread rate, smoke production, heat release potential, and structural stability of materials used in building construction should all be considered. Certain expanded plastic insulation core panel walls should be used only in buildings with automatic sprinkler protection, and the panels should be covered with fire-resistant material. Most building codes limit the use of exposed, expanded foam plastic insulation. Lightweight steel and wood truss construction now commonly used in newer buildings is susceptible to early structural collapse when exposed to an intense fire as is expected in most storage occupancies. Steel columns within storage racks over 15 ft (4.6 m) high may require additional protection, such as automatic sprinklers installed in the column web or enclosing the columns in fire-rated construction.

The rack structures used in automated storage and retrieval systems may double as the structural frame of the building. Properly designed, installed, and maintained automatic sprinkler protection is necessary to prevent extensive damage or total destruction of storage buildings using any of these lightweight methods of construction.

Buildings up to 100 ft (30 m) high used for such rack storage are not uncommon. Fully automated rack systems usually have narrow aisles between racks. Providing fire suppression within the racks may be difficult even in buildings protected by automatic sprinklers. Fires involving upper portions of high-rack storage present unusual problems and severe risks to fire suppression forces. Access to the upper portion for complete extinguishment and overhaul is limited. Using ground ladders inside buildings is difficult, dangerous, and generally limited to the length of a typical fire department ground ladder, about 35 ft (10.5 m). Storage damaged by the fire or wetted by sprinklers and hose streams often falls from the racks blocking aisles and posing a hazard to fire fighters.

Smoke and Heat Venting

Smoke and steam generated during a fire can obscure visibility, making it difficult for fire suppression forces to locate the fire. Venting aids in smoke removal, which, in turn, aids fire-fighting operations and rescue. Installation of heat and smoke vents in storage occupancies provides a method for fire fighters to vent accumulated heat and smoke from the building. The vents may be automatic or manually operated. Although there is some disagreement between various fire protection groups, the vents installed in buildings protected by automatic sprinklers should generally be arranged for manual operation because the sprinkler design criteria in NFPA 13 are based on a building without automatic venting. In buildings without automatic sprinkler protection, venting combined with draft curtains or curtain boards can reduce the horizontal smoke and heat spread along the ceiling. In some cases roof vents may be supplemented or replaced by mechanical heat and smoke exhaust systems. Special mechanical ventilation systems should be considered for large-area storage occupancies. The systems should be designed and installed in accordance with NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences.* See Section 18, Chapter 4, "Venting Practices."

Smoke and heat venting facilities, as well as automatic sprinkler protection, are essential for life safety in windowless buildings and underground structures. The installation of smoke and heat venting should be in accordance with NFPA 204, *Standard for Smoke and Heat Venting.*

Separation

Buildings used for both manufacturing and warehousing should be separated by properly constructed fire walls with all openings protected by automatic closing fire doors. Incidental areas, such as boiler rooms, maintenance areas, and offices, should also be separated from storage areas by rated fire barriers. The rating depends on the requirements of the applicable codes and standards, and the site-specific fire risk management objectives.

AUTOMATIC SPRINKLER PROTECTION

Automatic sprinkler protection, supplemented by manual fire-fighting operations and sound storage and housekeeping practices, is a proven effective and practical means of protecting warehouse and storage occupancies from fire. The automatic sprinklers for a warehouse or storage occupancy must be specifically engineered to match the hazards posed by the storage, installed in accordance with NFPA 13, and inspected, tested, and maintained in accordance with NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*.

Basic Approaches

Current automatic sprinkler technology provides three basic approaches to providing sprinkler protection of storage operations: standard spray sprinklers, large drop sprinklers, and early suppression fast response (ESFR) sprinklers.

Standard Spray Sprinklers. The standard spray sprinkler category includes standard orifice, large orifice, and extra large orifice (ELO) sprinklers. Any of these sprinklers may be equipped with fusible elements for standard response or fast response.

Large Drop Sprinklers. Large drop sprinklers produce much larger water droplets with more mass to better penetrate a fire plume and reach the seat of high-challenge fires, such as those involving rubber tires or roll paper. The standard spray sprinkler and large drop sprinkler are designed to control a fire and limit its spread until the arrival of a trained fire suppression force that can extinguish the fire.

EFSR Sprinklers. The ESFR sprinkler incorporates a fast response operating element and a large orifice. They are designed to operate at relatively high pressures and discharge up to 175 gpm (662 L/min) each during the initial stages of a fire. The ESFR sprinkler is the only sprinkler designed to extinguish a fire. Refer to Section 16, "Water-Based Fire Suppression Equipment," for more detailed discussions regarding the design and operation of the various types of sprinklers and sprinkler systems.

Most building codes require automatic sprinkler systems in high-hazard storage occupancies. Some codes require sprinkler protection when materials are stored in racks or piles more than 12 ft (3.7 m) high. Most building codes permit low- and ordinary-hazard storage buildings of unlimited floor area when they are protected by sprinkler systems.

Effective Sprinkler Operation

Properly designed automatic sprinkler protection is essential to control a fire and limit damage in a warehouse or storage occupancy. It follows then that a major factor contributing to large-loss fires in warehouses and storage areas is the inability of the sprinkler system to control the fire. This may result from a change in the type, volume, height, or configuration of storage that raises the hazard level beyond that for which the sprinkler system was designed. Any change in the storage or configuration must be accompanied by a comprehensive hazard analysis to assure the change does not outstrip the capabilities of the sprinkler system.

Impairment of the sprinkler system, such as broken piping, shut valve, or piping obstruction, may prevent the sprin-

klers from controlling the fire. Many serious fires have occurred during periods of sprinkler shutdown. Facility managers must implement an effective impairment-handling program that limits the number, extent, and duration of sprinkler system impairments. Complying with the requirements of NFPA 25 minimizes the probability of sprinkler system impairment when a fire occurs.

SUPPLEMENTAL FIRE PROTECTION

Although they are the most important fire protection feature, automatic sprinklers are not the only fire protection necessary for a fully protected warehouse or storage occupancy. Although sprinklers may extinguish a fire, most sprinkler systems are designed to control a fire until trained fire suppression personnel can extinguish it with portable fire extinguishers or hose lines. Other provisions, such as hose systems, portable extinguishers, and effective prefire planning and fire prevention efforts are essential ingredients of any complete warehouse fire safety program.

Large and Small Hose

Warehouses of moderate area close to public hydrants present no special manual fire suppression problems. Where the smaller dimension of a warehouse exceeds about 200 ft (61 m), hose lays from public hydrants to the far side of the building are difficult and time-consuming. Strategically located private hydrants on the building perimeter near building access doors are important to the overall facility fire protection plan. Private hydrant spacing of 250 ft (76 m) is common in such situations. NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances,* provides guidance on the number and location of private hydrants.

Indoor hose connections are recommended in high-piled or rack storage buildings for use on incipient fires. Their relatively good reach and unlimited supply make them more effective than portable fire extinguishers in most situations. However, they do not eliminate the need for portable fire extinguishers. Although not a requirement, the supply for hose connections should come from a system separate from the automatic sprinklers protecting the area. This permits the hose connections to remain in service even if the sprinkler system must be shut down for inspection, testing, or repair.

Provision of interior hose connections requires that the connections, nozzles, and attached hose be inspected, tested, and maintained in accordance with NFPA 25. OSHA regulations require that occupants expected to use the hoses during a fire be trained in their use.

Multistory, large-area, and high-hazard warehouses should be equipped with a standpipe system. A Class III standpipe system provides 1½ in. (38 mm) hose lines for use by building occupants trained in their use and a 2½ in. (64 mm) connection for use by the fire department or a fire brigade. Connections should be located so that all portions of the area can be reached. Providing hose connections for high-rack systems, particularly automated storage and retrieval systems, requires special consideration. In addition to connections at floor level, additional connections may be needed at various heights to enable hose lines to reach all levels. Standpipe systems should be installed in accordance with NFPA 14, *Standard for the Installation of Standpipe and Hose Systems.*

Portable Fire Extinguishers

Portable fire extinguishers should be located throughout the premises in accordance with NFPA 10, *Standard for Portable Fire Extinguishers*. They can be effective during the incipient stages of a fire if used by properly trained operators. All employees should be familiar with the locations and use of portable fire extinguishers. Extinguishers should be in visible, readily accessible locations. Employee training should stress the importance of sounding an alarm and notifying the fire department before attempting to fight a fire with portable fire extinguishers. Up to half the required extinguishers may be replaced by hose connections equipped with hose and a nozzle.

Pre-Emergency Planning

Action in an emergency is seldom effective unless it is carefully planned and executed. Facility management must develop a program that identifies the types of fires and other emergencies likely to occur in the facility. The plans should detail how employees should respond to each type of incident. A program must then be implemented to train employees in the proper methods of response to each type of emergency.

In most cases, employees are not expected to respond to fires and participate in fire suppression operations beyond the incipient stage. Nevertheless, certain information will assist warehouse personnel to understand the interrelationship between fire protection systems and manual fire-fighting operations.

Fire tests and actual fire experience show that even when automatic sprinklers are properly designed and are successful in controlling a warehouse fire, they will not usually extinguish a fire. Personnel trained and equipped for manual fire suppression operations must accomplish final extinguishment. This may be the facility fire brigade, the public fire department, or a combination of the two. Even under the most favorable conditions this is a challenging task that requires careful planning, training of employees, and coordination with public response agencies.

OSHA regulations require that all facilities with more than ten employees have a written emergency action plan (EAP). The plan must identify and explain emergency egress routes and any required emergency procedures. Emergency procedures might include the shutdown of hazardous processes, closure of fire doors, or other operations that make the facility safer during a fire. If specific employees are designated to remain behind to complete critical tasks until their evacuation becomes necessary, the EAP must detail these requirements. The plan must also include procedures to account for employees after building evacuation. Employees must be given the names and contact information for individuals who have additional information about the plan. The employer is also required to review the plan with each employee at the time of development or at the time of initial job assignment. Facility managers should consult 29 CFR 1910 Subpart E for the complete OSHA requirements related to emergency planning.

All planning should be developed in coordination with the public agencies that respond to the facility during an emergency. Plans that are not developed and practiced with the cooperation of the public fire department are unlikely to be effective during an actual emergency. A later section of this chapter provides detailed information for use by fire brigades and public fire departments in developing prefire plans for warehouse and storage occupancies. NFPA 600, *Standard on Industrial Fire Brigades,* and NFPA 1620, *Recommended Practice for Pre-Incident Planning,* should be consulted for additional guidance.

Fire Prevention

Fire prevention efforts to eliminate common sources of ignition are the most effective method of limiting fire loss in warehouses and storage occupancies. Among the leading causes of fires in storage facilities are incendiarism or arson; open flames; exposure to fire from another structure, such as an adjoining building; malfunction or failure of electrical distribution equipment, particularly wiring; and heating equipment. Table 20.16.2 shows the leading causes of warehouse fires.

Fire prevention efforts should be directed toward reducing or eliminating any potential sources of ignition in the warehouse or storage area. This should include proper installation and maintenance of electrical equipment, prohibition of smoking and other sources of open flames, limiting access by unauthorized personnel, and proper installation and maintenance of heating equipment. Facility management should make routine tours of the warehouse to look for and correct any potential ignition sources.

SPECIAL STORAGE FACILITIES

Cold Storage

Cold-storage warehouses are used primarily for extended storage of food and other products at temperatures that prevent or retard spoilage. Products such as pharmaceuticals, antibiotics, and unstable chemicals may also require refrigerated storage.

Depending on the products or processes involved, cold-storage warehouse temperatures may reach a low of –50°F (–46°C) or lower. Despite low temperatures, cold-storage warehouses are not immune to fire hazards. Low temperatures present unusual fire prevention and control problems. Combustible materials in such warehouses include cork or expanded plastic insulation; wood dunnage, pallets, boxes, and baskets; fiberboard containers; paper and cloth wrapping; plastic containers and boxes; and grease- or wax-impregnated materials. These pose a large loss potential.

Construction. Refrigerated warehouses may be constructed of combustible or noncombustible material or a combination of both. The current trend is to build larger and higher buildings in which automated storage racks are structural units supporting the walls and roofs of the buildings. Such construction is acceptable if the rack structure supports wind and snow loads. Although the structural materials themselves are noncombustible, such buildings must be properly sprinklered to protect both the structure and the stored material. When cork or foam insulation ignites, it can generate temperatures high enough to weaken structural steel members.

Polyurethane foam, either in sheets or foamed-in-place, and polystyrene foam are two common insulation materials. When used in walls or ceilings, these materials should be protected by an approved thermal barrier or by a ½ in. (12.7 mm) coat of cement plaster on metal lath attached to the building's framing. For polystyrene, the barrier also may be either ½ in. (12.7 mm) Type X gypsum wallboard or ¾ in. (19 mm) fire-retardant plywood supported by studs or furring attached to the framing. To meet sanitary standards, these thermal barriers must be coated with a U.S. Department of Agriculture (USDA) approved washable finish. If used in the floor, the insulation should be covered with concrete and the joint between floor and wall provided with a cove or curb. Automatic sprinklers should be provided below suspended ceilings, and the space above the ceiling should be protected against fire spread and sprinklered if combustible.

Refrigerant Gases. Refrigerant gases present two basic hazards: toxicity and flammability. Sprinklers are very effective at mitigating the fire hazard because the spray dilutes, disperses, and cools escaping gases.

Storage Arrangements. As in other warehouses, storage arrangements in refrigerated warehouses can be in bulk, solid piling, palletized, or in racks. One exception to this arrangement is the hook storage of meat and poultry products awaiting further processing. This storage method poses a minimal fire hazard because of the absence of combustible packaging.

Sprinkler Protection. The same sprinkler system design used for nonrefrigerated buildings is appropriate for refrigerated storage, except that it must be a dry-pipe or other nonfreeze-type system. In chill rooms and coolers, sprinkler systems of the electrically operated pre-action type are preferable to dry-pipe systems. In freezers or holding rooms, systems are often a combination preaction/dry-pipe system. Figure 20.16.3 shows such a system. In this system, a ⅛ in. (3.2 mm) orifice in a bypass maintains water pressure under the dry-pipe valve. A deluge valve holds back the main water supply. A separate fire detection system electrically activates the valve. Where racks are used for storage, it may be necessary to use in-rack sprinklers.

All sprinklers in refrigerated warehouses should be designed and installed in accordance with NFPA 13. They should be designed so that they can be easily inspected and disassembled to remove ice plugs that commonly form due to moisture condensation in the piping.

The combination dry-pipe deluge system shown in Figure 20.16.3 minimizes the potential for filling the piping with water should there be accidental actuation of a dry-pipe valve. When this arrangement is used, note the following requirements:

1. The dry system should be manifolded to the deluge valve.
2. The protected area should not exceed 40,000 ft^2 (3716 m^2).
3. The distance between valves should be as short as possible.

TABLE 20.16.2 Reported U.S. General Warehouse Structure Fires, 1994–1998 Average Annual Values, by Form of Heat of Ignition

Form of Heat of Ignition	*Fires*	*Percentage*	*Civilian Deaths*	*Percentage*	*Civilian Injuries*	*Percentage*	*Direct Property Damage (in Millions of Dollars)*	*Percentage*
Electric-powered equipment	310	23.2	0	22.1	9	34.3	18.3	23.7
Exposure fire	196	14.6	0	0.0	0	0.0	3.1	4.0
Match	114	8.6	0	0.0	1	2.9	4.7	6.1
Lighted tobacco product	103	7.7	0	0.0	1	4.9	14.0	18.1
Torch	101	7.5	0	0.0	6	24.5	13.3	17.2
Unclassified or unknown-type open flame	80	6.0	0	0.0	0	1.0	3.3	4.3
Gas-fueled equipment	64	4.8	0	0.0	1	5.9	2.6	3.4
Open fire	63	4.7	0	0.0	0	2.0	1.8	2.3
Rekindle or reignition	40	3.0	0	0.0	0	0.0	1.2	1.5
Spontaneous ignition or chemical reaction	35	2.6	0	0.0	0	1.0	1.4	1.8
Lightning	29	2.1	0	0.0	0	0.0	2.4	3.1
Electric lamp	22	1.6	0	0.0	0	0.0	0.4	0.6
Solid-fueled equipment	20	1.5	0	0.0	0	0.0	0.3	0.5
Liquid-fueled equipment	19	1.4	1	77.9	0	2.0	0.1	0.1
Unclassified form of heat	17	1.3	0	0.0	0	0.0	0.6	0.8
Lighter	17	1.2	0	0.0	0	0.0	1.6	2.0
Incendiary device	16	1.2	0	0.0	0	0.0	1.9	2.5
Multiple forms of heat	16	1.2	0	0.0	1	3.9	5.3	6.8
Heat or spark from friction	14	1.1	0	0.0	0	0.0	0.4	0.5
Unclassified or unknown-type hot object	14	1.1	0	0.0	1	2.9	0.1	0.1
Hot ember or ash	12	0.9	0	0.0	1	3.9	0.0	0.0
Other or unknown-type fueled equipment	11	0.8	0	0.0	0	0.0	0.1	0.2
Molten or hot material	6	0.5	0	0.0	0	0.0	0.2	0.3
Other known form of heat of ignition	18	1.4	0	0.0	3	10.8	0.1	0.2
Total	1338	100.0	1	100.0	25	100.0	77.3	100.0

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires, deaths, and injuries are estimated and direct property damage rounded to the nearest hundred thousand dollars. Sums may not equal totals due to rounding errors. Percentages are based on the total number of fires reported between 1994 and 1998 and not on the total annual average in the table. Damage has not been adjusted for inflation.

Source: National estimates based on NFIRS and NFPA survey.

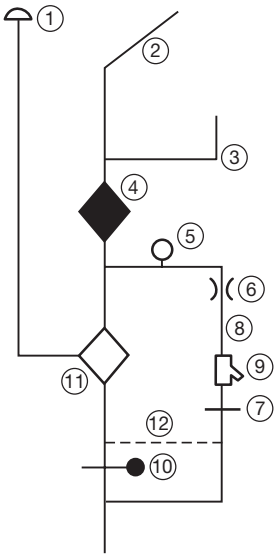
4. The chamber between deluge and dry-pipe valves should be pressurized from the supply side of the deluge valve.
5. An approved ball drip valve should be installed on the dry-pipe valve.

Properly located heat detectors in the protected area automatically actuate the deluge valve. An electrically actuated deluge valve is preferred.

Figure 20.16.4 shows an acceptable alternative to the deluge valve/dry-pipe valve combination. Approved equipment should be used throughout, and all electrical equipment should be compatible. The piping to the heat-actuated devices should be supervised. The control piping should be arranged so both loss of sprinkler piping air pressure and operation of a heat-actuated device occur before the deluge valve release mechanism operates.

Piers and Wharves

Warehouses often form the superstructure of piers and wharves. They may be called "sheds" and often project great distances over the water. They share the same general characteristics as other warehouses, but present more fire protection and suppression problems. Among these are reduced accessibility for land-based fire department vehicles; the usual combustible nature of the substructures, which can be exposed to floating burning debris



1. Heat-actuated device
2. To sprinklers
3. To air supply
4. Dry-pipe valve
5. Pressure gauge
6. ⅛ in. (3.2 mm) brass restricting orifice
7. Valve (normally open)
8. ½ in. (12.7 mm) brass pipe
9. Strainer
10. Main water supply valve
11. Deluge valve
12. Alternate connection to main water supply

FIGURE 20.16.3 Piping to a Combination Dry-Pipe Preaction Sprinkler System

or flammable liquids; the danger of water supply mains freezing; and the hazard of ships colliding with piers. More favorably, commodities tend to be piled low because of the temporary, transfer nature of the storage—that is, ship-to-shore or shore-to-ship.

NFPA 307, *Standard for the Construction and Fire Protection of Marine Terminals, Piers, and Wharves,* requires a water supply for both hose streams and sprinkler systems to be available for at least 4 hours—about double the usual requirement. To protect the combustible underside of the pier, sprinklers should be either standard pendant sprinklers in the upright position or old-style sprinklers in the upright position to wet the undersurface of the substructure.

Parking Garages

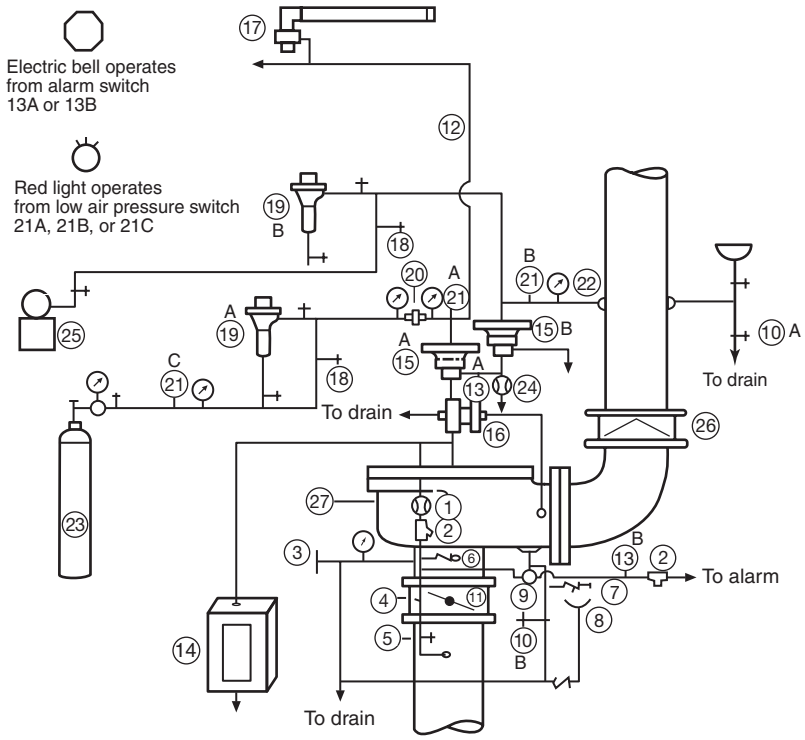
There are two types of parking garages: those in which vehicles are parked exclusively by attendants or mechanical means and those in which customers park the vehicles. NFPA *101* and *NFPA 5000* address the egress requirements of garages in which the customer parks the vehicle.

For more information on parking garages, see NFPA 88A, *Standard for Parking Structures*.

Occupancy Characteristics. Parking garages may be several levels above or below grade and may be enclosed or open. A garage is considered open when there are uniformly distributed openings in exterior walls on not less than two sides totaling not less than 40 percent of the building perimeter.

Parking garages are often found in conjunction with other uses, such as hotels, apartments, and office buildings. In garages used for both parking and repairs, the repair area should be separated from the parking area and treated as an industrial occupancy.

Hazards Associated with Garages. Motor vehicles generally contain fast-burning fuels, including gasoline, diesel fuel,



1. ⅛ in. (3.2 mm) restrictor orifice
2. Strainer
3. Flow test valve*
4. Priming pipe
5. Priming water valve*
6. Check valve
7. Drip check
8. Drip cup
9. Alarm test valve
10. System drain valve*
11. Main water supply valve
12. ½ in. (12.7 mm) thermostatic release piping
13. Alarm switch
14. Emergency trip valve
15. Diaphram bypass valve
16. Pilot-operated relief valve
17. Model "C" thermostatic release
18. Air bypass valve*
19. Air pressure maintenance device
20. 1/32 in. (0.8 mm) restriction plug
21. Low air pressure switch
22. Circle seal check
23. Nitrogen cylinder and regulator
24. 0.046 in. (1.2 mm) restrictor orifice
25. Air compressor
26. Sprinkler system check valve
27. Deluge valve

* Valves are normally closed

FIGURE 20.16.4 Pneumatic Dual-Release Automatic Water Control Valve

or LP-gas. Major parts of newer model vehicles are made of plastic. These materials can cause severe fires that produce copious amounts of smoke. Gasoline is dispensed in some garages. NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages,* and NFPA 88A list requirements for this type of operation. In addition, NFPA *101* and *NFPA 5000* contain special requirements for garages where gasoline is dispensed.

Only a few persons at any one time usually occupy parking garages. However, structures that are located near large assembly occupancies, such as civic centers or theaters, can be occupied by a large number of persons at one time after a show or event ends. During this time, many people move throughout the structure, either going to their vehicles or waiting in their vehicles to exit the parking garage.

Life Safety Considerations. Every floor level of a parking structure must have access to at least two separate exits, arranged so that the travel path is in two different directions. Vehicle ramps can serve as exit access under special conditions. The travel distance permitted to reach an exit depends on whether the building is open or enclosed and whether automatic sprinklers protect the garage.

Special consideration must be given to the location of fuel pumps to avoid trapping occupants if there is a fire or explosion at the pumps. Travel in any direction must lead to an outside exit at the same level or to properly arranged egress stairs. Where parking areas are located below gasoline dispensing pumps, each floor must have direct access to the outside. This arrangement minimizes the potential for gasoline vapor accumulation in enclosed exit stairs.

The means of egress should be provided with illumination and emergency lighting when the garage is used at night or has no natural lighting from windows or other openings during the day. Most people using a parking garage are unfamiliar with the location of exits. Exits and access to the exits must be marked and identified.

Enclosed parking garages must have a fire alarm system when the total aggregate floor area exceeds 100,000 ft^2 (9300 m^2). Open-air parking structures and parking structures protected throughout by an approved automatic sprinkler system do not require fire alarm systems. In general, automatic sprinkler protection is required in enclosed garages located below grade and in those over 75 ft (23 m) in height.

Grain and Other Bulk Storage Elevators

Grain and other bulk storage elevators structures move, store, and process grain, such as wheat, corn, oats, soybeans, and sunflower seeds (Figure 20.16.5). Commodities are stored in bulk form in concrete and steel silos, wooden bins, and steel tanks. Handling the commodity generates dust, making the grain stream susceptible to fire and explosion. NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities,* lists fire protection and

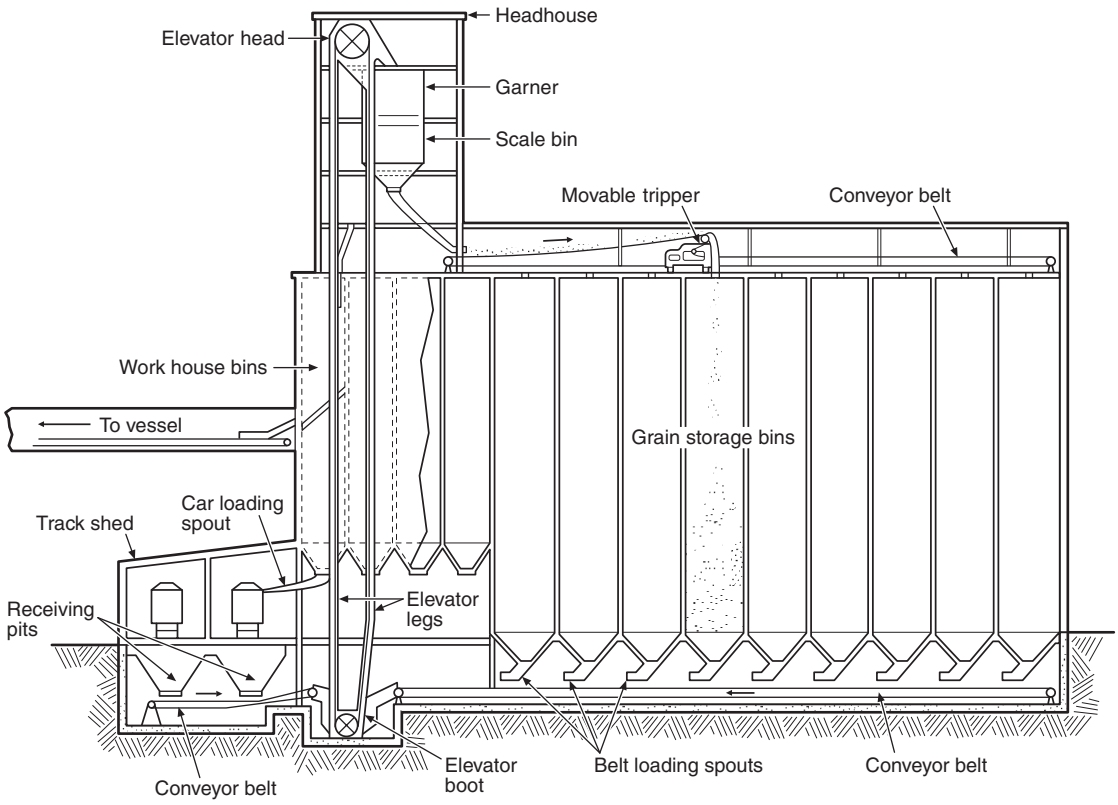


FIGURE 20.16.5 Grain and Bulk Storage Elevator

safety requirements for the installation and operation of grain elevators.

Structures of this type are unique and particularly dangerous. They pose serious life safety hazards for all occupants. Grain elevators account for some of the largest loss-of-life incidents in storage occupancies. In many dust explosions, the primary or only means of exiting from the upper parts of an elevator may be damaged or destroyed by the initial explosion, trapping workers on top of the structure.

NFPA *101* addresses life safety considerations based on the occurrence of fires. Basic life safety requirements require that at least two means of egress be available. The exits must be arranged to be remote from each other. These means of egress should be available from all working areas and from the headhouse located on top of the storage structure. All working areas should have access to at least one stairway leading to an exit discharge point at ground level. This stairway should be constructed within a dust- and fire-rated enclosure.

In addition to the stairway, an alternative means of escape is required. This secondary means should provide a continuous path to the ground from the top of the elevator structure, but it need not meet all provisions for a means of egress. This secondary escape can consist of exterior stairs or basket-type ladders accessible from all working levels of the headhouse. This escape means provides passage to the ground or to the top of adjoining structures.

An exterior stair or basket-type ladder should be provided from the top of storage structures such as silos, conveyors, galleries, and gantries. This secondary escape should be located at the end of the structure opposite the headhouse.

Most grain elevators have underground passages for conveyors beneath the silos. These spaces should have at least two means of egress without dead ends. One means of egress can be a ladder or other escape method that leads to a window, hatch, or panel that can be opened to permit escape.

For more information on grain elevators, see Section 9, Chapter 7, "Storage and Handling of Grain Mill Products."

Aircraft Hangars

An aircraft hangar is a structure for the storage or maintenance of aircraft. Because it is generally impractical to remove all fuel from aircraft before moving them into a hangar, large quantities of flammable or combustible liquids are usually present inside the structure. Some maintenance procedures use highly flammable solvents and unstable toxic chemicals. Fire during maintenance and servicing operations can pose hazards to personnel in the hangar and potentially endanger aircraft worth millions of dollars. Special precautions for ventilation and control of ignition sources are needed.

Aircraft hangars provide a particular challenge when designing adequate exiting and egress facilities. The large open area needed for aircraft, especially commercial airliners, requires extended travel distances to reach exits. The presence of flammable and combustible liquids compounds this problem. Exits must be located at intervals not exceeding 150 ft (46 m) along all exterior walls of the hangar. Each part of the hangar or servicing area must have access to at least two exit locations. If approved interior horizontal exits are provided, then exit locations along the wall must be provided at intervals not exceeding 100 ft (30 m). Since a large hangar door cannot be left open in poor weather, small access doors can be installed in hangar doors. Egress from mezzanines must be arranged so that an exit can be reached within a maximum travel distance of 75 ft (23 m). These exits must lead directly to an approved enclosed stairway that discharges directly to the outside, to another fire-separated area, or to outside stairs.

For life safety purposes, a fire alarm system is required in hangars not protected by automatic sprinkler systems if the total floor area exceeds 100,000 ft^2 (9300 m^2). For additional requirements related to constructing and protecting aircraft hangars from fire, refer to NFPA 409, *Standard on Aircraft Hangars.*

Isolated Storage Buildings

Some high-value warehouses are needed for only a few years, such as those for construction projects in remote areas. At times, these warehouses may contain large quantities of electrical and electronic equipment, wire, cables, fixtures, and production equipment. Experimental or mining sites may also have large warehouses. These remote areas often lack public water mains or fire departments. Several factors must be weighed, such as the importance of the building to the project and the time needed to replace vital contents. Standards and building codes do not apply rigidly in these situations. Good loss prevention and control practice is to separate unprotected warehouses into small units, to provide fully adequate private protection, or to compromise and use protection systems with a limited water supply. Increased vigilance over guard service, housekeeping, maintenance, and smoking control should accompany any compromised physical protection.

Underground Storage

Large underground warehouses can be a boon to energy conservation because rock caverns have a nearly constant temperature and humidity. In the United States, some caverns have stored compressed gas, and old mines are used for records storage. Caves used for warehousing and storage should be protected with automatic sprinklers.

In general, the problems associated with underground structures include egress, venting smoke and heat, and limited access for fire fighting. Automatic sprinkler protection installed under constructed floors and ceilings is vital to protect combustible storage and personnel. NFPA 520, *Standard on Subterranean Spaces,* provides minimum requirements for the design, operation, and maintenance of developed subterranean spaces for safety to life and property from fire and similar hazards.

Air-Supported Structures

For warehousing in temporary or remote locations, such as at construction sites, or as a low-cost adjunct to more permanent conventional buildings, large air-supported structures are sometimes used (Figures 20.16.6 and 20.16.7). These structures are plastic-coated fabric envelopes resembling balloons and are kept rigid by internal positive air pressure. Structures less than

FIGURE 20.16.6 Typical Air-Supported Structure Suitable for Warehouse Purposes (Source: Air Structures American Technologies, Inc.)

FIGURE 20.16.7 Interior of a 100 ft by 300 ft (30 m by 91 m) Air-Supported Warehouse Showing Storage (Source: Air Structures American Technologies, Inc.)

150 ft (46 m) in width or diameter should comply with NFPA 102, *Standard for Grandstands, Folding and Telescopic Seating, Tents, and Membrane Structures,* which deals with wind resistance, strength, load distribution, and pressurizing air-supported structures. A trend toward using a cable harness net system to encapsulate the envelope in all directions increases the structure's stability during wind loading.

Because these structures cannot support overhead piping, conventional automatic sprinkler protection is not generally feasible. Such buildings are unsuitable for long-term storage of high-value or hazardous materials. When reasons to use these structures are compelling, a number of separate smaller units are preferable to one large structure.

WAREHOUSE FIRE-FIGHTING OPERATIONS AND PRE-INCIDENT PLANNING

The following information is intended primarily for fire brigade officers and public fire officials who must develop and implement a pre-incident plan for a warehouse. It will also assist fire officials in command positions who are responsible for tactical and strategic decisions made on the fireground.

Because automatic sprinkler protection is the most effective—and in many instances, the only—method to successfully control a warehouse fire, all fire-fighting operations should be geared toward support of the sprinkler system where present. This support not only increases the likelihood of fire control but also maximizes fire fighter safety because it is unnecessary for fire fighters to be exposed to the hazards of an interior fire attack.

After effective support for the sprinklers has been established, the fire emergency can be considered stabilized. This provides sufficient time to carefully organize a safe and successful fire suppression operation. In addition, sprinklers buy time and help maximize safety and operational effectiveness—hurried fire-fighting operations are not only disorganized but are also unsafe and often ineffective.

The overall success of a warehouse fire-fighting operation is determined long before the first smoke is visible—in fact, it is determined before actual ignition occurs. The operation's success is determined as the warehouse pre-incident plan develops.

The pre-incident plan must be a cooperative effort among the building owner, plant emergency teams, and the public fire department expected to respond to the fire. Other agencies may also provide valuable input to the prefire plan. Such agencies include plant security forces, plant engineering staff, public utility companies, and the insurance carrier.

Developing a Pre-Incident Plan

The pre-incident planning process begins with a warehouse tour. Arrangements should be made with the building owner for someone with a working knowledge of the facility and its operations to accompany the fire department representatives on the tour. Building owners should cooperate fully with the public fire department when they develop a pre-incident plan. Architectural drawings and diagrams of the facility showing the building layout, construction, storage configurations, and the design of the fire protection systems and equipment should be provided for examination prior to the tour.

The tour's purpose is to gather information that the fire department will use to predict the type of fire anticipated and the possible complications encountered during fire suppression operations. Information gathered should include at least the following:

- Evaluation of building size and construction characteristics to determine a fire's probable effect. For example, a roof

supported by lightweight steel bar joists or trusses can be expected to collapse early during a serious fire.

- Location of fire walls, fire barriers, and fire doors that separate the storage area from the surrounding operations. Fire doors should be checked for proper operation because they must be relied on during an emergency to inhibit the spread of the fire.
- Identification of the commodities stored within the warehouse. Knowledge of their burning characteristics is essential. For example, burning aerosol products, flammable liquids, or similar materials may be beyond the capabilities of the sprinkler system.
- Determination of the method of packaging materials in the warehouse. For example, cardboard cartons can be expected to collapse quickly into the aisle, and plastic straps attaching materials to pallets can be expected to melt quickly.
- Identification of storage method, for example, racks, solid piles on the floor, or palletized.
- Evaluation of normal and maximum storage levels. Stock levels must be assessed as to relative stability from season to season. Pre-incident plans should be based on the worst case. For example, the worst-case fire in a department store warehouse might occur in September or October when it is filled to capacity with holiday sale merchandise.
- Determination of the type and design of the automatic sprinkler systems. Obtaining complete information on the capability of the sprinkler systems is very important so it can be compared to the hazards the storage in the warehouse pose. If sprinkler design is inadequate for the storage type and arrangement, fire control is unlikely.
- Determination of minimum flow and pressure required to supply sprinkler systems. To evaluate the adequacy of the available water supplies, water supply demands for the sprinklers must be known. If the water supply is inadequate, sprinklers will not perform as designed. If current water supply test results are not available, tests should be conducted to obtain current information.
- Identification of the type and number of water supplies available for fire protection and information on how to start fire pumps so that fire fighters may start them manually, if necessary.
- Location of public hydrants and fire department sprinkler connections. Fire apparatus should not steal water from the sprinkler systems by connecting to yard hydrants. The location of suitable public hydrants and static water sources to supply fire apparatus must be noted and evaluated.
- Arrangement of interior standpipes and hose connections. Are they fed from overhead sprinklers? Can they remain in service with the sprinklers shut off? All hose connections must have the same hose threads as those used by the public fire department.
- Assessment of type, capacity, and method of operation of any automatic or manual heat and smoke venting facilities. How can exhaust fans be activated? How is the power supply to the fans arranged? Will power be lost when electric power for the warehouse shuts down during an emergency?
- Determination of primary and alternate means of access to the warehouse. What security features make access more difficult? Are security guards or guard dogs normally in the warehouse after normal working hours?
- Determination of type of training provided for the plant emergency organization. Also assess how many members will be available during a fire, and what procedures they follow in a fire.
- Assessment of types of manual fire suppression equipment available to the plant emergency organization and whether the public fire department can utilize this equipment.
- Assessment of general storage practices in the building. Are piles neat and orderly? Are they sloppy and in disarray, indicating poor housekeeping practices conducive to rapid fire spread?
- Investigation of aisle storage. Even so-called temporary storage blocks access to the aisles in an emergency and can cause rapid bridging of a fire across aisles.
- Determination of the materials-handling equipment available during overhaul operations to move stock out of the building. Will employees be available to operate the equipment or must fire fighters be trained to use the equipment?

After this basic information has been gathered, development of the actual pre-incident plan begins. The plan, of course, should be developed in conjunction with the building owner so that everyone knows their specific responsibilities during an emergency incident. Employees and the plant emergency organization should be instructed in the procedures for reporting a fire, making sure that employees are evacuated, checking to ensure that sprinkler control valves are open, and closing fire doors to prevent fire spread.

Strategic Fire-Fighting Considerations

The strategy employed in fighting structure fires is to confine the fire to the smallest possible area after arrival of the first fire department unit. In most cases, this means confining the fire to the room or compartment of origin. Even in large commercial buildings, fire fighters can usually depend on at least some degree of compartmentation to at least slow a fire's spread and intensity. When compartmentation works as intended, fires are "simple" room-and-contents fires.

Unfortunately, modern warehouses often lack such compartmentation. Warehouses with several hundred thousand square feet (100,000 ft^2 equals 9300 m^2) of floor area under a single roof with few, if any, true fire walls or fire barriers are not uncommon. Conveyor openings, drive-through doors, and holes for utilities to pass through often compromise existing fire walls and fire barriers. Firestopping or automatically closing fire doors may or may not properly protect these openings.

Sizing up a warehouse fire can, and most likely will, be very difficult. A serious fire may be burning in a large warehouse, but very little smoke may be visible from outside. Smoke visible from the building's exterior may not indicate the location of the fire within. Because most warehouses have few if any windows, there may be no easy method of determining the fire's size, location, or current status. This makes having an up-to-date pre-incident plan even more important.

Sprinkler System Support

Sprinklers begin fighting the fire before the fire department arrives, discharge water directly into the fire area, and are unaffected by poor visibility, heat, and toxic gases. The best course of action is to support the sprinkler system's operation by pumping into the fire department sprinkler connection at full capacity. The higher the pressure available to the sprinkler system, the more water discharged from the operating sprinklers and the better will be the chance of controlling the fire. After support for the sprinklers has been established, the fireground commander has time to carefully size up the situation to determine the best use of available resources.

To support sprinklers, the fire department must pump into the fire department sprinkler connections and ensure that proper pressures are maintained within the system. Steps must also be taken to ensure that water for manual fire suppression operations is not taken from the sprinklers or that fire apparatus connected to yard hydrant systems do not rob water from sprinklers. In cases where water supplies were marginal, fire departments have taken water from the system, causing pressure within the sprinkler system to drop to critically low levels. Fire fighters should understand that, although a flow of 1000 gpm (63 L/sec) may be a high rate of flow for many fire types, the sprinkler system in a warehouse may require from 1500 to over 3000 gpm (95 to 190 L/sec) to operate effectively.

Arriving fire companies may face a number of different situations that hinge mostly on the effectiveness of the automatic sprinkler system. Such situations are discussed in the following paragraphs.

No Sprinklers Provided. If the warehouse has no automatic sprinklers and the fire is beyond the incipient stage, controlling it will be very difficult. Saving anything in the compartment of origin may be unlikely, and efforts should be directed toward preventing the fire's spread beyond the compartment currently involved. This can be accomplished by closing fire doors, using hose lines to prevent the fire's spread through unprotected openings in fire walls and fire barriers, and using master streams through doorways to contain the fire. Entry into the fire area can be extremely dangerous due to the speed with which the fire spreads and the probability of early structural collapse. A good water supply should be secured as soon as possible to supply the large hose streams required to control the fire and protect exposures.

Sprinklers Provided but Not Operating. If sprinklers are provided but not yet operating when fire companies arrive, one of two situations has occurred:

- It is possible that the fire has not yet grown large enough to actuate any sprinklers. In this case, hose lines can be advanced into the area to control the fire.
- Sprinklers may not be operating because the sprinkler system is impaired. One or more valves may be closed for maintenance or repair. Also, someone may have intentionally closed the sprinkler valves in an incendiary incident. Personnel should always be assigned to verify sprinkler control valves and water supplies are in service. At least one engine company should be assigned to support the sprinkler systems by pumping into the sprinkler connection, which may be arranged to bypass closed valves.

Sprinklers Operating and Controlling the Fire. If sprinklers are operating on arrival and appear to be controlling the fire, a first arriving engine company should be assigned to pump into the sprinkler connection. Increasing the pressure available to the sprinklers results in quicker, more effective, fire control. After the sprinklers have controlled the fire, there will be time to plan operations needed for final extinguishment, overhaul, and salvage.

Sprinklers Operating but Not Controlling the Fire. If the sprinklers are not controlling the fire on arrival, pressure in the sprinkler system must be increased immediately by connecting to and pumping into the fire department sprinkler connection. There will be very little time to establish support for the sprinklers before the sprinkler systems are overwhelmed. If only one sprinkler connection is available, it should be used to maximum advantage by connecting multiple hose lines to it. Additional water can be supplied to the sprinkler systems by pumping into wall hydrants or private yard hydrants, if available.

Hazards Posed by Stock

Personnel at a warehouse fire must be familiar with specific hazards of stock in the warehouse. Materials such as flammable liquids, flammable aerosols, and toxic chemicals pose obvious hazards. Hazards of other materials are often overlooked. For example, baled materials, such as scrap paper or paper pulp, can be deadly. These materials absorb water from fire suppression operations and can collapse on fire fighters operating inside the building. Another hazard of materials as they absorb water is that they may expand when wet. If materials such as paper pulp are packed into a building against masonry walls, it is possible that, as the material expands, it may push walls outward, causing local or total collapse of the structure. When developing preincident plans, such possibilities must always be considered.

Materials stored in cardboard cartons also may collapse as the cartons become wet and weak. In fact, in some cases a pile collapse is considered advantageous from a fire control standpoint because it exposes fire in the pile's interior to discharge from the sprinkler system. Fire fighters should understand that fire protection engineers may want a pile in a warehouse to collapse to facilitate fire control.

An example of the hazards of collapsing stock occurred in Idaho where three members of an industrial fire department and two other employees died during a fire in a sprinklered paper warehouse. The noncombustible storage building was 46 ft by 72 ft (14 m by 23 m) and fully protected by automatic sprinklers. Part of a paper mill, it stored scrap paper baled for recycling to a height of about 15 ft (4.6 m). An employee discovered a fire started by welding and grinding operations, and the plant fire department was notified. Arriving fire fighters found the building heavily charged with smoke and sprinklers operating at the ceiling. They entered the building with hose lines to find the seat of the fire. One crew of fire fighters was only 10 to 12 ft (3 to

3.7 m) into the building when bales of paper collapsed on them and trapped two fire fighters. Other fire fighters and employees outside the building rushed in to assist the trapped fire fighters. A second collapse trapped seven would-be rescuers. By the time the incident ended, the collapsing bales killed two employees and three fire fighters. All victims died of suffocation. Seven other fire brigade members were injured in the incident. The NFPA investigative report on the incident said, "This fire clearly illustrates the hazard to fire fighters of the collapse of storage materials which expand with the absorption of water. The hazard is particularly acute in sprinklered warehouses and must be considered in the pre-incident plans of fire departments that protect plants or storage facilities involving such commodities."[3]

Personnel must also be aware of the potential of stock falling from racks. In many cases, racks may be over 30 ft (9.1 m) high. Some warehouses have storage heights exceeding 100 ft (30.5 m). Burning stock falling from such heights could easily be fatal to anyone unfortunate enough to be working in the aisles. Regardless of the type of stock, the storage arrangement, or the design of the fire protection systems, fire fighters should always be alert to the possibility of collapsing stock and protect themselves accordingly.

Visibility

Visibility inside a warehouse during a fire incident is usually limited. Most warehouses are built with limited access and few windows. Natural lighting may not exist, resulting in poor visibility, especially if electric power to the building is cut as often happens when a fire occurs. When smoke fills the building, visibility is reduced even further.

Like a hose line discharged into an enclosed area, sprinklers operating in the fire area disrupt the thermal layers normally present in a fire. Contrary to what some believe, sprinklers do not "drive" smoke to the floor. As they operate, steam forms and cools the atmosphere in the fire area. As every fire fighter knows, cool, damp smoke is difficult to vent. However, the automatic sprinklers should never be shut down in an attempt to improve visibility until it is verified the fire is extinguished or under control. A fire fighter should remain at the sprinkler control valve in case the system needs to be reactivated.

Ventilation

Ventilation is important in a warehouse fire, as in any other structure fire. Automatic smoke and heat vents or mechanical smoke exhaust systems may aid fire fighters. If no heat and smoke venting facilities are provided, ventilation may be accomplished by more traditional methods, such as opening the roof. Cross-ventilation may be accomplished by opening overhead doors or breaking eave-line windows, if they are present.

It is important that fire-fighting personnel not be committed to the roof of a steel-frame building unless the sprinklers have positively controlled the fire. If the fire is not under control, the lightweight steel structural members could quickly fail, causing the roof to collapse. Personnel should also never be committed to the roof of a wood-truss-supported structure. Wood-truss buildings can collapse quickly and without warning during a fire.

Charged hose lines should be available before venting because ventilation, although necessary to improve visibility, may increase fire intensity. As mentioned in the visibility discussion, properly operating sprinklers cause steam to form in the fire area, and smoke saturated with steam becomes difficult to move. Cross-ventilation may be the best method of clearing the building. Positive pressure ventilation may also be used.

Fire Fighter Orientation

Warehouses are typically large buildings. Aisles and storage pile arrangements can become confusing. If fire-fighting personnel are not careful, they can easily become disoriented and lost in the building, especially when visibility is limited. Personnel operating inside a warehouse should always maintain contact with a hose line or a lifeline that they can follow outside to safety.

Logistics

The logistics of a warehouse fire-fighting operation must not be underestimated. Even under ideal circumstances, successfully fighting a fire requires large numbers of personnel and supplies. Physical demands on fire fighters due to the sheer size of the building require regular rotation of personnel out of the fire area for rest and rehabilitation. Pre-incident plans should contain provisions for assembling a large pool of trained personnel to assist in fire-fighting operations.

Other required supplies include air cylinders. Most self-contained breathing apparatus (SCBA) have only a 30- to 45-minute rating and probably last only half that long during strenuous fire-fighting operations. Fire fighters who must walk 300 ft (91.5 m) into the building to the actual fire area may only be able to spend 5 to 7 minutes fighting the fire before they must replenish their air supplies.

Materials-handling equipment for moving stock during overhaul and salvage operations must also be available, as well as qualified personnel who can operate it under emergency conditions. This may require that the operators be trained to use SCBA so they can assist with overhaul operations.

Fire Control Priorities

After ensuring life safety, the primary problem confronting the fire department on arrival at a warehouse fire is controlling the fire. Establishing control simply means preventing the fire from spreading. Assuming that sprinklers are operating, water damage should not be a concern until the fire has been extinguished.

If building owners or tenants complain about water flowing into the building, fire fighters may feel pressure to shut off the sprinklers to prevent further water damage. They must ignore such pressure.

Overhaul

As effectively as sprinklers control a warehouse fire, final extinguishment must be accomplished manually. This means that personnel must break open smoldering pallets, extinguish residual fire inside loads, and then remove them from the warehouse. If possible, personnel should accomplish this under the protec-

tion of operating sprinklers. At the very least, multiple-charged hose lines must be available in the area.

Overhauling a warehouse fire can present several challenges, especially if rack storage is involved. For example, how can fire fighters and hose lines reach the 30 ft (9.1 m) or the 80 ft (24.4 m) level in a high-rack storage area for final extinguishment and overhaul? The pre-incident plan must address such problems and should be practiced during on-site drills.

Rekindling

Fire may rekindle during overhaul operations when cartons of stock are broken open. If the sprinklers are shut down, someone with a radio should be stationed at the sprinkler control valve(s) to restore the system quickly to service if rekindling occurs.

In general, basic rules for shutting down the sprinkler system are as follows:

- Do not shut the sprinklers off until fire extinguishment is positively determined. If there is any doubt, the sprinklers should remain in operation.
- Make available charged hose lines in the fire area(s) before sprinklers are shut down.
- Station someone with a radio at the sprinkler control valve(s) to reopen the valve(s) if rekindling occurs.
- Restore the sprinkler system to full operation as soon as possible.

Limitations of Manual Fire Suppression

The best method of protecting a warehouse is to install a properly designed automatic sprinkler system and maintain it in proper working order. If sprinklers are not provided or they are not in service due to poor maintenance, the chances of saving a warehouse involved in a fire are greatly reduced. Personnel should not be committed to dangerous positions in an attempt to control an uncontrollable fire. The best-equipped fire department can never compensate for the lack of an effective sprinkler system.

OUTDOOR STORAGE

Truly engineered fire protection is difficult to achieve for outdoor storage. Depending on the hazard, monetary value, and storage area, a basic fire protection plan can be developed. For small amounts of incidental and transitory outdoor storage, appropriate protection might consist merely of good security fencing and outdoor lighting. On the other hand, very large, high-value storage yards warrant more elaborate safeguards.

Choosing the Site

Size. The storage area should be large enough to hold the quantity of stored material, with allowance for spacing between piles. If the area is inadequate, additional sites should be found. Congestion can be a major factor in fire spread.

Terrain. The ground should be leveled, if possible. Sloping terrain is undesirable because it makes piles unstable and complicates fire-fighting operations.

Exposure. Adequate clearances to adjacent properties should be maintained to minimize mutual fire exposure. Zoning regulations often specify clear distances to a property line. If no such regulations exist, the nature of future development on adjacent property should be considered, as it may affect the size of the storage area.

Other exposure considerations include protection from grass, brush, or forest fires, as well as protection from potential ignition sources, such as sparks generated by rolling railroad equipment, incinerator stacks, electrical transformers on poles, or lighted cigarettes discarded from nearby cars.

Fire Protection. Because fixed automatic systems are usually not an option, manual fire protection features available dictate the arrangement of outdoor storage, including pile size and the clearances required from adjacent piles, buildings, and property boundary lines. Local fire protection features, such as public water supply and its reliability, the available fire flow, fire department location and travel time, and the means available for notifying the fire department, should be evaluated.

Floods and Windstorms. Areas subject to flooding or windstorms should be avoided. Windstorms present a particular problem in some coastal areas. Fires occurring during high winds pose an exposure problem against which protection is almost impossible. Winds can carry burning materials and brands over considerable distances, even though the fire may be confined to a relatively small area.

Preparing the Site

Site Clearance. Vegetation should be cleared away so that it cannot dry out and become fuel for ignition or fire spread. The site should be leveled as much as possible and then paved. If the entire yard is not surfaced, care should be taken to ensure that fire apparatus can easily maneuver throughout the yard. This requires properly developed roadways capable of supporting heavy trucks. Proper site drainage is also essential.

It is good practice to paint lines within the yard to show aisles and roadways, as well as the location of yard hydrants, extinguishers, and hose houses.

Site Layout. A site plan should be developed. It should detail where specific materials are stored, the proper separation distances between piles, and access points to all site areas, including fences and gates.

The density of stored materials influences the manner in which the material burns. Lumber stacked in solid, orderly piles to a height of 20 ft (6 m) does not present the same problem as lumber stored in "stickered" piles, or wood stacked with spaces between to enhance air flow. In the latter case, fire develops more rapidly because of air spaces in the piles. Pulpwood is sometimes stored in piles 200 ft (61 m) in diameter and 100 ft (30 m) high; the logs' rough and varied shapes create air spaces and pockets in the piles, which accelerate burning.

Certain materials burn quickly and produce a great deal of heat. Baled cotton, hay, lumber, packing materials, pallets, plywood, pulpwood, and rubber are examples of such materials,

and considerable clearance should be provided between and around these piles. Aisle widths equal to the height of the pile are desirable for these types of commodities.

Both the yard itself and the piles within the yard must be easily accessible for fire fighting. Access to storage close to railroad spurs is often difficult because of boxcars and other railroad equipment left on the tracks. Driveways at least 15 ft (4.5 m) wide should be provided to permit fire department apparatus to reach all portions of the storage area. Aisles of 10 ft (3 m) or more should be provided to reduce the likelihood of fire spreading from pile to pile. In unusually large storage yards or moderate-size yards with valuable commodities, main aisles or firebreaks subdivide the storage much like firewalls do indoors. Overall, ideal aisle width depends on a number of factors, including the type of material, how it is stored, storage height, anticipated wind conditions, fire-fighting capabilities, and fire-fighting equipment.

In some cases, packaging and palletizing affect storage methods, particularly of irregularly shaped or small materials. Combustible pallets may present an added hazard. Some materials are packed in heavy crates. Usually, they do not increase hazard except after severe weathering or where handling has caused breakage or splintering. Tarpaulins and other weather-resistant materials used to cover stock should be of fire-retardant-treated material.

A stable pile under normal conditions may present a severe hazard in a fire. It is wise to anticipate how fire and water affect the stability of piles when planning their sizes and configurations. Collapsing piles may enhance fire spread and hamper fire-fighting operations.

Areas used to service and maintain equipment should be designated, marked, and separated from the storage. Flammable and combustible liquids, such as fuel for lift trucks, should be stored in accordance with NFPA 30, *Flammable and Combustible Liquids Code*. Fuel storage tanks should be located so spills do not flow under or around storage and, conversely, so that a fire in a storage area will not expose any flammable or combustible liquid storage area.

Installation of Fire Protection. Fire protection features and equipment should be installed during site preparation. Depending on the site's size and location, installing private water mains and hydrants throughout the yard may be necessary.

In planning for hydrants and yard mains, the water supply, whether from public mains or private sources, should be able to furnish the needed fire flow.

Properly marked portable fire extinguishers, preferably the nonfreezing water type, should be placed so that the distance to the nearest unit is 75 ft (23 m) or less. For active and normally occupied sites, fully equipped hose houses should be provided and personnel trained to use them in a fire.

A means to notify the fire department is essential. A system that directly signals the fire department is best; minimally, a telephone should be accessible.

Security Measures. Outdoor storage yards may have problems with trespassing, vandalism, and theft. Security measures, such as installing fencing and lighting, can minimize these problems. A fence, however, must not prevent ready access to the yard by the fire department. The fire department should be consulted about incorporating remote gates in the fencing to provide additional access under fire conditions.

Security guards can provide fire protection and loss control surveillance for outdoor storage yards. NFPA 601, *Standard for Security Services in Fire Loss Prevention,* covers the selection, duties, instruction, and training of such personnel.

Utilizing the Site

Management. When a yard is selected and laid out, the maximum amount of material to be stored in it is also established. Frequent inspections should monitor the quantity of the material and other fire prevention and protection features, including disposal of waste materials.

In general, management's attitude toward the yard's fire protection provides an example that employees are likely to follow.

Fire Protection and Prevention. All fire protection equipment, including hydrants, fire pumps, fire extinguishers, and any suppression, detection, or alarm systems on the storage site, must be properly inspected, tested, and maintained. All materials-handling equipment at the site should be equipped with a multipurpose portable fire extinguisher suitable for any type of fire.

The locations of all hydrants, hose houses, portable extinguishers, alarm boxes, and other fire protection equipment should be properly marked, preferably with elevated signs. Arrows and signs painted on the pavement are the minimum markings required.

If material to be torch cut or welded cannot be moved from the storage yard to a remote location, work should be done only after taking appropriate precautions (see NFPA 51B).

Smoking should be prohibited or restricted to specific areas that are remote from combustible storage. Adequate signs should be displayed and regulations strictly enforced.

A private fire brigade of employees can provide initial fire-fighting capabilities. If there are enough employees to organize a fire brigade, the availability and ability of a public fire department normally govern the level of organization, training, and equipment provided to the brigade. The larger the storage yard and the more valuable its contents, the greater the need for a private fire brigade for immediate response to an incident. NFPA 600 provides minimum requirements for their organization and training.

Maintenance and Housekeeping. Repairs to fencing, lighting, and the yard surface should be made promptly, and materials-handling equipment should be kept in good condition. Suitable safeguards should be provided to minimize the hazard of sparks from equipment, such as refuse burners, boiler stacks, vehicle exhausts, and locomotives.

Good housekeeping also includes controlling weeds and vegetation. Weeds, grass, and other vegetation should be sprayed with an acceptable herbicide or ground sterilizer. Dead vegetation should be removed.

In many instances, scrap lumber, broken pallets, broken containers, bales, or pieces of material stored on the site are

discarded into the clear space around the yard. Daily checks should be made for such discarded materials; where found, they should be properly removed. Care should be taken to prevent the accumulation of windblown debris and other combustible materials around the storage.

Outdoor Storage of Specific Materials

A discussion of safe storage practices for a few common materials follows. As a source for good practices, see the NFPA publications previously referenced and industry or insurance company standards. Many times, the application of inside storage guidelines for a commodity is a good starting point for devising outdoor storage guidelines.

Wood and Wood Products. Because wood is moved from the forests only at certain times of the year, large quantities of logs are stored at sawmills, paper mills, and pulp mills. Large circular piles with logs dumped on the top are called "stacked piles." Logs stacked parallel, like matches in a box, are called "ranked piles." Stacked piles are usually much larger, with pile heights often approaching 100 ft (30.5 m). Ranked piles are usually 10- to 15-ft (3- to 5-m) high. Because maintaining separation and aisles is much easier for ranked piles, fire protection for them is also much easier (Figure 20.16.8).

Controlling log yard fires can require large quantities of water. This can require that many portable turrets and monitor nozzles, each discharging about 1000 gpm (3785 L/min) operate simultaneously. A looped underground fire main system with hydrants spaced throughout the yard is good practice. Monitor nozzles on towers are advantageous in log yards, especially those with high-stacked piles. Burrowing fires in large stacked piles are difficult to extinguish even after surface burning is under control.

Chip storage has replaced log storage at many pulp and paper mills. Two completely different types of fires occur in chip piles: surface fires and internal fires. The amount of water needed to control a chip pile fire varies, depending on the pile size. Weather conditions, operating methods, geographic location, wood chip type, and the degree to which wetting may be employed all influence fire conditions. Exposure to long periods of hot, dry weather with no regular surface wetting creates conditions under which fast-spreading surface fires occur.

Frequency of pile turnover and operating methods influence the potential for fires. Piles built using methods that allow a concentration of fines (the dust and small pieces of material in the pile) are subject to internal heating, which, if undetected, can cause intense internal fires. This is also true of piles stored for long time periods with no turnover.

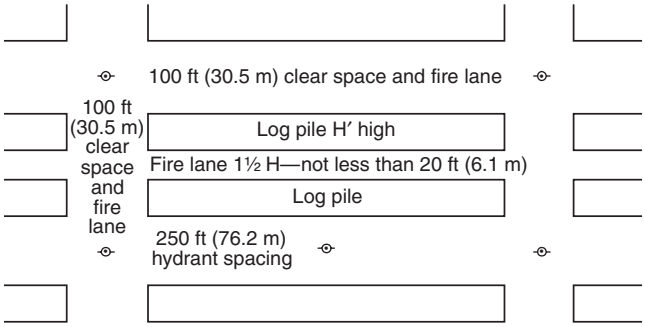


FIGURE 20.16.8 Good Layout for Ranked Piles of Logs in a Storage Yard

Paper and Paper Products. Some paper and paper products are stored outdoors. Roll paper is normally stored in large rolls weighing 2 tons (1814 kg) or more. Tightly wound paper is difficult to ignite; however, roll paper stored outdoors is more vulnerable. Once ignited, the rolls burn with great intensity as the paper exfoliates and exposes more paper to burning.

Baled wastepaper does not produce as intense a fire as roll paper does, but instead tends to produce burrowing fires. Broken bales are difficult to handle after wetting. A motorized vehicle with a shovel may be needed to move debris in order to complete extinguishment. Spontaneous ignition can occur in wastepaper if foreign materials subject to spontaneous heating become trapped in bales. Fire protection for wastepaper storage is generally the same as for other outdoor storage.

SUMMARY

Fires in warehousing and storage areas pose a number of fire protection challenges that must be addressed in a facility fire protection plan. The provision of a properly designed, installed, and maintained automatic sprinkler system is the best method of controlling a storage fire until it can be extinguished by the facility fire brigade or the public fire department. Effective action during a fire can limit the loss; such action must be carefully planed in advance. Ideally, the building owner and the public fire department must partner to develop an effective response plan.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on general indoor and outdoor storage discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 13E, *Recommended Practice for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems*

NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*
NFPA 30B, *Code for the Manufacture and Storage of Aerosol Products*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities*
NFPA 70, *National Electrical Code®*
NFPA 72®, *National Fire Alarm Code®*
NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*
NFPA 88A, *Standard for Parking Structures*
NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA *101®*, *Life Safety Code®*
NFPA 102, *Standard for Grandstands, Folding and Telescopic Seating, Tents, and Membrane Structures*
NFPA 204, *Standard for Smoke and Heat Venting*
NFPA 307, *Standard for the Construction and Fire Protection of Marine Terminals, Piers, and Wharves*
NFPA 409, *Standard on Aircraft Hangars*
NFPA 434, *Code for the Storage of Pesticides*
NFPA 505, *Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operations*
NFPA 520, *Standard on Subterranean Spaces*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 601, *Standard for Security Services in Fire Loss Prevention*
NFPA 1620, *Recommended Practice for Pre-Incident Planning*
NFPA 5000®, *Building Construction and Safety Code®*

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Chapter 17

Library and Museum Collections

Danny L. McDaniel

Chapter Contents

Causes of Cultural Property Fires
Fire Prevention Principles
Fire Protection for Library and Museum Collections
Construction Considerations
Fire Emergency Management
Damage Limitation
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Key Terms

bookstack, compartmentation, cultural resource properties, historic building, means of egress, museum, place of worship

This chapter discusses the incidence of fire in cultural resource properties, analyzes the differences between fires in which large and minimal losses occur, and describes principles and practices for managing cultural resources to reduce the risk of fire occurring in them and to minimize losses when they do occur.

At first glance historic buildings, libraries, museums, and places of worship seem quite different because of the nature of their use, contents, and degree of public access. Nevertheless, most museums contain libraries, many libraries feature exhibits of art or other culturally significant objects, most museums and many libraries and places of worship are in historic buildings, many places of worship house important collections of artifacts, art objects, and library materials, and all contain archival records essential to understanding our cultural heritage. Moreover, the fire protection problems are similar. Cultural resource properties nearly always include large quantities of combustible, high-value, and often irreplaceable materials. Another striking similarity is that although places of worship, libraries, and museums are public assembly occupancies, the open construction and extraordinarily high fuel loads are more typical of warehouse occupancies.

From a fire protection viewpoint, places of worship, libraries, and museums are mixed-use occupancies with significant public assembly and storage components but also may include cooking and eating facilities, laboratories, child care facilities, and even sleeping accommodations. A popular program in museums, for example, is to allow groups, usually children, to camp overnight in a gallery. Such programs have long been part of the educational outreach offered by historic sites and living history museums, and, of course, some places of worship provide shelter for the homeless and other disadvantaged persons as part of their community outreach. The fire risk in these occupancies should not be underrated. Public areas, such as assembly areas, library reading rooms, and museum exhibit galleries, generally are no-smoking areas with low fuel loads and high standards of housekeeping, and they may be monitored by staff or security officers. Nevertheless, such areas regularly suffer costly fires.

Nonpublic areas, such as storerooms, bookstacks, collection storage, work areas, exhibit preparation areas, food preparation areas, and conservation laboratories, present additional special hazards. Fuel loads are much higher in these areas, and housekeeping and smoking are more difficult to control.

A review of fire experience in NFPA 909, *Code for the Protection of Cultural Resource Properties—Museums, Libraries, and Places of Worship,* and NFPA 914, *Code for Fire Protection of Historic Structures,* clearly demonstrates the risk to cultural resource properties. Recent fires worthy of special attention include those at the Los Angeles Central Public Library (two in 1986 and one in 1988); the Hampton Court Palace in Richmond on Thames, England, in 1986; the Louisiana State Museum in New Orleans in 1988; the Library of the USSR Academy of Sciences in St. Petersburg, Russia, in 1988; Windsor Castle in Berkshire, England, in 1992; the Hofburg Palace in Vienna, Austria, in 1992; the Norwich Central Library in Norwich, England, in 1994; La Fenice Opera House in Venice, Italy, in 1996; and the First Presbyterian Church in Lexington, Virginia, in 2000.

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See also Section 1, Chapter 6, "Premises Security"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 8, Chapter 13, "Electrical Systems and Appliances"; Section 9, Chapter 8, "Protection of Records"; Section 11, Chapter 2, "Housekeeping Practices"; Section 12, Chapter 9, "Fire and Emergency Services Protective Clothing and Protective Equipment"; Section 12, Chapter 18, "Pre-Incident Planning for Emergency Response"; Section 14, Chapter 2, "Automatic Fire Detectors"; Section 16, Chapter 2, "Automatic Sprinklers"; Section 16, Chapter 6, "Residential Sprinkler Systems"; Section 16, Chapter 8, "Water Mist Fire Suppression Systems"; Section 17, Chapter 5, "Fire Extinguisher Use and Maintenance"; Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems"; and Section 20, Chapter 1, "Assessing Life Safety in Buildings."

CAUSES OF CULTURAL PROPERTY FIRES

In 1999, the Federal Emergency Managment Agency implemented Version 5.0 of the National Fire Incident Reporting System, which changed some of the cause codes used in earlier versions. Therefore, only relative comparisons can be made between leading causes of fires from data collected before 1999 and data collected thereafter. Tables 20.17.1, 20.17.3, and 20.17.5 show leading cause data for fires in libraries, places of worship, and museums for the period 1980 through 1998. Tables 20.17.2, 20.17.4, and 20.17.6 show the same data for the period 1999 through 2002.

Arson is the leading cause of fires in libraries and places of worship (Tables 20.17.1, 20.17.2, 20.17.3, and 20.17.4), both in the number of fires and in the value of property damaged. Arson also was the second most frequent cause of fires in museums during the period 1980 through 1998 (Table 20.17.5) and the third leading cause in the period 1999 through 2002. From 1980 to 1998, arson accounted for 85 percent of the property loss in library fires, including the disastrous Los Angeles Central Public Library fire in 1986, and in the same period, arson accounted for 42 percent of the property loss in places of worship fires, and 26 percent of the fire losses in museums (see Table 20.17.5). In the period 1999 through 2002, arson accounted for 13 percent of the property losses in libraries and 20 percent in places of worship. The second most significant cause of fires in libraries and places of worship, and the third leading cause in museums in the period 1999 through 2002, have been failures in electrical distribution equipment. Electrical distribution equipment fires accounted for 13 percent of the property damage losses in libraries, places of worship, and museums during 1980 to 1998 and 21 percent in the period 1999 through 2002. Together, incendiary and suspicious causes and electrical distribution equipment problems accounted for nearly half the fires in cultural properties from 1980 through 1998 and about 33 percent of the fires from 1999 through 2002.

FIRE PREVENTION PRINCIPLES

Fire prevention is the cultural property's first line of defense against fire. Fire prevention consists of controlling and separating ignition sources from the supply of fuel.

Ignition Control

Ignition control involves identifying all sources of heat that could cause ignition in combustibles and isolating these sources from the fuel.

Arson. Arson is a difficult crime to prevent, and the arsonist is an unpredictable variable in the fire prevention program. A determined arsonist can circumvent even the most carefully defined fire prevention program. However, most arsonists are not so determined and have no special knowledge of fire or safety systems. Although preventing all deliberately set fires may be impossible, a fire prevention program that incorporates a strong security program can limit risk.

Fundamental precautions against arson are a strong access control program backed by detailed opening and closing procedures and strong measures to deter and detect unauthorized entry. At a minimum a security program should include the following:

1. A detailed, written, access control policy with two objectives: (1) to control (define) legitimate access and (2) to prevent illicit or unnecessary access. These objectives can be met by establishing levels of access to spaces and degrees of access to protected areas or objects. Legitimate access to grounds or buildings does not mean access to nonpublic areas. Access to storage does not necessarily mean access to protected objects. Likewise, access does not mean uncontrolled access. Visitor escorts are a legitimate means of access control.

   An effective access control policy includes the following provisions:

   - Identification of those who may obtain access (both routine and occasional) to nonpublic spaces and under what circumstances, for example, employees, scholars, researchers, visitors, service vendors, emergency response personnel, and others.
   - Procedures to obtain legitimate access to nonpublic areas. The policy should identify which staff can grant access, how much access they may grant, and on what basis. The policy should identify who must be escorted in nonpublic areas.
   - Responsibility for keeping access lists up-to-date and for making sure they are used routinely.

2. The best access and key control program is of little value if the facility is improperly opened or closed. Following written opening and closing procedures is the safest way to make the transition from one condition to the other. Standardizing how the facility is opened and closed establishes a baseline condition of the facility during each period. In the risk assessment process, these baseline conditions dictate the additional physical security tools needed to achieve acceptable security levels. Opening and closing procedures should:

   - Identify who may open or close. As the basis of the facility's access control program, designating, in writing, who has authority to open a building or controlled area establishes both the responsibility and authority to control access.

TABLE 20.17.1 Major Causes of U.S. Library Structure Fires, 1980–1998 Annual Averages

Major Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Dollars)*	
Incendiary or suspicious	78	(40.0%)	0	(NA)	0	(24.5%)	4,018,200	(84.5%)
Electrical distribution	38	(19.6%)	0	(NA)	0	(10.0%)	281,400	(5.9%)
Other equipment	16	(8.3%)	0	(NA)	0	(0.0%)	16,700	(0.4%)
Open flame, ember, or torch	12	(6.2%)	0	(NA)	0	(10.3%)	17,800	(0.4%)
Smoking materials	11	(5.9%)	0	(NA)	0	(11.4%)	65,300	(1.4%)
Heating equipment	11	(5.7%)	0	(NA)	0	(32.5%)	143,200	(3.0%)
Cooking equipment	8	(4.0%)	0	(NA)	0	(0.0%)	14,900	(0.3%)
Appliance, tool, or air conditioning	7	(3.8%)	0	(NA)	0	(11.4%)	31,200	(0.7%)
Child playing	5	(2.3%)	0	(NA)	0	(0.0%)	56,600	(1.2%)
Natural causes	4	(2.0%)	0	(NA)	0	(0.0%)	30,900	(0.6%)
Exposure (to other hostile fire)	3	(1.3%)	0	(NA)	0	(0.0%)	78,100	(1.6%)
Other heat source	2	(0.9%)	0	(NA)	0	(0.0%)	300	(0.0%)
Total	195	(100.0%)	0	(NA)	1	(100.0%)	4,754,400	(100.0%)

Note: This table shows the causes of structure fires (incident type 11) in libraries (fixed property use 151). These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires, civilian deaths, and civilian injuries are expressed to the nearest one and property damage is rounded to the nearest hundred dollars. Sums may not equal totals due to rounding errors. Property damage figures have not been adjusted for inflation. The 12 major cause categories are based on a hierarchy developed by the U.S. Fire Administration. Fires in which the cause was unknown were allocated proportionally among fires of known cause.

Source: National estimates based on NFIRS and NFPA survey.

TABLE 20.17.2 Leading Causes of Structure Fires in Libraries, 1999–2002 Annual Averages

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Dollars)*	
Intentional	32	(26%)	0	(NA)	0	(NA)	171,000	(13%)
Electrical distribution and lighting equipment	17	(14%)	0	(NA)	0	(NA)	441,000	(33%)
Cooking equipment fires	11	(9%)	0	(NA)	0	(NA)	16,000	(0%)
Identified cooking equipment	4	(3%)	0	(NA)	0	(NA)	2,000	(0%)
Confined cooking fire	7	(6%)	0	(NA)	0	(NA)	2,000	(0%)
Heating equipment	8	(7%)	0	(NA)	0	(NA)	2,000	(1%)
Smoking materials	6	(5%)	0	(NA)	0	(NA)	34,000	(0%)
Torch	5	(4%)	0	(NA)	0	(NA)	2,000	(3%)
Contained trash or rubbish fire	10	(8%)	0	(NA)	0	(NA)	16,000	(0%)

Note: These are the leading causes, obtained from the following list: intentional (from the NFIRS field "cause"); playing with fire (from factor contributing to ignition); confined heating (including confined chimney and confined fuel burner or boiler fires), confined cooking, and contained trash or rubbish (from incident type); identified heating, identified cooking, clothes dryer or washer, torch (including burner and soldering iron), electrical distribution and lighting equipment, medical equipment, and electronic, office or entertainment equipment (from equipment involved in ignition); smoking materials, candles, lightning, and spontaneous combustion or chemical reaction (from heat source); and mobile property involved (from mobile property involved in ignition). Exposure fires include fires with an exposure number greater than zero, as well as fires identified by heat source or factor contributing to ignition when no equipment was involved in ignition that were not intentionally set. The same fire can be listed under multiple causes, based on multiple data elements.

These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires, deaths, and injuries are rounded to the nearest one. Direct property damage is rounded to the nearest thousand. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey.

TABLE 20.17.3 Major Causes of U.S. Structure Fires in Churches, Chapels, Temples, or Mosques, 1980–1998 Annual Averages

Major Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Incendiary or suspicious	510	(32.3%)	1	(52.3%)	3	(17.8%)	18.4	(41.5%)
Electrical distribution	230	(14.8%)	0	(0.0%)	2	(13.5%)	5.8	(13.1%)
Heating equipment	180	(11.7%)	0	(16.0%)	3	(14.3%)	5.9	(13.4%)
Open flame, ember, or torch	120	(7.3%)	0	(5.8%)	2	(8.5%)	2.0	(4.5%)
Other equipment	110	(7.1%)	0	(0.0%)	5	(25.0%)	3.6	(8.1%)
Natural causes	90	(5.5%)	0	(8.3%)	1	(4.6%)	4.0	(8.9%)
Exposure (to other hostile fire)	70	(4.6%)	0	(0.0%)	0	(0.4%)	0.7	(1.5%)
Cooking equipment	70	(4.5%)	0	(9.2%)	1	(7.6%)	0.4	(1.0%)
Appliance, tool, or air conditioning	60	(3.9%)	0	(0.0%)	0	(1.4%)	1.3	(2.9%)
Other heat source	50	(3.3%)	0	(0.0%)	1	(3.9%)	1.2	(2.6%)
Smoking materials	40	(2.8%)	0	(8.5%)	0	(0.9%)	0.6	(1.4%)
Child playing	40	(2.4%)	0	(0.0%)	0	(2.1%)	0.5	(1.1%)
Total	1580	(100.0%)	2	(100.0%)	18	(100.0%)	44.2	(100.0%)

Note: This table shows the causes of structure fires (incident type 11) in churches, chapels, temples, or mosques (fixed property use 131). These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires are rounded to the nearest ten, civilian deaths and civilian injuries are expressed to the nearest one, and property damage is rounded to the nearest hundred thousand dollars. Sums may not equal totals due to rounding errors. Property damage figures have not been adjusted for inflation. The 12 major cause categories are based on a hierarchy developed by the U.S. Fire Administration. Fires in which the cause was unknown were allocated proportionally among fires of known cause.

Source: National estimates based on NFIRS and NFPA survey.

TABLE 20.17.4 Leading Causes of Structure Fires in Places of Worship and Funeral Parlors, 1999–2002 Annual Averages

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Intentional	290	(17%)	0	(0%)	0	(0%)	19.6	(20%)
Electrical distribution and lighting equipment	290	(16%)	0	(0%)	2	(9%)	20.6	(21%)
Heating equipment	200	(12%)	0	(0%)	1	(4%)	8.5	(9%)
Identified heating equipment	180	(10%)	0	(0%)	1	(4%)	8.3	(9%)
Confined heating equipment fire	30	(2%)	0	(0%)	0	(0%)	0.1	(0%)
Cooking equipment fires	230	(13%)	1	(54%)	6	(29%)	2.4	(2%)
Identified cooking equipment	150	(8%)	1	(54%)	5	(26%)	2.4	(2%)
Confined cooking fire	80	(5%)	0	(0%)	1	(3%)	0.0	(0%)
Candle	110	(6%)	0	(0%)	2	(11%)	2.2	(2%)
Torch (including burner or soldering iron)	80	(4%)	0	(0%)	1	(4%)	2.2	(2%)
Lightning	80	(4%)	0	(0%)	0	(0%)	11.4	(12%)
Smoking materials	70	(4%)	1	(50%)	1	(6%)	10.7	(11%)
Exposure to other fire	60	(3%)	0	(0%)	0	(0%)	3.6	(4%)
Playing with fire	60	(3%)	0	(0%)	0	(0%)	3.6	(4%)
Contained trash or rubbish fire	40	(2%)	0	(0%)	1	(3%)	0.0	(0%)

Note: These are the leading causes, obtained from the following list: intentional (from the NFIRS field "cause"); playing with fire (from factor contributing to ignition); confined heating (including confined chimney and confined fuel burner or boiler fires), confined cooking, and contained trash or rubbish (from incident type); identified heating, identified cooking, clothes dryer or washer, torch (including burner and soldering iron), electrical distribution and lighting equipment, medical equipment, and electronic, office or entertainment equipment (from equipment involved in ignition); smoking materials, candles, lightning, and spontaneous combustion or chemical reaction (from heat source); and mobile property involved (from mobile property involved in ignition). Exposure fires include fires with an exposure number greater than zero, as well as fires identified by heat source or factor contributing to ignition when no equipment was involved in ignition that were not intentionally set. The same fire can be listed under multiple causes, based on multiple data elements.

These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest hundred thousand dollars. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey.

TABLE 20.17.5 Major Causes of Structure Fires in U.S. Museums or Art Galleries, 1980–1998 Annual Averages

Major Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Dollars)*	
Electrical distribution	21	(24.6%)	0	(NA)	0	(22.3%)	532,300	(27.2%)
Incendiary or suspicious	16	(18.3%)	0	(NA)	0	(0.0%)	502,200	(25.7%)
Other equipment	9	(10.9%)	0	(NA)	0	(6.1%)	263,600	(13.5%)
Open flame, ember, or torch	8	(9.1%)	0	(NA)	0	(14.3%)	38,400	(2.0%)
Heating equipment	7	(8.0%)	0	(NA)	0	(19.9%)	500,800	(25.6%)
Smoking materials	6	(7.5%)	0	(NA)	0	(0.0%)	12,700	(0.6%)
Cooking equipment	6	(7.1%)	0	(NA)	0	(0.0%)	24,800	(1.3%)
Exposure (to other hostile fire)	4	(4.3%)	0	(NA)	0	(0.0%)	51,600	(2.6%)
Natural causes	4	(4.1%)	0	(NA)	0	(0.0%)	21,800	(1.1%)
Appliance, tool, or air conditioning	3	(3.5%)	0	(NA)	0	(30.8%)	1,900	(0.1%)
Other heat source	1	(1.7%)	0	(NA)	0	(6.5%)	4,600	(0.2%)
Child playing	1	(0.7%)	0	(NA)	0	(0.0%)	0	(0.0%)
Total	86	(100.0%)	0	(NA)	1	(100.0%)	1,954,800	(100.0%)

Note: This table shows the causes of structure fires (incident type 11) in museums or art galleries (fixed property use 152). These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires, civilian deaths, and civilian injuries are expressed to the nearest one, and property damage is rounded to the nearest hundred dollars. Sums may not equal totals due to rounding errors. Property damage figures have not been adjusted for inflation. The 12 major cause categories are based on a hierarchy developed by the U.S. Fire Administration. Fires in which the cause was unknown were allocated proportionally among fires of known cause.

Source: National estimates based on NFIRS and NFPA survey.

TABLE 20.17.6 Leading Causes of Structure Fires in Museums, 1999–2002 Annual Averages

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Dollars)*	
Heating equipment	10	(16%)	0	(NA)	0	(0%)	65,000	(6%)
Identified heating equipment	9	(14%)	0	(NA)	0	(0%)	755,000	(74%)
Confined heating equipment fire	1	(2%)	0	(NA)	0	(0%)	114,000	(11%)
Cooking equipment fires	8	(13%)	0	(NA)	3	(100%)	114,000	(11%)
Identified cooking equipment	3	(6%)	0	(NA)	3	(100%)	0	(0%)
Confined cooking fire	4	(7%)	0	(NA)	0	(0%)	1,000	(0%)
Intentional	8	(8%)	0	(NA)	0	(0%)	1,000	(0%)
Electrical distribution and lighting equipment	4	(7%)	0	(NA)	0	(0%)	0	(0%)
Candle	3	(5%)	0	(NA)	0	(0%)	0	(0%)
Torch	3	(5%)	0	(NA)	0	(0%)	12,000	(1%)
Smoking materials	2	(3%)	0	(NA)	0	(0%)	0	(0%)
Contained trash or rubbish fire	3	(5%)	0	(NA)	0	(0%)	9,000	(1%)

Note: These are the leading causes, obtained from the following list: intentional (from the NFIRS field "cause"); playing with fire (from factor contributing to ignition); confined heating (including confined chimney and confined fuel burner or boiler fires), confined cooking, and contained trash or rubbish (from incident type); identified heating, identified cooking, clothes dryer or washer, torch (including burner and soldering iron), electrical distribution and lighting equipment, medical equipment, and electronic, office or entertainment equipment (from equipment involved in ignition); smoking materials, candles, lightning, and spontaneous combustion or chemical reaction (from heat source); and mobile property involved (from mobile property involved in ignition). Exposure fires include fires with an exposure number greater than zero, as well as fires identified by heat source or factor contributing to ignition when no equipment was involved in ignition that were not intentionally set. The same fire can be listed under multiple causes, based on multiple data elements.

These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires, deaths, and injuries are rounded to the nearest one. Direct property damage is rounded to the nearest thousand. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey.

- Establish locking, unlocking, entry sequences, and paths. When opening or closing a building, a clearly defined entry and exit procedure should assure continuity and complete coverage. Opening and closing procedures should be designed so the person opening the building starts at one selected point and the person closing the building finishes at the same point. This procedure assures that all critical areas are consistently checked.
- Establish procedures to inspect the building for stay-behinds. Large buildings usually have many places where someone intent on remaining in the building can avoid detection. The first step in dealing with stay-behinds is to make it as difficult as possible for unauthorized persons to get into areas where they can hide. Nonpublic areas, such as utility closets, mechanical areas, office spaces, and the like, should be locked while visitors are in the building. In some cases isolated spaces should have local daytime intrusion detectors to alert staff if an unauthorized person enters one of them. At the end of the day, it is important to search the building in a systematic way, usually starting at the top and working down and out. If possible, lock or secure building areas as they are inspected to prevent an intruder from moving back into a space after inspection. Opening and closing procedures should highlight areas that are particularly vulnerable to stay-behinds for special consideration. Where installed, the intrusion detection system may be zoned so that it can be activated in sections to help keep cleared areas secure.
- Identify other specific features of concern in the building.

3. Windows and doors should be secured with good-quality locking devices. Panic hardware on emergency exit doors allows doors to be opened from the inside and remain locked from the outside. Doors into nonpublic areas should be kept locked to prevent uncontrolled access by the general public.
4. Windows and doors should be equipped to provide an alarm on any unauthorized opening. In some communities intrusion alarms may be connected directly to the police or fire department. Alarm monitoring services also are available from commercial organizations.
5. Closed-circuit television can be extremely useful for monitoring little used spaces, exhibit areas, print rooms, and other collection study facilities, as well as emergency exits. In addition, the presence of a camera often is a psychological deterrent to illegal behavior.
6. Exterior lighting is an important element in the security program. Illuminating concealed building areas, potential entry points, and large windows let police, security patrols, and others in the neighborhood observe activity around the building. Where public utilities do not provide it, lighting should be added at all concealed approaches to the building.
7. Libraries should eliminate book drops used for after-hours book return, isolate them from the building by fire-resistant construction, or equip them with an automatic fire suppression system. Book drops are favorite targets for arsonists and vandals.[1]
8. If feasible, security patrols should inspect the building along well-planned and monitored routes at irregular intervals.
9. Staff should regularly and closely inspect ashtrays, waste receptacles, soiled linen hampers, electric heating appliances, and other places that can support fire development. Although not specifically an arson prevention measure, this routine can uncover hazards that could involve incendiarism, such as a filled wastebasket hiding a time-delay igniter, or other unusual conditions.

Electrical System. Wiring installed in accordance with the requirements of NFPA 70, *National Electrical Code®*, is equipped with overcurrent protection that opens the circuit before current flow reaches a level that dangerously overheats the conductor or its insulation. Nevertheless, overcurrent devices may fail, and under some conditions overloaded or partially grounded wiring may generate enough heat to ignite combustibles without blowing fuses or tripping circuit breakers.[2] For example, circuits subjected to flooding when a water line breaks or a steam line leaks, must be thoroughly dried. Otherwise, water can partially ground the circuit, generating excessive heat when current is applied.[3] The most common example of problems leading to failure of overcurrent protection, however, involves improperly altering the circuit by installing an improperly sized fuse or circuit breaker.[4] A comprehensive preventive maintenance program for the building's electrical distribution system is an essential element in the fire prevention program.

The proliferation of information processing equipment (computer terminals, word processors, PCs, modems, printers, and facsimile and photocopying machines) adds significant electrical loads that can exceed the existing building wiring system's capacity. More often, however, the problem is either a shortage of electrical outlets to accommodate the equipment or a shortage of outlets where they are needed. The temptation is to make the existing arrangement work by adding multiple outlet adapters to expand the capacity of an existing outlet or to use extension cords to bring power from a less conveniently placed outlet. Neither solution is acceptable. Multiple outlet adapters encourage overloading of the electrical circuit and should never be permitted. Extension cords are not an acceptable substitute for fixed wiring for the following reasons: (1) they are subject to mechanical damage, and (2) they can be overloaded easily. Extension cords usually are made with smaller gauge wire than the fixed wiring in the building. Electrical resistance increases significantly as wire size decreases and length increases. Where permitted, extension cords must be for temporary, short-term use only. The conductor must be rated to carry the current load expected over the distance it will be used. In addition, where extension cords have multiple outlet assemblies, they should have a circuit breaker at the output end to provide overcurrent protection for the extension cord. Extension cords must be protected from mechanical damage and never concealed under carpets. (See Section 8, Chapter 13, "Electrical Systems and Appliances.")

Surface temperatures of incandescent lamps vary widely. Spotlights, for example, easily can reach the ignition temperature of paper or textiles. Incandescent bulbs near, or in contact with, combustible materials may ignite them even if their surface

temperature is below the ignition temperature of the combustible material. Steady application of a heat source below a combustible material's ignition temperature can generate enough heat to ignite the material, given enough time.

The cooler surface temperatures of fluorescent lamps do not present the ignition hazards of incandescent bulbs. Nevertheless, ballasts in fluorescent light fixtures generate heat and are potential ignition sources, particularly when installed in a way that traps heat. For example, ballasts mounted flush against combustible, low density, cellulose fiberboard or other materials of similar combustibility present a potentially severe fire hazard. Fluorescent light ballasts also may be a source of ignition when they fail. At a minimum, a failing ballast may generate significant quantities of acrid smoke.

Heating Equipment. Heating equipment malfunction or misuse is an important potential cause of fires. Boilers and furnaces of central heating systems should be isolated in a fire-resistant enclosure, either separate from or attached to the cultural resource property. Fixed or portable space heaters and portable heaters should not be used in combustible collection storage areas.

Because cellulosic materials, such as wood, paper, or textiles, store heat, they may ignite after prolonged contact with hot objects that are well below the materials' usual ignition temperature. Such materials should not be in contact with steam piping, heat ducts, or other low-grade heat sources.

Appliances. If not prohibited entirely, space heaters, hot plates, microwave ovens, coffee makers, and other small appliances should be rigidly regulated and closely monitored. Where permitted, each appliance should satisfy the following conditions:

- Listed by an independent testing laboratory
- Placed on a noncombustible base
- Located so they are adequately separated from combustible materials
- Located where air circulation prevents heat buildup

Those responsible for closing the building or area should have a listing of the location of each heating appliance and should inspect them as part of the building closing procedure. The inspection should ensure that the appliance works properly, that combustible materials are not touching or close to the appliance, and that appliances not necessary for building protection are turned off. If the facility has security officers, they should also have a listing of each heating appliance and should check each appliance during their rounds. Where feasible, heating appliances should be unplugged when not in use.

Smoking. Most cultural resource buildings are smoke-free facilities. Where permitted, smoking should be limited to those places, such as administrative offices, staff rest areas, and designated visitor lounges, where fire-safe practices can be monitored and controlled. As more facilities ban smoking, however, it is important to recognize that a total ban may result in surreptitious smoking in unsupervised locations, thus actually reintroducing the risk of fire from smoking practices. Where smoking is banned inside the building, adequate facilities should be provided outside the building to accommodate those who wish to smoke.

Open Flame Devices. Open flames used in building repairs, laboratory operations, or in the interpretation of historic environments are severe ignition hazards, as are hot metal sparks or slag from welding and cutting. Candles are a large part of many worship services, including both lit candles fixed in place and lit candles carried by worshipers. Use of open flame devices should require the written approval of a responsible management official. Before signing such an authorization, the official should evaluate the risk to life safety and collection materials, and should prescribe protective measures as conditions of the authorization. Management conditions for authorization should include at least:

1. Relocating combustible materials, especially irreplaceable, valuable, sensitive materials as in an exhibit or collection, a safe distance from the ignition source.
2. Requiring a fire watch of one or more trained persons with appropriate fire-extinguishing equipment. The fire watch should be on site continuously, with no other duties, while the hazardous activity is performed and should remain in the area long enough to ensure the discovery of any hidden fire after interruption or termination of the activity. A fire watch should monitor the area for at least 30 minutes after welding and cutting torches have been used.

Fuel Control

Fuel control must include all combustible contents, including any collections and ancillary records, as well as furniture, interior finish, packaging materials, and flammable liquids. Control measures include arrangement of storage to limit fire spread and separation of fuel from ignition sources. Much of this can be accomplished through good housekeeping practices. (See Section 11, Chapter 2, "Housekeeping Practices.")

Flammable Liquid Storage and Handling. Where possible, flammable and combustible liquids should be stored in fire-resistant structures isolated from the building. Where this is not feasible, small quantities of flammable or combustible liquids may be stored in approved, self-closing, flammable liquid storage cabinets. All flammable or combustible liquids permitted inside the building should be contained in safety cans. When in use, only that quantity of flammable or combustible liquid required during an 8 hour shift should be permitted outside the flammable liquid storage cabinet. It must be in safety cans until actually used. Special attention is required to ensure adequate ventilation, and ignition sources must be eliminated or carefully controlled. (See Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids.")

Spontaneous Heating. Oil- and solvent-soaked cloths and rags, such as those used with oil-based paint, mineral spirits, and some cleaning products, can heat spontaneously. They should be placed in a metal can with a tightly fitting metal top immediately after use and completely removed from the building no later than the end of each day.

Fuel Geometry and Overcrowding. A useful way to consider the combustible materials contained in a cultural resource building is to see them as arranged in fixed fuel packages: exhibit cases, bookstacks, desks, tables, chairs, pews, hymnals, heavy curtains or drapery, and so on. These fuel packages also may contain quantities of movable fuel, such as loose paper, which can vary the total fuel load and radically change the ignition characteristics of individual fuel packages. Although these fuel packages usually are not contiguous, and indeed may be housed in a noncombustible building shell, they may become contiguous because of combustible interior finishes. Increasing the distance between the fuel packages and using interior finish materials, such as carpet, wall coverings, and draperies, with a low flame spread rating, minimizes the risk of fire spreading from one package to another.

Interior Finish. Interior finish materials with high flame spread rates, such as fiberboard and some textile coverings (analogous in composition to carpet floor coverings) when vertically oriented, negate the effectiveness of distance as a tool to isolate fuel packages. For example, flame can spread in low-density cellulosic fiberboard and acoustic ceiling tile, as shown in Figure 20.17.1, as fast as people can run. Decades ago flame spread index ratings for low-density cellulosic fiberboard and acoustic ceiling tile products were reported to range from 225 to 350.[5,6]

Although building test fires in 1959 demonstrated this flame spread potential, these materials still may be found in some cultural resource properties across North America.[7] Where such low-density finish materials still exist, they should be replaced. During removal it is especially important to also remove any adhesive used to attach the tile to ceilings or walls. The adhesive has been identified as a key factor in the rapid flame spread over ceiling tiles.[8] If replacement is not feasible, these materials should be encapsulated behind fire-rated gypsum board. Treatment with intumescent paint may not provide the intended protection unless this application is approved by the listing laboratory and maintained as the manufacturer prescribes.[9] Textile coverings may present a similar hazard when used in exhibits or when applied to wall surfaces unless they are specifically tested to establish an acceptable rate of flame spread when vertically installed.

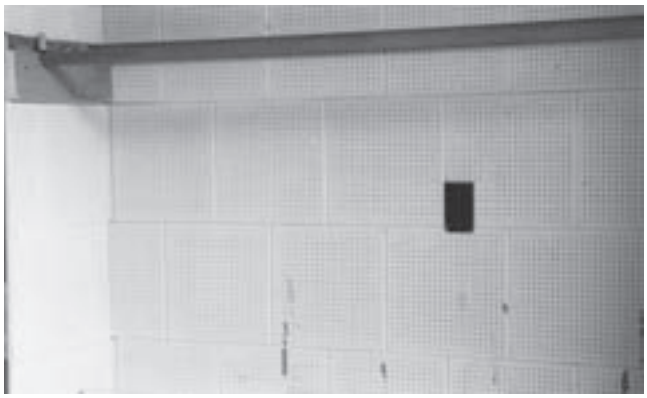

FIGURE 20.17.1 Typical Low-Density Cellulosic Acoustical Tile

Inadequate Space. Museums and libraries collect; therefore, growth of the collection is inevitable. As collections grow, staffing levels tend to grow also. Adding space is expensive and usually the last resort. These conditions cause overcrowding of both collections and staff, reducing the space between fuel packages. Overcrowding increases the risk that a fire will grow by spreading to adjacent fuel packages rather than burning itself out. Periods of overcrowding, therefore, require compensating emphasis on other elements of the fire prevention program, especially control of ignition sources.

FIRE PROTECTION FOR LIBRARY AND MUSEUM COLLECTIONS

Experience shows that early detection followed by quick action to stop fire growth can prevent large fire losses. A common element in most large-loss fires is the absence of automatic suppression systems to control or extinguish fire in its early stages. Some preservation specialists—museum curators, librarians, and archivists—believe water is a greater hazard to the building and collections than fire. They emphasize fire prevention almost exclusively, limiting fire protection to the installation of automatic detection systems. Cultural resource property fires continue to occur despite this heavy emphasis on fire prevention. Table 20.17.7 shows that 24 percent of all reported library fires occur between 9 p.m. and 9 a.m.; an additional 23 percent start between 5 p.m. and 9 p.m.—times when libraries have little or no staff on duty.[10] These off-hour periods also account for about half the property loss. However, fires have steadily declined in cultural resource properties (Tables 20.17.8, 20.17.9, and 20.17.10).

Total dependence on fire prevention and manual extinguishment places the cultural resource property at serious risk of catastrophic loss when prevention fails. The 1986 fire in the Los Angeles Central Library illustrates the point clearly. In this fire, smoke detectors warned building occupants, who evacuated safely. Nevertheless, despite timely notification to the Los Angeles Fire Department, lack of an automatic suppression system allowed the fire to spread. Bringing it under control took more than 7 hours. The fire destroyed more than 400,000 objects, and 700,000 wet books were placed in cold storage to await restoration.

Because fire prevention efforts can lessen, but not eliminate, the possibility of fire, knowledge of the options available to limit fire spread is essential. Local fire and building codes provide minimum requirements for the survival of the building and for the life safety of its occupants. Nevertheless, sole reliance on code provisions will not adequately preserve building contents, especially highly valuable collections. Fire protection features to protect the building contents are needed over and above minimum requirements that local codes impose.

Systems Approach to Fire Safety

A systems approach to fire safety is a useful management tool for selecting the appropriate level of fire protection to limit fire loss to an acceptable level. The systems approach uses decision tree analysis, failure modes and effects analysis, and other

TABLE 20.17.7 U.S. Library Structure Fires, by Time of Alarm, 1980–1998 Annual Averages

Time of Alarm	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Dollars)*	
12:01 a.m. to 1:00 a.m.	2	(1.2%)	0	(NA)	0	(0.0%)	4,900	(0.1%)
1:01 a.m. to 2:00 a.m.	3	(1.5%)	0	(NA)	0	(0.0%)	26,800	(0.6%)
2:01 a.m. to 3:00 a.m.	4	(2.3%)	0	(NA)	0	(0.0%)	691,900	(14.6%)
3:01 a.m. to 4:00 a.m.	2	(1.0%)	0	(NA)	0	(0.0%)	884,300	(18.6%)
4:01 a.m. to 5:00 a.m.	2	(0.8%)	0	(NA)	0	(0.0%)	115,100	(2.4%)
5:01 a.m. to 6:00 a.m.	2	(1.0%)	0	(NA)	0	(0.0%)	6,200	(0.1%)
6:01 a.m. to 7:00 a.m.	3	(1.6%)	0	(NA)	0	(0.0%)	8,800	(0.2%)
7:01 a.m. to 8:00 a.m.	4	(1.9%)	0	(NA)	0	(0.0%)	21,200	(0.4%)
8:01 a.m. to 9:00 a.m.	9	(4.5%)	0	(NA)	0	(0.0%)	44,100	(0.9%)
9:01 a.m. to 10:00 a.m.	9	(4.7%)	0	(NA)	0	(12.5%)	14,800	(0.3%)
10:01 a.m. to 11:00 a.m.	11	(5.6%)	0	(NA)	0	(25.0%)	1,993,900	(41.9%)
11:01 a.m. to Noon	10	(5.4%)	0	(NA)	0	(12.5%)	18,400	(0.4%)
12:01 p.m. to 1:00 p.m.	11	(5.8%)	0	(NA)	0	(6.3%)	14,200	(0.3%)
1:01 p.m. to 2:00 p.m.	13	(6.8%)	0	(NA)	0	(0.0%)	58,100	(1.2%)
2:01 p.m. to 3:00 p.m.	12	(5.9%)	0	(NA)	0	(0.0%)	148,000	(3.1%)
3:01 p.m. to 4:00 p.m.	14	(7.3%)	0	(NA)	0	(18.8%)	13,800	(0.3%)
4:01 p.m. to 5:00 p.m.	21	(10.8%)	0	(NA)	0	(0.0%)	38,000	(0.8%)
5:01 p.m. to 6:00 p.m.	15	(7.5%)	0	(NA)	0	(12.5%)	62,000	(1.3%)
6:01 p.m. to 7:00 p.m.	13	(6.6%)	0	(NA)	0	(0.0%)	297,400	(6.3%)
7:01 p.m. to 8:00 p.m.	9	(4.6%)	0	(NA)	0	(0.0%)	29,800	(0.6%)
8:01 p.m. to 9:00 p.m.	9	(4.8%)	0	(NA)	0	(12.5%)	21,600	(0.5%)
9:01 p.m. to 10:00 p.m.	6	(3.2%)	0	(NA)	0	(0.0%)	162,600	(3.4%)
10:01 p.m. to 11:00 p.m.	4	(2.2%)	0	(NA)	0	(0.0%)	8,800	(0.2%)
11:01 p.m. to Midnight	6	(3.0%)	0	(NA)	0	(0.0%)	69,600	(1.5%)
Total	195	(100.0%)	0	(NA)	1	(100.0%)	4,754,400	(100.0%)
Hourly average	8	(4.2%)	0	(NA)	0	(4.2%)	198,100	(4.2%)
9:01 a.m. to 5:00 p.m. Subtotal	102	(52.4%)	0	(NA)	1	(75.0%)	2,299,200	(48.4%)
9:01 a.m. to 5:00 p.m. Hourly average	13	(6.5%)	0	(NA)	0	(9.4%)	287,400	(6.0%)
5:01 p.m. to 9:00 p.m. Subtotal	46	(23.4%)	0	(NA)	0	(25.0%)	410,800	(8.6%)
5:01 p.m. to 9:00 p.m. Hourly average	11	(5.9%)	0	(NA)	0	(6.3%)	102,700	(2.2%)
9:01 p.m. to 9:00 a.m. Subtotal	47	(24.2%)	0	(NA)	0	(0.0%)	2,044,300	(43.0%)
9:01 p.m. to 9:00 a.m. Hourly average	4	(2.0%)	0	(NA)	0	(0.0%)	170,400	(3.6%)

Note: This table shows the alarm times for structure fires (incident type 11) in libraries (fixed property use 151). These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires, civilian deaths, and civilian injuries are expressed to the nearest one, and property damage is rounded to the nearest hundred dollars. Sums may not equal totals due to rounding errors. Property damage figures have not been adjusted for inflation.

Source: National estimates based on NFIRS and NFPA survey.

systems techniques to identify hazards, assess probability, establish maximum acceptable fire loss, and identify fire defense alternatives.

A critical element in the systems approach is to develop fire safety objectives for the facility based on life safety considerations, the value and vulnerability of the collections, and obligations for continuity of service. The fire safety objectives adopted by the Library of Congress in Washington, DC, may provide a useful reference point.[11] The General Firesafety Objectives and Critical Space Objectives, shown graphically in Figure 20.17.2, are similar to those the U.S. General Services Administration (GSA) originally adopted for federal office buildings nationwide.[12] This graph shows the fire safety objectives for Library of Congress buildings and represents the desired minimum probability of success in limiting a fire's growth from its start to full building involvement. Adoption of

TABLE 20.17.8 Structure Fires in Libraries by Year, 1980–2002

Year	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage (in Dollars)
1980	386	0	0	2,170,000
1981	266	0	0	215,000
1982	276	0	0	13,864,000
1983	194	0	0	3,557,000
1984	238	0	3	225,000
1985	279	0	0	1,424,000
1986	206	0	5	42,859,000
1987	197	0	0	15,163,000
1988	150	0	0	482,000
1989	151	0	0	1,916,000
1990	171	0	2	679,000
1991	175	0	0	118,000
1992	158	0	1	1,940,000
1993	124	0	0	2,264,000
1994	144	0	0	170,000
1995	131	0	0	927,000
1996	182	0	2	1,187,000
1997	140	0	0	341,000
1998	132	0	2	833,000
1999	153	0	0	2,195,000
2000	102	0	0	1,846,000
2001	115	0	0	1,015,000
2002	118	0	0	342,000

Note: This table shows the structure fire (incident type 11 through 1998 and incident types 110–129 in 1999–2002) experience by year in libraries (fixed property use 151). These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires, deaths, and injuries are rounded to the nearest one; direct property damage is rounded to the nearest thousand. Property damage has not been adjusted for inflation.

Source: National estimates based on NFIRS and NFPA survey.

TABLE 20.17.9 Structure Fires in Museums and Art Galleries, by Year, 1980–2002

Year	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage (in Dollars)
1980	98	0	0	880,000
1981	120	0	0	1,096,000
1982	105	0	0	544,000
1983	72	0	0	828,000
1984	117	0	7	4,702,000
1985	105	0	0	8,304,000
1986	137	0	2	2,045,000
1987	82	0	2	599,000
1988	86	0	0	363,000
1989	101	0	3	7,633,000
1990	64	0	0	397,000
1991	84	0	1	341,000
1992	79	0	3	694,000
1993	78	0	2	2,438,000
1994	59	0	2	3,708,000
1995	78	0	1	1,025,000
1996	59	0	2	734,000
1997	70	0	0	419,000
1998	42	0	0	390,000
1999	55	0	0	688,000
2000	71	0	14	414,000
2001	55	0	0	2,319,000
2002	59	0	0	658,000

Note: This table shows the structure fire (incident type 11 through 1998 and incident types 110–129 in 1999–2002) experience by year in museums or art galleries (fixed property use 152). These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. Fires, deaths, and injuries are rounded to the nearest one; direct property damage is rounded to the nearest thousand. Property damage has not been adjusted for inflation.

Source: National estimates based on NFIRS and NFPA survey.

acceptable limits of fire loss should reconcile the cost of the fire defense system to achieve those limits with the resources available to the institution.[13]

Designing the Fire Safety System

The specific design selected for the fire protection system in a typical cultural resource property depends on the value of the exhibits, collections, or other unique contents and the value and characteristics of the building and its fuel load. At a minimum, the system should include fire detection, alarm notification, emergency communication, manual extinguishment, automatic fire suppression, protection for special hazards and other passive construction elements for safe occupant egress, limiting fire spread, and isolating hazardous operations and building systems.

Detection and Alarm. A fire detection and alarm system should be installed throughout the building. The system should include smoke detectors in all exhibit galleries, reading rooms, and collection storage areas; smoke, heat, or flame detectors, as appropriate, should be installed in other parts of the building. From 1994 to 1998, 39 percent of reported U.S. structure fires in churches and related properties and 70 percent in museums and libraries were reported with automatic fire detection present.

A detection and alarm system should alert building occupants of an unwanted fire before it becomes a threat. A properly designed and installed system will alert occupants in time to evacuate in an orderly manner. The system also will facilitate prompt notification of the fire service. Ideally the detection system also provides an opportunity for trained building staff to extinguish the fire before automatic fire suppression equipment activates or the fire service arrives. (Section 14 of this handbook describes types of detection and alarm systems.) Care and good judgment are imperative, however. Fire in concealed spaces can burn for a considerable period before activating detection equipment. In 1994–1998, roughly 10 percent of reported U.S.

TABLE 20.17.10 Structure Fires in Places of Worship and Funeral Parlors, by Year, 1980–2002

Year	*Fires*	*Civilian Deaths*	*Civilian Injuries*	Direct Property Damage (in Millions of Dollars) *As Reported*	*In 2002 Dollars*
1980	3500	2	23	62.1	135.7
1981	3340	0	14	79.2	156.4
1982	3350	16	58	43.3	80.6
1983	2850	7	26	114.0	205.7
1984	2930	3	45	50.4	87.1
1985	3020	0	30	60.5	101.0
1986	2770	2	29	51.5	84.6
1987	2660	4	23	51.7	81.8
1988	2360	4	14	69.0	105.0
1989	2160	3	11	59.0	85.6
1990	2100	0	17	62.1	85.6
1991	2120	2	34	56.9	75.1
1992	2190	0	28	70.7	90.7
1993	2030	5	41	57.7	71.8
1994	2040	1	25	60.7	73.7
1995	1890	5	62	52.1	61.5
1996	2180	1	27	62.1	71.3
1997	1950	0	25	43.6	48.9
1998	1910	4	25	68.0	75.1
1999	2000	3	26	100.8	108.8
2000	1620	0	16	94.9	99.2
2001	1750	0	24	85.2	86.6
2002	1670	1	15	104.3	104.3

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest hundred thousand dollars.

Source: NFIRS and NFPA survey. Inflation adjustments were based on U.S. Census Bureau's *Statistical Abstract of the United States: 2006,* "Table 705, Purchasing Power of the Dollar."

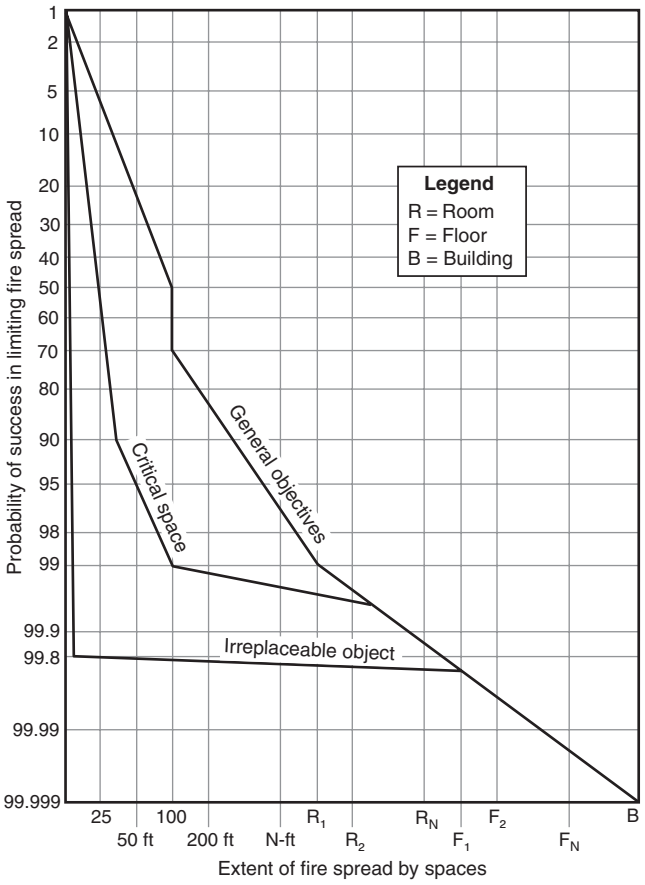

FIGURE 20.17.2 Illustrative Graphic Probability Analysis of Fire Safety Objectives

structure fires in libraries and museums and roughly 15 percent in places of worship began in concealed spaces. Those responding to investigate an alarm must be alert to signs that fire is well established. If there is any doubt, evacuate. Attempting to manually suppress a well-established, concealed space fire can lead to tragedy. When the fire breaks out of the concealed space, it can spread very quickly.

An automatic sprinkler system also can provide the alarm when the first sprinkler opens and water begins to flow in the system. However, this detection occurs at a later stage of fire development when fire and smoke may hamper orderly evacuation. Quick-response (QR) sprinklers may be an exception because they respond to heat at an earlier stage of fire development than standard sprinklers—in some configurations only seconds later than smoke detectors. For this reason some libraries, including the National Library of Canada, the National Library of Scotland, the New British Library, the U.S. Library of Congress, and the U.S. National Archives are installing QR sprinklers to protect their collection storage areas. (See Section 16, Chapter 6, "Residential Sprinkler Systems.")

In addition to sounding an alarm throughout the building, the detection and alarm system should be connected to a central station, the local fire department, or some other acceptable monitoring facility. The value of a detection system is as a communications tool. The detection system itself takes no action to control or extinguish fire. A local alarm may be adequate for evacuating building occupants, but a local alarm alone does not summon the fire department or other emergency assistance. This is particularly true when the building is unoccupied. For this reason connection of the detection system to a central station or equivalent is recommended.

A qualified fire protection specialist or engineer with experience in cultural resource property protection should design the fire detection and alarm systems to ensure proper building coverage and to minimize the risk of unwanted alarms. The designer must have knowledge of, and experience in, fire behavior in the type of facility to properly select fire detectors for the threat and the ambient environment. The designer must also be well versed in the requirements of applicable codes and standards.

After installation and acceptance tests have been completed, a regular test and maintenance program should be established. This is very important because testing is the only way to determine that no part of the detection and alarm system has failed.[14] Furthermore, because the sensitivity of smoke detectors can change as dust and dirt accumulate, periodic inspection and cleaning are needed to keep the detector working within its intended sensitivity range. (See Section 14, Chapter 2, "Automatic Fire Detectors.")

Communication. A public address system should be considered, especially in very large facilities, to provide emergency voice instructions and information to facilitate evacuation. Cultural resource properties can have complicated egress routes. If unfamiliar with the building layout, the general public may experience difficulty finding appropriate means of egress. Egress routes should be properly marked by illuminated exit signs as required by NFPA *101®*, *Life Safety Code®*, and *NFPA 5000®*, *Building Construction and Safety Code®*.

Manual Extinguishment. Portable extinguishers in the hands of trained users constitute an institution's first line of fire attack. To prevent the use of the wrong class of extinguisher on a particular fire, some institutions provide only multipurpose portable extinguishers. These should be appropriately located and regularly inspected and maintained, so they are fully charged and operational when needed. (See Section 17, Chapter 5, "Fire Extinguisher Use and Maintenance.")

Occupant-use standpipe hose lines require specific hands-on training and drills to avoid personal injury and unnecessary property damage. Hose lines must be inspected at least annually and should be service tested when doubtful conditions are identified. Unfortunately, because many building occupants are not trained to properly use a fire hose and because of a general tendency not to inspect and test hoses as required, municipal fire departments may arrive at a fire to find the occupant hose used ineffectively, sometimes dangerously, or not at all.

Obviously, the fire department also provides manual extinguishment. In buildings without automatic sprinkler systems, it follows occupant fire suppression efforts as the second and final line of fire suppression defense to control loss from fire. If the fire area has reached 2500 to 3000 ft^2 (232 to 279 m^2) at the time of water application, the fire may be confined but not readily extinguished. Figure 20.17.3 suggests that the probability of fire department success actually begins to drop rapidly when fire areas exceed 750 to 1500 ft^2 (70 to 140 m^2).[15]

The most significant concern with manual extinguishment is that once fire enters the free burning phase, fire damage increases exponentially until the fire is under control.[16] Fire protection systems that depend entirely on manual extinguishment risk disaster if human response is delayed or unavailable.

Automatic Sprinklers. As stated earlier, lack of an automatic suppression system is a major contributing factor to large-loss fires in cultural resource properties. Sprinkler systems have been shown to reliably and effectively minimize the risk of large-loss fires in cultural properties.[16] A Factory Mutual Research Corporation (FMRC, now FM Global Research) study found that the average dollar loss in fires with adequate sprinkler protection in the 5 year period 1984 through 1988 was 5.8 times less than the average loss during the same period in fires studied without adequate sprinkler protection. For this study, fires where adequate sprinkler protection existed were those reported to FMRC in which (1) sprinklers were in service, (2) there were no sprinkler system or water supply deficiencies, and (3) sprinkler density was appropriate for the risk.[17] In 1994–1998 U.S. structure fires reported to local fire departments, sprinklers were present on only 4 percent of fires in places of worship and 32 percent of library and museum fires. Average dollar loss per fire was reduced by sprinklers by 32 percent in places of worship and by 72 percent in libraries and museums. This is roughly consistent with the general finding that average loss is reduced by one-half to two-thirds.

For many years, cultural resource management professionals opposed automatic water sprinkler protection, fearing water damage even more than fire damage. Many library and museum planning references reflect this attitude.[18–20] Through the years libraries and museums have experienced water damage from various sources: roof leaks, storm damage, plumbing problems, rivers overflowing, and so on. By comparison, water damage from sprinklers is rare.

Water damage is more likely, however, when fire department hose lines are used to fight fires. Automatic sprinklers actually minimize the potential for water damage. An automatic sprinkler releases 20 to 25 gpm (76 to 95 L/min) in a spray pattern, in contrast to the 150 to 250 gpm (568 to 946 L/min) of pressurized water from each fire fighter's hose stream. Most fires in buildings with automatic sprinklers are controlled with fewer than five sprinklers opening, which collectively release less water per minute than one hose stream. Hoses can sweep materials from shelves and displays into a disorganized mass on a flooded floor. Prospects of salvaging wet materials that remained in place under the relatively gentle action of sprinklers are much better than for materials knocked to the floor, soaked, and possibly trampled on.

Another consideration is that sprinklers discharge water directly in the area of the fire. Sprinklers respond to heat, and only those in the direct fire area become sufficiently hot to open. Fire department hose streams, on the other hand, must be directed to the general area of the fire until smoke clears sufficiently for fire fighters to find and soak the concentration of fire. Therefore, whereas sprinklers tend to restrict damage to the room of origin, fire department hose streams can spread water damage much more widely.

Finally, sprinklers operate early in fire growth, reducing the amount of water needed to extinguish the fire. Fire department hose streams are used much later in the growth of the fire, usually after free burning begins. Therefore, extinguishing fire with a fire department hose stream requires significantly more water. The combination of more water flowing, more area to cover, and more water needed for extinguishment means that fire department hose streams pour huge quantities of water on a fire. This water has to go somewhere: it floods out of the fire area through every available drain and crack and drains to the building's lowest point. Therefore, fires on upper floors can result in extensive water damage to materials many floors below. The

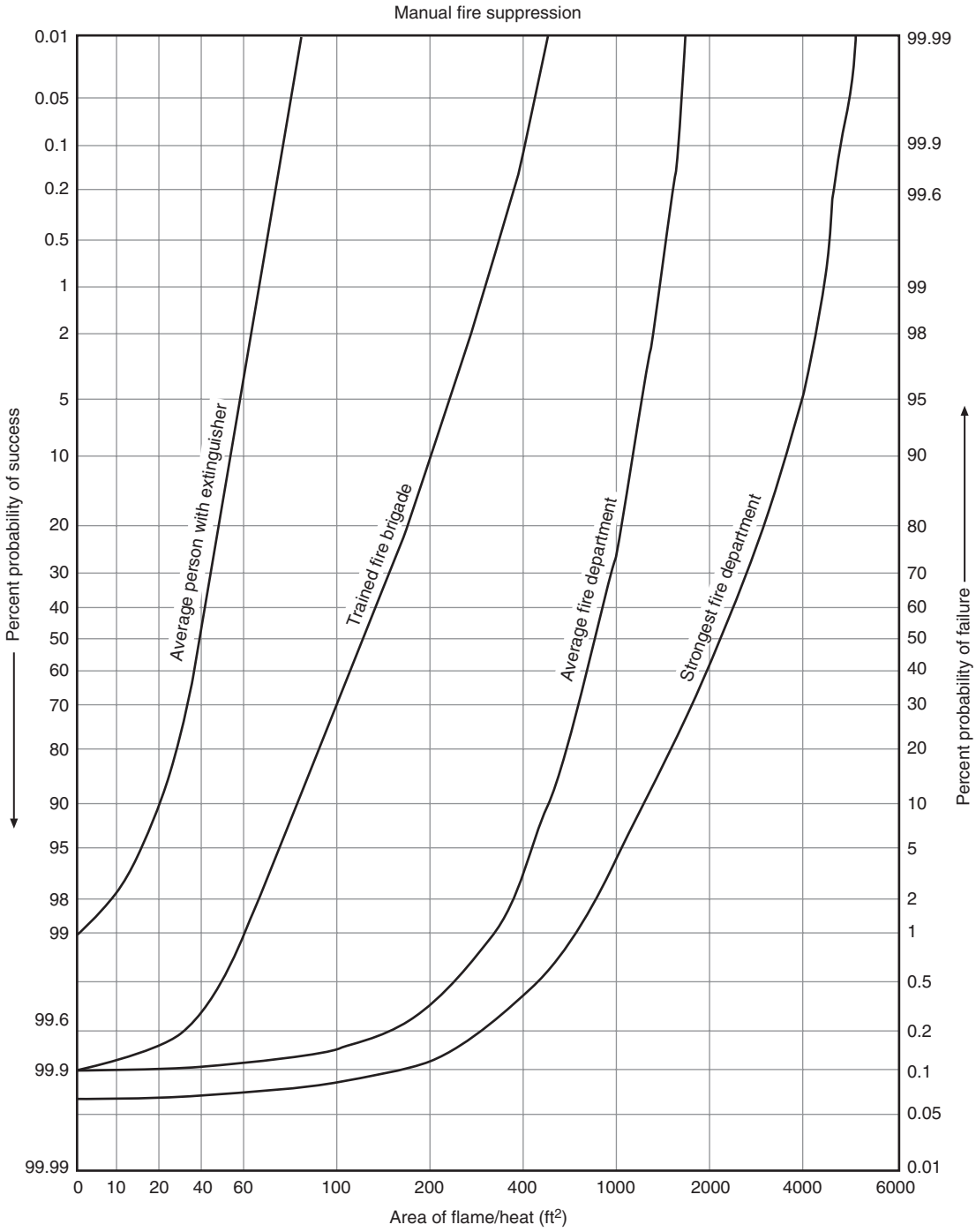

FIGURE 20.17.3 Illustrative Graph of Probability of Success at Different Levels of Manual Extinguishment

use of high-density compact storage modules on lower floors and in basements has magnified this problem in recent years. Compact movable storage modules for libraries significantly increase floor load requirements, and, especially in retrofits, only the ground floor or basement of a building has sufficient floor loading capacity. This concentrates collections in a building's lowest areas, so fighting a fire on an upper floor, or on the roof, can result in significant water damage.

Alternatives to the standard wet-pipe sprinkler system, such as on/off sprinklers and automatic recycling systems, minimize water damage after a fire has been extinguished.

Another alternative, the preaction sprinkler system, may be used where fear of water damage from damaged sprinklers or broken piping is a significant concern. The preaction sprinkler system piping is dry until a signal from an automatic fire detection system opens the water supply valve. Failure of the fire

detection system, however, eliminates the automatic operation of a preaction sprinkler system and requires manual operation of the water supply valve. The fire detection system, then, is a single point of failure in a preaction system, reducing its reliability below that of a wet-pipe sprinkler system. Furthermore, preaction systems require higher levels of regular maintenance to preclude additional potential failure modes. This further reduces their reliability relative to wet-pipe systems. Higher installation and maintenance costs, and less reliability, are the trade-offs for any increased confidence that a preaction system is less likely to accidentally release water than a wet-pipe system. For reasons of reliability, maintainability, and cost, facility owners may elect to install wet-pipe sprinkler systems or even convert their preaction systems to wet pipe.

Corrosion damage in dry pipe and preaction sprinkler systems is emerging as a significant concern in museums and libraries. Oxidation caused by water trapped at low points in sprinkler piping, microbiologically influenced corrosion (MIC), or a combination thereof, can cause severe damage to pipe walls and joints in a relatively short time. Over the last 3 years, for example, one museum has replaced severely damaged systems in two of its buildings—one less than 10 years old and the other 20 years old. At a minimum, where such systems are installed, pipe interiors should be inspected regularly in accordance with NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems.*

Sprinkler systems retrofitted into operating cultural resource facilities can pose a problem when the system is initially charged with water. Final acceptance testing of a sprinkler system requires a 2-hour 200 psi (1034 kPa) hydrostatic test on all piping, fixtures, and sprinklers. Newly installed sprinkler systems can leak, at least a little, when the system is first charged. This is unacceptable where collections are still in place. One solution, used by the Office of the Architect of the U.S. Capitol in the installation of wet-pipe sprinkler systems in Library of Congress bookstacks, requires pneumatic testing of each system before proceeding with normally required hydrostatic testing.

Where sprinkler systems are used in special or high-value areas, those items especially vulnerable to water damage should be stored in cabinets, manuscript boxes, or other appropriate containers. This practice serves several purposes: (1) containerized materials are more difficult to ignite, (2) the containers not only shield contents from water spray in the event of sprinkler discharge but also from intrusion of water from other sources (for example, roof leaks, plumbing problems, etc.), and (3) containers protect contents from smoke damage.[21]

Since about 1970, a number of new and existing libraries and museums have installed automatic sprinkler systems to achieve fire safety objectives and to keep fire risk within manageable, and often insurable, limits. The reduction in insurance premiums can pay off the sprinkler system's installation cost in a few years.[22] Even if the presence of automatic sprinklers does not reduce insurance premiums, their presence may make the facility a more attractive and marketable risk. This can be a significant advantage in getting competitive bids on a facility's property insurance program. (See Section 16, Chapter 1, "Principles of Automatic Sprinkler System Performance," and Section 16, Chapter 2, "Automatic Sprinklers.")

Protection for Special Risks. Areas containing highly valuable or especially vulnerable collections or equipment, or areas essential for continuity of operations, may require a higher level of fire protection to minimize damage or to keep interruption of service within acceptable limits than the combination of a smoke detection system with automatic sprinklers can provide.[22] NFPA 550, *Guide to the Fire Safety Concepts Tree,* is an excellent tool to help managers assess the effectiveness of fire protection strategies, such as installing special fire protection systems or other techniques to achieve higher protection levels within the limits of affordability.[23]

In devising protection strategies for special risks, particular attention should be given to passive fire protection, for example, using special fire- and water-resistant vaults, cabinets, manuscript boxes, or other containers to protect highly valuable collection items. Passive features may be less expensive to install and maintain and may, over time, be more reliable than more complicated alternatives. Nevertheless, relatively low levels of heat can destroy film and other heat-sensitive materials. Therefore, passive features are not a substitute for timely detection and suppression; rather, a combination of active and passive fire protection elements increases the likelihood that sensitive, highly valuable contents, furnishings, and finishes can survive a fire intact. (See Section 9, Chapter 8, "Protection of Records.")

Some items may be so valuable, rare, or vulnerable that their protection becomes one of the institution's highest priorities: the only acceptable level of loss is zero. When this is true, the institution may opt for a special protection system in addition to automatic sprinklers to provide nearly instantaneous response. Such special systems may include sophisticated air-sampling smoke detection, flame detectors, linear heat detectors, or other rapid-detection devices that automatically activate special fire suppression systems, using a gaseous agent or a water mist system. Everything else being equal, a fire in a space protected with a special protection system will be extinguished in the first seconds of combustion, thus limiting damage to the lowest possible level.

Unless it at least matches the automatic sprinkler system's reliability and maintainability, the special system installed for this purpose should be used in combination with, and not as a substitute for, the sprinkler system. The installation cost of a special system to augment a standard automatic sprinkler system should be justified based on the extraordinary value and/or irreplaceability of the items it protects or because it is required for continuity of operations that cannot accept any downtime, such as in the control room for the facility fire protection/security systems and building utilities. The justification should demonstrate a need for a very high probability of success in confining fire growth to an area significantly smaller than would be possible using standard automatic sprinklers alone—for example, less than 100 ft^2 (9.3 m^2). A sprinkler system is a vital backup to the special protection system, however, if the special system fails to extinguish the fire.

Halon 1301 often was used to provide this extra level of protection. Cultural institutions found it particularly attractive because it could be used in normally occupied areas, rapidly extinguished the flaming portion of fires, left no residue, and was not known to harm objects chemically or physically. The envi-

ronmental issues associated with halon 1301, however, have rendered its use impractical for the majority of applications. See Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems," for more information on halon 1301 and halon alternatives.

Water Mist. Water closely fits all requirements of the ideal fire suppression agent. It is safe for the environment and for people, it has excellent extinguishment properties, and it has the advantages of being both inexpensive and abundant. A relatively recent development in fire protection, water mist technology promises to provide all advantages of water with less subsidiary damage and much faster response. In addition, facilities in remote locations, where the cost of installing a water supply for a sprinkler system is prohibitive, may find that water mist systems with self-contained water supplies, or with relatively small water supply tanks, can provide cost-effective fire protection. For more information, see Section 16, Chapter 8, "Water Mist Fire Suppression Systems."

Other Special Hazards. Although the same fire safety principles are applicable to all cultural resource properties, several activities common to museums and some libraries require special attention. These include the following:

- Storing art and other valuable objects
- Packing and unpacking traveling exhibits
- Storing shipping crates and packing materials
- Cleaning and restoring art and other objects
- Constructing and renovating displays

Areas where these activities occur should be isolated and sprinklered. Good practice limits storage of combustible materials to the minimum required for the current exhibit(s) under preparation or being dismantled, with all other materials stored off-site.

Places of worship also house activities requiring special attention. These include the following:

- Storing combustible decorative materials used in services, lawn mowers, and other gasoline powered equipment, and candles
- Operating kitchen and cooking facilities
- Operating child-care and nursery facilities
- Operating temporary shelters for the homeless

These activities should be monitored carefully and the areas should be protected by an automatic fire suppression system. Storage should be controlled to limit the quantity of combustible materials, and all flammable materials or gasoline-powered equipment should be stored away from the structure.

CONSTRUCTION CONSIDERATIONS

Intrinsic design features should include fire safety aspects of site planning, fire-resistant construction, interior finish smoke control, water supply for fire protection, and special requirements for underground structures. Topics deserving special attention in this chapter are compartmentation, means of egress, lighting, and gallery flexibility.

Compartmentation

A well-protected building is subdivided into compartments where walls provide barriers to the spread of fire. Compartments should be as small as possible, and walls should be designed to resist the estimated fire duration, based on maximum fuel loads in the compartments. Where small fire compartments would restrict flexible use of space, the installation of automatic sprinkler systems permits larger compartment areas and compensates for heavy fuel loads in places like collection storage areas and bookstacks.

Smoke damages valuable contents and harms occupants. Fire barriers should confine smoke to the compartment of fire origin. Fire doors protecting openings in these walls must be self-closing or automatic-closing. Self-closing fire doors must never be propped open by wedges, "kick-down" doorstops, or other unapproved means. Where it may be necessary for efficient operations to hold open these doors, this may be done only where automatic devices, such as electromagnetic hold-open devices installed in compliance with NFPA *101,* and *NFPA 5000,* automatically release the door on a signal from a smoke detector or from the fire detection system. In the past, some building codes allowed fusible link assemblies to be used to hold doors open with automatic door closers. They are not acceptable for smoke control or life safety because they depend on heat at the door to release them. By the time the fusible link reaches its release temperature, the fire has already made the door opening unusable, and smoke, which precedes the fire, has already spread beyond the space.

High-hazard contents areas where large quantities of combustible material are used or stored should be separated by fire walls from areas with large exposure of people or sensitive, valuable contents, such as exhibit galleries, reading rooms, other public areas, bookstacks, and collection storage areas. These high-hazard contents areas include carpenter shops; display or exhibit preparation shops; research, restoration, and conservation laboratories; paint rooms; packing rooms; and restaurant kitchens, among other places. When possible, hazardous materials such as flammable liquids, including some paints, should be housed in a structure separate from the building. Fire barrier walls protecting high-hazard areas should be designed to withstand fires involving the maximum fuel loads they will enclose rather than the minimum building code requirements.

Means of Egress

Library and museum security arrangements commonly require all patrons and employees to enter and leave the building at one or two closely monitored points. Unfortunately, this often means that other doors required by NFPA *101* and *NFPA 5000* for exit access or egress are locked. This problem most often arises in museums and libraries with valuable collections and in libraries with heavily used reference collections, such as college and university libraries. Use of electromagnetic and electromechanical door locking systems is gaining acceptance as a way to resolve this conflict between life safety and security. Such systems should include features that provide a level of life safety equivalent to that NFPA *101* and *NFPA 5000* require.

NFPA *101* and *NFPA 5000* allow delayed release locks, with strict limitations, in assembly occupancies, provided automatic sprinklers or fire detectors protect the entire building. Also see NFPA 909 and NFPA 914. Places of worship typically lack the need for such close monitoring and may not limit the number of points of entry.

Attendance in exhibition galleries and reading rooms varies with the exhibit's popularity and the season. For example, a blockbuster museum exhibit draws thousands of visitors each day. Places of worship will see peak attendance in conjunction with religious holidays and certain events, such as weddings. During periods of high attendance, museums and libraries must control occupant loading of the building to ensure egress capacity is not exceeded.[24] Particularly at peak times, a complete emergency plan and a well-trained staff are critical. Staff must take the lead in helping visitors evacuate safely, especially those with disabilities that might make emergency evacuation difficult. As mentioned previously in this chapter, the use of voice communications should be considered for large facilities or those with high attendance or complex egress paths. Voice communications facilitate coordination and reduce occupants' fears and anxieties during evacuation.

Lighting

Art museums typically use as much natural light as possible. They often have features such as glass roofs, light-diffusing glass ceilings, and window walls, which all increase the museum's vulnerability to fire exposure. Conversely, to protect collections from ultraviolet radiation and achieve complete light control, some museums have minimal wall and roof openings. Complex wiring systems carrying unusually heavy electrical loads compensate for the absence of natural light in these buildings. In addition to general area lighting, museums use independent light sources for case and exhibit lighting. Therefore, museums need numerous electrical outlets in floors, walls, and ceilings to provide flexibility for frequent exhibit changes and to avoid dangerous use of extension cords. Electrical installations should comply with NFPA 70.

Gallery Flexibility

Movable walls, temporary furring, and lightweight partitions facilitate rearranging exhibit spaces and changing exhibits. Such features, however, should not be allowed to impede occupants' movement in an emergency, nor should materials used increase fire risk by adding significant quantities of combustible material to the building's fuel load.

FIRE EMERGENCY MANAGEMENT

Managing a cultural resource facility fire involves decisions and actions necessary to mitigate the consequences before, during, and immediately following an incident. Effective management includes continuous monitoring to ensure that fire protection systems and features are always operational and never degraded or defeated by space changes or other building modifications. This also includes providing emergency electric power to support emergency lighting, communications, security systems, and fire protection systems. (See Section 10, Chapter 1, "Emergency and Standby Power Supplies.")

At a minimum, a viable fire emergency plan should provide for planning with the fire department and pre-emergency training of all building staff in evacuation and salvage operations. (See Section 12, Chapter 18, "Pre-Incident Planning for Emergency Response.") The decision to establish fire brigades should depend on whether the building(s) are close enough to a municipal or county fire department for timely response and whether employees are expected to use portable fire extinguishers and standpipe hose lines. In deciding whether to require employees to use fire-fighting equipment, management must be prepared to comply with state and federal regulations for protective clothing, training, and maintenance of fire-fighting equipment.[25] (See Section 12, Chapter 9, "Fire and Emergency Services Protective Clothing and Protective Equipment.") In addition to safety considerations, emphasis should be placed on minimizing water damage and protecting or removing endangered, highly valuable collections. Prefire planning also must provide security for valuable materials after their removal from the building.

DAMAGE LIMITATION

Using freeze/vacuum drying techniques, library preservation specialists have been successful in limiting damage to water-soaked library, archival, and other collection materials. However, water is only one hazard to which collections are vulnerable during a fire. Others include smoke, acids contained in combustion products, and chemical agents used in fire fighting. These hazards perhaps endanger museum collections more than water.

Damage Limitation in Places of Worship and Museums

With much higher values per item and fewer items than libraries, museums and places of worship must concentrate damage limitation efforts on removing endangered collections from the fire area to a safe location as quickly and carefully as possible. Conservation-oriented fire-fighting strategies and techniques enhance salvage efforts and minimize collection losses.

The Winterthur Museum in Wilmington, Delaware, has developed fire-fighting techniques that other museums and libraries might adopt.[26,27] Fire-fighting efforts are divided into three concurrent phases that the fire marshal and staff direct: (1) collection protection and damage limitation operations, led by the housekeeping supervisor and staff; (2) security for collections removed from the fire area, which is the responsibility of the security supervisor and staff; and (3) overall coordination, provided by the building superintendent or a designee.

Damage Limitation in Libraries

The success and cost of limiting damage in water-soaked library collections depend on advance planning and how wet the materials are. Freeze/vacuum drying very effectively removes water and smoke odors, while using ethylene oxide, a sterilizing agent, during the process arrests the mold growth. Freeze/vacuum dry-

ing cannot, however, restore physical damage inflicted by hose streams, trampling, or mishandling.

Before the Fire. Planning for damage limitation efforts before a fire must include the following:

1. Establishing priorities. This facilitates decision making under emergency conditions by identifying, in advance, the items or collections to save first.
2. Identifying preservation specialists who can provide needed guidance
3. Identifying sources of materials, equipment, and facilities to support damage limitation that are available on short notice
4. Organizing and training employees who will be needed in the damage limitation effort during and after the fire
5. Orienting and training the fire service to understand where vulnerable or especially valuable collections or objects are stored. The fire department should prepare a prefire plan that takes these factors into account and provides ongoing damage limitation during fire suppression operations.

During the Fire. Damage limitation efforts during the fire include:

1. Removing endangered highly valued collections if this can be done without placing staff at risk. Where this is not possible, the fire service may perform this function with guidance.
2. Using tarpaulins or plastic sheeting to protect materials that remain in or near the fire area, but are not directly involved in the fire, from water. Here, too, staff must be alert to hazards and must not place themselves at risk to save objects. A well-developed fire department prefire plan will include provisions to accomplish these objectives.

After the Fire. Damage limitation efforts after the fire include:

1. Wrapping and freezing damaged articles
2. Obtaining guidance from a preservation specialist experienced in damage limitation
3. Determining appropriate restoration procedures

Much less damage limitation and restoration work should be needed in facilities protected by automatic sprinklers. Water absorption is minimized when materials are left on shelves undisturbed by the gentler action of automatic sprinklers, as opposed to hose streams' more forceful action. An automatic sprinkler system also greatly reduces the quantity of materials requiring restoration by limiting the size of the fire area to that covered by the operation of one or just a few sprinklers.[28]

FIRE SAFETY IMPLICATIONS OF AUTOMATION AND NEW TECHNOLOGY

Automation of Library Catalogs and Museum Accession Records

Automation has replaced traditional card catalogs and paper museum accession records in most libraries. Continuity of public service increasingly depends on computers and necessitates a high level of fire protection including automatic suppression to ensure continuity of operation. Duplicates of magnetic media containing a library's computer-based catalog or a museum's accession records should be maintained in a safe, remote, offsite location.

Bookstacks

Multitier Bookstacks. Bookstacks, modeled after those developed for the U.S. Library of Congress in 1893, have been used for several decades in many libraries (Figure 20.17.4). Typically, unprotected iron or steel columns and beams at intervals of 7 ft (2.14 m) support decks or tiers. Vertical openings between decks permit heating of bookstack areas by convection or air currents. (See "Deck slit" in Figure 20.17.5.) Under fire conditions, these same openings function as flues to accelerate vertical fire spread to the tiers above.

Smoke barriers should be installed in these vertical openings, or deck slits, to facilitate smoke detection on the tier or deck of fire origin. This was not done when the smoke detection system was installed in the multitier bookstack of the Los Angeles Central Public Library because a ducted ventilation system had not been installed for bookstacks. When an arsonist set a fire on the fifth tier, the first detectors to activate were on the sixth tier, one tier above the tier of fire origin. A delay in finding the fire resulted, and occupants lost the opportunity to stop the fire with portable extinguishers while it was small, with catastrophic results.[29] It took nearly 350 fire fighters and over 70 pieces of fire apparatus 7 hours to extinguish the ensuing inferno.[30]

Modern versions of these systems are still sold but without vertical openings in the modules (Figure 20.17.6). Unprotected steel support structures are vulnerable to collapse in a fire, however. Cast iron and steel structural members lose strength at high temperatures encountered in fires and may collapse. For this reason, the fire service may not be able to enter a multitier bookstack for manual fire suppression. This also applies to any variation on this bookstack design that uses exposed steel structural elements. Because it may be impossible for the fire service to provide manual fire suppression in bookstacks of this or similar design, it is essential that the bookstacks be equipped with automatic fire suppression systems to defend against fire.

In new library construction, multitier bookstacks replace freestanding bookstack ranges installed on structural fire-resistant floors. The difference in fuel load between multitier stacks and freestanding stacks is substantial. All levels in a multitier system are usually considered as one fire compartment, due to the absence of vertical fire barriers between tiers. Fire loads depend on the number of tiers in the bookstack. With shelf loading at 70 percent of capacity, the expected fire load in each tier would be 55 to 65 lb/ft^2 (268 to 317 kg/m^2). Thus, for a multitier bookstack with 10 tiers in a single fire compartment, fire duration is estimated at 70 to 85 hours. Conversely, a fire in a free-standing bookstack that is seven shelves high and set on a fire-resistant floor, would be limited to a single tier and a fire duration of 7 to 8 hours.

Compact Storage or Track Files. Bookstack shelving units, or ranges, mounted on carriages that roll on tracks are common in

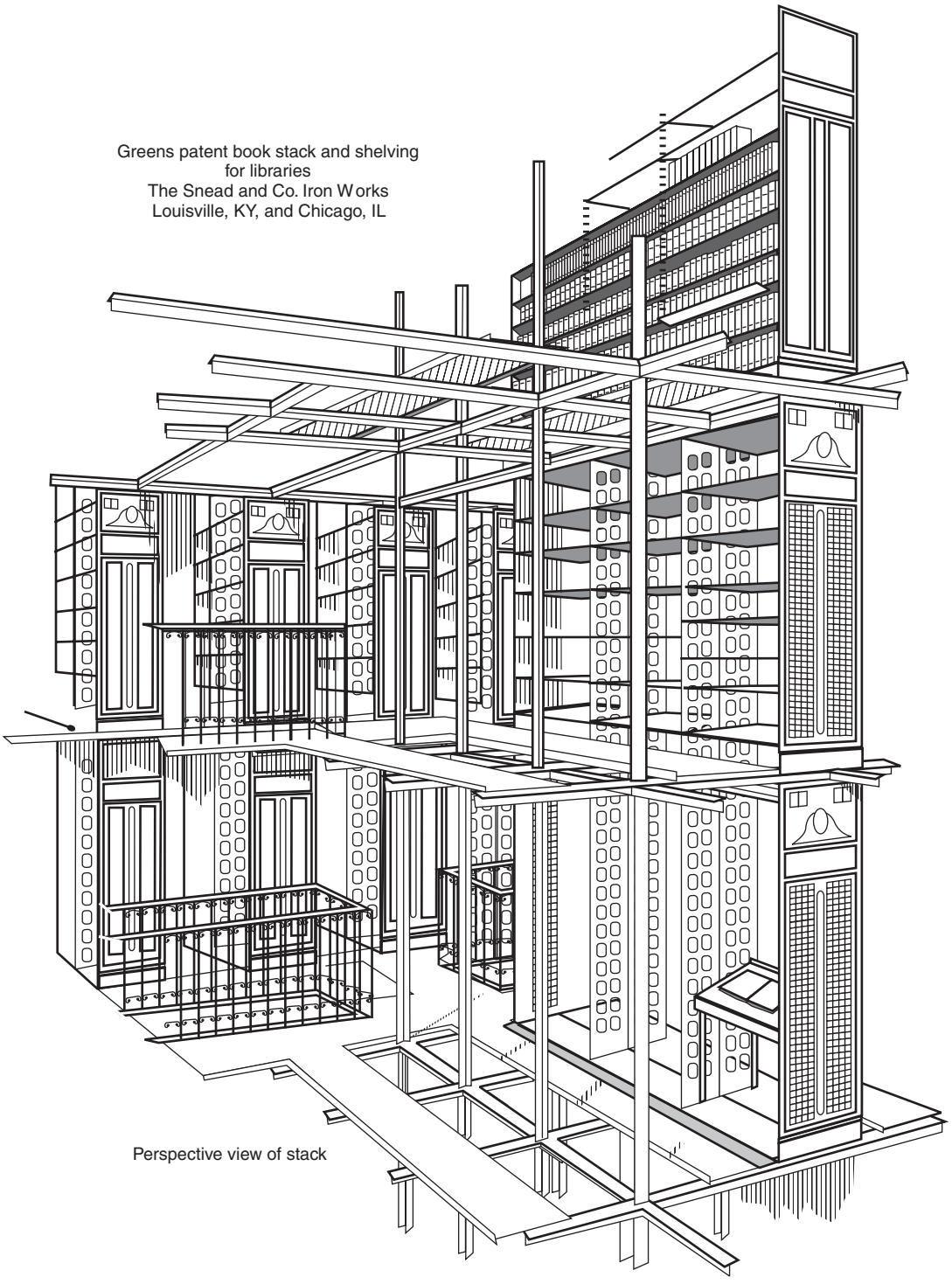

FIGURE 20.17.4 Multitier Bookstack as Installed in the Library of Congress, Circa 1893

new library and museum construction and in renovations. In this space-saving storage system, one moving aisle serves several ranges. The track systems are modular, with two or more mobile ranges between two fixed-end ranges in each module (Figure 20.17.7). This storage method can create fire loads exceeding 120 lb/ft^2 (586 kg/m^2) and fire durations exceeding 15 hours. This is more than enough to challenge the most fire-resistant barriers and construction prescribed by building and fire codes.

The NFPA Technical Committee on Protection of Cultural Resources recommends automatic sprinkler protection for compact storage installations. Without such protection, a fire in a facility with this type of storage system endangers not only the

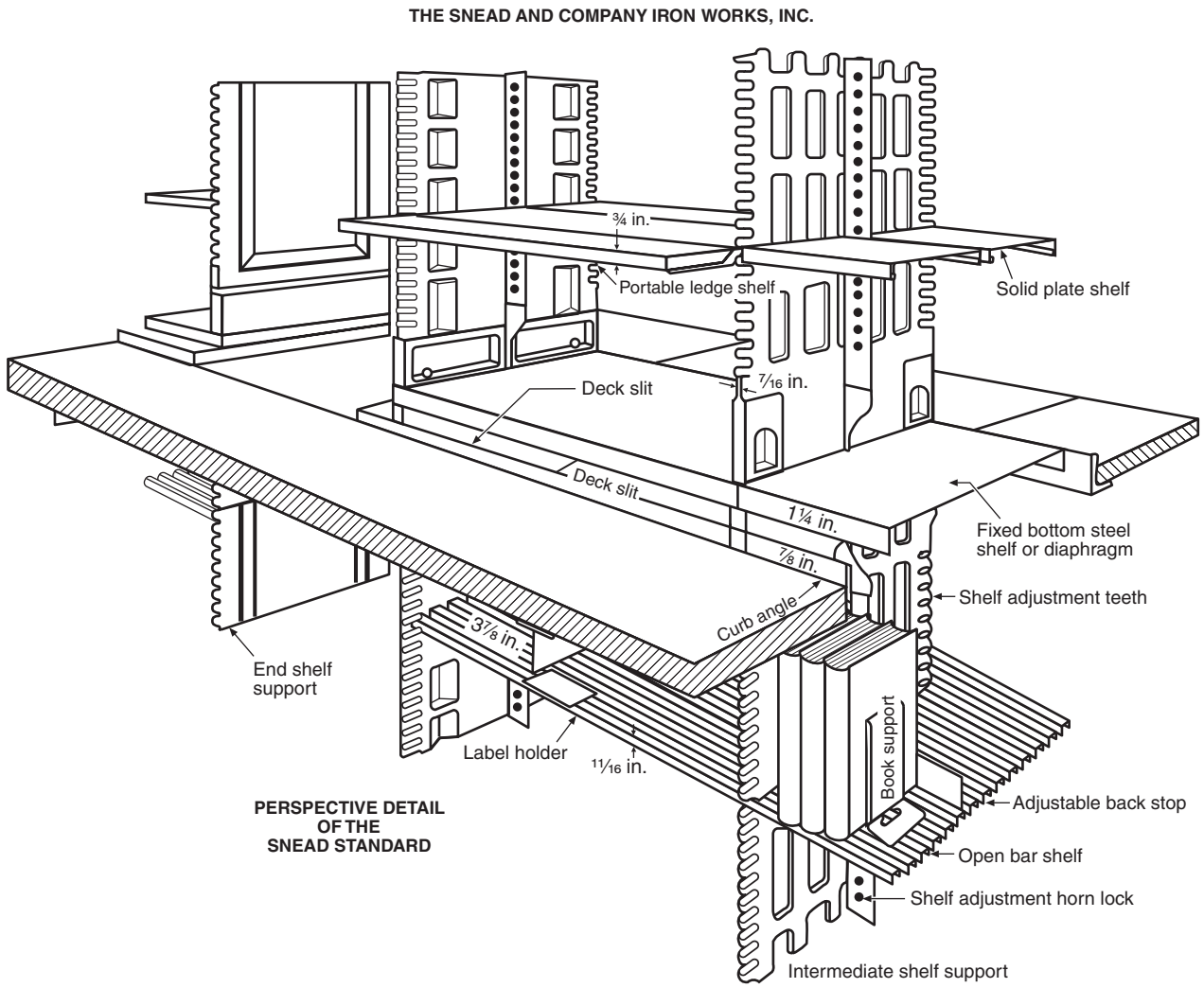

FIGURE 20.17.5 Multitier Bookstack—Showing Section Through Deck Flooring, Deck Slit, Fixed Bottom Shelf, and Adjustable Shelves

collection, but may cause severe structural failures and perhaps building collapse as well. An independent analysis[31] of fire tests conducted to evaluate sprinklers' effectiveness on a compact storage system[32] concluded that sprinklers, installed over a compact storage module, will most probably prevent a fire that originates in the module from damaging building structural elements outside the module. Furthermore, the tests showed (1) there is a good probability that sprinklers will prevent fire spread across 4 ft (1.22 m) aisles between compact storage modules, and (2) sprinklers may effectively prevent fire spread between back-to-back shelves of adjacent modules when a sheet metal panel with a 1 in. (25 mm) air space between adjacent panels backs each shelf. Thus, automatic sprinklers can be expected to limit fire development to that portion of the module of fire origin between the fixed-end range and the open aisle. Nevertheless, total loss of contents within that portion of the storage module is possible (see Figure 20.17.7).

Facility designers must carefully consider the following points in designing compact storage systems:

1. More efficient use of space results in greater density or concentration of values. That is, it increases the number of items subject to fire damage per unit volume of storage space. This risk should be considered in determining the maximum number of ranges to include in each module.
2. Existing automatic fire detection and fire suppression systems may have to be modified, and gaseous agents may be ineffective. In an existing facility with sprinkler protection where compact storage systems are retrofitted, particular attention must be given to water density, ceiling clearances, and structural features of the space. Tests conducted for the National Library of Canada clearly showed that for compact storage systems installed where "explicit compliance with current installation standards" is not possible, it may be necessary to go well beyond normal sprinkler design criteria to achieve adequate protection.[33]
3. Compact storage modules may conceal the origin of smoke, thereby compounding the difficulty in locating and extinguishing a fire.

FIGURE 20.17.6 Modern Multitier Bookstack Installation

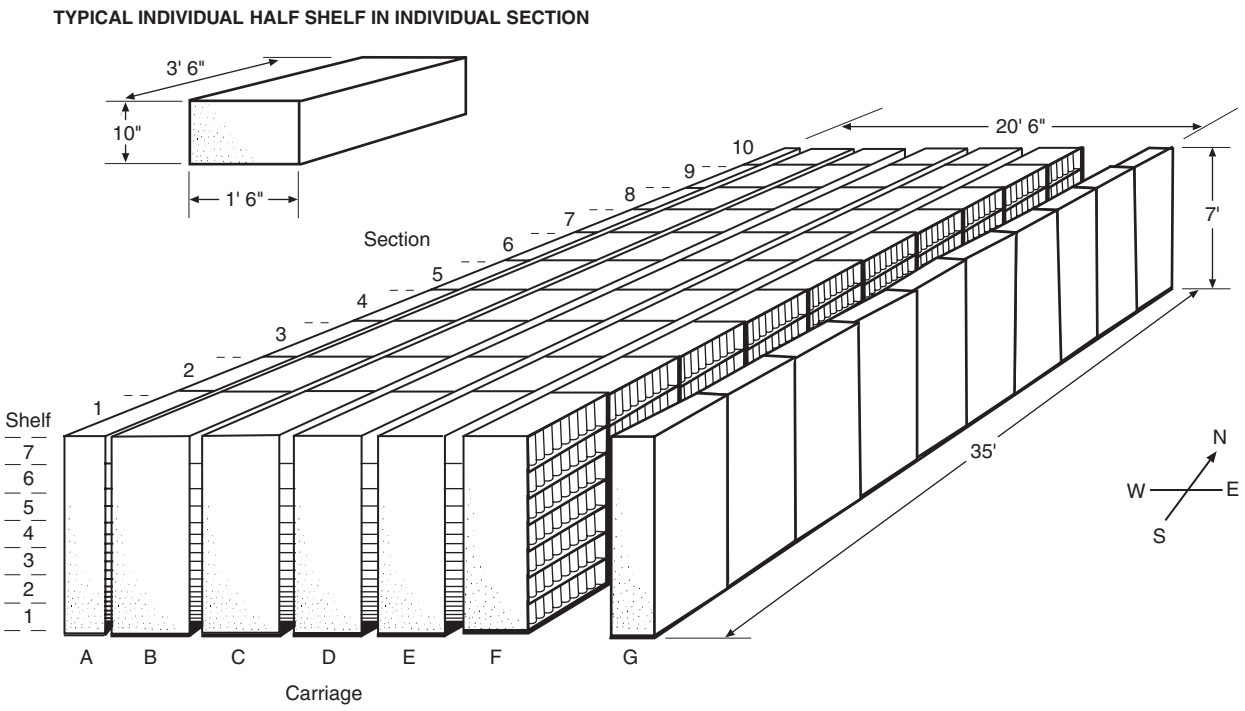

FIGURE 20.17.7 Compact Mobile Shelving

4. Compact storage modules prevent penetration of water from hose streams for fire extinguishment and delay detection by trapping smoke and heat. Consider designing the system so that ranges can be parked with a 5 in. (12.7 cm) gap between them during inactive storage periods. Underwriters Laboratories tested this arrangement with satisfactory results for the U.S. National Archives and Records Administration using quick response sprinklers. Paper record loss was limited to 10 ft^3 (0.28 m^3) and computer record loss to 3 ft^3 (0.08 m^3).[34]
5. Water mist fire suppression test results in bookstack scenarios show promise for special application to the burrowing fire problem in compact storage. It may be possible to design water mist systems for compact storage that limit fire and water damage loss even more effectively than the sprinkler system design tested for the U.S. National Archives and Records Administration.[34]
6. Bookstack ranges may be moved electrically or manually. In compact storage systems that are moved electrically, the electric motor in each bookstack range is a potential ignition source.

FIRE PROTECTION DECISIONS

The elapsed time between a fire's discovery and the beginning of effective manual suppression can easily be too long to prevent unacceptable loss, especially when the building is unoccupied. Faced with this reality, directors of museums and libraries and their governing bodies are deciding to incorporate automatic fire suppression systems as the primary defense against fire loss.

In a 1989 survey of museums of various sizes, including 30 of the largest in the United States, 77 percent reported that they use automatic sprinkler protection.[16] The list of museums that made this decision includes the 15 Smithsonian museums: National Air and Space Museum, National Museum of American History, National Museum of Natural History, National Portrait Gallery, the Sackler Gallery, National Museum of African Art, National Museum of the American Indian, and so on. It also includes the J. Paul Getty Museum, the High Museum of Art in Atlanta, the Phillips Gallery in Washington, DC, and the Dewitt Wallace Museum and Abby Aldrich Rockefeller Folk Art Museum in Williamsburg, Virginia, to name a few.

Similarly, the list of libraries, large and small, equipped to defend their collections against fire loss by installing automatic sprinkler systems continues to grow. Examples include city libraries in Atlanta; Dallas; Houston; Los Angeles; Portland, Maine; and Portland, Oregon, as well as many academic libraries, the State Library of Michigan, and national libraries, such as the Saudi Arabian National Library, the U.S. Library of Congress, the National Library of Canada, and the National Library of Scotland, and the British Library at St. Pancras.[35]

NFPA 909 and other chapters of this handbook provide guidance for procuring, installing, testing, and maintaining fire protection systems.

HISTORIC BUILDINGS AND SITES

Historic buildings house museums, places of worship, office buildings, residences, schools, libraries, restaurants, hotels, restaurants—to name a few. Historic sites include structures as small as covered bridges or as large as entire communities. Historic buildings and sites are often off the beaten path and at a considerable distance from organized fire-fighting services. Often it is as important to protect the structure of a historic building or site as it is to protect the contents. Fire can damage decorative architectural features quickly and burned historic building fabric is lost forever.

Life safety issues in historic buildings may be complicated as well. Historic structures may contain highly combustible structural materials and finishes, and means of egress may be inadequate by today's standards. Fire develops and spreads rapidly via open stairways or where fire and smoke barriers and other smoke and fire control features are absent.[36,37] Historic buildings may not have modern exit signs and emergency lighting, which may cause confusion in an emergency. Building managers must control the occupant load and have a well-developed evacuation plan where such conditions exist.[36]

Historic Building Fires

Fire service reports classify buildings by occupancy type, so data on the frequency or causes of fires in historic buildings are incomplete. Those that are coded as historic buildings experienced 35 U.S. structure fires per year reported to local fire departments from 1994 to 1998. Nevertheless, where data are available, the reported fire causes, in order of 1994–1998 frequency, are arson; electrical distribution equipment, such as fixed wiring; heating equipment; natural causes, such as lightning; cooking equipment; smoking; appliances; open flame; children playing; and exposure from newly burning structures, grass, and woodlands.[36,37] Historic buildings often contain outdated mechanical and electrical systems, and many historic building museums use candles, fireplaces, forges, stoves and other open-flame devices as interpretive aids.

Fire can grow and spread in historic buildings because of inadequate barriers, absence of sprinklers or other means of automatic protection, and delayed discovery and reporting of the fire. The first few minutes after ignition can be critical, particularly in historic buildings of combustible construction. Absence of automatic fire detection or other automatic protection leaves discovery of a fire to a night guard or to chance. Historic buildings require painstaking attention to details to preserve historic authenticity, but experience shows that it is possible to provide appropriate levels of fire protection for the structure and safety for staff and visitors while maintaining original construction or historical appearance.[38,39]

Historic Building Fire Safety

Each historic building or site is unique and the planner must address merits and problems individually. A fire protection plan that systematically achieves fire safety goals includes compartmentation, structural analysis, alarm and communications, means of egress, smoke control, fire suppression, water supply, ignition prevention, fuel control, and impact on authenticity.[38] Managing a historic building for fire safety includes the following:

- Examining the physical conditions and developing a fire defense plan

- Incorporating automatic detection and alarm or fixed extinguishing systems or both
- Providing or having available a trained, properly equipped fire-fighting and salvage organization
- Instituting management and operational practices that eliminate causes of fire, and promoting organized training of personnel so they act effectively when called on

Other Considerations

Chimneys. Flues should be examined for deteriorated mortar joints that may permit sparks or excessive heat to pass into wood framing or other combustible material. Chimneys should be lined and repointed before they are used. If the condition of a flue is questionable or if it cannot be repaired without seriously affecting the building structure around the chimney, then it should not be used.

Electrical Service. Electrical wiring should be approved. Old wiring systems may include deteriorated materials, fittings, and connections that do not meet current codes. A licensed electrician or engineer should inspect and evaluate electrical circuits and wiring. Inadequate or unsafe components should be replaced, and fuses and circuit breakers should be labeled to indicate the areas they control.

Exposure Fires. The fire safety plan should consider exposure of the structure to outside fires. Structures in or adjacent to forests or tall grass must have fire lanes and cleared areas to protect the property from a forest or grass fire. Other nearby structures may present an exposure fire threat where insufficient clear space exists to reduce fire spread from one structure to another. If the historic building is wood frame construction, fire-resistive roofing and siding may help protect it, although eaves, cornices, and windows may still be exposed. Strategically located exterior sprinklers at window openings, along combustible cornices and walls, and on combustible roofs provide protection. See Figure 20.17.8 for an example of automatic sprinklers utilized for exposure fire protection. Fire doors or fire shutters that automatically close in a fire can protect openings in brick and masonry walls. Careful architectural planning can minimize the impact of these protective devices on the historic fabric or appearance of the structure.

Open Flames. Historic building museums use fireplaces and stoves for cooking and heating and to create the desired atmosphere and often use candles and lamps—oil, gas, and kerosene—for illumination. Any flame is a potential ignition source that must be safeguarded and monitored.

Housekeeping. Good housekeeping is a vital element in fire prevention. Clutter and waste invite fire. Rubbish and trash should be removed regularly and exterior housekeeping should be monitored. Debris, tall grass, brush, and fallen leaves that can cause fire to spread should be removed.

Fire Suppression. Even small communities usually have a fire department. However, if the structure is isolated or distant from a fire station, on-site emergency equipment and personnel training for its operation are prudent. The fire service must know the location of hydrants or alternative sources of water such as streams, rivers, ponds, or cisterns if hydrants are not available and must carefully plan how to use alternative sources effectively. It may be prudent to install a dry hydrant with the supply line beneath the frost line so the fire department can use an alternate water source.

FIGURE 20.17.8 Typical Sprinkler Protection for Exposure Fires

Performance-Based Design

Designing fire protection systems in historic buildings requires imagination and innovation to minimize the intrusion on authenticity. A team that includes a fire safety professional with experience in protecting historic buildings, preservation specialists, the building owner or manager, and the authority having jurisdiction should evaluate the building and consider acceptable alternatives. The planning team may conclude that traditional codes and standards do not provide practical solutions to correcting the fire protection deficiencies. To meet this challenge, NFPA 914 contains performance-based alternatives for solving fire protection problems in historic buildings. NFPA 914 provides a road map, written in code language, for designers developing performance-based alternatives that may be acceptable to the authority having jurisdiction. It also includes provisions to include management operating systems as acceptable elements of the overall fire safety system.

SUMMARY

Places of worship, libraries, and museums are mixed-use occupancies that present unique fire protection challenges. Although the public areas of these cultural resource properties usually have low fuel loads and high standards of housekeeping, these

areas do suffer costly fires. Fire prevention in cultural resource properties is the first line of defense against fire. Early detection and quick action to stop fire growth can prevent large fire losses. Useful fire protection features include a systems approach to fire safety and a specifically designed fire protection system. Construction considerations, such as compartmentation, means of egress, lighting, and gallery flexibility, must be considered in fire safety planning.

The effective fire emergency management of cultural resource facilities includes continuous monitoring of fire protection systems, providing emergency electric power to support fire protection systems, planning with the local fire department, and prefire training of all building staff.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on library and museum collections discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1, *Uniform Fire Code™*
NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 40, *Standard for the Storage and Handling of Cellulose Nitrate Film*
NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals*
NFPA 70, *National Electrical Code®*
NFPA *101®*, *Life Safety Code®*
NFPA 232, *Standard for the Protection of Records*
NFPA 550, *Guide to the Fire Safety Concepts Tree*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 909, *Code for the Protection of Cultural Resource Properties—Museums, Libraries, and Places of Worship*
NFPA 914, *Code for Fire Protection of Historic Structures*

NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*
NFPA 5000®, Building Construction and Safety Code®

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Chapter 18

Industrial Occupancies

David P. Demers

Chapter Contents

Loss History
Hazard Assessment and Evaluation
Building Construction
Occupant Characteristics
Fire Protection Features
NFPA *101* and *NFPA 5000*
Prefire Planning

Key Terms

computer fire models, general industrial occupancy, high-hazard industrial occupancy, industrial occupancy, industrial fire brigade, special-purpose industrial occupancy

Industrial occupancies encompass a broad spectrum of purposes. Some employ many people to work in a single building. Other facilities house large items of equipment but have very few employees. Industrial occupancies are generally divided into two categories: general-purpose industrial, which are low- and moderate-hazard facilities, and high-hazard facilities. Examples of industrial occupancies include factories, power plants, refineries, and laundries.

This chapter discusses the loss history of industrial occupancies; general risk assessment; occupancy and occupant characteristics; fire protection features available; NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®, criteria; and prefire planning.

For additional information relevant to life safety in industrial occupancies, see Section 11, Chapter 5, "Control of Electrostatic Ignition Sources"; Section 18, Chapter 1, "Confinement of Fire in Buildings"; Section 18, Chapter 2, "Interior Finish"; and Section 20, Chapter 20, "Occupancies in Special Structures." Explosion suppression devices are covered in Section 17, Chapter 8, "Explosion Prevention and Protection." Section 3, Chapter 5, "Introduction to Fire Modeling," provides information on computer fire models.

LOSS HISTORY

Industrial and manufacturing facilities experienced 11,400 structure fires reported to U.S. local fire departments in 2002, with associated losses of 11 civilian deaths, 342 civilian injuries, and $774 million in direct property damage.[1] The number of fires declined more than 73 percent from 1980, whereas civilian deaths declined by 50 percent (Table 20.18.1 and Figure 20.18.1). The variety of industrial and manufacturing activities is reflected in the loss history (Table 20.18.2), although certain activities stand out with larger shares of the fire problem.

Of the 25 costliest U.S. fires and explosions in history (as of the end of 2002), after adjusting for inflation, nine involved industrial or manufacturing facilities, and all but two of those occurred in the last decade and a half of the twentieth century—a 1989 Texas polyolefin plant fire (number 5 costliest of all time), a 1999 Michigan automobile manufacturing complex power plant fire (number 9), a 1995 Massachusetts textile mill fire (number 11), a 1947 Texas ship and chemical plant fire (number 13), a 1988 Louisiana petroleum refinery fire (number 14), a 1987 Texas chemical plant fire (number 21), a 1975 Alabama nuclear power plant fire (number 22), and a 1999 Louisiana aluminum plant fire (number 24).

The same 1989 Texas polyolefin plant fire and a 1991 North Carolina chicken processing plant fire are the most recent examples of the continued potential for major life loss in these facilities, as more than 20 people died in each incident.[2]

However, the deadliest recent industrial fire in the world by far occurred in a toy factory in Thailand in 1992.[3] That fire killed 188 workers, surpassing the death toll of 145 in the Triangle Shirtwaist Company fire of 1911, which is still the deadliest manufacturing plant incident not involving an explosion in U.S. history.

Another fire, this one in 1992 in China, occurred in a doll factory and took the lives of 81 occupants.[4] These and other less deadly incidents around the world underline the need for a higher standard of global industrial fire safety. Setting that standard starts with recognizing the many ways

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TABLE 20.18.1 Structure Fires in Industrial and Manufacturing Properties by Year, 1980–2002

Year	Fires	Civilian Deaths	Civilian Injuries	Direct Property Damage (in Millions of Dollars) As Reported	Direct Property Damage (in Millions of Dollars) In 2002 Dollars
1980	42,100	21	775	609	1331
1981	39,000	31	1322	659	1302
1982	35,000	50	1118	450	837
1983	29,900	51	1091	727	1312
1984	30,400	88	853	804	1389
1985	30,900	37	779	569	950
1986	26,400	24	821	516	847
1987	25,800	44	991	542	858
1988	24,100	30	847	676	1028
1989	21,700	60	783	1796	2606
1990	18,700	79	830	689	949
1991	18,300	21	641	647	854
1992	17,500	11	545	539	691
1993	16,400	13	893	566	705
1994	18,000	16	648	567	689
1995	16,300	32	587	1254	1479
1996	16,500	8	540	786	902
1997	17,800	16	485	709	795
1998	16,100	20	520	632	698
1999	17,200	29	609	1116	1204
2000	14,000	9	566	688	719
2001	12,700	17	321	846	859
2002	11,400	11	342	774	774

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest million dollars.

Source: NFIRS and NFPA survey. Inflation adjustments were based on the consumer price index found in the U.S. Census Bureau's *Statistical Abstract of the United States: 2006*, "Table 705, Purchasing Power of the Dollar."

in which serious fires can occur in industrial and manufacturing facilities. Table 20.18.3 shows the cause patterns for fires and associated property damage in industrial and manufacturing properties. The wide variety of potentially hazardous industrial and manufacturing process is clearly reflected in these figures, but so are more familiar hazards associated with heating, electrical service, arson, and smoking. Although the process or manufacturing area that defines the facility's activity and purpose is the leading area of fire origin, most fires and losses occur in fires that began somewhere else (Table 20.18.4).

Even when they occur, industrial fires need not be deadly and need not be costly. Many factors typically contributed to turn an industrial fire into a major loss of life or property. One common factor is the lack of functioning fire suppression systems in a structure. From 1994 to 1998, 59 percent of reported structure fires in industrial and manufacturing facilities were in properties without sprinklers. When sprinklers were present, the chances of dying were 30 percent lower and the average loss per fire was 66 percent lower.[1]

A factor that has contributed to large loss fires in sprinklered industrial occupancies is a change in the hazard for which the sprinkler systems were originally designed. When the hazard or fuel load changes, suppression systems need to be re-evaluated. Yet another factor is improperly designed egress systems. Unfortunately, locked exits still contribute to fatalities. Locked and blocked exits contributed to the 25 deaths in the 1991 North Carolina chicken processing plant fire. An important cause of the loss of life in the 1992 Thailand toy factory fire was inadequate exit arrangements. It is only one example of how major industrial fires tend to involve a failure to follow well-established fire safety requirements. NFPA *101* and *NFPA 5000* provide requirements for designing appropriate egress systems.

HAZARD ASSESSMENT AND EVALUATION

To provide adequate life safety for an industrial occupancy, the relative degree of fire and life safety risk must be evaluated. Since the industrial classification is so broad, the hazards involved vary greatly. The first concern is the amount of time available for evacuation. Both the contents of the building and the interior construction affect this, as well as the materials of the building itself if they contribute to the fire during occupant evacuation. Examples of items to consider are interior finish, rate of fire spread, burn rate, toxic fume evolvement, potential ignition sources, fuel load, and smoke generated. After employees evacuate, the problem becomes one of property protection.

Many resources exist to aid in hazard assessment. Examples include talking to plant operators, reviewing building blueprints, and so on. The NFPA codes contain valuable information on various hazards. Insurance companies and records of previous fires also provide useful information. Section 20, Chapter 1, "Assessing Life Safety in Buildings," describes methods for assessing life safety from fire in buildings.

Computer models can assist in assessing an occupancy's hazard. After determining the appropriate potential fire, a computer model can help predict the impact of fire on a facility. This is valuable in determining the possible time available for occupants to exit the area or facility before conditions become untenable. The ASET, FPETOOL, and CFAST models do this. (See Section 3, Chapter 5, "Introduction to Fire Modeling.") The assessment can be done in conjunction with egress analysis. Required safe egress time is a model to analyze egress. Combined models can evaluate whether there is sufficient time for the occupants to exit before conditions become untenable. This particular method of assessing hazard and evaluating life safety is common practice in code-enforcement systems that accept performance-based designs.

Because explosions are probably the most destructive industrial accidents in terms of life and property loss, they require special attention. Flammable dust, vapor, mist, or gas presents an explosion hazard. A carefully designed system is needed to ensure life safety from explosive forces. Two primary ap-

TABLE 20.18.2 Structure Fires in Industrial and Manufacturing Facilities, 1999–2002 Annual Averages

Occupancy	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*
Utility, defense, agriculture, or mining	3,400	9	78	284
Energy production plant	200	3	31	174
Laboratory	300	0	8	5
Defense, computer, or communications center	100	0	4	3
Utility or distribution system	500	1	13	24
Agriculture	1,700	4	13	57
Forest, timberland, or woodland	100	0	3	1
Mine or quarry	100	0	1	9
Unclassified or unknown-type utility, defense, agriculture, or mining	400	1	5	13
Manufacturing or processing	10,500	7	382	571
Total	13,800	17	460	856

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey.

proaches to the problem exist: prevent the explosion—obviously the better choice—and control the damage from the explosion. Specialized equipment designed to detect, suppress, and control damage from explosions is available. NFPA 69, *Standard on Explosion Prevention Systems,* provides additional information.

BUILDING CONSTRUCTION

NFPA *101* does not include construction requirements for industrial occupancies; however, *NFPA 5000* does. The varying types of industrial occupancies use many different types of construction. Smaller facilities might be constructed of unprotected wood, corresponding to Type V in NFPA 220, *Standard on Types of Building Construction,* and *NFPA 5000,* whereas larger buildings might be of fire-resistive construction, Type I. Additionally, buildings can range from totally enclosed high-rises and windowless buildings to open structures providing equipment protection from weather. The type of construction is generally based on local building codes for the type of use rather than on life safety concerns.

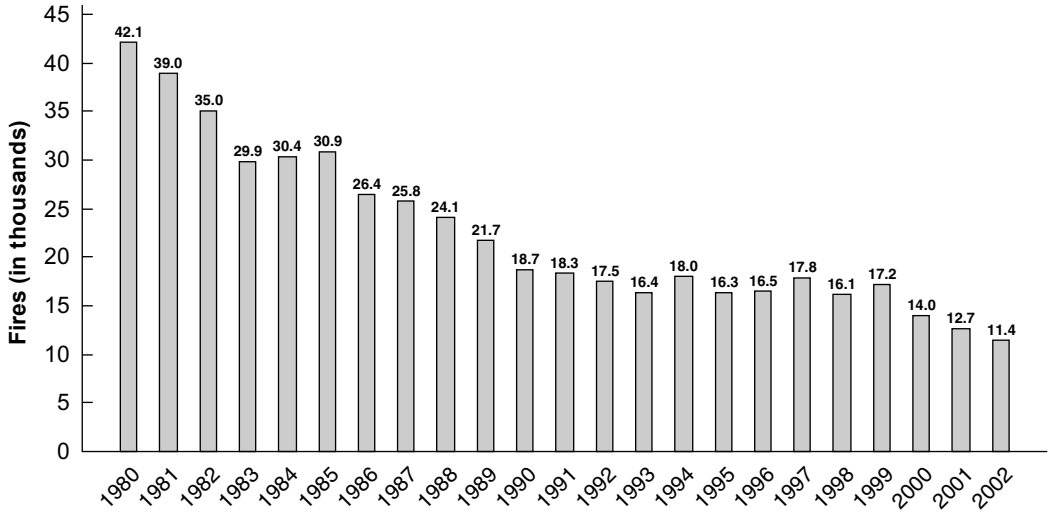

FIGURE 20.18.1 Structure Fires in Industrial and Manufacturing Properties by Year, 1980–2002 (Source: U.S. Fires in Selected Occupancies, NFPA, 2006)

TABLE 20.18.3 Leading Causes of Structure Fires in Industrial and Manufacturing Properties, 1999–2002 Annual Averages

Cause	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Shop tools or industrial equipment, except torches	3500	(25%)	3	(19%)	192	(42%)	167	(20%)
Electrical distribution and lighting equipment	1400	(10%)	4	(25%)	33	(7%)	94	(11%)
Heating equipment fires	1400	(10%)	0	(0%)	30	(6%)	47	(5%)
Identified heating equipment	1000	(7%)	0	(0%)	23	(5%)	46	(5%)
Confined heating equipment fire	400	(3%)	0	(0%)	6	(1%)	2	(0%)
Torch (including burner or soldering iron)	1000	(7%)	1	(6%)	51	(11%)	53	(6%)
Intentional	700	(5%)	6	(36%)	14	(3%)	73	(9%)
Cooking equipment fires	500	(4%)	0	(0%)	11	(2%)	17	(2%)
Identified cooking equipment	400	(3%)	0	(0%)	10	(2%)	13	(2%)
Confined cooking fire	100	(1%)	0	(0%)	1	(0%)	4	(0%)
Smoking materials	500	(4%)	0	(0%)	13	(3%)	29	(3%)
Spontaneous combustion or chemical reaction	500	(4%)	0	(0%)	11	(2%)	38	(4%)
Exposure to other fire	400	(3%)	0	(0%)	3	(1%)	15	(2%)
Contained trash or rubbish fire	500	(3%)	0	(0%)	2	(0%)	0	(0%)

Note: These are the leading causes, obtained from the following list: intentional (from the NFIRS field "cause"); playing with fire (from factor contributing to ignition); confined heating (including confined chimney and confined fuel burner or boiler fires), confined cooking, and contained trash or rubbish (from incident type); identified heating, identified cooking, clothes dryer or washer, torch (including burner and soldering iron), electrical distribution and lighting equipment, medical equipment, and electronic, office, or entertainment equipment (from equipment involved in ignition); smoking materials, candles, lightning, and spontaneous combustion or chemical reaction (from heat source); and mobile property involved (from mobile property involved in ignition). The statistics on smoking materials and candles include a proportional share of fires in which the heat source was heat from an unclassified open flame or smoking material. Exposure fires include fires with an exposure number greater than zero, as well as fires identified by heat source or factor contributing to ignition when no equipment was involved in ignition and the fires were not intentionally set. Because contained trash or rubbish fires are a scenario without causal information, they are shown at the bottom of the table if they account for at least 2 percent of the fires. Casual information is not routinely collected for these incidents. The same fire can be listed under multiple causes, based on multiple data elements.

These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest million. Property damage has not been adjusted for inflation.

Source: NFIRS and NFPA survey.

OCCUPANT CHARACTERISTICS

In general, occupants of an industrial facility are able-bodied adults. Statistically less at risk of injury from fire, they are ambulatory and capable of responding quickly to a fire. These occupants should be familiar with facility hazards and emergency exit locations. The likelihood also exists that employees in an industrial setting have received some emergency training. As density of the occupant load varies significantly, it must be considered in exit system design. Facilities employing many physically and mentally disabled people require supplemental prefire planning to ensure safe evacuation.

FIRE PROTECTION FEATURES

A primary life safety feature of an industrial occupancy should be an automatic sprinkler system. Originally developed as a property protection feature, it has proved effective in preventing loss of life. Automatic sprinklers mitigate the effects of fire, thereby allowing occupants sufficient time to evacuate the building. In addition, the sprinkler system waterflow alarm can alert building occupants of the fire earlier and thereby give them more time to react. Several sources have documented the effectiveness of sprinkler systems. The U.S. Department of Energy (DOE) reported on the effectiveness and reliability of the sprinkler systems protecting DOE facilities during the years 1952 to 1980.[5] Several conclusions resulted from the study:

- Sprinkler systems are over 98 percent effective in controlling or extinguishing fires.
- Considering only building fires, sprinklers reduce the loss by at least a factor of 5.
- About one-third of all fires may be completely extinguished with only one sprinkler head operating.

TABLE 20.18.4 Structure Fires in Industrial and Manufacturing Properties by Area of Origin, 1999–2002 Annual Averages

Area of Origin	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Process or manufacturing area or workroom	2500	(18%)	3	(18%)	167	(36%)	182	(21%)
Machinery room or area or elevator machinery room	1300	(10%)	3	(19%)	52	(11%)	73	(9%)
Storage room, area, tank, or bin	600	(5%)	0	(0%)	14	(3%)	50	(6%)
Maintenance or paint shop area	600	(4%)	1	(3%)	27	(6%)	58	(7%)
Duct for HVAC, cable, exhaust, heating, or air conditioning	500	(3%)	0	(0%)	8	(2%)	13	(2%)
Unclassified equipment or service area	500	(3%)	1	(4%)	20	(4%)	37	(4%)
Unclassified area	400	(3%)	2	(11%)	10	(2%)	48	(6%)
Heating equipment room	400	(3%)	1	(3%)	11	(2%)	16	(2%)
Attic or ceiling/roof assembly or concealed space	400	(3%)	0	(0%)	2	(1%)	18	(2%)
Exterior roof surface	400	(3%)	0	(0%)	5	(1%)	7	(1%)
Exterior wall surface	400	(3%)	0	(0%)	4	(1%)	9	(1%)
Unclassified storage area	400	(3%)	2	(11%)	21	(5%)	62	(7%)
Wall assembly or concealed space	300	(2%)	0	(0%)	2	(0%)	8	(1%)
Unclassified structural area	300	(2%)	1	(7%)	2	(1%)	18	(2%)
Trash or rubbish chute, area, or container	300	(2%)	0	(0%)	4	(1%)	6	(1%)
Storage of supplies or tools or dead storage	200	(2%)	0	(0%)	5	(1%)	16	(2%)
Kitchen or cooking area	200	(2%)	0	(0%)	5	(1%)	4	(0%)
Switchgear area or transformer vault	200	(1%)	1	(8%)	13	(3%)	18	(2%)
Confined chimney or flue fire	200	(1%)	0	(0%)	5	(1%)	0	(0%)
Shipping, receiving, or loading area	200	(1%)	0	(0%)	8	(2%)	59	(7%)
Ceiling/floor assembly or concealed space	200	(1%)	0	(0%)	0	(0%)	10	(1%)
Office	200	(1%)	1	(4%)	1	(0%)	11	(1%)
Confined fuel burner or boiler fire	200	(1%)	0	(0%)	1	(0%)	1	(0%)
Unclassified technical processing area	200	(1%)	0	(0%)	14	(3%)	7	(1%)
Conveyor	200	(1%)	0	(0%)	2	(1%)	13	(2%)
Laboratory	200	(1%)	0	(0%)	15	(3%)	6	(1%)
Computer room, control room or center	200	(1%)	0	(0%)	1	(0%)	8	(1%)
Lawn, field, or open area	100	(1%)	1	(4%)	0	(0%)	3	(0%)
Confined cooking fire	100	(1%)	0	(0%)	1	(0%)	4	(0%)
Conduit, pipe, utility, or ventilation shaft	100	(1%)	0	(0%)	2	(0%)	2	(0%)
Laundry room or area	100	(1%)	0	(0%)	1	(0%)	3	(0%)
Garage or vehicle storage area	100	(1%)	0	(0%)	2	(1%)	6	(1%)
Lavatory, bathroom, locker room, or check room	100	(1%)	0	(0%)	4	(1%)	4	(1%)
Confined compactor fire	100	(1%)	0	(0%)	0	(0%)	0	(0%)
Unclassified service facility	100	(1%)	0	(0%)	3	(1%)	6	(1%)
Confined incinerator fire	100	(1%)	0	(0%)	3	(1%)	2	(0%)
Dark room, printing, or photo room or area	100	(1%)	0	(0%)	2	(0%)	6	(1%)
Crawl space or substructure space	100	(1%)	0	(0%)	0	(0%)	3	(0%)
Chimney	100	(1%)	0	(0%)	0	(0%)	1	(0%)
Unclassified outside area	100	(1%)	0	(0%)	0	(0%)	6	(1%)
Other known service or equipment area	200	(1%)	0	(0%)	3	(1%)	12	(1%)
Other known assembly or sales area	100	(1%)	1	(4%)	1	(0%)	4	(0%)
Other known means of egress	100	(1%)	0	(0%)	5	(1%)	4	(1%)
Other known function area	100	(1%)	1	(4%)	3	(1%)	7	(1%)
Other known vehicle area	100	(1%)	0	(0%)	6	(1%)	4	(0%)
Other known area	200	(1%)	0	(0%)	5	(1%)	20	(2%)
Contained trash fire	500	(3%)	0	(0%)	2	(0%)	0	(0%)
Total	13,800	(100%)	17	(100%)	460	(100%)	856	(100%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries are rounded to the nearest one, and direct property damage is rounded to the nearest million dollars. Property damage has not been adjusted for inflation. Nonconfined and noncontained structure fires in which the area of origin was unknown or not reported have been allocated proportionally among fires with known area of origin. Totals may not equal sums due to rounding errors.

Source: NFIRS and NFPA survey.

Additionally, a book from the Australia Fire Protection Association on the performance of automatic sprinklers in Australia and New Zealand, 1886–1968,[6] includes a detailed analysis of fire involving different occupancies. The section on industrial occupancies is broken down into different categories. Sprinklers operated effectively over 98 percent of the time. Life loss in these facilities was minimal, nil in the majority of incidents.

Both these studies were limited to special groups of facilities in which design, usage, or maintenance may tend to be better than the average U.S. practice. As noted earlier, NFPA analysis of industrial and manufacturing facility fires reported to U.S. fire departments indicates sprinklers reduce the average loss per fire by two-thirds.

To be effective, a system must be operable. A closed sprinkler control valve was a contributing factor to a 1993 fire at a Newark, New Jersey, electrical power plant in which three workers died.[4] Programs must be in place to provide for inspection of control valves to ensure they are open and for maintenance of associated trim for alarm piping, dry-pipe valves, and preaction and deluge systems. For preaction and deluge systems, the associated detection systems must also be operational.

NFPA *101* AND *NFPA 5000*

Classification of Occupancy

To design the appropriate exit system for an industrial occupancy, the life safety industrial occupancy hazard classification per NFPA *101* and *NFPA 5000* must be established. The three basic classifications include general industrial, special-purpose industrial, and high-hazard industrial occupancy.

General-Purpose Industrial Occupancy. General-purpose industrial occupancies involve low- and ordinary-hazard industrial operations occurring in any type of building, be it single-story, multistory, or multiple tenant. These occupancies normally have a higher density of employees than other classifications. Examples are a laundry or a vehicle assembly plant having low- or moderate-hazard operations.

Special-Purpose Industrial Occupancy. Special-purpose industrial occupancies also involve low- and ordinary-hazard industrial operations. They are characterized by low employee density with most of the floor area occupied by equipment. An example is a structure built to protect large processing equipment from weather, where people associated with the process work in a separate control room, thereby reducing employee exposure to fire. These occupancies have slightly different egress requirements that are generally more lenient, such as an increase in the travel distance allowed. Also, egress is designed for the actual number of employees in the structure, rather than the calculated occupant load. A telephone switch building or a turbine generator building at a power plant meets the definition of low or moderate hazard and very reduced number of occupants.

High-Hazard Industrial Occupancy. A high-hazard industrial occupancy differs from low- and ordinary-hazard industrial occupancies by the materials used and the potential results and by-products of their use. High-hazard industrial occupancies include structures in which there are processes involving highly combustible, highly flammable, or explosive materials, or structures in which materials are likely to burn with extreme rapidity or to produce poisonous fumes or gases. Also included are industrial facilities in which flammable liquids are routinely handled, used, or stored in large quantities or those in which explosive dusts from grain, wood, flour, plastic, aluminum, magnesium, or other explosive-dust-generating materials are produced. Plants such as a grain handling facility or a gasoline refinery are examples of high-hazard industrial occupancies.

Structures with adequately protected, incidental high-hazard uses do not have to be classified as high-hazard facilities. These structures may include specific fire prevention measures such as a small flammable liquid storage room designed to meet NFPA 30, *Flammable and Combustible Liquids Code.* The restricted use of flammable liquids does not require a high-hazard classification. An example is a metalworking plant, normally classified as low hazard, that has a flammable solvent dip tank coater. Although adequate means of egress away from the coater are required, the classification of the entire facility does not change to high hazard.

The classification of the life safety hazard of an industrial occupancy must be carefully considered. The goal is to evaluate the hazard of the contents, process, and other factors affecting fire development. The time available for occupants to evacuate can be very much affected by the growth of the fire. Many resources are available to assist in the determination. Review of pertinent NFPA literature, including the codes and this handbook, is helpful. Officials in other jurisdictions with similar occupancies and plant operators can provide additional valuable information. Chapter 34 of *NFPA 5000* contains a comprehensive package of requirements for buildings that contain high-hazard contents.

Means of Egress Design Requirements

Designing the egress system for a building requires consideration of many factors. Some involve distance requirements, such as travel distance, common path of travel, and dead ends. These distances vary based on the life safety hazard classification and the absence or presence of automatic sprinklers. Egress distance limitations are shown in Table 20.18.5. To use some of the greater distances involves special requirements, such as application to one-story buildings only, with automatic sprinklers mandatory and smoke and heat venting.

High-hazard occupancies are very restrictive on means of egress distances allowed, with no dead ends or common paths of travel permitted. Generally, two exits are required from every story or section. However, NFPA *101* and *NFPA 5000* provide exceptions to this requirement. By careful design, the listed requirements can be met. The addition of exit tunnels, overhead passageways, or horizontal exits can aid in meeting prescribed distance limits.

Fire Alarm Systems

As illustrated by Figure 20.18.2, industrial and office park facilities coexist side by side and can be large and complex.

TABLE 20.18.5 Egress Distance Limitations

	Travel Distance			Dead End	Common Path of Travel	
Industrial Occupancy	*Unsprinklered ft (m)*	*Sprinklered ft (m)*	*Special ft (m)*	*ft (m)*	*Unsprinklered ft (m)*	*Sprinklered ft (m)*
General purpose	200 (61)	250 (76)	400 (122)*	50 (15)	50 (15)	100 (30)
Special purpose	300 (91)	400 (122)	—	50 (15)	50 (15)	100 (30)
High hazard	NP	75 (23)	—	0	0	0

*Special requirements in NFPA *101* and *NFPA 5000* for this travel distance in general-purpose industrial occupancies.
NP = Not permitted.

Due to the size and complexity of most industrial facilities, a fire alarm system is a valuable tool for life safety. It can alert designated personnel, such as an industrial fire brigade, to a fire and allow for prompt response to evacuate occupants, fight the fire, shut down equipment, and other actions, as required. NFPA *101* and *NFPA 5000* require a fire alarm system for most industrial occupancies. Exceptions are based on occupant load, where total capacity is less than 100 persons and fewer than 25 persons are located above or below the level of exit discharge. In low- and ordinary-hazard industrial occupancies, the fire alarm must sound an audible alarm at a continuously attended location to initiate emergency action. At high-hazard industrial occupancies, in addition to the foregoing, the fire alarm must initiate an occupant evacuation signal. In these occupancies, early notification can be critical to life safety.

PREFIRE PLANNING

Individual preplanning is appropriate for property protection. Training in the use of fire extinguishers for incipient fires must be provided if employees are expected to use them. Designated employees need to be trained to check that fire protection equipment is operating as designed—for example, that sprinkler control valves are open. The responding fire department should be made familiar with the facility, and an employee should be designated as their primary contact. Hazardous materials should be identified and their location noted on a building plan. Full participation in drills is necessary to completely test the plan.

The prefire plan should be evaluated routinely through simulated fire exercises. Such exercises are critical to identify deficiencies in the plan. If possible, request the participation of the responding fire department.

If there are industrial fire brigades at the site, they must be adequately trained. Training should include brigade organization and responsibility, the basics of fire behavior, special on-site fire and health hazards, and hands-on training with the fire equipment they are expected to use (see NFPA 600, *Standard on Industrial Fire Brigades*). Available equipment might include fire extinguishers, standpipes, hoses, and hydrants. Appropriate use of this equipment on incipient fires can contribute to a major reduction in the risk of fire loss and loss of life in industrial occupancies. Restricting the spread of fire also reduces the threat to life.

FIGURE 20.18.2 Fire at the Large River City Business Park in Iowa (Source: Davenport Fire Department)

SUMMARY

Industrial occupancies must be adequately evaluated to determine fire hazard. Fire hazard affects the potential for life loss and property damage. Loss history can be used to see whether current designs and requirements are effective. NFPA *101* and *NFPA 5000* requirements for industrial facilities are briefly discussed. It is important that building design and fire protection systems allow for safe occupant egress in the event of fire. The effectiveness of sprinklers has been documented from two sources in particular.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the industrial occupancies discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 69, *Standard on Explosion Prevention Systems*
NFPA *101®*, *Life Safety Code®*
NFPA 220, *Standard on Types of Building Construction*
NFPA 600, *Standard on Industrial Fire Brigades*
NFPA 5000®, *Building Construction and Safety Code®*

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Chapter 19

Motion Picture and Television Studios and Soundstages

Raymond A. Grill

Chapter Contents

Occupancy Characteristics
Historical Fire Experience
Occupancy Hazards
Life Safety/Egress
Fire Protection
Operating Features

Key Terms

assembly occupancy, auxiliary heating, combustible load, hot work, industrial occupancy, proximate audience, pyrotechnics

NFPA 140, *Standard on Motion Picture and Television Production Studio Soundstages and Approved Production Facilities,* provides minimum requirements for the design, construction, operation, and maintenance of soundstages and approved production facilities, as defined here. Now in its second edition, the standard defines motion picture and television studios as buildings, portions of buildings, or groups of buildings designed and constructed for use by the entertainment industry to produce motion pictures, television shows, or commercials, or to broadcast television programs utilizing a soundstage. Although NFPA 140 covers all pre- and postproduction facilities including construction shops, warehouses, soundstages, control rooms, editing facilities, and other exterior filming locations on the studio property, the requirements of NFPA 140 are focused on soundstages and approved production facilities. An approved production facility is an existing building, portion of a building, or group of buildings that has been altered to be used for motion picture, television, or commercial production and that has been approved by the authority having jurisdiction (AHJ) for that purpose. Approved production facilities function as soundstages.

The motion picture and television industry is dynamic in nature, and soundstages and production facilities need to be flexible. As a result, the fire protection needs of these types of facilities must be evaluated based on the hazards present, which change from production to production, and the industry's operational needs. Many occupancies and hazards found at a studio are similar to those in typical light industrial facilities.

This chapter, therefore, focuses primarily on fire protection issues relating to soundstages and approved production facilities. It does not deal with locations or exterior production areas that might be found on a studio lot. For instance, construction shops for building sets contain the same hazards as many other shops or factories and should be treated as such. Warehouses on studio property can also be treated like other warehouses, while bearing in mind their contents' dynamic nature. Administrative areas, control rooms, and commissaries can also be treated from a fire protection and life safety standpoint like other similar occupancies. However, soundstages, which are specifically designed for filming or live broadcasts, have special operational needs, and an understanding of their specific fire protection hazards and features is required.

See also Section 20, Chapter 1, "Assessing Life Safety in Buildings"; Section 20, Chapter 9, "Assembly Occupancies"; and Section 20, Chapter 18, "Industrial Occupancies."

OCCUPANCY CHARACTERISTICS

A soundstage is a building or a portion of a building, usually insulated from outside noise and natural light, used to produce motion pictures, television shows, or commercials. Soundstages like the one shown in Figure 20.19.1 are specifically designed and constructed to create a controlled environment that can be isolated from exterior noise and light.

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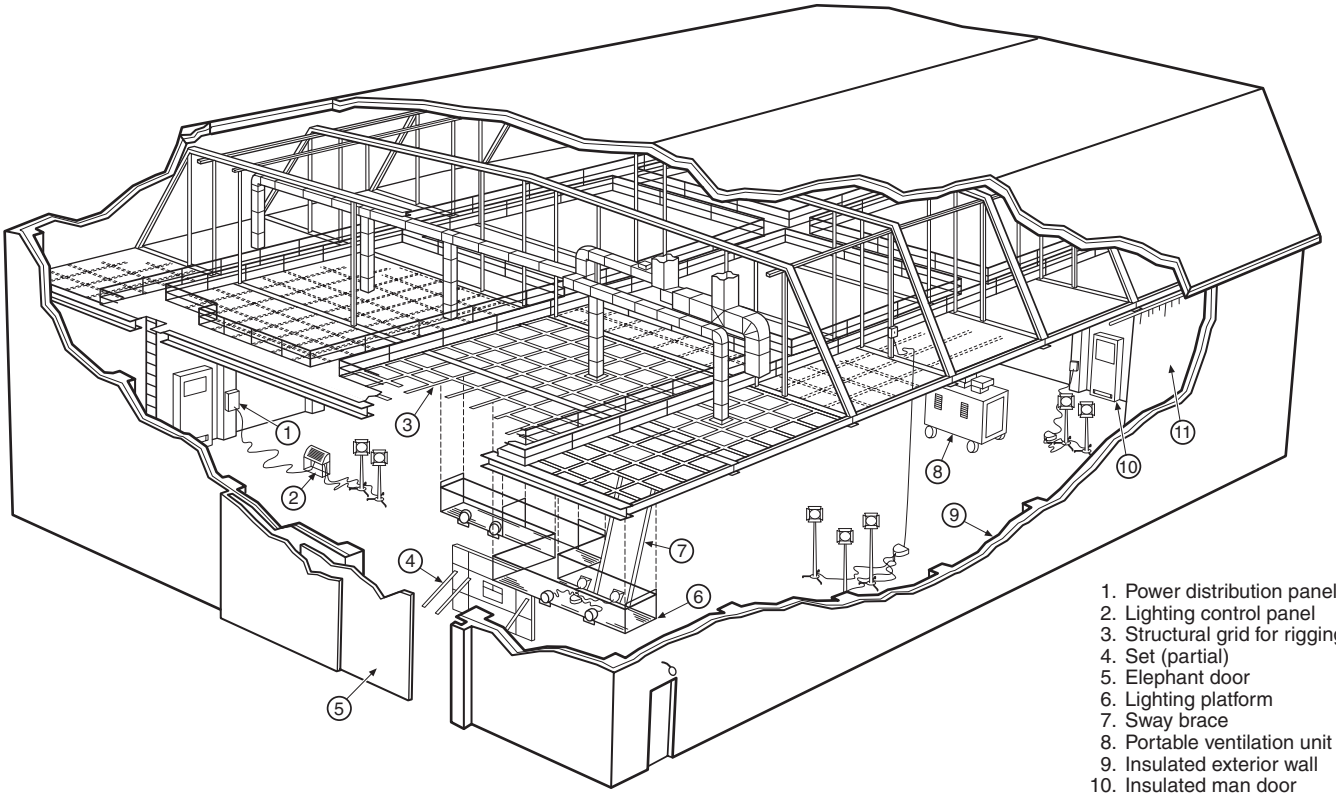

FIGURE 20.19.1 Typical Soundstage

Soundstages are often stand-alone buildings but can also be a room within a larger mixed-used building. Mixed use is often found in television production and broadcasting. Multiple soundstages can also be located within a single building.

The motion picture and television production industry commonly converts existing buildings to soundstages. This process may or may not include a change of occupancy classification for the existing facility. Vacant warehouses have been the primary type of existing facility converted into soundstages because of their openness. Its contents make a soundstage unique and the contents and configuration can change frequently to meet the needs of the production.

Live broadcast facilities, such as those for the production of network news broadcasts, incorporate production activities within other activities, such as newsrooms and offices. Some productions also include live audience environments within the soundstage. Introducing a live audience, depending on its size, can impact occupancy classification and other life safety and fire protection issues. These issues are discussed later in this chapter.

Sets within soundstages can be very elaborate. The duration of their use varies significantly from production to production. Some sets for television series may be used for years; others are specifically constructed for an episode. A set may be developed to simulate an entire building or series of buildings within the soundstage. Sets are typically constructed of wood and generally treated as temporary structures.

HISTORICAL FIRE EXPERIENCE

In 2006, the National Fire Protection Association Fire Analysis and Research Division analyzed fire losses in motion picture and television studios based on annual averages between 1999 and 2002.[1] The information gathered was based on data from NFPA's annual stratified random sample survey and the United States Fire Administration's National Fire Incident Reporting System (NFIRS).

Between 1999 and 2002, an estimated nine structure fires were reported annually to U.S. fire departments as occurring in motion picture studios and resulted in an average total fire loss of $65,000 in property damage per year. During the same period, an average of 18 reported structure fires in radio or television studios annually resulted in a yearly average of $71,000 in direct property damage. Due to the small number of fires, extreme caution should be used in interpreting these statistics.

Motion Picture Studios

Thirty-eight percent of the reported motion picture studio fires were unintentional, 27 percent were intentionally set, and 27 percent were caused by a failure of equipment or heat source. In 27 percent of these fires, electrical wire or cable insulation was the item first ignited; 18 percent of the fires began with upholstered furniture. Electrical arcing was the heat source in 27 percent of these fires.

Radio and Television Studios

Forty percent of the reported 1999–2002 radio or television studio fires were unintentional, 30 percent resulted from a failure of equipment or heat source, and 14 percent were intentionally set. Eleven percent of the fires were confined chimney or fuel burner fires; causal information is not routinely collected for these incidents. Electrical distribution equipment was involved in 18 percent of the fires in these properties. Including the confined fires, heating equipment was involved in 16 percent. Electrical wire or cable insulation was the item first ignited in 18 percent of these fires.

OCCUPANCY HAZARDS

Due to the unique nature of motion picture and television production, the contents of a soundstage and its combustible load vary from time to time. Soundstages themselves may also include combustible materials as part of their construction. Supplemental and temporary equipment, as well as set construction, contributes to the potential hazard within the soundstage. Introduction of occupants (performers and audiences) also needs to be addressed from a life safety exposure and egress perspective.

Combustible Fuel Load

Production sets can consist of simple platforms, backdrops, or very elaborate structures. Sets are typically constructed of wood framing. They may consist of a simple platform to provide for appropriate camera angles or may include walls and ceilings to simulate a room or building. Some model building codes generally exempt motion picture and television sets from permit requirements. Sets are typically considered temporary because changes occur regularly. *NFPA 5000®*, *Building Construction and Safety Code®*, mandates compliance with NFPA 140.

Set construction might obstruct sprinkler protection and other fire protection features. Ceilings of sets may be movable or built with materials that are not self-venting and, therefore, obstruct heat flow and sprinkler operation.

Set Construction/Hot Work

The use of arc welders, oxyacetylene torches, and grinders is common during set construction. NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work,* provides comprehensive criteria for managing the potential hazards of these operations. Requirements include management responsibilities as well as operators' responsibilities. Fires caused by hot work can best be prevented by separating combustibles from ignition sources or by shielding combustibles. Regular inspections should be conducted to verify that compressed gas cylinders are adequately secured, hoses and cables are in good condition, combustible materials and flammable liquids are appropriately separated, and adequate fire-fighting equipment is provided.

Electrical Considerations

Electrical equipment and installations should comply with applicable sections of NFPA 70, *National Electrical Code®*. Specific articles in NFPA 70 address theaters, audience areas of motion picture and television studios, and similar locations. These articles include specific requirements for equipment, switchboards, lighting, and grounding. They address portable wiring, which is extensively used in motion picture and television production.

Mobile power generators are routinely used in motion picture production. Soundstages are not constructed to accommodate the temporary power needs of all production activities. Therefore, portable generators often supplement normal building power. When routing auxiliary power cables, care should be taken not to obstruct or interfere with fire ratings of walls, doors, or windows. NFPA 140 prohibits cables from being routed through fire-rated windows or doors. NFPA 140 allows cables to pass through fire-rated assemblies, when the penetrations are protected in accordance with NFPA 221, *Standard for High Challenge Fire Walls, Fire Walls, and Fire Barrier Walls*. Temporary electrical equipment can also obstruct egress and fire-fighting operations. When laying cables and locating portable generators, exit routes should be carefully avoided.

The location of portable generating equipment is subject to the approval of the AHJ based on NFPA 140.

The location of portable power-generating equipment should include consideration of the following:

- Potential exposure to the soundstage and adjacent structures
- Potential obstruction of egress or fire-fighting access
- Service and fueling needs

Portable power generators should be regularly inspected for leaks and adequate portable fire extinguishers should be available for use on this equipment.

Portable Heating, Venting, and Air Conditioning

Auxiliary heating, venting, and air-conditioning equipment often supplements the built-in capacity of a soundstage. These units should be listed by an approved testing laboratory and located so they do not obstruct egress or access. Flexible ducts used with these systems should be noncombustible and also arranged not to block egress and access.

Special Effects

Special effects might significantly impact the safety of soundstage occupants. Special effects may include pyrotechnic materials, gas, or other open flames, theatrical smoke, or fuel-powered vehicles. Clearly, special effects' impact is greater when there is an audience.

Pyrotechnics. Based on NFPA 140, use of pyrotechnic special effects is subject to the approval of the AHJ. Therefore, the proposed use of pyrotechnics on a soundstage must be reviewed with the AHJ prior to use.

NFPA 1126, *Standard for the Use of Pyrotechnics Before a Proximate Audience,* applies to the indoor display of pyrotechnic special effects in television and movie production only if the production is before a proximate audience. Special effects are

partially defined as visible or audible effects for entertainment purposes, frequently an illusion. NFPA 1126 defines proximate audience as "an audience closer to pyrotechnic devices than allowed by NFPA 1123, *Code for Fireworks Display*." This NFPA standard contains requirements on storage, permits, operator qualifications, labeling of preloads and use of pyrotechnics. It should be consulted when pyrotechnic special effects will be used indoors before an audience.

NFPA *101*®, *Life Safety Code*®, addresses pyrotechnic devices in its chapters on assembly occupancies by requiring compliance with NFPA 1126.

Open Flame. Based on NFPA 140, use of open flames is subject to the approval of the AHJ. Therefore, the proposed use of open flames on a soundstage must be reviewed with the AHJ prior to use. NFPA *101* also addresses open-flame devices in assembly occupancies. It allows open flame on stages and platforms as a necessary part of a performance, when precautions satisfying the AHJ are taken to prevent ignition of combustible material or injury to occupants. It permits gas lights under similar conditions. Prior to the performance, use of open flame or gas lights before an audience should be worked out with the AHJ.

Smoke. Theatrical smoke used as a special effect should not obscure exit signs, particularly if an audience is present. If no audience is present, and dense smoke is integral to the production, those affected by the smoke should be trained and drilled regarding egress routes.

Decorations

Combustible drapes, drops, hangings, cycloramas, cut greenery, and other decorative materials are required by NFPA 140 to be maintained in a flame-retardant condition. Depending on the material and the duration of use, this may necessitate periodic reapplication of fire retardant.

Foam plastic materials used for decorative purposes, scenery, or props must be limited to materials with a maximum heat release rate of 100 kW when tested in accordance with UL 1975, *Standard for Fire Tests for Foam Plastics Used for Decorative Purposes*.

Housekeeping/Smoking

Combustible waste and other combustible materials should be stored in a manner that limits their potential of coming in contact with ignition sources. Approved self-closing metal containers should be provided for containing combustible waste. Housekeeping hazards include accumulated sawdust or wood scraps; accumulated litter; combustible storage below platforms; storage of props, equipment, and material that may block exits, fire protection equipment, and electrical equipment.

NFPA 140 prohibits smoking on soundstages unless it is required as part of a production.

LIFE SAFETY/EGRESS

A soundstage may have two separate and distinct uses, depending on the presence of an audience. If no audience is anticipated, the soundstage can be considered an industrial occupancy. Means of egress should meet the requirements of NFPA *101* and *NFPA 5000*. Soundstages exceeding 1500 ft^2 (139 m^2) are required by NFPA 140 to have an aisle along the perimeter, clear to 7 ft (2.1 m) above the floor. Motion picture soundstages often maintain a 4 ft (1.2 m) aisle, with that portion of the floor painted yellow to clearly indicate that it is to be kept open. NFPA 140 also limits the travel distance to an exit in a soundstage to 150 ft (46 m).

If an audience of 50 or more people may be present, the requirements for assembly occupancies of NFPA *101* and *NFPA 5000* apply. Other portions of this handbook, NFPA *101,* and NFPA *5000* address exiting from assembly spaces, and the reader should refer to them for guidelines and requirements on number of exits, stair and handrail criteria, aisle and seating arrangements, emergency lighting, and the need for sprinkler and alarm systems.

If an audience is present, maintaining clear and obvious egress paths is important, especially if special effects or other visual illusions are used.

FIRE PROTECTION

Soundstages should be provided with automatic sprinkler protection to control and suppress fires in their incipient stages. New soundstages and new approved production facilities are required by NFPA 140 to be provided with an approved, supervised automatic sprinkler system. The systems are required to be designed in accordance with NFPA 13, *Standard for the Installation of Sprinkler Systems,* and maintained in accordance with NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems.* The design of automatic sprinkler systems needs to consider the special circumstances created by platforms and solid-ceiling sets. In recognition of the temporary nature of platforms and sets it might be necessary to permit omission of sprinklers in these areas when alternative protective means are provided. Such means might include limiting the size of platforms and solid ceilings, limiting use below platforms, and installation of heat or smoke detectors in areas that are shielded from sprinklers. NFPA 140 also recognizes the potential for obstructions. When the design of the building's automatic sprinkler system is increased to Extra Hazard, Group 2 density and area of coverage, NFPA 140 allows obstructions to sprinkler discharge that can be created by construction of sets. When a fire is shielded from sprinklers, it might develop beyond its incipient stage before sprinkler activation. The Extra Hazard, Group 2 design criteria are necessary to control a fire of this type.

Soundstages have unique needs with respect to audible and visible alarms. Audible and visible notification appliances within soundstages are allowed by NFPA 140 to be deactivated during production provided the following conditions are met:

1. Alarm system activation causes notification appliances to activate at a constantly attended location.
2. The attendants of the location have a means of communicating with the building fire command center, if one is provided, and with the occupants of the soundstage.

3. Deactivation of notification appliances on the soundstage activates an appropriately labeled visible signal at an approved location that remains illuminated while notification appliances on the soundstage are deactivated.

This approach is most likely to be utilized in a soundstage that is part of another building having a fire alarm system.

Portable fire extinguishers should be provided throughout soundstages in accordance with the requirements of NFPA 10, *Standard for Portable Fire Extinguishers*.

OPERATING FEATURES

Several other NFPA standards may apply to soundstage operations. These include NFPA 1, *Uniform Fire Code*™, regarding maintenance of systems, waste, and refuge accumulation; and elimination or mitigation of hazards. NFPA 30, *Flammable and Combustible Liquids Code,* and NFPA 58, *Liquefied Petroleum Gas Code,* address flammable and combustible liquids and liquefied petroleum gases, respectively. Welding is addressed by NFPA 51, *Standard for the Design and Installation of Oxygen–Fuel Gas Systems for Welding, Cutting, and Allied Processes,* and NFPA 51B.

Of primary importance in the operation of a motion picture or television production facility is the need to continually monitor and maintain the fire protection provided. Occupancies, uses, and hazards can change daily. Thew operator should assign a person to maintain proper fire protection and life safety who can apply good fire protection practice and common sense to day-to-day operations. This person needs to interface effectively with AHJs and must have enough internal authority to correct or mitigate hazards as they arise.

SUMMARY

Motion picture and television studios and soundstages are part of a dynamic industry. Fire protection needs to take into account the fact that hazards, occupancies, and operational needs will change from production to production. Hazards typical of production facilities that need to be constantly monitored include combustible loading, set construction, hot work, electrical systems, portable heaters and air conditioners, and special effects. Fire protection and life safety measures include clearly marked exits, an alarm system, an automatic sprinkler system, and the presence of portable fire extinguishers.

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Reference Cited

1. NFPA Fire Analysis and Research Division.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the motion picture and television studios and soundstages discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of the current edition of the following documents.)*

NFPA 1, *Uniform Fire Code*™
NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 51, *Standard for the Design and Installation of Oxygen–Fuel Gas Systems for Welding, Cutting, and Allied Processes*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 70, *National Electrical Code*®
NFPA *101*®, *Life Safety Code*®
NFPA 140, *Standard on Motion Picture and Television Production Studio Soundstages and Approved Production Facilities*
NFPA 221, *Standard for High Challenge Fire Walls, Fire Walls, and Fire Barrier Walls*
NFPA 1123, *Code for Fireworks Display*
NFPA 1126, *Standard for the Use of Pyrotechnics Before a Proximate Audience*
NFPA 5000®, *Building Construction and Safety Code*®

Chapter 20

Occupancies in Special Structures

Wayne D. Holmes

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Mall Buildings
Open Parking Structures
Special Amusement Structures
Piers and Wharves
Water-Surrounded Structures
Membrane Structures and Tents
Grandstands
Towers
Open Structures

Key Terms

air-supported structures, below-grade fires, grandstands, Hartford circus fire, lighthouses, limited-access structures, mall buildings, marine terminals, membrane structures, offshore platforms, open structures, parking garages, piers, Six Flags Great Adventure Amusement Park fire, special amusement structures, tents, towers, underground structures, wharves, windowless structures

Every occupancy has unique needs for fire safety. Other chapters in this section describe fire protection techniques for various general occupancy types. For the most part, the fire protection techniques described in the other chapters are presented without regard to the type of structure. It is generally assumed that occupancies will be situated in "ordinary" structures with no unusual building features.

Some structures, because of their physical arrangement or construction methods, may present additional fire safety challenges that warrant additional protection measures, regardless of the occupancy. Special structures might present impediments to fire-fighting and rescue access, impediments to occupant egress, or fire and smoke management challenges. For purposes of this chapter, special structures include limited-access and underground structures, mall buildings, open parking structures, special amusement structures, piers and wharves, water-surrounded structures, membrane structures and tents, grandstands, towers, and open structures.

This chapter addresses some of the extraordinary fire safety aspects of special structures and presents some particular fire protection features that should be provided, regardless of the occupancy classification, in addition to the occupancy-based features that are described in other chapters in this section.

Another type of special structure, the high-rise building, is addressed in Section 20, Chapter 8, "High-Rise Buildings."

ACCEPTABLE DESIGN

Unique building arrangements of special structures are limited only by the designer's imagination. As a result, it is impossible for model codes, such as NFPA *101*®, *Life Safety Code*®, and *NFPA 5000*®, *Building Construction and Safety Code*®, to anticipate precisely all of the conditions and hazards that such a design could create. It is incumbent upon building owners, designers, and code officials to include those additional, beyond-the-codes, fire safety features that may be deemed necessary due to the uniqueness of the special structure and to the atypical fire safety problems that it may create.

Although the primary goals of fire protection will likely remain unchanged for occupancies in special structures, the prescriptive requirements of codes and standards, which typically apply to ordinary structures, might not be directly applicable. Thus, appropriate levels of fire protection for occupancies in special structures might require a special degree of sound design, engineering judgment, common sense, and cooperation between the designers and code officials.

When it is not possible to follow prescriptive requirements, alternative designs are necessary. Modern codes, including NFPA *101* and *NFPA 5000,* recognize performance-based options

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as alternate means of achieving compliance. Both NFPA *101* and *NFPA 5000* include a "Performance-Based Option" chapter. Goals, objectives, and performance-based criteria are established, in conjunction with the codes' fundamental requirements, to achieve alternative means of complying with the codes' objectives. In order to develop an appropriate alternative design, basic information must be agreed on. The designer, building owner, and authority having jurisdiction (AHJ) together need to discuss design philosophy and specific performance requirements. The following should be considered:

- Minimum required fire protection systems and features
- Building characteristics
- Operational status and effectiveness of building systems and features
- Occupant characteristics
- Reasonable assumptions, limitations, and safety factors

All aspects of the performance-based design must be documented. NFPA *101* and *NFPA 5000* require that not less than eight design fire scenarios be considered with respect to initial fire location, rate of growth in fire severity, and smoke generation.

Finally, the proposed alternative design should be reviewed. Ultimately, the AHJ will determine if the provisions of NFPA *101* or *NFPA 5000* are met by the performance-based design. NFPA *101* and *NFPA 5000* permit the AHJ to require an approved, independent third party to review the proposed design and provide an evaluation of the design. If the AHJ is uncomfortable reviewing and accepting it, there are several options to consider. One is to have another competent fire protection engineer review the design. Perhaps the review cost can be included as part of the building permit fee. Or the AHJ could work jointly with another competent fire engineer on the review. The design could be sent elsewhere within the same jurisdiction for competent review. However it is done, the design, particularly one involving an extensive, complicated submittal, should be thoroughly reviewed prior to acceptance. The building owner is also required to annually certify compliance with the conditions and limitations of the performance-based design and submit a warrant of fitness acceptable to the AHJ.

Regardless of whether prescriptive code requirements are followed or performance-based fire safety practices are applied, occupancies in special structures should be afforded the same level of fire safety as similar occupancies in ordinary structures. The unique challenges of the special structure must be recognized, addressed, and overcome. This chapter describes some types of special structures and discusses some of the fire safety challenges presented in those structures.

LIMITED-ACCESS AND UNDERGROUND STRUCTURES

The hazards of underground and limited-access (known as "windowless" prior to the 2003 edition of NFPA *101*) structures are very similar. Both of these types of special structures present challenges with regard to smoke and heat venting, access for fire fighting and rescue, and, in some cases, for means of egress for occupants. Therefore, underground and limited-access structures pose similar concerns.

The feasibility of ventilating the structure should be considered in relationship to the classification, nature, and character of the occupancy. In the event that the occupancy is of such a character that a large number of occupants could be present, smoke control and smoke venting capabilities could have a significant impact on the overall level of life safety.

The following features of limited-access and underground buildings make them special structures:

- Due to the lack of windows, there are fewer points of entry into the building for manual fire suppression forces.
- Ventilation during emergencies and removal of products of combustion, such as heat and smoke, depend on mechanical systems and door openings. If there are no mechanical systems designed for ventilation and smoke removal, then emergency operations may be hindered or additional damage/downtime may occur, as compared to buildings with large numbers of access openings or windows.
- Natural illumination is limited or nonexistent. This issue has an impact on egress and emergency operations within the building.
- Limited-access and underground structures may make the fire department's initial size-up more difficult due to the lack of visibility from the exterior. Many times, size-up will be delayed until an initial interior observation can be made.

It is sometimes difficult to determine whether a building that appears to be windowless is a limited-access structure as defined by the codes. It is unusual to find a building that does not have at least a few access points and windows. It is necessary to review the definition of limited-access structures and to understand its intent in order to determine whether the structure meets the definition of a limited-access structure.

NFPA *101* and *NFPA 5000* define a limited-access structure as "a structure or portion of a structure lacking emergency openings." An emergency access opening is a window, panel, or similar opening of certain minimum dimensions and location that is readily identifiable from both the exterior and interior and readily openable from both the exterior and interior.

Emergency access panels provide fire-fighting access for fire control and rescue as well as a means for providing manual ventilation. With respect to emergency access panels, NFPA *101* and *NFPA 5000* state that a building need not be considered a limited-access structure if emergency access panels are provided on two sides of the first story, spaced not more than 125 ft (38 m) apart, and every story above the first floor is provided with emergency access panels on two sides of the building, spaced not more than 30 ft (9.1 m) apart.

Figure 20.20.1 provides an example of a structure that would not be considered a limited-access structure because openings meeting the dimensional and operational requirements of the codes are provided on two sides of the structure, where

$$D_1 \leq 125 \text{ ft } (38 \text{ m})$$

$$D_2 \leq 30 \text{ ft } (9.1 \text{ m})$$

$$x \geq 22 \text{ in. } (560 \text{ mm})$$

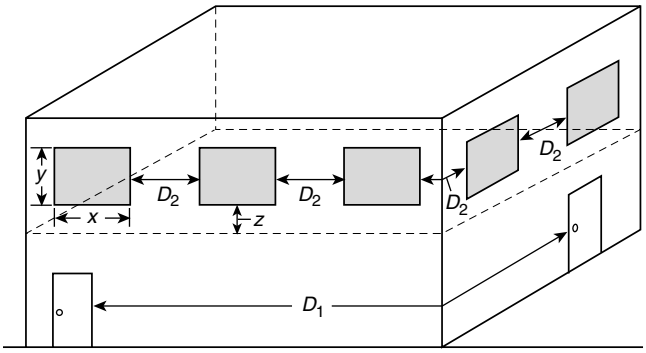


FIGURE 20.20.1 Emergency Access Openings (Source: *NFPA 5000® Handbook,* 2003, Figure 31.1, p. 731)

$y \geq 24$ in. (610 mm)

$z \leq 44$ in. (1120 mm)

Underground structures present additional problems not experienced in most other structures. The two primary issues are lack of accessibility and below-grade fires.

As with limited-access structures, it can be difficult to identify and classify underground structures. Many times, the difficulty occurs when a building or structure is constructed on a site with varying grades. This may result in some levels of the building being below grade on one or more sides and at, or above, grade on other sides. One example is a four-story structure built into the side of a steep hill. Although this arrangement might create a building in which more than 50 percent of the total wall surface is below ground, the building is not necessarily considered an underground structure provided that the levels of exit discharge and adequate accessibility are provided above grade.

NFPA *101* and *NFPA 5000* give specific guidance in determining when a building is considered an underground structure. The lowest floor used as a level of exit discharge may be considered the demarcation point for above and below grade. This may be true even if much of the wall surface of that floor is below grade. NFPA defines an underground structure as a structure or portion of a structure in which the floor level is below the level of exit discharge. A structure is not considered to be an underground structure if the story is provided with not less than 20 ft^2 (1.9 m^2) of emergency access opening entirely above the adjoining grade level in each 50 lineal ft (15 lineal m) of exterior enclosing wall area.

Exits from underground structures having an occupant load of more than 100 persons in the underground portions of the structure and having a floor used for human occupancy more than 30 ft (9.1 m) or more than one level below the lowest level of exit discharge should be arranged as follows:

- Exits should be cut off from the level of exit discharge.
- Exits should be provided with outside smoke-venting facilities or other means to prevent the exits from becoming charged with smoke from any fire in the areas served by the exits.

Furthermore, the underground portions of new underground structures should be provided with approved automatic smoke venting where the underground structure has the following:

- An occupant load of more than 100 persons in the underground portions of the structure
- A floor level used for human occupancy more than 30 ft (9.1 m) or more than one level below the lowest level of exit discharge
- Combustible contents, combustible interior finish, or combustible construction

From a practical standpoint, a limited-access structure has fire protection problems similar to an underground structure, but the windowless building can be constructed more easily to meet natural ventilation and rescue accessibility requirements. An underground structure must meet the requirements of a limited-access structure, and, in addition, some form of smoke management system must be provided. If a limited-access or windowless structure cannot meet the ventilation and rescue requirements, it should be considered equivalent to an underground structure, and the same code requirements should be applied.

Both underground and limited-access structures with occupant loads of more than 50 persons should be provided with approved, supervised automatic sprinkler systems throughout the underground or limited-access portions and all areas and floors traversed in traveling to the exit discharge.

Some examples of how occupancies and occupant loads affect code compliance for these special structures are helpful. For example, an underground space of 6000 ft^2 (560 m^2) housing an ordinary hazard industrial occupancy (occupant load factor of 100 ft^2 [9.3 m^2] per person) has an occupant load of 60 persons (6000/100 = 60). For this underground occupancy, NFPA *101* would require an approved, supervised automatic sprinkler system in all areas and floor levels traversed in traveling to the exit discharge.

For the same 6000 ft^2 (560 m^2) space housing a mercantile occupancy below grade and below the level of exit discharge (occupant load factor of 30 ft^2 [2.8 m^2] per person), the occupant load is 200 persons (6000/30 = 200). For this underground occupancy, NFPA *101* would require both an approved, supervised automatic sprinkler system in all areas and floor levels traversed in traveling to the exit discharge and an approved smoke venting system. It is important to consult specific code requirements for special provisions for occupancies in limited-access and underground structures.

Other general fire safety precautions should be observed for limited-access and underground structures. The use of combustible construction and other than Class A interior finish materials should be avoided. Foam plastics should not be left exposed; rather, they should be protected by a thermal barrier acceptable to the AHJ.

Compartmentation by fire barriers will help limit the extent of spread of fire and smoke. Barriers will help to reduce the severity of exposure to occupants and provide extended time for safe evacuation or relocation of occupants.

Manual fire-fighting equipment, such as standpipe and hose systems and portable fire extinguishers, can provide for quick suppression of small fires when handled by trained personnel.

Drainage of water from automatic sprinklers or from hose streams can be a significant problem in underground structures and requires preplanning. If drainage is required for reasons other than fire protection, it may be possible to use one drainage system for all purposes, provided that it is designed to handle the maximum flow.

For occupancies in underground caverns and similar subterranean spaces, refer to NFPA 520, *Standard on Subterranean Spaces*.

MALL BUILDINGS

Mall buildings are often associated with large shopping centers. However, mall buildings are increasingly being constructed for multiple uses. Mixed uses of mall buildings might include airport terminals, amusement and recreation operations, business operations, restaurants, broadcast studios, and other occupancies in addition to mercantile occupancies. Mall buildings are characterized by large, open areas under a single roof or multiple roofs that might include large populations of people and multiple occupancies. Mall buildings may or may not be subdivided into smaller spaces and are often constructed with multiple levels open to each other.

As used in NFPA documents, a mall is "a roofed or common pedestrian area within a mall building that serves as access for two or more tenants and does not exceed three levels open to each other." In the same context, a mall building is "a single building enclosing a number of tenants and occupancies wherein two or more tenants have a main entrance into one or more malls."

Like limited-access and underground structures, mall buildings can present challenges to smoke and heat venting and access for fire fighting and rescue. In fact, many malls may also be classified as limited-access or underground structures and may need to meet code requirements for such structures. Further, the large open spaces presented by many mall buildings can allow for extensive, uninterrupted spread of smoke and other fire products.

Mall buildings are typically large buildings with an extensive perimeter and may include multiple grade levels. This arrangement, often combined with vehicle parking facilities surrounding the mall building, limits fire department vehicular access to the mall building. There may also be limited building access points to the large enclosed area, which will contribute to the difficulty in providing fire-fighting access.

Large open areas can contribute to the spread of fire and smoke. Building code height and area requirements might limit the size of fire areas and require fire barrier walls to divide sections of the mall building, but openings to the pedestrian mall area may be allowed to be unprotected. Large areas are thus exposed to unimpeded spread of fire and smoke.

Because of the large, open areas, mall buildings should be provided with approved, supervised automatic sprinkler systems throughout the building to suppress fires before they grow to endanger occupants or cause significant property damage. Mall buildings with more than two interconnected levels should be provided with smoke control systems to reduce the danger to occupants in the event of a fire. See NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces,* for details on designing smoke control systems for mall buildings. Means of egress, particularly means of egress alternate from the main entrances, should be properly identified by sufficient numbers of exit signs. Fire detection and alarm systems, with appropriate means for occupant notification, will enhance the fire safety of mall building occupants.

OPEN PARKING STRUCTURES

Parking garages that permit drivers to drive their own vehicles to a parking space have been the subject of recurring and ongoing fire safety concerns. The general concern has been for the survival of the structure's integrity when exposed to a fire potentially involving the fuel tank, tires, and other combustible elements and contents of more than one car parked near a structural element. However, research has consistently shown that the effect of permanently open exterior walls on the dissipation of smoke and heat prevents a serious threat to the structure, even with an unusually challenging initial fire scenario.

Numerous tests in the United States and elsewhere have demonstrated the validity of this conclusion. One such test, known as the "Scranton Fire Test," was conducted in 1972 by the American Iron and Steel Institute (AISI) in a multistory, open parking structure with exposed structural steel members.[1] Three automobiles parked next to each other, each with a fuel tank containing 10 gal (38 L) of gasoline, were used as the test ignition and fuel source. The center automobile was gutted 48 minutes after crumpled newspapers in the rear seat were ignited. The contents of its fuel tank were spilled or consumed, but the fire did not spread to the adjacent automobiles and the overhead structural steel was essentially unaffected. The temperature of the steel remained far below critical levels throughout the test. A similar test conducted by the British at the Borehamwood Fire Test Station yielded similar results.[2] These results do not necessarily apply to aboveground enclosed garages or to underground garages.

Building codes, such as *NFPA 5000,* recognize the test results and permit noncombustible parking structures of unlimited area up to 75 ft (23 m) high to have no structural fire protection, as long as they are used for no other purpose and have ample permanent wall openings for the free dissipation of smoke and gases. Applicable building codes should be consulted for minimum amounts of exterior wall openings and construction requirements. NFPA *101* contains means of egress requirements specific to parking structures and NFPA 88A, *Standard for Parking Structures,* contains fire protection requirements.

SPECIAL AMUSEMENT STRUCTURES

Special amusement structures, whether used to house permanent rides or exhibits (amusement parks), temporary rides or exhibits (fairs and carnivals), or seasonal exhibits (haunted houses), present unusual situations for fire and life safety. Such venues are often dark and intended to deceive or confuse occupants. The occupants often include young children with immature decision-making skills who are easily deceived. In some cases,

the structure or interior details might be quickly and haphazardly constructed of light materials that can contribute to rapid fire spread. Unapproved temporary wiring, special lighting effects, pyrotechnics, or other ignition sources might be present. Paths of travel are often convoluted, and the means of egress might be obscured. Most of these structures can be classified also as limited-access structures. In some cases, special amusement buildings might be located on piers, which further complicates fire-fighting and rescue access.

NFPA defines a special amusement building as "a building that is temporary, permanent, or mobile that contains a device or system that conveys passengers or provides a walkway along, around, or over a course in any direction that is a form of amusement arranged so that the egress path is not readily apparent due to visual or audio distractions or an intentionally confounded egress path, or is not readily available due to the mode of conveyance through the building or structure." Special amusement buildings include multilevel play structures in a restaurant or shopping mall, Halloween haunted house displays, and large roller coaster rides located within a building.

History records many fires in special amusement buildings. One of the most significant fires occurred in a "haunted castle" amusement attraction, made up of 17 interconnected commercial trailers, at the Six Flags Great Adventure Amusement Park in Jackson Township, New Jersey, on May 11, 1984.[3] Eight visitors in the structure were unable to immediately exit and died in the rapidly developing fire. Major factors contributing to the loss of life were the lack of properly designed fixed detection and suppression systems, ignition of synthetic foam material from which fire spread to other combustible contents and interior finish, and the difficulty occupants had in trying to escape along a convoluted, smoke-filled path.

Special amusements, whether they are permanent or only intended to last for a few days, must be carefully planned to assure fire safety. Ignition sources must be controlled. Open flames and pyrotechnics should be prohibited. Permanent or temporary electrical wiring should be in strict compliance with NFPA 70, *National Electrical Code®*. Gasoline and gasoline-powered internal combustion engines should not be stored or used inside special amusement structures.

If possible, the structure housing the special amusement occupancy should be of noncombustible construction. All interior finish, contents, and furnishings should have appropriate fire ratings by applicable fire test methods. Exposed foam plastic and other combustible materials should be prohibited.

To provide prompt detection of any developing fire, special amusement buildings should be provided with an approved smoke detection system throughout that alarms to a constantly attended location on the premises. To suppress fires and allow for ample time for safe evacuation, an approved, supervised automatic sprinkler system should be installed throughout special amusement buildings. In addition to providing an alarm, actuation of the smoke detection system or sprinkler system should automatically increase lighting in darkened spaces and immediately terminate any sounds or visual effects that might serve to confuse occupants.

As in all structures, ample exits must be provided for special amusement structures. The exits should be readily identifiable with floor proximity exit signs. Special arrangements to identify the means of egress might be necessary in amusement spaces that include mirrors, mazes, and other confusing paths of travel. Lobby areas should not interfere with egress paths.

Amusement operators are urged to work closely with fire safety specialists and AHJs in the planning and operation of special amusements to help assure the fire safety of occupants.

PIERS AND WHARVES

When piers or related structures partially surrounded by water are used for places of amusement, for restaurants, for mercantile operations, or similar uses, they fall out of the normal use category—that is, mooring of vessels and handling of cargo—and into the special structure category. The question of fire and life safety is of primary concern, because these structures, which may contain large numbers of people, may have limited egress facilities and limited fire-fighting access due to their location or arrangement on the water.

Figure 20.20.2 illustrates Balboa Pier in Newport Beach, California, on which a restaurant is located.

NFPA 307, *Standard for the Construction and Fire Protection of Marine Terminals, Piers, and Wharves,* defines a pier as a structure, usually of greater length than width, projecting from the shore into a body of water with direct access from land that can be either open deck or provided with a superstructure. NFPA 307 deals mostly with property conservation features of piers and wharves and does not include explicit provisions for means of egress or safety to life. NFPA *101* and *NFPA 5000* specifically address the unique characteristics of piers. Any occupancy situated on a pier must meet the applicable

FIGURE 20.20.2 Balboa Pier, Newport Beach, California (Source: *NFPA 5000® Handbook,* 2003, Figure 31.4; © Ron Niebrugge/wildnatureimages.com)

occupancy-specific requirements of the code (for example, those for assembly occupancies in the case of a restaurant with an occupant load of 50 or more) in addition to the special provisions for piers.

Piers used exclusively to moor cargo vessels and to store materials are exempt from a number of means of egress requirements when provided with proper means of egress from structures thereon to the pier and a single means of access to the mainland, as appropriate for the pier's arrangement.

Piers occupied for other than cargo handling and storage and extending over 150 ft (45 m) from shore should also be provided with the following:

- The pier should be arranged to provide two separate ways to travel to shore, such as by two well-separated walkways or independent structures.
- The pier deck should be open, fire-resistive, and set on noncombustible supports.
- The pier should be open, unobstructed, and not less than 50 ft (15 m) in width if less than 500 ft (150 m) long, or its width should not be less than 10 percent of its length if more than 500 ft (150 m) long.
- The pier deck should be provided with an approved, supervised automatic sprinkler system for combustible substructures and superstructures.

WATER-SURROUNDED STRUCTURES

This category includes structures fully surrounded by water, including lighthouses and offshore platforms. Occupant loads could vary from a limited number of people in some cases to hundreds of people on offshore oil platforms. A large, water-surrounded structure could include areas that contain assembly, industrial, or residential occupancies. Egress from the entire structure is limited because of its location.

Other than the fact that the structure is surrounded by water, traditional occupancy requirements and fire protection features remain the same with respect to the actual occupancy classifications being evaluated. The occupancy should be addressed as if it was not surrounded by water, and the particular circumstances created by the special structure should then be applied. The special structure features should be evaluated as they relate to the occupancy at hand.

In some cases, either sufficient outside ground area, such as an island, is needed for refuge or a separate, fire-resistant platform should be provided for this purpose. A communications system and means of transportation for evacuating the occupants from the refuge area may be needed. Means of transportation might be limited to either boats or helicopters depending on the nature and location of these special structures. With limited fire-fighting access from the outside and limited means of egress, preplanning of emergency response for fire fighting and for occupant safety is imperative.

It is possible, as in the case with deep-water oil platforms, that a water-surrounded structure can be more than 100 miles from shore and very remote from any emergency response from outside of the structure. The world's worst water-surrounded structure disaster occurred in the North Sea in 1988. An explosion and ensuing fire on the Piper Alpha oil platform resulted in the deaths of 167 workers.[4]

The structure may be subject to severe environmental conditions, including wind, wave action, and heavy rain. NFPA *101* and *NFPA 5000* exempt water-surrounded structures from their provisions if the structure is under the jurisdiction of the U.S. Coast Guard and is in compliance with U.S. Coast Guard regulations. The additional regulations of the U.S. Coast Guard should be consulted for such facilities.

MEMBRANE STRUCTURES AND TENTS

Membrane Structures

NFPA defines a membrane structure as a building or portion of a building incorporating an air-inflated, air-supported, tensioned-membrane structure; a membrane roof; or a membrane-covered rigid frame to protect habitable or usable space. For cost-reduction, usability, and aesthetic purposes, membrane structures are being increasingly used in modern construction to house numerous types of occupancies. Membrane structures are used for both permanent and temporary structures.

Some membrane structures are of the air-inflated type, where the air pressure is within a series of tubes, which then form the structure and keep it upright. In this case, the occupants are not within a pressurized atmosphere. Others, such as the one shown in Figure 20.20.3 are air supported where the shape is maintained by air pressure and in which occupants are within the elevated pressure area. Also included as membrane structures are cable-supported membrane structures, such as some newer sports stadiums, where cables support the roof and air pressure may or may not be provided. In other types of structures, the membrane is tensioned, and weather protection is usually provided without enclosing walls (Figure 20.20.4). Finally, there are the framework-type structures in which the membrane is stretched over the frame to form enclosing walls and a roof.

The fire and life safety concerns with membrane structures include the combustibility of the membrane when exposed to ignition sources and the structural stability of the membrane

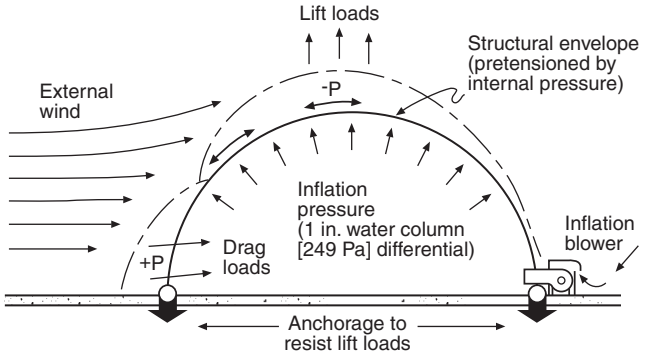


FIGURE 20.20.3 Loads on a Typical Single-Walled, Air-Supported Structure

FIGURE 20.20.4 Example of a Tensioned-Membrane Structure: Denver International Airport (Source: *NFPA 5000® Handbook,* 2003, Figure 32.2; courtesy of the Denver International Airport)

structure when exposed to fire. NFPA *101* and *NFPA 5000* address both of these concerns in their requirements. For permanent membrane structures, membrane materials cannot be used where fire resistance ratings are required for walls or roofs. Both permanent and temporary membrane structures are required to use flame-resistant membrane materials that are satisfactorily tested in accordance with NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films.* Membranes used in permanent membrane structures must be tested to provide a Class A flame-spread rating. All membrane materials must be tested as weathered-membrane materials. Blowers for air-supported and air-inflated membrane structures must meet special design requirements for reliability. Blowers must be provided with fully automatic standby power systems.

The area around temporary membrane structures must be clear of flammable and combustible materials and vegetation for a distance of at least 10 ft (3 m) to reduce potential fire exposures. Approved portable fire-extinguishing equipment must also be provided for temporary membrane structures.

Tents

The fire and life safety concerns associated with tents as places of assembly were made evident by a disastrous circus tent fire in Hartford, Connecticut, on July 6, 1944, in which 168 people died and 487 were injured.[5] The fire and life safety concerns for tents are similar to those for temporary membrane structures. As such, NFPA *101* applies the same requirements for tents as for temporary membrane structures for flame resistance, clear area around tents, and portable fire-extinguishing equipment. Tents should only be permitted on a temporary basis.

Additionally, tents should not cover more than 75 percent of the premises and stake lines should be not less than 10 ft (3 m) apart to help prevent fire propagation to adjacent tents. Additional spacing should be provided if needed to provide for adequate means of egress.

GRANDSTANDS

Grandstands are typical examples of structures found in places of outdoor and indoor assembly and are structures that can constitute a safety problem. These structures must have adequate aisles, proper distance between rows of seats, strong guard railings, and other means of egress features to ensure rapid and orderly evacuation to areas of safety. Requirements applicable to such installations are found in NFPA *101*. Grandstands should also be designed to withstand predetermined deadweight and live loads, as well as anticipated wind loads.

Since many grandstands are constructed entirely or partially of wood, basic fire protection principles of division of areas and separation from exposures apply. Long, combustible grandstands should be divided by fire partitions or be constructed in smaller sections with adequate separation between the sections.

Frequently, the space underneath a grandstand is used to store materials and for concession booths. The space underneath a grandstand might be become littered with combustible refuse. Refuse under the grandstand was a major factor in the soccer stadium fire in Bradford, England, on May 11, 1985, which claimed 56 lives.[6]

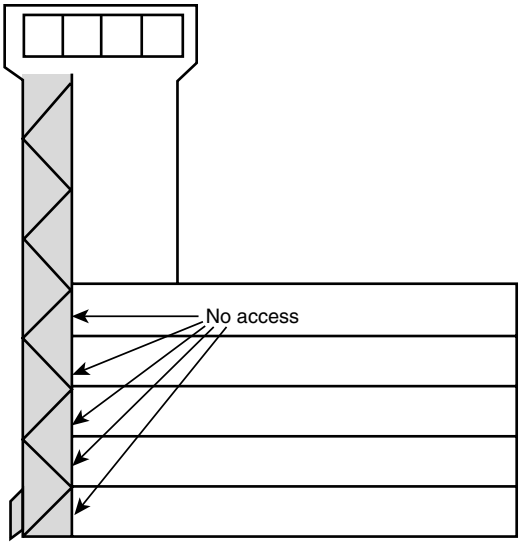
TOWERS

NFPA defines a tower as an enclosed, independent structure or portion of a building with elevated levels for support of equipment or occupied for observation, control, operation, signaling, or similar limited use where (1) the elevated levels are provided to allow adequate observation or line-of-sight for personnel or equipment, and (2) the levels within the tower below the observation level and equipment room for that level are not occupied. This definition does not include towers used for routine industrial, business, or assembly purposes. When a tower is used for these or other traditional occupancy purposes, it must comply completely with the appropriate occupancy classification and code provisions in NFPA *101, NFPA 5000,* and other applicable codes.

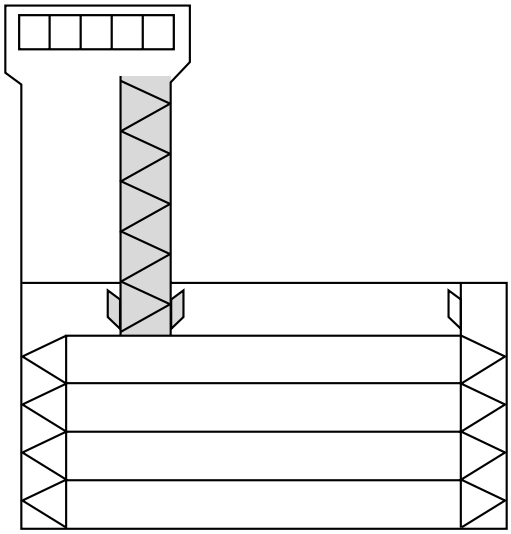
When a tower is being used in accordance with its definition, the special structures chapters of NFPA *101* and *NFPA 5000* apply. In some cases, the means of egress from a tower may be a single exit and, in some cases, may be only a ladder. If only one means of egress exists, caution must be taken to ensure that occupants cannot be trapped. In such cases, occupancy of the tower is limited to fewer than 25 persons, and the tower cannot be used for sleeping or living purposes.

Where a tower with a single means of egress is located above a building, special precautions must be taken to prevent the tower's single means of egress from being compromised by a fire in the building below. In Figure 20.20.5(a), the single exit stair enclosure for the tower is separated from the building by fire-resistance rated construction. Additionally, the single existing stair enclosure has no openings to the floors of the building above which the tower is positioned, thus preventing a fire in the building from rendering the stair unusable.

In Figure 20.20.5(b), the single exit stair positioned above the building serves the tower. It provides direct access to the



(a)



(b)

FIGURE 20.20.5 Single Exit from a Tower (Source: *NFPA 5000® Handbook,* 2003, Figure 31.3)

exit stair enclosure on the left, which also serves the building floors. If a fire prevents the use of the exit stair enclosure on the left, the tower stair permits tower occupants to traverse the top floor of the building and access a second exit stair enclosure on the right.

Fire-resistant or noncombustible construction should be used, with either Class A or B interior finish. There should be no high-hazard occupancies in the tower or immediate vicinity. If the tower is located above a building, the exit enclosure should be separated from the building or an exit enclosure should be provided leading directly to an exit enclosure serving the building and another door allowing access to the top floor of the building that provides access to a second exit serving that floor. Towers with 360 degree line-of-site requirements are permitted to have a single means of egress for a distance of travel not exceeding 75 ft (23 m) or 100 ft (30 m) if the tower is protected throughout by an approved, supervised automatic sprinkler system.

The amount of combustible materials in, under, or around a tower must be carefully controlled. Combustibles should be totally eliminated except for necessary furniture and operating supplies. Careful judgment should be used in determining what combustible materials to allow in the immediate vicinity of the tower. Similar care should be used in evaluating a tower located near high-hazard occupancies. The tower should be separated by a reasonable distance, especially when it has only a single means of egress.

Towers surrounded by water or offshore structures require special consideration and are strictly controlled by the U.S. Coast Guard. Coast Guard regulations and those of similar regulatory bodies in foreign countries normally take precedence over NFPA *101* and *NFPA 5000* requirements.

In small towers where there will be no more than three occupants at any one time, the means of egress may be a fire escape ladder. This might include forest fire observation or railroad signaling towers. Ladders should be arranged according to requirements of ANSI A-14.3, *Safety Requirements for Fixed Ladders,* and must provide continuous access to grade at all times. In towers with a single escape ladder, vertical openings need not be protected because such a requirement does not significantly increase protection for occupants.

In some special cases, towers subject to occupancy by not more than 90 persons are permitted to use elevators as the means of egress. This might include special operations such as aircraft control towers. NFPA *101* and *NFPA 5000* provide special provisions that apply to elevators when they are used as a second means of egress from towers. Among the limitations are the following:

- The tower and any attached structure must be protected throughout by an approved, supervised automatic sprinkler system.
- The primary means of egress must discharge directly to the outside.
- No high-hazard content areas may exist in the tower or attached structure.
- One hundred percent of the required egress capacity must be provided independent to the elevator(s).
- An evacuation plan, specifically including the use of the elevator, must be implemented and staff must be trained in elevator operations and procedures.
- The tower must not be used by the general public.

Further restrictions apply to the elevator, elevator lobby, controls, and operations, including the following:

- The elevator car must have a capacity of not less than eight persons.
- The elevator lobby must have a capacity of not less than 50 percent of the occupant load of the area being served by the lobby.
- On every floor served by the elevator, there must be an elevator lobby with a fire resistance rating of not less than 1 hour, with self-closing or automatically closing 1 hour

rated, temperature-rise-rated fire doors that close in the event of a fire alarm signal.
- Building elements must be used to restrict water exposure of elevator equipment.
- Power and control wiring for the elevator must be supplied from both normal and standby power and must be located and protected to ensure at least 1 hour of operation in the event of a fire.
- The elevators must be provided with fire fighter service controls in accordance with ASME A17.1, *Safety Code for Elevators and Escalators*.
- Elevators must have the capability of orderly shutdown during earthquakes where such shutdown is an option of ASME A17.1.

OPEN STRUCTURES

At the opposite extreme of the limited-access and underground structures are open structures. Whereas limited-access and underground structures are fully enclosed, thus making egress, access, and smoke venting more difficult, open structures are totally unenclosed.

Open structures are those that support equipment and operations not enclosed within building walls. Open structures are most often found in industrial operations, where the structure would come under the guidelines of an industrial occupancy (Figure 20.20.6). It is often difficult to determine whether the occupancy should be classified as general, special-purpose, or high-hazard industrial. The hazard classification usually is determined by the classification of the hazards of the contents that can be present. Occupancies in open structures are commonly classified under special-purpose industrial as defined in NFPA *101* and *NFPA 5000.*

NFPA *101* and *NFPA 5000* have several provisions for special-purpose industrial occupancies. The special-purpose industrial occupancy is typically characterized by a relatively low density of employee population, where most of a structure is occupied by machinery or equipment. Typically, the open structure facilitates access to the equipment by use of platforms, gratings, stairs, and ladders.

FIGURE 20.20.6 Typical Industrial Open Structure

It is sometimes difficult to determine when a structure is open and when it is enclosed. An open structure may include a roof to provide some protection from the elements. Additionally, open structures may be provided with partial walls intended to shield the operations from environmental conditions or to segregate the operations. The AHJ must determine whether the open structure truly meets the definition of an open structure or whether the facility is a building. As a guide, the AHJ could determine whether the structure would react as an enclosed building in the event of fire.

Within a building, walls acting in conjunction with a roof enclose the combustion process and products of combustion, thereby allowing fire to spread both horizontally and vertically to other areas. The advantage of an open structure is that it allows the products of combustion to vent to the atmosphere, instead of spreading to unaffected areas of the structure. This depends on wind and climatic conditions in addition to the design of the structure.

If the roof and walls could direct or channel products of combustion to other unaffected portions of the structure, thereby preventing their free venting to the atmosphere, then that portion of the open structure could be considered a building. It is not uncommon to have buildings constructed within the framework of an open structure, resulting in a mixed classification.

Open structures that are occupied by not more than three persons are permitted to have a single exit provided that the exit can be reached within 200 ft (60 m) from any point. Fire escape ladders are permitted for open structures where the occupant load does not exceed three persons.

Open structures are exempt from NFPA *101* and *NFPA 5000* requirements for capacity of means of egress, travel distance, illumination, emergency lighting, marking of means of egress, protection of vertical openings, and detection and alarm systems.

SUMMARY

Special structures, regardless of type, present out-of-the-ordinary fire protection challenges, independent of the hazards associated with the occupancy in the structure. Often, these challenges include impediments to fire-fighting access and rescue, impediments to means of egress, and impediments to smoke and heat venting. Special structures include limited-access and underground structures, mall buildings, open parking structures, special amusement structures, piers and wharves, water-surrounded structures, membrane structures and tents, grandstands, towers, and open structures.

The unique fire safety complexities of the special structure must be addressed in addition to the fire safety requirements for the occupancy. In some cases, occupancies might be housed in structures that could be classified as multiple types of special structures. For example, a shopping mall might be classified as both a covered mall and a limited-access or underground building. An amusement center might be located in a facility that could be a special amusement structure, a limited-access

structure, and a pier structure. An airport terminal might be classified as a covered mall, a limited-access building, and a tower.

A combination of sound design and engineering judgment, common sense, and cooperation between the designers and code officials might be necessary to ensure an adequate level of life safety and property protection for the unique exposures of occupancies in special structures. Performance-based fire protection analysis and design methods can be useful in creating fire-safe special structures.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on occupancies in special structures discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 70, *National Electrical Code®*
NFPA 88A, *Standard for Parking Structures*
NFPA 92A, *Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences*
NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*
NFPA *101®*, *Life Safety Code®*
NFPA 307, *Standard for the Construction and Fire Protection of Marine Terminals, Piers, and Wharves*
NFPA 520, *Standard on Subterranean Spaces*
NFPA 701, *Standard Methods of Fire Tests for Flame Propagation of Textiles and Films*
NFPA 5000®, *Building Construction and Safety Code®*

SECTION

21

Transportation Fire Safety

Carl H. Rivkin

21.1 Passenger Vehicle Fires
21.2 Fire Safety in Commercial Vehicles
21.3 Automotive and Marine Service Station Operations
21.4 Vehicle Fueling Using Gaseous Fuels
21.5 Fuel Cell Vehicles
21.6 Recreational Vehicles
21.7 Fixed Guideway Transit and Light Rail Systems
21.8 Rail Transportation Systems
21.9 Aviation
21.10 Marine Vessels
21.11 Road Tunnels and Bridges

The 20th edition of the *Fire Protection Handbook*® concludes with Section 21 on transportation fire safety. Five of the eleven chapters in this section are new.

The first new chapter is Chapter 1, "Passenger Vehicle Fires," which discusses regulations and standards associated with passenger vehicle fire safety and presents relevant data and research. Also new is Chapter 2, "Fire Safety in Commercial Vehicles," addressing hazards and standards related to commercial vehicle fire safety.

The list of new chapters continues with Chapter 3, "Automotive and Marine Service Station Operations." Automotive and marine service stations, whose operations include both refueling and repairs, present a fire risk because of the storage of flammable and combustible liquids and the transfer and use of these liquids.

The next two chapters deal with the subject of alternative fuels. Chapter 4, "Vehicle Fueling Using Gaseous Fuels," considers the implications of the growing use of alternative fuels, such as compressed natural gas (CNG), liquefied natural gas (LNG), and liquefied petroleum gas (LP-gas). Chapter 5, "Fuel Cell Vehicles," is a new chapter that describes current fuel cell vehicles and operating features being developed to facilitate commercialization and acceptance by the general public and regulatory authorities.

Chapter 6, "Recreational Vehicles," is also new. This chapter discusses the types of recreational vehicles and their development and use, RV standards, the fire and life safety issues associated with RVs, their fire safety record, and existing oversight programs.

Chapter 7, "Fixed Guideway Transit and Light Rail Systems," describes system characteristics and explains underground trainways, underground stations, and surface-level and elevated transit systems.

Chapter 8, "Rail Transportation Systems," identifies different types of rail rolling equipment used by North American railroads, both freight and passenger, and discusses fire hazards associated with them. The chapter generally discusses the rail transportation of hazardous materials and discusses in detail the transportation of hazardous materials in rail tank cars and in intermodal tank containers.

Chapter 9, "Aviation," provides information on airport and aircraft fire safety and aircraft maintenance and servicing.

Fire safety on pleasure craft, small commercial boats, and commercial vessels is presented in Chapter 10, "Marine Vessels." Marine fire hazards and emergency response to ship fires are also discussed.

Chapter 11, "Road Tunnels and Bridges," addresses the unique fire protection and life safety considerations and challenges posed by road tunnels and road bridges. A road tunnel is defined as any enclosed facility through which road vehicles (cars, vans, buses, and trucks) travel. Emergency communications and tunnel fire tests are also discussed.

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SECTION 21

Chapter 1

Passenger Vehicle Fires

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Helene L. Grossman ❑ Ben Thomas ❑ Robert Strassburger

Chapter Contents

Federal Regulation of Passenger Vehicle Fire Safety
Passenger Vehicle Fire Data Analysis
Passenger Vehicle Fire Research
Hazard Mitigation Strategies
Design and Safety Considerations

Key Terms

Federal Motor Vehicle Safety Standard (FMVSS), National Highway Traffic Safety Administration (NHTSA), passenger vehicle, tenability

According to the Centers for Disease Control and Prevention, the reduction of the rate of fatalities[1] attributable to motor vehicle crashes in the United States "represents the successful public health response to a great technologic advance of the 20th century—the motorization of America."[2] More than six times as many people drive today as in 1925, and the number of motor vehicles in the country has increased 12-fold since then to approximately 246 million. The number of miles traveled in motor vehicles is 24 times higher than in the mid-1920s. The annual fatality rate has declined from 18 per 100 million vehicle miles traveled (VMT) in 1925 to 1.45 per 100 million VMT in 2005—a 92 percent decrease.[3]

Motor vehicle fire safety has also realized significant improvements over the past several decades. Comparing today's vehicles to model year 1978 and earlier vehicles, the risk of passenger vehicle fire fatality per one million vehicles in use has decreased more than 50 percent. If the comparison is restricted to new vehicles only (defined as 4 years old or newer), in order to eliminate effects attributable to vehicle age, then it is found that the risk of fire fatality per one million vehicles in use is about 25 percent lower for today's vehicles than for model year 1982 to 1986 vehicles.

This risk reduction is even more pronounced when the comparison is done per vehicle mile traveled. The risk of passenger vehicle fire fatality per one billion vehicle miles traveled is almost 70 percent lower for today's vehicles than for model 1978 and earlier vehicles. If only new vehicles (4 years old or newer) are considered, it is found that the risk of fire fatality per one billion vehicle miles traveled is about 30 percent lower for today's vehicles than for model year 1982 to 1986 vehicles.

In terms of total numbers, the number of highway vehicle fires and associated fatalities has decreased by approximately 25 percent over the past quarter century. This reduction has occurred despite the significant increase in exposure to fire risk. In the last 25 years the number of highway vehicles registered in the United States has grown by 60 percent and the number of vehicle miles traveled annually has nearly doubled, growing by 91 percent. The probability of fire increases with vehicle age. Beginning in 1975, people began to hold onto their vehicles longer and scrap them later. Prior analyses indicate that as the median age of vehicles increases, the number of motor vehicle fatalities with postcollision fires grows. Between 1980 and 2004, the median age of passenger cars rose by 50 percent to almost 9 years of age. Similarly, the median lifetime of passenger cars

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Robert Strassburger is the vice-president of vehicle safety and harmonization with the Alliance of Automobile Manufacturers.

increased by 47 percent to 16.9 years. Finally, the use of plastics and plastic composites in highway vehicles to replace metal materials has increased to 7.6 percent of total weight in 2004 from 5.0 percent in 1978. In 2004, the typical passenger car contained 258 pounds (117 kg) of plastic materials, up 78 pounds (35 kg) from 1978.[4] The increased use of plastics increases the amount of combustibles available to ignite and/or contribute to a fire.

Nevertheless, advancing motor vehicle safety remains a significant public health challenge—one that automakers are addressing daily. Automakers make huge investments in safer vehicle design and technology. According to recent data, in the United States, approximately 32,000 passenger vehicle occupants are fatally injured annually as a result of traffic crashes. Of these fatalities, approximately 1.2 percent (385) are attributable to postcollision fires. In addition, there are approximately 40 passenger vehicle fire fatalities per year that are not collision-related.

This chapter discusses regulations and standards associated with passenger vehicle fire safety and presents relevant data and research.

See also in Section 21: Chapter 2, "Fire Safety in Commercial Vehicles," Chapter 3, "Automotive and Marine Service Station Operations," and Chapter 6, "Recreational Vehicles."

FEDERAL REGULATION OF PASSENGER VEHICLE FIRE SAFETY

History of the National Highway Traffic Safety Administration

In 1966, the United States Congress passed the Highway Safety Act and the National Traffic and Motor Vehicle Safety Act (Vehicle Safety Act) which authorized the federal government to establish safety standards for motor vehicles. The Highway Safety Act created the National Highway Safety Bureau (NHSB), which later became the National Highway Traffic Safety Administration (NHTSA). The first director of the NHSB, Dr. William Haddon, defined a systematic approach to motor vehicle–related injury prevention. Haddon, a public health physician, recognized that standard public health methods and epidemiology could be applied to preventing motor vehicle–related and other injuries. He defined interactions between host (human), agent (motor vehicle), and environmental (highway) factors before, during, and after crashes resulting in injuries.

Shared Responsibilities for Vehicle Fire Safety

Many changes in both vehicle and highway design have followed since the passage of the Highway Safety Act. As such, safety features for vehicles (agents) have improved substantially over the years, as advancements have been made in air bag design, side impact protection, and fuel tank integrity, to name a few. Vehicles (agents) were built with new safety features including head rests, energy-absorbing steering wheels, shatter-resistant windshields, and safety belts. Roads (environment) were improved by better delineation of curves (i.e., edge and center-line stripes and reflectors), use of breakaway sign and utility poles, improved illumination, addition of barriers separating oncoming traffic lanes, and guardrails.

The fatality rate per 100,000 population dropped from 25.89 in 1966 to 16.46 in 1991 (25 years later) and to 15.86 in 1996 (30 years later). The traffic safety indicator (fatalities per 100 million VMT) dropped from 5.50 in 1966 to 1.91 in 1991 (25 years later) and to 1.69 in 1996 (30 years later).[5]

Changes in driver and passenger (host) behavior also have reduced motor vehicle crashes and injuries. Enactment and enforcement of traffic safety laws, reinforced by public education, have led to safer behavior choices. Examples include enforcement of laws against driving while intoxicated (DWI) and underage drinking, and enforcement of safety belt, child safety seat, and motorcycle helmet use laws.

Enhancing motor vehicle safety is a shared responsibility of government, industry, and consumers. Government and community recognition of the need for motor vehicle safety prompted initiation of programs by federal and state governments, academic institutions, community-based organizations, and industry. State and local governments have enacted and enforced laws that affect motor vehicle and highway safety, driver licensing and testing, vehicle inspections, and traffic regulations. Preventing motor vehicle–related injuries has required collaboration among many professional disciplines (e.g., biomechanics has been essential to vehicle design and highway safety features). Citizen and community-based advocacy groups have played important prevention roles in areas such as drinking and driving and child-occupant protection.

NHTSA FMVSS Standards

As part of its mandate, NHTSA is responsible for adopting and enforcing federal motor vehicle safety standards (FMVSS). These safety standards apply to the manufacture and sale of new motor vehicles and motor vehicle equipment (see 49 U.S.C. 30112). The FMVSS adopted by NHTSA encompass most aspects of motor vehicle safety performance and must be practicable, meet the need for motor vehicle safety, and be stated in objective terms.[6] States and localities are precluded by the Vehicle Safety Act from adopting and enforcing standards for motor vehicles that are inconsistent with these federal standards.

With respect to motor vehicle fires, NHTSA has promulgated a suite of standards to enhance fire safety as outlined below. The two principal federal motor vehicle safety standards addressing motor vehicle flammability, FMVSS 301, *Fuel System Integrity,* and FMVSS 302, *Flammability of Interior Materials,* were the first to be issued by the agency to address flammability issues.

FMVSS 301, *Fuel System Integrity.* Issued in 1968, FMVSS 301,* *specifies* requirements for the postcollision integrity of motor vehicle fuel systems. Its purpose is to reduce deaths and injuries occurring from fires that result from fuel spillage during

*FMVSS 301 was amended on December 1, 2003, to upgrade the rear impact test used to assess fuel system integrity. The final rule replaced the full rear impact test procedure that was conducted at a speed of 30 mph (48 km/h) with an offset rear impact test procedure conducted at 50 mph (80 km/h). See 68 Fed. Reg. 67068.

and after motor vehicle crashes. FMVSS 301 applies to passenger cars, multipurpose passenger vehicles, trucks, school buses and other buses with a gross vehicle weight rating (GVWR) of 4536 kg (10,000 lb) or less. The standard dictates a maximum fuel tank leakage of 28 g per minute after a collision.

FMVSS 302, *Flammability of Interior Materials.* Issued in 1972, FMVSS 302 specifies burn resistance requirements for materials used in the occupant compartments of motor vehicles. Its purpose is to reduce deaths and injuries to motor vehicle occupants caused by vehicle fires, especially those originating in the interior of the vehicle from sources such as matches or cigarettes. FMVSS 302 applies to passenger cars, multipurpose passenger vehicles, trucks, and buses. The standard dictates that all materials used in the passenger compartment should not allow a flame to propagate faster than 4 in./min (0.1 m/min), setting criteria for flammability performance. The test is performed on a sample of material in a horizontal orientation under controlled laboratory conditions.

FMVSS 303, *Fuel System Integrity of Compressed Natural Gas Vehicles.* FMVSS 303 specifies requirements for the integrity of motor vehicle fuel systems using compressed natural gas (CNG), including the CNG fuel systems of bifuel, dedicated, and dual-fuel CNG vehicles. The purpose of this standard is to reduce deaths and injuries from fires that result from fuel leakage during and after motor vehicle crashes. FMVSS 303 applies to passenger cars, multipurpose passenger vehicles, trucks, and buses that have a GVWR of 10,000 lb (4536 kg) or less and use compressed natural gas as a motor fuel, and school buses regardless of weight that use compressed natural gas as a motor fuel.

FMVSS 304, *Compressed Natural Gas Fuel Container Integrity.* FMVSS 304 specifies requirements for the integrity of compressed natural gas (CNG) motor vehicle fuel containers. The purpose of this standard is to reduce deaths and injuries from fires that result from fuel leakage during and after motor vehicle crashes. FMVSS 304 applies to containers designed to store CNG as motor fuel on board any motor vehicle.

PASSENGER VEHICLE FIRE DATA ANALYSIS

Every year in the United States, approximately 32,000 passenger vehicle occupants are fatally injured as a result of traffic accidents. Of these fatalities, approximately 1.2 percent (385) are attributed to postcollision fires. In addition, there are approximately 40 passenger vehicle fire fatalities per year that are not collision-related. There exist several data sources from which an estimate of the number of passenger vehicle fire fatalities may be derived. In this section, these data sources are identified and any differences reconciled to derive the estimate presented immediately above. These statistics illustrate that there are two main categories of interest in postcollision fires. The first category is postcollision fuel-fed fires, and the second category is postcollision fires that originate in the engine compartment and spread into the passenger compartment.

Passenger Vehicle Fire Fatalities

Using data from the U.S. Fire Administration's National Fire Incident Reporting System (NFIRS), the National Fire Protection Association's (NFPA's) annual survey of U.S. fire departments, and the NHTSA's Fatality Analysis Reporting System (FARS), an analysis of passenger vehicle fire injuries and fatalities can be conducted to examine such factors as the fuel involved in the fire, the point of origin of the fire, and the percentage of these fires associated with a crash.

NFPA survey data, as given in "Fire Loss in the United States," indicate that there are approximately 480 civilian fatalities per year due to highway vehicle fires (average for 1999–2004).[7] According to NFIRS data, approximately 88 percent of these fatalities, or 425 per year, are due to passenger vehicle fires. NFPA estimates of fire fatalities only include those that are judged by the fire department investigator to result from the fire itself, rather than related trauma such as a collision. All fatalities occurring up to a year following the fire are included, although tracking subsequent deaths is not always feasible.

These estimates differ from the estimate of 360 annual passenger vehicle fire fatalities for 1999–2003 presented in the NFPA report, "U.S. Vehicle Fire Trends and Patterns."[8] There are several reasons for this discrepancy. The analysis presented here used NFPA survey data directly to estimate highway vehicle fire fatalities. In contrast, the NFPA report used NFPA survey data to estimate *all vehicle* fire fatalities and then used NFIRS data to allocate the data into highway versus nonhighway vehicle fire fatalities. These two methods yield estimates of highway vehicle fire fatalities that differ by about 8 percent.* The advantage to using the direct NFPA survey estimate of highway vehicle fire fatalities is that the NFPA survey follows up on fatalities to distinguish those caused by the fire versus those caused by related trauma, whereas NFIRS does not conduct such follow-up. Hence, the direct NFPA estimate of highway vehicle fire fatalities may be more reliable.

Both the NFPA report and the analysis presented here used NFIRS to allocate highway vehicle fire fatalities into passenger vehicle versus nonpassenger vehicle fire fatalities. However, the NFPA report used NFIRS mobile property type "Passenger road vehicles," which includes passenger cars, buses, motorcycles, offroad recreational vehicles, and trailers, whereas the analysis presented here excludes some of those vehicles (motorcycles, offroad recreational vehicles, and trailers), but includes additional vehicles such as pickups and general-use trucks.

The estimates derived from NFPA/NFIRS data can be compared with those from the NHTSA's FARS. FARS is a census of all highway vehicle fatalities that occur on public roadways and for which the death is attributable to the accident and occurs within 30 days. A query of the FARS system indicates that there are approximately 1635 fatalities associated with highway vehicle fires each year, of which about 88 percent, or 1440 fatalities per year, involve passenger vehicles. The vast majority, approximately 99 percent, of passenger vehicle fires reported in FARS

*The fatality estimates given here are rounded to the nearest 5. The 8 percent difference between the NFPA/NFIRS and FARS estimates is calculated using nonrounded estimates rather than rounded estimates.

TABLE 21.1.1 Estimates of Passenger Vehicle Fire Fatalities from NFPA/NFIRS and FARS

	NFPA, NFIRS	FARS			
Year	*Civilian Fatalities Resulting from Passenger Vehicle Fires**	*Fatalities Where Fire Is Most Harmful Event for Passenger Vehicle*	*Fatalities Where Postcollision Fire Is Most Harmful Event for Passenger Vehicle*	*All Fatalities Associated with Passenger Vehicle Fires*	*All Fatalities Associated with Postcollision Passenger Vehicle Fires*
1999	385	300	295	1445	1440
2000	400	365	355	1515	1500
2001	415	360	350	1460	1445
2002	505	415	410	1495	1490
2003	385	425	410	1385	1375
2004	455	485	480	1335	1335
Average 1999–2004	425	390	385	1440	1430

Note: Numbers have been rounded to the nearest 5.
*NFPA estimates of highway vehicle fires are taken from NFPA's Fire Loss Series and are allocated into passenger vehicle fires/nonpassenger vehicle fires using NFIRS percentages.

are postcollision fires. However, the number of fatalities that result from the fire, rather than from collision-related trauma, is only about one-quarter of the total fatalities, approximately 390 annual deaths resulting from passenger vehicle fires, of which about 385 result from postcollision fires.* These numbers are averages for 1999 through 2004.

The estimates of fatalities associated with passenger vehicle fires of 425 and 390 per year from NFPA/NFIRS and FARS, respectively, are similar. The NFPA/NFIRS estimates are higher than the FARS estimates by about 8 percent, possibly because some fires that are not accident-related appear in the NFPA/NFIRS estimates, but do not occur on public roadways and are not included in the FARS database. Table 21.1.1 shows the NFPA and FARS estimates of passenger vehicle fire fatalities for 1999–2004.

For this analysis, NFIRS data were used to provide detailed information on the causes and ignition characteristics of fires. Because NFIRS only captures one-third to one-half of fire incidents in the United States, it was necessary to use the NFPA survey data to scale up the NFIRS data to obtain national estimates; the scaling factor depended on the category of interest (i.e., fires, deaths, injuries). Data were analyzed from the 6 year period 1999 through 2004 (2004 is the most recent year for which NFIRS data are publicly available). Fires for which a characteristic was unknown or not reported were allocated proportionally, assuming the same proportions as the fires with a known characteristic. The analyses and results that follow all pertain to passenger vehicle fires.

Based on the NFIRS and NFPA data, approximately half of passenger vehicle fire fatalities (about 220 fatalities per year) result from postcollision fires. However, according to the FARS analysis using the "most harmful event" code, there are approximately 385 fatalities per year resulting from postcollision passenger vehicle fires. It appears that the NFIRS data underestimate the proportion of fires and fatalities associated with collisions, probably due to factors other than "collision" being recorded as the factors contributing to ignition. This is further evidenced by the fact that roughly 50 percent of passenger vehicle fires do not have any factor contributing to ignition recorded (in the analysis discussed here, these unknowns were allocated proportionally). Therefore, the FARS estimate of postcollision fire fatalities and the NFPA/NFIRS estimate of total vehicle fire fatalities were used in this analysis to get a more conservative estimate of fatal passenger vehicle fires.

Results of the statistical analysis presented here are summarized in Figure 21.1.1. As shown in the leftmost part of the figure, the annual number of passenger vehicle fire fatalities is small compared to the total population of passenger vehicle fatalities due to traffic accidents. Of the fatalities due to fires, shown in the center chart, the vast majority are associated with postcollision fires.

Postcollision fires account for 90 percent of all passenger vehicle fire fatalities, while noncollision fires account for 10 percent. Of these noncollision fire fatalities, 5 percent are due to intentional fires and 95 percent are due to unintentional fires. Approximately 50 percent of the fatalities resulting from unintentional passenger vehicle fires involve the occupant being asleep or impaired by alcohol or other drugs prior to the fire.

Case studies of postcollision fires have indicated that there are two major categories: fuel-fed (gasoline) pool fires and engine compartment fires. Fuel-fed fires generally occur when collision damage causes a gasoline leak and then this fuel is the first material ignited. As shown in the rightmost chart of Figure 21.1.1, about 60 percent of postcollision passenger vehicle fire fatalities result from fires in which gasoline is the first material ignited.

Whereas more than half of postcollision fires involve gasoline as the first ignited material, almost half originate in the

*The "most harmful event" code in FARS was used to determine the fatalities resulting from fire. Different states code harmful events differently.

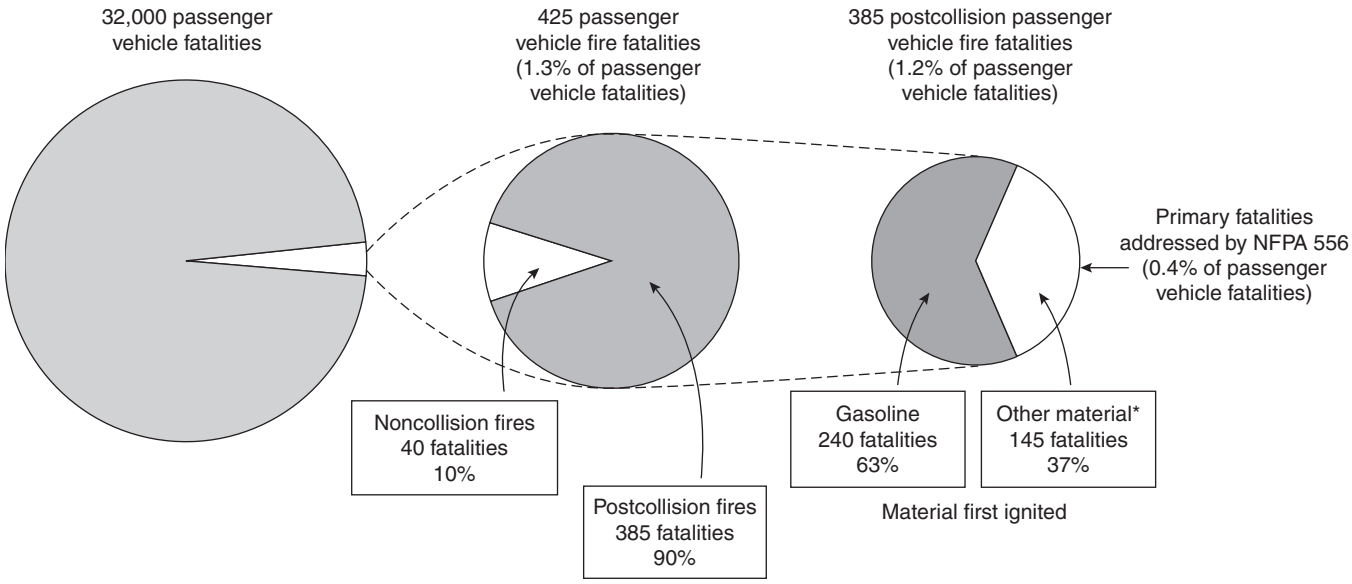


FIGURE 21.1.1 Summary of Statistical Analysis Results. *Includes the category "multiple types of fuels," so it is possible that gasoline was involved. (Sources: FARS, NFPA, and NFIRS 1999–2004 Annual Averages)

engine compartment, as shown in Figure 21.1.2. These facts indicate that fuel-fed fires and those that originate in the engine compartment are two of the most important passenger vehicle fire scenarios. These two fire scenarios have been the subject of extensive research and are discussed in more detail later.

Fire Risk Trends

Passenger vehicle fire safety has realized significant improvements over the past several decades. As shown in Figure 21.1.3, the risk of passenger vehicle fire fatalities per million vehicles in use has decreased from 3.7 per million registered vehicles per year for model year 1978 and earlier vehicles to an average of 1.8 per million registered vehicles per year for model year 1996 through 2004 vehicles, a more than 50 percent decrease.

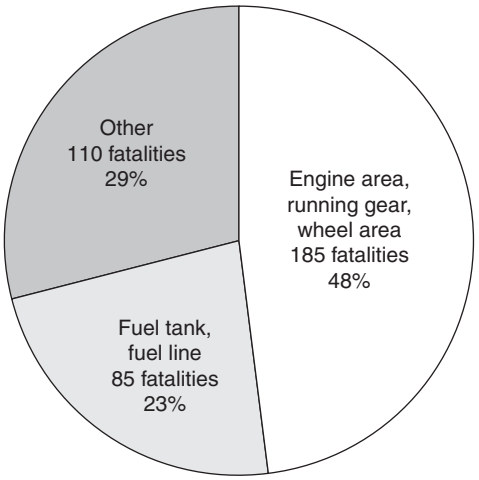


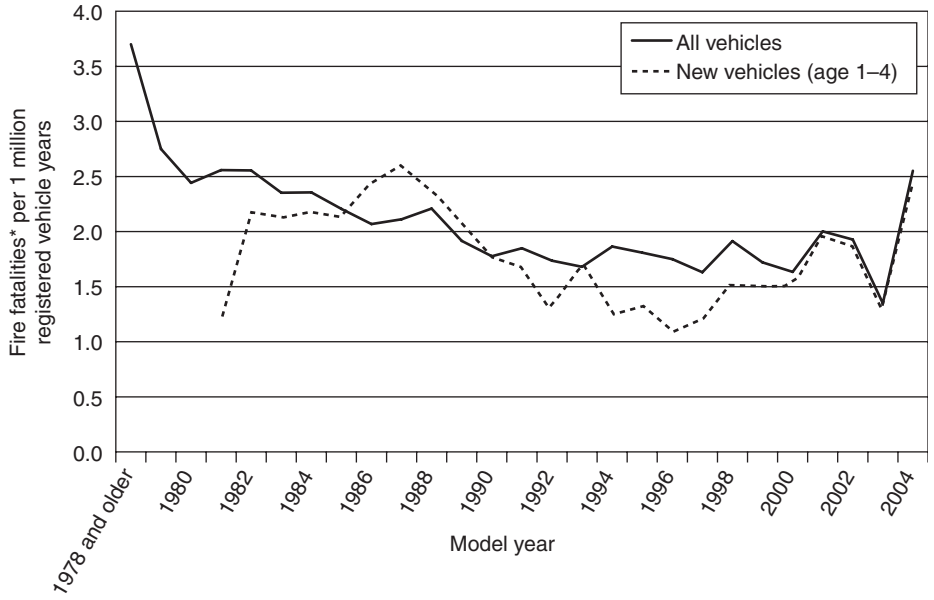
FIGURE 21.1.2 Area of Origin of Fatal Postcollision Fires (Sources: FARS, NFPA, and NFIRS, 1999–2004)

The observed increase in risk for model year 2004 vehicles may be an artifact of small sample size (only 40 fatalities listed in FARS). The lower bound on the 95 percent confidence interval for this risk is 1.8 fatalities per million registered vehicle years, which is equivalent to the average risk for model year 1996 through 2004 vehicles. Thus, the observed increase in risk for model year 2004 vehicles is not statistically significant.

Also shown in Figure 21.1.3 is the risk of passenger vehicle fire fatalities per million registered vehicles per year, restricted to new vehicles (vehicles aged 1 to 4 years). Although it appears that the risk increased between model years 1981 and 1982, the sample size is very small for model year 1981 vehicles aged 1 to 4 years (only 12 fatalities listed in FARS), so this increase is not statistically significant. The average risk for model year 1982 to 1986 vehicles aged 1 to 4 years was 2.2 fire fatalities per million registered vehicle years, whereas the average risk for model year 1996 to 2004 vehicles aged 1 to 4 years was 1.6 fire fatalities per million registered vehicle years. Thus, the fire fatality risk, restricted to new vehicles only, has decreased by about 25 percent between these time periods.

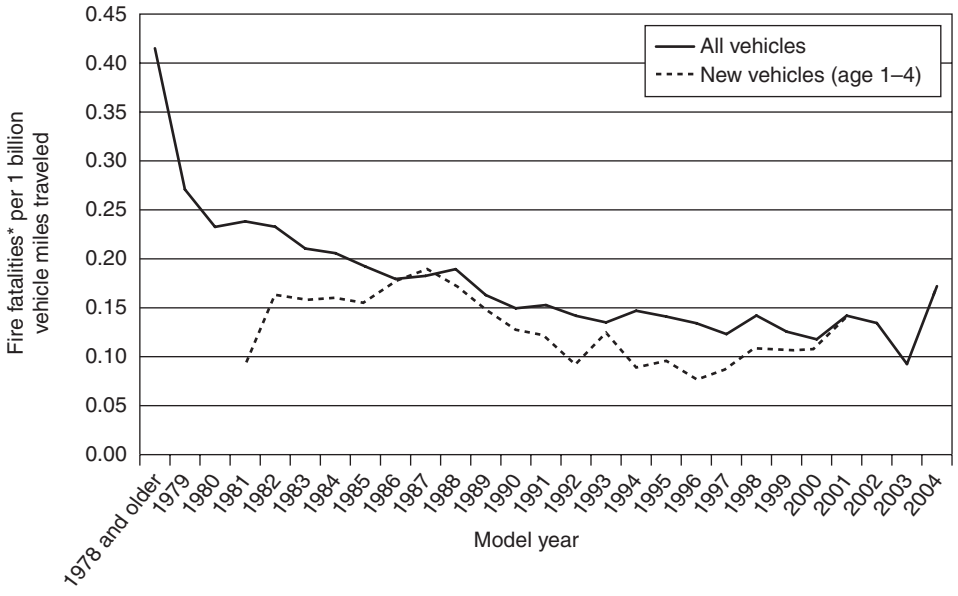
Figure 21.1.4 shows the risk of passenger vehicle fire fatalities per billion vehicle miles traveled. This risk has decreased from 0.42 per billion vehicle miles traveled for model year 1978 and earlier vehicles to an average of 0.13 per billion vehicle miles traveled for model year 1996 through 2004 vehicles, a decrease of almost 70 percent. This analysis takes into account decreases in annual mileage as vehicles age, as determined from the 1995 and 2001 National Household Travel Surveys.[9]

Figure 21.1.4 also shows the risk of passenger vehicle fire fatalities per billion vehicle miles traveled, restricted to new



*Only includes fatalities when fire is coded as the most harmful event for the vehicle.

FIGURE 21.1.3 Passenger Car and Light Truck Fire Fatalities per 1 Million Registered Vehicle Years (RVY), by Model Year of Vehicle, 1978–2005. (Source: FARS and R. L. Polk, 1985–2005)



*Only includes fatalities when fire is coded as the most harmful event for the vehicle.

FIGURE 21.1.4 Passenger Car and Light Truck Fire Fatalities per 1 Billion Vehicle Miles Traveled (VMT), by Model Year of Vehicle, 1978–2005. (Source: FARS, 1985–2005, R. L. Polk, 1985–2005; National Household Travel Survey, 1995 and 2001)

vehicles (vehicles aged 1 to 4 years). As with the risk per registered vehicle year analysis, it appears that the risk increased between model years 1981 and 1982. As discussed previously, the sample size for new vehicles of model year 1981 is small (only 12 fatalities listed in FARS), so this increase is not statistically significant. The average risk for model year 1982 to 1986 vehicles, aged 1 to 4 years, was 0.16 fire fatalities per billion vehicle miles traveled, whereas the average risk for model year 1996 to 2004 vehicles, aged 1 to 4 years, was 0.11 fire fatalities per billion vehicle miles traveled. Thus, the fire fatality risk, restricted to new vehicles only, has decreased by about 30 percent.

PASSENGER VEHICLE FIRE RESEARCH

The statistical analysis demonstrates that, on average, there are 425 fatalities per year attributed to fires associated with passenger vehicles, and that a vast majority of these fatalities (90 percent) are associated with postcollision fires. Other key findings are that about 60 percent of postcollision passenger vehicle fire fatalities result from fuel-fed fires, and about 50 percent result from fires originating in the engine compartment. These findings are consistent with a report prepared for the Motor Vehicle Fire Research Institute (MVFRI),[10] which illustrated that of all the vehicle collision fires reported by the National Automotive Sampling System (NASS), the majority were caused by front-end collisions and were initiated in the engine compartment.

The following sections briefly describe recent research conducted on postcollision fires and a number of strategies to mitigate the risk to occupants of passenger vehicles involved in postcollision fires. The establishment of valid performance criteria is critical before creating a model or test method.

Postcollision Fire Research

One of the most challenging aspects of the research to better understand postcollision passenger vehicle fires is to reproduce the coupling between the impact damage, fire initiation, and fire propagation. Another key component and challenge is the ability to determine when, and by what mechanism, conditions within the passenger compartment become untenable.

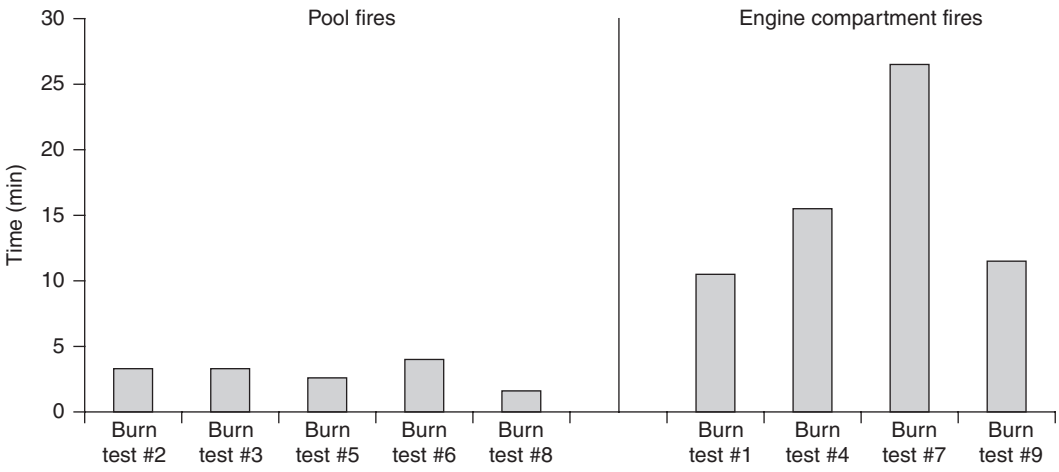
A major milestone in research associated with postcollision fires occurred as part of the DOT/GM Settlement Agreement. This agreement resolved a defect investigation opened by NHTSA into the postcollision fuel tank integrity of General Motors' pickup trucks, model years 1973–1987. As part of the settlement, a 5 year/$10 million vehicle fire research program was initiated to better understand fire initiation and propagation following a vehicle collision.[11] This study is by far the most extensive and detailed study of its kind and provided valuable data related to both understanding postcollision fires as well as mitigating the fire hazard to motor vehicle occupants.

Crash Tests. Consistent with real-world postcollision passenger vehicle fires, the 11 crash tests conducted as part of this study were intended to be severe, providing substantial damage to the vehicle structure, electrical systems, fluid systems, and the fuel tank. Crash test configurations included a moving deformable barrier, similar to the barrier used to assess compliance with the requirements of FMVSS 214,[12] with the vehicle traveling at 53 mph (85 km/hr) for rear impacts and 65 mph (104.6 km/hr) for front impacts, at 34 mph (54.7 km/hr) for frontal pole impacts, and frontal at 37 mph (59.5 km/hr) for oblique barrier impacts (only one oblique test was conducted). The crash tests were conducted with all normal engine fluids (except for the main fuel tank which was filled with Stoddard solvent for the crash test) with the engine running, and were heavily instrumented to attempt to capture the mechanism of ignition and propagation, should a fire occur. Once the crash tests were conducted, carefully controlled and heavily instrumented burn tests were performed in a manner consistent with the expected method of fire causation for each crash test. The data collected from the burn test were then used to calculate the point in time in which conditions would have become untenable for any occupants within the passenger compartment.

Untenable Conditions. One of the important findings from this work was that the time at which untenable conditions were reached was strongly correlated to the time that flames entered the passenger compartment. Regardless of how or where flames entered the passenger compartment, conditions became untenable in a matter of several minutes. It should be noted that untenable conditions depend on where measurements were taken. In larger vehicles, tenable and untenable conditions may occur at the same time in different locations within a burning vehicle. In the case of the pool fire tests, flames from the pool fire underneath the vehicle penetrated into the passenger compartment though gaps around deformed doors or underbody seams created by crash-induced damage. The time to reach untenable conditions ranged from 1.6 to 4.0 minutes, a relatively short period for rescue by emergency personnel. For fires which initiated in the engine compartment, flames entered the passenger compartment in one of three manners: (1) through the windshield when it failed; (2) through the heating and air conditioning system vents; and/or (3) through pass-throughs in the bulkhead. A comparison of the times required to reach untenable conditions for both the pool fires and the engine compartment fires is shown in Figure 21.1.5.

It should be noted that a comparison of individual times to untenable conditions within a given test series must also be analyzed based on the manner and location in which the fire was initiated and the type of crash. Although pool fires are less common than engine compartment fires, they are responsible for a large number of fatalities. In the period from 1994 through 1998, NFPA data indicate that fuel-fed fires accounted for 27 percent of highway vehicle fires, but they were responsible for 56 percent of vehicle fire fatalities. Pool fires (or fuel-fed fires) differ from other vehicle fires in that the power output of the initial fire is controlled not by the material flammability characteristics of the vehicle components but by the size of the fuel pool.

Further, flame penetration times into the passenger compartment vary depending on the condition of the vehicle. Time to penetration can be reduced in postcollision fires, as the



Note: A comparison of individual times to untenable conditions within a given test series must also be analyzed based on the manner and location in which the fire was initiated and the type of crash.

FIGURE 21.1.5 Time to Reach Untenable Conditions in Postcollision Fire Tests.

vehicle structure and metal panels can be torn or otherwise breached, allowing flames and smoke to more quickly enter the passenger compartment. As such, the onset of untenable conditions is linked to the condition of the vehicle and hence whether there has been a collision event. In the case of pool fires, untenable conditions that can cause injuries and fatalities can occur quickly, much quicker than the response times of emergency personnel. (See Figure 21.1.5 reference to NFPA report that has response time information.) Thus the strategies involving fire performance of materials and components inside the vehicle are not expected to have a significant effect on the outcome of a fuel-fed fire.[13]

Material Flammability Research

As part of the NHTSA's mandate to reduce deaths, injuries, and economic losses related to crashes and vehicle fire hazards, the NHTSA not only reviews existing standards internally and evaluates their effectiveness on a periodic basis, but also considers requests from any person or organization to develop new or revised standards. This standard development process incorporates the extensive technical expertise and resources available in the automotive industry. It also provides a mechanism to evaluate and compare the potential safety benefits of a new or revised standard with the associated cost to the public. Furthermore, this process assesses design and safety trade-offs associated with a wide range of interdependent technical issues, including crashworthiness, fire safety, human health, toxicology, environmental impact, and fuel economy.

Small-Scale Testing. As part of an effort to determine the feasibility and benefit of improving the FMVSS 302 test procedure, NHTSA recently funded a Southwest Research Institute (SwRI) study.[14] The purpose of this study was to identify or develop new small-scale test methodologies to rate automotive materials consistent with actual fire performance in full-scale vehicle burn tests and to explore levels of performance for this test methodology that would significantly increase survivability. The study, which addressed materials in the engine compartment, identified the cone calorimeter (ASTM E1354) as the most suitable bench-scale test apparatus to rate the flammability characteristics of automotive materials. The cone calorimeter is a small-scale, or bench-scale, flammability testing apparatus that subjects small 4 in. by 4 in. (100 mm by 100 mm) samples of a material or materials to an applied heat source. The heat source heats the material and the material, if possible, is ignited by means of a spark igniter. The equipment provides a measure of the material's heat release rate (HRR) and ignition time, and can be equipped to collect other data, including quantities of products of combustion produced as well as mass loss rate data, among other things. Using the cone calorimeter data, a model was formulated for evaluating the fire hazard of a particular engine component material. There was no validation of the proposed model, although validation was proposed as part of future work through full-scale vehicle burn tests. No specific performance criteria that would significantly alter the fire outcome in terms of injury or survivability were offered.

The difficulty of establishing a link between bench-scale test results and the performance of materials in full-scale vehicle tests was highlighted in several of the tests associated with the GM/DOT settlement described previously. To examine the influence of fire retardants, a test vehicle was identified from previous testing where the engine compartment fire penetrated into the passenger compartment through the HVAC unit and windshield.[15] These tests set out to examine if a flame-retardant HVAC unit would alter this behavior.

In these full-scale tests, one passenger vehicle was equipped with a factory supplied HVAC unit and the other otherwise iden-

tical vehicle was equipped with the fire-retardant HVAC. Each of these vehicles was crashed in identical crash tests. These crashed vehicles were then burned using identical ignition sources in identical locations within the engine compartment. The instrumentation associated with the burn tests was the same as used in previous burn tests in the GM/DOT research program, such that the time to untenable conditions could be evaluated for each vehicle.

In bench-scale tests, as expected, the polymer material treated with the fire retardant exhibited a significantly lower heat release rate.[16,17] The heat release rate of the material with untreated polypropylene exceeded 200 kW/m^2 whereas the heat release rate of the flame-retarded HVAC unit was approximately 5 kW/m^2.

Full-Scale Testing. Results from the full-scale vehicle burn tests demonstrated that the fire retardant was ineffective. The heat release rates from the two burn tests were essentially identical. As expected with very similar fire growth rates, the times to reach untenable conditions were also essentially identical. These results are in sharp contrast to the bench-scale cone calorimeter and intermediate-scale results described previously and indicate the difficulty in using bench-scale tests to predict behavior in full-scale vehicle burn tests. Not only did the fire retardant not produce an improvement in the time to untenable conditions, the addition of the fire retardant actually degraded fire safety by producing higher levels of toxic gases.

HAZARD MITIGATION STRATEGIES

Role of ASTM E1546

ASTM E1546, *Standard Guide for Development of Fire-Hazard-Assessment Standards,* describes the development of a fire hazard assessment. ASTM E1546 outlines the manner in which scientific data should be compiled in order to ensure that the information is relevant to the assessment of a fire hazard of a product under specific conditions of use.

According to ASTM E1546, the purpose of a fire hazard assessment is to reveal whether a product produces an increase, no increase, or a decrease in fire hazard for all scenarios relevant to the use of such product. As part of this assessment, it is necessary to first determine the nature of the product's involvement in a potential fire (i.e., initial heat source, initial fuel source, principal or largest fuel source, etc.). This factor is critical in assessing the role that the product plays in fire growth and spread, and how its material properties affect the evolution of the fire. Once this determination is made, it is possible to define the material properties that would provide a "significant variation" on the fire hazard of the product. Once the area of greatest concern is determined, it is then possible to define the test methods or calculation procedures that will measure the product's contribution to the fire hazard.

The environment in which the product is used is also of importance. ASTM E1546 states that it is possible to use data from fire tests of isolated parts. However, the relative importance, interaction, and relevance of the fire test response characteristics, individually and collectively, to the hazard posed by the product in real fires must be established by comparison to more thorough assessments, such as established scientific principles, large-scale tests, and analyses of real fires.

This requires that testing and/or analysis be performed not only for the isolated product (i.e., at the component level), but also as a component in a system (i.e., in actual vehicles under actual fire scenario conditions). Apart from the product analysis, it is also important to identify and measure the impact (i.e., reduction in injuries and fatalities) of the product's flammability properties on the outcome of a possible fire.

Application of ASTM E1546 to Vehicle Fire Safety

ASTM E1546 provides general guidelines for fire hazard assessments. In the case of vehicle fires, it is important to take into account the special circumstances involved and to use any available data on such incidents. In particular, emphasis should be placed on types of fires that are likely to result in injuries and fatalities. It is also important to have a clear understanding of the types of fires commonly involved in vehicle accidents and how such fires progress. This information must then be used to assess what factors play the largest role in the evolution and growth of vehicle fires. Only then can the major fire hazards be identified and quantified.

The fundamental requirement to prevent fatalities due to postcollision fires is that egress or extinguishment occurs before conditions become untenable in the passenger compartment. Mitigating the risk of injury to the occupants of passenger vehicles involved in postcollision fires can be accomplished by any combination of the four factors that follow:

1. Reduce the risk of ignition, that is, prevent the fire from occurring
2. Decrease the time necessary to egress or to be extricated
3. Decrease the time required to extinguish the fire
4. Increase the time until untenable conditions exist within the passenger compartment

Reducing the Ignition Probability. The most obvious way to reduce the number of postcollision fire injuries and deaths is to prevent fires from occurring. Limited research has been conducted to evaluate the mechanisms responsible for ignition of postcollision fires, particularly those that did not involve gasoline as the first material ignited. More research is necessary in this area to better understand the processes that cause ignition as a result of collisions and the methods that may be used to reduce the probability of ignition.

Decreasing the Time Required to Egress. In cases where the occupants of the vehicle are incapacitated or trapped, the time required to egress is related to the involvement of bystanders or emergency response personnel. Time to egress is also influenced by specific crash-induced damage to the vehicle and the ability of occupants to egress. The response of emergency personnel depends of a number of complex factors and has been studied extensively. In 1999, NHTSA funded

a study to address the possibility of reducing the crash-to-notification times to 1 minute using an automated collision notification (ACN) system.[18] This system was expected to also shorten the notification-to-arrival time due to automated directions to the site. The system was evaluated by NHTSA,[19] with a program initiated in 1995, in order to assess its effectiveness. In the end, it was found that the ACN produced an unacceptable number of false alarms and was too complicated and costly.

Decreasing the Time Required to Extinguish the Fire. Excluding the possibility of bystanders extinguishing a postcollision fire, the two main methods to decrease the time required to extinguish the fire are decreasing the emergency personnel response time (and associated time to notify emergency responders) or designing and installing an effective on-board fire suppression system. Because fuel-fed fires can become untenable before emergency personnel arrive on scene, one of the leading hazard mitigation strategies in this scenario is an on-board fire suppression system.

The great diversity of collisions and the associated postcollision fires create a complex set of problems which must be overcome in developing a robust, on-board fire suppression system. Factors such as the amount of damage sustained to the vehicle, vehicle movement, wind direction and speed, and reignition after suppressant release can substantially reduce the effectiveness of an automatic suppression system in extinguishing a postcollision fire.[20] Overall, these technologies show some promise, but there is still much research required to improve their reliability and effectiveness in an actual postcollision vehicle fire. Tewarson et al. relayed in their work that one set of tests conducted produced results indicating that it is highly improbable that an on-board fire suppression system would be able to extinguish most engine compartment and underbody fires.[21]

Increasing Tenability Time. Another approach to hazard mitigation of postcollision fires (at least those which do not involve a fuel-fed fire) is to slow the spread of the fire into the passenger compartment. A strategy that has received significant attention is the use of fire retardants in plastic automotive components. Although bench-scale tests have shown that fire retardants can lower the heat release rate of plastics, the ability of fire retardants to increase the time to untenable conditions in the vehicle interior has not been demonstrated in full-scale tests. Whereas the benefits of using fire retardants are unclear, there are numerous potential negative consequences to using fire retardants, many of which are toxic to humans. These include toxic effects of the fire retardant coming into contact with people, the toxic gases produced by fire retardants when they burn, environmental concerns about disposing of these toxic materials at the end of a vehicle's life, and the potential adverse effects that fire retardants may have on the intended function of the component, such as energy absorption, strength, weight, wear, durability, and appearance. Additional research is necessary to evaluate the effectiveness of fire retardants on motor vehicle safety and to ensure that the toxic effects of fire retardants are not a detriment to the public.

DESIGN AND SAFETY CONSIDERATIONS

Other physical properties and component relationships related to vehicle safety other than flammability and fire response must be included in the hazard assessment in order to assess whether changes in component flammability or fire response will adversely affect other safety attributes of the components and the entire vehicle system (i.e., trade-offs).

From the standpoint of fire safety, all vehicle components could theoretically be made of noncombustible materials. This, however, is not feasible, as has been previously discussed in the literature.[22] In the case of a passenger vehicle, the choice of materials to be used in the vehicle should be driven by overall safety and function. For example, it would not be prudent to decrease the fire hazard related to automobile components while increasing the risk of injury during a crash.

Automobile components are specifically designed to be used for extended periods of time, under a variety of environmental conditions and (most importantly) be able to perform well during a crash. Before any additional requirements (such as changes in flammability performance) are suggested regarding vehicle components, it is necessary to determine that these new requirements are not detrimental to other safety properties of such materials. The following is a discussion of some possible considerations.

Need for a Systems Approach

Safe vehicle design requires a systems-level approach, instead of focusing solely on prescriptive, individual material performance requirements. Other physical properties related to the ability to manufacture a working component, the functionality of a finished component or assembly, the durability of the component, occupant protection in a crash, and other safety parameters, are necessary and equally important considerations in designing components for use in passenger vehicles. Changes to the formulation of combustible materials that result in improved flammability and/or fire response characteristics based on bench-scale tests alone could adversely affect other material physical properties and may negatively impact manufacturability, durability, functionality, and crash protection.

Physical Properties

Many of the components in today's vehicles are designed with specific material properties intended to increase the survivability of passengers during a collision or rollover. As an example, some fire mitigation strategies may have adverse and unwanted effects on FMVSS 201* performance such as energy absorption due to change in materials stiffness if new materials were substituted for current materials. Another example is the use of fire retardants that may compromise crash safety performance, because of the reduction in energy absorption due to the increase of material stiffness. In the case of very specialized components, such as airbags or seatbelts, the addition of fire retardants would

*FMVSS 201 specifies requirements for occupant protection in interior impacts.

have to be thoroughly evaluated and analyzed if the materials used in their construction were altered.

Although ordinary fire-retardant treatments have been shown to improve the flammability properties of polymer materials under bench-scale testing, their behavior under real fire conditions is currently not well understood. In one study of automotive material flammability, it was noted that "ordinary fire retardant treatments are not effective in preventing the flame to penetrate the passenger compartment and thus concepts based on modifying the fundamental thermo-physical-chemical and fire properties under high heat flux exposure conditions need to be utilized to enhance the fire retardancy of automotive polymers."[23]

Although the desired performance requirements may be met with the addition of fire retardants in automotive materials, an increase in time to ignition and a decrease in heat release rate performance may yield an increase in toxicity levels and provide no net benefit in overall fire safety. The smoke and fumes inside the passenger compartment during a fire should be considered in a fire hazard assessment. Toxic fumes could overcome passengers that have become entrapped or otherwise incapacitated inside the passenger compartment due to the use of fire-retardant chemicals.[24,25]

Health and Environmental Hazards

Potential health and environmental hazards also need to be evaluated. Next to homes and offices, we spend the most time inside automobiles, an average of 101 minutes per day.[26] During this time, we are exposed to the materials within the automobile in an enclosed space, increasing our contact with any volatiles or contaminated particulates. This means that care must be taken to reduce the toxicity of materials and/or reduce the use of toxic materials within an automobile. Chemicals within a passenger vehicle are exposed to extreme conditions, which may accelerate their decay. Summer air temperatures inside parked vehicles can reach 192°F (88.88°C), with dash surface temperatures of up to 248°F (120°C) recorded.[27] In addition, most vehicle windows transmit long-wave UV light, which can increase the rate of decomposition of materials.

The literature contains numerous papers addressing health and/or environmental concerns associated with the historical use of flame-retardant substances. Asbestos and PCBs are just two examples of materials adopted as flame retardants because of their chemico-physical properties. Only later did scientists and the industry develop an understanding of the biological consequences of that decision.

There are many different potential flame-retardant additives that can be used in plastics in order to meet specified performance requirements. Not all of these chemicals have been thoroughly investigated in terms of their human or ecological health hazard. Prior to their implementation, each of the various chemical options deserves to be assessed fully in order to characterize these hazards.

Another important concern is that when a flame retardant is brought into the marketplace, there is an abundance of opportunities for its distribution into the environment. People may be exposed during the manufacture of the flame retardant. Sometimes, particularly toxic chemicals are necessary to synthesize the agent. From there, the retardant needs to be placed in packages and then shipped. The areas of potential risk can be divided into three main categories: risk to workers, risk to consumers, and risk to the environment. Each area must be examined before making changes in material properties.

SUMMARY

Motor vehicle fire safety has realized significant improvements over the past several decades. Considering new vehicles only (4 years old or newer), to eliminate effects attributable to vehicle age, it is found that the risk of fire fatality per one billion vehicle miles traveled is about 30 percent lower for today's vehicles than for model year 1982 to 1986 vehicles. Nevertheless, advancing motor vehicle safety remains a significant public health challenge—one that automakers are addressing daily. According to recent data, in the United States, approximately 32,000 passenger vehicle occupants are fatally injured every year as a result of traffic accidents. Of these fatalities, approximately 1.2 percent (385) are attributed to postcollision fires. In addition, there are approximately 40 passenger vehicle fire fatalities per year that are not collision-related. These statistics indicate that the current standard has been empirically demonstrated to produce a low risk of fatality.

The complexities of passenger vehicle safety require a broad approach in order to ensure that efforts to increase fire safety performance do not undermine other important safety considerations. Any new motor vehicle fire hazard mitigation strategy must address safety trade-offs, such as the extent to which other critical safety features may be compromised if new strategies are implemented. Potential design changes, such as changing the flammability properties of individual components, will have an effect on other component properties, either immediately or over time.

Research to improve vehicle fire safety involving postcollision fires is in its infancy, and few full-scale vehicle burn tests have been conducted to validate new strategies. Significant additional research is necessary to develop robust, cost-effective hazard mitigation strategies for postcollision fires.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire safety in passenger vehicles discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*
NFPA 385, *Standard for Tank Vehicles for Flammable and Combustible Liquids*
NFPA 1192, *Standard on Recreational Vehicles*

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Chapter 2

Fire Safety in Commercial Vehicles

Revised by
Brian Routhier

Chapter Contents

Nature of Vehicle Fires
Federal Regulations Affecting Motor Vehicle Fire Safety
NFPA and Related Standards on Motor Vehicles
Preventing Motor Vehicle Fires
Cargo Tanks (Tank Trucks)

Key Terms

cargo tank, commercial vehicle, Federal Motor Vehicle Safety Standard (FMVSS), hazardous material, motor vehicle, National Transportation Safety Board (NTSB), road trailer, vehicle electrical system, vehicle fuel tank

Many factors influence motor vehicle fire safety. Among these are vehicle design and construction; materials from which a vehicle is constructed or which are carried by a vehicle, particularly upholstery, plastic, wood, fuel, and hazardous materials cargoes; vehicle maintenance, including safeguards against fire during vehicle repair; vehicle operation, including avoidance of collisions and of other accidents, such as those involving smoking materials; and garaging or storage of vehicles.

The degree of fire hazard depends on the vehicle type, such as passenger car, motorcycle, motor home, or tank truck; the use of the vehicle for pleasure driving, commercial service, or off-road; the climate and environment in which it is used; the age, condition, and maintenance of the vehicle; the material and construction standards to which it is built, particularly the fuel and electrical systems; and the type of fuel used—gasoline, diesel fuel, propane, natural gas, or alcohol—and the way the fuel is contained in the vehicle.

Research into causes of motor vehicle fires based on individual crash investigations and collections of crash and other loss data indicate the magnitude of the motor vehicle fire problem and some specific causal factors in motor vehicle fires.

Each year, the United States experiences approximately 6200 highway vehicle fires due to collision and 12.7 million on-the-road vehicle accidents. Yet serious injury from vehicle fires occurs overwhelmingly from crash-related fires—fires that occur at a rate of approximately 1 per 1000 crashes. Three-fifths of fire deaths in motor vehicle fires come in postcrash incidents.[1,2]

In 2000, there were an estimated 325,000 fires involving highway vehicles, causing 450 civilian deaths and 1325 civilian injuries. Table 21.2.1 presents information on the U.S. highway vehicle fire problem for the years 1980 to 2002.

For related topics, see the following chapters in Section 21: Chapter 1, "Passenger Vehicle Fires"; Chapter 3, "Automotive and Marine Service Station Operations"; Chapter 4, "Vehicle Fueling Using Gaseous Fuels"; and Chapter 6, "Recreational Vehicles." See also Section 13, Chapter 6, "Public Fire Protection and Hazmat Management"; and Section 13, Chapter 8, "Managing the Response to Hazardous Material Incidents."

NATURE OF VEHICLE FIRES

As with other fires, motor vehicle fires require a flammable substance, an ignition source, and oxygen. Virtually all motor vehicles carry flammable fuel—gasoline, gasohol, diesel fuel, or another hydrocarbon compound. Vehicle upholstery, insulating and sound-deadening materials, electrical wiring insulation, and plastic body and trim also can fuel a motor vehicle fire. Materials carried as cargo and fare in or on motor vehicles, particularly trucks, also may be flammable.

Ignition sources include electrical short circuits or other electrical malfunctions that cause excessive heating of conductors or components; sparks from an engine ignition system; hot exhaust system components; engine backfire; overheating of tires, brakes, and wheel bearings; friction-generated

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TABLE 21.2.1 U.S. Highway Vehicle Fire Problem, by Year: 1980–2002

Year	*Fires*	*Civilian Deaths*	*Civilian Injuries*	*Direct Property Damage (in Millions of Dollars)*	*Loss in 2002 Dollars (in Millions of Dollars)*
1980	411,300	600	3,350	478	1,044
1981	417,500	680	2,930	477	942
1982	398,400	570	2,850	409	761
1983	405,400	640	3,250	532	959
1984	411,600	550	3,080	592	1,024
1985	417,000	710	3,060	702	1,172
1986	417,600	740	3,180	608	998
1987	429,300	700	2,620	687	1,088
1988	416,000	730	2,520	728	1,108
1989	379,100	520	2,570	751	1,090
1990	383,000	590	2,920	792	1,092
1991	371,200	480	2,500	801	1,058
1992	335,700	590	2,510	758	971
1993	354,600	500	2,380	723	900
1994	330,100	460	1,960	779	946
1995	334,700	380	1,780	790	932
1996	327,800	470	1,520	774	888
1997	355,100	430	1,860	1,025	1,149
1998	313,600	420	1,610	1,010	1,115
1999*	288,000	350	1,150	911	984
2000	252,400	310	1,100	903	943
2001	257,500	390	1,440	1,064	1,081
2002	281,600	480	1,540	1,143	1,143
1980–2002 annual average	360,400	530	2,330	758	1,017
1999–2002 annual average	269,900	380	1,310	1,005	1,038

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries to the nearest ten, and direct property damage is rounded to the nearest million dollars.

*NFIRS data for 1999 and later was received in the Version 5.0 format. Due to the many coding changes, the 1999–2002 data can better be analyzed separately from data from previous years.

Source: NFIRS and NFPA survey; Table 697, "Purchasing Power of the Dollar" from U.S. Census Bureau's *Statistical Abstract of the United States: 2004–2005* (124th Edition).

sparks from a collision or from metal components scraping against the pavement; and careless use of cigarettes and other smoking materials. Generally, oxygen in the ambient atmosphere is sufficient for a motor vehicle fire.

Table 21.2.2 summarizes passenger and freight vehicle fires, by area of origin of fires, from 1999 to 2003. More detailed but dated analyses have been developed by the Federal Motor Carrier Safety Administration (FMCSA) of the U.S. Department of Transportation (DOT).

Death and injury in motor vehicle fires can result from direct exposure to heat and from inhalation of toxic combustion products. In major vehicle crashes involving fire, determining with certainty whether death resulted from the crash or from the fire may not be possible. In some cases, injury results from or is exacerbated by the inability of a vehicle's occupant to get out of the burning vehicle—doors or seats are jammed by a crash, or the occupant is injured or stunned.

Hazardous materials in motor vehicles present a particular fire problem. The National Transportation Safety Board (NTSB), the FMCSA, and NFPA all carried out a number of detailed accident investigations into such fires. These investigations led to changes in regulations for hazardous materials containers and in other aspects of the transportation of such cargoes. Despite such precautions, hazardous materials cargo fires and explosions occur.

The NTSB has issued investigative reports on accidents in which hazardous materials exploded or burned following a crash. (These and other NTSB reports are available from the National Technical Information Service, Springfield, Virginia 22161.) As a result of these and other highway crash investigations, the NTSB made numerous recommendations to the FMCSA, the Research and Special Programs Administration (RSPA) of DOT, and to other agencies concerning modification and enforcement of safety and hazardous materials regulations.

TABLE 21.2.2 U.S. Highway Vehicle Fires, by Area of Fire Origin, 1999–2003 Annual Averages

Area of Fire Origin	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions)*	
Engine area, running gear, or wheel area	212,000	(65%)	170	(39%)	740	(49%)	$618	(53%)
Operator or passenger area	53,800	(17%)	90	(20%)	270	(18%)	$264	(23%)
Unclassified vehicle area	14,400	(4%)	50	(11%)	70	(5%)	$55	(5%)
Exterior, exposed vehicle surface	10,200	(3%)	10	(2%)	50	(3%)	$33	(3%)
Cargo or trunk area	9,900	(3%)	10	(3%)	100	(7%)	$44	(4%)
Fuel tank or fuel line	5,400	(2%)	80	(17%)	150	(10%)	$41	(4%)
Unclassified area of origin	4,300	(1%)	10	(2%)	10	(1%)	$22	(2%)
On or near highway, parking lot, or street	4,100	(1%)	10	(3%)	10	(1%)	$17	(1%)
Separate operator or control area	3,200	(1%)	0	(1%)	10	(1%)	$18	(2%)
Other known area	7,900	(2%)	10	(3%)	80	(6%)	$44	(4%)
Total	325,100	(100%)	440	(100%)	1,500	(100%)	$1,156	(100%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest hundred, civilian deaths and injuries to the nearest ten, and direct property damage is rounded to the nearest million dollars. Sums may not equal totals due to rounding errors. Property damage figures are not adjusted for inflation. Percentages were calculated on the actual estimates, so two figures with the same rounded-off estimates may have different percentages. Fires in which the area or origin was unknown or not reported were allocated proportionally among fires with known area of origin. A proportional share of fires in which the mobile property type was unknown or not reported are included in this table.

Source: NFIRS and NFPA survey.

FEDERAL REGULATIONS AFFECTING MOTOR VEHICLE FIRE SAFETY

As you read the statistics in this section, note that the data were current at the time of writing. As always, it is wise to check Federal Motor Vehicle Safety Standards for the most current information.

Federal Motor Vehicle Safety Standards

The National Traffic and Motor Vehicle Safety Act of 1966 authorized the National Highway Traffic Safety Administration (NHTSA) of DOT to set minimum safety standards applicable to new motor vehicles, trailers, and motor vehicle equipment manufactured after the effective date of the standard, or any subsequent amendment. To date, only four fire-related standards have been issued for new vehicles, and none has been issued for vehicles in use. The NHTSA also has the authority to investigate motor vehicle defects, some of which may present fire hazards, and to order manufacturers to notify owners and repair defects.

Federal Motor Vehicle Safety Standard (FMVSS) 301 sets requirements for the fuel system integrity of passenger cars, trucks, buses, and multipurpose vehicles having a gross vehicle weight rating (GVWR) of 10,000 lb (4536 kg) or less. The standard also applies to school buses of more than 10,000 lb (4536 kg) GVWR using fuel with a boiling point of more than 32°F (0°C).

FMVSS 301 is intended specifically to reduce the fire hazard resulting from fuel leakage in crashes. It was first applied to passenger cars manufactured on and after January 1, 1968. Since that time, the standard has been made increasingly stringent.

Under provisions that became effective on September 1, 1977, all vehicles with a GVWR of 10,000 lb (4536 kg) or less must pass prescribed front, side, and rear crash barrier tests and a rollover test. Front tests are conducted at an impact speed of 30 mph (48 km/hr), rear tests at 50 mph (80 km/hr), whereas lateral impact speed is 33 mph (53 km/hr). In the crash barrier tests, fuel leakage cannot exceed 1 oz (28 g) by weight from impact until the vehicle stops moving, 5 oz (142 g) by weight in the 5 minutes following cessation of motion, or 1 oz (28 g) by weight per minute for 25 minutes.

In the rollover test, the vehicle is turned about its longitudinal axis in 90° increments and is held for 5 minutes in each position. Rotation occurs every 1 to 3 minutes. Fuel leakage cannot exceed 5 oz (142 g) by weight in the first 5 minutes of each segment or 1 oz (28 g) per minute for the remainder of the segment.

The school bus test procedure for buses over 10,000 lb (4536 kg) GVWR uses a special, moving, contoured barrier that strikes the test vehicle at the front, rear, and sides. No rollover test is prescribed for these buses. Maximum permissible fuel leakage is the same as indicated above for front, side, and rear barrier crash tests.

FMVSS 302 sets flammability limits for materials used in interiors of vehicles in the driver and passenger space. Its requirements are directed at reducing the hazards of interior fires caused by smoking and matches. Vehicle appointments specifically covered by the standard include seat cushions, seat backs, seat belts, headlining, arm rests, trim panels, compartment shelves, head restraints, floor covering, engine compartment covering, padding, and the surface of crash protection components.

FMVSS 302 specifies a horizontal flame test for all materials and incorporates detailed requirements for the test procedure. Material under test must not burn or transmit a flame across the surface at a rate exceeding 4 in. per minute (1.7 mm/s).

FMVSS 303, *Fuel System Integrity of Compressed Natural Gas Vehicles—Passenger Cars, Multipurpose Passenger Vehicles, Trucks, and Buses,* covers vehicles that have a gross vehicle weight rating of 10,000 lb (4536 kg) or less and use compressed natural gas as a motor fuel. FMVSS 303 also covers school buses (regardless of weight) that use CNG as a motor fuel.

FMVSS 303 specifies requirements for the integrity of motor vehicle fuel systems using CNG, including CNG fuel systems of bi-fuel, dedicated, and dual-fuel CNG vehicles. The purpose of the standard is to reduce deaths and injuries resulting from fires after fuel leakage during and after motor vehicle crashes.

FMVSS 304, *Compressed Natural Gas Container Integrity,* specified requirements for the integrity of CNG motor vehicle fuel containers. FMVSS 304 applies to containers designed to store CNG as motor fuel on board any motor vehicle.

Federal Motor Carrier Safety Regulations

FMCSA administers the Federal Motor Carrier Safety Regulations (FMCSRs), which can be found online at http://www.fmcsa.gov. These regulations apply to vehicles in use, as contrasted with the Federal Motor Vehicle Safety Standards promulgated by the National Highway Traffic Safety Administration (NHTSA) that apply to new vehicles.

The FMCSRs are set forth in Title 49 of the Code of Federal Regulations, Parts 325–399, and apply to commercial vehicles in interstate or foreign commerce. Because most states have adopted these regulations by reference, they also apply, *de facto,* to most commercial vehicles in intrastate commerce.

Provisions of these regulations that address fire safety issues for commercial vehicles include the following:

- A requirement for fire extinguishers and for the driver to check the extinguisher at the start of each trip
- A prohibition against attaching a flame-producing warning device to a vehicle and a prohibition against using flame-producing devices on vehicles transporting certain explosives and tank vehicles transporting flammable liquids or gases (loaded or empty), or any commercial vehicle using compressed gas as a fuel
- Fueling precautions including a prohibition against smoking, a requirement to maintain contact between the tank and the nozzle, and restrictions on fueling buses when passengers are aboard
- Standard for installing and protecting the electrical system, including the battery, and standards for constructing and testing fuel tanks
- Special driving and parking rules applicable to drivers transporting hazardous materials including requirements to periodically check for overheated tires, a requirement that someone be present at the nozzle when the vehicle is being fueled, and a prohibition against smoking in or within 25 ft (7.6 m) of a vehicle transporting specified classes of hazardous materials

Hazardous Materials Regulations

Federal hazardous materials regulations, other than those governing driving and parking, are published in Title 49, Code of Federal Regulations, Parts 105–180. By law, hazardous materials regulations apply to both intrastate and interstate transportation. Many provisions of these regulations have been promulgated specifically to meet the needs of emergency responders by providing essential information pertaining to the materials in transport and to warn the public of those vehicles transporting hazardous materials in excess of specified quantities. For further information on the federal hazardous materials regulations, refer to Section 13, Chapter 6, "Public Fire Protection and Hazmat Management"; and Section 13, Chapter 8, "Managing the Response to Hazardous Material Incidents."

Provisions of the hazardous materials regulations address the following:

- Preparation of shipping documents to facilitate the recognition and identification of hazardous materials including a 24 hour emergency telephone that can be contacted for additional information, if needed
- Job-specific training requirements for employees involved in transporting hazardous materials at any level
- Emergency instructions to be carried in vehicles and kept in motor carrier terminals where hazardous materials are handled
- Marking and labeling of hazardous materials packaging to identify its contents and to indicate that the packaging complies with applicable specifications
- Specifications for bulk packaging such as cargo tanks and portable tanks, and for nonbulk packaging such as cylinders, boxes, drums, and bags used for hazardous materials
- Requirements for shippers that specify the types of packaging to be used for hazardous materials shipments based on the commodity's specific hazard(s)

State Activity

Most states have adopted by reference the provisions of the Federal Motor Carrier Safety Regulations and the DOT hazardous materials regulations. A number of other states have regulations similar to the federal requirements. As these trends continue, they will foster increasing uniformity of legal requirements.

National Transportation Safety Board

The National Transportation Safety Board, an independent federal agency, oversees safety for all types of transportation. Probably best known for its investigations of aircraft accidents, the agency is also concerned with fire-related highway accidents. The NTSB is responsible for making recommendations for improved safety, based on its investigations. The majority of its recommendations deal with suggested changes in the regulations and practices of federal and state government agencies, but they may also be directed at others, such as vehicle manufacturers and users.

Role of Congress

In Congress, the responsibility for legislation and oversight of transportation rests with the Senate Committee on Commerce and the House Committee on Transportation and Infrastructure. These committees take a keen interest in the activities of the federal government in the field of motor vehicle safety. They regularly hold legislative and oversight hearings on FMCSA and NHTSA activities and occasionally on NTSB activities. Reports of these hearings are available from the U.S. Superintendent of Documents or from the committees.

NFPA AND RELATED STANDARDS ON MOTOR VEHICLES

Several NFPA standards contain requirements for transportation by truck of specific hazardous materials. NFPA 495, *Explosive Materials Code,* details fire and explosion prevention related to the transportation of explosive materials, including driver qualifications, vehicle design, placarding, fire-fighting equipment, and vehicle operation. This code is widely used as the basis for state regulations.

NFPA 385, *Standard for Tank Vehicles for Flammable and Combustible Liquids,* and NFPA 407, *Standard for Aircraft Fuel Servicing,* both contain requirements for design and construction of cargo tanks of tank vehicles, for auxiliary equipment, and for operation of tank vehicles. NFPA 407 covers only special requirements for aircraft fuel servicing tank vehicles and aircraft fuel servicing hydrant vehicles.

NFPA 58, *Liquefied Petroleum Gas Code,* contains requirements for transporting liquefied petroleum gases, including requirements for transporting portable containers, for cargo tanks, and for parking and garaging vehicles used to carry LP-gas. NFPA 58 also includes requirements for installing LP-gas systems in vehicles fueled by LP-gas. It has been adopted for regulatory purposes by 47 states and by the DOT for vehicles in interstate commerce.

NFPA 52, *Vehicular Fuel Systems Code,* covers design and installation of compressed natural gas (CNG) engine fuel systems on vehicles of all types and their associated fueling systems. NFPA 52 applies to the design, installation, operation, and maintenance of liquefied natural gas engine fuel systems on vehicles of all types and to their fueling facilities.

NFPA 58 covers parking and garaging of LP-gas cargo vehicles. Another NFPA standard includes provisions relating to parking trucks: NFPA 498, *Standard for Safe Havens and Interchange Lots for Vehicles Transporting Explosives.*

The dependence of the fire service upon motor vehicles is well recognized, and it is particularly important that fire apparatus be safely constructed. NFPA 1901, *Standard for Automotive Fire Apparatus,* and NFPA 414, *Standard for Aircraft Rescue and Fire-Fighting Vehicles,* detail practices that should be followed on these types of apparatus.

Underwriters Laboratories Inc.

Certain over-the-road motor vehicle components and signaling appliances have special fire hazard significance. Underwriters Laboratories Inc. tests and lists them in UL's *Accident, Automotive, and Burglary Protection Equipment* directory. Specific items listed include the following:

1. Electrical equipment such as automobile fuses and switches
2. Fill and vent fittings
3. Fuel equipment such as backfire deflectors, fuel feed systems, electric gasoline gages, automotive-type LP-gas accessories, automotive fuel tanks, and tubing
4. Automotive heaters of the combustion type
5. LP-gas automotive vehicles—that is, farm and road tractors incorporating fuel systems designed for use of LP-gas as engine fuel and LP overfill prevention
6. Mufflers for automobiles
7. Signals and signaling appliances or highway emergency signals

UL also has its own standard, UL 395, *Standard on Automotive Fuel Tanks,* for liquid fuel tanks mounted outside the frame or in other exposed locations on gasoline- or diesel-powered trucks, tractors, or trailers. It has issued UL 307(a), *Standard on Liquid Fuel-Burning Heating Appliances for Mobile Homes and Recreational Vehicles,* and UL 307(b), *Standard for Gas Burning Heating Appliances for Mobile Homes and Recreational Vehicles.*

Society of Automotive Engineers, Inc.

The Society of Automotive Engineers, Inc. (SAE) is concerned with any vehicle that moves under its own power. SAE's standardization program covers passenger cars, trucks and buses, farm and earth-moving machinery, marine propulsion units, aircraft, and space vehicles, as well as the materials and components that go into them. Content of the SAE standards is limited to environmental and operating problems with these vehicles. The *SAE Handbook* contains all the society's surface vehicle documents.

Other Organizations Interested in Highway Safety

American Petroleum Institute (API). Active in the field of truck transportation of petroleum products, API publishes a number of publications of interest and value from the fire safety viewpoint. More information is available at http://www.api.org.

American Trucking Associations, Inc. The association reproduces the federal hazardous materials regulations in their entirety as "Hazmat Transport Regs." The association's safety department sets trucking industry standards for selecting, training, and supervising employees and develops a variety of materials for the use of trucking companies dealing with general safety and safe transportation of hazardous materials. More information is available at http://www.truckline.com.

Canada Safety Council. The council is a national, nongovernmental organization that promotes public safety initiatives in English and French. See http://www.safety-council.org.

Center for Auto Safety. The center is a consumer advocate organization dedicated to improving the safety and value of automobiles, other motor vehicles, highways, and mobile homes. The center regularly issues reports, books, comments on federal rule making, and other materials. See http://www.autosafety.org.

American Chemistry Council. The council has an active technical service on transportation and packaging. It also operates the Chemical Transportation Emergency Center (Chemtrec), 1-800-262-8200, http://www.chemtrec.com, which provides information on hazardous materials involved in emergencies. For more information, see http://www.americanchemistry.com.

Compressed Gas Association, Inc. (CGA). CGA provides technical services on products of interest and concern to its membership. See www.cganet.org.

Consumers Union of U.S., Inc. (CU). A nonprofit consumer information organization with a large technical staff, CU regularly tests automobiles—and occasionally trucks and other motor vehicles—and publishes its findings monthly in *Consumer Reports* magazine. For more information, see http://www.consumersunion.org or http://www.consumerreports.org.

Cooperative Hazardous Materials Enforcement and Development (COHMED). COHMED develops and promotes training programs for personnel responding to hazardous materials emergencies. More information on COHMED, an outreach activity of the U.S. Department of Transportation, is available at http://hazmat.dot.gov/cohmed.htm. Other DOT sites and resources on hazardous materials include the following:

- DOT regulations at http://www.myregs.com/dotrspa
- DOT Hazmat Law at http://www.hazmat.dot.gov/regs/notices/dotbill.pdf
- DOT main page at http://www.dot.gov

Hazardous Materials Advisory Council. The council is concerned with all aspects of hazardous materials transportation affecting shippers, all modes of transportation, and manufacturers of packaging. It also conducts training in the safe transportation of hazardous materials. See http://www.hmac.org.

Insurance Institute for Highway Safety. The institute is an independent, nonprofit, scientific, and educational organization dedicated to reducing losses resulting from crashes on the nation's highways. See http://www.iihs.org.

National LP-Gas Association. This association develops LP-gas standards and provides safety programs for the general public. See http://www.pgas.com.

National Safety Council (NSC). A nonprofit organization dedicated to accident prevention, the council has an extensive program on highway safety geared principally to the motoring public. NSC produces numerous publications on transportation and highway safety. More information is available at http://www.nsc.org.

National Tank Truck Carriers, Inc. (NTTC). NTTC helps members, who are operators of tank truck fleets, solve problems associated with safe handling of flammable liquids, gases, and chemicals. See http://www.tanktruck.org.

Truck Trailer Manufacturers Association. A trade association of manufacturers of truck trailers, it cooperates, through its various committees and representatives, with NFPA, other allied industry associations, and governmental agencies in matters affecting tank transport design and fabrication. See http://www.ttma.net.

Trailer and Truck Box Design and Construction Safeguards

Currently there are no FMVSS, NHTSA, or FMCSA standards for fire retardance of cargo trailers or bodies. In large truck bodies and in freight-carrying trailers, wood is used as flooring. It withstands torsional stresses, impacts, and abrasions encountered in this type of service, and replacement of worn or damaged sections is relatively economical. Wood provides safety benefits because blocking and bracing can be nailed in place to prevent shifting of cargo. It offers a high coefficient of friction for safe forklift operation and a slip-resistant footing for personnel who handle cargo.

Plywood is used for interior lining material in van-bodied trucks and trailers because it effectively protects other structural components from damage that may occur during loading, unloading, and transportation of freight. As with wood flooring, replacing damaged sections is relatively inexpensive.

Plywood flooring is used in buses for essentially the same reasons. Metal flooring would create "tin canning" under torsional stress and a resulting noise level unacceptable to passengers.

These uses of wood do not create any significant fire hazards. In the forms used, the wood is relatively difficult to ignite and burns slowly. Specific provisions of the Federal Motor Carrier Safety Regulations require that flooring be in good condition. The use of flooring permeated with oil or gasoline is prohibited.

In major incidents involving fire, wood can be a contributing factor, but usually only in incidents so severe that their outcomes would have been little affected if wood had not been present.

When the cargo must be covered during transportation on flatbed, open-top, and other types of nonenclosed vehicles, the use of tarpaulins is the only practicable means of providing needed protection. Such tarpaulins normally are not given flame-retardant treatment, but they pose little risk of fire.

Vehicle Fuel Tanks and Systems

The location, construction, and security of fuel tanks are important design features for fire safety in motor vehicles. Liquid fuel tanks for general passenger car use are generally of plastic or thin-gauge steel of various shapes and dimensions, dependent upon other body and chassis characteristics. The vast majority of U.S.-built cars, trucks, and buses have liquid fuel tanks located at the rear of the vehicle, frequently in such a position that

they are not entirely enclosed in the body. The greatest risk of loss of life and property from fire in vehicles, therefore, occurs in fires following rear-end collisions.

The Federal Motor Carrier Safety Administration (FMCSA) has developed fuel tank regulations applicable to commercial vehicles operating in interstate or foreign commerce. These regulations closely parallel Underwriters Laboratories (UL) standards. In 1973, requirements that previously had been limited to gasoline tanks were extended to include tanks for diesel fuel. This action also required protection for diesel fuel crossover lines located below the bottom of a tank or sump. The DOT regulations include requirements for tank construction and installation and for adequate fillpipe closure. Tanks must pass drop, rupture, vent, and spillage tests. Required safety vent systems must limit pressure rise to 50 psig (345 kPa) in a specified fire test.

Tanks must be marked by a manufacturer's certificate to indicate that they meet DOT-FMCSA specifications for side-mounted or non-side-mounted tanks, as applicable.

Efforts have been made to gain DOT approval for plastic fuel tanks for truck service. Despite certain advantages their manufacturers claim, doubts about the safety of such tanks in commercial vehicle operations have not been satisfactorily resolved.

Vehicles using flammable compressed gas as a motor fuel must be equipped with fuel systems constructed and installed in accordance with applicable provisions of NFPA 58 or NFPA 52. Likewise appropriate LNG tanks are required.

Fuel systems must be maintained so they are free of leaks. Fuel tanks must be capped, and connections must be checked regularly. Metal fuel lines are subject to vibration-induced fatigue, and flexible lines may deteriorate with age. Chafing, cutting, or proximity to hot surfaces also can damage lines. In a gasoline system, carburetor flooding due to dirt in the float valve or electric fuel pumps that do not shut down may cause gasoline to overflow onto a hot surface and result in a fire.

These problems are somewhat less critical on diesel-powered vehicles because diesel fuel has a higher flashpoint. Diesel engines are designed to operate at higher temperatures to control exhaust emissions. This, in turn, led to higher fuel temperature in the return flow line, thus making the fuel more prone to ignition if the warmed, leaking fuel contacts a hot surface.

PREVENTING MOTOR VEHICLE FIRES

Fire prevention in motor vehicles requires the attention of everyone involved. Vehicle designers must be aware of fire hazards in their products. Sources of heat and ignition must be kept away from flammable materials as much as possible. Consideration should be given to the vulnerability of fuel system components, in particular to their basic integrity, their location away from the perimeter of the vehicle and from crash-collapsible and intrusive parts, and their location away from potentially hot exhaust and electrical components.

Examples of location hazards were found in 1971–1976 Ford Pintos and 1975–1976 Mercury Bobcats. These cars' fuel filler necks and tanks could separate in a rear-end collision, resulting in fire. Manufacturers recalled 1.4 million of these vehicles for retrofitting of longer fuel filler necks and for installation of protective shields on the front of fuel tanks. Improperly routed fuel lines to the carburetor have been the subject of recalls because of potential rupture and underhood fires.

Because electrical system failures can cause fires resulting in property damage, particular attention must be paid to routing of wiring, aging of insulation and components, and failure modes of components.

To minimize potential fuel leakage in any crash, extraneous plumbing and openings should be eliminated in fuel and hazardous liquid and gaseous cargo containers. Necessary plumbing should be designed so it is protected from potential crash damage.

In vehicle construction, care must be taken to ensure that fuel and electrical lines are correctly routed and connections secure. In addition, location of sharp or pointed components near fuel or hazardous cargo tanks should be avoided.

A major hazard during the vehicle repair process is the use of torches, usually in the repair of exhaust systems and crash damage. Some items used in vehicle repair are particularly flammable, such as paint, solvents, adhesives, and oily rags.

Care must be taken when maintaining and rebuilding damaged vehicles to ensure that their fuel and electrical systems are free of hazards not present in the original vehicle.

Vehicle Electrical Systems

Automotive lighting and accessory circuits are usually 6 or 12 V, but vehicle ignition systems have high voltage and low amperage. Automobile electrical system fire safety is largely a matter of proper installation, fusing, and maintenance. Important checkpoints include the location and protection afforded the battery; battery cable integrity and protection of exposed battery terminals; adequate flame-retardant insulation on all wiring; proper fusing of normal lighting and accessory circuits; proper support, location, and security of all wiring, with adequate protection by rubber insulating bushings where wiring passes through metal; and good ignition system maintenance.

Electrical fires can be fed by oily deposits in and around the engine or by combustible materials, such as interior fabric linings and upholstery. In collision or upset, electrical short circuits can occur and may ignite fuel vapors. It is desirable, particularly on buses and trucks, to provide an approved type of manual battery/generator disconnect switch, preferably one incorporating short circuit supervision. However, use of such devices on vehicles is rare.

Miscellaneous Vehicle Hazards

Proper exhaust system installation is important because the system's hot surfaces can ignite nearby combustible components. Hot carbon particles and hot gases discharged from the exhaust can ignite flammable liquids, grease, or similar exposed materials, such as insulation on electrical wiring.

Catalytic converters in exhaust systems can cause wildland fires, if automobiles are driven through dry grass or vegetation.

Overuse of vehicle brakes can result in sufficient overheating to cause severe smoldering and sometimes fire. Improper adjustment that prevents full release of a brake can lead to similar conditions. Overheated brake drums or rotors can cause ignition of fuel if spillage occurs onto the brakes during refueling.

The problem of overheating brakes increases with the vehicle's size and gross weight. On long downgrades, a driver must rely on the braking effect of the engine for primary control of the vehicle, limiting brake use to slowing for sharp turns or unanticipated, localized, hazardous conditions, and to stop. The engine's maximum braking effect is achieved only in the transmission lower gears. Particularly on trucks and buses, it is essential for the driver to get into a low gear at the top of the grade before the vehicle reaches a speed at which downshifting is no longer possible. Engine braking devices are used on diesel-powered trucks, especially in mountainous regions. Other types of electrically and hydraulically operated retarders are used in special situations.

If one tire of a dual-tire installation runs flat or is seriously underinflated, flexing may cause sufficient internal heat to build up to cause ignition. This possibility also exists if tires are seriously overloaded and may be exacerbated by sustained high-speed operation and high ambient temperature. Occasionally, fire results if dual tires are spaced so closely together that they rub or chafe against each other when the vehicle is in motion.

Provisions of the Federal Motor Carrier Safety Regulations for all heating systems used on vehicles in interstate commerce have been upgraded. Reducing such fires has also been aided by technological advances in heaters.

Fire Hazards of Special Vehicles

Certain types of special vehicles, such as farm tractors, motorcycles, all-terrain vehicles, and others, have special problems resulting from the close spacing of such components as the fuel tank and other parts of the fuel system, the engine, the ignition system and other electrical components, and the exhaust, coupled with minimal protective bodywork that increases the susceptibility of these fire-sensitive components to damage.

The need for care to avoid fuel spillage and sparks from static electricity is especially important when refueling in the field from portable containers.

Vapor recovery nozzles on gasoline pumps introduced a potential fire hazard in fueling motorcycles and other vehicles with small fuel tanks. The depth to which the nozzle must be inserted in order to activate vapor recovery control and permit fuel flow is so great that effective refueling cannot be accomplished in the normal manner. It has become necessary to use a device to bridge the fill-pipe opening. Otherwise, the operator must pull back the bellows with one hand and activate the nozzle trigger with the other to obtain fuel.

Use of Fire Extinguishers

Commercial vehicles operating in interstate commerce must be equipped with fire extinguishers to comply with Federal Motor Carrier Safety Regulations. These regulations provide two minimum levels of protection: a 5-B:C extinguisher (or two 4-B:C extinguishers) is required if the power unit is not transporting hazardous materials in sufficient quantity to require marking or placarding the vehicle, and a 10-B:C extinguisher is required on a power unit used for transporting hazardous materials.

Many states have similar requirements for commercial vehicles, through adoption of applicable provisions of federal regulations or their own regulations. Some state laws require additional or larger extinguishers on tank vehicles transporting flammable liquids or gases, combustible liquids, or Class A and/or Class B explosives.

There are no legal requirements for carrying fire extinguishers in private passenger cars, vans, or light trucks, although many people do keep them in vans and motor homes. As a minimum, the vehicle owner should consider buying a portable extinguisher that can deal with Class B (flammable liquids) and Class C (electrical) fires. Also on the market are extinguishers using multipurpose agents for use on Class A fires (ordinary combustibles), as well as Class B and C fires. Anyone equipping a vehicle with a fire extinguisher must understand that the best chance for its successful use lies in prompt action in the fire's early stages and proper use to avoid wasting the agent and exhausting the extinguisher's contents prematurely. NFPA 10, *Standard for Portable Fire Extinguishers,* gives additional information on ratings and use of fire extinguishers.

Other Fire Hazards

While the vehicle is operating, the driver should be alert for any indication of fire or a fire hazard, such as the smell of something hot, of unusual fumes, or of leaking fuel or lubricant. The driver should check for conditions that can create sufficient heat buildup to cause a fire, such as exhaust leaks and dragging brakes.

Carrying extra gasoline in a can is extremely dangerous because of the possible accumulation of fumes. The hazard increases if glass or plastic containers are used, because they're more likely to break and leak.

Smoking by a driver or passengers presents the potential for fire if sparks, hot ashes, or incompletely extinguished matches get into upholstery or other interior materials. Water or an agent suitable for Class A fires can extinguish such fires; the burn area then must be watched in case it continues to smolder and eventually rekindles.

In an accident, the engines and all electrical accessories of all involved vehicles should be turned off to minimize the danger of fire. At night, headlights can be left on to protect the scene, but persons in the vicinity should be alert for indication of overheated wiring or fire. Smoking and all use of open flames or lights must cease, particularly if leaking fuel is detected. If a travel trailer or motor home is involved, the probable presence of liquefied petroleum gas should be kept in mind, smoking should be prohibited, and open flames and lights should be kept well away from the scene.

When a vehicle fire occurs, the following basic steps should be taken, regardless of the type of vehicle involved:

1. Shut off the engine and all electrical systems that can be reached.
2. Get everyone out of the burning vehicle and well away from it, preferably uphill and upwind. The potential for fire is one justification for quickly moving injured persons from the scene of an accident.
3. Summon the fire department by the best available means.
4. Attempt to fight the fire only if it can be done without endangering anyone's personal safety.

Basic principles to be observed in attempting to fight a vehicle fire with a portable fire extinguisher are:

1. First, see item 4 above. The fire should be fought from the windward side so that wind, if any, will help carry the fire extinguishing agent toward the fire and help blow smoke and flame away from the person attempting to extinguish it.
2. The fire extinguisher should be aimed at the base of the flames.
3. If leaking flammable liquid is involved, work toward the source of the leak in putting out the flames. Ultimate control may depend on the ability to shut off leaking fuel at its source.
4. If flammable gas is burning, allow it to continue to burn until the source of any leak is controlled. Otherwise, extinguishing the fire may permit leaking gas to accumulate, with later fire or explosion likely. If flames impinge on a flammable gas container, the container should be kept cool to avoid a flame-induced weakening and possible rupture or a boiling liquid expanding vapor explosion (BLEVE). If fire-fighting hose streams are not available, RUN. Leave IMMEDIATELY.
5. If no extinguisher is available, throw sand or dirt on a fire to control flames.
6. If stopping to help at the scene of a vehicle fire, park uphill, preferably upwind, and at a safe distance from the burning vehicle.
7. After a fire has been extinguished, do not operate the vehicle until all burned parts are cool and the cause of the fire has been corrected.
8. During an electrical fire, turn off the ignition switch and lights to try to cut off the flow of current and permit faster extinguishment. If tools are available and it can be done safely, disconnect the battery.
9. In fighting an underhood fire, use great care in opening the hood to avoid injury in case of a sudden flareup.
10. Inspect and recharge all extinguishers without delay.

The following special considerations apply to fires and potential hazards involving commercial vehicles:

1. Any hazardous situation should be evaluated to avoid endangering lives and wasting extinguishing agent.
2. If a vehicular combination unit is involved in a fire, the power unit should be unhooked and moved a safe distance away from the vehicle if it can be done safely.
3. Drivers must be alert for the hard pulling characteristics that may indicate dragging brakes and must readjust brakes before a fire develops.
4. A driver must examine each tire on a motor vehicle at the beginning of each trip and each time the vehicle is parked. FMCSA regulations require this practice for a vehicle placarded for transportation of hazardous materials.
5. Drivers should check rearview mirrors frequently for signs of smoke and must stop and investigate any smoke detected.
6. A hot or underinflated tire should be moved well away from the vehicle. As an alternative, the driver should remain with the vehicle until the tire is cool to the touch and then make repairs. If a vehicle is left with a hot tire, the tire may burst into flames, destroying the vehicle and its load. With proper tire-changing equipment and a pair of heavy leather gloves, a driver can safely remove a hot tire that has not burst into flames.
7. Because a tire fire results from internal heat buildup, portable extinguishers normally cannot do more than control open flames. The cooling effect of large quantities of water is required for extinguishment.
8. If fire is suspected inside a closed van body—usually indicated by smoke seeping out around the doors—the doors should be left closed until fire department assistance is at hand. Should the doors be opened, oxygen reaching the fire may cause a sudden flareup. As long as the doors are closed, the fire can only smolder from lack of oxygen.

In the interest of preventing cargo fires, motor carriers generally prohibit smoking while vehicles are being loaded or unloaded, so sparks or hot ashes do not lodge in the cargo and burst into flame later.

Federal Motor Carrier Safety Regulations prohibit smoking during refueling; while loading, unloading, or transporting explosives, flammable liquids, gases, or solids, or oxidizing materials requiring marking or placarding of the vehicle; and while driving an empty tank vehicle that last contained a flammable liquid or gas and that was required to be marked or placarded.

CARGO TANKS (TANK TRUCKS)

Cargo tanks and portable tanks are large containers for hauling liquids and gases in bulk. Cargo tanks are sometimes called "tank motor vehicles" or "tank trucks." Any person offering a hazardous material in a container for transportation must determine that the container used is authorized for the commodity. Specifications for cargo tanks, portable tanks, and all other hazardous materials packaging other than rail tank cars are in 49 CFR, Part 178. Authorized packaging is prescribed in 49 CFR, Part 173, the shipper regulations for the particular material, as listed in 49 CFR 172.101. If a carrier supplies a container, such as a cargo tank, the shipper still must determine that the tank supplied is a proper container for the material being offered. The shipper must either examine the manufacturer's specification marking on the tank or obtain papers from the carrier certifying that the tank is proper for the material, per 49 CFR, Part 173.22.

Cargo tanks are the most common transport vehicles used to move combustible, flammable, and corrosive liquids, as well as compressed gases, both flammable and nonflammable. Hazardous materials in powder or granular form are transported in hopper-type, dump-bodied vehicles. When these hazardous materials are transported in bulk containers, such as cargo tanks, and an accident occurs, the disaster potential is substantial.

To minimize risks involved in transporting hazardous materials and to reduce hazards should an accident occur, the federal government specifies requirements for the manufacture, operation, maintenance, inspection, testing, and repair of cargo tanks.

DOT's hazardous materials regulations apply to interstate and intrastate commerce and are enforced by both federal and state authorities. DOT phased in new cargo tank regulations designed to reduce spillage and to ensure that tanks are properly constructed, maintained in safe condition, and properly repaired. The new cargo tank regulations are designated in 49 CFR, Part 180.

Leakage is likely to occur in both contact and noncontact accidents, leading to high cost in terms of personal injury and

property damage. The major causes of unintentional release of hazardous materials are poor maintenance and deviation from tank specifications.

Potential hazards to fire fighters dealing with cargo tanks transporting hazardous materials are as follows:

1. Multipurpose tanks holding improper commodities for the specific container
2. Multicompartment containers hauling materials in more than one hazard class (corrosive/flammable/poison/oxidizer)
3. Defective or missing safety controls
4. Release of large quantities of hazardous materials
5. Increase of potential fires—extra equipment required to fight fires and control spills
6. Potential for a boiling liquid expanding vapor explosion (BLEVE)
7. Incorrect or missing placarding and identification markings on exterior of cargo tank
8. Missing, incomplete, or incorrect shipping papers

Persons receiving a report of an actual or potential highway transportation hazardous materials emergency should obtain as much of the following information as possible:

1. Location of the emergency
2. Type of commercial vehicle(s) involved, such as cargo tank, flatbed, van, and so on
3. Class(es) of hazardous material(s) as indicated by placards, if visible, including the four-digit identification number, if visible
4. Proper shipping name(s), hazardous class(es), and identification number(s) of hazardous materials, if shipping papers are available
5. Nature of the emergency—Is it a fire? Is there leakage? Are persons affected or injured by hazardous materials?
6. Name and address of trucking company
7. Other vehicles and/or property involved
8. Weather conditions and wind direction
9. Type of area

Upon arriving at the scene, emergency responders should take time to assess the situation and make every effort to ascertain what type(s) of hazardous materials and packaging is involved. The scene should be approached from upwind. Responders must avoid contact with spilled or leaking materials that may penetrate protective or other clothing, resulting in death or injury.

Figures 21.2.1 through 21.2.6 display tank construction, denoting areas where leakage is most likely. All these diagrams

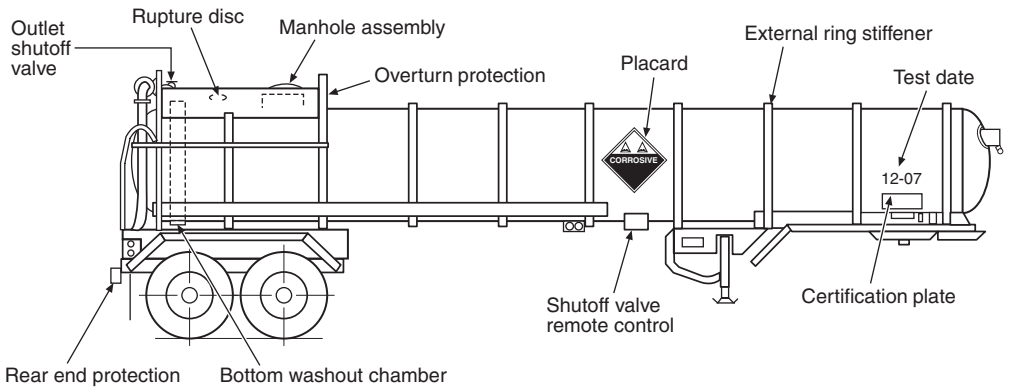

FIGURE 21.2.1 Corrosive Materials Cargo Tanks Equipped with an Internal Shutoff Valve for Unloading from the Bottom

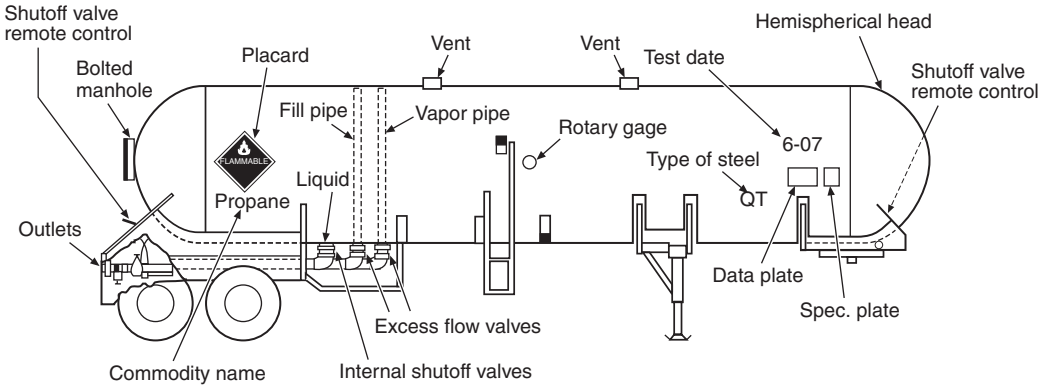

FIGURE 21.2.2 Compressed Gas Cargo Tanks Equipped with Internal Shutoff Valves at Liquid and Vapor Discharge Openings

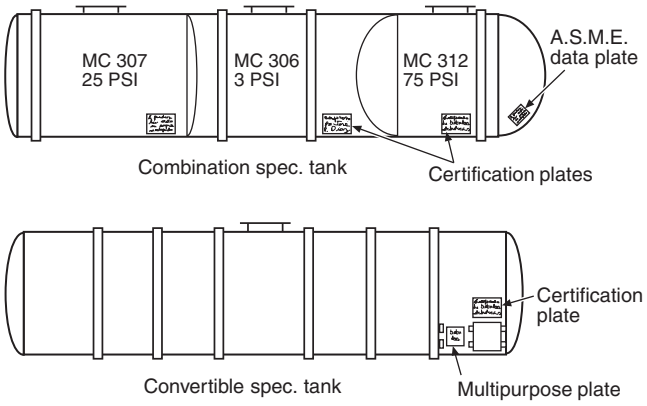

FIGURE 21.2.3 Profiles of Combination (Multiple-Compartment) and Convertible (Single-Compartment) Cargo Tanks

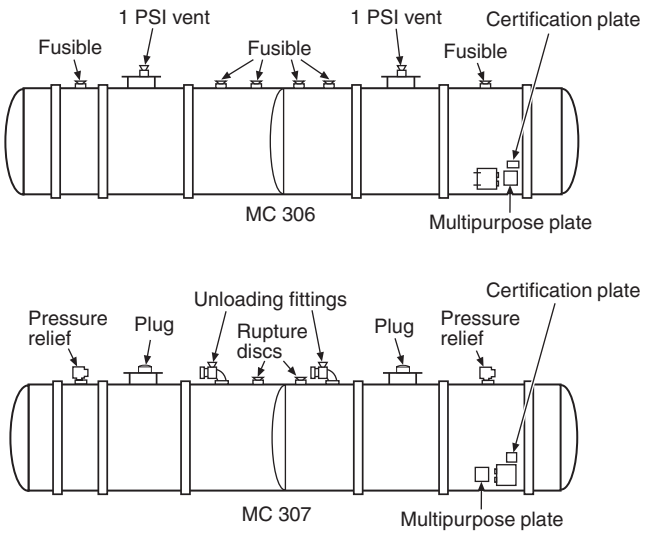

FIGURE 21.2.4 Profiles of Two-Compartment Convertible Cargo Tanks

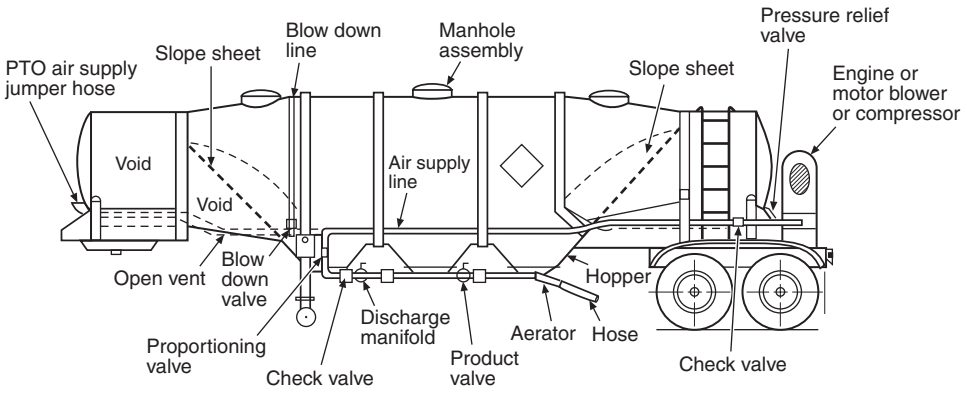

FIGURE 21.2.5 Profile of a Dry Bulk Cargo Tank Used to Transport Cargo Such as Ammonium Nitrate, an Oxidizer, or Corrosive Solids

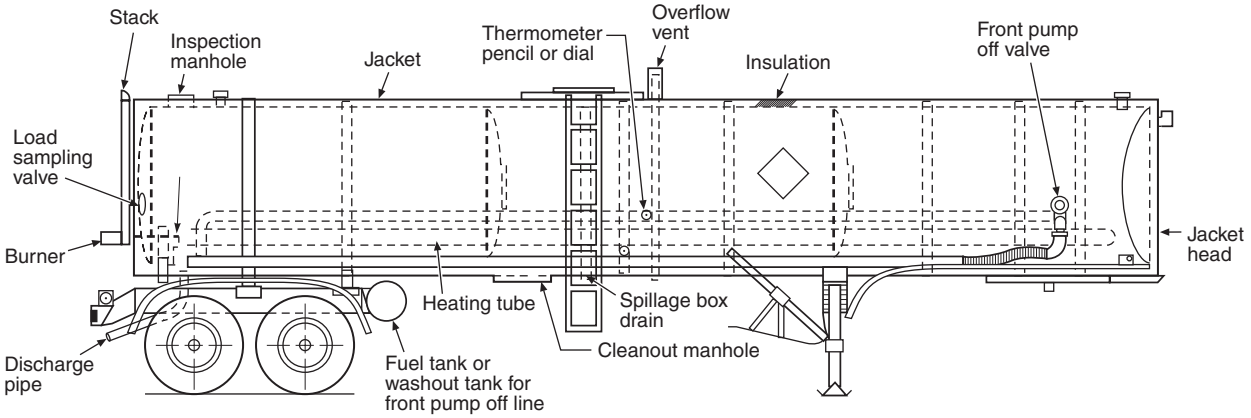

FIGURE 21.2.6 A Nonspecification Asphalt Cargo Tank

should be considered as guidelines rather than constants. Figures 21.2.7 and 21.2.8 show common tank shapes and internal/external inspection items. Emergency response personnel must be aware that many variations of road trailers, not illustrated here, are used for shipping chemical products. Suggested guides are for the most hazardous products that these trailer types may transport. Recommended guides should be considered as a last resort if the product cannot be identified by any other means.

Many tank vehicles contain hazardous materials of one or more types. These units, which include farm "nurse" tanks, tank trucks, tank trailers, and railroad tank cars, must be treated with equal respect. Each emergency must be sized up quickly and individually, taking into consideration the safety of every person at the scene.

SUMMARY

This chapter has described the magnitude of the problem of commercial motor vehicle fires in the United States and has outlined the several types of regulations and standards directed

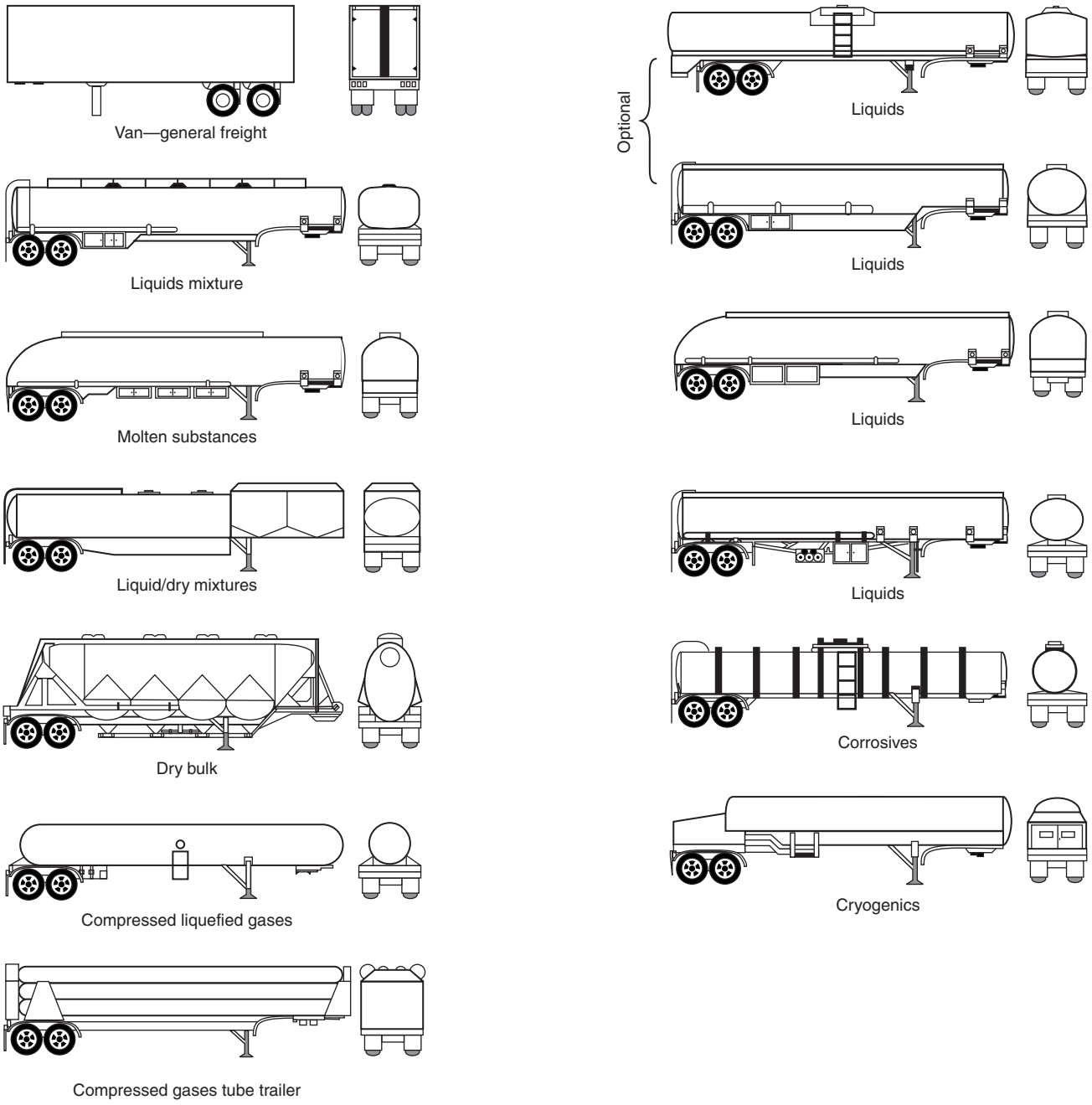

FIGURE 21.2.7 General Shapes of Road Trailers

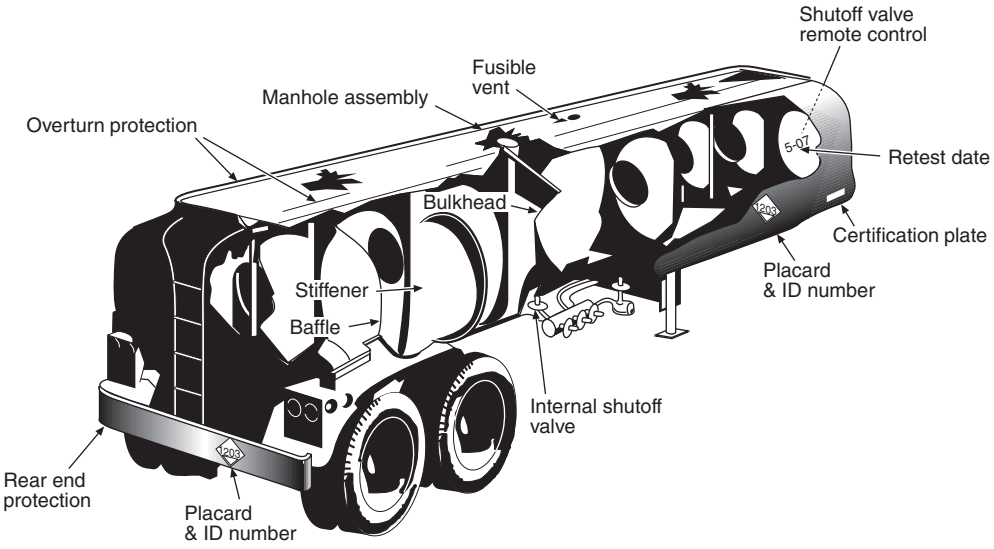

FIGURE 21.2.8 Cargo Tank Inspection Guide (MC 306)

at commercial motor vehicle fire safety. Organizations with an interest in highway safety have been identified. Hazards and safeguards have been outlined.

BIBLIOGRAPHY

References Cited

1. Ahrens, M., "U.S. Vehicle Fire Trends and Patterns," Fire Analysis and Research Division, National Fire Protection Association, Quincy, MA, Aug. 2001.
2. *Statistical Abstract of the United States 2000,* U.S. Census Bureau, Washington, DC, Dec. 2000.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fire safety in commercial vehicles discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 52, *Vehicular Fuel Systems Code*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 385, *Standard for Tank Vehicles for Flammable and Combustible Liquids*
NFPA 407, *Standard for Aircraft Fuel Servicing*
NFPA 414, *Standard for Aircraft Rescue and Fire-Fighting Vehicles*
NFPA 495, *Explosive Materials Code*
NFPA 498, *Standard for Safe Havens and Interchange Lots for Vehicles Transporting Explosives*
NFPA 1192, *Standard on Recreational Vehicles*
NFPA 1901, *Standard for Automotive Fire Apparatus*

Chapter 3

Automotive and Marine Service Station Operations

Carl H. Rivkin

Chapter Contents

Basics
Design and Construction
Operations Safety Requirements
Fire Suppression
Special Requirements for Marine Refueling Facilities
Service Station Maintenance and Inspection

Key Terms

automotive service station, flammable liquid, fuel dispensing system, fuel tank, hazardous material, marine service station, refueling, repair garage, service station

Automotive and marine service stations, whose operations include both refueling and repairs, present a fire risk because of the storage of flammable and combustible liquids and the transfer and use of these liquids. Many of these transfer operations involve the general public, which increases the risk associated with transfer. Unlike an industrial facility, in which personnel involved in flammable liquid* transfer operations can be restricted to those trained in the hazards of the materials and the operations, anyone can use the services of a public automotive or marine service station.

Also, the transfer operations at a service station occur more frequently than at an industrial facility. Service stations that include repair facilities also use flammable liquids in the repair and servicing of vehicles and these operations present additional risks. This chapter covers the hazards associated with flammable liquids at automotive and marine service stations.

For related topics, see Section 6, Chapter 12, "Flammable and Combustible Liquids"; Section 7, Chapter 2, "Storage of Flammable and Combustible Liquids"; Section 21, Chapter 4, "Vehicle Fueling Using Gaseous Fuels"; and Section 21, Chapter 5, "Fuel Cell Vehicles."

BASICS

Public Service Station Fire Data

NFPA analyzes fire data and prepares reports on topics of interest, including fires at public service stations.[1] Fire data from private service stations are not readily available. Data from public service stations indicate where the greatest fire risk at a service station lies. Over the period 1994 to 1998, 62 percent of fires at public service stations were categorized as vehicle fires. This does not mean that the fire involved the vehicle only. Several of these fires spread beyond the area where the vehicle was located to parts of the facility. Code requirements address vehicle activity in several areas and because vehicle fires account for such a large percentage of the fires documented, these requirements need to be examined.

Another factor potentially influencing the increased percentage of fires at service stations involving vehicles over the 1994 to 1998 time period is the change in the types of products sold at service stations. As of the year 2000, there were approximately 210,000 retail outlets selling motor fuel. Many of these motor fuel retail outlets also have repair facilities, but the trend in motor fuel retail facilities has been toward the sale of other merchandise as well as fuel and repairs. Many service stations are paired with convenience stores or food retail businesses. These new arrangements are bringing increased vehicle traffic through the service station area. Also, vehicles might

*Although "flammable liquids" is referred to throughout this chapter, the term is meant to encompass both flammable and combustible liquids.

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be parked at the service station. These changes could be causing an increased number of vehicle fires at service stations.

Basic Service Station Refueling Components

Figures 21.3.1, 21.3.2, and 21.3.3 provide an overview of the basic refueling components at a service station. Figure 21.3.1 shows double-walled tanks and the associated safety and filling appurtenances for these tanks. The use of the safety devices illustrated in this figure is a code requirement, including pressure relief devices, cathodic protection, and the concrete foundation. The concrete foundation prevents damage to the tank from the supports settling or other movement of the supporting soil. The cathodic protection prevents the tank metal from corroding.

Figure 21.3.2 shows (a) standard installation of aboveground horizontal tank and (b) the basic components of a standard fuel dispenser. Figure 21.3.3 is an illustration of (a) a dispenser with (b) a below-grade cutaway showing the lines that feed the dispenser. Also shown are the breakaway valve at the dispensing nozzle and the shear valve on the fuel-feed line. Both of these valves limit the release of fuel in the event of a break in the fuel piping or hoses.

Properties of Hazardous Materials at Service Stations

Because flammable liquids have varying volatility, they will both vaporize at different rates and migrate at different rates to potential ignition sources. Table 21.3.1 lists flammable liquids commonly found at service stations and repair garages. The data provide indicators about how the material behaves when it is accidentally released and exposed to ignition sources. The information on each material includes the flashpoint, the class under NFPA 30, *Flammable and Combustible Liquids Code* (which is based on the flashpoint), the boiling point, and the minimum ignition temperature in air.

The *flashpoint* is the minimum temperature of a liquid at which sufficient vapor is given off to form an ignitable mixture with the air, near the surface of the liquid or within the vessel used, as determined by the appropriate test procedure and apparatus. NFPA 30 gives additional information about appropriate procedures for determining the flashpoint of a material.

The table data indicate why gasoline is more hazardous than other materials commonly used at service stations and repair garages. It has a flashpoint of –50°F (–40°C), which is 150°F (83°C) lower than that of diesel fuel #1. The flashpoint for gasoline is so low that only under severely cold conditions would it not have the potential to form an ignitable mixture.

DESIGN AND CONSTRUCTION

Design and construction safety requirements for the different refueling and repair components found at service stations are based on NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages.*

General Building Requirements

Code Requirements. Building construction requirements apply to general categories of structures in which flammable

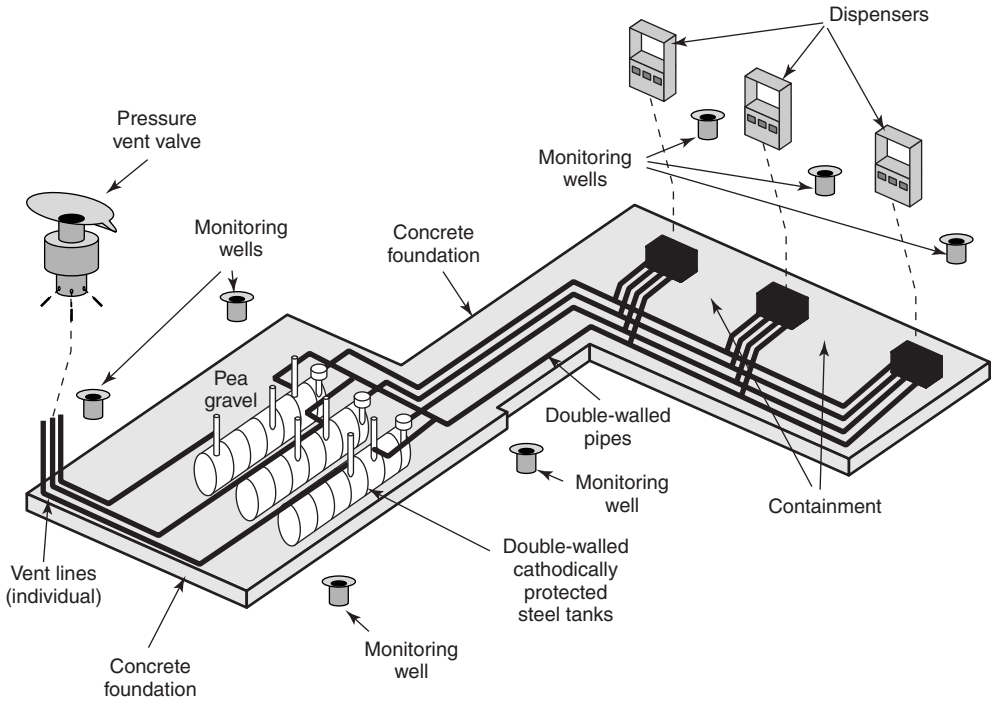


FIGURE 21.3.1 Fuel Dispensing System Assembly (Source: Based on information from Florida Department of Environmental Protection)

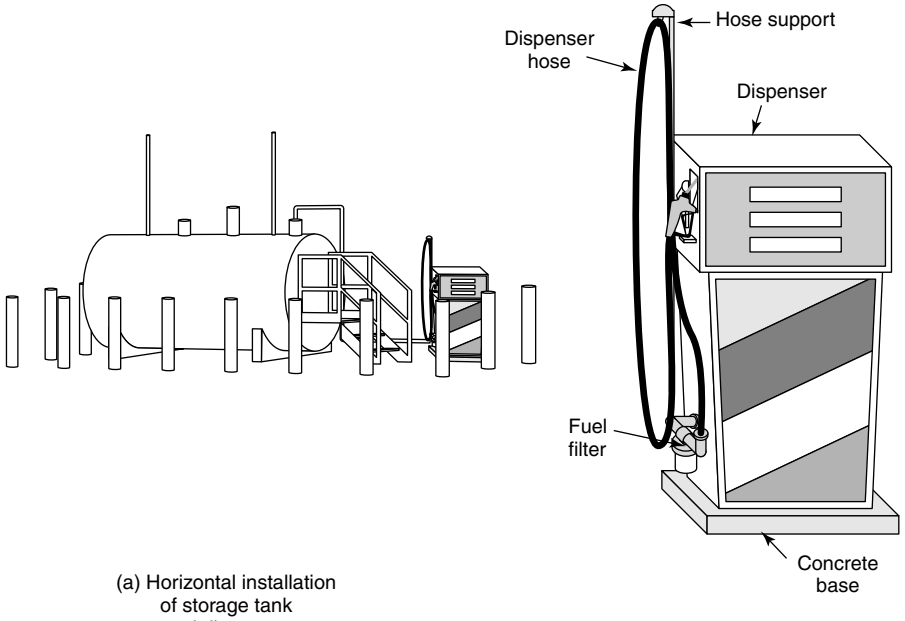


FIGURE 21.3.2 (a) Aboveground Fuel Dispensing System with Dispenser and (b) Standard Fuel Dispenser (Source: Based on information from Florida Department of Environmental Protection)

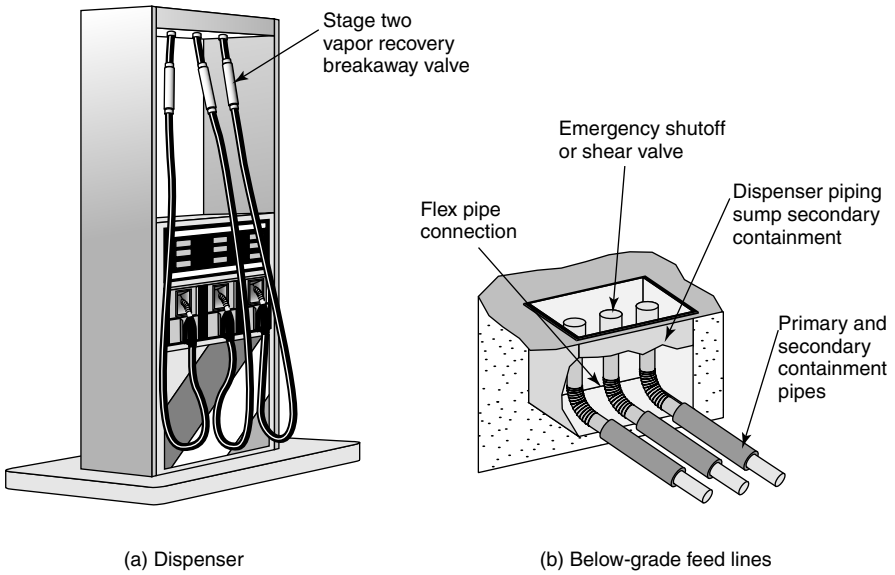


FIGURE 21.3.3 Dispenser Assembly with (a) Dispenser and (b) Below-Grade Feed Lines (Source: Based on information from Florida Department of Environmental Protection)

liquids present a hazard. The two types of structures of concern are buildings housing fuel dispensing operations and repair garages.

Structures that house refueling or repair operations must not have obstructions in egresses that restrict building evacuation. Specific requirements for egress can be found in NFPA *101*®, *Life Safety Code*®, in the chapter on industrial occupancies. Refueling facilities and repair garages are classified as special-purpose industrial occupancies. Such special-purpose industrial occupancies conduct ordinary and low-hazard industrial

TABLE 21.3.1 Properties of Flammable and Combustible Liquids Commonly Found in Service Stations

Liquid	*Flashpoint*	*NFPA 30 Class*	*Boiling Point*	*Minimum Ignition Temperature in Air*
Antifreeze	230°F (110°C)	IIIB	300°F (149°C)	—
Brake fluid	300°F (149°C)	IIIB	540°F (282°C)	—
Chassis grease	400°F (204°C)	IIIB	>800°F (>427°C)	>800°F (>427°C)
Crankcase drainings	—	IIIB	—	—
Diesel fuel no. 1	100°F (38°C)	II	—	—
Diesel fuel no. 2	125°F (52°C)	II	—	—
Diesel fuel no. 4	130°F (54°C)	II	—	—
Gasoline	–40 to –50°F (–40 to –46°C)	IB	100 to 400°F (38 to 204°C)	~825°F (~441°C)
Gear lubricant	395°F (202°C)	IIIB	>800°F (>427°C)	>800°F (>427°C)
Kerosene (fuel oil no. 1)	100°F (38°C)	II	303 to 574°F (151 to 301°C)	440°F (227°C)
Lithium-moly grease	380°F (193°C)	IIIB	>800°F (>427°C)	>900°F (>482°C)
Lubricating oils	300 to 450°F (149 to 232°C)	IIIB	—	—
Power steering fluid	350°F (177°C)	IIIB	>550°F (>288°C)	—
Dexron II transmission fluid	395°F (202°C)	IIIB	>800°F (>427°C)	>800°F (>427°C)
Type F transmission fluid	380°F (193°C)	IIIB	>800°F (>427°C)	>800°F (>427°C)
White grease	465°F (241°C)	IIIB	>800°F (>427°C)	>800°F (>427°C)
Windshield washer fluid (methanol/water mixtures)				
100% methanol	54°F (12°C)	IB	148°F (64°C)	725°F (385°C)
50% methanol	80°F (27°C)	IB	—	—
20% methanol	118°F (48°C)	II	—	—
5% methanol	206°F (97°C)	IIIB	—	—

operations in buildings designed for, and suitable only for, particular types of operations. Such occupancies are characterized by a relatively low density of employee population, with much of the area occupied by machinery or equipment.

Spill Control. Spill control must be provided to prevent fuels from flowing either through the floor or into other parts of the building. The drainage system must have an oil trap or separator if it connects to public sewers or waterways.

Fuel Dispensing Buildings

Hazards. Most public service stations do not have indoor fuel dispensing and, therefore, do not have fuel dispensing buildings. Occasionally parking garages include fuel dispensing. Buildings housing fuel dispensing areas present special hazards, and requirements have been developed to address these hazards. Fuel dispensing is more likely to produce a material release than are other components of the refueling system.

Construction, Design, and Location. Dispensing areas within the building must be separated from other portions of the building by 2-hour fire-resistant structures. Openings into the dispensing space must be designed to prevent a fire from moving to other parts of the building. This containment is accomplished by using fire doors and fire dampers.

Fuel dispensing areas must be located at street level, not more than 50 ft (15.2 m) from the building entrance or exit. This requirement prevents the release of material at a location that would be difficult for emergency responders to access. The dispensing areas are also limited to the size required to service four vehicles or fewer.

Safeguards and Controls. The dispensing area must have a dedicated mechanical exhaust system that is interlocked with the dispensing system. If the system were not dedicated, there would be the potential to transfer fuel vapors and vehicle exhaust to other parts of the facility. The system has to provide airflow across all portions of the floor of the fuel dispensing area to prevent the potential buildup of ignitable vapors. Serious accidents have occurred in which vapors released in a part of a facility free of ignition sources migrated into locations where ignition sources were present through pathways that had not been considered before the accident. For specific information on designing ventilation systems see NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids,* and the American Conference of Industrial Hygienists, *Industrial Ventilation: A Manual of Recommended Practice.*[2]

Repair Garages

Hazards. Repair garages present different hazards from those found in refueling operations because of the use of pits or below-grade areas required to work on vehicles. These areas normally have special ventilation requirements and fixed fire protection to allow personnel to function in the workspace.

Construction, Design, and Location. Pits and below-grade work areas must be constructed of noncombustible materials and be provided with ventilation and means of egress previously described. These areas, although not viewed as confined spaces, can present oxygen-deficient atmosphere risks under certain conditions such as restricted airflow or displacement of air. This is another reason why egress and ventilation are important.

Safeguards and Controls. Fixed fire protection is required for larger repair garages if any of the following situations exist:

- The garage is two or more stories in height, including basements, and any one floor exceeds 10,000 ft^2 (930 m^2).
- The garage is one story and exceeds 15,000 ft^2 (1400 m^2) in floor area.
- The garage is in the basement of a building.

The larger repair garages will likely handle more material, conduct more operations, and therefore present a greater fire risk.

Heating, ventilating, and air-conditioning (HVAC) for repair garages must be independent and designed to provide good airflow and mixing in the ventilated space. Air from below-grade areas should not be recirculated into the building HVAC system.

Heat-producing appliances present an ignition source hazard and must be carefully controlled in repair garages. In several incidents, heat-producing appliances were the ignition source the ignitable vapor eventually located. Cleaning floors with gasoline is a common unsafe practice that can lead to fires and explosions. Heat-producing appliances have to be of types approved for use in a repair garage. Solid fuel burning devices and space heaters are typically not considered an approved type of appliance. Heat-producing appliances must be separate from areas dispensing or transferring Class I liquids, such as gasoline. This separation can be accomplished by placing the device in another room or at least 8 ft (2.4 m) above the floor. At this height, the device should be above any flammable vapors.

Storage

General. All flammable liquids must be stored in either an approved closed container or a tank. In service stations, containers cannot exceed 60 gal (227 L) in volume. Tanks can be located underground, aboveground, or in vaults. A vault is a protective enclosure that does not allow the tanks to contact the ground even if installed below grade. Underground tanks present less fire hazard but they have a greater potential to impact the environment. Environmental regulations place more stringent requirements on underground tanks than aboveground tanks. Vaulted tanks present a potential solution to these conflicting concerns of fire safety and environmental impacts by allowing an above-grade installation with additional fire protection.

All tanks must be constructed to consensus-based construction standards. Underwriters Laboratories is an example of an organization that promulgates these types of tank construction standards.

Underground Tanks. Underground tanks require vent pipes of sufficient diameter to prevent blowback of vapor or liquid at the fill opening while the tanks are being filled. The vent pipes also should not be obstructed, which would effectively reduce their diameter. Undersized vent piping will impede the refilling process because it is more difficult to displace the air in the tank. The discharge point for vent pipes should be at least 12 ft (3.7 m) above ground level for tanks storing Class I liquids (gasoline) and higher than expected snow level for tanks storing Class II liquids (diesel fuel). The discharge point must also be located away from building openings and power ventilation air intakes. Allowing flammable materials to infiltrate a structure could possibly result in material in the flammable range being exposed to

a source of ignition. The vent pipe must also be higher than the fill pipe to prevent spills during tank fill operations.

Underground tanks must be provided with external corrosion protection, either in the form of a cathodic protection system or corrosion-resistant materials. The type of protection employed must be determined on a location-by-location basis.

Underground tanks must be installed so that they are no less than 1 ft (0.3 m) from any wall of a basement or pit and 3 ft (0.91 m) from any property line that can be built on. The tanks must be set on a firm foundation and surrounded by noncorrosive material such as sand or gravel. They also must be buried sufficiently deep or be protected on the surface so that they are not subject to vehicle damage.

Aboveground Tanks. Aboveground tanks must be separated from the property line, important buildings, other fuel dispensing devices, public ways, and other tanks. These distances vary based on the size of the tank and the level of fire protection the tanks are constructed to meet. Aboveground tanks must be provided with spill protection. NFPA 30 provides options for spill control.

All aboveground tanks must be provided with an alarm that sounds when the level inside reaches 90 percent of tank capacity. All tanks must be provided with physical protection to prevent unauthorized access and to protect from vehicle impact. However, it is difficult to prevent all vehicle impact accidents because of the unpredictability of driving behavior and the tremendous force involved in high-speed impact. As an example of this problem, see the following case.

CASE STUDY: South Carolina. In South Carolina in 1991, a driver was killed when his pickup truck careened off the road, striking the piping for two 4000 gal (15,142 L) aboveground fuel tanks located at a convenience store. The collision broke the piping and resulted in the release of gasoline that quickly found an ignition source.

Vaulted Tanks. Gasoline tanks installed in vaults must have ventilation systems and vapor and liquid detection systems. The vapor detection system should sound an alarm when the concentration of vapor in the vault equals or exceeds 25 percent of the lower flammable limit (LFL) for the material.

Piping

Piping is one of the most vulnerable components in a fuel system because vehicle impacts can easily rupture pipes, corrosion can cause leaking, and stresses can cause cracking. Piping must be protected from mechanical damage. Piping that runs through buildings must be enclosed in fire-resistant material. All piping must be identified by color code or some other readily identifiable system to indicate the material contained in the pipe. There are significant differences in the physical characteristics of gasoline and diesel fuel, and confusing the two could result in damage to vehicles.

Fuel Dispensing Systems

The requirements for fuel dispensing systems cover the following seven areas:

1. Dispensing devices
2. Remote or submersible pumps (i.e., pumps not located at the device)
3. Hoses
4. Nozzles
5. Emergency electrical disconnects
6. Vapor recovery systems
7. Hazardous location electrical equipment

The requirements are structured to prevent the accidental release of material either from liquid or vapor leaks in the dispensing system or from overfilling of the container into which the system is feeding liquid.

General Requirements. Two general requirements apply to all fuel dispensing systems. The first is that all portions of the vehicle being refueled must be on the dispensing facility property. The reason for this is straightforward. The vehicle should not be in a position in which it could be struck by other vehicles while refueling. The second general requirement is that fuel not be dispensed by applying pressure to the container in which the fuel is stored but instead by means of pumps. The reason for this requirement is that containers are not constructed to allow external pressure to be used as a means for moving fuel out of the container.

Dispensing Devices. The requirements for dispensing devices address several points in the dispensing process which have the potential for the release of fuel. The first requirement is that the dispensing device not operate when the dispenser nozzle is in the holding bracket or routine rest position. This requirement prevents the release of material when no person is present to stop it.

The dispensing devices must be protected from physical damage that could cause the release of material. This protection should take the form of bolting the dispensing devices to a concrete island situated to keep vehicles not being refueled from passing through the refueling area. Because there are vehicles moving through a refueling area in close proximity to pedestrians (people refueling their vehicles), a major safety concern is vehicles striking pedestrians.

The dispensing devices must incorporate an emergency shutoff in the line that supplies fuel to the dispensing device. This emergency shutoff must be designed to be activated by severe impact or fire exposure. The purpose of the shutoff is to prevent fuel from flowing to the dispensing device in the event of an accident. When installed, the emergency shutoff device must be tested at least annually after the initial test.

CASE STUDY: Saint John, New Brunswick. In January 1974, a fire killed five people at a service station in Saint John, New Brunswick, Canada. A large amount of fuel was released because the emergency shutoff valve failed to operate when the

dispenser was knocked over by a vehicle. The service station was located on the roof of a tire warehouse (the structure was located on a slope so that one side of the service station was on ground level) and the fuel released migrated into the warehouse where it was ignited and exploded. Because the explosion took place in the enclosed warehouse space, there was tremendous damage in addition to the loss of life.

Remote or Submersible Pumps. If fuel is transferred to the dispenser by a pump located outside of the dispenser, such as a submersible turbine pump located in the fuel storage tank, then the pump is subject to additional requirements. The pump must have a device that would detect whether there is a leak in the portion of the dispensing system upstream from the pump discharge. Pumps also must be located at least 5 ft (1.5 m) from building entrances and 10 ft (3 m) from property lines. These separation distances would reduce the risk of fuel being released into the building.

Hoses. Hoses must be listed by an independent testing organization for their intended use. The hose length should be no more than 18 ft (5.5 m). Although this is based on "weights and measures" laws, it also serves to reduce the chance of the hose being damaged or rupturing. If the hose is carrying gasoline, it should be constructed with a breakaway device that will retain the gasoline in the hose. This feature would prevent someone from releasing gasoline by accidentally driving away from a refueling area while the hose is still inserted in the vehicle fill pipe.

Nozzles. Hose nozzles for dispensing gasoline must have an automatic-closing valve to prevent the flow of gasoline when the valve-opening device is not depressed. This device combined with the hose breakaway device should prevent the release of anything but small amounts of gasoline if the person operating the dispenser either drives away from a refueling area with the hose nozzle still inserted in the vehicle fill pipe or neglects to shut off the flow valve for other reasons. Figure 21.3.4 illustrates a standard nozzle, pressure vent valves, and vent pipes.

Emergency Electrical Disconnects. Remotely located emergency electrical disconnects are a critical component in the fuel safety system for two reasons: (1) they will remove an ignition source from areas where there is the potential of an ignitable vapor mixture, and (2) they can stop the flow of liquid if other safety devices do not function, thereby preventing the release of large amounts of liquid.

The emergency disconnect must be located between 20 and 100 ft (6.1 and 30.5 m) from the fuel dispensing device. This range would create sufficient separation distance from the fuel dispensing device for the disconnect to be safely activated without being so far away that it could not be readily activated in an emergency situation. The emergency disconnect device must be interconnected so that if there are multiple emergency disconnects, the activation of any one disconnect device will

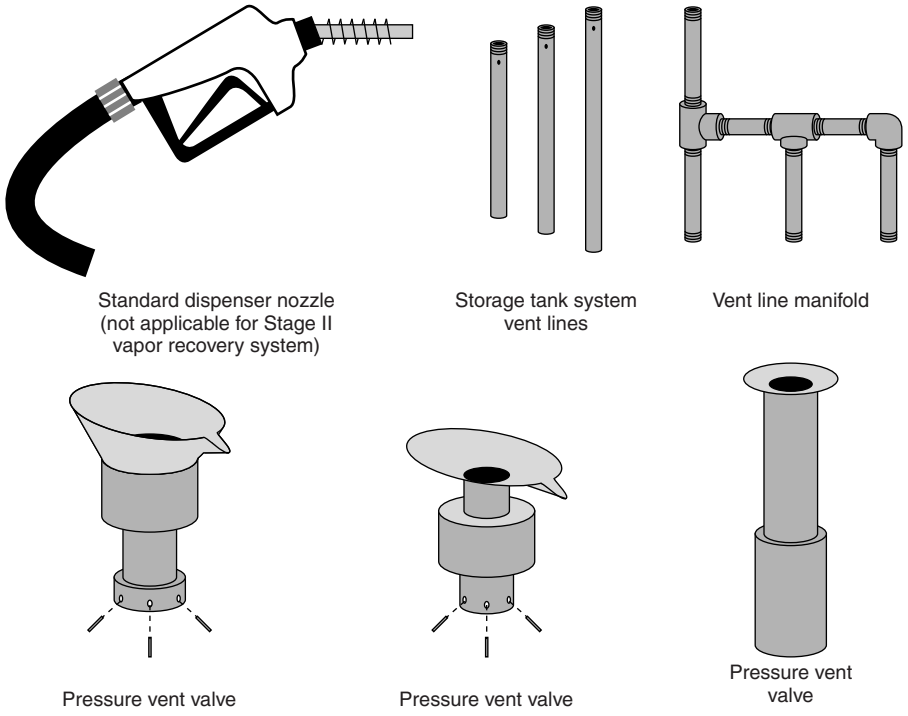


FIGURE 21.3.4 Dispenser Hose Nozzle, Pressure Vent Valves, and Vent Pipes (Source: Based on information from Florida Department of Environmental Protection)

cut off all power in hazardous locations surrounding the fuel dispensing devices.

Vapor Recovery Systems. Environmental regulations require vapor recovery systems in many locations. These devices must be listed for application as vapor recovery devices and must be designed to prevent the release of vapor when they are attached to the dispenser and not being used.

Hazardous Location Electrical Equipment. For a height 18 in. (0.5 m) above grade in a 20 ft (6.1 m) radius from refueling areas, special electrical equipment is required. The following case is an example of how electrical equipment not classified for use in a potentially dangerous area can be an ignition source.

CASE STUDY: Gadsden, Alabama. An explosion occurred at a gasoline station outside of Gadsden, Alabama, in August 1976. In this incident, a tank truck was filling aboveground storage tanks at the station using an electric pump that was missing a cover on the junction box. The lack of a cover allowed the pump to become an ignition source for fugitive vapor emissions lost during the transfer operation. These vapors were ignited, the fire spread to the truck, which exploded, and three responding fire fighters were killed in the explosion.

OPERATIONS SAFETY REQUIREMENTS

Many accidents are the result of improper use of properly designed equipment; therefore, it is important to understand how a construction safety feature is utilized through operational requirements. For example, the requirement that delivery vehicles must be separated from aboveground tanks is an operational requirement that directly connects to construction requirements. If the separation distance from property line and other exposures is met, the separation distance for the refueling vehicle should be less difficult to comply with.

Operations requirements can be divided into those requirements that apply to fueling operations and those that apply to repair operations. Fueling operations include both the filling of tanks at refilling facilities and the refueling of vehicles at these facilities. Because the refueling of vehicles is done so much more frequently than the refilling of storage tanks, these transfers account for a large percentage of the incidents at service stations. However, NFPA incident data have several accounts of serious accidents taking place during tank filling and servicing operations. The following case is an example of this type of incident.

CASE STUDY: Portland, Maine. A gas tank explosion occurred at an abandoned service station in Portland, Maine, in May 1986. This incident resulted from the ignition of vapors that were being removed with a vacuum pump from abandoned tanks at the service station. The vapors were being discharged at street level without any ventilation on a day when there was insufficient natural ventilation to dissipate the gasoline vapor withdrawn from the underground tanks. A vehicle that was allowed in the area where there was the potential for ignitable vapors provided the ignition source. The result was one fatality and three other people injured.

Filling and Fueling Operations

Mass Balance. Inventory records, which must be kept on a daily basis, indicate whether material is being lost from the system. The relatively simple process of performing a mass balance can reveal a small leak before it becomes a large leak and prevent the loss of significant amounts of material and subsequent safety and environmental problems. A mass balance is a comparison between the material going into a system and the material discharged from the system. The difference between these two numbers is the amount lost (leaked) from the system.

Tank Filling. For tank filling operations, 25 ft (7.6 m) must separate the delivery vehicle from any aboveground tank. All parts of the delivery vehicle must be on the premises when the delivery is made. This requirement prevents refilling from taking place at locations where the tank truck could block traffic in the public access road to the facility. Fill covers must identify the tanks that they service (Figure 21.3.5).

Portable Container Dispensing. Dispensing into portable containers is allowed, provided that the containers are approved and labeled and the dispensing is done manually. The container must be on the ground when being filled—not in or on the vehicle. If the container is not secured in the vehicle, a spill could result that would be very difficult to clean.

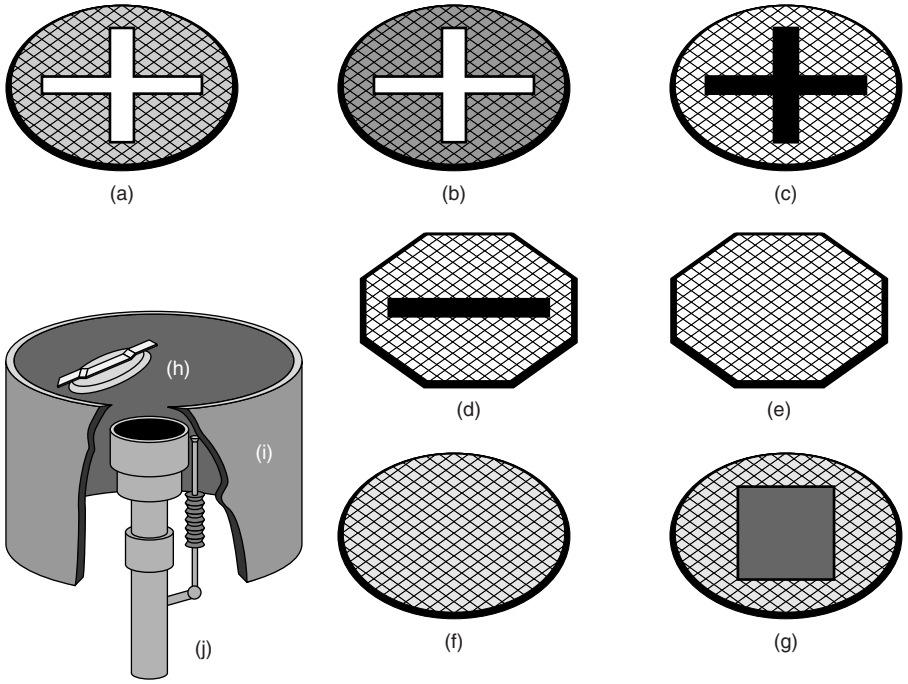
Motor Fuel Dispensing. Motor fuel–dispensing facilities can be divided into attended and unattended operations and many facilities offer both. Attended fueling operations theoretically have an increased level of safety because a human observer can detect problems that would not be observed at an unattended facility. Because of this difference, unattended facilities must have automatic-closing hose nozzles and a telephone or other device to notify the fire department.

Another potential problem in unattended facilities is that persons performing the refueling might reenter their vehicle during refueling and then remove the nozzle from the vehicle after they have built up a static charge from moving across the seat of the vehicle. Persons refueling at an unattended facility are required to stay outside of their vehicle throughout the duration of the refueling operation to prevent this static buildup, which could potentially ignite residual vapors released after the nozzle is removed from the vehicle fill pipe.

Repair Areas

Requirements for repair areas or facilities fall into the following four general categories:

1. Hot work
2. Spray painting and undercoating



(a) Hi-grade fill cover *(red with a white cross)*
(b) Mid-grade fill cover *(blue with white cross)*
(c) Low-grade fill cover *(white with black cross)*
(d) Hi-sulfur fill cover *(yellow with blue dash)*
(e) Low-sulfur diesel fill cover *(yellow)*
(f) Stage I dry break cover *(orange)*
(g) Used oil cover *(a purple square)*
(h) Fill pipe with cap
(i) Fill containment *(spill protection)*
(j) Release valve

FIGURE 21.3.5 Fill Area Assembly with Color-Coded Covers (Source: Based on information from Florida Department of Environmental Protection)

3. Parts cleaning
4. Housekeeping

Hot Work. Hot work is defined in NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work,* as "any work involving burning, welding, or similar operations that is capable of igniting fires or explosions." Hot work operations must be performed in specially designed areas, because they present excellent sources of ignition. Performing these operations in a defined, controlled area is the best way to reduce the risk that these operations will become an ignition source for a flammable vapor release.

Spray Painting and Undercoating. Spray painting operations are restricted to work on only small parts of a vehicle and these operations must be located at least 20 ft (6.1 m) from any potential ignition source.

Parts Cleaning. Parts cleaning operations can present a significant risk because they may involve relatively large amounts of heated solvent. To reduce this risk, nonflammable cleaning solvents should be used whenever possible. If flammable solvents must be used, they should be used only under conditions in which the opportunities for creating a flammable atmosphere are also controlled or eliminated. This means that ignition sources should be kept away from the areas where flammable atmospheres could be created. If the solvent is heated, it should have a shutoff device that prevents the solution from getting close to the temperature at which a flammable atmosphere would be created.

Housekeeping. Housekeeping requirements are extremely important for fire prevention. Mixing incompatible materials, such as oxidizing substances and flammable liquids, is one undesired outcome of poor housekeeping. There are some general organizational and cleaning procedures that should be followed to achieve good housekeeping.

The work area should be kept clean and free from obstructions. Materials should be stored in assigned areas and not allowed to be left in work areas as part of ongoing work projects. Combustible rubbish should be placed in covered metal receptacles until removed for disposal. These materials should not be allowed to accumulate. Personnel should know if combustible rubbish is in a waste receptacle to prevent adding an incompatible material to the receptacle.

Most important, a daily inspection should be conducted of the work area to identify and eliminate hazards. This daily

inspection should give facility managers timely information about the storage of materials and the condition of equipment so that they can respond to a hazard before it causes a fire.

FIRE SUPPRESSION

Fixed Fire Protection

Fixed fire protection is often recommended for refueling areas at service stations. It is required at larger repair garages (as defined earlier) because these are facilities where people work and in which operations involving the transfer of flammable liquids occur routinely. These transfer operations are often not as well controlled as in vehicle refueling areas but instead can vary depending on the type of repair and specific vehicle being worked on.

Fire Extinguishers

Each motor fuel–dispensing facility should have one or more listed fire extinguishers that have a minimum capability of 40-B:C. A B:C fire extinguisher is one suitable for use on fires involving flammable liquids, combustible liquids, petroleum greases, tars, oils, oil-based paints, solvents, lacquers, and alcohols (Class B fires) or fires involving energized electrical equipment in which the electrical nonconductivity of the extinguishing media is of importance (Class C fires). The 40 number indicates the relative strength of the extinguisher—the greater the number, the greater the extinguishing power. The extinguishers should be located within 100 ft (30 m) of each pump, storage tank fill-pipe opening, and lubrication or service room.

Materials that obstruct access to fire-fighting equipment or important piping system control valves must not be placed on a pier. Where the pier is accessible to vehicular traffic, there should be an unobstructed roadway to the shore end of the wharf. This roadway is required for access by fire-fighting apparatus.

SPECIAL REQUIREMENTS FOR MARINE REFUELING FACILITIES

Many of the requirements for automotive refueling also apply to marine refueling, but because marine refueling is done on piers, special requirements apply. At marine refueling facilities, a fuel line is often run from a storage tank located on land to a dispensing device located on the pier, wharf, or floating dock. This run of pipe increases the risk for an accidental release of material. The additional safety requirements for marine refueling facilities focus on preventing a release of material from the fuel supply line that runs between the onshore storage tank and the dispenser.

Storage

Storage tanks for marine refueling have to comply with the same requirements that motor vehicle refueling must meet, with a few differences. Pumps that are not a part of the dispensing device must be placed on shore. The tank must have a device that would prevent the gravity flow of liquid if the supply hose were broken.

Piping Systems

Piping systems must be protected against movement that might occur because the dispenser is located on a structure in or at the water. The piping also must be protected against physical damage that could result from its being exposed. A valve is required in each pipeline at or near the approach to the pier and at the shore end of each marine refueling facility to shut off the liquid supply from shore.

Fuel Dispensing System

Dispensing hose must be listed and hose length should be kept to less than 18 ft (5.5 m), if possible. The dispensing device should be designed so that it does not prevent people from leaving the pier in an emergency situation.

Boats should not be berthed (parked) at a refueling area or attached to boats that are being refueled. Boats have several ignition sources and these must be kept away from the refueling area. Unlike automotive refueling, there should always be an attendant on duty when marine refueling is done because of the less routine nature of marine refueling. Fueling should not be undertaken at night except under well-lighted conditions.

Sources of Ignition

Electrical arcs and open flames are the most likely ignition sources in the marine refueling environment. Each dispensing unit must have a clearly identified electrical disconnect to shut off power to all pumps and motors in the dispensing system. All wiring should be located on the side of the structure opposite the piping to reduce the opportunity for the ignition of fugitive emissions from the piping.

During refueling, the fuel nozzle must be electrically bonded by contact to the vessel fill pipe throughout the refueling operation. This contact should reduce the opportunity for potential difference between the nozzle and another surface that would receive the charge and that could create an electrical arc.

Pipelines on piers must be bonded and grounded. In bonding, the pipeline is connected to an electrically conductive material. In grounding, this material is connected to a ground or a conductor that discharges to ground.

Smoking materials, including matches and lighters, should not be used within 20 ft (6 m) of areas used for fueling. The area should be marked to warn people not to use these materials.

Because people are less likely to shut off the motor of a boat during refueling, it is important that the attendant ensure that all motors are turned off during refueling. Hot engines have the potential to act as ignition sources.

Containers and Movable Tanks

Movable refueling tanks and portable containers present a greater fire risk than fixed installations because of the decreased control associated with mobile equipment. Because of this increased risk, the conditions under which movable tanks can be used are limited.

With the approval of the authority having jurisdiction, movable tanks can be used for dispensing fuel at locations inaccessi-

ble to the public. This additional level of approval should reduce the chance of releasing material during transfer operations.

Gasoline should not be put into a portable container unless the container is approved for the storage of gasoline. Only containers less than 12 gal (45.4 L) should be filled on vessels.

Marine Facilities

Marine motor fuel–dispensing facilities should have one or more listed fire extinguishers having a minimum classification of 40-B:C. An extinguisher should be within 100 ft (30 m) of each pump, each dispensing device, and each pier-mounted liquid storage tank.

Piers that extend more than 500 ft (152 m) in travel distance from shore should have a Class III standpipe. A standpipe system is an arrangement of piping, valves, hose connections, and allied equipment installed in a building or structure, with the hose connections located so that water can be discharged in streams or spray patterns through the attached hose and nozzles. This is accomplished by connections to municipal water supply systems or by pumps, elevated gravity tanks, and other equipment necessary to provide an adequate supply of water to the hose connections. A Class III standpipe system has a minimum flow rate for the hydraulically most remote standpipe of 500 gpm (1893 L/min) and a minimum flow rate for additional standpipes of 250 gpm (946 L/min). The total flow rate should not exceed 1250 gpm (4731 L/min).

SERVICE STATION MAINTENANCE AND INSPECTION

The checklist in Figure 21.3.6, which describes the different components of a service station and the applicable fire safety requirements, is designed to assist in a safety inspection of the facility. This checklist is not comprehensive and is intended only to make people aware of the areas of concern. State and federal regulations and codes and standards contain detailed requirements that address these various areas. The checklist parallels the material discussed in this chapter.

SUMMARY

Because the operations of automotive and marine service stations include both refueling and repair and, therefore, involve the storage, transfer, and use of flammable liquids, they present a distinct fire risk. The risk associated with the transfer of

	Dispensing System	*Tank*	*Repair Work Area*
Are hoses listed for use?			
Are pumps and nozzles listed for use?			
Are emergency shutoff devices installed correctly?			
Are ignition sources controlled?			
Are emergency shutoff switches present and properly located?			
Are required operating procedures and warnings posted?			
Is electrically safe equipment being used in areas classified for type of electrical equipment?			
Is physical protection in place for pumps and piping?			
Do tanks have adequate spill control?			
Are proper separation distances being followed for operations involving ignition sources and Class I liquids?			
Is housekeeping adequate?			
Is cleanup routinely performed after operations?			

(continued)

FIGURE 21.3.6 Service Station Inspection Checklist

	Dispensing System	*Tank*	*Repair Work Area*
Are flammable liquids stored properly?			
Are other hazardous materials stored in proximity to flammable liquids?			
Are required communication devices working properly?			
Is required egress obstructed?			
Are required fire extinguishers present and properly located?			
For larger repair garages, is sprinkler protection installed?			
Is piping properly color coded?			
Are below-grade work areas properly ventilated?			
Are fuel dispensing devices in buildings properly located?			
Is any flammable liquid waste properly stored and labeled?			
Are work areas free of combustible waste material?			
Are containers listed for use and properly labeled?			

FIGURE 21.3.6 Continued

flammable liquids is also increased because this operation involves the general public, who are not trained in the hazards of the materials.

This chapter covered construction, design, and location requirements for dispensing areas and repair facilities, including, for example, oil traps or separators for spill control; dedicated mechanical exhaust systems; container and tank storage requirements; as well as special requirements for piping, dispensing devices, hoses, and other system components. This chapter also covered operations safety requirements that include such items as performing a mass balance to detect leaks; dispensing into approved and labeled containers; and following specific requirements when performing hot work, spray finishing, and parts cleaning.

Fixed fire suppression is recommended for refueling areas at service stations and is required at larger repair garages. Each motor fuel–dispensing facility, including marine facilities, should have listed fire extinguishers on hand. Additional safety requirements for marine refueling facilities focus on preventing a release of material from the fuel supply line, controlling sources of ignition, and limiting conditions under which movable tanks can be used.

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2. *Industrial Ventilation: A Manual of Recommended Practice,* 23rd ed., American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 1998.

NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on liquid fueling and repair operations at automotive and marine service stations discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA *101®*, *Life Safety Code®*

Chapter 4

Vehicle Fueling Using Gaseous Fuels

Carl H. Rivkin

Chapter Contents

Introduction to the Use of Alternative Fuels
Impact of Clean Air Act Amendments of 1990 on Alternative Fuel Use
Prevention of Unintentional Releases and Required Risk Management Programs
Analysis of the Chemical and Physical Properties and Hazards of Alternative Fuels
Boiling Liquid Expanding Vapor Explosions
Health and Safety Concerns
Applicable NFPA Standards
Vehicle Fueling Stations
Vehicle Components, Design, and Operation
Emergency Response to Alternative Fuel Incidents

Key Terms

alternative fuel, automotive exhaust, boiling liquid expanding vapor explosion (BLEVE), Clean Air Act, compressed natural gas (CNG), compressed natural gas (CNG) vehicle, fuel cell powered vehicle, liquefied natural gas (LNG), liquefied natural gas (LNG) vehicle, liquefied petroleum gas (LP-gas), liquefied petroleum gas (LP-gas) vehicle, odorization, particulate matter emissions, vehicle fueling station

The use of alternative fuels for vehicles is becoming more predominant. Forces driving their use are increasing air pollution and the United States' dependence on foreign oil. Federal regulations such as the Energy Policy Act (EPACT) of 1992 and the Clean Air Act Amendments (CAAA) of 1990 were specifically designed to increase the driving public's use of alternative-fueled vehicles to benefit the environment and to increase the use of natural resources available in North America. From 1992 to 2000, there was a 6.9 percent average annual percent increase in alternative fuel vehicles in use in the United States. As of 2000, they accounted for 0.2 percent of all registered motor vehicles in the United States.[1] This chapter discusses several areas, including properties and hazards associated with different alternative fuels, vehicle fueling stations, vehicle component designs and operation, emergency response to alternative fuel incidents, and federal regulations that may impact alternative fuels users.

For related topics, see the following chapters in Section 21: Chapter 1, "Passenger Vehicle Fires"; Chapter 2, "Fire Safety in Commercial Vehicles"; Chapter 4, "Vehicle Fueling Using Gaseous Fuels"; and Chapter 5, "Fuel Cell Vehicles."

INTRODUCTION TO THE USE OF ALTERNATIVE FUELS

Alternative Fuels Defined

A variety of alternative fuels are currently used in the United States. However, the review of alternative fuels in this chapter is limited to compressed natural gas (CNG), liquefied natural gas (LNG), and liquefied petroleum gas (LP-gas), specifically propane. The scope is limited to these three gaseous fuels because the hazards of alternative fuels, like flammable liquids (alcohols and reformulated gasoline), are better known and generally accepted. Hydrogen is the least used of these three fuels but hydrogen may become a more important alternative fuel as hydrogen vehicle applications and technology continue to develop. Gaseous fuels have recently gained popularity and more information is needed on their use as motor vehicle fuel.

Additionally, the three main alternative fuels are used by over 85 percent of the light alternative fuel vehicles and by over 95 percent of the heavy alternative fuel vehicles. Over 95 percent of the alternative fuel refueling sites are for CNG, LNG, or LP-gas[2] (Tables 21.4.1 through 21.4.13).

The Clean Air Act Amendments (CAAA) define alternative fuels as methanol, ethanol, and other alcohols; reformulated gasoline; reformulated diesel (for trucks only); natural gas; propane; hydrogen; or electricity. The Energy Policy Act (EPACT) includes all fuels listed under CAAA except for reformulated gasoline and diesel. EPACT also defines other alternative fuels, that is, fuels derived from biomass, liquid fuels derived from coal, and alcohol blended with other fuels containing at least 85 percent alcohol by volume.[3]

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TABLE 21.4.1 Estimated Number of Alternative-Fueled Vehicles in Use in the United States, by Fuel, 1995–2004

Fuel	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*	*2002*	(Projected) *2003*	(Projected) *2004*	*Average Annual Growth Rate (Percentage)*
Liquefied petroleum gases (LP-gas)	172,806	175,585	175,679	177,183	178,610	181,994	185,053	187,680	190,438	194,389	1.3
Compressed natural gas (CNG)	50,218	60,144	68,571	78,782	91,267	100,750	111,851	120,839	132,988	143,742	12.4
Liquefied natural gas (LNG)	603	663	813	1,172	1,681	2,090	2,576	2,708	3,030	3,134	20.1
Methanol, 85 percent (M85)[a]	18,319	20,265	21,040	19,648	18,964	10,426	7,827	5,873	4,917	4,592	–14.3
Methanol, neat (M100)	386	172	172	200	198	0	0	0	0	0	0.0
Ethanol, 85 percent (E85)[a,b]	1,527	4,536	9,130	12,788	24,604	87,570	100,303	120,951	133,776	146,195	78.8
Ethanol, 95 percent (E95)[a]	136	361	347	14	14	4	0	0	0	0	0.0
Electricity[c]	2,860	3,280	4,453	5,243	6,964	11,830	17,847	33,047	45,656	55,852	39.1
Non-LP-gas subtotal	74,049	89,421	104,526	117,847	143,692	212,670	240,404	283,418	320,367	353,515	19.0
Total	246,855	265,006	280,205	295,030	322,302	394,664	425,457	471,098	510,805	547,904	9.3

Note: Estimates for 2003 are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available.

[a]The remaining portion of 85 percent methanol and both ethanol fuels is gasoline.

[b]In 1997, some vehicle manufacturers began including E85-fueling capability in certain model lines of vehicles. For 2002, the EIA estimated that the number of E85 vehicles that are capable of operating on E85, gasoline, or both, is about 4.1 million. Many of these alternative-fueled vehicles (AFVs) are sold and used as traditional gasoline-powered vehicles. In this table, AFVs in use include only those E85 vehicles believed to be intended for use as AFVs. These are primarily fleet-operated vehicles.

[c]Excludes gasoline-electric hybrids.

Sources: 1995: Science Applications International Corporation, "Alternative Transportation Fuels and Vehicles Data Development," unpublished final report prepared for the Energy Information Administration (McLean, VA, July 1996) and U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. 1996–2004: Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels. Beginning in 2000, federal data were derived from the DOE/GSA Federal Automotive Statistical Tool (FAST).

Alternative Fuel Users

Many entities such as private, state, federal, and local government fleets and the general public use alternative fuels to power their vehicles. Fleets using alternative fuels can be small or large and are typically located predominantly in urban areas.

The Clean Fleets Program established by CAAA states that by 1998, serious, severe, and extreme ozone nonattainment areas must purchase alternative fuel vehicles. This applies to fleets with 10 or more vehicles capable of being centrally refueled and located in an area with a population of 250,000 or more. The law excludes emergency, farm, construction, rental, demonstration, and privately garaged vehicles.[3]

EPACT, which took effect in 1992, mandates the purchase of alternative fuel vehicles, with the intent of reducing the United States' dependence on oil imports. Federal and state fleets, as well as private-sector companies that produce alternative fuels, are required to purchase alternative fuel vehicles as a percent of their annual vehicle acquisitions. This can be a phased schedule for fleets of 50 or more vehicles, with at least 20 that can be centrally refueled, and located in an area with a population of 250,000 or greater. The law can extend to include municipal and private fleet owners if the U.S. Environmental Protection Agency (EPA) determines that EPACT's goals cannot be met.

IMPACT OF CLEAN AIR ACT AMENDMENTS OF 1990 ON ALTERNATIVE FUEL USE

Alternative fuel use has increased since the EPA established maximum concentration levels called national ambient air quality standards (NAAQs) for certain pollutants in the ambient air. The standards targeted the following pollutants:

- Automotive exhaust pollutants such as volatile organic compounds (VOCs) that lead to the formation of ozone
- Nitrous oxides (NO_x)
- Carbon monoxide (CO)

TABLE 21.4.2 Estimated Number of Alternative-Fueled Vehicles in Use in the United States, by Fuel and Weight Category, 2001–2003

Fuel	*Light Duty*	*Medium Duty*	*Heavy Duty*	*Total*
	2001			
Liquefied petroleum gases (LP-gas)	124,790	53,634	6,629	185,053
Compressed natural gas (CNG)	84,077	15,041	12,733	111,851
Liquefied natural gas (LNG)	381	0	2,195	2,576
Methanol, 85 percent (M85)[a]	7,819	0	8	7,827
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	100,287	15	1	100,303
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[c]	17,056	445	346	17,847
Non-LP-gas subtotal	209,620	15,501	15,283	240,404
Total	334,410	69,135	21,912	425,457
	2002			
Liquefied petroleum gases (LP-gas)	124,877	55,671	7,132	187,680
Compressed natural gas (CNG)	87,340	18,449	15,050	120,839
Liquefied natural gas (LNG)	452	0	2,256	2,708
Methanol, 85 percent (M85)[a]	5,865	0	8	5,873
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	120,809	140	2	120,951
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[c]	31,926	671	450	33,047
Non-LP-gas subtotal	246,392	19,260	17,766	283,418
Total	371,269	74,931	24,898	471,098
	2003			
Liquefied petroleum gases (LP-gas)	125,110	57,873	7,455	190,438
Compressed natural gas (CNG)	91,231	24,525	17,232	132,988
Liquefied natural gas (LNG)	463	0	2,567	3,030
Methanol, 85 percent (M85)[a]	4,911	0	6	4,917
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	133,634	140	2	133,776
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[c]	44,334	674	648	45,656
Non-LP-gas subtotal	274,573	25,339	20,455	320,367
Total	399,683	83,212	27,910	510,805

Note: Light duty includes vehicles less than or equal to 8500 gross vehicle weight rating (GVWR); medium duty includes vehicles 8501 to 26,000 GVWR; heavy duty includes vehicles 26,001 GVWR and over. Estimates for 2003 are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available.

[a]The remaining portion of 85 percent methanol and both ethanol fuels is gasoline.

[b]In 1997, some vehicle manufacturers began including E85-fueling capability in certain model lines of vehicles. For 2002, the EIA estimated that the number of E85 vehicles that are capable of operating on E85, gasoline, or both, is about 4.1 million. Many of these alternative fuel vehicles (AFVs) are sold and used as traditional gasoline-powered vehicles. In this table, AFVs in use include only those E85 vehicles believed to be intended for use as AFVs. These are primarily fleet-operated vehicles.

[c]Excludes gasoline-electric hybrids.

Source: Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels and the DOE/GSA Federal Automotive Statistical Tool (FAST).

Other pollutants exhausted from diesel fuel in trucks and buses include sulfur dioxide (SO_2) and particulate matter (PM_{10}, which stands for particulate matter 10 microns or less in diameter, and $PM_{2.5}$, which stands for particulate matter 2.5 microns or less in diameter). The phase out of leaded gasoline is controlling lead, the sixth criteria pollutant. However, there are still some lead nonattainment areas in the western United States. *Criteria pollutants* are those for which EPA has

TABLE 21.4.3 Estimated Number of Alternative-Fueled Vehicles in Use in the United States, by Fuel and Census Region, 2001–2003

Fuel	*Northeast*	*South*	*Midwest*	*West*	*Total*
			2001		
Liquefied petroleum gases (LP-gas)	9,613	88,314	33,949	53,177	185,053
Compressed natural gas (CNG)	20,809	35,644	12,593	42,805	111,851
Liquefied natural gas (LNG)	0	834	0	1,742	2,576
Methanol, 85 percent (M85)[a]	315	379	331	6,802	7,827
Methanol, neat (M100)	0	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	13,018	39,190	21,732	26,363	100,303
Ethanol, 95 percent (E95)[a]	0	0	0	0	0
Electricity[c]	5,505	3,996	1,187	7,159	17,847
Total	49,260	168,357	69,792	138,048	425,457
			2002		
Liquefied petroleum gases (LP-gas)	9,670	90,577	33,023	54,410	187,680
Compressed natural gas (CNG)	22,346	38,180	13,681	46,633	120,839
Liquefied natural gas (LNG)	0	895	0	1,813	2,708
Methanol, 85 percent (M85)[a]	237	284	249	5,103	5,873
Methanol, neat (M100)	0	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	14,485	46,023	33,662	26,781	120,951
Ethanol, 95 percent (E95)[a]	0	0	0	0	0
Electricity[c]	10,178	7,395	2,121	13,353	33,047
Total	56,916	183,354	82,736	148,092	471,098
			2003		
Liquefied petroleum gases (LP-gas)	9,935	90,375	35,642	54,486	190,438
Compressed natural gas (CNG)	24,339	41,701	15,289	51,659	132,988
Liquefied natural gas (LNG)	0	986	0	2,044	3,030
Methanol, 85 percent (M85)[a]	198	239	209	4,271	4,917
Methanol, neat (M100)	0	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	16,018	50,899	37,236	29,623	133,776
Ethanol, 95 percent (E95)[a]	0	0	0	0	0
Electricity[c]	13,955	10,196	2,957	18,549	45,657
Total	64,445	194,395	91,333	160,632	510,805

Note: Estimates for 2003 are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available.

[a]The remaining portion of 85 percent methanol and both ethanol fuels is gasoline.

[b]In 1997, some vehicle manufacturers began including E85-fueling capability in certain model lines of vehicles. For 2002, the EIA estimated that the number of E85 vehicles that are capable of operating on E85, gasoline, or both, is about 4.1 million. Many of these alternative fuel vehicles (AFVs) are sold and used as traditional gasoline-powered vehicles. In this table, AFVs in use include only those E85 vehicles believed to be intended for use as AFVs. These are primarily fleet-operated vehicles.

[c]Excludes gasoline-electric hybrids.

Source: Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels and the DOE/GSA Federal Automotive Statistical Tool (FAST).

set national ambient air quality standards. States and other municipalities must measure ambient air according to an EPA-approved plan to determine whether they meet these ambient standards. Both mobile and stationary sources generate all of these pollutants. Aboveground storage tanks, industrial processes, and diesel-fueled generator sets introduce pollutants into the atmosphere.

A county or area can be designated a nonattainment area when concentrations of any one of these pollutants exceed NAAQ limits. The nonattainment categories are extreme, severe, and moderate. Ozone, PM_{10}, and CO nonattainment are the predominant nonattainment pollutants. Individual states are responsible for attaining each EPA NAAQ. States accomplish this by utilizing state implementation plans, which outline specific actions to reduce emissions. One method of reducing mobile sources of criteria pollutants is using alternative fuels instead of more traditional fuels such as gasoline or diesel.

TABLE 21.4.4 Estimated Number of Alternative-Fueled Vehicles in Use, by State, 2001–2003

State	2001	2002	2003	State	2001	2002	2003
Alabama	7,501	8,979	9,870	Nebraska	5,142	5,814	6,303
Alaska	1,288	1,277	1,433	Nevada	5,318	5,571	5,968
Arizona	11,046	11,771	13,303	New Hampshire	935	1,096	1,218
Arkansas	2,873	2,839	3,014	New Jersey	5,854	5,956	6,569
California	66,366	71,501	77,761	New Mexico	9,643	10,624	11,042
Colorado	11,120	11,925	12,447	New York	26,890	32,423	37,559
Connecticut	3,981	5,147	5,606	North Carolina	8,661	9,770	10,695
Delaware	679	1,378	1,492	North Dakota	1,818	1,819	2,133
District of Columbia	3,105	3,243	3,674	Ohio	8,296	9,939	11,097
Florida	15,959	16,542	17,829	Oklahoma	21,440	22,283	23,336
Georgia	12,959	15,567	17,912	Oregon	5,769	5,878	6,568
Hawaii	2,487	2,513	2,707	Pennsylvania	7,326	7,611	8,351
Idaho	2,759	5,233	5,821	Rhode Island	745	844	936
Illinois	12,912	15,401	16,521	South Carolina	6,018	7,460	7,992
Indiana	5,515	6,584	7,405	South Dakota	1,765	1,802	1,906
Iowa	3,163	4,139	4,823	Tennessee	5,430	6,654	7,343
Kansas	5,633	5,985	6,332	Texas	54,254	56,190	55,820
Kentucky	4,676	5,718	6,298	Utah	6,583	7,162	7,621
Louisiana	3,154	3,325	3,582	Vermont	675	748	844
Maine	376	390	417	Virginia	9,686	10,495	11,706
Maryland	9,031	9,157	9,791	Washington	9,122	9,166	9,764
Massachusetts	2,478	2,700	2,946	West Virginia	1,022	1,012	1,098
Michigan	10,675	12,307	14,335	Wisconsin	4,168	5,813	6,457
Minnesota	4,403	6,032	6,482	Wyoming	2,737	2,780	2,924
Mississippi	1,908	1,876	1,990				
Missouri	6,302	7,102	7,540	U.S. Total	425,457	471,098	510,805
Montana	3,812	3,557	4,228				

Note: Excludes gasoline-electric hybrids.Estimates for 2003 are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available. Total may not equal sum of components due to independent rounding.

Source: Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels and the DOE/GSA Federal Automotive Statistical Tool (FAST).

Automotive Exhaust Pollutants

The use of alternative fuels significantly reduces the production of ozone. Alternative fuels can reduce ozone generation by reducing both the amount of volatile organic compounds (VOCs) in tailpipe emissions and the photochemical reactivity of VOC emissions. Hydrogen used in fuel cells produces no VOC emissions because there is no carbon in the fuel cell feed stream. Ozone is not a direct product of the combustion process but a result of atmospheric photochemical reactions between VOCs and the oxides of nitrogen (NO_x). NO_x is primarily produced when nitrogen and oxygen in combustion air combine at high temperatures. VOCs result from incomplete combustion of hydrocarbon fuels used in motor vehicles.[4]

Simple compounds such as methane and propane predominantly comprise LNG, CNG, and LP-gas fuels. The amount of VOCs these fuels generate is lower than the amount gasoline generates. Furthermore, ozone formation increases when constituents of tailpipe emissions have high photochemical reactivity.[4] Fuels composed of small molecules such as methane generate less ozone because they are unreactive in the atmosphere. Propane is more reactive than methane but significantly less reactive than large molecules of hydrocarbon fuels, such as the constituents of gasoline.

As of the year 2000, 26 states, the District of Columbia, and almost every major urban area in the United States had areas classified as nonattainment for ozone. One area, the South Coast Air Basin (which includes the city of Los Angeles and has a population of over 13,000,000 people), is classified as extreme. Approximately 100,000,000 people in the United States live in a nonattainment area for ozone.[5]

Carbon Monoxide Pollutants

As of the year 2000, there were eight areas classified as serious nonattainment areas for carbon monoxide: Anchorage, Alaska; Fairbanks, Alaska; Denver–Fort Collins, Colorado; Las Vegas, Nevada; Los Angeles–South Coast Basin, California; Phoenix, Arizona; and Spokane, Washington. Several other areas are in the moderate nonattainment class.[5] Approximately 80 percent of CO discharged to the atmosphere is from mobile sources, primarily from emissions from gasoline-powered vehicles. Alternative fuels composed of methane and propane emit much less CO than gasoline does because they have lower carbon to

TABLE 21.4.5 Estimated Number of Alternative-Fueled Vehicles in Use, by State and Fuel Type, 2002

State	Liquefied Petroleum Gases	Natural Gas	Methanol	Ethanol	Electricity	Total
Alabama	4,289	1,341	0	2,713	636	8,979
Alaska	145	401	0	720	11	1,277
Arizona	1,082	7,243	201	1,583	1,662	11,771
Arkansas	2,199	340	0	300	0	2,839
California	21,537	24,990	4,787	9,517	10,670	71,501
Colorado	5,611	2,694	3	3,491	126	11,925
Connecticut	379	2,762	1	1,849	156	5,147
Delaware	85	489	10	783	11	1,378
District of Columbia	7	1,462	50	1,408	316	3,243
Florida	4,171	4,152	6	7,856	357	16,542
Georgia	4,418	4,484	39	2,076	4,550	15,567
Hawaii	842	0	0	1,467	204	2,513
Idaho	1,581	3,412	0	240	0	5,233
Illinois	5,259	3,120	17	6,916	89	15,401
Indiana	1,426	3,397	0	1,670	91	6,584
Iowa	2,179	18	27	1,903	12	4,139
Kansas	3,565	748	1	1,649	22	5,985
Kentucky	2,214	1,191	0	2,313	0	5,718
Louisiana	1,117	896	3	1,309	0	3,325
Maine	158	77	0	134	21	390
Maryland	2,570	3,634	7	2,901	45	9,157
Massachusetts	249	1,006	36	1,331	78	2,700
Michigan	4,822	991	48	4,840	1,606	12,307
Minnesota	2,162	509	0	3,361	0	6,032
Mississippi	1,193	140	0	543	0	1,876
Missouri	2,642	476	95	3,878	11	7,102
Montana	2,980	268	0	309	0	3,557
Nebraska	4,338	370	0	1,095	11	5,814
Nevada	1,487	3,111	0	973	0	5,571
New Hampshire	718	42	0	169	167	1,096
New Jersey	358	2,723	4	2,681	190	5,956
New Mexico	6,069	1,969	11	2,140	435	10,624
New York	6,213	13,100	88	3,723	9,299	32,423
North Carolina	4,560	559	0	4,539	112	9,770
North Dakota	1,310	155	0	354	0	1,819
Ohio	2,487	2,647	26	4,537	242	9,939
Oklahoma	17,839	3,322	0	1,122	0	22,283
Oregon	3,084	1,034	20	1,528	212	5,878
Pennsylvania	1,107	2,299	108	4,008	89	7,611
Rhode Island	122	331	0	391	0	844
South Carolina	3,047	362	0	4,051	0	7,460
South Dakota	1,374	44	0	384	0	1,802
Tennessee	2,623	763	0	3,068	200	6,654
Texas	39,279	9,961	162	6,706	82	56,190
Utah	3,227	1,961	8	1,966	0	7,162
Vermont	366	5	0	199	178	748
Virginia	927	4,735	7	3,740	1,086	10,495
Washington	4,397	1,925	73	2,760	11	9,166
West Virginia	39	378	0	595	0	1,012
Wisconsin	1,459	1,207	35	3,075	37	5,813
Wyoming	2,368	303	0	87	22	2,780
U.S. Total	187,680	123,547	5,873	120,951	33,047	471,098

Note: Natural gas includes compressed natural gas (CNG) and liquefied natural gas (LNG). Methanol includes M85 and M100. Ethanol includes E85 and E95. Excludes gasoline-electric hybrids. Totals may not equal sum of components due to independent rounding.

Source: Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels and the DOE/GSA Federal Automotive Statistical Tool (FAST).

TABLE 21.4.6 Estimated Number of Alternative-Fueled Vehicles in Use by U.S. Private Entities, by Fuel and Weight Category, 2001–2003

Fuel	*Light Duty*	*Medium Duty*	*Heavy Duty*	*Total*
		2001		
Liquefied petroleum gases (LP-gas)	100,297	44,678	5,038	150,013
Compressed natural gas (CNG)	44,598	9,075	8,761	62,434
Liquefied natural gas (LNG)	264	0	2,020	2,284
Methanol, 85 percent (M85)[a]	4,010	0	0	4,010
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	36,176	4	1	36,181
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[c]	11,939	91	262	12,292
Non-LP-gas subtotal	96,987	9,170	11,044	117,201
Total	197,284	53,848	16,082	267,214
		2002		
Liquefied petroleum gases (LP-gas)	100,926	46,498	5,539	152,963
Compressed natural gas (CNG)	47,417	11,465	10,338	69,220
Liquefied natural gas (LNG)	315	0	2,110	2,425
Methanol, 85 percent (M85)[a]	3,207	0	0	3,207
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	43,521	40	2	43,563
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[c]	26,156	312	361	26,829
Non-LP-gas subtotal	120,616	11,817	12,811	145,244
Total	221,542	58,315	18,350	298,207
		2003		
Liquefied petroleum gases (LP-gas)	101,335	48,652	5,900	155,887
Compressed natural gas (CNG)	49,529	15,242	11,837	76,608
Liquefied natural gas (LNG)	321	0	2,414	2,735
Methanol, 85 percent (M85)[a]	2,456	0	0	2,456
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	45,091	38	2	45,131
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[c]	35,482	313	520	36,315
Non-LP-gas subtotal	132,879	15,593	14,773	163,245
Total	234,214	64,245	20,673	319,132

Note: Light duty includes vehicles less than or equal to 8500 GVWR; medium duty includes vehicles 8501 to 26,000 GVWR; heavy duty includes vehicles 26,001 GVWR and over. Estimates for 2003 are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available.

[a]The remaining portion of 85 percent methanol and both ethanol fuels is gasoline.

[b]In 1997, some vehicle manufacturers began including E85-fueling capability in certain model lines of vehicles. For 2002, the EIA estimated that the number of E85 vehicles that are capable of operating on E85, gasoline, or both, is about 4.1 million. Many of these alternative fuel vehicles (AFVs) are sold and used as traditional gasoline-powered vehicles. In this table, AFVs in use include only those E85 vehicles believed to be intended for use as AFVs. These are primarily fleet-operated vehicles.

[c]Excludes gasoline-electric hybrids.

Source: Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels.

TABLE 21.4.7 Estimated Number of Alternative-Fueled Vehicles in Use by Local Governments, by Fuel and Weight Category, 2001–2003

Fuel	*Light Duty*	*Medium Duty*	*Heavy Duty*	*Total*
		2001		
Liquefied petroleum gases (LP-gas)	17,700	7,884	889	26,473
Compressed natural gas (CNG)	19,114	3,889	3,755	26,758
Liquefied natural gas (LNG)	86	0	165	251
Methanol, 85 percent (M85)[a]	2,986	0	8	2,994
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	6,384	0	0	6,384
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[c]	3,601	304	70	3,975
Non-LP-gas subtotal	32,171	4,193	3,998	40,362
Total	49,871	12,077	4,887	66,835
		2002		
Liquefied petroleum gases (LP-gas)	17,810	8,205	977	26,992
Compressed natural gas (CNG)	20,321	4,914	4,431	29,666
Liquefied natural gas (LNG)	106	0	136	242
Methanol, 85 percent (M85)[a]	2,501	0	8	2,509
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	7,681	0	0	7,681
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[c]	3,921	331	76	4,328
Non-LP-gas subtotal	34,530	5,245	4,651	44,426
Total	52,340	13,450	5,628	71,418
		2003		
Liquefied petroleum gases (LP-gas)	18,063	8,322	991	27,376
Compressed natural gas (CNG)	21,227	6,532	5,073	32,832
Liquefied natural gas (LNG)	102	0	141	243
Methanol, 85 percent (M85)[a]	2,306	0	6	2,312
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	8,122	0	0	8,122
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[c]	6,086	333	109	6,528
Non-LP-gas subtotal	37,843	6,865	5,329	50,037
Total	55,906	15,187	6,320	77,413

Note: Light duty includes vehicles less than or equal to 8500 GVWR; medium duty includes vehicles 8501 to 26,000 GVWR; heavy duty includes vehicles 26,001 GVWR and over. Estimates for 2003 are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available.

[a]The remaining portion of 85 percent methanol and both ethanol fuels is gasoline.

[b]In 1997, some vehicle manufacturers began including E85-fueling capability in certain model lines of vehicles. For 2002, the EIA estimated that the number of E85 vehicles that are capable of operating on E85, gasoline, or both, is about 4.1 million. Many of these alternative fuel vehicles (AFVs) are sold and used as traditional gasoline-powered vehicles. In this table, AFVs in use include only those E85 vehicles believed to be intended for use as AFVs. These are primarily fleet-operated vehicles.

[c]Excludes gasoline-electric hybrids.

Source: Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels.

TABLE 21.4.8 Estimated Number of Alternative-Fueled Vehicles in Use by State Governments, by Fuel and Weight Category, 2001–2003

Fuel	*Light Duty*	*Medium Duty*	*Heavy Duty*	*Total*
		2001		
Liquefied petroleum gases (LP-gas)	6,395	1,019	629	8,043
Compressed natural gas (CNG)	5,063	303	96	5,462
Liquefied natural gas (LNG)	2	0	0	2
Methanol, 85 percent (M85)[a]	747	0	0	747
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	18,218	10	0	18,228
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[c]	967	0	0	967
Non-LP-gas subtotal	24,997	313	96	25,406
Total	31,392	1,332	725	33,449
		2002		
Liquefied petroleum gases (LP-gas)	5,835	944	561	7,340
Compressed natural gas (CNG)	4,623	478	124	5,225
Liquefied natural gas (LNG)	2	0	0	2
Methanol, 85 percent (M85)[a]	83	0	0	83
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	22,600	73	0	22,673
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[c]	1,004	0	0	1,004
Non-LP-gas subtotal	28,312	551	124	28,987
Total	34,147	1,495	685	36,327
		2003		
Liquefied petroleum gases (LP-gas)	5,418	877	521	6,816
Compressed natural gas (CNG)	4,829	635	142	5,606
Liquefied natural gas (LNG)	2	0	0	2
Methanol, 85 percent (M85)[a]	79	0	0	79
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	27,787	73	0	27,860
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[c]	1,555	0	0	1,555
Non-LP-gas subtotal	34,252	708	142	35,102
Total	39,670	1,585	663	41,918

Note: Light duty includes vehicles less than or equal to 8500 GVWR; medium duty includes vehicles 8501 to 26,000 GVWR; heavy duty includes vehicles 26,001 GVWR and over. Estimates for 2003 are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available.

[a]The remaining portion of 85 percent methanol and both ethanol fuels is gasoline.

[b]In 1997, some vehicle manufacturers began including E85-fueling capability in certain model lines of vehicles. For 2002, the EIA estimated that the number of E85 vehicles that are capable of operating on E85, gasoline, or both, is about 4.1 million. Many of these alternative fuel vehicles (AFVs) are sold and used as traditional gasoline-powered vehicles. In this table, AFVs in use include only those E85 vehicles believed to be intended for use as AFVs. These are primarily fleet-operated vehicles.

[c]Excludes gasoline-electric hybrids.

Source: Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels.

TABLE 21.4.9 Estimated Number of Alternative-Fueled Vehicles in Use by the U.S. Federal Government, by Fuel and Weight Category, 2001–2003

Fuel	*Light Duty*	*Medium Duty*	*Heavy Duty*	*Total*
		2001		
Liquefied petroleum gases (LP-gas)	398	53	73	524
Compressed natural gas (CNG)	15,302	1,774	121	17,197
Liquefied natural gas (LNG)	29	0	10	39
Methanol, 85 percent (M85)[a]	76	0	0	76
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a]	39,509	1	0	39,510
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[b]	549	50	14	613
Non-LP-gas subtotal	55,465	1,825	145	57,435
Total	55,863	1,878	218	57,959
		2002		
Liquefied petroleum gases (LP-gas)	306	24	55	385
Compressed natural gas (CNG)	14,979	1,592	157	16,728
Liquefied natural gas (LNG)	29	0	10	39
Methanol, 85 percent (M85)[a]	74	0	0	74
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a]	47,007	27	0	47,034
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[b]	845	28	13	886
Non-LP-gas subtotal	62,934	1,647	180	64,761
Total	63,240	1,671	235	65,146
		2003		
Liquefied petroleum gases (LP-gas)	294	22	43	359
Compressed natural gas (CNG)	15,646	2,116	180	17,942
Liquefied natural gas (LNG)	38	0	12	50
Methanol, 85 percent (M85)[a]	70	0	0	70
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)[a]	52,634	29	0	52,663
Ethanol, 95 percent (E95)[a]	0	0	0	0
Electricity[b]	1,211	28	19	1,258
Non-LP-gas subtotal	69,599	2,173	211	71,983
Total	69,893	2,195	254	72,342

Note: Light duty includes vehicles less than or equal to 8500 GVWR; medium duty includes vehicles 8501 to 26,000 GVWR; heavy duty includes vehicles 26,001 GVWR and over. Estimates for 2003 are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available.

[a]The remaining portion of 85 percent methanol and both ethanol fuels is gasoline.

[b]Excludes gasoline-electric hybrids.

Source: The DOE/GSA Federal Automotive Statistical Tool (FAST).

hydrogen ratios. In addition, alternative fuel vehicles do not need to run fuel rich during cold weather like gasoline-fueled vehicles do.[3] This reduced fuel consumption lowers CO emissions.

Particulate Matter (PM) Emissions

PM emissions can be reduced by using alternative fuels because the primary mobile source of these emissions is diesel-powered vehicles.[4] Diesel fuels' high sulfur content and aromatic hydrocarbons contribute to high PM emissions. In gaseous alternative fuels, sulfur is not present in appreciable amounts, and aromatic hydrocarbons are not present at all.

As of the year 2000, there were six serious nonattainment areas for PM_{10}: Clark County, Nevada; Coachella Valley, California; Los Angeles–South Coast Air Basin, California; Owens Valley, California; Phoenix, Arizona; and San Joaquin Valley, California. Additionally, many other areas are classified as moderate nonattainment areas.[5]

TABLE 21.4.10 Estimated Consumption of Vehicle Fuels in the United States, 1995–2004

Fuel	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*	*2002*	(Projected) *2003*	*2004*
Alternative fuels										
Liquefied petroleum gases (LP-gas)[a]	232,701	239,158	238,356	241,386	209,817	212,576	215,876	223,143	230,486	242,368
Compressed natural gas (CNG)[a]	35,162	46,923	65,192	72,412	79,620	86,745	104,496	120,670	141,726	159,464
Liquefied natural gas (LNG)[a]	2,759	3,247	3,714	5,343	5,828	7,259	8,921	9,382	10,514	10,868
Methanol, 85 percent (M85)[b]	2,023	1,775	1,554	1,212	1,073	585	439	337	274	257
Methanol, neat (M100)	2,150	347	347	449	447	0	0	0	0	0
Ethanol, 85 percent (E85)[a,b]	190	694	1,280	1,727	3,916	12,071	14,623	17,783	20,092	22,405
Ethanol, 95 percent (E95)[b]	995	2,699	1,136	59	62	13	0	0	0	0
Electricity[c]	663	773	1,010	1,202	1,524	3,058	4,066	7,274	9,633	11,836
Subtotal[a]	276,643	295,616	312,589	323,790	302,287	322,307	348,421	378,589	412,725	447,198
Oxygenates										
Methyl tertiary butyl ether (MTBE)[d]	2,691,200	2,749,700	3,104,200	2,903,400	3,402,600	3,296,100	3,352,200	2,383,000	NA	NA
Ethanol in gasohol[a]	910,700	660,200	830,700	889,500	950,300	1,085,800	1,143,300	1,413,600	1,792,900	2,052,000
Biodiesel	NA	NA	NA	NA	NA	6,816	7,076	16,917	26,758	36,599
Total alternative and replacement fuels	3,878,543	3,705,516	4,247,489	4,116,690	4,655,187	4,711,023	4,850,997	4,192,106	2,232,383	2,535,797
Traditional fuels										
Gasoline[e]	115,943,000	117,783,000	119,336,000	122,849,000	125,111,000	125,720,000	127,768,000	131,299,000	132,961,000	136,374,000
Diesel	28,555,040	30,101,430	31,949,270	33,665,360	35,796,800	36,990,370	37,085,270	38,305,630	39,930,170	40,740,760
Total fuel consumption[a,f]	144,774,683	148,180,046	151,597,859	156,838,150	161,210,087	163,032,677	165,201,691	169,983,219	173,303,895	177,561,958

Note: Fuel quantities are expressed in a common base unit of gasoline-equivalent gallons to allow comparisons of different fuel types. Gasoline-equivalent gallons do not represent gasoline displacement. Gasoline equivalent is computed by dividing the lower heating value of the alternative fuel by the lower heating value of gasoline and multiplying this result by the alternative fuel consumption value. Lower heating value refers to the Btu content per unit of fuel excluding the heat produced by condensation of water vapor in the fuel. Totals may not equal sum of components due to independent rounding. Estimates for 2003 and 2004 are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available.

[a]1999 and 2002 estimates have been revised.

[b]The remaining portion of 85 percent methanol and both ethanol fuels is gasoline. Consumption data include the gasoline portion of the fuel.

[c]Excludes gasoline-electric hybrids.

[d]Includes a very small amount of other ethers, primarily Tertiary Amyl Methyl Ether (TAME) and Ethyl Tertiary Butyl Ether (ETBE).

[e]Gasoline consumption includes ethanol in gasohol and MTBE.

[f]Total fuel consumption is the sum of alternative fuel, gasoline, and diesel consumption. Oxygenate consumption is included in gasoline consumption.

NA = Not available.

Sources: 1993–2002 Oxygenate Consumption: Energy Information Administration, Petroleum Supply Monthly. 1993–2004 Traditional Fuel Consumption: Energy Information Administration, Petroleum Supply Annual, Volume 1 (June 2000). Highway use of gasoline was estimated as 97.1 percent of consumption, based on data in the Transportation Energy Data Book: Edition 16, prepared by Oak Ridge National Laboratory for the U.S. Department of Energy (July 1996). Diesel consumption was adjusted for highway use by multiplying by 0.568 derived from Energy Information Administration, Fuel Oil and Kerosene Sales 1999. 2002–2004 Oxygenate and Traditional Fuel Consumption: Energy Information Administration, Short Term Energy Outlook, September 2002. Alternative Fuel Consumption: Science Applications International Corporation 1992–1995, "Alternative Transportation Fuels and Vehicles Data Development." Unpublished final report prepared for the Energy Information Administration (McLean, VA, July 1996) and Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels for 1996–2004.

TABLE 21.4.11 Estimated Share of Alternative Transportation Fuel Consumption, by Census Region, 2000, 2002, and 2004

Fuel	*Northeast*	*South*	*Midwest*	*West*
	2000			
Liquefied petroleum gases (LP-gas)	11	28	37	24
Compressed natural gas (CNG)	18	12	27	43
Liquefied natural gas (LNG)	0	1	50	49
Methanol, 85 percent (M85)*	5	7	6	82
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)*	2	81	11	6
Ethanol, 95 percent (E95)*	0	0	0	0
Electricity	14	7	22	57
Total	8	23	26	43
	2002			
Liquefied petroleum gases (LP-gas)	11	28	37	24
Compressed natural gas (CNG)	18	12	27	43
Liquefied natural gas (LNG)	0	1	50	49
Methanol, 85 percent (M85)*	5	7	6	82
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)*	2	81	11	6
Ethanol, 95 percent (E95)*	0	0	0	0
Electricity	14	7	22	57
Total	8	23	26	43
	2004			
Liquefied petroleum gases (LP-gas)	11	28	37	24
Compressed natural gas (CNG)	18	12	27	43
Liquefied natural gas (LNG)	0	1	50	49
Methanol, 85 percent (M85)*	5	7	6	82
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)*	2	81	11	6
Ethanol, 95 percent (E95)*	0	0	0	0
Electricity	14	7	22	57
Total	8	23	26	43

Note: Estimates for 2002 are revised. Estimates for 2004 are based on plans or projections.
*The remaining portion of 85 percent methanol and both ethanol fuels is gasoline. Consumption data include the gasoline portion of the fuel.
Source: Energy Information Administration, Office of Coal, Nuclear, Electric, and Alternate Fuels.

As mentioned earlier, nonattainment of ozone, PM_{10}, and CO is the most widespread. Using alternative fuels such as CNG, LNG, and LP-gas can significantly reduce these pollutants.

PREVENTION OF UNINTENTIONAL RELEASES AND REQUIRED RISK MANAGEMENT PROGRAMS

The Prevention of Accidental Releases of CAAA of 1990, Title III, Section 112 R, aims to prevent inadvertent chemical releases at storage locations and to minimize their consequences. Section 112 R of Title III of CAAA exempts the following propane facilities from developing and submitting risk management plans:

- Propane facilities where the propane is stored for use as fuel at the facility
- Facilities that store 10,000 lb (4540 kg) of propane or less
- Facilities where the propane is held for sale and the facility itself is considered a retail facility (one at which more than half of the income is obtained from direct sales to end users or at which more than half the fuel sold, by volume, is sold through a cylinder exchange program)

The requirements of Title III, Section 112 R, apply to existing and new stationary sources in excess of threshold quantities. The list of regulated flammable substances includes methane and propane with threshold storage quantities of 10,000 lb (4540 kg). LNG is composed of 95 to 99 percent methane;

TABLE 21.4.12 Estimated Consumption of Alternative Transportation Fuels in the United States, by Fuel and Vehicle Weight, 2000, 2002, and 2004 (Thousand Gasoline-Equivalent Gallons)

	2000			2002			2004		
Fuel	*Light Duty*	*Medium/ Heavy Duty*	*Total*	*Light Duty*	*Medium/ Heavy Duty*	*Total*	*Light Duty*	*Medium/ Heavy Duty*	*Total*
Liquefied petroleum gases (LP-gas)	60,340	152,236	212,576	61,715	161,428	223,143	62,010	180,358	242,368
Compressed natural gas (CNG)	38,436	48,309	86,745	42,528	78,142	120,670	46,387	113,077	159,464
Liquefied natural gas (LNG)	278	6,981	7,259	358	9,024	9,382	412	10,456	10,868
Methanol, 85 percent (M85)*	576	9	585	330	7	337	254	3	257
Methanol, neat (M100)	0	0	0	0	0	0	0	0	0
Ethanol, 85 percent (E85)*	12,071	0	12,071	17,783	0	17,783	22,405	0	22,405
Ethanol, 95 percent (E95)*	0	13	13	0	0	0	0	0	0
Electricity	1,726	1,332	3,058	5,224	2,050	7,274	9,006	2,830	11,836
Total	113,427	208,880	322,307	127,938	250,651	378,589	140,474	306,724	447,198

Note: Light duty includes vehicles less than or equal to 8500 GVWR; medium duty includes vehicles 8501 to 26,000 GVWR; heavy duty includes vehicles 26,001 GVWR and over. Fuel quantities are expressed in a common base unit of gasoline-equivalent gallons to allow comparisons of different fuel types. Gasoline-equivalent gallons do not represent gasoline displacement. Gasoline equivalent is computed by dividing the lower heating value of the alternative fuel by the lower heating value of gasoline and multiplying this result by the alternative fuel consumption value. Lower heating value refers to the Btu content per unit of fuel excluding the heat produced by condensation of water vapor in the fuel. Totals may not equal sum of components due to independent rounding. Estimates for 2000 are revised. Estimates for 2002 are preliminary. Estimates for 2004 are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available.

*The remaining portion of 85 percent methanol and both ethanol fuels is gasoline. Consumption data include the gasoline portion of the fuel.

LP-gas is predominantly propane. Assuming commercial automotive grades of LNG and LP-gas, facilities using stationary containers with capacities greater than 2780 gal (10.5 m^3) of LNG or 2380 gal (9.0 m^3) of LP-gas may be required to prepare a risk management plan. The rule should not impact most CNG fueling stations because storage is normally below the threshold storage quantity. Natural gas from a distribution line is usually compressed at the facility, so it is usually unnecessary to store large quantities. Hydrogen is also listed in table 3 to 40 CFR 68.30 of the Risk Management Plan list of regulated flammable materials with a threshold of 10,000 lb.

The risk management program and its implementation consist of three components: (1) a hazard analysis, (2) a program for preventing accidental releases, and (3) an emergency response program. A Risk Management Plan must be submitted to the implementing agency, the State Emergency Planning Committee, the Local Emergency Planning Committee, and the Chemical Safety and Hazard Investigation Board. The three elements of the risk management program must be summarized in a Risk Management Plan and submitted to the above organizations. The report must be reviewed every 5 years. *Risk Management Program Guidance for Propane Storage Facilities* (40 CFR Part 68) is available from the EPA to assist regulated facilities in complying with risk management programs.[6]

Hazard Analysis

Hazard assessment is a determination of the worst-case release scenario, identification of other more likely significant releases of propane or LNG, an analysis of the off-site consequences, and a history of unintentional releases of propane or LNG. Under 40 CFR 112.R, worst-case releases are determined by assuming that in an instantaneous release, all mitigation systems fail. Other more likely accidental releases can include failure of transfer hoses, excess flow valve, emergency shutoff controls, piping, and other significant equipment failures. The rule also states that consequences must be determined from the rate and quantity of the substance lost in the air, the event's duration, the distance to exposures such as single- and multiple-family dwellings, the populations within these distances, and the potential for environmental damage. The owner or operator must maintain a 5 year history that includes such information as the date and time of a release and its quantity and duration.

Program to Prevent Unintentional Releases of Propane

The prevention program's intent is to evaluate potential hazards present at a storage and dispensing station and to find the best way to control them. The program consists of a management system,

TABLE 21.4.13 Estimated Consumption of Alternative Transportation Fuels in the United States, by Vehicle Ownership, 2000, 2002, and 2004 (Thousand Gasoline-Equivalent Gallons)

Fuel	*Federal*	*State/ Local*	*Private*	*Total*
		2000		
Liquefied petroleum gases (LP-gas)	458	19,730	192,388	212,576
Compressed natural gas (CNG)	6,294	34,061	46,390	86,745
Liquefied natural gas (LNG)	101	6,031	1,127	7,259
Methanol, 85 percent (M85)*	2	193	390	585
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)*	2,661	5,482	3,928	12,071
Ethanol, 95 percent (E95)*	0	13	0	13
Electricity	639	595	1,824	3,058
Total	10,155	66,105	246,047	322,307
		2002		
Liquefied petroleum gases (LP-gas)	213	20,097	202,833	223,143
Compressed natural gas (CNG)	6,142	52,482	62,046	120,670
Liquefied natural gas (LNG)	124	7,797	1,461	9,382
Methanol, 85 percent (M85)*	2	103	232	337
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)*	3,495	9,215	5,073	17,783
Ethanol, 95 percent (E95)*	0	0	0	0
Electricity	191	1,165	5,918	7,274
Total	10,167	90,859	277,563	378,589
		2004		
Liquefied petroleum gases (LP-gas)	164	19,277	222,927	242,368
Compressed natural gas (CNG)	7,449	73,217	78,798	159,464
Liquefied natural gas (LNG)	146	9,035	1,687	10,868
Methanol, 85 percent (M85)*	1	82	174	257
Methanol, neat (M100)	0	0	0	0
Ethanol, 85 percent (E85)*	4,331	12,713	5,361	22,405
Ethanol, 95 percent (E95)*	0	0	0	0
Electricity	291	1,461	10,084	11,836
Total	12,382	115,785	319,031	447,198

Note: Fuel quantities are expressed in a common base unit of gasoline-equivalent gallons to allow comparisons of different fuel types. Gasoline-equivalent gallons do not represent gasoline displacement. Gasoline equivalent is computed by dividing the lower heating value of the alternative fuel by the lower heating value of gasoline and multiplying this result by the alternative fuel consumption value. Lower heating value refers to the Btu content per unit of fuel excluding the heat produced by condensation of water vapor in the fuel. Totals may not equal sum of components due to independent rounding. Estimates for 2004 are based on plans or projections. Estimates for historical years may be revised in future reports if new information becomes available.

*The remaining portion of 85 percent methanol and both ethanol fuels is gasoline. Consumption data include the gasoline portion of the fuel.

Source: Energy Information Administation, Office of Coal, Nuclear, Electric, and Alternate Fuels.

process hazard analysis, process safety information, standard operating procedures, training, maintenance, prestartup reviews, management of change, safety audits, and incident investigations.

The rule states that the process hazard analysis must be conducted by using quantitative or qualitative methodologies such as what-if, fault tree analysis, hazard and operability study (HAZOP), or other accepted practices. The process hazard analysis should address the hazards of the process; identify previous incidents that impacted off-site exposures, engineering, and administrative controls; predict the consequences of control or human failures, and stationary source sitting; and qualitatively evaluate possible safety and health effects if controls fail.

Emergency Response Program

Of particular importance to emergency response personnel is the rule that requires the owner or operator of an LNG or LP-gas fueling station to establish and implement an emergency response program for responding to and mitigating unintentional releases. The emergency response must include information on evacuation

routes, employee instructions, descriptions of response and mitigation technologies at the fueling station, and procedures for informing the public and emergency response agencies of a release.

The rule states that procedures for the testing, maintenance, and use of response equipment must be established. In addition, the owner or operator is responsible for training employees in emergency response procedures and documenting all training activities. The rule states that drills or exercises will be conducted and documented, but does not specify the frequency of these drills. However, other regulations, such as those promulgated by OSHA, do establish the required frequency of emergency drills.

The emergency response program requires facilities storing LNG or LP-gas to document first aid and emergency medical treatment procedures necessary to treat persons exposed. The emergency response plan must coordinate with other local emergency response plans developed by the Local Emergency Planning Committee (LEPC) or other local emergency response agencies.

ANALYSIS OF THE CHEMICAL AND PHYSICAL PROPERTIES AND HAZARDS OF ALTERNATIVE FUELS

When a vehicle is being fueled or repaired, release from the vehicle to the fueling or repair facility is a reasonable scenario that requires fire fighters' consideration. The impact of potential releases can be analyzed using computer dispersion models that predict where the maximum ground level concentration for a specific release scenario would occur. The models (of which there are many variations) can predict concentrations at other distances from the release than the distance at which the maximum concentration would occur. A sensitivity analysis could be performed to show which parameter(s) would contribute most to the release impacts and potentially how best to reduce the impacts from a release.

Chemical and Physical Properties

The properties of each fuel require consideration in determining its potential hazard. Whether the hazard becomes "real" depends on various time-dependent conditions, the fuel system design, and the quality of the fuel system's manufacture and installation. This is due to the properties and hazards of the materials, whether release occurs inside or outside of a building, and the release scenario. This chapter discusses the relationships between identified properties and hazards of CNG, LNG, and LP-gas.

Compressed Natural Gas. Mixing and dispersion of gases depend on discharge velocities, vapor density, diffusion characteristics of the gas, and conditions and location of release. CNG can be expected to disperse readily, mix, and quickly form combustible mixtures. Under unconfined conditions, methane gas mixtures dilute rapidly to concentrations below the lower flammable limit. In contrast, the ability to form combustible mixtures rapidly generates a hazardous situation if fuel leaks in confined areas without significant ventilation.

Hydrogen. Hydrogen is used both as a liquid and a gas. Hydrogen has a molecular weight of approximately 1, but hydrogen occurs as a diatomic molecule with an approximate molecular weight of 2. Because of its extremely low density (0.07 relative to air), hydrogen typically is stored at much higher pressures than CNG. This is also the reason why some storage systems use liquid hydrogen with vaporizers to convert the hydrogen to a gas for the specific application. Gaseous hydrogen in the flammable range (4 to 75% by volume in air) can be easily ignited but because it is the lightest gas, it disperses rapidly. Because of its extremely low boiling point, liquid hydrogen boils rapidly if released. Liquid hydrogen releases can cause oxygen to condense out of the air and present this additional hazard.

Liquefied Natural Gas. LNG is natural gas liquefied by cryogenic refrigeration and stored at a temperature of –260°F (–162°C). The vapor cloud above a pool of released LNG is fairly difficult to ignite. However, the very low temperature of LNG causes normally buoyant methane to become heavier than air, creating large volumes of flammable methane-air mixtures that can spread significantly beyond the area of the initial spill. The possibility of ignition increases, and the potentially large volume of combustible gas mixture constitutes a major safety risk in substantial LNG spills.[7] When LNG vaporizes, the gas vapor cloud begins to warm and comes into thermal equilibrium with the atmosphere. LNG and CNG are primarily composed of natural gas; however, prior to liquefaction of LNG, constituents such as carbon dioxide, water, hydrogen sulfide, the odorant, and trace metal oxides are removed because they solidify at LNG storage temperatures.[8]

LP-Gas. One relative safety comparison of the three alternative fuels discussed here found that safety ranking of LP-gas appears to be similar to that of gasoline.[4] This can be attributed to heavier-than-air LP-gas vapors that do not disperse as quickly as those of other alternative fuels.

Automotive grade natural gas contains 95 to 99 percent methane and a mixture of several other gases.[8] Methane is the simplest hydrocarbon, with one carbon molecule bonded to four hydrogen molecules. Other hydrocarbons present include ethane, propane, and butane, in addition to trace amounts of metal oxides, nitrogen, carbon dioxide, water, helium, and hydrogen sulfide.

LP-gas can be either butane, propane, or a mixture of both. However, LP-gas used as an alternative fuel is composed of commercial propane. Commercial propane is not pure, but contains varying percentages of butane, ethane, ethylene, propylene, isobutane, and butylene. Propane is a straight-chain saturated hydrocarbon composed of three carbon atoms and eight hydrogen atoms. Propane is a gas at room temperature, but is liquefied when stored under a pressure equal to its vapor pressure.

Fire Hazards

The need to understand the fire hazards associated with CNG, LNG, and LP-gas grows as the number of alternative-fueled vehicles increases. For example, emergency response personnel need to recognize that these fuels present significantly different fire hazards than traditional fuels such as gasoline and diesel.

Table 21.4.14 summarizes chemical, physical, and fire hazard properties of the three alternative fuels. CNG and LNG have

TABLE 21.4.14 Properties of Fuels

Property	*Gasoline*	*No.2 Diesel Fuel*	*Methanol*	*Ethanol*	*MTBE*	*Propane*	*Compressed Natural Gas (CNG)*	*Hydrogen*
Chemical formula	C_4 to C_{12}	C_3 to C_{25}	CH_3OH	C_2H_5OH	$(CH_3)_3COCH_3$	C_3H_8	CH_4	H_2
Molecular weight	100–105[a]	≈200	32.04	46.07	88.15	44.1	16.04	2.02
Composition, weight percent								
Carbon	85–88[b]	84–87	37.5	52.2	66.1	82	75	0
Hydrogen	12–15[b]	33–16	12.6	13.1	13.7	18	25	100
Oxygen	0	0	49.9	34.7	18.2	—	—	0
Specific gravity, 60° F/60° F	0.72–0.78[b]	0.81–0.89[d]	0.796[c]	0.796[c]	0.744[m]	0.508	0.424	0.07[u]
Density, lb/gal at 60° F	6.0–6.5[b]	6.7–7.4[d]	6.63[b]	6.61[b]	6.19[m]	4.22	1.07[r]	—
Boiling temperature, °F	80–437[b]	370–650[d]	149[c]	172[c]	131[c]	–44	–259	–423[u]
Reid vapor pressure, psi	8–15[k]	0.2	4.6[o]	2.3[o]	7.8[e]	208	2,400	—
Octane no.[1]								
Research octane no.	90–100[u]	—	107	108	116[t]	112	—	130+
Motor octane no.	81–90[s]	—	92	92	101[t]	97	—	—
(R + M)/2	86–94[s]	N/A	100	100	108[t]	104	120+	—
Cetane no.[1]	5–20	40–55	—	—	—	—	—	—
Water solubility, at 70°F								
Fuel in water, volume percent	Negligible	Negligible	100[c]	100[b]	4.3[e]	—	—	—
Water in fuel, volume percent	Negligible	Negligible	100[c]	100[b]	1.4[e]	—	—	—
Freezing point, °F	–40[g]	–40–30[4]	–143.5	–173.2	–164[c]	–305.8	–296	–435[v]
Viscosity								
Centipoise at 60°F	0.37–0.44[3,p]	2.6–4.1	0.59[j]	1.19[j]	0.35[j]	—	—	
Flashpoint, closed cup, °F	–45[b]	165[d]	52[o]	55[o]	–14[e]	–100 to –150	–300	—
Autoignition temperature, °F	495[b]	≈600	867[b]	793[b]	815[e]	850–950	1,004	1,050–1,080[u]
Flammability limits, volume percent								4.1[u]
Lower	1.4[b]	1	7.3[o]	4.3[o]	1.6[e,k]	2.2	5.3	
Higher	7.6[b]	6	36[o]	19[o]	8.4[e,k]	9.5	15	74[u]
Latent heat of vaporization								
Btu/gal at 60°F	≈900[b]	≈700	3,340[b]	2,378[b]	863[5]	775	—	—
Btu/lb at 60°F	≈150[b]	≈100	506[b]	396[b]	138[5]	193.1	219	192.1[v]
Btu/lb air for stoichiometric mixture at 60°F	≈10[b]	≈8	78.4[b]	44[b]	11.8	—	—	—
Heating value[2]								
Higher (liquid fuel-liquid water) Btu/lb	18,800–20,400	19,200–20000	9,750[2]	12,800[q]	18,290[h]	21,600	23,600	61,002[v]
Lower (liquid fuel-water vapor) Btu/lb	18,000–19,000	18,000–19,000	8,570[b]	11,500[q]	15,100[h]	19,800	21,300	51,532[v]
Higher (liquid fuel-liquid water) Btu/gal	124,800	138,700	64,250	84,100	—	91,300	—	—
Lower (liquid fuel-water vapor) Btu/gal at 60°F	115,000	128,400	56,800[3]	76,000[3]	93,500[4]	84,500	19,800[6]	—

Heating value, stoichiometric mixture								
Mixture in vapor state, Btu/cubic foot at 68°F	95.2[b]	96.9[5,q]	92.5[b]	92.9[b]	—	—	—	—
Fuel in liquid state, Btu/lb or air	1,290[b]	—	1,330[b]	1,280[b]	—	—	—	—
Specific heat, Btu/lb °F	0.48[g]	0.43	0.6[j]	0.57[j]	0.5[j]	—	—	—
Stoichiometric air/fuel, weight	14.7[3]	14.7	6.45[l]	9[l]	11.7[j]	15.7	17.2	34.3[u]
Volume percent fuel in vaporized stoichiometric mixture	2[b]	—	12.3[b]	6.5[b]	2.7[j]	—	—	—

Notes:

1. Octane values are for pure components. Laboratory engine Research and Motor octane rating procedures are not suitable for use with neat oxygenates. Octane values obtained by these methods are not useful in determining knock-limited compression ratios for vehicles operating on neat oxygenates and do not represent octane performance of oxygenates when blended with hydrocarbons. Similar problems exist for cetane rating procedures.
2. The higher heating value is cited for completeness only. Since no vehicles in use, or currently being developed for future use, have power plants capable of condensing the moisture of combustion, the lower heating value should be used for practical comparisons between fuels.
3. Calculated.
4. Pour Point, ASTM D97 from Reference (c).
5. Based on cetane.
6. For compressed gas at 2400 psi.

Sources:

[a]The basis of this table and associated references was taken from American Petroleum Institute (API), Alcohols and Ethers, Publication No. 4261, 2nd ed. (Washington, DC, July 1988), Table B-1.

[b]"Alcohols: A Technical Assessment of Their Application as Motor Fuels," API Publication No. 4261, July 1976.

[c]*Handbook of Chemistry and Physics,* 62nd Edition, The Chemical Rubber Company Press, Inc., 1981.

[d]"Diesel Fuel Oils, 1987," Petroleum Product Surveys, National Institute for Petroleum and Energy Research, October 1987.

[e]ARCO Chemical Company, 1987.

[f]"MTBE, Evaluation as a High Octane Blending Component for Unleaded Gasoline," Johnson, R. T., Taniguchi, B. Y., Symposium on Octane in the 1980's, American Chemical Society, Miami Beach Meeting, September 10–15, 1979.

[g]"Status of Alcohol Fuels Utilization Technology for Highway Transportation: A 1981 Perspective," Vol. 1, *Spark-Ignition Engine,* May 1982, DOE/CE-56051–7.

[h]American Petroleum Institute Research Project 44, NBS C-461.

[i]*Lang's Handbook of Chemistry,* 13th Edition, McGraw-Hill Book Company, New York, 1985.

[j]"Data Compilation Tables of Properties of Pure Compounds," Design Institute for Physical Property Data, American Institute of Chemical Engineers, New York, 1984.

[k]Petroleum Product Surveys, Motor Gasoline, National Institute for Petroleum and Energy Research, Summer 1986, Winter 1986/1987.

[l]Based on isoctane.

[m]API Monograph Series, Publication 723, "Teri-Butyl Methyl Ether," 1984.

[n]BP America, Sohio Oil Broadway Laboratory.

[o]API Technical Data Book—Petroleum Refining, Volume I, Chapter I. Revised Chapter 1 to First, Second, Third and Fourth Editions, 1988.

[p]"Automotive Gasolines," SAE Recommended Practice, J312 May 1986, SAE Handbook, Volume 3, 1988.

[q]"Internal Combustion Engines and Air Pollution," Obert, E. F., 3rd Edition, Intext Educational Publishers, 1973.

[r]Value at 80 degrees F with respect to the water at 60 degrees F (Mueller & Associates).

[s]National Institute for Petroleum and Energy Research, Petroleum Product Surveys, Motor Gasolines, Summer 1992, NIPER-178 PPS 93/1 (Batlesville, OK, January 1993), Table 1.

[t]P. Dorn, A. M. Mourao, and S. Herbstman, "The Properties and Performance of Modern Automotive Fuels," Society of Automotive Engineers (SAE), Publication No. 861178 (Warrendale, PA), 1986, p. 53.

[u]C. Borusbay and T. Nejat Veziroglu, "Hydrogen as a Fuel for Spark Ignition Engines," Alternative Energy Sources VIII, Volume 2, Research and Development (New York: Hemisphere Publishing Corporation), 1989, pp. 559–560.

[v]Technical Data Book, Prepared by Gulf Research and Development Company, Pittsburgh, PA, 1962.

similar fire hazards because some natural gas properties do not change between the two different physical states. Flammability limits and autoignition temperature of natural gas are the same in the two physical storage states of CNG and LNG. Its flammable range is narrow, and its autoignition temperature is high. LP-gas produces a flammable mixture in air at lower concentrations than natural gas but has a narrower flammable range.

Fire Hazards of Compressed Natural Gas. Natural gas, which has a vapor density of less than 1, tends to rise at ambient conditions. This is one important property of natural gas to consider because vapor density varies under different temperatures. However, because of the extremely low boiling point of natural gas, the vapor density will be less than air under most conditions. CNG released into the atmosphere at normal temperatures and pressures rapidly rises and disperses into the air. CNG-fueled vehicles provide a high degree of safety if a release occurs outdoors because the compressed methane diffuses rapidly in unconfined locations. If a container relief valve operates or the fuel line piping breaks, the duration of the release is limited because the gas discharges at high pressures.

When CNG vents from a relief device or pipe opening, it forms a gas jet that "blows" into the atmosphere in the direction the hole faces, continually entraining and mixing with air. If the CNG encounters an ignition source, a flame jet of considerable length may form. Flame jets pose a thermal radiation hazard to the vehicle and persons nearby and are particularly hazardous if they impinge on the exterior of adjacent containers. This can lead to the operation of additional pressure-relief devices, increasing the fire's thermal flux. Compressed methane gas releases are of relatively short duration. The ensuing fire usually involves only combustibles on the vehicle because natural gas is rapidly consumed during the jet fire.

A CNG release in an enclosed space can present a higher risk for a deflagration because the contained gas may not readily diffuse. Because methane has a vapor density of 0.6, it rises rapidly and pools if contained by a ceiling. Light fixtures and air-handling equipment normally installed at a building's ceiling or roof can serve as potential ignition sources.

Studies have evaluated the deflagration hazard resulting from a leak in a CNG vehicle fuel system or relief device operation inside parking garages and transit tunnels.[9] A gas utility corporation commissioned a study that examined the consequences of a fuel pipe leak or the operation of a container pressure relief device inside a partially open public parking garage. The study found that a leak in the fuel piping was the most credible event, whereas the operation of the container relief valve was the worst-case event. Recognizing that the three model codes and NFPA 88A, *Standard for Parking Structures,* require a method for mechanically ventilating carbon monoxide exhaust, and that all parking garages have fairly open spaces, vapor dispersion models related to this study were created to evaluate selected leak scenarios. Analyses of the most probable event resulted in no flammable concentrations beyond the leak point's immediate vicinity. The leak did not result in accumulated flammable gas in the garage. The operation of the container relief valve did result in the brief formation of a gas puff that was within the flammable limits of methane. However, the vapor puff was effectively mitigated by the rapid diffusion of the gas in open space and its removal from the garage by the mechanical exhaust system. The study showed that a CNG vehicle poses no extraordinary risk; that is, the CNG vehicle's risk is equal to or less than the risk a gasoline-fueled vehicle poses.

One study[10] compared the flammable vapor clouds formed following a fuel line failure of a hypothetical CNG-powered and gasoline-powered van inside ventilated and unventilated tunnels with various types of ceiling construction. Depending on tunnel ventilation, the hypothetical CNG vehicle would be expected to produce both a smaller and shorter-lived flammable gas region than the equivalent gasoline van. Effective ventilation could be mechanical ventilation by fans or ventilation induced by a vehicle's motion. The study recommended that transportation authorities develop policies limiting the size of vehicles allowed in tunnels.

Fire Hazards of Liquefied Natural Gas. LNG is stored at an approximate temperature of –260°F (–162°C). Studies show that at temperatures less than –180°F (–118°C), LNG is more dense than air at 60°F (16°C).[8] Because LNG is a flammable cryogen, the integrity of the container and piping is of primary concern; a container or piping failure can result in a cryogen liquid spill. However, loss of liquid from a container requires that the outer steel shell, insulation, and inner vessel all fail. All three components are less likely to fail than are single-wall, atmospheric storage tanks found on conventional gasoline- or diesel-fueled vehicles. Nonetheless, the probability of a spill is still a consideration.

The liquid from an LNG spill begins to vaporize rapidly and forms a white cloud as cold vapors condense in air. Initially, the vapor is negatively buoyant and sinks to the ground until it warms to approximately –180°F (–118°C). At this temperature, the vapor becomes positively buoyant and begins to rise.

The vaporization rate and distance the gas cloud travels and disperses depends on the four following factors:

1. *Wind speed.* Wind speed is influential because as velocity increases, the LNG evaporation rate tends to increase. Increased wind velocity helps to induce mixing of methane vapors with air, causing the vapor cloud to disperse into smaller clouds, or puffs. This reduces the flammable atmosphere's area.
2. *Surface area of the spill.* The larger the spill area, the greater its vaporization rate. This can result in larger vapor clouds, increasing the boundary of the flammable atmosphere.
3. *Surface type.* The surface where the LNG spills influences its vaporization rate. Vaporization rates are high on wet surfaces, such as muddy soil, because water acts as a heat sink. Asphalt promotes vaporization because its dark color acts as a heat radiator. If LNG spills onto a good heat-insulating surface, boiling may eventually slow down, but the remaining liquid pool continues to evaporate rapidly. Evaporation maintains the remaining liquid near its boiling point as it absorbs heat from its surroundings.
4. *Time of the incident.* At night, lack of atmospheric heating by the sun and ground reduces the evaporation rate of LNG. While this influences the vaporization rate, it also influences the distance from the source spill in which the vapor

puff remains in its flammable range. At night, the distance is greater because the time needed to heat the vapor until it is lighter than air increases.

Fire fighters should remember that LNG vapor formed during the phase change is colorless and odorless at normal temperature and pressures. They cannot rely on visual or olfactory indicators to establish safe boundaries. Only gas detection equipment designed to detect methane can establish safe exclusion and operating zones when dealing with LNG releases.

Fire Hazards of LP-Gas. LP-gas is stored as a liquefied gas at its vapor pressure and at ambient temperature. At ambient conditions, propane's vapor density is 1½ times that of air. This means that propane released to the atmosphere sinks to the ground and forms a vapor cloud that can follow surface contours over a large area. Because of the vapor density and expansion ratio of LP-gas, this class of materials can challenge fire fighters. Incidents involving LP-gas containers can result in jet fires, vapor cloud ignition, or boiling liquid expanding vapor explosions (BLEVEs). Because the alternative-fueled vehicles on the road are predominantly LP-gas fueled, fire fighters can expect to respond to incidents involving LP-gas more than other alternative fuels.

Two types of LP-gas releases can occur: vapor phase release and liquid phase release. A vapor phase release can occur if a component installed above the liquid line is damaged or the container is punctured or otherwise damaged above the liquid line. During a vapor release, LP-gas vents at a high velocity from the opening, possibly creating some liquid droplets during the process. The velocity of the release reduces with time as boiling inside the container cools the liquid mass. The tank's surface forms a layer of frost due to the refrigeration effect of the liquid being cooled. The gas may continue venting for a considerable time until no liquid is left in the container.

A liquid phase release occurs if an LP-gas component installed below the liquid line is damaged or if the container is punctured or damaged below the liquid line. When the release occurs below the liquid level, the liquefied gas may jet from the hole. The velocity of the liquid discharge depends on the amount of liquid in the container and the gas vapor pressure. During a liquid phase release, large amounts of the liquid flash into gas or vapor. Depending on the temperature and pressure, a propane release in its liquid phase can discharge a large mass of vapor mixed with small droplets suspended as an aerosol. Sometimes, liquid propane pools on the ground surface and typically boils off into gas.

During a vapor phase or liquid phase release, volatile gases and vapors, if not ignited immediately, form a plume that moves downwind of the container. If the plume contacts an ignition source, and the vapor plume is within the flammable range, the flame may flash back toward the source of the release. Unprotected people within the cloud may be severely injured. If the velocity of the flame front is great enough, air, products of combustion, and unburned fuel can compress to a point where a vapor cloud explosion could occur. In this case, the deflagration's pressure can also impact persons and property.

Fire Hazards of Hydrogen Gas and Liquid Hydrogen. Hydrogen gas has a flammable range of 4 percent to 75 percent in air by volume. It can be easily ignited and if contained can explode. Hydrogen has a vapor density of 0.07 relative to air, so it will disperse rapidly. Hydrogen has a boiling point of –423°F (–253°C), which means that any liquid release will quickly vaporize. Liquid hydrogen released from a pipe will under many conditions vaporize before contacting the ground resulting in no free-flowing liquid hydrogen. Liquid hydrogen releases may cause oxygen to condense out of the air presenting the additional hazard of an oxygen-enriched environment.

BOILING LIQUID EXPANDING VAPOR EXPLOSIONS

A boiling liquid expanding vapor explosion (BLEVE) is defined as a major container failure, into two or more pieces, at the moment in time when the contained liquid is well above its normal boiling point at atmospheric pressure.[11] Gas and LNG containers are susceptible to BLEVEs. BLEVEs occur when liquids are stored in a container under pressure at a temperature above their boiling points.

LNG and LP-gas both possess high expansion ratios. For instance, 1 ft^3 (0.028 m^3) of LNG expands to 618 ft^3 (17.4 m^3) of natural gas at ambient conditions, and 1 ft^3 (0.028 m^3) of liquid propane expands to approximately 265 ft^3 (7.5 m^3) of propane gas at normal temperature and pressure. Expansion of a liquefied gas increases the pressure on tank walls if pressure relief valves fail to open or if relief valves are incapable of adequately relieving internal tank pressure. A puncture in the tank wall or heating of the container surface due to an exposure or pool fire could cause expansion. As the tank walls' strength decreases and liquefied gas within the tank continues to expand, the tank fails, breaking into two or more pieces. The flammable gas can ignite simultaneously with tank failure.

The insulation of LNG containers that are constructed according to ASME Boiler and Pressure Vessel code helps protect the inner tank from exposure to high temperatures resulting from flame impingement. Storage vessels used at LNG fueling sites are similar to those used for storing cryogenic liquids. LNG containers' outer metal jacket protects an insulating material maintained under a vacuum. This assembly surrounds an inner steel vessel that holds the cryogenic natural gas liquid. This outer jacket and insulation, combined with the liquid's extreme cold, are expected to provide substantial protection from radiant heat exposure due to a pool fire. Fire tests conclude that the pressure relief valves for an uninsulated cryogenic vessel activate within 1 hour. If the tank insulation and vacuum are intact, the relief valve does not actuate for several days.[12]

Additional information on BLEVEs involving LP-gases can be found in Section 6, Chapter 10, "Gases."

HEALTH AND SAFETY CONCERNS

Health Hazards

Health risks of the three alternative fuels discussed in this chapter generally result from two different exposure routes: (1) skin contact and (2) inhalation. Ingestion is usually not a likely route of exposure.

Potential for skin contact with CNG is very low. Almost immediate dispersion results when a container releases CNG stored at pressures in excess of 2400 psi (16,546 kPa). LNG, a cryogenic liquid stored at –260°F (–162°C), can cause burns or frostbite upon contact. Hypothermia can also occur from prolonged exposure to LNG vapor.

Asphyxiation occurs when other gases displace oxygen in the air and the oxygen concentration decreases to less than a tenable level. LNG vapor is not toxic; however, there is potential for lung damage or asphyxiation. Lung damage could occur from prolonged breathing of cold vapors. Neither CNG or LNG has an established time-weighted average because they are simple asphyxiates; LP-gas has a time-weighted average of 1000 ppm. All the gaseous alternative fuels may cause asphyxiation if released in a confined space.

Hydrogen does not present a toxicity hazard. However, liquid hydrogen storage systems operate at extremely low temperatures and present cryogen burn hazards. Also, gaseous hydrogen storage systems operate at extremely high pressures, and the potential energy of these high pressures presents a hazard.

Odorization

Odorization of odorless gas such as natural gas or propane is an important safety precaution. It indicates, by odor, a gas leak or a release event. Natural gas is odorized within the pipeline prior to general distribution. Natural gas is normally odorized at a level allowing detection at 20 to 25 percent of the lower flammable limit of methane. CNG taken from a distribution line and compressed contains the odorants typically added to natural gas. One major difference between CNG and LNG is that LNG has no odor. Consequently, LNG leaks cannot be detected by smell. San Diego Gas and Electric Company developed an odorization technique for LNG in the 1970s. The technique used the same odorants used in natural gas, but blended them with a carrier gas such as liquid propane. A Gas Research Institute study revealed that odorants such as ethyl mercaptan, *i*-propyl mercaptan, and *t*-butyl mercaptan could be used with carrier gases such as liquid propane and *i*-butane to odorize LNG.[13] Although the study indicates viable options for odorization of LNG, NFPA 59A, *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG),* does not require it.

LP-gas is odorized before delivery to a bulk plant.[14] Like natural gas, it is detectable by odor at a concentration in air at less than one-fifth of the lower flammability limit. Typical odorants used include ethyl mercaptan and thiophane.

It is not possible to warn everyone of a gas leak by using odorants. Odorants can fade in transmission lines and containers due to oxidization by oxygen, rust, or iron oxides. Furthermore, olfactory senses diminish with increasing age, allergies, and during smoking and eating.

Hydrogen is typically not odorized. Because hydrogen has a boiling point of –423°F (–253°C) most chemicals would be in the solid phase if mixed with liquid hydrogen. Gaseous hydrogen is often used in fuel cells where the odorants would contaminate the fuel cell catalysts and prevent the fuel cells from functioning. Therefore, odorants are not used in hydrogen. As hydrogen becomes more widely used in fuel cells, there may be odorants developed that would not contaminate the fuel cell. Research is being conducted on this topic.

APPLICABLE NFPA STANDARDS

NFPA standards have been developed for all alternative fuels described in this chapter. NFPA 52, *Vehicular Fuel Systems Code,* 2006 edition, contains requirements for the use of CNG, LNG, and hydrogen. NFPA 57, *Liquefied Natural Gas Vehicular Fuel Systems Code,* has been incorporated into NFPA 52 and no longer exists as an independent document. The 2006 edition of NFPA 52 contains new requirements for both liquefied and gaseous hydrogen. NFPA 58, *Liquefied Petroleum Gas Code,* contains requirements for LP-gas. NFPA 59, *Utility LP-Gas Plant Code,* has requirements for storing and constructing LNG containers. However, the standard was originally written for site-erected LNG containers similar to those found at peak-shaving plants. Conversely, LNG stations normally use shop-constructed containers. Many station designers and operators wanted a separate standard that specifically applies to vehicle fuel systems and LNG dispensing. The National Fire Protection Association responded by developing NFPA 57, which was incorporated into NFPA 52 in 2005.

VEHICLE FUELING STATIONS

There were over 5000 refueling sites in the United States in 2006. The majority of these sites (2771) are for LP-gas refueling (Table 21.4.15). There are 754 sites for CNG refueling, leaving approximately 1500 sites for all other types of alternative fuels. Of these approximately 1500 remaining sites, 37 are for LNG refueling. These sites are both public and private refueling sites, which may skew the distribution toward LP-gas; but even considering this possibility, it is clear that there is much greater access to LP-gas. Note that Alaska and Hawaii do not have CNG refueling facilities and that the majority of states do not have LNG refueling facilities. However, the number of refueling facilities has steadily increased, and if current trends in the increased use of alternative fuel vehicles continue, the number of refueling facilities should also increase.

Compressed Natural Gas Vehicle Fueling Stations

CNG fueling stations can be generally categorized according to the time needed to fuel. The method used depends on the filling time the user desires. Available equipment combinations result in facilities being categorized as either "fast-fill dispensing" or "slow-fill dispensing."

Refueling a standard passenger vehicle at slow-fill CNG stations can commonly take up to 8 hours. These stations connect to the natural gas service line that typically supplies fuel for building heat. CNG slow-filling systems use a small compressor, eliminating the need for high gas flow and large gas supply piping. The small compressor usually combines with the dispensing equipment to form a compact module mounted next to the vehicle's parking space. Typically, no storage containers

TABLE 21.4.15 Alternative Fueling Station Counts by State and Fuel Type, 2006

State	*CNG*	*E85*	*LPG*	*ELEC*	*BD*	*HY*	*LNG*	*Totals by State*
Alabama	1	0	74	0	0	0	0	75
Alaska	0	0	12	0	0	0	0	12
Arizona	30	4	74	18	4	1	4	135
Arkansas	4	0	57	0	0	0	0	61
California	179	3	257	405	17	9	30	900
Colorado	21	11	72	4	22	0	0	130
Connecticut	11	0	19	4	1	0	0	35
Delaware	1	0	3	0	3	0	0	7
Dist. of Columbia	1	0	0	0	0	1	0	2
Florida	23	2	70	7	4	0	0	106
Georgia	20	5	55	0	18	0	0	98
Hawaii	0	0	6	11	3	0	0	20
Idaho	8	1	28	0	2	0	1	40
Illinois	11	96	73	0	9	0	0	189
Indiana	11	18	42	0	10	0	0	81
Iowa	0	40	29	0	8	0	0	77
Kansas	3	7	49	0	4	0	0	63
Kentucky	0	5	36	0	6	0	0	47
Louisiana	8	0	14	0	0	0	0	22
Maine	1	0	6	0	2	0	0	9
Maryland	13	4	19	0	3	0	0	39
Massachusetts	9	0	28	28	1	0	0	66
Michigan	15	4	94	0	13	2	0	128
Minnesota	3	196	35	0	2	0	0	236
Mississippi	0	0	40	0	6	0	0	46
Missouri	6	21	88	0	2	0	0	117
Montana	2	5	31	0	6	0	0	44
Nebraska	1	26	23	0	1	0	0	51
Nevada	16	3	25	0	10	1	0	55
New Hampshire	3	0	13	10	10	0	0	36
New Jersey	15	0	11	0	1	0	0	27
New Mexico	8	3	60	0	2	0	0	73
New York	37	6	28	0	3	0	0	74
North Carolina	10	9	69	0	38	0	0	126
North Dakota	4	20	16	0	0	0	0	40
Ohio	13	6	77	0	16	0	0	112
Oklahoma	53	4	71	1	5	0	0	134
Oregon	14	1	34	4	14	0	0	67
Pennsylvania	31	1	64	0	11	0	0	107
Rhode Island	6	0	4	2	0	0	0	12
South Carolina	5	28	41	2	24	0	0	100
South Dakota	0	30	22	0	0	0	0	52
Tennessee	6	5	59	0	9	0	0	79
Texas	29	4	628	2	10	0	2	675
Utah	63	3	27	0	3	0	0	96
Vermont	1	0	6	10	5	0	0	22
Virginia	13	2	25	0	10	0	0	50
Washington	14	2	60	0	17	0	0	93
West Virginia	2	2	8	0	0	0	0	12
Wisconsin	18	12	56	0	2	0	0	88
Wyoming	11	3	33	0	13	0	0	60
Totals by fuel	754	592	2771	508	350	14	37	5026

Source: U.S. Department of Energy.

are associated with these units, which contributes to longer filling times. Mostly used for overnight fueling, slow-fill units are typically used by fleets of less than 30 vehicles that do not operate continuously. Compact unit design and smaller supply requirement makes slow-fill fueling possible at private residences, depending on local regulations. The installation shown in Figure 21.4.1 uses vehicle refueling appliances (VRAs) to fuel CNG-powered vans overnight. Average fill time for an automobile or van is 4 to 8 hours, depending on the size and number of cylinders.

Fast-fill CNG stations normally fuel a conventional passenger vehicle in less than 5 minutes. Sometimes, fixed storage vessels are used as supply sources and must be transfilled from a high-pressure transport tube trailer that is brought to the station site. More commonly, a connection to the nearest domestic natural gas distribution system supplies the natural gas. A pressure cascade system compresses and dispenses low pressure natural gas (60 to 100 psi [413 to 689 kPa]) at the higher pressures (2500 to 4500 psi [16,536 to 31,005 kPa]) the CNG vehicle requires. These systems can be found at locations typically serving more than 30 vehicles.

CNG Siting Considerations. CNG fueling is performed at public service stations, small private fleet operations, metropolitan mass transit facilities, school districts, cab companies, government agencies, and residences (if local regulations allow). CNG fueling typically is performed outdoors. CNG compression, storage, and dispensing systems should take into consideration setback distances from property lines, on-site adjacent buildings, overhead power lines, nonclassified overhead electrical lighting, and ignition sources. Protective canopies and open structures installed to protect equipment should be of noncombustible construction, with a roof design that ensures adequate ventilation and prohibits pocketing or collection of CNG due to the buoyancy of natural gas. Typical unintentional releases of CNG will be completed in a matter of seconds due to very high compression and storage pressures. The quick release and buoyancy of CNG minimize the potential threat from open-air flammable vapor cloud ignitions. Ignition of leaking high-pressure gas is possible, and the resulting jet fire can extend from 10 to 30 ft (3 to 9 m) in length, depending on the leak's size and CNG pressure. This makes the orientation of storage cylinders and relief valves an important site consideration. With the addition of protective measures and depending on local regulations, CNG fueling can be accomplished indoors. This is a potential consideration when weather- or freeze-protection is needed for the compression, storage, and dispensing systems. Indoor fueling with CNG can only be accomplished inside structures dedicated to this purpose or within rooms or additions provided with at least 2 hour fire-resistive walls as separation from other occupancies. When dispensing CNG indoors, overpressure protection, such as explosion venting, is necessary. Mechanical ventilation that is continuous or activated by a gas detection system must be installed. To allow for delays in the mechanical ventilation startup, the gas detection system should activate ventilation at a level not exceeding 20 percent of the lower flammable limit. An audible alarm should also sound at the 20 percent lower flammability level. Activation of the gas detection system must result in automatic shutdown of compression and dispensing equipment by placement of solenoid switches and automatic shutoff valves. Although not required by NFPA 52, some model building and fire codes may require the installation of an automatic sprinkler system for indoor dispensing and storage of CNG. Local approvals for indoor dispensing may vary, but public structures, such as parking garages, are commonly unacceptable for fueling of any type of conventional or alternative fuel.

FIGURE 21.4.1 Slow-Fill Vehicle Refueling Appliance (Source: Fuelmaker, Inc.)

When considering the siting of CNG fueling stations, the general public is probably most familiar with the hazard potential of natural gas. Their expectation or acceptance of hazard is commonly based on the low pressure natural gas used for home cooking and heating. Mentioning high-pressure natural gas used in CNG fueling is likely to conjure up consequences associated with large-diameter, high-pressure natural gas transmission pipelines. Major CNG fueling facilities that use large-capacity compressors sometimes require the extension of a larger and higher pressure natural gas pipeline. Those who live near large CNG fueling stations may question their safety and acceptability because they fear CNG fueling components and the increased size of natural gas mains in the public right-of-way.

CNG Compressor Components. The very large range of CNG compressors' capacity makes fill time vary. Small, slow-fill units with a compressor capacity of approximately 5 to 10 SCF/min are small enough to fit in the front seat of a car. NFPA 52 defines these compressors as residential refueling appliances or vehicle refueling appliances (see Figure 21.4.1). They generally require only a normal domestic natural gas supply line. Medium-sized, fast-fill compressors typically found at public fueling stations are capable of supplying approximately 1000 SCF/min (28.3 m^3/min). A normal domestic supply line can also supply these medium-sized compressors. Like the slow-fill units, these fast-fill compressor sets are sometimes packaged with other fueling components and are available as portable, premanufactured units that fit in the space required for a passenger vehicle. Large industrial compressors can compress approximately 5000 SCF/

min (142 m^3/min) at about 3600 psi (24,804 kPa) and can fill the space needed to park a bus. Depending on the number of large compressors needed, supply from a 6-in. (152-mm) diameter natural gas pipeline is not uncommon.

Compressors require pressure relief devices set for each stage pressure. A four-stage compressor might have relief valves set for 250, 1250, 1400, and 4150 psi (1724, 8618, 9652, and 28,610 kPa), depending on the compression chamber's size and associated piping into which they are installed. CNG compressors are also required to have automatic shutdown capability in the event of high discharge pressure or low suction pressure. Compressor controls must be manually reset if an automatic shutoff or power failure occurs. Internal combustion engines, modified to operate using natural gas, usually drive compressor sets. NFPA 52 requires the design, construction, and maintenance of these compressor drivers to be in accordance with NFPA 37, *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines.*

CNG Storage Components. Pressure vessels are a common method of storing compressed natural gas. NFPA 52 requires pressure vessels to be constructed in accordance with the ASME Boiler and Pressure Vessel Code. Fast-fill dispensing transfers CNG from a bank of pressure vessels to the vehicle in a fairly short time, usually less than 5 minutes. These pressure vessel banks, or cascades, are usually multiple compressed gas cylinders, spherical vessels, or horizontal tubes. Normally, three pressure banks are involved in a cascade system (Figure 21.4.2). To "top off" a vehicle container, dispensing begins from a storage vessel having lower pressure until pressure equalizes, then automatic controls switch to a vessel of higher storage pressure. This automatic switching between cascade banks continues sequentially until vehicle fueling is complete. Subsequent vehicles can be filled until cascade pressure drops too low. Then the system automatically switches to the compressor. This, however, increases fill time, so the capacity of storage containers at a site usually reflects the number of vehicles to be served.

Bulk CNG storage is infrequently required when obtaining an on-site natural gas supply to compress is not possible or when the economics of installation does not justify the cost of a compressor. Bulk storage is usually accomplished by transporting gas compressed at another site, then transfilling from the transport tube trailer into pressure vessels. Bulk vessels do not draw down at the same rate when fueling a vehicle, but their automated systems operate like the cascade system. Bulk compressed gas is usually dispensed from at least three vessels (see Figure 21.4.2).

CNG cascade and bulk storage vessels must be adequately supported on no more than two longitudinal points and should be adequately protected from vehicle impact. A check valve should be installed so that backpressure cannot bleed back to the supply, and adequate pressure-relief devices must be installed in each vessel. The pressure-relief devices should be vertically vented and protected against weather. Pressure gauges installed on each vessel or pressure bank determine the fullness of a storage vessel. Sometimes, outlets for storage vessels are fitted with excess flow valves. These devices restrict flow from the vessel if the tubing or piping leaks. A check-type valve closes when flow exceeds that rated for the piping system. Usually, carbon or stainless steel tubing and piping connect the cascade or bulk vessels, and approved flexible metallic hose is installed for expansion, contraction, jarring, vibration, and settling where necessary.

CNG Dispenser Components. Dispensing equipment can look like conventional gasoline dispensing equipment, or it can simply be a hose and nozzle rated for high-pressure service and mounted on a post (Figure 21.4.3). Fuel dispensers should be provided with protection from vehicle impact, using islands, pipe bollards, or other appropriate designs.

If located at a public service station, the dispenser usually measures "equivalent gallons" of fuel; otherwise, the unit of measure varies depending on the owner's needs or local weights and measures standards. Underground piping usually connects

FIGURE 21.4.2 Pressure Vessels for Storing Compressed Natural Gas

FIGURE 21.4.3 CNG Dispensers

CNG dispensers to the storage and compression systems. Just as at a conventional service station, multiple CNG dispensers are not typically installed on one supply line. Instead, each has individual, dedicated piping from the storage or supply.

CNG dispensing systems require electronic or pneumatic controls that sense vehicle container fill pressure and automatically stop the flow. Settings for these controls are based on outside temperature. In addition, an emergency shutdown device commonly installed at the storage and compressor activates if there is a problem at the dispenser. Even so, a "quarter turn" manual shutoff valve is located at the dispenser just upstream from the dispensing hose and its required breakaway device. The hose breakaway device, located outside the dispenser end, closes if a vehicle moves away from the dispenser without breaking the vehicle fueling connection. CNG breakaway devices release and seal at approximately 44 lb (22 kg) of force from any direction.

The CNG fueling hose must be rated for the system's service pressures. Like the flammable liquids dispensing hose, the CNG hose must be nonconductive. A significant feature of the CNG fueling hose is the inclusion of a second hose, usually designed as integral to the supply hose. When fueling is complete, this second hose collects natural gas from the vehicle fueling connection and supply hose. Some dispensing units vent the hose automatically; others require a manual valve to accomplish this venting. In either case, the vehicle connection does not release until the connection and hose is depressurized. After CNG fueling is complete, vented gas returns to the dispenser and ultimately to storage or an approved vent stack, depending on local requirements. Typical CNG fueling hose is easy to handle and is approximately ½ to ¾ in. (1.27 to 1.91 cm) in diameter. CNG dispensing hose cannot be more than 25 ft (7.6 m) long and must be supported aboveground, usually by a retractable cord like those used on conventional fuel dispensers.

The CNG dispensing nozzle that connects the fueling hose to the vehicle is similar to a typical quick-connect coupling used on compressed air hoses, except it includes breakaway protection. The vehicle fueling receptacle, fuel control valve, and dispenser nozzle are designed in accordance with ANSI/American Gas Association NGV 1, *Basic Requirements for Compressed Natural Gas Vehicle Fueling Connection Devices.*[15] The NGV 1 standard includes requirements for the vehicle fueling receptacle, the dispenser nozzles, and the fuel control valve installed at the dispenser. Depending on the component's style, devices are rated for service pressure between 2400 and 3600 psig. The NGV 1 standard defines three types of nozzles:

- Type 1 nozzles use an integral valve operating mechanism that vents the gas between the vehicle's fill line check valve and the nozzle inlet valve and then disconnects the nozzle from the vehicle (Figure 21.4.4). CNG nozzles are similar to quick-connect couplings used on compressed air hoses. The Type 1 nozzle shown in Figure 21.4.4 has an integral valve that vents the gas between the vehicle's fill-line check valve and nozzle inlet before it can be disconnected from the vehicle.
- Type 2 nozzles use an external valve that must be vented before disconnection.

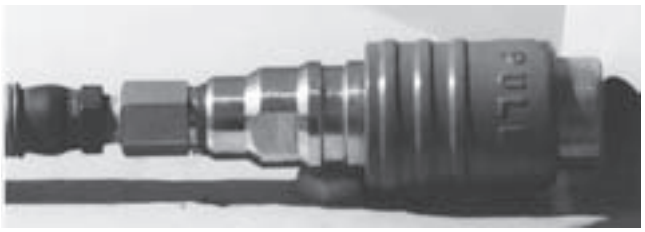

FIGURE 21.4.4 CNG Nozzle

- Type 3 nozzles use controls that automatically depressurize the fill line upon dispenser shutdown. They are normally found on vehicle refueling appliances or residential refueling appliances.

Each type must be designed so that the fueling system is depressurized before the nozzle can be removed.

Liquefied Natural Gas Vehicle Fueling Stations

LNG fueling stations can be characterized according to the method used for obtaining liquid transfer pressure. Some use gravity available from a vertical bulk storage vessel to fill a smaller transfer vessel at 75 to 100 psi (517 to 689 kPa). A portion of the LNG passes through a vaporizer and back into the smaller transfer vessel to warm the liquid. The 618:1 expansion ratio of the LNG in the smaller vessel increases the pressure to as much as 230 psi (1586 kPa) to force liquid into the LNG vehicle. Transfer rates of 40 to 50 gal/min (0.15 to 0.19 m^3/min) are not uncommon.

The other common type of LNG fueling station uses a centrifugal cryogenic pump supplied from a vertical or horizontal bulk LNG storage vessel. Centrifugal cryogenic pumps typically provide LNG fueling rates of 30 to 50 gal/min (0.11 to 0.19 m^3/min), depending on the LNG vehicle tank pressure required. The net positive suction head that the centrifugal pump requires is important. Some installations experience cavitation and poor performance when storage design does not provide enough suction head. Fueling stations that use underground LNG bulk storage vessels are available but not as common. Underground installations use a slow-action, positive-displacement pump that lifts LNG about 25 ft (7.6 m), provides 30 to 50 gal (0.11 to 0.19 m^3/min) of liquid per minute, and delivers at pressures as high as 200 psi (1379 kPa).[16] LNG fueling facilities that use cryogenic pumps typically operate on electricity.

LNG fueling facilities can also be designed to supply CNG vehicles. LNG fueling stations normally create some vapor due to external heat absorption of the stored LNG, priming of pumps, and temperature equalization of equipment. In addition to normal vaporization, LNG is sent to a vaporizer to create gas specifically for fueling CNG vehicles. Under some conditions, LNG to CNG fuel supply or liquefied-compressed natural gas (LCNG) may be cheaper than CNG supplied from domestic natural gas lines. Facilities that use vapor expansion for LNG fueling pressure provide a compressor and cascade system to fuel CNG vehicles. Systems with high-pressure LNG pumps combine LNG pump capacity and gas expansion, through the

vaporizer, to fill the CNG cascade storage. The CNG must be odorized with an odor potent enough to be detected to down to a concentration in air of not over one-fifth of the lower limit of flammability.

LNG Siting Considerations. LNG vehicle fueling is typically associated with large fleet operations in heavily populated urban areas. These include such facilities as mass transit, cab companies, and government agencies. Some rural fleets that use large vehicles, such as mining operations or transport trucking, have also converted to LNG use. Because a significant number of fleet vehicles are necessary for LNG fueling to be economical, self-serve general public vehicle fueling with LNG is not expected to become commonplace.[12] In addition, indoor fueling with LNG is not typically performed. However, it has been proposed that this activity be limited to the use of less than 125 gal (0.47 m^3) containers when necessary gas detection, ventilation, fire protective, and building construction features are provided.

NFPA 57 sets distances from impoundment areas to building and property lines. These distances are based on the container volume and range from 0 for containers of 0.5 m^3 or less to 23 m for containers of 114–265 m^3. This range of 0.5–265 m^3 should include most LNG storage containers. Additionally, there are minimum distances between storage containers set in NFPA 57; these distances range from 0 for containers 0.5 m^3 or less to one-fourth of the diameter of adjacent container(s) for containers ranging from 114 to 265 m^3. There are also requirements for container seismic design that specify the horizontal and vertical forces that shop-built ASME containers must meet based on the amount of seismic activity at the location where the container is to be installed.

Normally buoyant, natural gas vaporizing from a supercooled liquid state remains initially heavier than air. While cool, the natural gas forms a vapor cloud that follows the ground surface until it heats sufficiently to regain its lighter-than-air characteristics. In addition to separation, site consideration should include containment of the fueling facility. Containment helps limit the surface area of an LNG spill, reduces the spill vaporization rate, and thereby reduces the distance a potential vapor cloud travels before becoming buoyant. Separation and containment are important requirements, particularly when locating an LNG fueling facility near other land uses that are densely populated or provide potential ignition sources.

LNG Storage Components. LNG storage and use is not something that very many communities have experienced. Members of the general public who are presently familiar with LNG facilities usually live in areas that have bulk LNG supply for domestic natural gas distribution or power plant peak shaving needs. Cryogenic gas storage and liquid transfer have a long history, but bulk storage and dispensing of LNG vehicle fueling is a relatively new use of an adapted technology. Compared with the other types of alternative fuels, LNG use in private vehicles does not seem to be as well demonstrated. This could result in hesitation to accept the additional hazards associated with LNG storage and vehicle fueling in densely populated urban areas or the costs associated with LNG systems versus CNG systems.

LNG is normally transported from a liquefaction plant to the fueling facility by cryogenic bulk transport trailers. Transfilling may occur at night because LNG-fueled fleets need to be filled before business hours. The number of vehicles to be filled and the capacity of on-site storage dictate the frequency of LNG transport and transfilling. Bulk LNG at typical fueling sites is stored in containers having a total capacity of approximately 15,000 gal (57 m^3). This quantity allows unloading of one transport that usually carries 11,000 to 13,000 gal (42 to 49 m^3) (Figure 21.4.5). Depending on delivery schedules and demand, more than one container might be located at a fueling site. Containers can be horizontal or vertical, depending on owner preference, aesthetics, and available space.

Siting of containers should be based on the requirements of NFPA 59A. Transfer of LNG from the supply truck trailer to bulk storage is accomplished by increasing the trailer's normal storage pressure of 10 psi (70 kPa) to approximately 40 to 50 psi (276 to 345 kPa). If a vertical bulk storage vessel is used, transfer pressure may be as high as 250 psi (1724 kPa). This is accomplished by boiling off some LNG in an auxiliary line and allowing it back into the trailer. A small amount of LNG may leak out of the hose connection to the bulk vessel because of the temperature difference between the inside and outside of the fueling connection. LNG bulk storage containers have liquid level gauges and a high liquid level alarm or indicator that warns the operator to stop filling the bulk vessel. When transfer is complete, a pump on the supply truck transfers any LNG remaining

FIGURE 21.4.5 A 13,500 gal (51 m^3) LNG Container Used for Vehicle Refueling

in the hose to the storage vessel. During transfer, a pressure differential of at least 15 psi is maintained between the transport trailer and the bulk storage vessel. In the event of a backfill condition, a backflow check valve is required on the transfer fill piping of an LNG bulk storage vessel.

LNG spill containment should include the following requirements:

- Impounding area that has the volumetric capacity to hold the greatest volume of LNG that could be discharged into the area during a 10 minute release from any single accidental leakage source
- Measures to prevent any release of LNG from the plant property and for surface water drainage
- Provisions to clear rain or other water from the impounding area
- Separating the point of transfer from the nearest important building not associated with the LNG facility by 25 ft (7.6 m)
- Selecting a design and materials appropriate for LNG
- Operating instructions identifying the location and operation of emergency controls

The use of insulated materials considerably reduces vapor dispersion distances. The containment system's design and the type of insulating material used can reduce the vaporization rate as much as 30 percent.[17] Equipment within the containment should be limited to LNG-related apparatus. CNG equipment such as compressors, vaporizers, and CNG storage cylinders should not be located within the LNG secondary containment, due to potential fire exposure and damage from high pressure.

Pressure-relief valves must be designed with a capacity to not only vent vaporized natural gas adequately if fire exposure occurs but also include capacity for the flow of liquid in the event an overfill of the bulk storage occurs. Pressure-relief valves are typically located in the storage vessel, the insulation space of the vessel, and any insulated piping that can be isolated between two block valves. Typically, a system of air-operated valves controls the flow of liquid for vehicle fueling. Air supply lines for the flow control valves commonly consist of low-melt-point plastic tubing. If exposed to fire, these air supply lines will melt and cause the valves to shut in a fail-safe manner.

LNG Dispenser Components. Dispensers available for LNG fueling can look like conventional fuel dispensers. Typically they do not. Instead they are an assembly of a cryogenic coupling nozzle, insulated cryogenic hose, shutoff valves, and panel or pole mounted gauges. Sometimes the fueling hose attaches to a rotating arm that supports the hose as it is attached to the vehicle. If not, a retractable stainless steel cable supports the cryogenic hose. LNG fueling hoses are insulated and can be 3 to 4 in. (7.6 to 10.2 cm) in diameter. They are fitted with a large cryogenic coupling, about 1 in. (2.5 cm) in diameter. Compared to conventional fuel hoses and nozzles, this assembly can be cumbersome.

A shutoff valve is attached on the open end of the cryogenic hose, just before the LNG coupling that connects to the vehicle. This coupling includes an interlock device that does not allow release during transfer. LNG couplings operate like sexless fittings commonly used on fire hose. A manual emergency shutoff valve is placed in the transfer system, near the connection to supply piping at the storage vessel. This manual shutoff valve must be readily accessible by the operator. Bleed or vent connections incorporated into the coupling let dispenser hoses be drained, depressurized, and sometimes purged with nitrogen. These connections usually drain to a vaporizer, and natural gas either vents or is transferred to a CNG fueling process. LNG dispensing units may have electronic level sensors that automatically activate the dispensing shutoff valve. More often, a level gauge provided on the vehicle requires the operator to measure the vehicle tank level and then manually stop dispensing. Even with these controls, providing drainage should be considered so that accidental LNG spills drain into the storage vessel secondary containment.

Liquefied Petroleum Gas Fueling Stations

Types of LP-Gas Fueling Stations. LP-gas used for vehicle fueling is typically propane. Propane has a long history of use in industrial applications and predominately rural areas as a home-and-business heating fuel. Although most domestic propane heating appliances use vapor as fuel, vehicle fueling transfers propane in liquid form. The equipment needed has been used for many years at bulk plant facilities for transfer to bobtail propane delivery trucks and for container filling. This equipment has also been extensively used for forklift truck fueling at manufacturing and storage occupancies.

Historically, propane vehicle fueling in the United States has been predominantly at bulk plant locations or with the other traditional propane supply services. Some consider LP-gas vehicle fueling the least complicated of the three alternative fuels discussed in this chapter. The mechanics of supplying liquefied gases for fueling vehicles does not vary significantly from the processes used for supplying LP-gas for heating. LP-gas at vehicle fueling locations is typically moved to the fueling site by highway transport truck and then transfilled into the bulk fueling storage container.

There are three common ways to transfer LP-gas in the liquid phase: (1) by use of an LP-gas pump, (2) by gravity, and (3) by use of a compressor. Using LP-gas pumps to transfer liquid is the most common method. This is because of the flexibility afforded by not having a required tank elevation or hazards associated with vessel pressurization. LP-gas pumping has been used extensively to fill LP-gas bobtail delivery trucks from bulk storage vessels. The same pump technology has been adapted for use in fueling vehicles with propane. Positive displacement pumps, such as sliding vane, gear pumps, or centrifugal pumps, are common with the pump discharge pressure limited to a maximum of 350 psig (2412 kPag). Electricity usually powers the LP-gas pumps used at vehicle fueling stations.

LP-gas vehicle fueling facilities can use horizontal, vertical, or, sometimes, underground pressure vessels. Vehicle fueling at LP-gas bulk storage operations is typically in horizontal pressure vessels. LP-gas vehicle fueling at locations with space limitations sometimes uses vertical pressure vessels. Underground pressure vessels dedicated for LP-gas vehicle fueling are not as common because of additional cost, maintenance respon-

sibilities associated with corrosion protection, and, sometimes, prohibitive soil conditions.

LP-Gas Siting Considerations. Vehicle fueling with LP-gas should be limited to outdoors. The liquid–vapor expansion ratio of propane is approximately 270:1,[14] so an unintended liquid discharge releases a greater quantity of vapor than does a leak from the LP-gas vessel's vapor space. In addition, vapor release from emergency relief valves due to unintended container overfilling makes LP-gas vehicle fueling hard to justify as an enclosed, indoor activity. Even outdoors, propane tends to form a vapor cloud that, under the right conditions, can travel downwind at flammable concentrations until it encounters an ignition source. This is because LP-gas has a vapor density approximately 1.5 times that of air. Less common, but possible, is an LP-gas container BLEVE incident initiated by an emergency relief device failure or rapid container exposure to intense radiant heat.

Setback distances from adjoining property lines and adjacent buildings should be evaluated not only for building exposure from leaks at the LP-gas fueling station but also for building fire exposure on the fueling station. Considering mutual exposure is sometimes complicated. Many published setback requirements intend to prevent smaller, more common LP-gas vapor releases from reaching an ignition source. These distances also provide space to buy time for implementing emergency activities such as applying water to a propane pressure vessel to protect it from an adjacent fire's radiating heat. Typically these distances offer protection for releases, such as those from emergency relief valves, that result from container overfilling. A large, continuous liquid leak from a damaged or malfunctioning container connection, transfer piping, or pump casing can produce more serious vapor cloud, BLEVE, and shrapnel hazards. The hazards associated with these situations exceed the largest setback distances specified for LP-gas applications. The setback distances given in NFPA 58 should be considered minimum requirements to reduce risk. These distances should not be treated as safe distances that would eliminate all risk or eliminate the effect of all types of hazardous events associated with LP storage and transfer operations.

Historically, the location of LP-gas applications has been predominantly in rural or suburban areas, or in commercial or industrial areas. In these locations, hazards are commensurate with other hazardous operations and exposure to the public has been limited accordingly.[18] The addition of LP-gas vehicle fueling stations to heavily populated urban areas offers LP-gas suppliers new markets, sometimes near congested residential areas that historically supported conventional public fueling stations. Additional setbacks and protective equipment should be considered in these situations. These help limit urban public exposure to a risk level enjoyed before the alternative fuels market expanded. NFPA 58 gives a set of alternative provisions for the installation of American Society of Mechanical Engineers (ASME) containers, which includes additional safety requirements that allow for setback distance reductions. These provisions would allow the installation of ASME containers at locations, such as conventional refueling facilities, without increasing the risk that these installations create. These additional safety measures include low emission transfer and automatic shutdown of all primary valves in the event of a fire or hose pull-away. Figure 21.4.6 shows a fueling facility that stores and dispenses gasoline, CNG, and LP-gas in an urban area. A release or fire from such an aboveground fueling facility would impact surrounding fire exposures, the general public, and emergency responders.

LP-Gas Storage Components. LP-gas vehicle fueling has typically been accomplished at bulk storage facilities where large volumes are stored in horizontal pressure vessels. With LP-gas vehicle fueling increasing at existing industrial and commercial fleet sites, limited available land area has made the use of vertical pressure vessels more common. The size of pressure vessel used for storage varies because some installations are not dedicated solely to LP-gas vehicle fueling. Typically, installations dedicated for public vehicle fueling use storage pressure vessels having a water capacity of 1000 to 2000 gal (3.8 to 7.6 m^3).

These storage vessels must meet standards addressed in the *ASME Boiler and Pressure Vessel Code*[19] or the API-ASME *Code for Unfired Pressure Vessels for Petroleum Liquids and Gases.*[20] LP-gas pressure vessels must meet design or service pressures, which depend on the vapor pressure of the LP-gas stored. Propane storage vessels used for fueling require a minimum design pressure of 250 psig (1724 kPa). Structural support for LP-gas storage vessels containing propane can vary from

FIGURE 21.4.6 Fueling Facility Storing and Dispensing Gasoline, CNG, and LP-Gas in Densely Populated and Congested Urban Area

concrete saddles on horizontal vessels to structural metal supports protected with a fire-resistive coating on vertical tanks. LP-gas fueling vessels should be permanently fastened to paved surfaces or concrete pads, adequately protected from vehicle impact, and protected from tampering by chain-link fencing. Secondary containment is not provided at LP-gas vehicle fueling facilities because when spilled or released, nonrefrigerated liquid propane immediately vaporizes.

Bobtail tanker trucks with a capacity of 2000 to 4000 gal (7.6 to 15.2 m^3) most commonly supply LP-gas vehicle fueling stations. The operator transfers liquid by a pump mounted on the transport vehicle. A transfer hose connected to the pump discharge is attached to a threaded fill pipe connection located a short distance away from the storage vessel. This fill pipe allows the operator to top fill the fueling station storage container without having to climb on top. NFPA 58 has setback requirements for various types of exposures from the point of transfer if that point is not located on the container. For bulk LP-gas storage, transport hose connections at the fill pipe include breakaway protection. At bulk plants, bulkhead devices provide this protection with cable-activated or pneumatic emergency shutoff valves. On smaller vessels dedicated for LP-gas vehicle fueling, these are not typical. Instead, their design usually incorporates a breakaway valve in the vessel fill piping. In addition, a required backflow check valve at the inlet to the storage vessel prevents pressurized contents from flowing from the fill connection if the piping is damaged.

Filling the storage vessel proceeds until the operator notes that the liquid level has reached the maximum allowed. Several options exist for monitoring when the storage vessel is full. Using a fixed maximum liquid level gauge is a popular method. A No. 54 drill hole bleed valve in this device connects to an internal dip tube. When vessel filling is to begin, the valve is opened and normally vents invisible vapor. The operator notes refrigerated air moisture through the bleed valve when vaporizing liquid reaches the predetermined interior dip tube height. The operator then stops the liquid transfer. Variable liquid level gauges, such as a slip tube or rotary tube, operate similarly but indicate liquid height on a scale that the operator reads to determine when the vessel is properly filled.

Emergency shutoff valves are required at LP-gas vehicle fueling facilities. These consist of emergency devices associated with dispensing from storage into the vehicle. Manual shutoff valves, excess flow check valves, backflow check valves, and quick closing internal valves can be used at liquid bypass, vapor recycle, liquid withdrawal, and equalizing connections. Storage vessel discharge connections located at the bottom of the vessel can be provided with shear protection in the event the discharge piping is damaged. To protect the vessel against significant fire exposure in the event of a leak, a fusible link shutoff valve is commonly installed at the vessel liquid opening, usually in conjunction with an excess flow check valve.

The excess flow check valve for discharge from the vessel is usually installed internal to the vessel; some valves are manufactured to be installed in-line. A spring normally holds excess flow check valves open. The valves close automatically when the device's rated liquid flow is exceeded. Excess flow check valves operate only if a break in the vessel discharge line is sufficiently large for flow to exceed the rated valve setting. Pump bypass liquid lines and vapor equalization lines, commonly connected to LP-gas storage, also have excess flow check valves.

LP-gas storage vessels used for vehicle fueling must have one or more pressure relief devices installed in their vapor space. ASME vessels having a water capacity greater than 1200 gal (4.5 m^3) must have spring-loaded pressure-relief valves that directly communicate with the vessel vapor space. These self-actuated relief valves help to limit the accidental release of LP-gas because they normally close when excess pressure is relieved. Other devices, such as frangible or rupture disks, let the entire contents of the pressure vessel discharge and, therefore, are not used in LP-gas pressure vessels. In addition to spring-loaded relief valves, fusible plugs not exceeding ¼ in. (0.6 cm) diameter may be installed in pressure vessels with a water capacity lower than 1200 gal (4.5 m^3).

LP-Gas Dispenser Components. LP-gas dispensing devices typically include a meter, vapor separator, hydrostatic relief valves, check valve, solenoid valve, pressure differential valve, and manual shutoff valves. As with the other types of alternative fuels, dispensers can be the simple assemblies mounted on a post that are common at fleet operations or the manufactured dispensing units for public fueling locations. Manufactured dispensing units can look like those used for conventional gasoline or diesel fueling. Excess flow check valves in a shear plate are generally installed below the dispensing unit and function like shear valves under conventional flammable liquid fuel dispensers.

LP-gas dispensers can fill at a maximum rate of approximately 18 gal/min (0.07 m^3/min).[21] Pursuant to NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages,* LP-gas dispensers should be located at least 20 ft (6.1 m) from gasoline or diesel dispensers. LP-gas fuel hoses must be fitted with a listed emergency breakaway device to prevent propane releases in the event a driver pulls away while the fueling hose is still connected. The LP-gas vehicle fueling hose, commonly known as "wet" hose, is required to be continuously marked "LP-GAS," "Propane," and "350 PSI WORKING PRESSURE." Fueling hose typically connects to the vehicle via a U.S. standard 1¾ in. (4.5 cm) acme-threaded connection. These connectors are designed with a mechanism that prohibits liquid flow unless connected to a vehicle. A "quarter turn" valve located before the threaded connection controls flow. Flow control valves are available with a lever action similar to conventional gasoline-dispensing nozzles. The main difference is that LP-gas lever valves do not presently shut off automatically when the liquid level is full. Instead, an outage gauge or outage vent valve is located on the vehicle, near the hose connection.

The vehicle outage gauge operates like bulk vessel liquid level gauges. When the vehicle tank is approximately 80 percent full, a small amount of liquid propane is released through the outage vent. The operator recognizes that the vehicle container is full and manually disengages the dispensing flow valve. This venting to atmosphere at each refueling has been recognized as a potential problem. Automatic shutoff devices, such as a float valve inside the vehicle tank, are available, and computer-controlled overfill systems are being developed. When per-

fected, these systems might be required on all LP-gas vehicles or dispensers.

VEHICLE COMPONENTS, DESIGN, AND OPERATION

The appearance and shape of alternative-fueled vehicles are the same as conventional-fueled vehicles. In many cases, they are conventional-fueled vehicles that have been retrofitted to operate with alternative fuels. Several vehicle manufacturers are developing alternative-fueled versions of their popular conventionally fueled models. How the fuel is carried and consumed differs in the vehicles. Although vehicle storage containers and delivery systems differ for each type of fuel, the concept is the same for all hydrocarbon alternative fuels. CNG, LNG, and LP-gas vehicles store and consume a mixture of flammable gas. Understanding fuel storage and consumption is important from the perspectives of the vehicle's operator, the individual fueling the vehicle, and the emergency responder.

There are two types of alternative-fueled vehicles: (1) those converted from another fuel, called bi-fueled conversions, and (2) those designed to be exclusively powered by CNG, LNG, or LP-gas. Bi-fuel converted vehicles may operate on natural gas or propane and a conventional fuel, such as gasoline or diesel, because the liquid fuel system remains intact. CNG-, LNG-, or LP-gas-fueled vehicles can cost more than conventionally fueled vehicles because of the vehicle fuel tank expense.

Compressed Natural Gas Vehicles

CNG vehicles include conventional passenger vehicles, light- and medium-duty trucks, and heavy-chassis vehicles such as transit buses. CNG vehicles store natural gas compressed at pressures of 2500 to 4000 psig (17,235 to 27,576 kPa) in compressed gas cylinders equipped with a pressure relief device, a filling connection, and a shutoff valve. The vehicle fuel container connects to either a manifold or single fuel line equipped with a manual shutoff valve. Natural gas is dispensed to the engine via a pressure regulator that reduces the gas to the service pressure the engine uses. After its pressure is reduced, the gas enters a gas-air mixer to produce a flammable mixture that is injected into the internal combustion engine.

NFPA 52 applies to the design and installation of CNG fuel systems on all types of vehicles and their fuel dispensing systems. The standard's scope includes the CNG element of bi-fueled vehicles and vehicles originally manufactured to operate using CNG. Fuel is delivered from a CNG dispenser through its nozzle and introduced into the vehicle's container through the vehicle fueling receptacle. The attachment is like a typical quick-connect coupling used on compressed air hoses. Vehicle fueling receptacles are designed in accordance with ANSI/American Gas Association NGV 1.

CNG Fuel Containers. CNG fuel containers are designed to store compressed methane gas at high pressures. The gas is stored in a compressed state to increase the quantity that can be stored on board the vehicle, thus increasing the vehicle's driving range. American Natural Standards Institute/American Gas Association NGV2, *Basic Requirements for Compressed Natural Gas Vehicle Fuel Containers,*[22] addresses the design and construction of CNG fuel containers. NGV2 containers have service pressures between 2400 and 4350 psi (16,546 and 29,989 kPa) at 70°F (21°C), capacities not greater than 35.4 ft^3, and a service life of 15 years. NGV2 containers are either constructed of metal (NGV2–1), a metal liner reinforced with hoop-wrapped (NGV2–2) or full-wrapped (NGV2–3) resin-impregnated continuous filament, or a full-wrapped continuous filament with a nonmetallic liner (NGV2–4). All construction materials must be capable of operating throughout a temperature range of –40 to 180°F (–40 to 82°C). Containers installed in vehicles require identification using a label that reads "CNG ONLY." This label is required to prevent the installation of cylinders not designed for CNG service.

CNG vehicle fuel containers are subject to nondestructive pressure and leak tests. To achieve certification, metal containers and liners must successfully pass destructive tests that evaluate the materials yield strength, tensile strength, elongation, and its performance under mechanical impact. Other requirements that must be met include drop, fire exposure, gunfire, gas permeation, pressure cycling, and burst tests. These tests ensure the container maintains its integrity over its service life.

Vehicle containers can be located inside, below, or above the driver or passenger compartment, provided all connections to the container are either external or sealed and vented from the area where the driver or passengers sit. Containers are installed in a location that minimizes the probability of damage resulting from a collision. Neither containers nor container components can be located ahead of the vehicle's front axle or behind its rear bumper.

The mounting mechanism must secure the CNG vehicle fuel container to the vehicle's frame, body, or cargo box to prevent damage resulting from road hazards, container slippage, and loosening or rotating of the container. The method used for mounting the container must withstand a static force of eight times the weight of a fully pressurized cylinder applied in six directions of loading. When subjected to this load test, the container is allowed a maximum displacement of ½ in. (1.3 cm) in any direction of loading. Unless shielded, containers require a minimum 8 in. (20.3 cm) clearance from vehicle exhaust systems. If metallic clamps or clamping bands are used, they cannot be in direct contact with the container. This necessary provision protects the container from exterior corrosion resulting from moisture accumulation or mechanical vibration. To satisfy the requirement, a resilient, water-resistant material is commonly installed between the clamp and the container supports.

CNG Pressure-Relief Devices. Vehicle fuel containers are required to be fitted with one or more pressure-relief devices. Pressure-relief devices protect the container from catastrophic failure due to overpressure resulting from fire exposure.

Pressure-relief devices for CNG cylinders are constructed in accordance with Compressed Gas Association Pamphlet S-1.1, *Pressure Relief Device Standards, Part 1—Cylinders for Compressed Gases.*[23] Pressure-relief devices can be rupture disks, fusible plugs, a combination rupture disk/fusible plug,

or a pressure-relief valve. A rupture disk is the component of a pressure-relief device designed to burst at a predetermined pressure and allow gas to discharge. Rupture disks are preformed metal designed to fail at a particular pressure or temperature. When a rupture disk operates, it vents the entire contents of the container. Rupture disks do not close. Fusible plug devices are also nonreclosing pressure-relief devices designed to function when a plug of fusible material melts at a suitable temperature. Fusible plugs are designed to operate at a nominal yield temperature of either 165°F or 212°F (74°C or 100°C), depending on the material selected.

Pressure-relief valves are safety valves designed to relieve excessive pressure. They reclose and reseal to prevent the further flow of gas from the container after the reseating pressure has been achieved. Pressure-relief devices are installed so the relief device is in direct communication with the fuel. Additionally, a shutoff valve should not be installed between the pressure-relief device and the cylinder, or after the pressure-relief devices.

When containers are installed inside vehicles, such as in the cargo trunk of a passenger car, these are the following requirements concerning how the pressure-relief device is installed and terminated to the vehicle's exterior:

- Installation in the same vehicle compartment of the container
- Termination to the exterior using piping or tubing of at least the same diameter as the pressure-relief device
- Termination of the vent opening so that road debris will not block it
- Enclosure of the container neck and all CNG fittings within a gastight compartment

Valves located at the container and the engine isolate the piping system from the container and the engine. A vehicle manual shutoff valve is also located along the frame rail. These valves are provided for the safety of the vehicle user, persons performing repairs, and emergency responders.

A valve is required for the vehicle container. The container valve can be operated manually or with a normally closed remotely activated shutoff valve. When the container has a remotely activated valve, the valve must be equipped with a means that allows the cylinder to be depressurized. Regardless of the valve type used, authorities having jurisdiction should ensure that personnel performing maintenance activities on CNG vehicles clearly understand the manufacturer's procedures for depressurizing a charged cylinder of CNG. In Texas in March 1993, the Austin Fire Department responded to a fire involving a CNG vehicle. The fire resulted from a mechanic improperly depressurizing the container by not electrically bonding the depressurizing tool to the vehicle frame. The high-pressure discharge of natural gas created a static accumulation and spark that ignited the gas jet, forming a flame jet approximately 15 ft (4.6 m) long, as witnessed by arriving fire fighters. Although the fire did not result in any fire fighter or civilian injuries, the vehicle of fire origin was destroyed and an exposed vehicle suffered damage from the thermal flux of the flame jet.[24]

A second valve is required between the engine and the fuel cylinder that permits fire fighters and repair personnel to isolate the containers from the remainder of the fuel system. This manual shutoff valve must be installed in an accessible location and can have no more than a 90° rotation from open to closed position. Labels or stencils stating "MANUAL SHUTOFF VALVE" identify the valve location. The manual shutoff valve requires protection from vibration and road hazards (Figure 21.4.7).

CNG Piping. Finally, a third valve is required in the fuel system that automatically prevents the flow of CNG when the engine is not running but the ignition switch is in the "ON" position. This ensures that methane does not flow during repairs while the vehicle's electrical system is energized.

Piping is used in a CNG fueling system because it offers a reliable, safe, and affordable method of moving high-pressure gas from the container to the engine. Normally, rigid or flexible stainless steel fuel lines connect the fuel containers, engine, and vehicle fueling receptacle. The use of certain materials for CNG piping service is prohibited: plastic piping and fittings for high-pressure service and galvanized piping and fittings. Even so, other considerations, such as temperature and vibration, must be taken into account.

Piping installed on vehicles is subjected to a fairly rigorous service life. As a result, the piping installed between the container and the secondary shutoff valve located along the vehicle's frame must capably withstand a hydrostatic pressure of at least four times the rated service pressure without structural failure. This generally results in only stainless steel tubing being used for CNG vehicle fuel lines.

Pipe connections can be welded, mechanically bent, or mechanically connected. When piping or tubing is threaded, the pipe sealing material must be impervious to natural gas and be applied to all male pipe threads before assembly. When mechanical joints or connections are used, joints must be located in an accessible location. Pipe routing must consider the effects of vibration, corrosion, damage from road objects and collisions, and normal service life wear and tear. Piping routed through engine compartment fire walls or other vehicle panels requires protection from abrasive wear through the use of grommets or other acceptable means.

When the engine requires fuel, the gas leaves the storage containers and flows to a high-pressure regulator. The gas pressure from the fuel container reduces to an intermediate pressure. As the gas expands from a fuel container pressure of 2500 to 4000 psig (17,235 to 27,576 kPa) to the intermediate pressure of 120 to 300 psig (827 to 2068 kPa), its temperature drops by

FIGURE 21.4.7 A Typical Label Identifying the Location of the Manual Shutoff Valve Between the Fuel Containers and Engine, as Required by NFPA 52

as much as 100°F (38°C). If the gas contains too much moisture, it can freeze and damage the fuel system and engine. Also, cold gas can harden pipe seals in the fuel system and result in leaks. For these reasons, most CNG vehicles have pressure regulators heated by engine coolant.

From the high-pressure regulator, the methane gas flows toward the engine through another line to the low-pressure regulator. Located in the engine compartment, the low-pressure regulator reduces gas pressure to approximately 100 psi (689 kPa). Engine coolant does not normally heat this regulator because the refrigeration effect is negligible. From the low-pressure regulator the gas flows to the engine, entering the fuel injectors and the cylinder's combustion chamber.

Liquefied Natural Gas Vehicles

LNG vehicles can be used for such applications as midsize and heavy-duty truck chassis vehicles, such as refuse trucks and transit vehicles. However, LNG is also a viable fuel for railroad locomotives and marine vessels. LNG vehicle fuel systems have several components, such as a pressure regulator and gas-air mixer, that are like those on CNG vehicles. Because engines cannot consume cryogenic fluids, the liquid must be converted to gas, which requires a heat exchanger.

NFPA 57 applies to the design and installation of LNG fuel systems on vehicles and their fuel-dispensing systems. The standard scope includes the CNG element of bi-fueled vehicles and vehicles originally manufactured to operate using LNG. Vehicles fueled by LNG have components designed to operate at temperatures and pressures encountered in cryogenic service. These components are on the system's liquid side. Major components on the cryogenic side of the fuel system include the vehicle's LNG storage tank and fuel lines. When LNG vaporizes into a gas, its components are designed for compressed gas service. Major components on the vapor phase side of the system include the heat exchanger and pressure regulator.

LNG Fuel Containers. LNG vehicle containers commonly use a vacuum-jacketed Dewar-type design, based on the Dewar flask. This double-walled vessel has reflective surfaces on the container's exterior where vacuum is maintained between the two walls. This helps prevent the LNG loss when the container and liquid become warm. An important consideration in LNG vehicle containers' design is hold time. Hold time is the length of time a vehicle can remain unused until pressure in its tank builds to a point that it must be vented. Hold time depends on the liquid/vapor ratio in the tank, as well as the tank's construction. The liquid/vapor ratio depends on the amount of tank ullage. Space is always required to allow for vaporization and liquid expansion that occurs as temperature and pressure increase. The ullage is typically 5 to 10 percent of the vehicle's tank volume. Ullage is necessary in the event the tank reaches a vent pressure. When the pressure-relief valve functions to relieve pressure, gas, not LNG, is discharged.[25]

LNG vehicle fuel containers are constructed with an inner tank and outer tank. The inner tank is normally constructed of stainless steel. Because it serves as a cryogenic pressure vessel, the inner tank's design meets Section VIII, Division 1 of the *ASME Boiler and Pressure Vessel Code* or U.S. DOT regulations 49 CFR 178, for example, DOT 4L tank. It normally contains a baffle and method of indicating the level of liquid in the container. The outer tank is constructed of either stainless or carbon steel. The inner tank connects to the outer tank with supports designed to minimize heat conduction but maintain the container's structural integrity. To minimize radiation heat transfer, insulation consisting of multiple layers of aluminum/polyester film separated by nylon netting is placed in the container's interstice. A vacuum drawn in the interstice minimizes the effect of convective heat transfer. Common LNG vehicle containers are cylindrically shaped with elliptical heads. The structural integrity of an LNG vehicle fuel container during normal operation and under fire or other abnormal stress is analyzed in the tank design. The structural integrity of the LNG container must be evaluated against vibration, acceleration, and shock loads to determine crashworthiness.

LNG vehicle fuel containers are required to have identification features for individuals performing repairs and emergency responders. With the exception of openings for pressure relief or liquid gauging, all openings are designated as to whether they open into the vapor or liquid space. The total volume of the container is identified, and signs indicate that the container can only be used for LNG service. Valves to control liquid and vapor flow must be readily accessible and operable without the use of tools.

Location of the LNG storage container on a vehicle is an important consideration. Containers should not be located ahead of the vehicle's front axle, beyond its rear bumper, or on its roof. Containers may be installed in the interior of vehicles, provided the compartment is not in direct communication with the driver, passenger, or any space containing radio transmitters or spark-producing equipment. This can be accomplished by providing gastight enclosures over the equipment and venting the enclosure outside the vehicle. When LNG is not odorized, a continuous monitoring methane gas detection system is required in the compartment holding the container. The detection system should be designed to sound an alarm when the atmosphere in the compartment exceeds 20 percent of the lower flammable limit for methane. The gas detection system is not required to stop the flow of fuel or turn off the engine's ignition.

LNG Pressure-Relief Devices. LNG storage containers require pressure-relief devices. Most vehicle containers are equipped with pressure-relief valves and rupture disks. Pressure-relief valves relieve the pressure that develops during the LNG hold time in the container. If the pressure-relief device fails, pressure increases until the rupture disk fails. The burst pressure of the disk is higher than the relief valve setting but lower than the container's design pressure. Unlike conventional relief valves, rupture disks are not designed to close. If a rupture disk operates, LNG vapor is released until the tank is empty. If the vehicle is involved in an incident in which the container is overturned and the rupture disk operates, LNG discharges from the pressure-relief opening.

LNG Heat Exchanger and Piping. LNG must be converted from liquid to gas for proper combustion in reciprocating

engines. A heat exchanger performs the phase change. Commonly called a vaporizer, the heat exchanger raises the temperature of LNG vapors so that the phase change from liquid methane to methane gas is efficient. A commonly used heat-transfer medium is engine coolant recirculated between the heat exchanger and the engine's radiator. At maximum fuel flow rate, the heat exchanger must have the capacity to completely vaporize the LNG. In addition, it must heat the gas to the appropriate temperature before the gas enters the fuel regulator. Identifying the maximum allowable working pressure for heat exchangers is a necessity to protect the device against possible overpressurization resulting from the installation of an improperly sized relief device.

From an emergency response perspective, the heat exchanger is the component in the fuel system dividing the cryogenic side and the vapor phase, or noncryogenic side. A pressure regulator ahead of the heat exchanger controls the pressure of gas consumed at the mixer or carburetor.

Piping transfers LNG from the vehicle container's liquid withdrawal connection, through the heat exchanger and pressure regulator, to the carburetor or fuel injector. As LNG travels from the fuel container through the fuel line to the heat exchanger, it begins to warm, causing condensation on exterior surfaces. Most fuel lines are insulated to retard heat loss. Piping designed for LNG vehicles is required to withstand pressure of at least twice the container's maximum allowable working pressure. Typical construction materials for piping include stainless steel, brass, and copper that are fitted using threaded, welded, or brazed joints. Where valves are arranged such that LNG could be trapped between them, a pressure-relief device must be installed in the pipe section to relieve any excess pressure the warm LNG causes.

Liquefied Petroleum Gas Vehicles

LP-gas vehicles include industrial trucks, farm equipment, and vehicles ranging in size from automobiles to heavy-duty trucks. LP-gas has the longest history of all the alternative fuels. Propane used to heat rural homes has also been readily available on the farm for use as a vehicle fuel. According to the DOE's *Transportation Energy Data Book* (Edition 20-2000), approximately 270,000 vehicles in North America are fueled using LP-gas (see Table 21.4.1). This figure does not include off-road vehicles; including these vehicles would increase this number significantly.

LP-gas vehicles normally use propane, a flammable, liquefied petroleum gas stored at pressures of approximately 120 to 200 psig (827 to 1379 kPa), depending on its specific gravity and storage temperature. The vehicle container connects to either a manifold or single fuel line that dispenses propane to the engine via expansion of the liquefied gas. The gas enters a propane carburetor and produces a flammable mixture that is injected into the engine's combustion chamber.

NFPA 58 applies to the design, installation, and maintenance of LP-gas fuel systems on all vehicles and fuel dispensing systems. NFPA 58 covers the installation of fuel systems supplying engines used to propel vehicles such as passenger cars, taxicabs, multipurpose passenger vehicles, buses, recreational vehicles, trucks (including tractors, tractor semitrailer units, and truck trains), and farm appliances.

LP-Gas Containers. NFPA 58 regulates the design, fabrication, and construction of LP-gas containers designed for installation on vehicles. LP-gas vehicle fuel containers must meet either the requirements of *ASME Boiler and Pressure Vessel Code,* Section VIII, Division 1, "Rules for Construction of Unfired Pressure Vessels," or U.S. DOT requirements. Normally, pressure vessels used for LP-gas service have a minimum design pressure of 250 psig (1724 kPa), based on NFPA 58 and ASME requirements for gases with a vapor pressure of 215 psig (1482 kPa) at 100°F (38°C). However, when the pressure vessel is intended for installation on a motor vehicle, such as an automobile or bus, the minimum design pressure for the container increases to 312.5 psig (2154 kPa). The higher design pressure ensures that the pressure-relief device has an increased operating setting because the container may be subjected to operating temperatures not normally found at stationary LP-gas installations. In addition, premature operation of a relief valve on, for example, a school bus filled with children introduces a variety of concerns to vehicle operators and emergency responders. Establishing a higher starting pressure for opening a relief valve reduces the probability of premature LP-gas release.

Particular attention must be paid to the location of vehicle LP-gas containers. Containers must be located to minimize the possibility of damage to them and their fittings. Suitable locations may include the trunk of a passenger car, directly attached to the frame of a vehicle, or in the cargo box of a pickup truck. Containers should be installed in a location to minimize damage resulting from a collision. Containers and their components cannot be located ahead of the vehicle's front axle, behind its rear bumper, or on its roof.

A container installed inside a vehicle should be installed so that the driver or passengers are not exposed to any release of LP-gas, nor should it be within any space containing radio transmitters or other spark-producing equipment. NFPA addresses the three following options to satisfy this concern:

1. Locate the container and its appurtenances outside the passenger compartment.
2. Completely enclose the container appurtenances in a gastight enclosure or housing.
3. Store the container and its appurtenances in the trunk of an automobile and seal the compartment to form a separation from the passenger carrying space.

The size of the container on vehicles is also limited. Vehicles designed to transport passengers, such as buses or automobiles, are limited to an aggregate of not more than 200 gal (0.75 m^3) water capacity, or approximately 160 gal (0.6 m^3) of LP-gas. Vehicles not designed to carry passengers, such as farm machinery or mail trucks, may have an aggregate 300 gal (1.1 m^3) water capacity of volume, or approximately 240 gal (0.9 m^3) of LP-gas. In both instances, more than one tank can be used and manifolded, but the total volume cannot exceed the aggregate quantity.

A method of preventing the overfilling of vehicle LP-gas containers is required. Overfilled containers can be hazardous

when liquid LP-gas expands to the point where the containers become liquid-full, causing the pressure-relief valve to open and discharge LP-gas. To minimize the hazard, containers manufactured after January 1, 1984, and installed in vehicles must be equipped with a device that prevents overfilling. Listed stop fill valves designed to satisfy this requirement are available. Other means, such as a solenoid valve, may be used.[26]

LP-Gas Pressure-Relief Devices. Vehicle LP-gas fuel containers require a method of relieving excess pressure resulting from an external heat source. Spring-loaded pressure-relief devices accomplish this. The relief valve is recessed or flush with the surface of the pressure vessel. For ASME containers, the relief valve is normally designed to meet the requirements of Underwriter Laboratories Standard 132, *Safety Relief Valves for Anhydrous Ammonia and LP-Gas,*[27] Section UG-125 of the *ASME Boiler Pressure Vessel Code,* or other standards acceptable to the authority having jurisdiction. DOT containers require spring-loaded pressure-relief valves in accordance with CGA Pamphlet S-1.1. NFPA 58 prohibits the use of relief devices that use fusible plugs because the vehicle container can be subjected to considerable heat while garaged or in use.

LP-gas pressure-relief devices must be installed in direct communication with the vapor space of the vehicle fuel container. The relief device must also be located at the container's uppermost point. When this is not possible, the device should be internally piped to the uppermost practical point in the container's vapor space. Because propane has an approximate expansion ratio of 1:260, any liquid discharge from a relief device results in the development of a gas vapor cloud. The requirement for locating the relief valve at either the uppermost point of the container or the vapor space is based on experience with relief valves located at or directly above the 80 percent liquid level, in which the relief valve sometimes discharged liquid LP-gas. When the container is installed inside the vehicle, its discharge outlet must terminate outside the vehicle. It must also be directed so that it does not directly impinge on the vehicle fuel containers, the exhaust system, or any other part of the vehicle; it cannot be directed into the passenger compartment.

A manual shutoff valve is required for LP-gas vehicle fuel containers. This valve has an additional protective feature known as the internal excess flow check valve. It closes and stops the flow of gas from the container in the event the shutoff valve is sheared or broken off the container. The excess flow check valve does not operate if the shutoff valve is only partially damaged. Also, the valve does not stop the flow of LP-gas if a fuel pipe leaks downstream of the valve. Manual shutoff valves are normally installed at the container's liquid and vapor openings. These valves must also be readily accessible so they can be shut off using tools or other means.

LP-Gas Piping. The construction materials for piping, hose, and fittings used to connect the fuel container to the vaporizer and carburetion equipment are the same as for fixed installations. Piping must be corrosion-resistant or protected against corrosive action, free of leaks, and securely mounted on the vehicle. Any fuel piping that passes through a vehicle's floor must be installed so that the pipe is beneath or adjacent to the container and connections are outside the vehicle. Hydrostatic relief valves are required between any section of pipe or hose in which LP-gas could be isolated between shutoff valves. Carburetion equipment for LP-gas vehicles is designed to complete the phase change of propane from liquefied phase to gas phase. Equipment is required to be listed for vehicle service and should be acceptable to the authority having jurisdiction. Carburetion equipment is normally rated with a design pressure of 250 psig (1724 kPa), although operating pressures are normally limited to 125 to 250 psig (862 to 1724 kPa). Like CNG and LNG fuel systems, LP-gas fuel systems require an automatic shutoff valve provided as close as practical to the inlet of the pressure regulator. The valve prevents the flow of fuel to the carburetor when the engine is not running but the ignition switch is in the "ON" position. Pressure-relief requirements for carburetion equipment are the same as for containers installed on vehicles: relief devices must be spring-loaded pressure-relief valves; fusible plugs are not acceptable.

Hydrogen-Fueled Vehicles

Hydrogen-fueled vehicles are addressed in Section 21, Chapter 5, "Fuel Cell Vehicles." Most of these vehicles are fuel cell powered, where the hydrogen acts as a fuel for the fuel cell. However, there are some internal combustion engine vehicles that run on hydrogen. These vehicles present hazards that are similar to those presented by CNG vehicles. In Section 21, Chapter 5, the section on physical properties and fire hazards explains some of the differences between the behavior of CNG and hydrogen and will help in understanding how the gases would behave in an accident.

EMERGENCY RESPONSE TO ALTERNATIVE FUEL INCIDENTS

Highway operation of vehicles that use CNG, LNG, and LP-gas is increasingly common. Fire fighters must be prepared to respond to incidents involving the release of these alternative fuels. Emergency response to a vehicle or fueling station releasing alternative fuel requires an understanding of the fuel's hazards, release mechanisms, methods available to safely stop the release, and, in the event an ignition source is introduced, how to safely and effectively initiate a successful fire attack. Three plausible scenarios for emergencies involving the release of alternative fuels are as follows:

1. The vehicle is being fueled.
2. The vehicle is involved in an accident.
3. The vehicle is under repair.

Identifying Alternative Fuel Vehicles

Components of alternative fuel vehicles are normally protected and hidden from view to protect these components in an accident. Fire fighters approaching alternative-fueled vehicles cannot usually distinguish these vehicles from those fueled with gasoline or diesel. Fortunately, measures have been taken to identify these vehicles to responding fire fighters.

All three NFPA standards require that vehicles be identified with a weather-resistant, diamond-shaped label on the exterior vertical surface on the lower right rear of the vehicle (Figure 21.4.8). Most labels are placed on the trunk lid or rear cowl; they cannot be affixed to the bumper because they may be covered by bumper stickers or damaged in minor vehicle accidents. For CNG vehicles, NFPA 52 requires white or silver letters "CNG" on a blue background. NFPA 58 and NFPA 57 require white or silver letters "propane" and "LNG," respectively, on a blue background. The retroreflective labels are visible at night or in fog.

Response to Vehicle Fires and Accidents

Many variables outside fire fighters' control impact how an emergency response will be handled. It is important to understand that alternative fuels have somewhat predictable characteristics when released to the atmosphere, and all the alternative fuels are flammable gases at normal temperatures and pressures. These facts, along with an understanding of the basics of fireground safety, will result in the safe conclusion of an incident.

Apparatus should be placed upwind of a vehicle on fire or involved in an incident. If the vehicle is LNG fueled, the apparatus should be located away from the path of flowing LNG. However, this is not as critical as wind direction because flammable LNG or LP-gas vapors can travel significant distances downwind. LNG vapors will eventually become positively buoyant. Conversely, LP-gas vapors always remain heavier than air due to the molecular weight of the gas. Fire fighters should also recognize that LNG is normally unodorized, but LP-gas is odorized.

Fire fighters should accurately assess the scene before initiating a fire attack. Maintaining an adequate distance, fire fighters should walk completely around the vehicle, observing it and paying special attention to the right rear so they can identify the fuel used. Fire fighters should look for the blue or black retroreflective diamond that identifies which fuel is used.

FIGURE 21.4.8 Diamond-Shaped Label That Identifies the Fuel Used by the Vehicle

For CNG and LP-gas vehicles, water from attack streams can be used to control fire and enhance vapor dispersion. However, for LNG releases, applying water from fire streams greatly increases the vaporization rate for a pool of liquid methane. Fire fighters should attack LNG fires with potassium bicarbonate, ammonium phosphate, or sodium bicarbonate dry chemical fire extinguishers until they confirm that the fire does not involve fuel.

Regardless of the fuel, the primary concern at vehicle crash sites is to ensure the safety of fire fighters and civilians. The strategy is to control or stop the release of fuel and eliminate ignition sources. If a vehicle fuel release has been ignited, stopping the release of additional fuel, if possible, is critical before further fire-fighting activities are undertaken.

The fuel systems for CNG, LNG, and LP-gas can be stabilized by closing the primary shutoff valve at the storage containers. CNG vehicles normally have a second fuel isolation valve installed along the frame rail. NFPA 52 requires a method of identifying this valve's location. All alternative fuel containers are required to vent outside the vehicle. The fire fighter assigned the task of closing the primary valve should also locate and inspect the tank vent line to ensure that it is not blocked.

Closing the primary valve may require the operation of the tank vent. Before fire fighters attempt to isolate the fuel supply on LNG vehicles, they should check the vehicle's on-board gas detection system to determine if fuel is leaking. Because a collision could damage this system, fire fighters should also survey the vehicle and accident scene using gas detection equipment. After checking the vehicle and scene for leaks, fire fighters can proceed to close the liquid product valve. LNG containers have two valves, one for liquid product and the other for the tank vent. The vent line should not be closed because it lets the LNG vehicle container vent gas if tank pressure increases, as it does in a fire. If labels are missing or obscured, fire fighters can always locate the liquid valve because it will be covered with ice and frost formed from moisture in the atmosphere. The vent valve will not be covered with ice or frost.

Hydrogen Fueling Facilities

Hydrogen fueling systems (Figure 21.4.9) typically do not have feed lines from off-site storage but employ on-site storage. Because of the low density of hydrogen gas, hydrogen is often stored as a cryogenic fluid. Hydrogen systems may also have vaporizers to convert the liquid hydrogen to gaseous hydrogen. Additionally, hydrogen fueling systems operate at higher pressures than natural gas fueling systems. Natural gas systems operate in the 3000 to 4000 psi (20,684 to 25,579 kPa) range as compared to hydrogen systems that may reach pressures of 10,000 psi (68,948 kPa). The reason for this difference is that the low density of hydrogen gas means that higher vehicle tank pressures are required to store enough fuel on the vehicle to give it a practical driving range.

Response to Vehicle Fueling Stations

Response considerations for fueling stations are the same as those for vehicles. The difference between the fueling station and vehicle is the amount of fuel stored at the site and the types of safety features.

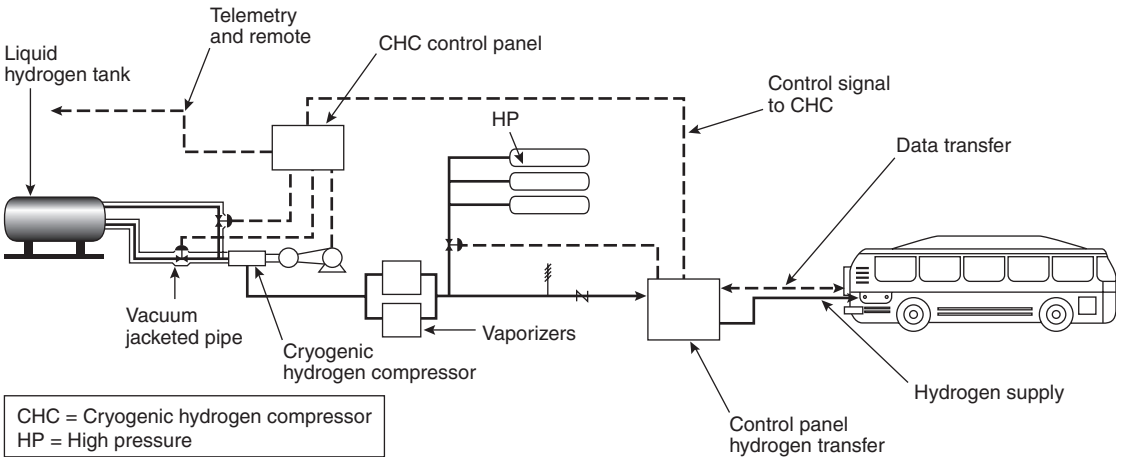

FIGURE 21.4.9 Compressed Hydrogen Gas Fueling System.

Fire fighters who might conceivably respond to a vehicle fueling station should prepare a written plan documenting how to manage and control the response to the facility in the event of a fire or fuel release. The pre-incident plan should consider points of access, required and available water supply, capabilities of fire department resources and personnel, buildings that could be exposed, safe evacuation of occupants, the location of fuel delivery valves and the method of closing them, and safety features or controls provided. The evaluation should also consider probable and worst-case event scenarios. For example, the overfilling of an LP-gas container or the operation of a relief valve on a pressure vessel storing compressed methane are not uncommon and will probably occur over the life of a facility. Conversely, worst-case scenarios can include a catastrophic container failure or a BLEVE. Although catastrophic incidents are rare, such an event can occur. Its consequences to the public and fire fighters must be considered before any response to the fueling station. Where available, fire fighters should consider using a vapor dispersion model such as CHARM (Chemical Hazard Airborne Release Model) to determine the anticipated size and boundary of the exclusion zones. Another resource is CAMEO (Computer-Aided Management of Emergency Operations). This software and supporting information is available at EPA's Chemical Emergency Preparedness and Prevention Office website (http://www.epa.gov/ceppo). CAMEO also has a specific support group website: http://www.CAMEOSupport.com.

The EPA's various guidance documents developed for implementing the Risk Management Program Rule can be used to give estimates of potentially affected areas resulting from an incident. Many of these documents are available through the EPA website, http://www.epa.gov.

All vehicle fueling stations require emergency shutoff devices. These can be simple electrical kill switches or valves designed with integral fusible-links that close if subjected to flame impingement or thermal flux. These devices' location and method of operation should be known and understood. LNG facilities normally require a gas detection system because of the lack of odorant. The gas detection system features and its sequence of operation should be included in the pre-incident plan.

Facility management should be cognizant of the hazards of the alternative fuel stored and should develop its own plan in the event of a release or fire. Further, the fire department and facility management should work jointly to prepare and communicate the pre-incident plan, so realistic action plans can be formulated and the consequences of probable and worst-case events are understood.

SUMMARY

The use of alternative fuels for vehicles has been increasing in the United States, as part of an effort to reduce air pollution and dependence on foreign oil. Compressed natural gas (CNG), liquefied natural gas (LNG), and liquefied petroleum gas (LP-gas) are the most commonly used alternative fuels in the United States. There is significant interest in using hydrogen as fuel for fuel cell powered vehicles. Although relatively few hydrogen-powered vehicles have been produced, there has been a good deal of development and research work done by automobile manufacturers, the U.S. Department of Energy, and other organizations that would play a role in the implementation of a hydrogen energy infrastructure. Hazards associated with these fuels are determined by their physical and chemical properties as well as by time-dependent conditions, the fuel system design, and the quality of the fuel system's manufacture and installation. NFPA codes and standards form the basis of many safety requirements concerning vehicle fueling, fuel storage, and vehicle fuel systems. Fire fighters must be prepared to respond to a vehicle or fueling station releasing alternative fuel and must have an understanding of the fuel's hazards, release mechanisms, ways to stop the release, and methods of conducting a successful fire attack if necessary.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on alternative fuels for vehicles discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of the current edition of the following documents.)*

NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*
NFPA 37, *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines*
NFPA 51, *Standard for the Design and Installation of Oxygen–Fuel Gas Systems for Welding, Cutting, and Allied Processes*
NFPA 52, *Vehicular Fuel Systems Code*
NFPA 54, *National Fuel Gas Code*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 59, *Utility LP-Gas Plant Code*
NFPA 59A, *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*
NFPA 88A, *Standard for Parking Structures*

Chapter 5

Fuel Cell Vehicles

Glenn W. Scheffler ■ William P. Collins

Chapter Contents

Advantages of Fuel Cell Vehicles
Description of Fuel Cell Vehicles
Fuel Cell Systems
Electric Drive Systems
Compressed Hydrogen Storage Systems
Hydrogen System Safety
Postcrash Considerations
Fuel Cell Organizations and Initiatives

Key Terms

auxiliary power unit (APU), bus (transit), compressed hydrogen, electric drive system, fault management, fuel cell, fuel cell vehicle, hybrid car, hydrogen, hydrogen fueling station

The world's leading automakers, fuel cell developers, material and component suppliers, national laboratories, and universities are in a race to bring fuel cell vehicles (FCVs) to the marketplace. FCVs offer an alternative to the internal combustion engine that promises to increase efficiency, lower emissions, and reduce our dependency on foreign oil. The goal is to meet these objectives without compromising the vehicle performance, cost, and safety that consumers have come to expect.

Many of the leaders in fuel cell vehicle development are members of the U.S. Fuel Cell Council. The U.S. Fuel Cell Council is dedicated to being "the voice of the fuel cell industry" and its membership contributed to this chapter. The Transportation Working Group includes producers of fuel cells and equipment, automakers, hydrogen suppliers, and government entities and national laboratories that are actively developing FCVs and the infrastructure to fuel and maintain these vehicles.

FCVs are already on the road in demonstration programs in California and throughout the nation. The California Fuel Cell Partnership estimates that its members will have approximately 300 fuel cell cars and buses operating in demonstrations in the state by 2007. To support these demonstration vehicles, a number of hydrogen fuel stations have been installed in Northern and Southern California, and the state has launched the California Hydrogen Highway Network to help expand fuel stations to support more hydrogen vehicles. Other projects are proceeding in Michigan, Connecticut, New York, Florida, and Washington, DC.

This chapter describes current fuel cell vehicles and operating features being developed to facilitate commercialization and acceptance by the general public and regulatory authorities.

For related topics, see Section 21, Chapter 1, "Passenger Vehicle Fires"; Chapter 2, "Fire Safety in Commercial Vehicles"; and Chapter 4, "Vehicle Fueling Using Gaseous Fuels."

ADVANTAGES OF FUEL CELL VEHICLES

Operating fuel cell vehicles results in a number of advantages for the country. These advantages include but are not limited to reduced emissions and energy independence and diversity.

Emissions

Hydrogen-fueled FCVs are true "zero emissions vehicles." The exhaust is only steam. The EPA and the California Air Resource Board have already certified Honda's FCX as a zero emitting vehicle (ZEV). There are emissions associated with producing the hydrogen, but typical feed stocks being considered for producing the hydrogen would yield emissions that are extremely low in comparison to internal combustion engines (ICEs).

Glenn W. Scheffler has a B.S. in aerospace engineering from Pennsylvania State University and an M.S. in mechanical engineering from the University of Connecticut and has 36 years' experience in the fields of fuel cells and hydrogen. He is chairman of the SAE Fuel Cell Vehicles (FCV) Safety Working Group, vice-chairman of the FCV Standards Committee, chairman of the US-TAG for ISO TC22/SC21 for Electric (and Fuel Cell) Vehicles, and a member of the Hydrogen Industry Panel on Codes (HIPOC).

William P. Collins has a B.S. in mechanical engineering from the University of Connecticut and an M.S. in management from Rensselaer Polytechnic Institute and has 26 years' experience in the fields of power generation, fuel cells, and hydrogen. He is a member of the SAE Fuel Cell Vehicles Standards Committee, the NFPA Electrical Generating Committee, the ASME B31.12 working group, and the US-TAG for ISO TC197.

Energy Independence and Diversity

After a century of continuous improvements, the internal combustion engine still converts on average only about 16 percent of the energy in gasoline to turn the car's wheels. FCVs can achieve energy efficiencies of over 50 percent. Given this significant improvement in energy efficiency, FCVs offer higher mileage and substantial reductions in greenhouse gas emissions and other monitored pollutants.

Additionally, hydrogen can be generated from a number of domestic sources, helping the United States to reduce its dependence on foreign energy. Fueling vehicles with hydrogen also offers the possibility of using renewable energy sources to produce transportation fuel.

DESCRIPTION OF FUEL CELL VEHICLES

The "heart" of the FCV is the fuel cell. Fuel cells are electrochemical devices similar to a battery except that, rather than consuming chemical energy that has been stored with the battery, the fuel cell uses a supply of hydrogen to produce electric power on an ongoing basis.

Hydrogen Storage and Supply

FCV developers are considering several methods to store and supply hydrogen to fuel cells. Examples of methods to store hydrogen are as follows:

- Compressed hydrogen gas
- Liquefied hydrogen
- Hydrogen stored in reversible metal hydrides
- Hydrogen as a chemical hydride

Alternatively, hydrogen (or a hydrogen-rich gas) can be generated on board the vehicles from hydrocarbon fuels and alcohol within fuel-processing systems. Although all of these methods of storing and supplying hydrogen have been demonstrated in FCVs, most FCVs currently utilize compressed hydrogen gas that is stored at high pressure in containers on the vehicle.

For an FCV to be propelled, the electrical power produced by the fuel cell needs to be converted to mechanical energy through traction motors that, in turn, drive the wheels. In its simplest form, the electric drive system has (1) a power control to translate driver "throttle input" into modulated electric power from the fuel cell to the drive motors and (2) electric drive motors for vehicle propulsion.

An example of a typical FCV with compressed hydrogen storage to supply hydrogen to the fuel cells, fuel cells to convert the chemical energy of hydrogen into electric power, and an electric drive system (including a power control and motors) to propel the vehicle is shown in Figure 21.5.1.

In general practice, many current FCVs use a hybrid electric architecture that also includes regenerative braking to recover motive energy from the vehicle during braking and batteries or ultracapacitors to store the energy for future use. The hybrid architecture increases efficiency (i.e., raises mileage) and can improve vehicle response and acceleration.

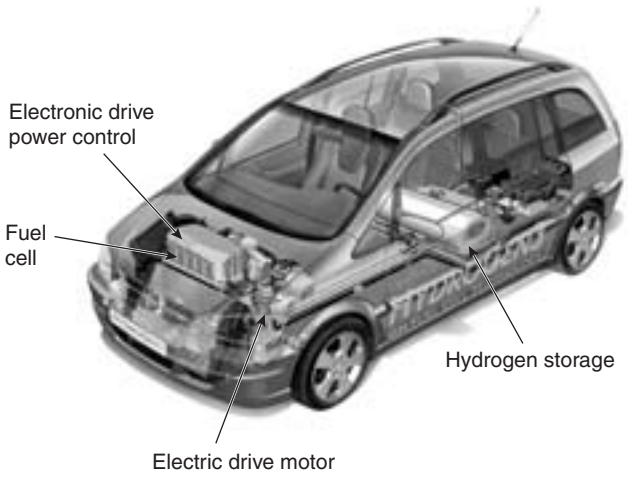

FIGURE 21.5.1 Typical Fuel Cell Vehicle (FCV) (Courtesy of General Motors Corporation)

In addition to propelling the vehicle, fuel cells typically provide electric power for vehicle auxiliary and ancillary systems, such as radios and air conditioners. On many FCVs, auxiliary and ancillary power is supplied by conventional 12 volt batteries or tapped off the fuel cell or electric drive bus; but, in some cases, dedicated power is provided from a separate fuel cell, called an auxiliary power unit (APU) (Figure 21.5.2). The typical power rating of an APU is between 3 and 10 kW.

Fuel cell vehicles are being developed by manufacturers throughout the world. FCVs range from 40 ft (12.2 m) transit buses down to motor scooters and fork trucks. Examples of buses and cars being developed by major vehicle manufacturers are provided in the following sections, along with a discussion of the design practices being employed for basic vehicle safety.

FIGURE 21.5.2 APU in Trunk of Passenger Vehicle (Courtesy of UTC Power)

Buses

Transit buses are widely viewed as a good early market for commercializing fuel cell vehicles. Many advantages have been identified regarding the use of transit buses as fuel cell platforms. Examples are as follows:

- Transit buses have well-defined duty cycles, centralized fueling and maintenance infrastructure, and dedicated maintenance personnel.
- Transit buses are large, providing ample room to install the fuel cell and related components.
- Many older diesel transit buses are noisy and polluting, providing fuel cells with an opportunity to make significant performance improvements.
- Transit agencies are subsidized by the government, thus helping to defray most of the risks and costs of technology development.
- Transit buses are highly visible in the community, providing an excellent showcase for fuel cells.

As a result, governments in North America, Europe, and Asia are supporting many demonstrations of fuel cell buses, causing the number of fuel cell buses to grow at an almost exponential pace (Figures 21.5.3 and 21.5.4).

Cars

A number of domestic car companies are actively developing FCVs. GM's HydroGen3 fuel cell minivan established a long distance driving record in 2004 by traveling 6200 miles from Norway to Portugal and is in service in Japan, California, and Washington, DC (Figure 21.5.5). Ford's Focus vehicles are used in California, Michigan, Florida, Canada, and Germany. DaimlerChrysler's A-class F-cells are in service in Germany, Singapore, Japan, and the United States (Figure 21.5.6).

Major Asian car companies are also very active. Honda's FCX is being used in demonstration programs in New York,

FIGURE 21.5.3 Van Hool Bus Powered by UTC Power's Fuel Cell (Courtesy of UTC Power)

FIGURE 21.5.5 General Motors FCV (Courtesy of General Motors and U.S. Postal Service)

FIGURE 21.5.4 DaimlerChrysler Citaro Bus Powered by Ballard Fuel Cells (Courtesy of DaimlerChrysler)

FIGURE 21.5.6 DaimlerChrysler FCV (Courtesy of DaimlerChrysler)

Nevada, California, and Japan. The company is also developing hydrogen fueling stations at customer sites. Toyota's Fuel Cell Hybrid Vehicle (FCHV) is in use in Japan and California (Figure 21.5.7). Nissan has X-Trail Fuel Cell Vehicles operating with both UTC Fuel Cells and Nissan stacks (Figure 21.5.8). Hyundai has introduced an improved version of its Tucson Fuel Cell Vehicle (FCV) using an advanced UTC Fuel Cells stack (Figure 21.5.9).

Most other automakers are also involved in public road tests with their fuel cell prototypes. For example, Mazda's Premacy FC-EV has undergone public road testing in Japan since 2001. Volkswagen's HyPower prototype has completed testing in cold temperatures and high altitudes in the Swiss Alps. The Mitsubishi FCV, based on the Grandis minivan, has been approved for road trials by Japan's Minister of Land, Infrastructure and Development. Suzuki's wagon R-FCV began Japanese road trials in 2005.

FIGURE 21.5.7 Toyota FCHV Fuel Cell Vehicle (Courtesy of Toyota Motor Company)

FIGURE 21.5.8 Nissan X-Trail FCV (Courtesy of Nissan Motor Company)

FIGURE 21.5.9 Hyundai FCEV Powered by UTC Power's Fuel Cell (Courtesy of UTC Power)

Design for Safety

The automotive industry is applying design practices developed over the past 100 years to ensure that FCV development and commercialization is successful and safe. Under normal and anticipated driving and vehicle scenarios, the vehicle and associated subsystems are designed with the objective that foreseeable single-point hardware or software failures do not result in an unreasonable safety risk to any person or uncontrolled vehicle behavior. This, in part, dictates the use of redundant safety features. Where this is not possible, a high safety factor is necessary to provide reasonable assurance that a component, such as a pressure vessel, will not fail.

A standard automotive industry approach to identifying and managing safety risks, particularly in new technologies and designs for higher volume products, is the use of a failure modes and effects analysis (FMEA).[1]

Hazardous conditions often depend on several conditions existing simultaneously. Prudent design, focused on the separation of hazards, prevents hazardous conditions from arising. Isolation and separation of hazards are approaches used to prevent cascading of failures and preclude unwanted or unexpected interactions.

Fail-safe design is a key philosophical approach. With regard to FCVs, automatic electrical disconnects should open and fuel shutoffs should close when de-energized. Utilizing this design philosophy, any interruption of this control signal (whether caused by accident, equipment failure, or human error) will cause isolation of electrical or fuel sources and minimize exposure of occupants, repair personnel, and emergency responders to hazards.

Fault Management

Faults that could result in a hazardous situation are detected and mitigated by control systems on the vehicle. When necessary, a staged warning and shutdown procedure is implemented to shut off the supply of fuel and open the electrical circuits to mitigate potential hazards. A staged warning and shutdown system is used when loss of vehicle power due to an automatic shutdown may, in itself, lead to a hazardous operating condition. In order

to ensure the safety of the driver and the passengers in the vehicle, the sequence and rate of actions depends on the operating state of the vehicle.[2]

A main switch function is usually provided in demonstration vehicles so that the operator can disconnect all vehicle power sources by electrically isolating both poles of a fuel cell stack module, traction battery, and other high voltage sources (if equipped). This main switch, such as a conventional ignition switch, should be easily accessible and activated by the operator.

Typically, when the vehicle is involved in a crash detected by the crash sensors, the fuel is automatically shut off and the electrical system is disconnected. Additionally, to provide protection against electric shock by emergency responders, vehicles are designed to maintain proper electrical isolation following accidents.[3]

FUEL CELL SYSTEMS

In 1839, British scientist Sir William Robert Grove discovered that hydrogen and oxygen could be combined to produce water and an electric current. Fredrick Ostwald helped provide the theoretical foundations of fuel cells in the 1880s and was also able to experimentally determine the roles played by the different parts of Grove's fuel cell. In the late 1950s, Francis Bacon's research team developed a more advanced fuel cell. This design was used for NASA's Apollo moon missions and Skylab programs. Fuel cells also provide electrical power for space applications on board NASA's space shuttle orbiter. Today, fuel cell technology is being brought back to earth to power everything from cars and buses, to homes and businesses, and even cellular phones and laptop computers.

Fuel Cell Operation

Although there are several different types of fuel cells based on the type or state of the electrolyte used within the cell, almost all prototype fuel cell cars and buses use proton exchange membrane (PEM) fuel cells. Each PEM fuel cell is a thin wafer with a catalyst-coated membrane resembling a plastic film that is enclosed in electrically conducting graphite or metal plates (Figure 21.5.10). One side of the membrane acts as an anode and is fed hydrogen gas. The other side of the membrane serves as the cathode and is bathed in air to provide oxygen. At the anode, a catalytic reaction takes place with the hydrogen atoms releasing their electrons and becoming hydrogen ions (protons). The protons are transported through the membrane to reach the cathode. Another catalytic reaction takes place on the cathode where the protons combine with oxygen and electrons to produce water. The electric circuit is completed by connecting the cathode and anode to a load so that the electrons released from the anode can flow through the load to the cathode.

Fuel Cell Stack

In order to meet vehicular requirements, fuel cells are assembled in stacks to generate sufficient power and voltage for the electric drive system (Figure 21.5.11). Fuel cell stacks with electric capacities between 50 to 150 kilowatts are powering prototype passenger cars, minivans, sport utility vehicles, and transit buses. Tremendous improvements in stack efficiency, as well as weight and size reductions, have been achieved in recent years, but more remains to be done to make fuel cells affordable.

Balance of Plant

The fuel cell stack is just one component of the overall fuel cell system. The remainder of the fuel cell system, known as the "balance of plant," performs the following basic functions:

- Delivery of the hydrogen to the fuel cell stack and discharge of exhaust
- Delivery of fresh air to the cathodes of the cell stack
- Management of the fuel cell stack temperature and water

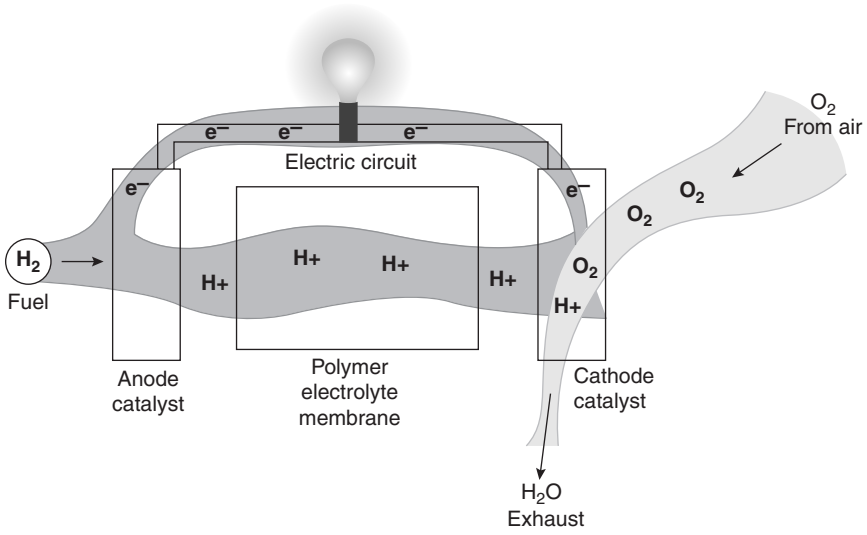

FIGURE 21.5.10 Operation of a PEM Cell (Courtesy of the U.S. Fuel Cell Council)

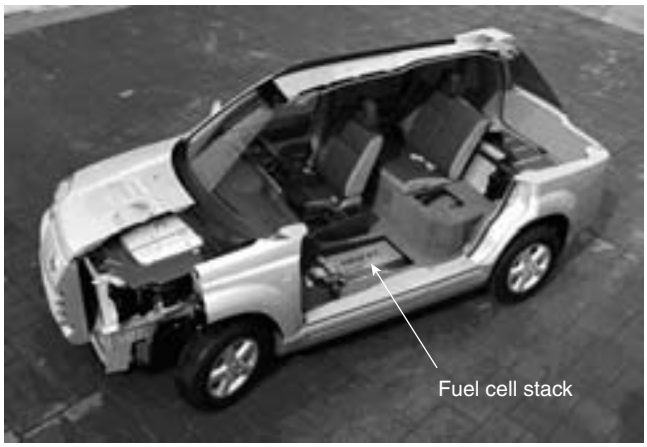

FIGURE 21.5.11 Fuel Cell Stack Installed in a Vehicle (Courtesy Nissan Motor Company)

To meet these functions, the balance of plant typically requires pumps, blowers or compressors, fans, heat exchangers, filters, and control valves. In many cases, standard off-the-shelf components are not suitable and specialized components must be designed and manufactured. Additionally, since many components in the balance of plant require electric power, the balance of plant often includes power conditioners to adjust fuel cell output power to an appropriate level for the component (Figures 21.5.12 and 21.5.13).

ELECTRIC DRIVE SYSTEMS

Operation of Electric Drive System

As described earlier in the chapter, the electric drive system converts the electric power from the fuel cell (and battery or ultracapacitor, if hybrid) into traction power for the FCV. Key functional elements of the system are shown in Figure 21.5.14 and described as follows:

1. The power control translates driver "throttle input" into modulated electric power from the fuel cell to the drive motors.
2. Electric drive motors convert the electric power into vehicle propulsion.
3. Batteries, ultracapacitors, or other methods of energy storage allow energy from regenerative braking to be captured for reuse and can provide improved vehicle response in hybrids.

A simplified electrical schematic is shown in Figure 21.5.15. The power control meets the driver's "throttle" request by varying the power from the fuel cell and the energy storage (if the vehicle is a hybrid) to meet in the propulsion requirement of the electric drive motor. Depending on the type of electric drive motor, the power control may also have to adjust the voltage level or convert the current from dc to ac. Additionally, in hybrid configurations, the power control also manages the recharge of the energy storage (i.e., batteries, ultracapacitors, or other devices) for optimum efficiency and performance of the vehicle.

Electrical Safety Elements

Typical voltages of the electric drive system range from 300 to 600 volts. Since the electrical system of a fuel cell vehicle is

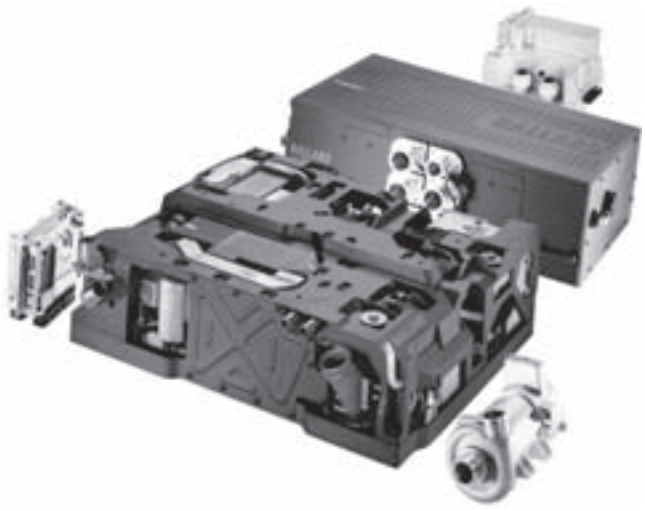

FIGURE 21.5.12 NuCellSys HY-80 Engine with Ballard Fuel Cell (Courtesy of Ballard)

FIGURE 21.5.13 PureMotion™ Fuel Cell Power Plant Installed in a Van Hool Bus (Courtesy of UTC Power)

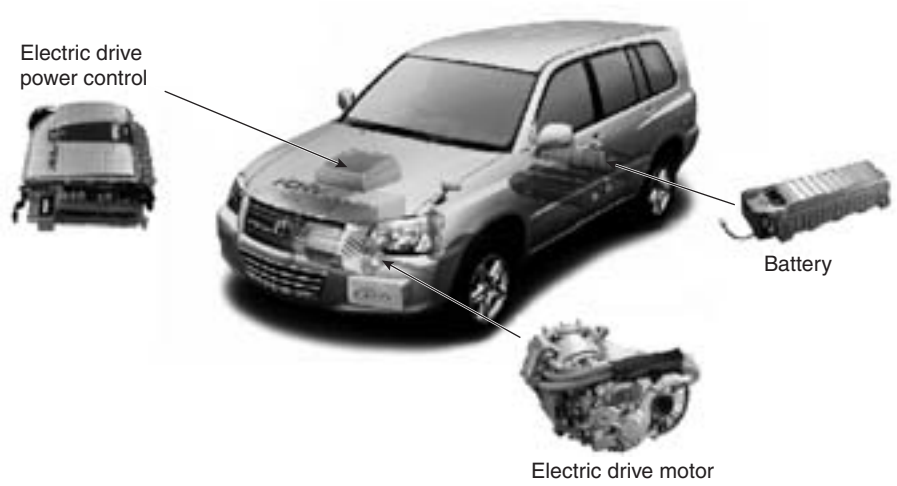

FIGURE 21.5.14 Key Components of the Electric Drive System in an FCV (Courtesy Toyota Motor Company)

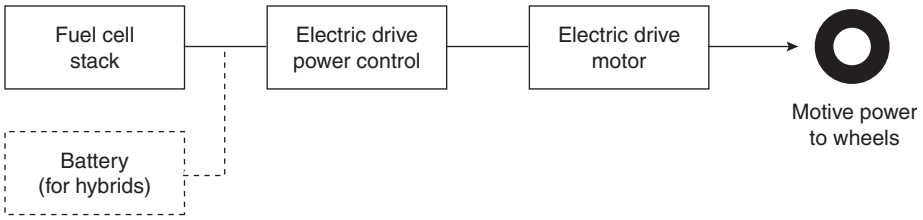

FIGURE 21.5.15 Simplified Schematic of the Electric Drive System

very similar to other electrical and hybrid vehicles, FCVs rely heavily on existing approaches from electric vehicles and hybrids to minimize hazards to vehicle occupants, repair workers, and emergency responders. Key elements of electrical safety include the following:

- *High voltage dielectric withstand capability.* Each high voltage system should demonstrate adequate dielectric strength of harnesses, bus bars, and connectors such that there is no indication of a dielectric breakdown or flashover after the application of voltage.[2,4]
- *Access to live parts.* An interlock, special fasteners, or other means should be provided on covers that are intended to prevent access to live parts with hazardous voltage.[2]
- *Electrical isolation.* Unlike low voltage circuits in vehicles that are bonded (or grounded) to the chassis of the vehicle, high voltage systems in current electric and hybrid vehicles as well as FCVs are isolated from the chassis. By so doing, the high voltage circuit can be touched in any single location without receiving an electric shock. This feature provides a second layer of protection in case the primary measures to prevent access to live parts are compromised by accident or repair activity.[2,3]
- *Fusing/overcurrent protection.* Like low voltage systems in vehicles, the high voltage system should be designed to prevent excessive current due to shorts or malfunctions from causing overheating and fires.[2,5]
- *High voltage wire identification.* High voltage cables and harnesses are visually identified with a permanent orange covering material (Figure 21.5.16).[2,6]
- *Labeling.* Hazardous voltage equipment or compartments containing hazardous voltage equipment should be identified

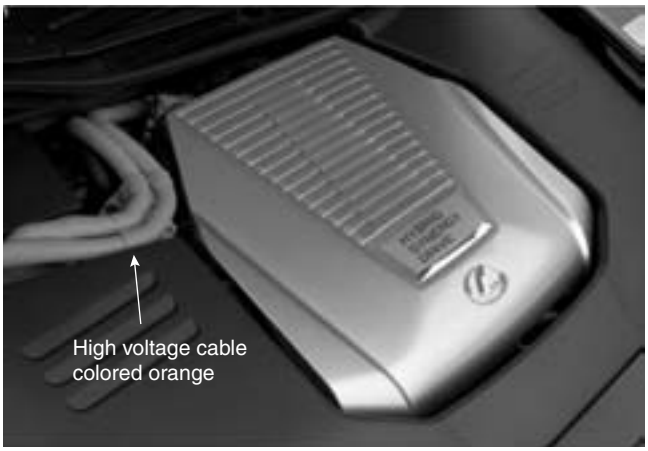

FIGURE 21.5.16 High Voltage Cable Identification as Shown Under the Hood of a Production Gasoline Hybrid Vehicle (Courtesy of Toyota Motor Company)

using the high voltage symbol, as shown in Figure 21.5.17, using black on a yellow background.[2,7]

- *Automatic disconnects.* An automatic disconnect function should provide a means of electrically isolating both poles of a fuel cell stack module, a traction battery, and other high voltage sources (if equipped) from external circuitry or components. This function would be activated by either the main switch or as an automatic triggering protection.[2]
- *Manual disconnects.* A means should be provided to disconnect both poles or de-energize the fuel cell module, a traction battery, and other high voltage sources (if equipped) from external circuitry or components. This function would be used for vehicle assembly, service, and maintenance operations.[2]

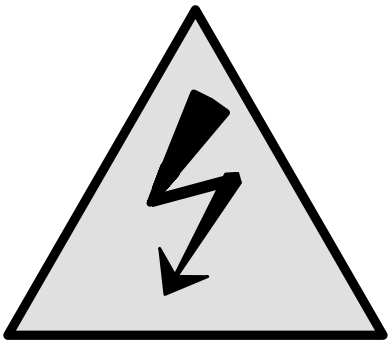

FIGURE 21.5.17 High Voltage Symbol

COMPRESSED HYDROGEN STORAGE SYSTEMS

Compressed hydrogen storage is the most common type of hydrogen storage on current FCVs. The technical challenge with compressed hydrogen is to store enough hydrogen on board the vehicle to achieve reasonable range between fuel refills. A typical FCV requires about 6 kg of hydrogen. To achieve this amount of hydrogen gas storage, manufacturers are increasing the storage pressures from the present level of 350 to 700 bar (5000 to 10,000 psig). Figure 21.5.18 illustrates a compressed hydrogen container installed on an FCV. A simplified process schematic for a compressed hydrogen system is shown in Figure 21.5.19.

FIGURE 21.5.18 Compressed Hydrogen Container in FCV (Courtesy of Toyota)

Functions and Features

Key functions and features of the compressed hydrogen storage system are as follows:

1. A filling receptacle on the vehicle is used to connect to the filling station. The receptacle (such as an SAE J2600 design[8]) typically has a check valve function built into the

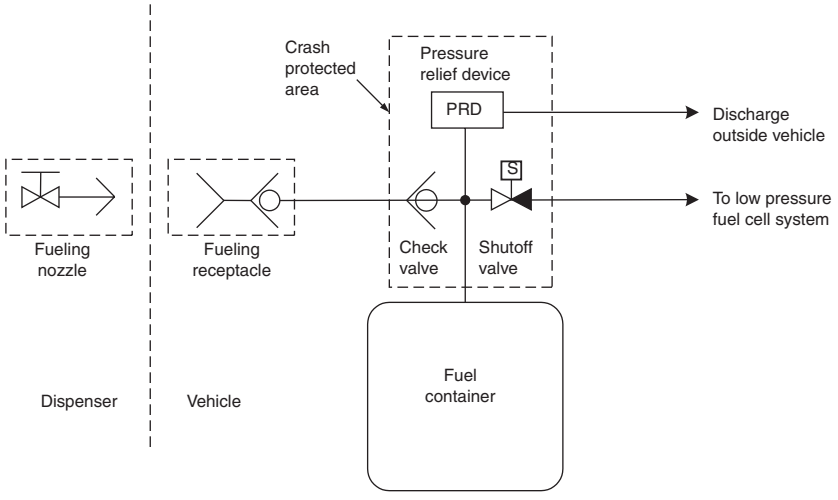

FIGURE 21.5.19 Compressed Hydrogen Storage System Process on FCVs

receptacle to prevent backflow leakage when the fill nozzle is disconnected. Additionally, there usually is a redundant check on the line between the nozzle and tank to meet design for safety requirements.
2. One or more containers on the vehicle store compressed hydrogen for use by the fuel cell.
3. Shutoff valves and pressure regulators are used to control the delivery of hydrogen to the fuel cells, as is done today with compressed natural gas vehicles.
4. One or more pressure relief devices (PRDs) are utilized to prevent tank burst in case the compressed hydrogen system is exposed to a fire due to an accident or other fault.

Safety Measures

The SAE is leading a cross-industry team of engineers from automotive, fuel cell, container, and component manufacturers, including technical experts from CSA (originally, Canadian Standards Organizations). The objective of this activity is to ensure the integrity of the hydrogen storage and fuel systems on the FCVs as well as other hydrogen vehicles that deliver hydrogen or hydrogen-rich gas to internal combustion engines. Guidance will be provided with regard to proper design and material selection. Systems-level, performance-based tests are being developed to demonstrate system integrity for normal operation and during fault management. The aim is to provide real-world system safety guidance while still facilitating rapid technology advances by the industry.

SAE recommendations for fuel cell and hydrogen vehicle safety are built on the excellent safety record for existing fuels. For example, labeling is very important for identifying unique items that are not on conventional vehicles and require special handling or awareness. Natural gas vehicles have historically been identified with a blue diamond with a "CNG" to convey to emergency responders and others that the fuel system on the vehicle is compressed natural gas. Based on the similarities to a natural gas fuel system, SAE has recommended vehicles with hydrogen fuel utilize a similar blue diamond. The difference with hydrogen vehicles would be that the diamond would indicate compressed hydrogen or another method used to store the hydrogen.

HYDROGEN SYSTEM SAFETY

Hydrogen is as safe as, if not safer than, other conventional fuels on the market today.[9] Experience has shown that hydrogen can be safely produced and transported; it has been in mass production and transportation for over 50 years in the United States. Ford Motor Company examined this issue under contract to the Department of Energy (DOE) and concluded in 1997 that "overall, [they] judge the safety of a hydrogen fuel cell vehicle system to be potentially better than the demonstrated safety record of gasoline or propane, and equal to or better than that of natural gas." A Norwegian study in 2002 reached a similar conclusion: "There are no technical or safety barriers that prevent the use of hydrogen for fuel in the transportation sector or as a medium for the storage and transportation of energy. It is possible to manufacture and utilize hydrogen just as safely as with today's gasoline systems."[10]

The automobile industry and government agencies have decades of experience in designing and testing for the safe use of fuels in motor vehicles. Fuels used in automobiles contain energy in a concentrated form. This same characteristic is why fuels must be handled appropriately. The past 100 years of experience with automobile fuels such as gasoline, diesel, and natural gas can be used and expanded upon for hydrogen as an automobile fuel.

The compressed hydrogen systems benefit from experience with compressed natural gas (CNG) and are designed to contain hydrogen and not burst. SAE is working to define performance-based standards for hydrogen systems designed to meet customer demand and use profiles of passenger and fleet vehicles.

Safety Measures

In the event that a leak does occur from the hydrogen system, SAE[2] has defined requirements to ensure that unintended hydrogen discharges do not cause a hazard within the vehicles. Discharges to any compartments within the vehicle that contain or may contain ignition sources are rendered nonflammable and the atmosphere in the passenger compartment is to be maintained nonhazardous through the use of active or passive barriers, dilution of potentially flammable gases, or the use of recombiners to eliminate flammable gases by catalytic reaction. If a leak is detected that exceeds the ability of these countermeasures to appropriately mitigate, then a staged warning and shutdown is executed following the guidance discussed in an earlier section (entitled "Fault Management") in this chapter.

Finally, vehicles are designed to protect the compressed hydrogen system during a crash. Typically, if a crash occurs, the hydrogen shutoff valves at the containers are closed to isolate the system, leaving only a small amount of hydrogen downstream of the shutoff valves as a minimal risk, given that the energy content is typically less than that in fuel lines on conventional gasoline vehicles. If the vehicle is exposed to a fire following the crash, pressure relief devices (PRDs) will thermally activate to release hydrogen and prevent a burst of the container.

Management of Discharges from FCVs

Successful commercialization of fuel cell and hydrogen vehicles requires that these vehicles be used in a manner consistent with current gasoline, internal combustion engine (ICE) vehicles. To achieve this objective, SAE[2] has defined recommended practices such that hydrogen vents, purges, leaks, and exhausts during operating and nonoperating states are consistent with usage in residential garages and commercial structures as well as general use outdoors and that safety is comparable to that presented by leaks and ruptures of fuel lines in present gasoline vehicles. To ensure that discharges are nonhazardous, the discharge is examined in two regions:

1. The local region where the discharge from the vehicle initially mixes with surrounding air
2. The atmosphere surrounding the vehicle after dispersal of the discharge

The local region where the discharges from the vehicle mix with the surrounding air should be locally unignitible at all times.

Discharges may be managed through dilution of potentially flammable gases, use of recombiners to eliminate flammable gases by catalytic reaction, or adjustment of process controls within the fuel cell or vehicle systems.

Hydrogen is potentially flammable in a gas mixture with oxygen and nitrogen (the primary constituents of air) when the concentration of hydrogen exceeds 4 percent (by volume) and the concentration of oxygen exceeds 5 percent (by volume). As shown in Figure 21.5.20, hydrogen discharges may or may not pass through regions of potential flammability during dispersal into the surrounding atmosphere, depending on the local concentration of hydrogen and oxygen concentration as the discharge mixes with the surrounding air. The situation is illustrated by two cases in Figure 21.5.20:

1. In the first case (indicated by the dotted line), the initial concentration of hydrogen is diluted to 5 percent with inerts before discharge. The discharge is always nonflammable as it mixes with surrounding air because the hydrogen concentration falls below 4 percent before the oxygen concentration reaches 5 percent.
2. In the second case (indicated by the dashed line), the initial hydrogen content is 100 percent at the point of discharge and a potentially flammable mixture is formed as the hydrogen mixes with surrounding air.

There is empirical evidence that discharges may not be ignitable even though the local concentration passes through the region of potential flammability. This is because the lower flammability limit (LFL) of hydrogen (4% in air) is based on testing a uniform mixture of gas in a quiescent state,[11] which is inconsistent with the mixing that occurs in the local region of discharge from the vehicle. Testing has shown that flow conditions and mixing during dispersal can actually suppress ignition and that hydrogen concentrations above 8 percent are typically required to ignite discharges.[12] A test method is being developed by the SAE to explore the areas of potential flammability (if they exist) with an ignition source. The objective of the test is to determine if there is a release of energy or the propagation of combustion into a standing flame that could represent a hazard to people or property. The local area of the discharge can therefore be demonstrated to be nonhazardous.

In order to complete the evaluation of hydrogen discharges from the vehicle, it is also necessary to look beyond the local region of discharge and evaluate the condition of the general atmosphere surrounding the vehicle. An approach was defined by the SAE[2] for assessing discharges when vehicles are being parked in residential garages[13] and being operated in mechanically ventilated commercial structures,[14] as well as when being operated out-of-doors.[15] The approach uses a combination of analysis and test for vehicle manufacturers to verify that the atmosphere surrounding the vehicle remains unclassified (see Article 500 of NFPA 70, *National Electric Code*®) and is therefore nonhazardous. By so doing, FCVs can be used and stored in the same manner as current gasoline-ICE-powered vehicles without modification to building codes.

Hydrogen Quality and Odorants

FCVs currently require a clean grade of hydrogen as a fuel. The industry is looking at a quality level that allows less than 1000 ppm of impurities. This is being done for several reasons. One reason is that a clean grade of fuel minimizes the buildup of noncondensable, nonhydrogen constituents. This buildup could reduce the operating efficiency of the fuel cell systems and result

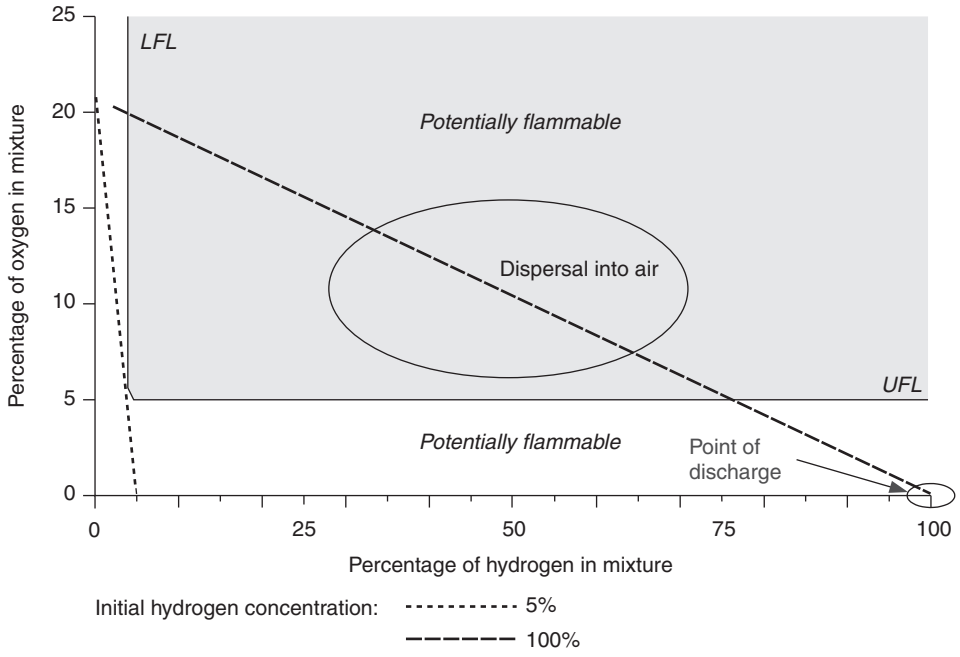

FIGURE 21.5.20 Potential Flammability of Hydrogen Discharges

in increased venting of hydrogen and these noncondensables. This venting would present additional emissions of flammable gases, which would have to be mitigated. Another reason is that some impurities are detrimental to both fuel cell components and fuel storage media. The removal of these impurities on the vehicle will add weight and cost to the vehicle, increase vehicle maintenance costs, and, in some cases, may not be technically practical.

Some parties have suggested odorizing the hydrogen fuel. Although this "low tech" approach has been used for nearly a century with natural gas, it is inconsistent with FCVs because fuel cells do not benignly consume (i.e., burn) the odorant as do internal combustion vehicles. The odorant either adversely reacts with components of the FCV or passes through the fuel cell system. If the odorant reacts with the system, the life and durability of the components will be severely limited. If it passes through the fuel cell system, it is concentrated by up to 500 times the original concentration in the hydrogen supply. This means that detection of a leak would be masked by the highly concentrated (and objectionable) odors emanating from the exhaust pipe.

Finally, the use of an odorant may be inconsistent with common types of hydrogen storage such as liquefied hydrogen and metal hydrides. With liquid hydrogen, for example, all compounds with the exception of helium are separated as solids at liquid hydrogen temperatures. This means that hydrogen could leak out of a containment system but the odorant would be retained inside the system, leaving the leaking gas not odorized and therefore not detected.

For these reasons, current FCVs are designed to operate with odorant-free fuel. As with a number of natural gas vehicle applications, if hydrogen is to be supplied to a filling station by pipeline, the fuel should be deodorized (if an odorant is present) before dispensing at the fueling station to hydrogen vehicles.

Vehicle Fueling

The commercialization of hydrogen fuel cell vehicles raises a "chicken-and-the-egg" question: Which comes first, mass-produced fuel cell vehicles or the hydrogen fueling infrastructure necessary to operate them? With a growing number of hydrogen fuel cell vehicles hitting public roads, the answer to this question may be getting clearer.

It is true that a supporting infrastructure for hydrogen fuel cell vehicles will be needed to make them practical. A fully integrated, fully deployed infrastructure is not, however, needed all at once. State and regional infrastructures are already planned and being developed. Recent examples include the California Hydrogen Highway and hydrogen station plans in the states of Florida and New York. Similar regional efforts are currently under way in Canada, Norway, Singapore, Germany, Japan, and other countries.[16]

These early hydrogen stations (Figures 21.5.21 and 21.5.22) serve to provide a limited infrastructure for fuel cell vehicle demonstrations and some commercial sales arrangements and also serve to research and demonstrate the various ways in which hydrogen can be produced and stored. The California Hydrogen Highway Plan serves to establish a baseline

FIGURE 21.5.21 Hydrogen Fueling Station in Oakland, California (Courtesy of Chevron)

FIGURE 21.5.22 Hydrogen Fueling Station in Washington, DC (Courtesy of General Motors)

network of hydrogen fueling and electrical generating stations along California's interstate highways by 2010. The hydrogen from these fueling stations will be from various sources, including renewables, such as renewable methanol and ethanol, and nonrenewables, such as natural gas.

In today's society, the use of gasoline as an automobile fuel has become so common that the safe handling of the fuel is practically engrained into the culture of users. While refueling their vehicles, users are aware of the precautions and operate in a certain manner, such as not running their vehicle and not smoking. Users often take for granted that fuel distribution systems have built-in safety features. For example, the prevention of static electricity is designed into both the vehicle and the refueling station[2,17] (see NFPA 77, *Recommended Practice on Static Electricity*). Vehicles are designed to maintain a conductive path from the fueling neck to the tires. The refueling station is designed in a manner that a conductive path exists from the

tire contact surface to the fueling nozzle. The result is a bonding and grounding path that prevents sparks that could ignite gasoline during filling. The countermeasures developed for gasoline fueling have been adapted to hydrogen fueling.

FCVs and other hydrogen vehicles will also depend on the filling station and dispenser to provide the following additional protective measures during vehicle filling[18] (see also NFPA 52, *Vehicular Fuel Systems Code*):

- Overpressure protection of the hydrogen storage system on the vehicle by relief valves on the filling station set to 1.38 times the nominal working pressure (service pressure)
- Provision for leak detection
- Emergency shutoff of hydrogen if a fault is detected
- Breakaway protection if the vehicle moves before the fueling nozzle is disconnected

Vehicle Maintenance and Service

Existing model building codes already address requirements for facilities conducting repairs on vehicles (NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*). These requirements are adequate for FCVs, as long as work on the hydrogen storage system is not being conducted.

Additional countermeasures should be considered for areas conducting work on the hydrogen storage systems. For example, a vent system will probably be required to defuel (depressurize and purge) the hydrogen storage system on the vehicle before major repairs are conducted. Additionally, requirements for ventilation, gas and fire detection, electrical classification, HVAC interconnection with other areas of the building, and fire rating of interior walls and doors should be considered, following standard practices for hydrogen systems[19] (see also NFPA 52).

POSTCRASH CONSIDERATIONS

Fuel cells vehicles will be expected to have crashworthiness that is equivalent to or better than current motor vehicles, and the SAE Fuel Cell Standards Committee is developing standards that will allow vehicle manufacturers to evaluate their designs and demonstrate that expectations are fulfilled. In this regard, there are two keys to FCV safety following a crash.

The first postcrash consideration is that occupants or emergency responders must not be exposed to electrical shock hazards. The SAE Fuel Cell Committee has updated SAE J1766 for electrical safety following a crash to account for the unique characteristics of fuel cells and modern hybrid electric drive trains. High voltage electrical circuits are to be discharged or appropriately isolated from ground such that circuits can be touched without receiving a harmful shock.[3]

The second postcrash consideration is that the hydrogen fuel needs to be contained. Crash standards for both gasoline and compressed natural gas (CNG) vehicles were reviewed by the SAE Fuel Cell Standards Committee, and an approach was defined to demonstrate that compressed hydrogen systems will retain their contents and thereby minimize exposure to potentially hazardous events.[2]

Additionally, the fuel system needs to protect against secondary events (such as fire from another vehicle) following the accident. CNG vehicles use pressure-relief devices (PRDs) to vent gas in the event of a fire. By so doing, the fuel tanks can be depressurized by venting fuel, and a potentially hazardous event, such as a container burst, can be avoided. Fuel cell vehicle manufacturers have already adopted this practice, and the SAE Fuel Cell Standards Committee is addressing postcrash situations as part of new standards being developed.

FUEL CELL ORGANIZATIONS AND INITIATIVES

U.S. Fuel Cell Council

The U.S. Fuel Cell Council is the industry association of the fuel cell industry. The council's membership includes producers of all types of fuel cells, major suppliers, automakers, universities, fuel cell customers, hydrogen suppliers, government entities and national laboratories, and other associations. Formed in 1998, the U.S. Fuel Cell Council provides its members with an opportunity to develop industrywide policies and procedures, work with codes and standards developers, conduct education and marketing activities for the fuel cell industry, and collaborate on a wide range of technical subjects.

The U.S. Fuel Cell Council is dedicated to commercializing fuel cell technology. Members of the U.S. Fuel Cell Council are spending their own resources to achieve this goal and are also partnering with government initiatives.

Fuel Cell Initiatives

Two high profile examples of government initiatives are the FreedomCAR Partnership and the California Fuel Cell Partnership (CAFCP).

FreedomCAR Partnership. The FreedomCAR Partnership is a collaboration between the U.S. Department of Energy (DOE), the United States Council for Automotive Research (USCAR), and five large energy providers. The goal of this organization is "the development of emission- and petroleum-free cars and light trucks." The focus is on the high-risk research needed to develop the necessary technologies, such as fuel cells and advanced hybrid propulsion systems, to provide a full range of affordable cars and light trucks that are free of harmful emissions and that do not sacrifice freedom of mobility and freedom of vehicle choice. The FreedomCAR Partnership is not designed to produce any particular vehicle, but rather to accelerate the adoption of advanced automotive technologies. The program has established technology goals to be reached by 2010 in order to target areas for research and development.

California Fuel Cell Partnership (CAFCP). The California Fuel Cell Partnership (CaFCP) is a unique collaboration of auto manufacturers, energy companies, fuel cell technology companies, and government agencies. This organization is demonstrating hydrogen vehicle technology that could move the world toward practical and affordable environmental solutions.

In addition to demonstrating fuel cell vehicles, the CaFCP is examining fuel infrastructure issues and beginning to prepare the California market for this new technology.

Three California transit agencies have a few demonstration sites: Sunline Transit Agency in Coachella Valley, Santa Clara Valley Transportation Authority in Silicon Valley, and AC Transit in Northeast San Francisco Bay. In addition, Santa Clara VTA and AC Transit opened hydrogen fueling stations for their fleets in 2005. For more information see http://www.cafcp.org.

SUMMARY

Fuel cell vehicles (FCVs) are being developed in response to the worldwide need to lower emissions and decrease dependence on oil. A risk-based approach has been used to identify both electrical and fuel system hazards on FCVs, and approaches to mitigate these hazards have been and are being developed based on past automotive experience and sound engineering practice. Overall, a philosophy of mitigating credible single-point failures was utilized as a minimum standard.

Because the electrical system of a fuel cell vehicle is very similar to that of other electrical and hybrid vehicles, the practices and requirements rely heavily on previously published work in these areas. Correspondingly, hydrogen requirements are based on previous experience with gasoline and compressed natural gas (CNG) internal combustion vehicles with appropriate adjustments and expansions for fuel cell propulsion. The overall objective is to establish recommended practices such that FCVs can be used and stored in the same manner as conventional gasoline, internal combustion vehicles while still facilitating rapid advances by the industry.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fuel cell vehicles discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*
NFPA 52, *Vehicular Fuel Systems Code*
NFPA 70, *National Electrical Code®*
NFPA 77, *Recommended Practice on Static Electricity*

Chapter 6

Recreational Vehicles

Bruce A. Hopkins

Chapter Contents

Overview of Recreational Vehicles
Recreational Vehicle Development and Use
Development of Recreational Vehicle Standards
Recreational Vehicle Fire and Life Safety

Key Terms

motor home, recreational vehicle, towable

Recreational vehicles (RVs) have been around since the beginning of motorized travel in the early 1900s. RVs are available in several styles, types, and sizes to offer people of all ages the opportunity to camp and travel to points of interest or special events and otherwise enjoy the great outdoors. Today nearly 8 million U.S. households own at least one RV—a 15 percent increase over the 4 years from 2001 to 2005 and a 58 percent rise since 1980, according to the 2003 edition of *Industry Profile: RVIA Year End Report.* One in twelve U.S. vehicle-owning households now owns at least one RV.[1]

This chapter discusses the types of recreational vehicles and their features, the development and use of RVs, the development of RV standards, the fire and life safety issues associated with RVs, their fire safety record, and the oversight programs that are in place to assist RV industry manufacturers in the safe production of these vehicles for recreation, travel, and seasonal use.

For related topics, see Section 21, Chapter 1, "Passenger Vehicle Fires"; and Section 21, Chapter 4, "Vehicle Fueling Using Gaseous Fuels."

OVERVIEW OF RECREATIONAL VEHICLES

Recreational Vehicle Defined

Based on the NFPA 1192, *Standard on Recreational Vehicles,* definition as refined by the Recreation Vehicle Industry Association (RVIA), a recreation vehicle (RV) is defined as a vehicle that combines transportation and temporary living quarters for travel, recreation, and camping. RVs may have their own motor power (as in the case of motor homes), may be mounted (as are truck campers), or may be towed by another vehicle (as are travel, fifth-wheel, and folding camping trailers). Not included in the RV definition are conversion vehicles, off-road vehicles, emergency living units, and manufactured housing for long-term residence (i.e., park trailers and mobile homes).

Types of Recreational Vehicles

The two main categories of RVs are *motor homes* (motorized RVs) and *towables* (RVs towed behind the family car, van, or pickup).[2]

Motor Homes. A motor home is a vehicle built on or as an integral part of a self-propelled motor vehicle chassis. It may provide kitchen, sleeping, and bathroom facilities, and it may be equipped with the ability to store and carry fresh water and sewage. Type A motor homes (Figure 21.6.1) are generally the largest, where the driving compartment is built by the RV manufacturer; Type B motor homes (Figure 21.6.2), or van campers, are the smallest and are built on vehicles where the chassis manufacturer provides the driving compartment and the entire exterior shell; and Type C motor homes have the driving compartment provided by the chassis manufacturer (Figure 21.6.3) and generally fall in between these two in size (see Table 21.6.1).

Bruce A. Hopkins is the vice-president of standards and education for the Recreation Vehicle Industry Association (RVIA) in Reston, Virginia. Mr. Hopkins has worked in the area of RV standards for 34 years, 28 of these with RVIA. He has been directly associated with the RV industry for over 40 years.

FIGURE 21.6.1 Type A Motor Homes—Generic Model and Actual Example (Source: Courtesy of RVIA)

FIGURE 21.6.2 Type B Motor Homes—Generic Model and Actual Example (Source: Courtesy of RVIA)

FIGURE 21.6.3 Type C Motor Homes—Generic Model and Actual Example (Source: Courtesy of RVIA)

Towables. A towable RV is designed to be towed by a motorized vehicle (e.g., auto, van, or pickup truck) and of such size and weight as not to require a special highway movement permit. It does not require permanent on-site hook-up. Types of towable RVs are conventional travel trailers (Figure 21.6.4), sports utility RVs (Figure 21.6.5), travel trailers with expandable ends (Figure 21.6.6), fifth-wheel travel trailers (Figure 21.6.7), folding camping trailers (Figure 21.6.8), and truck campers (Figure 21.6.9).

Construction Techniques

RVs are manufactured on production lines similar to that of the automobile industry, but only a few RV manufacturers use fully automated assembly lines. In a typical RV manufacturing facility, the vehicles are generally pushed manually along the assembly line. The stations within a typical production line might include chassis, floors, interior walls, cabinetry, roofs and exterior coverings, installation of electrical/plumbing/propane-

TABLE 21.6.1 Recreational Vehicle Types and Features

Type	*Features*	*Sleeps*	*Price Range*
Motor home—Type A	• Constructed on a specially designed motor vehicle chassis • Kitchen, sleeping, bathroom, living facilities accessible from driver's area	2–6	$76,275–$1,350,000
Motor home—Type B (or van camper)	• Referred to as a "van camper" • Panel-type truck with kitchen, sleeping, and/or bathroom facilities • Freshwater storage, city water hook-up, and top extension for more head room	2–4	$41,000–$72,660
Motor home—Type C	• Constructed on automotive manufacture van frame with attached cab • Kitchen, sleeping, bathroom facilities • Living area behind and above cab	6–10	$48,450–$298,910
Towable—conventional travel trailer	• Towable by car, van, or pickup • Kitchen, sleeping, bathroom, dining, living facilities • 12–35 ft (3.66–10.67 m) long	4–8	$8,085–$79,510
Towable—sport utility RV	• Built-in "garage" for cycles, ATVs, other sports equipment	Up to 8	$21,000–$58,000
Towable—travel trailer with expandable ends	• Built for "fresh air" experience • Folds for lightweight towing	Up to 8	$9,000–$18,000
Towable—fifth-wheel travel trailer	• Equipped same as conventional travel trailer • Raised forward section, allowing bilevel floor plan • Towable by vehicle equipped with fifth-wheel hitch	Up to 8	$10,870–$120,350
Towable—folding camping trailer	• Lightweight with collapsible sides • Towable by family vehicle (even some compacts) • Kitchen, sleeping, dining, (often) bathroom facilities	Up to 8	$4,380–$12,800
Towable—truck camper	• Loaded onto bed or chassis of truck • Most with kitchen, sleeping, dining, bathroom facilities	2–6	$4,580–$22,590

Source: Data from *RVIA Types & Terms,* Recreational Vehicle Industry Association, Reston, VA, 2005.

fuel systems, installation of appliances or furniture, final finish, and testing.

RECREATIONAL VEHICLE DEVELOPMENT AND USE

History

Early Years. The recreational vehicle industry developed and grew from its early roots in camping, hunting, and other outdoor activities.[3] Tents, provisions, and cooking and sleeping equipment were loaded and pulled around the countryside on wagons, carts, and other conveyances long before the advent of the automobile.

The development of the automobile in the years around 1900 greatly increased the range of these campers and vagabonds, and mechanical power made it easier for them to take more supplies and comforts along on their adventures. Early "auto campers" simply piled their tents, equipment, and supplies in and on their vehicles. Later, they attached carts and trailers to the cars, increasing carrying capacity greatly. The earliest trailers were often modified horse-drawn carts with wooden cartwheels. The cartwheels were shortly replaced with heavier auto-type wheels. This relative ease of travel, with all the needed camping supplies, brought about the beginnings of what is now recognized as the RV industry and its related lifestyle.

In the early 1910s, trailers were being built not only to transport camping supplies and equipment, but to also be used as "house trailers," or mobile cabins. These earliest units, mostly homemade or custom built by local handymen or carriage makers, allowed for the storage of provisions, preparation of meals, and comfortable and relatively "bug-proof" sleeping. "Living rooms" and most daytime activities were relegated to the great outdoors.

From the mid-1910s to the mid-1920s, individual builders were creating one-of-a-kind "house cars" by motorizing their camping vehicles. Some were permanently built on auto or truck chassis; others were bolt-on structures added to a rigid frame and could be removed and exchanged. It is estimated that 15 million campers and RVers were on the nation's roads in 1922. In 1926, the Chenango Camp Trailer Co. introduced the first

FIGURE 21.6.4 Conventional Travel Trailers—Generic Model and Actual Example (Source: Courtesy of RVIA)

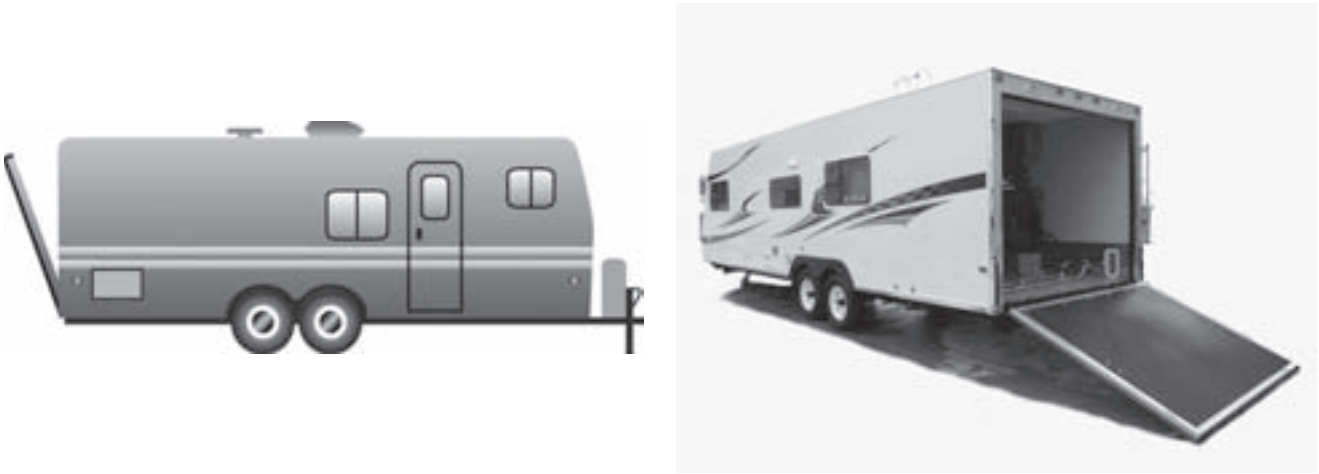

FIGURE 21.6.5 Sports Utility RVs—Generic Model and Actual Example (Source: Courtesy of RVIA)

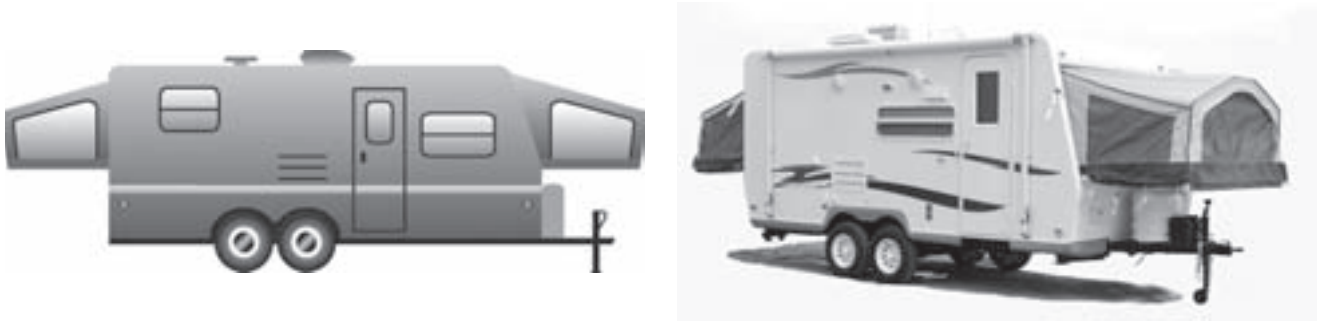

FIGURE 21.6.6 Travel Trailers with Expandable Ends—Generic Model and Actual Example (Source: Courtesy of RVIA)

FIGURE 21.6.7 Fifth-Wheel Travel Trailers—Generic Model and Actual Example (Source: Courtesy of RVIA)

FIGURE 21.6.8 Folding Camping Trailers—Generic Model and Actual Example (Source: Courtesy of RVIA)

FIGURE 21.6.9 Truck Campers—Generic Model and Actual Example (Source: Courtesy of RVIA)

assembly-line-produced travel vehicle, a fold-up tent trailer. A few other manufacturers followed, offering multiple units for sale, and the rush was on.

The rapid growth in numbers of these early "auto campers" and their demands for safe and scenic places to camp and enjoy the outdoors were a primary motivation for the development and early growth of the U.S. National Park system in the early 1920s. City- and county-operated camping sites were also becoming popular in the early 1920s as communities began to realize that the travelers, in most cases, brought money with them and would spend it with local businesses.

The economic disaster of the 1929 stock market crash slowed the rise of the new industry, but not for long. By the mid-1930s, one manufacturer, The Covered Wagon Company of Mt. Clemons, Michigan, was building 40 to 50 units per 8-hour shift from a single factory. Industry production records indicate that, in 1936, one-sixth of the nation's total recorded trailer production came from that single Detroit area factory.

By 1939, there were well over 100 manufacturing companies and an even larger body of suppliers and parts distributors active in the rapidly growing trailer coach industry. Associations of manufacturers were becoming organized, and national and international organizations of trailer owners were proving to be very popular.

The earliest activity of NFPA in the field of mobile homes and recreational vehicles was the formation of the NFPA Committee on Trailers and Trailer Camps in 1937. The first standard was adopted in 1940 and revised in 1952.

Local and national retail and wholesale trailer shows were being organized. The Tin Can Tourists of the World, organized in 1919, had become by far the largest of the consumer groups, with hundreds of thousands of members from the United States and Canada. In 1936 a Tin Can Tourists rally recorded well over 1000 units and nearly 3000 participants in attendance and hosted one of the first large retail shows.

World War II to the Present. World War II caused a second major pause in the dynamic growth of the RV industry, primarily due to very strict material rationing and the conscription of many potential customers and workers. Some manufacturers converted their production to various war-related items and others produced units as temporary housing for workers at war production facilities and military bases. The late 1940s and early 1950s saw a great burst of technological advances and living comforts for trailers, such as portable propane or butane cylinders, allowing gas stoves and heaters to replace liquid-fueled models, on-board refrigeration replacing ice boxes for food preservation, hot and cold running water, as well as on-board

toilets, showers, and 110-volt generators. With this growth came concerns regarding the safe installation of living systems, such as plumbing, LP-gas, and electrical. In the late 1950s, California introduced RV safety standards for the living systems and initiated a state-sponsored oversight program to ensure compliance. Many other Western states followed suit, often creating similar criteria, yet different enough to make manufacturing for multiple markets difficult.

Continued growth in the 1960s brought hundreds of new companies (many of today's industry giants) into the industry, as the baby boomers began to grow up and look for inexpensive recreational opportunities for their young families. In 1963, the Mobile Homes Manufacturers Association and the Trailer Coach Association worked together to create the *American Standard Installations of Plumbing, Heating and Electrical Systems in Travel Trailers* (A119.2–1963).

The growth of the RV industry, up to this point mostly trailer-based, was further enhanced with the advent and availability of affordable, assembly-line-produced motor homes. The development of modern pickup trucks also enabled the creation and popularization of the slide-in pickup carried campers and related Type C motor homes, which today are built mostly on van chassis rather than the original pickup truck chassis.

In the late 1960s, recognizing that these new motorized type products, different from travel trailers, were not included in the safety standards (A119.2-1963), the Mobile Homes Manufacturers Association, the National Fire Protection Association, the Recreational Vehicle Institute, and the Trailer Coach Association jointly sponsored the development of ANSI A119.2 and NFPA 501C, *A Standard for Recreational Vehicles,* 1970 edition. This standard also covered installation of plumbing, heating, and electrical systems. Additionally, definitions were added to clearly identify the product types known today as motor homes, travel trailers, camping trailers, and truck campers. This standard also assisted in defining the separation between mobile homes and recreational vehicles.

That 1960s boom in RV industry growth and the dramatic explosion of affordable motorized units was again nearly destroyed by the embargo-based fuel shortages and astronomically high interest rates of the 1970s, when almost half of the industry manufacturers either went out of business or merged into some of today's industry giants. Through the 1970s, the lifestyle was still primarily referred to as *camping,* and the rigs, whether motorized or towed, continued to be identified as *campers,* as they had been for over 50 years.

In the early 1980s, another dynamic change brought complete livability to the units. Many people with little interest in purely camping and nature-based outdoor activities became attracted to longer and larger rigs with living room space and the availability of features such as couches, recliners, TV, VCR, air-conditioning, and other homelike comforts. The lifestyle known today as RVing began to partially replace camping as the travel attraction, with many retirees and some families with itinerant-type jobs selling their real estate–based homes and residing full time on the road. Destination-oriented trips and not just family jaunts to favorite campsites became popular. This alteration in comforts and conveniences made the growth in popularity of "full-timing" possible. This change also forced the evaluation of fire safety standards developed in the late 1970s and adopted for the first time in the NFPA 501C and ANSI A119.2, *Standard for Recreational Vehicles,* in 1982. These requirements addressed interior finish, textile and film material flammability, exit facilities, fire detection equipment, and smoke alarms.

From the 1930s through the 1950s and into the early1960s, unit lengths were usually less than 20 ft (6.1 m) with 12 to 15 ft (3.66 to 4.57 m) long units very common. Most of the motorized as well as the towable units of the 1960s were less than 25 ft (7.62 m) long. With the improvement of both vehicles and highways, unit length began to grow through the 1970s, with RVs evolving into the common 30 to 40 ft (9.14 to 12.19 m) long units of today. It was this increase in length that allowed the addition of more homelike features to today's RVs.

Early unit pricing varied as widely as do prices today. Entry-level towable trailers in the Depression days of the 1930s were primarily sold in the $250 to $400 range with luxury trailers ranging as high as $1000. At the same time, luxury fifth-wheel rigs (which were often sold with a matching tow vehicle included) and "land yacht" motorized "house cars" up to 35 ft (10.67 m) long were being sold for $25,000 and up.

Today's RV lifestyle has come a long way from its earliest roots in the camping activities of the horse-and-buggy days and the early auto campers through the trailerites and Tin Can Tourists of the 1920s, 1930s, and 1940s. The medium-sized campers of the 1950s and 1960s began the move to modern conveniences and comforts, but the upsizing of vehicles and the resulting larger units of the 1970s and 1980s allowed campers to become RVers and made today's luxury RV lifestyle possible. This has attracted a completely new group of participants whose primary interest is not in camping and basic wilderness outdoor activities, but who enjoy the many benefits of self-contained travel both temporarily and full time.

From 1987 to 2005, NFPA 501C and ANSI A119.2 were updated every 3 years in an effort to harmonize safety and technology. Most of the changes through the mid-1990s were minor revisions and definitional improvements but also included substantive changes, such as requirements for increased exit sizes, requirements for carbon monoxide and LP-gas detectors, and provisions for RVs used for transporting or storing internal combustion vehicles. In 2005, NFPA 501c and ANSI A119.2 were combined to become NFPA 1192, *Standard on Recreational Vehicles.*

RV Ownership

U.S. ownership of RVs has reached record levels, according to a 2005 University of Michigan study.[4] Nearly one in twelve U.S. vehicle-owning households now owns an RV, almost 8 million households, or, as mentioned earlier, a 15 percent increase from 2001 to 2005 and a 58 percent gain from 1980 through 2005. The number of RV deliveries is also increasing, as seen in Table 21.6.2.[5]

Approximately 8.2 million RVs are on the nation's roads. RVIA, the national trade association for RV manufacturers and their component suppliers, estimates there are as many as 30 million RV enthusiasts, including RV renters, nationwide.

TABLE 21.6.2 Recreational Vehicle Shipment Totals, 1994–2006

Year	*Shipment*
1994	259,200
1995	247,000
1996	247,500
1997	254,500
1998	292,700
1999	321,200
2000	300,100
2001	256,800
2002	311,000
2003	320,800
2004	370,100
2005	384,400
2006	390,500

Source: *Industry Profile (RVIA Year End Report),* Recreational Vehicle Industry Association, Reston, VA, 2003.

DEVELOPMENT OF RECREATIONAL VEHICLE STANDARDS

Early NFPA RV Standards

The earliest activity of NFPA in the field of mobile homes and recreational vehicles was the formation of an NFPA Committee on Trailers and Trailer Camps in 1937. Its first standard, adopted in 1939, established a general overall outline of regulations for trailer camps. This edition was supplanted by the 1940 *Standard for Trailer Coaches and Trailer Coach Camps,* which expanded the requirements and addressed trailer vehicle construction, safety features pertaining to trailers in transit, and the regulation of trailers while not in transit. The standard, which applied to trailer coaches used as living quarters or for sleeping purposes, defined *trailer coach* as any structure intended for human habitation, mounted on wheels, and capable of being moved from place to place.

In 1952 the standard was revised into two parts and renamed *Standard for Fire Prevention and Fire Protection in Trailer Coaches and Trailer Courts.* Part A of this revised standard applied to trailer coaches intended for use as living quarters or for sleeping purposes. This part of the standard extended to awnings, porches, lean-tos, or other structures and equipment of a portable character designed to be carried in, on, or with the trailer and installed, assembled, or erected as appurtenances to the trailer when parked. Any structures built permanently in place in conjunction with a trailer were not considered as part of the trailer but considered as buildings and subject to the provisions of the building codes or other requirements.

Part B applied to trailer courts accommodating or providing a parking space for more than one trailer coach used for living or sleeping purposes. This part was limited to provisions affecting fire protection and prevention and was intended to be supplemented by municipal sanitary and public health codes. In addition, the standard recognized that local building codes were to be enforced if the wheels of a trailer were removed, if a trailer was permanently blocked up, or if the space beneath it was enclosed.

In 1960 NFPA approved a revised version of the standard, dividing it into two separate standards. NFPA 501A, *Standard for Fire Protection in Trailer Courts,* consisting of Chapters 10 through 19 of the 1952 standard, covered trailer courts intended to accommodate trailers designed (or intended) for living quarters. In 1961 NFPA 501B, *Standard for Fire Prevention and Fire Protection in Mobile Homes and Travel Trailers,* consisting of Chapters 1 through 9 of the original 1952 standard, was finalized.

In the early 1960s the Mobile Homes Manufacturers Association (MHMA) and the Trailer Coach Association (TCA) prepared, under the aegis of the American Standards Association (now American National Standards Institute, or ANSI), two standards that were subsequently approved as the *American Standard Installations of Plumbing, Heating and Electrical Systems in Travel Trailers* (A119.2–1963) and *Standard for Fire Prevention and Fire Protection in Mobile Homes and Travel Trailers* (A119.1–1963). In 1969 the Recreational Vehicle Institute (RVI) was added to the MHMA, NFPA, and TCA as a fourth cosponsor of the project. The first *Standard for Recreational Vehicles* developed under the consolidated efforts of NFPA, MHMA, TCA, and RVI was approved by NFPA in 1970 and by ANSI in 1971. This standard replaced ASA Standard A119.2–1963. In 1975 the MHMA and the TCA merged to become the Manufactured Housing Institute. Also in 1975 the Recreational Vehicle Institute absorbed the Recreational Vehicle Division of the Trailer Coach Association and was redesignated the Recreation Vehicle Industry Association.

This time period also saw the publication of two other NFPA standards: NFPA 501C, *Standard for Recreational Vehicles Installation of Plumbing, Heating and Electrical Systems,* and NFPA 501D, *Electrical Standard for Recreational Vehicle Parks.* Under various formats and titles, subsequent editions of the NFPA 501 series were published from 1972 through 1977, with only minor changes.

After 1977 NFPA withdrew as a cosponsor of the existing ANSI project and established its own ANSI-approved project, covering only the subject of fire safety for recreational vehicles. This committee, charged with developing a standard for fire safety for recreational vehicles and recreational vehicle parks, produced and revised three standards through the 1980s: NFPA 501A, *Standard for Fire Safety Criteria for Manufactured Home Installations, Sites, and Communities;* NFPA 501C, *Standard on Recreational Vehicles;* and NFPA 501D, *Standard for Recreational Vehicle Parks and Campgrounds.* These standards excluded all sections of the previous editions not considered within the committee scope, primarily plumbing and sanitary issues.

The standards continued through the 1990, 1993, and 1996 editions with only minor changes, including the size of alternate exits, clothes dryers, LP-gas detectors, and the expansion of provisions for recreational vehicles used for transporting or storing vehicles with internal combustion engines.

NFPA 1192, *Standard of Recreational Vehicles,* and NFPA 1194, *Standard for Recreational Vehicle Parks and Campgrounds*

In 1999 NFPA 501C was renumbered as NFPA 1192, *Standard on Recreational Vehicles,* and the requirements on LP-gas containers and connectors were updated. Changes also included modifications to requirements for exit facilities and special transportation provisions. Similarly, NFPA 501D was renumbered as NFPA 1194, *Standard for Recreational Vehicle Parks and Campgrounds.* NFPA 501A continues, most recently updated in 2005.

In 2002 there was a major editorial reorganization of both NFPA 1194 and NFPA 1192 in accordance with the NFPA *Manual of Style,* 2002 edition. Other changes occurred in the language of caution and warning labels.

In 2005 NFPA and RVIA once again merged the requirements from ANSI A119.2 into NFPA 1192, and ANSI A119.2 was no longer published. NFPA 1192 now contains minimum requirements for the installation of plumbing, fuel burning, electrical, and other safety-related systems in recreational vehicles. Technical changes to the standard include clarification of requirements for location and securing of propane containers, requirements for high-pressure piping, revision of requirements for fuel tank installation, and the inclusion of requirements for automatic generator starting systems.

NFPA 1192 Requirements. The following partial table of contents of NFPA 1192 shows the scope of this standard, which covers the fire and life safety criteria for recreational vehicles:

Chapter 4 General Requirements

4.1.1 Differing Standards
4.1.2 U.S. Federal Regulations
4.1.3 Exterior Labels
4.1.4 Electrical Requirements

Chapter 5 Fuel Systems and Equipment

5.1 Quality of Design and Installation
5.2 Propane Systems
5.3 Propane Piping Systems
5.4 Fuel-Burning Appliances
5.5 Venting, Ventilation, and Combustion Air
5.6 Marking Appliances (Installation and Operation Features)
5.7 Circulating Air Systems for Heating (Other Than Automotive Type)
5.8 Air Conditioning (Other Than Automotive Type)
5.9 Consumer Information
5.10 Gasoline or Diesel Fuel Systems
5.11 Propane Vehicle Propulsion Engine Installations

Chapter 6 Fire and Life Safety Provisions

6.1 Interior Finish and Textile or Film Materials
6.2 Recreational Vehicle Exit Facilities
6.3 Fire Detection Equipment
6.4 Other Considerations
6.5 Automatic Generator Starting System (AGS) Requirements

Chapter 7 Plumbing Systems

7.1 Plumbing System
7.2 Plumbing Fixtures
7.3 Water Distribution Systems
7.4 Drainage Systems
7.5 Waste Holding Tanks
7.6 Vents and Venting
7.7 Plumbing System Tests

NFPA 1194 Requirements. NFPA 1194, *Standard for Recreational Vehicle Parks and Campgrounds,* provides minimum construction requirements for safety and health for occupants using facilities supplied by recreational vehicle parks and campgrounds that offer temporary living sites for use by recreational vehicles, recreational park trailers, and other camping units. The following partial table of contents of NFPA 1194 shows the scope of this standard:

Chapter 4 General Requirements

4.1 Differing Standards
4.2 U.S. Federal Regulations
4.3 Electrical Requirements
4.4 Wildland/Urban Interface Areas
4.5 Recreational Park Trailers

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RECREATIONAL VEHICLE FIRE AND LIFE SAFETY

Safety and Fire Data

As the industry has matured, so have its safety efforts. Over the years, RV safety has expanded. Interiors now have fire retardant

requirements, fire extinguishers, propane detectors, CO detectors, and smoke alarms. The exit facilities have increased in size and their markings have improved to help occupants exit RVs in dangerous situations.

Fire and Life Safety Issues

Reasons for Decrease in Fatalities. Why deaths in RVs due to fire decreased between 1993 and 2002 is difficult to determine because records are limited and also because the manner of classifying vehicles in police accident reports is inconsistent. RVs are sometimes reported as mobile homes or manufactured homes, and motor homes and trailers are often referred to by brand names, such as Airstreams or Winnebagos, regardless of whether they are towable or motorized RVs. Also, other vehicles such as all-terrain vehicles and dune buggies are reported and documented as RVs, skewing the data available. All these reporting variables prevent the emergence of a true picture of how RVs perform over a specific period of time and of which factors affect the data.

RV Standard Changes Affecting Fire Safety Results. Some changes to the RV standards, beginning with the 1993 edition of NFPA 501C, that could be credited for enhanced fire and life safety resulting in fewer deaths by fire might include the following:

- The provisions for portable fire extinguishers mandated a size increase from 4B:C to 5B:C for towable RVs and later added the requirement for motorized RVs to have a 10B:C fire extinguisher.
- Carbon monoxide detectors were required in all RVs equipped with an internal combustion engine or designed with features to accommodate future installation of an internal combustion engine.
- Propane detectors were required in all RVs equipped with propane appliances and 120 volt ac systems.
- Emergency exit openings were increased in size and exit markings were added.
- Propane containers were required to be shielded from exhaust components and other high-heat sources.
- RVs designed for the transportation of internal combustion engine–type vehicles inside the RV required the transport area to have ventilation and vaportight separation from the living area, as well as requiring consumer information to be provided for guidance relating to fire and life safety.
- Low-voltage wire was required to have a minimum insulation rating of 90°C for interior applications and 125°C in an engine area.
- 30 A power supply assemblies were limited to a maximum of five branch circuits.
- RVs were required to have listed low-voltage lighting fixtures to reduce heat buildup at their mounting surfaces.
- Receptacles serving countertops with sinks were required to be provided with ground-fault circuit interrupter (GFCI) protection.
- RVs were limited to only one power supply assembly instead of two.

RV Manufacturer Compliance with Codes and Standards

The Recreation Vehicle Industry Association (RVIA), the national trade association representing more than 550 manufacturers and component suppliers that produce approximately 98 percent of all RVs and conversion vehicles manufactured in the United States, is headquartered in Reston, Virginia. Consumers shopping for an RV often look for the RVIA seal prominently displayed on the exterior of an RV. The seal means the manufacturer certifies compliance with more than 500 electrical, plumbing, heating, and fire and life safety requirements established under NFPA 1192. The oval-shaped RVIA seal comes in three colors, depending on RV type:

- Gold ovals with the word "MOTORHOME" for all Type A, B, and C motor homes
- Silver ovals with the words "TRAVEL TRAILER • FIFTH-WHEEL" for all conventional, hybrid, and fifth-wheel travel trailers
- White ovals with the words "TRUCK CAMPER • FOLDING CAMPING TRAILER" for all truck campers and folding camping trailers

As a condition of membership, all RVIA member manufacturers are subject to periodic, unannounced plant inspections by RVIA representatives to audit these member manufacturers' pledge to comply with NFPA 1192. Members who fail to maintain acceptable levels of compliance can be expelled from the association, thereby losing the right to display RVIA seals on their products.[6]

In addition to RVIA's oversight, which helps the manufacturers build safe RVs, the manufacturers must comply with the standards and regulations established by the U.S. Department of Transportation and with a variety of state regulations. All programs, both state and federal, are self-certification programs. There is no oversight by an outside agency to ensure compliance. However, compliance is of paramount importance to the manufacturer. Manufacturers are required by law to notify the government of all safety-related defects. Most safety-related defects require the manufacturer to conduct a recall campaign to fix the failed part or system. The federal government imposes the same program requirements on RV manufacturers as they do on the automotive industry.[6]

SUMMARY

Recreational vehicles (RVs) have been around since the beginning of motorized travel in the early 1900s. RVs, which are defined as vehicles that combine transportation and temporary living quarters for travel, recreation, and camping, may have their own motor power, as in the case of motor homes; be mounted, as in the case of truck campers; or be towable, as in the case of travel, fifth-wheel, and folding camping trailers. Discussed in this chapter are the types of recreational vehicles and their features; the historical development and use of RVs; and the development of the two main RV standards, NFPA 1192 and NFPA 1194. The chapter concludes with a discussion of the fire and life safety issues of RVs and the oversight programs that are in

place to assist RV industry manufacturers in the safe production of RVs for recreation, travel, and seasonal use.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on recreational vehicles discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 1192, *Standard on Recreational Vehicles*
NFPA 1194, *Standard for Recreational Vehicle Parks and Campgrounds*

Chapter 7

Fixed Guideway Transit and Light Rail Systems

Revised by
Tom Peacock

Chapter Contents

System Characteristics
Underground Trainways
Underground Stations
Surface-Level and Elevated Transit Systems

Key Terms

elevated transit system, fixed guideway transit system, King's Cross Station fire, passenger rail system, point of safety, rail car, traction power, transit vehicle, underground (transit) station, underground (transit) system

The environment of a transit and passenger rail system (the system) lends itself to peculiar and difficult fire safety problems. Large numbers of people who move through these subterranean enclosures and elevated structures compound the life safety dangers. Fires within subways—such as the 1987 fire at King's Cross Station in London in which 31 people died—have attracted international attention over the years due to the danger facing passengers who must evacuate trains through smoke-filled trainways and other emergency exitways. Figure 21.7.1 illustrates the King's Cross fire.

Among the causes of fire in a system can be mechanical failure of undercar components, high-energy electrical short circuits, accumulation of combustible debris along the trainways and within vent shafts, accumulation of road film and oils on the transit vehicle underside, combustible materials in car components, combustible construction of trainways including crossties, and hazards associated with the human factor, such as criminal or terrorist acts.

This chapter covers areas in a transit system requiring special attention, including underground trainways, underground stations, and surface-level and elevated transit systems.

For related topics, see Section 21, Chapter 8, "Rail Transportation Systems."

SYSTEM CHARACTERISTICS

Although underground and elevated trainways and underground stations pose the most serious threat to transit users from fire, certain basic considerations must be recognized throughout the system.

Traction Power

Traction power provides the electrical energy needed to run trains and may be carried throughout the system by means of a third rail or overhead contact system and is typically a nominal 600 to 750 V dc. For transit systems with traction power provided by a third rail, a coverboard of electrical insulating material is often installed throughout the system to prevent people from inadvertently coming in contact with the energized rail. The coverboard should be strong enough to hold a 250 lb (113 kg) weight. Warning signs should be affixed to the coverboard in any area accessible to the public.

Disconnect switches should be located strategically throughout the system so traction power can be removed as quickly as possible under emergency conditions. Otherwise, alternative prompt and reliable means for disconnecting power should be provided.

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FIGURE 21.7.1 Remains of Booking Hall After Fire at King's Cross Underground Station

Egress from Stations

When determining required exit capacity, future occupancy needs must be considered. After a station has been constructed, it becomes very difficult, if not impossible, to place additional stairs or escalators where they best serve the public. Complying with required exit width may present major difficulty to designers. NFPA *101*®, *Life Safety Code*® as modified by NFPA 130, *Standard for Fixed Guideway Transit and Passenger Rail Systems,* contains basic requirements.

To establish required exit widths for any structure, it is first necessary to determine occupancy classification. For example, the State of California, other jurisdictions, and NFPA *101* determined that places where people await transportation should be classified as assembly occupancies. Effective June 1983, however, NFPA 130 established requirements for life and fire safety in system stations, trainways, vehicles, and outdoor vehicle maintenance areas. The dynamic exiting concept in NFPA 130 determines occupancy based on estimated numbers of patrons waiting in stations and alighting from trains. NFPA 130 considers only those stations accommodating passengers and employees of the system and incidental occupancies. Where large numbers of people other than transit patrons are involved, such as where stations are incorporated into shopping malls, sports facilities, or other occupancies, NFPA *101* sets exit requirements.

Because transit systems are designed to move people rapidly, most new systems have installed escalators as the primary means to enter and exit stations. Escalators that are designed to be reversible, depending on commute conditions, are acceptable as emergency exits. However, escalators should not account for more than the number of units of exit at any one level that are specified by NFPA 130.

When escalators are designed as required exits, their usability in evacuating a station under emergency conditions must be seriously studied. For example, provisions must be made to stop all platform-bound escalators so that they can be used as egress. Reversible escalators should be set to run in the exit direction. NFPA 130 contains requirements for methods of stopping escalators in a manner that prevents injuries to patrons.

In many instances, escalators penetrate two or more floor levels to access the intended platform. This can pose special design problems because many designers prefer to maintain an open environment throughout a station complex. Vertical penetration of more than one floor without enclosures has been accomplished in some systems by increasing other fire protection components.

Exit Barriers

Stations contain two basic areas to separate those individuals who have paid their fare from those who have not. These are commonly referred to as "paid areas" and "free areas." Patrons in the free area can move directly to the outside without encountering barriers. Patrons within the paid area may go through fare barriers to access the free area. During emergency evacuation, either all fare barriers should open automatically, allowing patrons to evacuate the station rapidly, or specially designed access gates should be installed for the same purpose. With increased emphasis being directed to patrons with disabilities, access gates become more useful in basic station design.

Procedures and methods that allow operators to quickly control or limit the number of patrons allowed into a station in the event of a delay or a malfunction are most important. A public address system that notifies and advises patrons during an emergency or a malfunction is also considered essential.

Grills or steel doors completely close off many stations after normal revenue hours. Installing small doors in the grills can provide easy access for fire department personnel, as well as serve as an acceptable means of exit for any employees who may be working in the station.

Emergency Procedures

Due to the variety of hazards involved in a fixed guideway transit and passenger rail system, local fire authorities must establish a direct line of communication with the system's top management. Good inspection techniques must be developed, and coordinated emergency response procedures planned. Access points to all parts of the system must be pinpointed, and engine and truck company response patterns tailored to meet special access problems. Information regarding the system, such as floor plans, electrification, vehicle design, structures, fire protection systems, and communications, is needed to plan emergency procedures properly. Specially developed map books, known as "Fire Maps," for fire department use have proven valuable. A wise course for a fire department is to assign one command officer the responsibility of coordinating all emergency activities required to protect against fires on rapid transit trains, on the right of way, and adjacent to the right of way.

Communication must also extend in the other direction. Fires and other emergencies in adjacent properties may require modified transit operation. In downtown areas, fire suppression activities in nearby buildings can cause water drainage into subways, or flammable liquid spills can endanger below-grade stations. Elevated structures can block fire department access to adjacent buildings. The American Public Transportation Association, RT-S-OP-007-0 Standard for Rail Transit System Emer-

gency Management provides detailed guidance to rail transit systems on planning for emergency preparedness.

Transit and Passenger Rail Vehicle

The construction and use of the transit vehicle (the rail car) has received a great deal of attention regarding fire and life safety. With a reasonable degree of attention, all elements of the transit system—trainway, stations, wayside equipment, and maintenance facilities—can be designed with an acceptable level of fire protection. Construction materials and methods can provide a noncombustible, if not fire-resistive, profile. These elements are static, and many solutions for achieving a degree of fire resistance are already in use in related structures, such as buildings and bridges, and in support subsystems, such as elevators, escalators, and electrical and mechanical systems.

Because of performance and comfort considerations, the modern rail car has made extensive use of manufactured materials. The rail car includes many attractive and serviceable plastics, such as foams, fibers, and other synthetic materials. These are often quite combustible and may emit toxic combustion products while burning. These problems are not unique to the transit and passenger rail car. Combustible plastics are used in passenger compartments of other modes of transportation, including aircraft, buses, and the family car. However, transit vehicles can accommodate several thousand people—far more than even a jumbo jet—and this therefore presents the potential for great loss of life.

Much attention must be focused on the materials and finishes of every item that goes into each car, including insulation for propulsion motors and other electrical wiring. The rail car is typically a source of toxic smoke generated by, and fuel contributed to, a fire.

Therefore, the rail car is a primary concern in a fire and life safety program for a transit system. Unfortunately, many existing fire test methods used to measure performance of materials in fire test conditions have proven inadequate in predicting actual fire performance. NFPA 130 contains a table of required specific test methods and tests to be used for transit rail car materials. This table is based on a guideline for grantees developed by the Federal Transit Administration. The Federal Railroad Administration has incorporated a version of this table into the federal regulations that applies to commuter rail cars. The NFPA 130 requirements and the Federal Railroad Administration requirements are slightly different.

Considering all this, the complete fire hazard assessment for new or retrofitted cars should include fire propagation resistance, smoke emission, ease of ignition, and heat and smoke release rate. The cars' total combustible loading should be limited to as low a value as possible. Existing tests, such as those in NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials;* NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials;* ASTM E162; ASTM E84; and others can be used if results are interpreted in relation to the transit environment. With the sponsorship of the Volpe Transportation System, the National Institute of Standards and Technology is developing tests to better predict the performance of materials when subjected to elevated temperatures, especially with respect to the release of toxic products.

UNDERGROUND TRAINWAYS

Fires within the confines of an underground system, especially those in trainways, are among the most difficult to extinguish because fire fighters have limited room in which to operate. Access points for fire personnel, emergency exit locations for passengers, availability of water supply, and ventilation capabilities are among the fundamentals that must be considered in providing adequate safeguards for passengers and facilities for fire fighters responding to emergencies.

A direct liaison between system operating authorities and fire officials is essential to keep emergency forces apprised of current conditions in underground installations. Floor plans of stations and subways must be reviewed continually. Fire protection included in the original system design may have changed, thus requiring fire-fighting plans to be updated.

Ventilation

Ventilation of underground trainways in emergencies is of primary importance. The removal of smoke during fires must be seriously studied. Several commercially developed computer programs are available to model various smoke removal scenarios. Exiting schemes that allow passengers to exit rapidly into fresh air must also be developed. Some systems have installed fully reversible fans within vent shafts. They move large quantities of air by intake or exhaust, and thus purge smoke from the trainway in a predetermined direction so passengers can evacuate to the nearest station or exit. Ventilation shafts and fans are often placed at each end of an underground station and, in some instances, between stations. When vertical shafts are included in the ventilation construction, the possibility of flammable liquid spills entering the shaft at street level must be considered. Shafts should terminate in roadways only when absolutely no other alternative exists. Adequate sumps equipped with flammable vapor detectors must be developed to retain such spills. Ventilation equipment installed within shafts and fan rooms should meet requirements for expected fire exposure.

Transit systems need to develop safeguards to ensure that central control operators responsible for implementing fire emergency ventilation scenarios receive the correct initial information. Implementing the wrong scenario could move smoke to where the people are rather than away from them, resulting in disaster.

Access/Egress

Walkways. Primary consideration must be given to evacuation of large numbers of passengers to a point of safety if a train stopped between stations must be evacuated. A "point of safety" could be a station platform or direct access to the open air through vertical exitways. Some older systems evacuate passengers by having them descend from the train to the walkway, and then walk until they reach a vertical exit or station platform. In newer systems, passengers evacuate the rail car to a walkway

constructed alongside the rail car opposite the third-rail power source (Figure 21.7.2). This arrangement lets passengers step directly from the train to the walkway.

For trainways separated by noncombustible walls and fire doors, the walkway system also provides easy access to a train on the opposite trainway and an acceptable horizontal exit path that remains relatively free of smoke and heat. Obviously, adequate underground trainway lighting must be provided to allow safe evacuation.

Many systems currently operate underground on trainways completely separated from each other by noncombustible walls and fire doors (Figure 21.7.3). As previously mentioned, this concept provides a refuge for passengers, as long as adequate train control and planning is practiced. Separation walls should have no less than a 2 hour fire resistance rating, and openings in them should be protected by 1½ hour fire doors. Openings through the wall, protected by fire doors, can provide an acceptable horizontal exit path from the trainway on which an accident has occurred to the other trainway, which remains relatively free of smoke and heat. Cross-passageways between trainways can be used in lieu of emergency exit stairways to the surface. When used, cross-passageways should not be farther than 800 ft (244 m) apart. Hardware normally used in the installation of fire doors and frames has been found inadequate for the pressures generated by a train moving through the trainway and for the damp environment found in trainways. Special study and consideration must be given to the type of door, frame, hinges, locking device, and method of securing the frame to the opening. Sliding fire doors with counterweights require special attention.

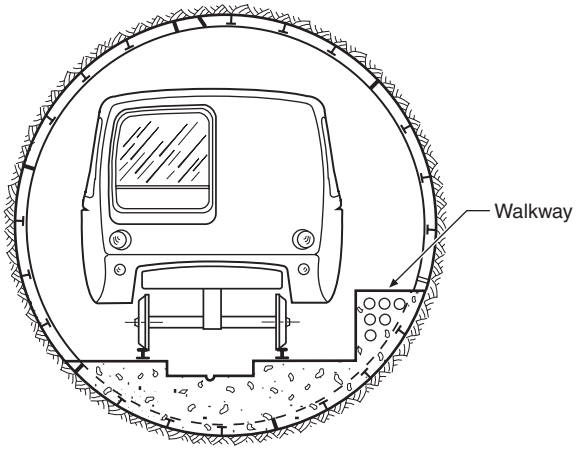

FIGURE 21.7.2 Sectional View of a Single-Tube Subway Tunnel, Showing Location of Emergency Passenger Walkway to Floor of the Car

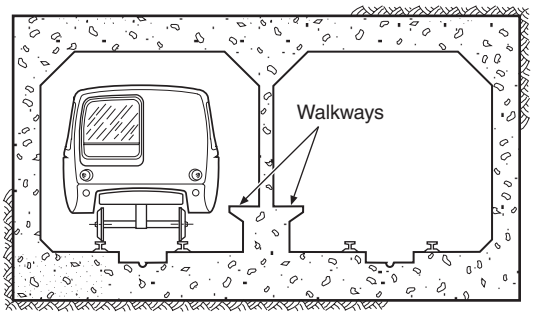

FIGURE 21.7.3 Sectional View of a Subway Tunnel Having Trainways Separated from Each Other by a Noncombustible Wall

Emergency Exits. Several factors must be considered to determine exit requirements from an underground subway system, including the following:

- Train length
- Depth of trainway below grade
- Accessibility to exit at grade
- Accessibility to exit at trainway
- Time and distance needed for people to exit to surface
- Available ventilation and controls
- Access to trainway for fire service

Due to transit systems' ability to control smoke using sophisticated ventilation systems, and since unlimited vertical shafts are impractical, NFPA 130 allows emergency exit shafts to be placed so that maximum travel distance does not exceed 1250 ft (381 m) in tunnels. The intent and basics of NFPA *101,* as modified by NFPA 130, should be followed in designing exit stairs. Hatches can be used at the surface, if there are provisions to prevent obstructions that would keep them from opening in an emergency.

Internally illuminated exit signs with two power supply sources should be installed at the trainway level to direct passengers, and emergency lighting should be provided within the exit enclosure.

Communication

Probably one of the most serious problems encountered during underground emergencies involves communications. Emergency telephones normally are identified throughout the underground system by a distinctive light: in most systems blue lights designate emergency phone locations. Communication from the trainway directly to a central control room is accomplished merely by picking up the phone.

Blue-light stations identifying the location of emergency telephones can also serve multiple purposes. For example, on the San Francisco Bay Area Rapid Transit (BART) System headquartered in Oakland, California, blue-light stations include a third-rail or power-disconnect button, a 110 V outlet, and a 20 lb (9 kg) multipurpose dry chemical extinguisher. Stations are spotted throughout the underground system at 1000 ft (30 m) intervals or in line of sight, whichever is shorter.

Communication (particularly radio communication) in an underground system is sometimes very difficult. Many newer subway systems have installed equipment to let fire department radios be used in underground stations and tunnels. Where this capability does not exist, fire authorities should make every ef-

fort to test their communication systems under actual conditions throughout the subway system. Consideration should be given to using hard-wired communication systems that may already exist. Portable radios or emergency phones with a direct line to the transit system's central headquarters or to train radios are both useful. Every system should have a radio network providing two-way communication connecting personnel on trains and other vehicles anywhere in the system.

During emergencies, radio frequencies and telephone lines quickly become overwhelmed. Portable hardwire telephones, dedicated to fire department use, should be available for point-to-point communications.

Fire Protection in Underground Trainways

A principal fire protection device in systems is the standpipe hose system. NFPA 14, *Standard for the Installation of Standpipe and Hose Systems,* provides good guidance for installations, and Class I or Class III service should be specified.

Standpipes. Standpipes should be located in stations and throughout the underground trainway system. Standpipes in tunnels should be at least 4 in. (101.6 mm) in diameter or sized by hydraulic calculations, and may be of the dry type. Generally speaking, local fire authorities determine locations of standpipe outlets, with consideration given to fire department access at tunnel level, available vertical access shafts for emergency forces, available street access to the fire department, and siamese connections at grade level.

Some systems require that dry standpipe outlets be no more than 200 ft (61 m) apart throughout the underground. Others have determined that maximum separation distances of 300, 400, and 500 ft (91, 122, and 152 m) are acceptable.

Some systems place bins or boxes containing 2½ in. (64 mm) hose near dry standpipe outlets and leave inspection and testing of such hose to system personnel. Fire authorities operating under this principle should seriously consider assigning personnel to witness hose inspections and required waterflow testing. Other systems and fire departments have agreed to only place hose and appliances in lockers at the base of access shafts. In areas where local fire authorities wish to use their own hose, provisions must be made to transport hose and other equipment to a fire site or to store necessary equipment in tunnels and stations.

Special Apparatus. In lieu of supplying the fire hose required at standpipe stations, some systems have taken innovative measures to ensure that hose is available when needed. BART, for example, with approval of fire authorities, removed all fire hose from its subway system, except the 1½ in. (38 mm) hose located within stations. In turn, BART provided five fully equipped, specially designed fire engines capable of traveling by street or rail to previously designated rendezvous points. The responding fire department then boards the apparatus and goes to the fire or emergency location within the underground. Each piece of apparatus includes, as part of its inventory, 1200 ft (366 m) of 2½ in. (64 mm) hose and 400 ft (122 m) of 1½ in. (38 mm) hose, as well as nozzles, a portable emergency generator, a power saw, a cutting torch, extension cords, floodlights, demand breathing apparatus, lifelines, miscellaneous tools, a high-expansion foam unit and nozzle, a 300 gal (1136 L) water tank, and a small pressure pump.

A more practical solution is manual pushcarts, designed to run on rails and stored in stations. These carts range from small commercially available maintenance carts to specially designed folding multilevel carts constructed using lightweight alloys. These pushcarts can also be used to evacuate stretcher cases.

Fire Department Operational Plans. Fire departments that respond to emergencies in underground systems must be extremely familiar with the layout, access, exit, communications, ventilation, and other special factors that must be part of an operational plan for both the fire department and the system. Such plans must be reviewed and practiced regularly, and all fire department members and system employees must be trained to respond appropriately to incidents.

Every fire fighter entering an underground system to fight a fire must have self-contained breathing apparatus (SCBA) to meet the requirements of NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program.* One challenge facing the fire department is how to maintain an adequate supply of replacement air cylinders for members working below grade level. This may require long-duration breathing apparatus and trucks to refill or deliver quantities of SCBA air cylinders.

Fire Extinguishers. Fire extinguishers should be placed on board each car. In addition, fire extinguishers should be placed near fixed equipment throughout the underground system where ignition sources and/or combustibles exist. Locations should include electrical equipment, sumps, ventilation equipment, and so on. If the blue-light or the emergency station is suitably located, one or the other would be a preferred place for extinguishers. The size and type of exposure expected dictates the extinguisher's size and type.

Drainage. Adequate drainage of water accumulated during a fire requires careful consideration. Fire authorities should be made aware of the underground system's drainage capabilities and recognize that large amounts of water could seriously impair other required rescue operations. When fighting structural fires at street level near station entrances or street ventilation grills, fire officers should alert transit system officials that water intrusion into their system may be expected and take steps to prevent water intrusion using tarps.

UNDERGROUND STATIONS

Design and Construction of Underground Stations

Underground stations should be constructed of minimum approved noncombustible materials—that is, Type I, Type II, or combinations thereof—as outlined in NFPA 220, *Standard on Types of Building Construction.* Many modern systems use reinforced concrete construction for the station's outer shell and protected steel beams, girders, and columns within the shell.

This results in a structure with a very substantial fire-resistive capability.

Very few major fires have occurred within stations. A notable exception is the King's Cross Station fire, which occurred in London, England, on November 18, 1987.[1] Thirty patrons and one fire fighter were killed in that fire. Among the many possible causes of station fires are poor housekeeping or electrical fires in escalator machine rooms.

A significant fuel source at stations, other than the trains, is the concessions. Small concessions that sell newspapers and magazines normally have a low-risk classification, whereas major concessions, such as restaurants or theaters, have a high potential risk classification for smoke and heat development.

Newspaper and magazine concessions should be limited in size and must not block required exits. Automatic sprinkler protection should be installed to protect concession areas. Possible future expansion of the area should be considered in designing the fire protection system.

Station public areas should be separated from nontransit areas with a fire barrier having at least a 3 hour fire rating. Major concessions or openings from public areas of the station into existing commercial structures should be protected by fire door assemblies having a 1½ hour fire protection rating. Even if the system owns the commercial activity and the station, good separation between the two areas is needed. Fire barriers can be established by installing fire doors or automatic fire extinguishing systems to prevent fire and smoke spread from the commercial occupancy into the station or from the station into the commercial occupancy. Before making any opening into a station, existing conditions on both sides of the proposed opening must be reviewed carefully so that an effective fire protection plan can be developed.

Fire Protection for Underground Stations

An underground station may be compared to a multiple-basement structure, except that a station generally has a very low fire-loading factor when compared to that of a commercial basement. Because of the substantial cost of code-compliant fire protection and transit car design, these may be good applications for performance-based design, in which tests and calculations are used to show that innovative approaches and designs meet the intent of the code, if not the letter of the code. In late 2001, ASTM adopted a guide for fire hazard assessment of rail cars as a step in the direction of supporting performance-based innovation.

Automatic Sprinkler Systems. All areas in stations that are used for concessions, storage, and fare collection, and other similar areas with combustible loadings, as well as the steel truss area of all escalators in a single-entry station, should be protected by automatic sprinklers equipped with flow alarms and supervision. Trainways are excluded. NFPA 13, *Standard for the Installation of Sprinkler Systems,* should be used. Other approved fire extinguishing systems, such as clean agent extinguishing systems in train control rooms, could also be used in lieu of the automatic sprinkler system, but only with the approval of the authority having jurisdiction (AHJ).

Deluge Systems. In the event of a fire in undercar equipment, train operators are instructed to bring trains to stations for passenger evacuation whenever possible. Some newer systems have opted for undercar deluge systems. These systems consist of fixed piping connected to a water supply, with open sprinklers located between rails. They are activated manually from the station attendant's booth or at the ends of the platform.

An alternative is an overcar deluge system designed to create a water curtain between a burning train and the platform. The system can be activated automatically by heat detectors in the trainway or manually as described previously. Examples of both types of installations are found in the Baltimore Metro System.

Emergency Communications. Underground stations typically do not have traditional fire alarm systems with pull stations and bells. Instead, the public address system alerts and directs passengers in the event of an emergency. Passengers can report emergencies through emergency voice alarm reporting devices located on the platform and throughout the station. Emergency communication systems must conform to *NFPA 72®*, *National Fire Alarm Code®*.

Fire Detection Systems. All nonpublic areas commonly classified as support or ancillary areas, if not protected by an automatic fire suppression system, should be fully protected by a fire detection system conforming to *NFPA 72.* Listed smoke alarms are preferable, although rate-of-rise detectors may be used if authorized by the concerned fire authority.

It is good practice to provide supervision for all fire detection and automatic fire suppression systems. Supervisory signals should be received at the system's command center and annunciated by zone at the station agent's booth or kiosk.

Wet Standpipes. Where separate standpipe and automatic sprinkler systems are provided, wet standpipes usually are supplied by a piping system that is separate and distinct from that used for automatic sprinkler systems. Fire department siamese connections, properly labeled and installed at grade level, let the fire department supply additional water to either system.

Fire hose cabinets may contain 1½ in. (38 mm) and 2½ in. (64 mm) control valves, as recommended in NFPA 14. A maximum of 100 ft (30 m) of attached 1½ in. (38 mm) hose with nozzle and/or 2½ in. (64 mm) hose and a spanner wrench may be stored in cabinets for use by the fire department at the discretion of the local AHJ. A suitable fire extinguisher may also be placed in the cabinet. To reduce pilferage of fire equipment, cabinets should be locked and a breakaway glass panel installed to allow ready access under emergency conditions. Some systems have installed intrusion alarms, which send a signal to the station agent if a fire hose cabinet has been opened.

SURFACE-LEVEL AND ELEVATED TRANSIT SYSTEMS

Generally, combating fires in transit systems at or above grade is no more difficult than fighting any other type of fire at grade.

Primary consideration must always be given to the traction power. Even when assured that the power has been shut off, fire department personnel should operate under the assumption that the third rail or overhead wire is still energized.

Although fires in trains on surface track or elevated trainways present a less serious exposure to the public, design must address certain basic considerations, such as means of egress along elevated trainways. As always, communication is paramount in any emergency operation. The ability to direct emergency forces to the scene of an incident and to place the system in a safe condition for egress is necessary for patrons and emergency personnel.

Access to a trainway also may require special provisions. Locating trainways in a joint corridor with a railroad or freeway may limit access for long distances of the trainway. Trainways extending from population centers through undeveloped areas sometimes extend where surface roads and water mains do not exist. Trainways in congested areas, trainways elevated to unusual heights, and trainways in other sections not accessible to emergency vehicles or paramedic units could create other problems. Trainway construction can also cause problems of fire exposure and access to adjacent structures. For example, an elevated trainway above existing city streets and adjacent to existing buildings can interfere with fire department operations at those buildings.

Similar problems can exist at stations. However, permanent exits provide both passenger evacuation and emergency personnel access. Recent systems have incorporated stations in the lower elevations of high-rise buildings or within mall complexes that have divergent occupancies. In these cases, detailed plans for coordination and compatible design are necessary.

Stations that can be considered to be buildings would normally be reviewed through normal code procedures. If a transit system passes through more than one jurisdiction, particularly if different basic codes apply, development of a common set of requirements is desirable to achieve uniformity throughout the system.

Most existing building codes do not usually address the subject of trainways, however. The exception is NFPA *101*. Items that should be considered during a plan review of a guideway include the following:

1. Designated location markers to provide a response location for fire personnel
2. Locations where overhead trainways may intersect with known street locations
3. Egress gates allowing passengers to exit the system under authorized employee supervision
4. Available wayside communications allowing the fire department to communicate directly with the system's command center
5. Locations of substations, switching stations, gap breaker stations, or other major electrical installations of concern to local fire authorities

SUMMARY

Fire protection of fixed guideway transit and passenger rail systems is similar to fire protection of other occupancies in many respects. Prevention of ignition is of paramount importance, as are safe evacuation of occupants and the safety of responding fire fighters. However, the unique characteristics of fixed guideway transit and passenger rail systems are more challenging, particularly in underground trainways and stations.

BIBLIOGRAPHY

Reference Cited

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fixed guideway transit and light rail systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*
NFPA 51B, *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work*
NFPA 58, *Liquefied Petroleum Gas Code*
NFPA 70, *National Electrical Code®*
NFPA 72®, National Fire Alarm Code®
NFPA 80, *Standard for Fire Doors and Other Opening Protectives*
NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*
NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*
NFPA *101®, Life Safety Code®*
NFPA 130, *Standard for Fixed Guideway Transit and Passenger Rail Systems*
NFPA 220, *Standard on Types of Building Construction*
NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations*
NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials*
NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*
NFPA 256, *Standard Methods of Fire Tests of Roof Coverings*
NFPA 505, *Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operations*
NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*

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Chapter 8

Rail Transportation Systems

Revised by
Charles J. Wright

Chapter Contents

Overview
Railroad Operations and Facilities
Hazardous Materials Transported by Rail
Safety on Railroad Property
Passenger Transportation
Motive Power
Freight Cars and Equipment
Rail Tank Cars
Intermodal Tank Containers

Key Terms

freight car, hazardous material, intermodal tank, locomotive, passenger train, rail transportation, railroad, refrigerator car, right-of-way, rolling equipment, rolling stock, tank car

The rail industry as a whole considers safety a top priority. The federal government, through the Federal Railroad Administration (FRA) and the Federal Transit Administration (FTA), provides the basis of regulation, which may be enforced by either FRA inspectors or state inspectors using federal guidelines. Design standards and recommended practices for new or rehabilitated railroad infrastructure are prepared and maintained by organizations such as the Association of American Railroads (AAR), the American Railway Engineering and Maintenance of Way Association, and the American Public Transportation Association (APTA). In some instances, the Code of Federal Regulations (CFR) references these standards and in other cases it cites them as guidelines and encourages compliance as a condition of accepting capital grant money. The codes and standards of the NFPA are often incorporated by reference or serve as a design and/or maintenance basis for the safe and efficient operation of railroad properties. Railroad systems are classified into two broad groups. The first group consists of systems that operate on the general railway system of the United States. These systems are regulated by the FRA and include the freight carriers, intercity rail services (Amtrak), and commuter rail systems. The second group is the rapid transit and light rail (trolley) lines in metropolitan areas not connected to the general railway system. These systems are regulated by state and local bodies with FTA oversight.

This chapter addresses the first group of rail systems only and introduces the reader to physical aspects of the rail transportation industry. It identifies different types of rail rolling equipment used by North American railroads, both freight and passenger, and discusses fire hazards associated with them. It also identifies fire problems involving rights-of-way and specialized railroad facilities and presents safety precautions, both general and situation specific, that all persons should follow while on railroad properties or near rail activities. The chapter generally discusses the rail transportation of hazardous materials. It also discusses in detail the transportation of hazardous materials in rail tank cars and in intermodal tank containers and describes emergency response capabilities of the rail industry.

The business of rail transportation touches on a wide variety of topics. Most chapters in this handbook provide useful assistance in dealing with at least some aspect of the industry. However, the reader is specifically referred to these chapters for discussions of related topics:

Section 13, Chapter 6, "Public Fire Protection and Hazmat Management"; Section 13, Chapter 8, "Managing the Response to Hazardous Material Incidents"; and Section 21, Chapter 7, "Fixed Guideway Transit and Light Rail Systems."

OVERVIEW

Rail Transportation Systems

Rail Transportation Systems, a membership section of the National Fire Protection Association, was organized in 1963 as the Railroad section. It is dedicated to promoting interest in, and improving the methods of, fire prevention and protection in the railroad industry and to encouraging proper safeguards and recommended practices against fire through the interchange of ideas and

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experience. The Rail Transportation System annual meeting is held each May in connection with the NFPA Annual World Fire Safety Congress and Exposition. This event provides an excellent forum for the exchange of ideas between the fire service and railroad fire safety specialists.

Terminology

Two important rail transportation terms are used in this chapter. *Rolling equipment,* or *rolling stock,* is an all-inclusive term that includes locomotives, freight cars of all types, cabooses, and on-rail track maintenance (maintenance-of-way) equipment. *Right-of-way* refers to the (usually) continuous strip of land on which tracks are laid and trains operate. Right-of-way also technically refers to the contiguous property areas on which shops, offices, switching yards, and other railroad facilities and activities are located or take place. The rail transportation company usually owns and maintains the right-of-way.

U.S. Freight and Commuter Railroads

According to the AAR,[1] the more than 562 freight railroads operating today in Canada, Mexico, and the United States are vital to North America's economic health. They form a seamless integrated system that provides the world's most efficient and cost-effective freight service. North American railroads operate over 140,806 (2005 data) miles of track and earn $42 billion in annual revenues.

Also, according to the AAR,[1] U.S. freight railroads fall into one of several classifications. *Class I* railroads, which comprise the largest classification, are those with operating revenue of at least $319.3 million in 2005. Currently there are seven Class I railroads. *Regional* railroads, of which there were 30 in 2005, are line-haul railroads that operate at least 350 miles of road and/or earn revenue between $40 million and the Class I threshold. *Local* railroads include freight railroads that are neither Class I nor regional; they operate less than 350 miles of road and earn less than $40 million. In 2005, there were 320 local railroads.

According to the APTA,[2] there are 20 commuter rail passenger systems associated with various transportation agencies in the United States. In addition, Amtrak provides intercity service.

Railroad Fire Losses

Since their inception, railroads have been associated with fires. Steam engines powered the earliest locomotives; burning wood made the steam. Engine exhaust sparks commonly ignited nearby dry vegetation. A published account of the first passenger train trip in the United States describes how these sparks ignited passengers' clothing and parasols. In the period from 1994 to 1998, rail vehicle fires that were reported to U.S. local fire departments averaged 650 per year, with associated losses of 6 civilian deaths, 12 civilian injuries, and $221.0 million in direct property damage per year.[3]

The rail transportation industry has fire risks primarily in the following three separate areas:

1. The company's fixed physical plant, which ranges from high-rise offices to locomotive heavy repair shops to diesel fuel storage and dispensing facilities
2. Fires on trains, involving locomotives, rolling stock, passengers, or cargo
3. Fires caused by trains or right-of-way maintenance activities that cause damage to railroad property or to adjacent, privately owned properties; railroads are unique in that they typically operate over a continuous right-of-way that they both own and maintain

Tank Car and Intermodal Tank Container Fire Hazards

Fire hazards of tank cars and intermodal tank containers are minimal unless a car is damaged in an accident. If a fire does occur, it is essential to learn the contents of the car or the container before attempting to fight the fire. A tank car or a container exposed to radiant energy from a fire, particularly direct flame impingement, should be approached cautiously. If a commodity absorbs too much heat, vapor pressure can build up and cause the pressure relief device to operate or the tank to rupture. If any of the commodity is released, personnel should be prepared to deal with corrosive, toxic, or otherwise harmful effects. Direct contact with vapors discharged from tank cars or containers under emergency conditions should be avoided, unless appropriate protective clothing and self-contained breathing apparatus are worn.

RAILROAD OPERATIONS AND FACILITIES

Technological Advances

Today, on all but the smallest of railroads, trains are dispatched from remote dispatching centers. On several of the largest railroads, one central dispatching center controls all trains on the entire system. Crews on the trains follow explicit instructions at all times and are in continual radio and electronic contact with a dispatcher. Some locomotives have full-time computer contact both with the dispatcher and with their company's central computer system. One railroad tracks its trains' locations by satellite.

Advances in electronics and their increased use permit other railroad operational efficiencies as well. One or more locomotives (the "locomotive consist") at the front of the train still pull most trains, but it is now practical in certain circumstances to place locomotives at the end of a train or at intervals throughout the train, providing important operational and control efficiencies. However, with such advances come potential problems: a train is no longer the predictable entity it used to be. The emergency responder faces more uncertainties as well as genuine benefits: advanced computer systems have made a tremendous amount of information on a train's cargo, its proper handling, and emergency response protocols instantly available even at remote locations. Thus, it is now more imperative than ever for nonrailroaders involved in rail transportation activities or responses to communicate with, and to coordinate their activities with, proper railroad officials.

Miscellaneous Railroad Facilities

Many railroad facilities are similar to industrial facilities with familiar hazards. However, other facilities are unique to the railroad industry, such as diesel locomotive running repair and heavy repair shops, freight car repair shops, paint shops, and locomotive fueling facilities. Hazards associated with a diesel locomotive repair shop include cutting, welding, poor housekeeping, and fuel leakage.

Fueling facilities need particular protection, not only because of the economic value of the systems and of the stored fuel but also because of the value of locomotives and the cost of interruption of service. Fuel pump houses should be of noncombustible construction and, preferably, equipped with automatic fire protection and with light fixtures and devices suitable for hazardous locations. Because leakage is a prime hazard, careful housekeeping and preventive maintenance are essential. Portable and wheeled dry chemical fire extinguishers should be located throughout the fueling area. It is most desirable to have a high-volume water supply nearby.

Other facilities are critical to railroad operation and, if involved in fire, could stop the movement of trains in a given territory. These facilities include computer centers, microwave communications facilities, centralized train control equipment, and the many support elements in classification yards. Private detection and protection systems should protect these facilities. Typical fire suppression systems range from sprinklers to carbon dioxide and other clean-agent designs. Nearby adequate water and hydrant systems are essential.

Bridges and Trestles

Fire prevention is the key to continued operation of bridges and trestles. Regular maintenance should be done to provide and maintain a 25 to 50 ft (7.5 to 15 m) clearance between combustible structures and nearby vegetation. Susceptibility to fire damage can be reduced by treating the structure with a fire retardant and by providing water barrels, fire detection systems, standby pipe and hose systems, and guard service.

At some particularly valuable and critical bridges, fireboats and water buckets that can be attached to helicopters have been provided, and noncombustible bridge segments have been constructed at regular intervals to limit damage should fire occur. Most railroads have been replacing combustible bridges and other track structures with noncombustible construction at every opportunity, thus reducing their exposure to fire-related losses.

Exposure Risks for Rail Equipment

Exposure fires that destroy loaded and unloaded freight equipment underscore the need for close analysis of terminal fire hazards. These fires can start both on and off railroad property. When classification or switching yards are designed, adequate fire protection, both private and public, should be a prime consideration.

Lack of nearby fire mains and hydrants can contribute to fire loss in large yards. In a major incident, fire-fighting activities should be confined to containment and protection of exposed property. A prefire plan should map fire mains and hydrants both in and near the yard, because protection in the yard may be rendered useless or inaccessible during a major event.

Railroad sidings present a similar exposure hazard, particularly at grain elevators, lumber yards, flammable liquid or LP-gas unloading facilities, and similar industrial properties.

Railroad Communications

Communication with railroads today is simple, effective, and very necessary. On most railroads, a call to any office can be quickly connected to any other, including dispatching centers, maintenance crews, railroad emergency response teams, and, often, even the train itself. Similarly, the crew on a train can immediately notify dispatchers of an emergency on or off railroad property and advise in detail as events unfold. Dispatchers are specially trained to make appropriate emergency contacts both inside and outside of their company. See the next section, "Hazardous Materials Transported by Rail," for information on railroad emergency response capabilities. Most railroads currently have a single telephone number to a central location for emergency situations. Personnel at these locations make notifications and provide appropriate information as necessary.

HAZARDOUS MATERIALS TRANSPORTED BY RAIL

Hazardous material shipments are strictly regulated by the U.S. Department of Transportation (DOT) through the Pipeline and Hazardous Materials Safety Administration (PHMSA). The FRA enforces these regulations.

Statistical Overview of Hazardous Shipments

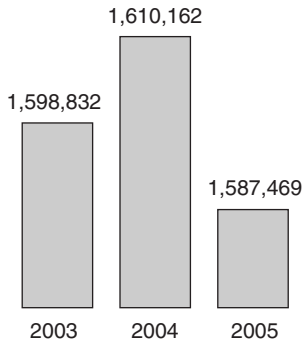
The Bureau of Explosives[4] reports that in 2005 U.S. and Canadian railroads originated 1,587,469 hazardous material shipments. During rail transportation 859 nonaccidental and 27 accidental releases (U.S. only) of hazardous materials occurred for a total of 886 releases of hazardous materials for the year. Figure 21.8.1 shows AAR/Bureau of Explosives' depiction of the total numbers of hazardous material shipments for 3 years (2003 to 2005).[4] Table 21.8.1 shows a summary of hazardous material shipments by hazard class.[4]

It is interesting to note that in 2005, 25 commodities accounted for approximately 93 percent of all the hazardous material that was shipped by rail (Table 21.8.2).[4]

Emergency Response

With the increased danger associated with emergencies involving hazardous materials, shippers, carriers, and local, state, and federal agencies, that is, fire, police, health, and environmental agencies, respond. The immediate purpose of the response is to minimize harm that would otherwise occur: death, injury, property damage, environmental damage, and system disruption. To accomplish this task, responders must identify hazardous materials involved in the emergency.

Sources for detecting the presence of hazardous materials include placards, markings, and shipping papers. Placards may



Note: The Bureau of Explosives' report breaks down these shipments by hazard class as follows: railroads transport hazardous materials in various types of rail cars, such as tank cars, covered hoppers, gondolas, box cars, and trailers and/or containers on flat cars (TOFC/COFC). The majority (85% in 2005) of rail shipments of hazardous materials move in tank cars.

FIGURE 21.8.1 Hazardous Material Shipments for the United States and Canada, 2003–2005

TABLE 21.8.1 Hazardous Material Shipments by Hazard Class for U.S. Originations, 2005

Hazard Class and Divisions	*All Rail HM Shipments*	*Tank Car HM Shipments*
Class 1 (explosives)	478	3
Division 2.1 (flammable gases)	229,355	229,132
Division 2.2 (nonflammable gases)	76,447	76,211
Division 2.3 (poison gases)	47,321	47,301
Class 3 (flammable liquids)	378,902	375,342
Combustible liquids	66,674	64,686
Division 4.1 (flammable solids)	22,407	22,307
Division 4.2 (spontaneously combustible)	1,482	1,293
Division 4.3 (dangerous when wet)	3,399	590
Division 5.1 (oxidizers)	50,329	15,448
Division 5.2 (organic peroxides)	6	0
Division 6.1 (poisonous materials)	31,615	31,037
Class 7 (radioactive materials)	11,074	0
Class 8 (corrosive materials)	278,763	276,772
Class 9	202,522	168,931
Mixed freight all kinds	139,103	660

be affixed to both sides and both ends of the rail car, trailer, or container. They alert response personnel to a hazardous material's presence and indicate the hazard class. The DOT identification number, which also may be found on both ends and both sides of the rail car, trailer, or container, will cross-reference the specific material involved, along with emergency response information. Another marking, the name of the contents, may be stenciled on the sides of the rail car, trailer, or container. Due to the orientation of the cars, placards and markings may not be visible in some emergencies. Because of the nature of the emergency, it may not be prudent to approach the car closely enough to read the placards and markings. Aided vision (binoculars, etc.) may be helpful in some cases. See the sections "Tank Car Markings" and "Tank Container Markings" for more information.

Shipping Papers

Rail cars, trailers, or containers transporting hazardous materials must be documented on shipping papers. Therefore, shipping papers are primary safety instruments in rail transportation for recognizing and identifying hazardous materials. The typical shipping paper for a train movement is a train consist or train list. This document lists the location of each rail car, trailer, or container in the train, including the location of each hazardous material in the train. The train consist/train list also includes emergency response information for each hazardous material on the train. It indicates the contents of each car, including the hazardous material shipments. Shipping papers may differ slightly among railroads; therefore, response personnel should be familiar with the railroads that move through their jurisdiction.

Shipping Paper Contents. The rail shipping paper typically includes the following entries: proper shipping name, hazard class, identification number, packing group, quantity, and hazardous material response codes (previously the 49 series Standard Transportation Commodity Code [STCC]). A 24 hour emergency response telephone number and detailed emergency response information are included with the shipping papers.

Shipping Paper Location. Shipping papers are available from the conductor on the train crew on-site or from the train dispatcher. Although traditionally found on the caboose, the conductor will be found in the lead locomotive of trains without cabooses. However, in an emergency involving hazardous material, the conductor and the rest of the train crew are likely to move to a safe location at least one-half mile upwind, uphill, or upstream of the problem.

Shipping Papers in Rescue Efforts. Upon notification of an accident or other occurrence involving rail equipment, response personnel should take the following actions:

1. Contact the responsible railroad. The telephone number should be identified in preemergency planning activities. Obtain a copy of the shipping papers and emergency response information, whether hard copy or from the railroad verbally.
2. Obtain as much information about the incident as is available: identify hazardous materials involved by name, DOT

TABLE 21.8.2 Top 25 Hazardous Materials in Rail Transportation, 2005

Rank	*Class*	*Commodity Name*	*Shipments*
1	2.1	Butane; liquefied petroleum gas; petroleum gases, liquefied; propylene; LP-gas; propane; isobutane; isobutylene; LP-gas (butylene/isobutane); LP-gas (butane/butylene); isopentane	166,310
2		Freight all kinds—hazardous materials	139,104
3	9	Elevated temperature liquid, N.O.S.	90,832
4	8	Sodium hydroxide solution (caustic soda)	82,892
5	8	Sulfuric acid	58,576
6	3	Alcohols, N.O.S.	75,057
7	4.1/9	Molten sulfur	62,261
8	3/CL	Diesel fuel	55,850
9	3/CL	Flammable liquid, N.O.S.	54,766
10	2.2	Anhydrous ammonia	52,634
11	3	Gasoline	47,362
12	2.3	Chlorine	36,475
13	3/CL	Fuel oil	31,452
14	8	Phosphoric acid	30,745
15	2.1	Vinyl chloride, stabilized	27,499
16	9	Environmentally hazardous substances, liquid, N.O.S.	26,182
17	3	Methanol (methyl alcohol)	22,641
18	9	Environmentally hazardous substances, solid, N.O.S.	22,401
19	8	Hydrochloric acid	22,154
20	2.2	Carbon dioxide, refrigerated liquid	20,245
21	5.1	Ammonium nitrate fertilizers	17,631
22	3	Styrene monomer, inhibited	17,279
23	2.1	Propylene	16,800
24	6.1	Petroleum distillates, N.O.S.	14,138
25	5.1	Sodium chlorate	14,043
Subtotal—top 25 commodities			1,218,656
Total—all hazardous commodities			1,587,469

identification number, or placard applied; determine the types of containers involved; determine the topography, bodies of water, population density, and so forth; obtain specific emergency location and best avenues of approach; ascertain whether any injuries have occurred; and determine when the emergency occurred.

3. Upon arrival at the scene, establish contact with the senior railroad official or representative before attempting to deal with the emergency.
4. Initiate command and control activities, including protecting yourself and others, initiating an incident command system, controlling access to the site, and making appropriate notifications.

In addition to the railroads, other organizations that can provide rail-oriented assistance include the following:

- AAR Bureau of Explosives (BOE)—BOE personnel will respond to major rail emergencies involving hazardous materials on request, typically from a railroad
- Carrier emergency response teams

Some carriers have developed emergency response capabilities to handle emergencies involving hazardous materials. Such teams are equipped with specialized tools and equipment to repair leaks and even transfer contents of damaged tank cars. For example, Union Pacific Railroad has two transfer vehicles equipped with tools and equipment to perform product removal activities as necessary (Figure 21.8.2).

Many rail carriers prepare guides and recommendations for handling rail emergencies involving hazardous materials and make them available to local emergency response agencies along their right-of-way. Railroads also present various training programs to local response agencies and assist at various local, state, and national fire school programs.

SAFETY ON RAILROAD PROPERTY

All who visit rail transportation properties under emergency or routine conditions need to exercise particular caution. The hazards are many and unfamiliar. The potential consequences are severe.

Taking Precautions

Always assume the tracks are "live"—expect a train to appear from either direction at any time. Rails are slippery—always

FIGURE 21.8.2 Union Pacific Railroad Transfer Vehicle Performing Multiple Liquid Transfers at an Incident

step over, not on, a rail, after first making sure the way is clear.

More and more often, a person at a distant dispatching center electrically operates track switches, the devices that physically move the rails and route a train from one track to another. Unlike the person who once stood near the switch and manually operated it, a remote operator cannot see the switch and is unaware of activities in its vicinity. Keep feet, hands, and equipment away from the moveable switch components.

Do not block tracks or place items across them without positive assurance from the railroad that all trains in the area have been stopped. Even then, minimize exposure to trains and clear the tracks as soon as practical. Hose lines laid across a railroad track can be cut by a passing train.

Until the railroad has given positive assurance that all trains in the area have been stopped, do not work around tracks or place equipment on or near tracks, until flaggers with red flags (in daylight) or red fusees (in darkness) have been deployed a minimum of 1½ miles (2.4 km) down the track in each direction. Where trains may be moving rapidly, an additional flagger should be placed a mile farther away in each direction. Fast-moving trains, freight or passenger, take at least that long to stop.

Rail emergencies on bridges and in tunnels with multiple tracks pose special hazards to the responder, as there usually is no work space except on tracks. Until positive assurance is received that all train activity in the area has stopped, there is no safe workplace for emergency activities and equipment and no safe haven for workers should a train appear on an adjacent track.

The railroad should be contacted at first opportunity whenever emergency activities occur on its property. This not only helps to maximize responder safety but it also activates the railroad's considerable emergency response capacity. Maintaining regular contact with each rail transportation entity in their area ensures that emergency responders are fully aware of the transportation company's emergency response resources that are available to them.

Self-Propelled Fire-Fighting and Derrick Equipment

Most carriers are well prepared to clear derailments and rerail freight equipment with their own forces or by standing arrangements with specialty contractors. They use lifting equipment with capacities ranging from 150 to 250 tons (136 to 227 metric tons). These may be mounted on a work train that also may carry water cars and fire pumps powered by the train air line or powered independently by an internal combustion engine. It is increasingly common to find wreck-clearing equipment with rubber tires or crawler tracks transported to the scene by highway. Carrier equipment usually includes fire hoses, nozzles, foam extinguishing compound, play pipes, and a quantity of extinguishers.

Work trains are especially valuable in incidents that occur in remote and inaccessible areas. Fire-fighting needs for such emergencies can be handled by driving a fire department pumper onto a flat car and taking it to the emergency by train.

Some railroads have self-propelled fire-fighting cars that can be used independently of the work train. The availability of such fire-fighting equipment is often overlooked in preemergency planning.

Rights-of-Way

A difficult problem is the right-of-way fire, or fire on railroad land adjacent to the roadbed. These fires can spread off railroad property. Such fires have occurred since the first days of railroading, but this risk has been greatly reduced by improved railroad equipment, controlled burning, chemical control of vegetation, and installation of fire breaks. Cooperation with the USDA Forest Service has led to development of spark arresters, spark arrester exhaust manifolds, and sparkless brake shoes. Planned vegetation, planting the right-of-way with fire-resistive vegetation, is a practice that, if properly maintained, can further reduce these fires.

PASSENGER TRANSPORTATION

Safety Precautions for Passenger Equipment

It is advisable to be aware of the following safety precautions, which are typically employed on passenger trains:

1. Passenger trains, including commuter trains, typically use 480 V ac power generated from a locomotive or a power car for onboard electrical systems, including heating, air conditioning, lighting, and food service. Generally, cables located beneath and between rail cars on both sides transmit this power. In an emergency situation, these cables may be damaged or loosened. Never attempt to disconnect any cables without assistance from the train crew. Never open any empty electrical receptacle until assured that the 480 V ac system has been deenergized. Contacts in the receptacle can be energized without the presence of cables and can produce an arc that can result in serious injury or death. Typically, 480 V ac systems are stepped down by transformers located under the car to provide 220/110 V ac power for onboard electrical equipment. Some electrical components use capaci-

tors, which store residual electrical energy for a time after the system has been shut down.

2. Typical passenger trains employ a 72 V dc emergency battery backup system for operation of lighting, electric doors, and public address systems when the 480 V ac power is lost. These batteries, typically nickel-cadmium and generally located under the car, can present a hazardous materials danger if damaged in an accident. In addition, train cars may be connected by 72 V dc jumper cables for public address and other systems. These cables must be approached with the same caution as 480 V ac cables.

3. Typical passenger trains also employ a pressurized air system, up to 140 psi (965 kPa), for operation of brakes, doors, and lavatories. Compressors in locomotives or power cars provide air pressure, and most passenger cars are equipped with at least one pressurized air reservoir. Some passenger cars ride on air-pressurized bellows instead of springs for improved passenger comfort. Emergency response personnel should be aware of the air pressure hazard and remain clear of any components where they hear the sound of leaking air, until assured that the system has been depressurized.

Passenger Equipment

Modern cars are constructed of steel and aluminum. Materials used for the interiors of today's passenger coaches, diners, and sleeping cars are, at the least, tested to the performance criteria outlined in Table 8.4.1 in NFPA 130, *Standard for Fixed Guideway Transit and Passenger Rail Systems.* Interiors designed to these criteria should show limited fire involvement when exposed to fire. Causes of fires on passenger trains include smoking materials, arson, and mechanical or electrical problems with equipment. However, extensive fire involvement can occur when cars have been exposed to an external fire source such as a flammable liquids fire. In diners, hazards include those inherent in stationary restaurants, such as grease and exhaust system fires. These, plus air-conditioning and heating systems, must be properly safeguarded, and regular preventive maintenance is essential.

Amtrak Trains

Amtrak sleeping cars are equipped with smoke detection systems that, when activated, shut down the HVAC system, sound an alarm within the car, and provide evacuation instructions to the car's passengers.

Amtrak high-speed trains operate along the Northeast Corridor from Washington, DC, to Boston, Massachusetts. These electric-powered trains operate as fixed train sets in which the individual cars are not typically separated. Each train set has a power car at each end. These train sets have some unique fire protection system features, such as the following:

- A deluge sprinkler system in the machine space of the locomotive, which is supplied with water through fire department connections located on each side of the unit
- A gaseous fire suppression system in some electric cabinets in the machine space, which is activated by a heat detection system connected to a control/releasing panel located in the cab of the engine
- On some units, an engineer's escape hatch in the roof of the cab of the power car; if the hatch is not present, there will be a marked "soft" spot in the roof of the cab
- The absence of drop steps on the passenger cars, which are present in older Amtrak cars; folding ladders are used for passenger evacuation, located in a marked compartment near each exit door
- A folded evacuation ramp stored beneath the train; the train crew is trained in the deployment of this ramp
- Every window in the car usable for evacuation; note that these windows are very heavy and care should be used when they are removed
- Presence of a marked "soft" spot located in the center of the roof of each passenger car; typical fire-fighting cutting equipment can be used to remove this soft spot to gain access to the car's interior

Emergency Response Efforts

Modern rail passenger equipment is designed to withstand the tremendous physical forces that would occur in a collision. This construction defeats typical rescue or forcible entry tools. Rescue and fire-fighting operations should be conducted through a car's doors and windows. The windows in passenger equipment generally are made of polycarbonate material that is far stronger and more flexible than safety glass—it cannot be smashed with an axe. Attempts to break windows can result in tool rebound, which can cause serious injury to the rescuer. Windows can be removed from inside or outside cars following the procedures given on labels or placards generally found adjacent to the windows.

Emergency response personnel must always assume that other trains are operating nearby. Modern passenger trains typically operate at up to 79 mph (127 kph) in most areas of the United States. In the Northeast Corridor, from Washington, DC, to Boston, trains operate at up to 125 mph (201 kph), with Amtrak's high-speed train operating at up to 150 mph (241 kph). The emergency stopping distance of a train traveling at 79 mph (127 kph) is approximately 1½ miles (2.4 km) after brakes are applied; at 125 mph (201 kph), it is 2½ miles (4 km); at 150 mph (241 kph), it is 3 to 3½ miles (4.8 to 5.6 km).

Emergency responders must protect the scene by providing flagging protection on the track in both directions from the incident at a distance of 1½ to 2 miles (2.4 to 3.2 km). In the high-speed corridor, this distance should be increased to 2½ to 3 miles (4 to 4.8 km). Flagging protection should be maintained until positive assurance has been received that the system operator or dispatcher knows that emergency response personnel are on the right-of-way and that other rail traffic has been notified. Even with these assurances, it is recommended that flagging protection be maintained for the event's duration.

Because of the weight and size of railroad passenger cars, stabilization in a derailment cannot be obtained using the highway-grade cribbing materials, portable rachet pullers, or air bags that emergency response personnel typically carry. It is strongly recommended that damaged or derailed cars be stabilized by using railroad ties (readily available at most derailment sites) or other suitably heavy-duty materials.

Most cars in a passenger train are those owned by the train's operator, usually Amtrak. Occasionally, however, privately owned passenger cars are attached to the train. Although most commercial passenger cars use electrical power for onboard lighting, food service, door operation, and heating/air-conditioning systems, privately owned passenger cars may employ liquefied petroleum gas (LP-gas) or diesel fuel for heating, cooking, or a generator system as an auxiliary power source. For this reason, responders must be prepared for such materials when dealing with a privately owned passenger car.

Rail transportation companies typically provide training for emergency response personnel on the proper procedures for dealing with a rail incident. Emergency responders with rail operations in their area should make certain that they take full advantage of the rail operators' training resources.

MOTIVE POWER

Diesel Electric Locomotives

What is generally referred to as a diesel locomotive is actually a diesel electric locomotive (Figure 21.8.3). The power is developed by the diesel engine, which drives a main traction generator (or alternator on ac locomotives). The output of this generator or alternator is then transmitted to the traction motors, which are mounted under the locomotive in massive frames called trucks and geared to the axles and wheels. The traction motors actually drive the locomotive. The numerous support systems of a locomotive include a battery that provides power to start the diesel engine, an auxiliary generator or alternator that charges the battery and supplies low-voltage current for control and lighting circuits, and an auxiliary alternator, mounted integrally with the main traction generator or alternator that furnishes field current for the main alternator and power for the radiator cooling fan motors and for a blower motor, which cleans the inertial carbody filters.

Main line locomotives have a normal service life of more than 30 years. Thousands of units still in service have operated far longer. Locomotives in main line service on a major railroad will average between 150,000 and 250,000 miles (241,403 and 402,338 km) per year.

The diesel electric locomotive is an enclosed, self-contained piece of equipment. Fire prevention in the engine room is almost exclusively limited to housekeeping and maintenance, which includes stopping and repairing fuel oil, lubricant oil, or exhaust leaks and ensuring that debris and products of leakage do not accumulate. Improved carbody filtration, through the development of self-cleaning inertial-type carbody filters and carbody pressurization, has also helped to improve engine room safety in modern diesel electric locomotives.

Improvements to electrical cabinets on newer locomotives include the use of fire-retardant wire and cable insulation and the practice of ventilating electrical cabinets with filtered air. This ventilation prevents flammable gases from collecting and keeps dirt out of the electrical cabinet. Other improvements include better wiring techniques, increased use of circuit breakers and fuses, and the pressurization of electrical cabinets. Design improvements, particularly in the extensive use of electronics throughout the locomotive, have also reduced fire hazards.

Fire protection for diesel locomotives includes the following:

Hot Engine Protection. To protect against excessive temperatures in the engine cooling system and hot engine oil, devices are installed to prevent excessive heat buildup in the engine and supporting systems.

Engine Crankcase Protection. This device is designed to detect a dangerous buildup of pressure in the engine and to shut down the engine when necessary.

High-Voltage Ground Protection. If a high-voltage fault develops on the locomotive and goes to ground, the ground relay detects the fault and disconnects the electrical load to the locomotive.

Emergency Fuel Cutoff Switches. In an emergency, the fuel supply to the engine can be stopped by pressing any one of three emergency fuel cutoff buttons. Two buttons are located on the

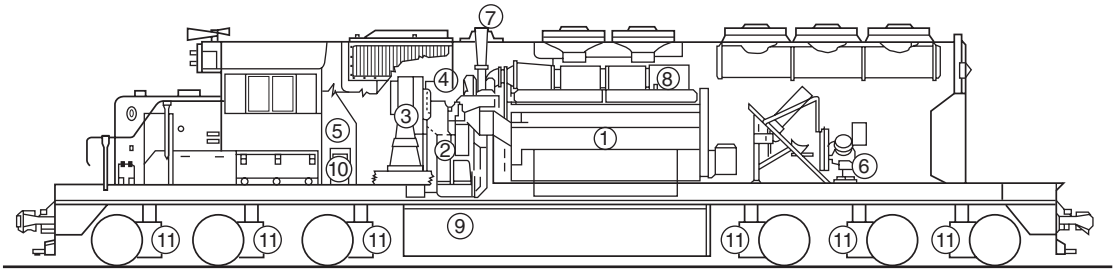


FIGURE 21.8.3 Diesel Electric Locomotive Showing the Location of Principal Components of the Power System

underframe near the fuel filler, one on either side of the locomotive, and a third is found on the engine control panel in the cab.

Main Battery Knife Switch. This large, single-throw knife switch is located in the engine cab at the lower portion of the fuse panel. It connects the battery to the locomotive low-voltage system.

Personnel Protection from High Voltage. Modern locomotives have their high-voltage electric componentry isolated in a labeled panel. This panel has interlocks and other design features to ensure that opening the panel door automatically de-energizes the electric components. Older units may not have this feature, however, so extreme caution is advised when working around locomotive electrical systems.

Portable Fire Protection Equipment. Each diesel electric locomotive is equipped with portable fire extinguisher protection, generally ordinary dry chemical. The quantity and type depend on the size of the locomotive and its use in yard, local, or main line service.

Preventive Maintenance and Inspections. Diesel electric locomotives are inspected, tested, and serviced on a regular schedule, based on life expectancy of component parts, empirical failure data, and Federal Railroad Administration (FRA) regulations.

Alternative Fuel Locomotives

The vast majority of locomotives operate on diesel fuel. The railroad industry is, after the federal government in the United States, the country's largest user of diesel fuel. Locomotive fuel is a significant element of a railroad's operating costs. Efforts are ongoing to reduce these costs, both the cost of the fuel itself as well as its storage, handling, and dispensing costs.

One railroad is now extending the range of some of its long-distance trains by placing a tank car of diesel fuel in its locomotive consist. This practice also permits the train to take on large quantities of fuel where the price is lowest. The larger quantity of locomotive fuel potentially involved in a train collision or derailment should be recognized by the fire community.

A few railroads are experimenting with liquefied natural gas (LNG) as a locomotive fuel. A handful of experimental units are in use on selected assignments. Some LNG locomotives designed only for use in switching yards use a relatively low-powered, spark-ignition engine that permits LNG to be the only fuel on board.

Other experimental LNG locomotives are high-horsepower units intended for long-distance hauling. They use engines with traditional diesel-type, compression-ignition technology. These units require that a percentage of diesel fuel be mixed with the LNG primary fuel to achieve combustion, so both diesel and LNG fuels are found on board. At present there is no uniformity of application: some units use high-pressure LNG technology; others use low-pressure designs.

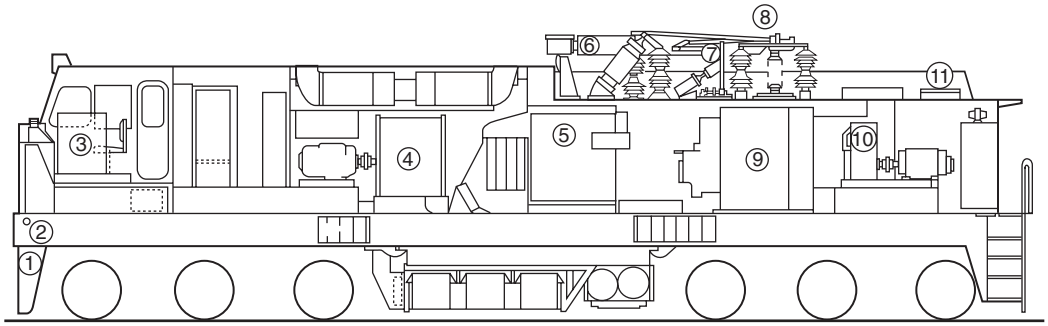
Refueling arrangements for LNG units are also in the experimental stage. Installations and practices vary widely, both within a single railroad and between different companies. Some locations have fixed LNG fueling facilities operated by railroad personnel. At other locations fueling may be by a vendor's crew and tank truck.

The LNG-powered locomotive consists for long-distance service in use or contemplated now have this basic similarity: all have two high-horsepower locomotives with an LNG fuel tank car, or tender, between them. Equipment is well protected from all known hazards, including break-apart. The LNG in the tender is not considered to be in commerce; therefore, the LNG-containing tender is not subject to the DOT regulations and does not need to be placarded. All experimental locomotives and locomotive consists, along with LNG fueling operations, can be expected to be well marked.

Electric Locomotives

Electric locomotives today are used almost exclusively on passenger trains in major metropolitan areas.

Figure 21.8.4 illustrates the general arrangement of an electric locomotive. This particular unit can deliver 5100 hp (3.8 MW) at the rail and operates on 25,000 or 50,000 V alternating



① Proximity switch
② Emergency stop button
③ Operator's console
④ Equipment blower
⑤ Main rectifier compartment
⑥ Vacuum circuit breaker
⑦ Pantograph grounding hook
⑧ Pantograph (in folded position)
⑨ Transformer
⑩ Air compressor
⑪ Roof hatch

FIGURE 21.8.4 Electric Locomotive Showing the Location of Some Essential Pieces of Apparatus

current from an overhead wire. Because the electric locomotive derives its power from an electrical circuit, it is necessary to deenergize the circuit to extinguish any electrical fire safely.

Emergency Stop Buttons. These buttons, one on each side of the locomotive under the operator's cab, can be reached from the ground. Pushing either button trips the vacuum circuit breaker on the roofs of all locomotives in the consist and removes the power.

Manual Pantograph Grounding Switch. Usually located in the right rear of the locomotive, this switch grounds the pantograph before personnel perform maintenance or climb to the roof through the rear hatch. Grounding the pantograph (catenary), which is described in special instructions, varies depending on locomotive type and the overhead system employed. Fire fighters should obtain this information from railroad officials and include it in prefire plans.

Emergency Shutdown Switch. This switch, located on the master control housing, is used in emergencies to remove power from the locomotive during single-unit operation or to remove power from all units of the consist during multiple operation.

Electric locomotives, by their very nature, operate with voltages considerably higher than diesel locomotives. Modern electric locomotives have vacuum breakers that trip in cycles, thereby considerably reducing short circuits that could cause fires on older motive power.

Preventive Maintenance. Preventive maintenance is mandatory to preclude downtime caused by fire or equipment failure. Electrical circuits are tested for grounds or other defects when equipment is at major shops or at intervals of no more than 3 months. All tests and scheduled maintenance are performed in compliance with U.S. DOT rules, as a minimum.

Portable Fire Protection Equipment. Electric locomotives are equipped with portable fire extinguishers. Gaseous extinguishers are normally located in each cab and in the equipment compartment. The number of onboard extinguishers varies with equipment type and company policy. To minimize damage to delicate equipment found on electric locomotives, every effort should be made to use a gaseous agent to extinguish a fire.

Safety Precautions. Certain precautions must be observed when boarding an electric locomotive in an emergency, such as the following:

1. Never climb on top of any railroad equipment under an overhead catenary system until obtaining positive assurance that the wires have been deenergized and that locomotive grounding switches are engaged. Failure to follow this procedure can result in severe burns and even electrocution.

2. It is imperative that all persons on or near electric locomotives be aware of hazards associated with the high voltages involved. Electricity supplied by the overhead catenary system is typically 11,000 V ac and from the third rail, 600 V dc. Voltages within locomotive electrical cabinets are 600 V dc and 480 V ac. If the catenary wire falls on the train body, it energizes the entire train with high voltage. Do not assume that safety features on the power system or locomotive have functioned and deenergized the circuits. Make certain the power is off or use suitable precautions.

3. Unless human life is threatened, no fire-fighting activity should be undertaken on an electric locomotive until the catenary power has been removed and the overhead wire grounded by a qualified electric traction (ET) representative from the railroad. If action is required before an ET representative arrives, consult the train crew's conductor or engineer. These individuals are trained in the proper procedures to lower and secure the pantograph and to ground the electrical equipment.

4. Never enter any high-voltage compartment when the locomotive is energized.

5. Never touch motors, switches, protective barriers, or other electrical apparatus without knowing their exact purpose and function.

6. To protect against serious or fatal personal injury, be sure the pantograph is actually latched down before opening the roof hatch.

FREIGHT CARS AND EQUIPMENT

Freight cars account for the largest share of rail vehicle fires (Table 21.8.3). Major causes of fire in freight equipment, including motive equipment, are collision/derailment, suspected arson, electrical, brake shoe sparks or overheated brakes, welding and cutting, hot journals, and heating appliances. Tables 21.8.4 to 21.8.6 provide additional information on leading causes of rail vehicle fires.

Design advances and preventive maintenance are keys to reducing or eliminating fires caused by brake shoe sparks, exhaust sparks, hot journals or "hot boxes," electrical failures, and hot particles emitted from internal combustion engines. Design advances that should lessen the frequency of fires include increased use of turbochargers; renewed attention to the design and maintenance of eductor tubes, long a source of hot carbon particles on turbocharged locomotives; spark retention exhaust manifolds; nonsparking brake shoes; roller bearings; heat detectors, sensors, and indication lamps that supervise electrical circuits and components; and increased use and efficiency of trackside devices to detect overheated journals and dragging equipment.

Cotton bales are shrink-wrapped, which eliminates the need for metal bale bands and virtually eliminates the possibility of cotton bale fires. Bale fires can be caused by friction heat, which results when the bale bands rub against and ignite loose strands of cotton.

Fires resulting from collisions and derailments are a major concern of the railroad industry. To reduce these incidents, operating rules and safety programs are undergoing major revisions. An inventory of all grade crossings is being used by individual states to establish priorities for crossing improvements. This systemized approach to reducing crossing accidents, combined with the Federal Aid Highway Act of 1976 and the "Operation

TABLE 21.8.3 U.S. Rail Vehicle Transport Fire Problem, by Type of Vehicle, 1994–1998 Annual Averages

Vehicle Type	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Property Damage (in Millions of Dollars)*	
Freight, box, or hopper car	220	(33.8%)	0	(0.0%)	0	(0.0%)	2.8	(31.2%)
Locomotive or engine	200	(30.0%)	2	(37.9%)	4	(32.2%)	11.5	(54.7%)
Passenger or diner car	60	(8.6%)	3	(51.7%)	4	(33.9%)	1.2	(5.9%)
Maintenance equipment car	40	(6.2%)	0	(0.0%)	0	(3.4%)	0.5	(2.3%)
Self-powered car, trolley, or rapid-transit car	30	(4.4%)	0	(0.0%)	1	(6.8%)	0.1	(0.5%)
Container or piggyback car	20	(2.6%)	0	(0.0%)	1	(6.8%)	0.1	(0.7%)
Tank car	10	(1.4%)	0	(0.0%)	0	(3.4%)	0.9	(4.4%)
Unclassified or unknown-type rail transport vehicle	90	(13.1%)	1	(10.3%)	2	(13.6%)	3.8	(18.3%)
Total	650	(100.0%)	6	(100.0%)	12	(100.0%)	21.0	(100.0%)

Note: These are fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies. Fires are rounded to the nearest ten, civilian deaths and injuries to the nearest one, and direct property damage to the nearest hundred thousand dollars. Sums may not equal totals due to rounding errors. Property damage figures are not adjusted for inflation. Percentages were calculated on the actual estimates, so two figures with the same rounded-off estimates may have different percentages.

Source: National estimates based on NFIRS and NFPA survey.

Lifesaver" educational program, is keeping the public alert to the dangers associated with railroad crossings.

Refrigerator Cars

Three types of cars commonly transport perishable and semiperishable commodities that require refrigeration, heater service, or protection from the extremes of heat or cold.

Standard Car. The standard ice car is virtually obsolete as a refrigerator car. Few railroads still furnish ice for shipment in such cars. However, some cars still may be used to keep commodities from freezing. Portable liquid fuel heaters that burn a mixture of methanol and isopropanol can be installed in the end ice bunkers. Alcohol foam is recommended as an extinguishing agent for these fuels because water may be ineffective.

Insulated Bunkerless Car. The insulated bunkerless car is widely used to protect semiperishable commodities such as canned goods, beer, grocery products, and drugs and medicines from extreme heat and cold. These cars provide no refrigeration, but they can be equipped with portable liquid fuel heaters. The heaters are usually suspended by chains from hooks, four per heater, in the ceiling of doorway areas. Heat shields protect the ceiling above each heater.

Refrigerated Car. The mechanically refrigerated car is the most modern and versatile of the freight cars used for perishables (Figure 21.8.5). It provides automatically controlled temperatures from 0 to 70°F (–18 to 21°C). Foamed-in-place polyurethane insulation helps to ensure consistent and dependable car temperatures. A compressor-evaporator is powered by a self-contained diesel-engine generator set located in a separate compartment within the car. The compressor-evaporator also can be powered directly from the alternator output of a diesel electric unit or from any suitable 220-V standby power supply. The fuel tank for the diesel engine is suspended below the car and normally carries 500 to 550 gal (1.9 to 2.1 m^3) of No. 1 or No. 2 diesel fuel oil. Fire fighting can be complicated by burning insulation and by the fact that fire fighters have not learned the location of the diesel engine stop control, which is clearly identified. Fire fighters should wear self-contained breathing apparatus when they enter a burning insulated or refrigerator car.

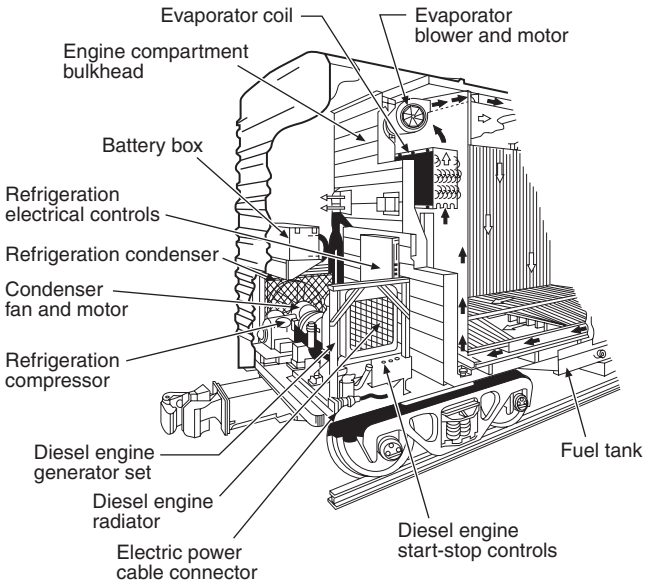


FIGURE 21.8.5 Engine Compartment of a Typical Mechanically Refrigerated Car. Note the start-stop control for the diesel engine at the lower left, mounted on the side of the car.

TABLE 21.8.4 U.S. Rail Transport Vehicle Fires, by Factor Contributing to Ignition Grouping, 1999–2002 Fires Reported to U.S. Fire Departments in NFIRS Version 5.0

Factor Contributing to Ignition	*Percentage of Fires*	*Percentage of Civilian Deaths*	*Percentage of Civilian Injuries*	*Percentage of Direct Property Damage*
Mechanical failure or malfunction	47	0	33	51
Unclassified mechanical failure or malfunction	27	0	0	27
Leak or break	13	0	33	23
Worn out	4	0	0	0
Backfire	2	0	0	0
Manual control failure	1	0	0	0
Misuse of material or product	19	0	0	7
Cutting or welding too close to combustible material	8	0	0	3
Heat source too close to combustible material	5	0	0	2
Abandoned or discarded material or product	2	0	0	0
Unclassified misuse of material or product	1	0	0	0
Flammable liquid used to kindle fire	1	0	0	0
Flammable liquid or gas spilled	1	0	0	1
Electrical failure or malfunction	15	0	67	6
Unclassified electrical failure or malfunction	8	0	0	2
Unspecified short circuit arc	3	0	0	0
Short circuit arc from defective, worn insulation	2	0	0	1
Arc or spark from operating equipment	1	0	0	0
Arc from faulty contact or broken conductor	1	0	67	0
Operational deficiency	7	100	0	7
Collision, knockdown, or overturn	1	100	0	0
Unclassified operational deficiency	1	0	0	1
Failure to clean	1	0	0	3
Overloaded equipment	1	0	0	0
Unattended equipment	1	0	0	2
Equipment not operated properly	1	0	0	0
Fire spread or control	5	0	0	32
Exposure fire	3	0	0	32
Rekindle	1	0	0	0
Unclassified fire spread or control	1	0	0	0
Design, manufacturing, or installation deficiency	2	0	0	0
Design deficiency	1	0	0	0
Manufacturing deficiency	1	0	0	0
Unclassified natural condition	2	0	0	0
Unclassified factor contributed to ignition	7	0	0	3

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. More than one factor contributing to ignition may be entered per incident. Fires in which the factor contributing to ignition was undetermined, not reported, or coded as "none" were allocated proportionally among fires with known factor contributing to ignition. Although this field is not required for fires that were coded as intentionally set or attributed to a cause of "other," the share of incidents with unreported data (fires—17%, deaths—0%, injuries—40%, property damage—54%) or fires with "none" (fires—27%, deaths—0%, injuries—0%, property damage—7%) generally exceeded those for undetermined (fires—11%, deaths—0%, injuries—0%, property damage—9%), suggesting that this type of allocation would be most appropriate.

Source: NFIRS and NFPA survey.

TABLE 21.8.5 U.S. Rail Transport Vehicle Fires, by Area of Fire Origin, 1999–2002 Fires Annual Averages

Area of Fire Origin	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Engine area, running gear, or wheel area	340	(45%)	0	(0%)	2	(2%)	6.0	(35%)
Cargo or trunk area of vehicle	120	(15%)	0	(0%)	2	(2%)	4.2	(24%)
Unclassified vehicle area	70	(9%)	0	(0%)	1	(1%)	3.1	(18%)
Exterior or exposed surface of vehicle	50	(6%)	0	(0%)	0	(0%)	1.0	(6%)
On or near railroad right-of-way	40	(6%)	0	(0%)	0	(0%)	1.6	(9%)
Operator or passenger area of vehicle	40	(5%)	5	(77%)	75	(95%)	0.5	(3%)
Unclassified area of origin	20	(2%)	0	(0%)	0	(0%)	0.1	(1%)
Separate operator or control area of vehicle	10	(2%)	0	(0%)	0	(0%)	0.0	(0%)
Fuel tank or fuel line	10	(1%)	1	(16%)	0	(0%)	0.1	(1%)
Storage room, area, tank, or bin	10	(1%)	0	(0%)	0	(0%)	0.2	(1%)
On or near highway, parking lot, or street	10	(1%)	0	(0%)	0	(0%)	0.0	(0%)
Unclassified storage area	10	(1%)	0	(0%)	0	(0%)	0.0	(0%)
Other known area	40	(5%)	0	(7%)	0	(0%)	0.4	(2%)
Total	770	(100%)	6	(100%)	79	(100%)	17.4	(100%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries to the nearest one, and direct property damage is rounded to the nearest hundred thousand dollars. Sums may not equal totals due to rounding errors. Property damage figures are not adjusted for inflation. Percentages were calculated on the actual estimates, so two figures with the same rounded-off estimates may have different percentages. Fires in which the area of origin was unknown or not reported were allocated proportionally among fires with known area of origin.

Source: NFIRS and NFPA survey.

Box Cars

The design of all box cars is essentially the same; only the capacity, length, and details of the cars vary. Additions, such as special racks, dunnage devices, and nailable steel floors, are made to prevent vibration damage to the contents of the car without adding combustibility.

Special-Purpose Rail Cars

Equipment used to meet special shipping needs includes articulated cars, multilevel and enclosed cars for automobiles, "high cube" (large-capacity) box cars, 100 ton (90 metric ton) capacity covered hoppers, side-loading "all door" box cars, and aerated cars to handle bulk materials that require pneumatic loading and unloading mechanisms to "inhale" cargo at the loading point and "exhale" it at the destination.

"Intermodal service," in which specially designed flatcars carry loaded cargo containers, intermodal tank containers, or highway-type truck trailers, is an increasingly important part of the rail transportation business. Loaded and sealed, containers and trailers are delivered to the railroad at special intermodal terminals, where they are placed, usually by crane, onto the flatcar. Intermodal cars usually are part of a regular train, but intermodal-only trains are increasingly common. A single intermodal flatcar carrying two trailers, or as many as four cargo containers, usually has a wider variety of cargo than a single box car. Intermodal service also uses articulated cars of various designs and length for transporting containers and trailers.

Cabooses

Once every train had a locomotive at one end and a caboose at the other. The caboose was the traveling office of the conductor, the person in charge of the train, and a rear brakeman. Today, cabooses are a rarity; end-of-train electronic devices have taken over their "train-completion" function. Now only two or three persons riding in the lead locomotive customarily staff long-haul trains. Cabooses today are found only on an occasional branch-line or short-line train.

Cabooses' chief fire hazards are their combustible furnishings and heating systems. Most cabooses are heated with oil or coal. Fires can start because stoves and stovepipes do not have adequate clearances from combustible materials. Fire protection varies from water extinguishers to portable dry chemical extinguishers, although some carriers have discontinued this protection because of continuing problems with extinguisher theft.

RAIL TANK CARS

A tank car is a type of bulk packaging in which the tank is an integral part of a rail transport vehicle. More than 250,000 tank

TABLE 21.8.6 U.S. Rail Transport Vehicle Fires, by Item First Ignited, 1999–2002 Annual Averages

Item First Ignited	*Fires*		*Civilian Deaths*		*Civilian Injuries*		*Direct Property Damage (in Millions of Dollars)*	
Unclassified item first ignited	170	(22%)	2	(40%)	0	(0%)	2.1	(12%)
Flammable or combustible liquid or gas, including accelerants, aerosols, and atomized vapor	130	(17%)	2	(30%)	29	(37%)	8.0	(46%)
Electrical wire or cable insulation	120	(16%)	0	(0%)	50	(63%)	1.4	(8%)
Rubbish, trash, or waste	40	(5%)	0	(0%)	0	(0%)	0.1	(1%)
Multiple items first ignited	30	(4%)	0	(0%)	0	(0%)	1.5	(9%)
Upholstered sofa, chair, or vehicle seat	20	(2%)	2	(30%)	0	(0%)	0.2	(1%)
Agricultural crop, including fruits and vegetables	10	(2%)	0	(0%)	0	(0%)	0.1	(1%)
Unclassified flammable or combustible liquid, piping, or filter	10	(2%)	0	(0%)	0	(0%)	1.2	(7%)
Unclassified organic materials	10	(2%)	0	(0%)	0	(0%)	0.0	(0%)
Baled goods or material	10	(2%)	0	(0%)	0	(0%)	1.1	(6%)
Floor covering, rug, carpet, or mat	10	(2%)	0	(0%)	0	(0%)	0.1	(1%)
Grass or light vegetation, excluding crops	10	(2%)	0	(0%)	0	(0%)	0.0	(0%)
Interior wall covering excluding drapes	10	(2%)	0	(0%)	0	(0%)	0.0	(0%)
Railroad ties	10	(2%)	0	(0%)	0	(0%)	0.0	(0%)
Bulk storage	10	(2%)	0	(0%)	0	(0%)	0.0	(0%)
Box, carton, bag, basket, or barrel	10	(2%)	0	(0%)	0	(0%)	0.2	(1%)
Tire	10	(2%)	0	(0%)	0	(0%)	0.0	(0%)
Palletized material or material stored on pallets	10	(1%)	0	(0%)	0	(0%)	0.3	(2%)
Pipe, duct, conduit, hose, or associated covering	10	(1%)	0	(0%)	0	(0%)	0.0	(0%)
Unclassified general materials	10	(1%)	0	(0%)	0	(0%)	0.0	(0%)
Packing or wrapping material	10	(1%)	0	(0%)	0	(0%)	0.1	(0%)
Structural member or framing	10	(1%)	0	(0%)	0	(0%)	0.0	(0%)
Unclassified structural component or finish	10	(1%)	0	(0%)	0	(0%)	0.1	(1%)
Dust, fiber, or lint, including sawdust and excelsior	10	(1%)	0	(0%)	0	(0%)	0.0	(0%)
Magazine, newspaper, or writing paper	10	(1%)	0	(0%)	0	(0%)	0.0	(0%)
Rolled or wound paper or fabric	10	(1%)	0	(0%)	0	(0%)	0.3	(2%)
Conveyor belt, drive belt, or V-belt	10	(1%)	0	(0%)	0	(0%)	0.0	(0%)
Empty pallet or skid	10	(1%)	0	(0%)	0	(0%)	0.0	(0%)
Other known item	30	(4%)	0	(0%)	0	(0%)	0.3	(2%)
Total	770	(100%)	6	(100%)	79	(100%)	17.4	(100%)

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Fires are rounded to the nearest ten, civilian deaths and injuries to the nearest one, and direct property damage is rounded to the nearest hundred thousand dollars. Sums may not equal totals due to rounding errors. Property damage figures are not adjusted for inflation. Percentages were calculated on the actual estimates, so two figures with the same rounded-off estimates may have different percentages. Fires in which the item first ignited was unknown or not reported were allocated proportionally among fires with known item first ignited.

Source: National estimates based on NFIRS and NFPA survey.

cars transport a diverse range of commodities—both hazardous and nonhazardous—including a variety of compressed and liquefied gases, liquids, and solids. The number and types of materials transported in a tank car depend on the size, construction, fittings, linings, and other physical features of the tank.

When faced with a tank car problem, communicating an accurate, detailed description of its contents, its condition, and other circumstances to tank car specialists not on the scene may be the most beneficial contribution an emergency responder can make. To help provide that information, one must under-

stand tank car construction and features, tank car markings, types of tank cars, and tank car fittings.

Tank Car Construction and Features

Typically, tank cars are enclosed longitudinal cylinders (with or without compartments) with rounded ends called heads. Tank cars may or may not have underframes. If not, the tank must bear the stresses of train movement. Tank cars have railroad running gear and safety appliances. Figure 21.8.6 shows the shape and components of typical tank cars.

Tank cars may have such features as insulation, thermal protection, linings, and claddings. Manufacturers add these features to a basic tank, depending on the physical properties of commodities the tank is to carry. Safety features are applied to tank cars to reduce the potential for a release. Older tank cars have been retrofitted with these newer safety features.

Tank cars are built to mechanical standards common to all rail freight cars. In addition, they must meet the requirements of both the *Hazardous Materials Regulations of the Department of Transportation* (49 CFR, Part 179) and the AAR *Manual of Standards and Recommended Practices, Section C—Part III, Specifications for Tank Cars.* They also meet or exceed the ASME standards for pressure vessels. Builders must obtain design approval from the AAR Tank Car Committee before building a tank car. Transport Canada's *Regulations for the Transportation of Dangerous Commodities by Rail* contains Canadian tank car requirements.

Repairs of tank car tanks requiring welding, riveting, removal of damage, alterations, or conversions must occur only at AAR-certified facilities, using procedures and materials the AAR Tank Car Committee has approved.

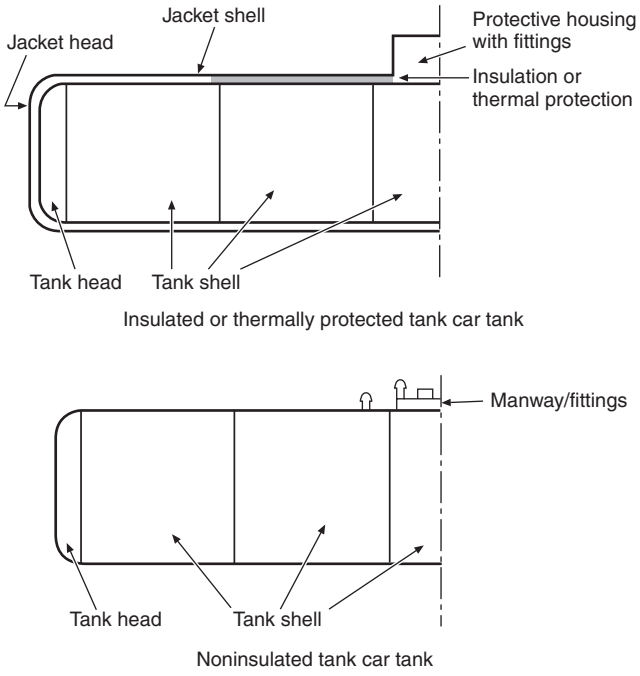


FIGURE 21.8.6 Tank Car Design and Nomenclature

Tank Car Tanks. Each tank car tank consists of a cylindrical shell closed at the ends by heads. The shell is constructed of two to seven rings formed from metal plates. Heads are made from plates pressed into a flanged-and-dished or an ellipsoidal shape; 2 to 1 ellipsoidal heads are the strongest. The rings and heads are fusion-welded together. In some older nonpressure tank cars, the tank parts are riveted together.

The completed tanks are heated to 1100°F (593°C) for 1 hour to relieve metal stresses caused by welding. Representative samples are X-rayed to identify possible flaws in the metal or the welds. Finally, they are hydrostatically tested.

Carbon steel is used in over 90 percent of tank car tanks, with aluminum making up most of the remainder. Stainless steel, referred to in the regulations as alloy steel, is used in a smaller number of cars. Nickel or nickel alloy is used for some tanks in acid or food services. Regulations specify the plate thickness of materials used to construct tank car tanks (Table 21.8.7).

TABLE 21.8.7 Minimum Tank and Jacket Plate Thickness

Minimum Plate Thickness After Forming	*Common Use of Plate Thickness*
Steel	
11 gauge (approximately ⅛ in.), also aluminum	Jacket of insulated tank cars, or jacket for thermally protected cars
7/16 in.	Tank for nonpressure tank cars, outer tank for nonpressure tank within a tank, or shell portion of outer tank for cryogenic liquid tank cars
½ in.	Head puncture resistance (head shield) or head portion of outer tank for cryogenic liquid tank cars
9/16 in.	Tank for steel pressure tank cars with tank test pressures of 200 psi and below
11/16 in.	Tank for steel pressure tank cars with tank test pressures of 300 psi and greater
¾ in.	Tank for steel pressure tank cars in chlorine service
Aluminum	
½ in.	Tank for nonpressure aluminum tank cars
⅝ in.	Tank for aluminum pressure tank cars

Notes:
1. If high-tensile-strength steels are used, plate thickness for pressure tank car tanks may be reduced but in no case should that thickness be less than ½ in.
2. Plate thickness for nonpressure steel tank cars with expansion domes is a function of where the plate is used in the tank and the diameter of the tank. Thickness ranges from ¼ to ½ in. For tank cars built after 1969, minimum plate thickness is 7/16 in., except for tank cars with a diameter of 12 to 122 in. where the thickness is ½ in.
3. For SI units: 1 in. = 2.54 cm; 1 psi = 6.9 kPa.

The capacities of tank car tanks vary from 4000 gal (15 m^3) to approximately 45,000 gal (170 m^3) in jumbo tank cars. Since 1970, however, the maximum capacity of new DOT specification tank cars transporting regulated hazardous materials is limited to 34,500 gal (130 m^3), or not more than 286,000 lb (119,295 kg) gross weight on rail.

Tank car tanks may be divided into as many as six compartments, each of which is actually a separate tank. Compartments may be of different capacities and may transport different commodities (Figure 21.8.7).

Car Structure. The completed tank is mounted on a car structure. The car structure consists of body bolsters attached to a framework (either continuous or stub sill). The framework rests on trucks at each end. The structure of the tank car includes the following components:

1. *Underframe.* Either a continuous underframe in which a one-piece assembly bridges the trucks of a tank car and assumes the draft and buff forces associated with train movement; or stub sill (underframeless), in which a short, longitudinal structural member welded to each end of the tank accommodates the coupler and draft gear assemblies and the attachment of the tank to its trucks
2. *Bolster.* In which a structural crossmember is mounted transversely to cradle the tank; tank cars have two body bolsters, one at each end of the tank
3. *Truck assembly.* Which consists of wheels, axles, sideframes, springs, truck bolster, and center bowl and pin; it supports one end of the car and allows it to be moved on the rail

Car Features. To increase their usefulness for a wide range of materials, tank cars may be equipped with various features, such as insulation, thermal protection, jackets, linings and claddings, and heater coils. These features have the following characteristics:

1. *Insulation.* Insulation is used on some tank cars to moderate the effects of temperature on the cars' contents. Fiberglass or polyurethane foams are the most common insulating materials. However, cork insulates tank cars carrying hydrocyanic acid, and perlite insulates cars transporting refrigerated liquid gases.

2. *Jacket.* Both insulation and jacketed thermal protection are held in place by a jacket, which also keeps out the elements. The jacket is constructed of a minimum of 11 gauge (approximately ⅛ in.) steel and serves as a heat-radiation shield. Metal brackets hold the jacket away from the tank. Jacketed cars can be recognized by a metal protective cover, or flashing, over the body bolster or tank bands; by the flattened appearance of the ends of the tank car; by flat sections on the sides of the car; or by the rough appearance of visible welds, even lap welds, which are generally thinner than the tank weld.

3. *Linings and claddings.* Some tank cars are lined to protect the tank from the corrosive or reactive effects of the contents or to maintain the contents' purity.

   a. Lining materials and coatings are applied after the tank is constructed. Rubber is most commonly used in hazardous materials service, but glass, lead, nickel, polyurethane, polyvinyl chloride, and stainless steel are also used.
   b. Cladding materials are applied to the tank base metal before the plate is formed. Nickel and stainless steel are used as cladding materials.

4. *Heater coils.* Some tank cars are equipped with heater coils, either inside or outside the tank. Steam, water, or hot oil from an external source runs through these coils to heat thick or solidified materials, such as asphalts, fused solids, heavy fuel oils, phenol, metallic sodium, or petroleum waxes to make them flow more easily when unloading. Outlets and inlets for interior heater coils have caps, which are in place when the car is loaded so that any damage to the coils does not release contents. Caps are off when the car is emptied and for cars equipped with external heat coils.

Safety Features

Various safety features have been instituted for tank cars to improve the safety of new and existing cars. The next four paragraphs provide examples of these programs.

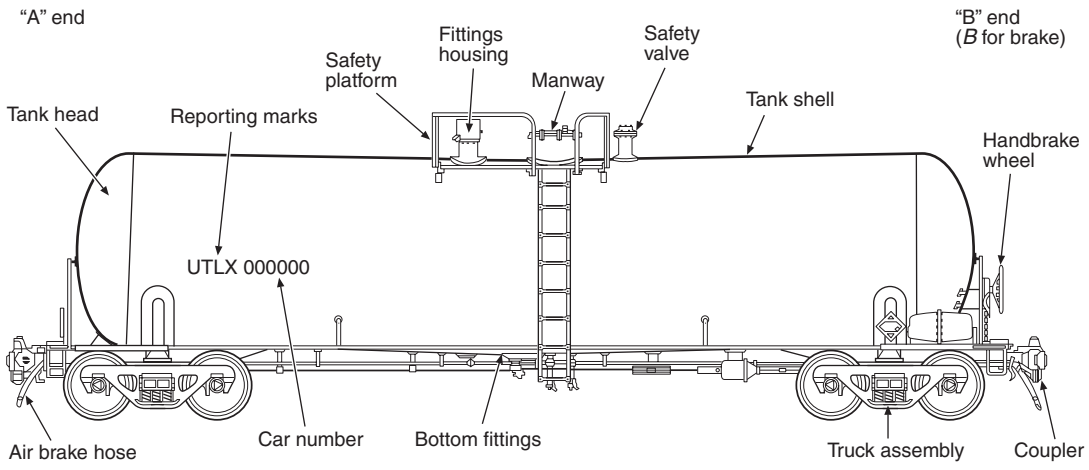


FIGURE 21.8.7 Typical Tank Car Tank with Some Basic Features Identified

Head Puncture Resistance (Head Shields). The head shield is applied to the lower portion of both ends or may cover the entire head to protect it against punctures. Some head shields are built into the jacket, whereas others are visible either as "half head" or trapezoidal-shaped plates of steel mounted on both ends of the tank car. Some head shields cover the entire head of the tank.

Top and Bottom Shelf Couplers. A top and bottom shelf coupler is a type of coupler with a vertical restraint mechanism, top and bottom, to reduce potential coupler disengagement in an accident.

Thermal Protection. Thermal protection, not to be confused with insulation, is used on some tank cars to protect the tank from flame impingement. It is designed to keep tank metal temperatures below 800°F (427°C) for 100 minutes (pool fire impingement) or 30 minutes (torch fire impingement). Thermal protection is used primarily on tank cars transporting liquefied flammable gases and on some nonpressure tank cars, such as the DOT-111J100W4 tank car for ethylene oxide. The following two types of thermal protection are used:

1. Jacketed thermal protection, in which mineral wool or various man-made ceramic fiber blankets are held in place by a metal jacket
2. Sprayed-on thermal protection, in which rough-textured coating sprayed onto the tanks or the jacket in some jacketed cars protects by expanding on exposure to fire

Bottom Discontinuity, or Skid, Protection. Skid protection is a safety device applied to the bottom of tank cars to protect bottom outlets, washouts, and sumps in a derailment.

Tank Car Markings

Various markings found on tank cars include initials, called reporting marks, and tank number; a specification marking; a DOT special permit (previously called an exemption) marking; tank and valve test dates; and tank identification plates.

Initials (Reporting Marks) and Tank Number. The car's initials and number identify the tank car, like any other freight car. The initials and number are found on both sides and both ends of a tank car. As one faces the side of the car, the initials and number are found on the left.

The initials indicate ownership of the car. An "X" as the last initial represents private ownership; that is, the railroad does not own the car. The number following the initials identifies the specific car. Most tank cars are owned by nonrailroad companies.

Using the car's initials and number, shippers, carriers, and emergency response personnel can identify a tank car's contents from the computer or shipping papers. The shipping papers indicate when the contents are hazardous.

Specification Marking. A specification marking identifies the standards to which a tank car is built. The specification marking is stamped into the head of the tank and stenciled on the car's sides. As one faces the side of the car, the specification number is to the right, opposite its initials and number.

The specification marking consists of a two- or three-letter prefix, followed by a series of numerals and/or letters. Specification markings may be as simple as DOT-103 or as detailed as DOT-111A60ALW1. A specification marking does not identify the car's contents but does indicate how the tank car was built. Specification information can be obtained from the railroad's computer using the car's initials and number (Figure 21.8.8).

Two- or three-letter prefixes of the specification marking include the following:

- DOT—Department of Transportation
- AAR—Association of American Railroads
- ICC—Interstate Commerce Commission (authority to DOT in 1966)
- CTC—Canadian Transport Commission
- TC—Transport Canada (replacing CTC)

Class. The *class* is the general designation of a tank car that may include several specifications (see Table 21.8.8). The term *class* designates a group of several specifications (e.g., Class DOT-112). The approving authority prefix and class number together indicate the class.

The specification is the specific designation of a tank car within a class (e.g., Specification DOT-112J340W).

Delimiter Letter. On most nonpressure tank cars, the letter *A* separates the class number from the tank test pressure and has no meaning. However, on pressure tank cars, cryogenic liquid tank cars, and some nonpressure tank cars, the letter indicates

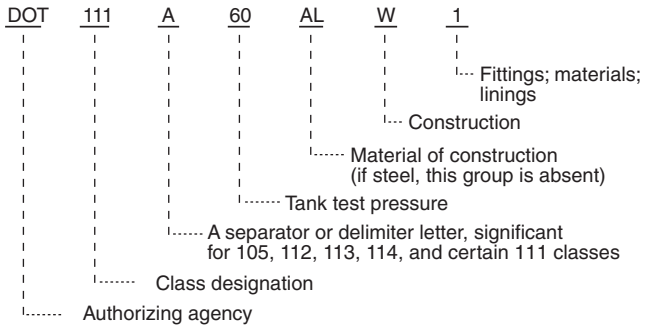


FIGURE 21.8.8 Explanation of Specification Marking

TABLE 21.8.8 Tank Car Classes

Nonpressure tank car classes
DOT-103 DOT-111 AAR-201 AAR-206
DOT-104 DOT-115 AAR-203 AAR-211

Pressure tank car classes
DOT-105 DOT-112 DOT-114 DOT-120
DOT-109

Cryogenic liquid tank car classes
DOT-113 AAR-204

how the car is equipped. The last number following the weld construction designator, if present, identifies special fittings, materials of construction (alloy steel), and linings.

You can get specification information from the railroad, shipper, car owner, or the Association of American Railroads (from the car's certificate of construction) by using the car's initials and number. The specification is the specific designation of a tank car within a class (e.g., Specification DOT-112J340W). The location of a specification marking is shown in Figure 21.8.9.

Capacity Stencil. The volume of the tank car tank, typically in gallons and liters, is stenciled on both ends of the car under the car's initials and number (Figure 21.8.10). The load limit, typically in pounds and kilograms, is stenciled on the sides of the car under the car's initials and number. *Load limit* means the same as *capacity.* Certain tank cars (e.g., DOT-111A100W4) have the water capacity (water weight) of the tank, typically in pounds and kilograms, stenciled on the sides of the tank near the center of the car.

FIGURE 21.8.9 Location of Specification Marking on Tank Cars with Qualification Stencil

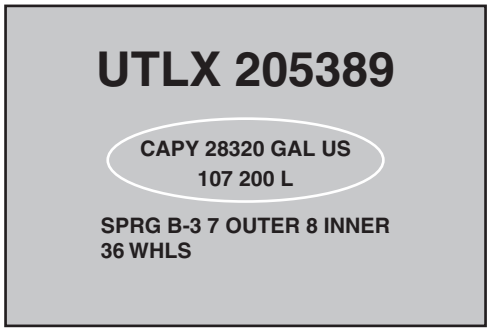


FIGURE 21.8.10 Capacity Stencil Marking Found on Heads of Tank Cars

DOT Special Permit (Previously Exemption) Marking. When special permits (exemptions) from the regulations for packages and containers and the preparation and offering of hazardous materials for shipment are made, the outside of each package must be plainly and durably marked DOT-SP (previously DOT-E) followed by the number assigned, such as DOT-SP8623 (previously DOT-E8623). On portable tanks, cargo tanks, and tank cars, the marking must be in 2 in. (50.8 mm) letters. This SP marking replaces the previously used E marking for an exemption from the regulations.

Tank Car Qualification Stencil. Tank and pressure-relief devices, if installed, have varying retest intervals, depending on the car's specification and/or age. Retest and test due dates must be marked or stenciled on the tank or on a dataplate. Interior coils are also tested (see Figure 21.8.9).

Tank Car Identification Plate. New tank cars will be equipped with two identical stainless steel identification plates. Plates (Figure 21.8.11) are permanently affixed in a visible location to the inboard surfaces of the AR and BL body bolster webs. The information on the dataplate includes the manufacturer, serial number, AAR certificate number, tank specification, shell and head material, insulation material, and date of manufacture.

Tank Car Types

Tank cars are classed according to their construction, features, and fittings. The tank's specification determines the product it may transport.

Nonpressure Tank Cars. Nonpressure tank cars, also known as general-service tank cars or acid-service tank cars, transport a wide variety of hazardous and nonhazardous materials at low pressures. Nonpressure tank cars transport hazardous materials, such as flammable and combustible liquids, flammable solids, oxidizers, organic peroxides and poison, corrosive materials, and molten solids. They also transport nonhazardous materials, such as tallow, clay slurry, corn syrup, and other food products.

Tank test pressures for nonpressure tank cars range from 60 to 100 psi (430 to 689 kPa). Capacities range from 4000 to 45,000 gal (15 to 181 m^3).

Nonpressure tank car tanks are cylindrical with rounded heads. Newer nonpressure tank cars have at least one manway to allow access to the car's interior. Some older nonpressure tank cars have at least one expansion dome with a manway (Figures 21.8.12 and 21.8.13). Fittings for loading and unloading, pressure and/or vacuum relief, gauging, and other purposes are visible at the top and/or bottom of the car.

Nonpressure "Tank-Within-a-Tank" Tank Cars. This nonpressure tank car is built as a tank within a tank. It consists of an inner tank of steel, alloy steel, or aluminum covered with thick insulation and enclosed within an outer tank. This tank car transports temperature-sensitive materials, such as food products.

FIGURE 21.8.11 Tank Identification Plate

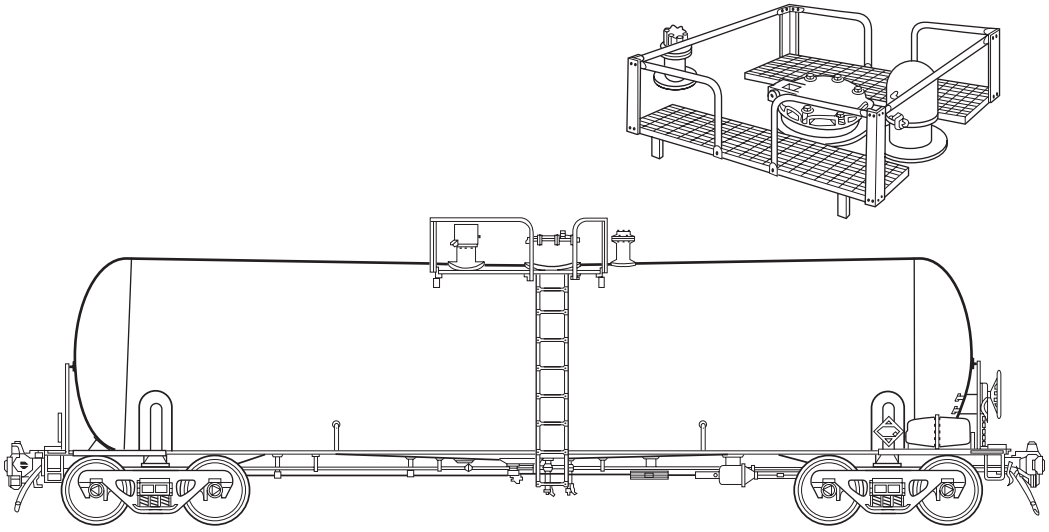


FIGURE 21.8.12 Typical Nonpressure Tank Car (DOT-111)

Tank Train®. The Tank Train is a series of nonpressure tank cars interconnected with flexible hoses that allow the cars to be loaded and unloaded from one end. A spring-loaded butterfly valve arrangement on each car is controlled pneumatically from the loading/unloading point. After loading, hoses are purged of liquid, and valves close automatically, isolating each car. The Tank Train transports hazardous and nonhazardous materials, including gasoline, fuel, oil, caustic soda, and pesticides.

Multicompartmented Nonpressure Tank Cars. Multicompartmented nonpressure tank cars have up to six compartments. Each compartment is considered a separate tank because of its

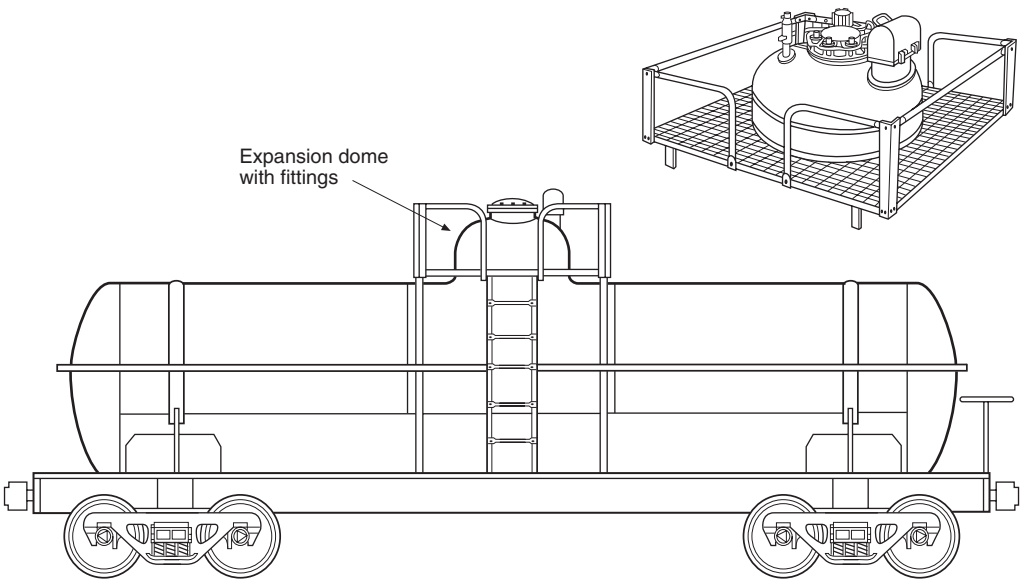


FIGURE 21.8.13 Typical Older-Style Nonpressure Tank Car (DOT-103) with an Expansion Dome

construction. Compartments may be of different capacities and may contain different materials. Each compartment has its own loading and unloading fittings.

Pressure Tank Cars. Pressure tank cars typically transport hazardous materials, including flammable, nonflammable, or poisonous gases at higher pressures. However, pressure tank cars can transport other commodities, depending on the characteristics of the product or the process for loading and unloading the tank. Other products transported in pressure tank cars are ethylene oxide, pyrophoric liquids, sodium metal, motor fuel antiknock compounds, bromine, anhydrous hydrofluoric acid, and acrolein (Figure 21.8.14).

Tank test pressures for these tank cars range from 100 to 600 psi (689 to 4137 kPa). Pressure tank cars range in capacity from 4000 to 45,000 gal (15 to 170 m^3).

Pressure tank cars are cylindrical, noncompartmented steel or aluminum tanks with rounded heads. They are top-loading,

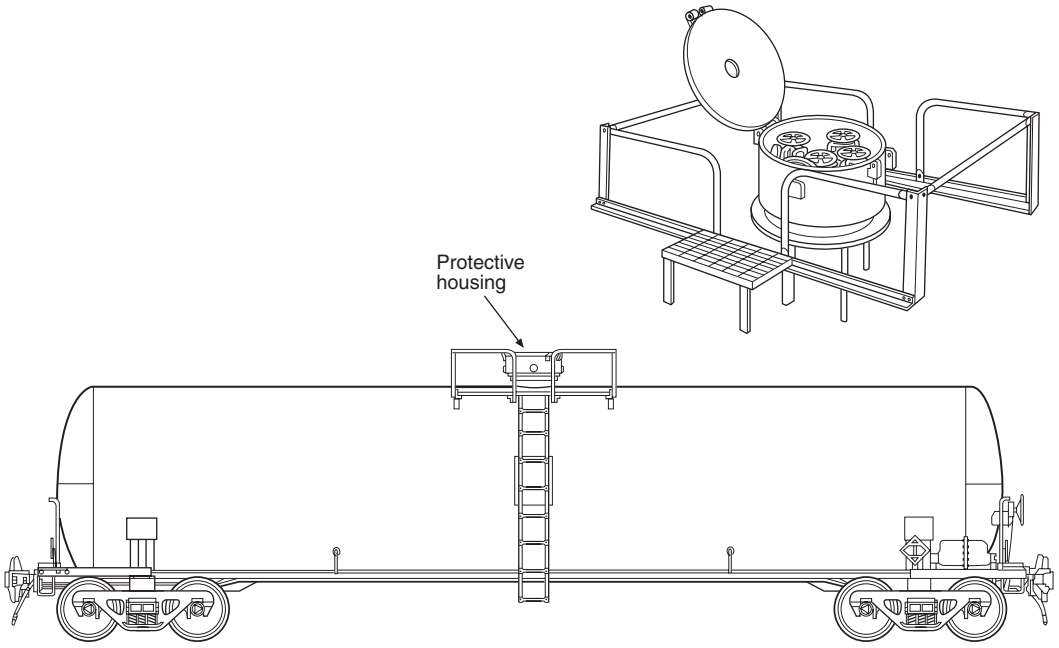


FIGURE 21.8.14 Typical Pressure Tank Car with Protective Housing

with fittings for loading and unloading, pressure relief, and gauging located inside protective housing mounted on a single manway.

Pressure tank cars may be insulated and/or thermally protected. The top two-thirds of pressure tank cars without insulation and without jacketed thermal protection will be painted white or another reflective color.

Cryogenic Tank Cars. Cryogenic tank cars carry low-pressure—usually 25 psi (172 kPa) or lower—cold liquids refrigerated to –155°F (–104°C) and below. Typical contents of these tanks are argon, ethylene, hydrogen, nitrogen, and oxygen (Figure 21.8.15).

Cryogenic tank car tanks (DOT-113) are of the tank-within-a-tank style with an alloy (stainless or nickel) steel inner tank inside an outer tank. The space between the inner tank and the outer tank is filled with insulation and under a vacuum. The combined vacuum and insulation protect the contents for only 30 days, making shipments in these cars time sensitive.

Fittings for loading and unloading, pressure relief, and venting are located in ground-level cabinets at diagonal corners of the car or in the center of one end of the car. Built to tank car specifications, the pneumatically unloaded covered hopper cars are covered hopper cars, which are unloaded through pressure differential, or pneumatics, by applying air pressure. Even though the pressure is used only during unloading, tank test pressures for the car range from 20 to 80 psi (138 to 551 kPa). Dry caustic soda is one commodity transported in this type of car (Figure 21.8.16).

Tank Car Fittings

Numerous fittings used on tank cars allow for loading and unloading and provide for safe transportation of their contents. All fittings are not found on all tank cars. This section addresses tank car fittings for nonpressure and pressure tank cars from a very general standpoint.

Fittings for Loading and Unloading Tank Cars. Various fittings are used to load and unload tank cars, including the following.

Manway. This large opening on top of the tank car allows access to the tank's interior. It is closed either with a permanently mounted cover plate with fittings attached or with a hinged-and-bolted cover opened for loading the car.

Liquid or Vapor Valves. These valves control the passage of liquid or vapor into or out of the tank in pressure tank cars (Figure 21.8.17).

Liquid valves, usually two, are used to load or unload liquids from tank cars. Unloading occurs as a result of pressure generated by the contents or when the tank is pressurized with air, nitrogen, or other gas. An eduction pipe reaches from the liquid valve to the tank's bottom.

One or two vapor valves are used to remove vapor from the tank or to pressurize the tank. On pressure tank cars, they are called vapor valves; on nonpressure tank cars, they are called air inlets or air valves. (Note: Excess flow valves found under various fittings shut when flow exceeds a predetermined amount.)

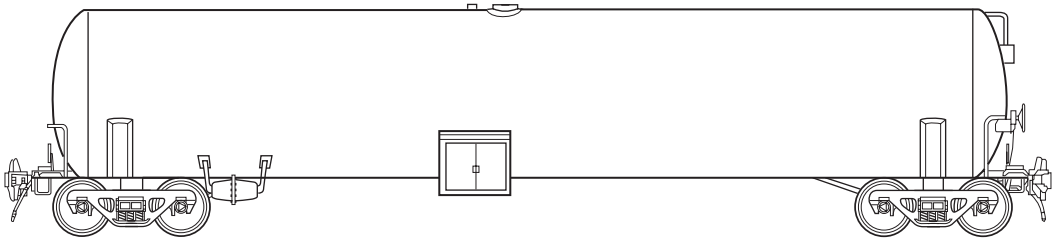


FIGURE 21.8.15 Typical Cryogenic Liquid Tank Car (DOT-113)

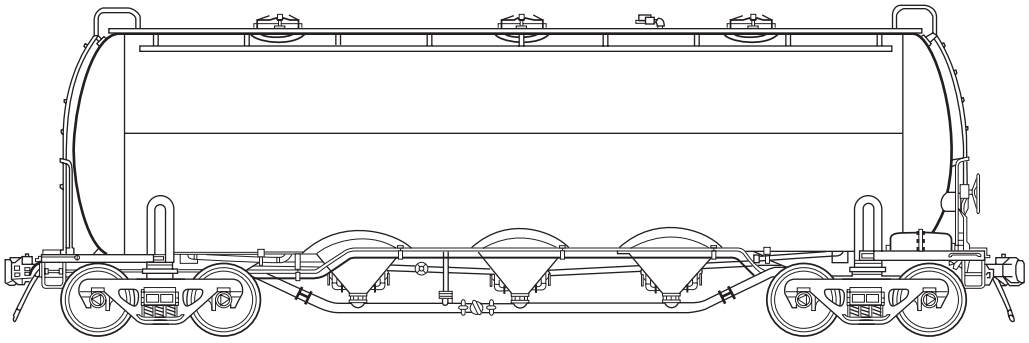


FIGURE 21.8.16 Pneumatically Unloaded Covered Hopper Car

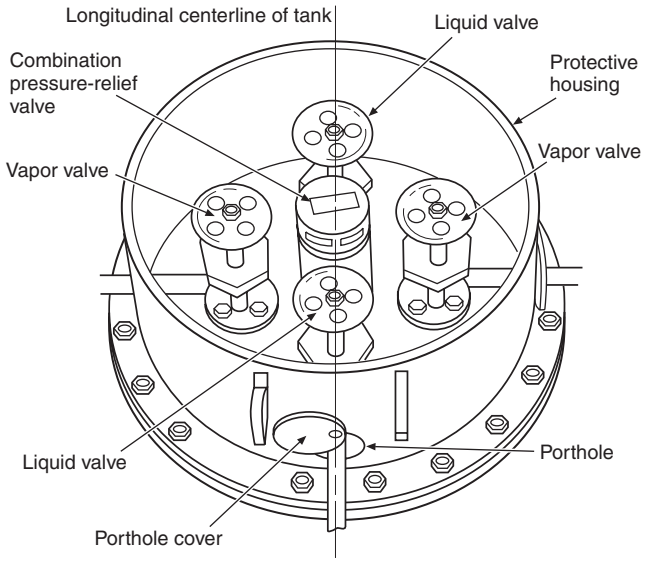


FIGURE 21.8.17 Fitting Arrangement in the Protective Housing on a Liquid Chlorine Tank Car

Bottom Outlet Valves. These valves are used to unload the tank from the bottom. Examples are a plug-type valve operated from the top of the tank, called a "top-operated bottom unloading valve"; a ball-type valve either external to or inside the tank and operated from ground level; or a wafersphere, or butterfly valve, mounted outside the tank.

Pressure-Relief Devices. These devices reduce the buildup of excess internal pressure that commodity vaporization and expansion cause. Pressure-relief valves are set at either 75 percent of the tank's test pressure or 33 percent of the tank's burst pressure.

Pressure-Relief Valve. This relief device has an operating part held closed by one spring or multiple springs. It is designed to open and reclose at predetermined pressures. The device can be mounted with the spring inside or outside the tank. It is typically set to activate when 75 percent of the tank test pressure is reached.

Safety Vent. This device uses a frangible disk, called a rupture disk, that seals the vent opening under normal conditions. The disk is designed to rupture at predetermined pressures and, once ruptured, does not reclose. Rupture disks are made of steel, plastic, rubber, or a combination of metal, plastic, or rubber. Lead is no longer authorized. Relief vents are used on certain nonpressure tank cars. Cars equipped with relief vents will be stenciled "Not for poisonous or flammable liquids."

Combination Pressure-Relief Device. This combination device uses a rupture disk and/or a breaking pin combined with a spring-operated pressure-relief valve.

Fittings for Gauging the Inage and Outage in Tank Cars. Gauging devices are used to determine the amount of lading in a tank. These devices allow one to measure the amount of liquid in the tank, such as liquefied or cryogenic gases (inage), or the amount of vapor space left in the tank (outage). Gauging devices usually measure outage. The following are two types of gauging devices:

1. *Open-type gauging devices.* These devices eject liquid once the liquid level reaches the bottom of a fixed- or adjustable-length tube; they read outage
2. *Closed-type gauging devices.* These devices use a float, coupled with a magnet on a measuring rod or a dial indicator, to show the liquid level of the commodity

Another method of determining the amount of lading in a tank car is to insert a measuring pole while using the appropriate inage/outage tables. Outage is also determined by gauge bars or "T" bars on most nonpressure cars.

Other Fittings. Various other fittings may be found on tank cars.

Sample Line. This device is used to obtain a sample of the commodity without opening the tank.

Thermometer Well. This closed tube, filled with a permanent-type antifreeze, extends into the tank. By inserting a thermometer into the tube, the temperature of the lading inside may be determined.

Bottom Washout. This bolted and flanged opening in the bottom of the tank car is used only when a tank is cleaned. There is no way to control the lading flow once the closure is removed.

Sump. This closed projection in the bottom of the tank allows the liquid eduction pipe to extend slightly below the bottom of the tank to unload the tank more completely.

Vacuum Relief Valve. This valve is designed to prevent excessive internal vacuum buildup (greater than 0.75 psi [5.5 kPa]) negative pressure in some nonpressure tanks. The vacuum relief valve used during unloading opens to admit air when a vacuum occurs and then recloses after normal conditions have been restored.

INTERMODAL TANK CONTAINERS

Since the early 1980s, the use of tank containers throughout the world has increased greatly. Factors accounting for this increase are improved safety, portability, lower transportation costs, and benefits of a multimodal transport system.

Advantages over alternative methods of transport, such as drums, tank trucks, and trailers, include reduction in the amount of handling required, faster transfer at ports and terminals, convenient storage options at the destination, and ready use of conventional container-handling equipment already in place.

Built according to many domestic and international standards, tank containers are used to transport diverse commodities, including an increasing number of hazardous materials.

Problems involving tank containers are best handled by giving an accurate, detailed description of the contents and condition of the tank container, and the circumstances to those with specialized knowledge and skills necessary to help handle the problem.

Tank Container Construction and Features

Tank containers consist of a single metal tank mounted inside a sturdy metal supporting frame. This unique frame structure, built to international standards, makes tank containers multimodal (intermodal). Thus, they are used interchangeably in two or more modes of transport, such as rail, highway, or water. Tank containers may be equipped with a variety of features.

Tank Container Tank. The tank container tank is generally built as a cylinder enclosed at the ends by heads. Other tank shapes—rectangular tanks—and configurations—tube modules—exist but are rare. Tanks with multiple compartments, each built as a separate tank, are also rare. A tank's capacity does not ordinarily exceed 6340 gal (about 24 m^3).

Ninety percent or more of the tanks are built of stainless steel; the rest are constructed of mild steel. Stainless steel is used because it resists cold temperatures. Aluminum and magnesium alloy tanks are available, but they cannot be used in water transport mode.

Minimum head and shell thickness is measured in terms of "equivalent thickness in mild steel" after forming. For steel tanks, the minimum thickness for nonregulated commodities is ¼ in. (6.35 mm). For regulated materials, the minimum thickness is ⅜ in. (9.5 mm). For stainless steel tanks, the minimum thickness for nonregulated materials is slightly less than ⅛ in. (3.2 mm). For regulated commodities, the minimum thickness is just under 3⁄16 in. (4.8 mm).

Most tanks are built according to the pressure-vessel standards of ASME, and the welds are X-rayed. Welds on carbon steel tanks are postweld heat-treated.

Supporting Frame. The supporting frame of a tank container protects the tank and provides for stacking, lifting, and securing the container. It also supports the walkways and ladders. Like other types of freight containers, supporting frames are built to the requirements of the International Standards Organization (ISO).

The most common size of supporting frame is 20 ft (6 m) long, 8 or 8½ ft (2.4 or 2.55 m) wide, and from 8 to 9½ ft (2.4 to 2.85 m) high. Except for the half-height tube modules and some cryogenic tank containers, some of which are 35 ft (10.5 m) long, very few tanks longer than 20 ft (6 m) are used in the United States.

There are two basic supporting frame types: the box type, which encloses the tank in a cagelike framework and the "beam type," which uses frame structures only at the ends of the tank.

Corner Casting. Supporting frames for all intermodal containers, including tank containers, are built with standard corner fittings, called corner castings. They are used to secure the tank and to lift it with standard container-handling equipment. Corner castings must conform to ISO standards. Cast-iron corner castings are prohibited. In an accident where proper lifting devices are not available, the corner castings may be used to lift or move the tank only after consulting the tank's owner or manufacturer.

Features. To increase their use for a wide range of cargoes, tank containers may be equipped with various features, such as linings that protect the tank from the lading, refrigeration units, electrical or steam heating, and insulation to maintain the desired temperature of the contents.

Foamed plastic, both polyurethane and polystyrene, is the predominant insulating material. However, mineral wool and fiberglass are also used. Insulation, generally 3 to 4 in. (76.2 to 101.6 mm) thick, is always covered with a weathertight jacket. Jackets are made of metal, at least 1⁄32 in. (1 mm) thick or of an equivalent thickness of plastic reinforced with either glass or fiber.

Tank Container Markings

Various markings may be found on tank containers, including the tank initials and number, the specification marking, the DOT exemption marking, the AAR 600 marking, the country and size/type markings, the dataplate, and the tank and valve test dates (Figure 21.8.18).

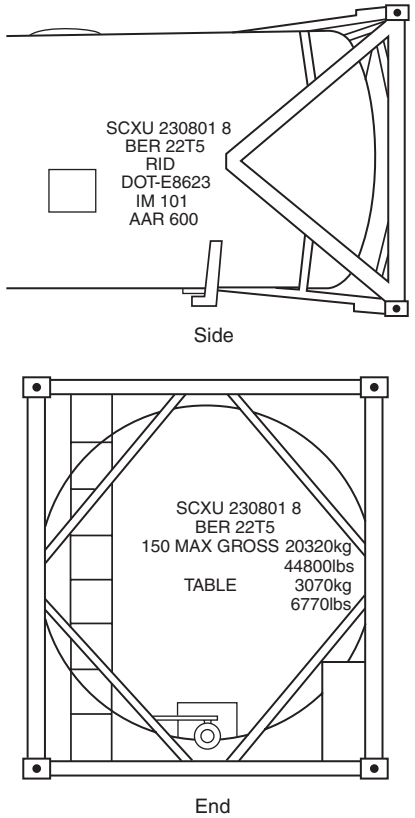


FIGURE 21.8.18 Typical Markings on Tank Containers

Tank Initials and Number. Tank containers must be registered with the International Container Bureau in France. They must be marked with initials, or reporting marks, and with a tank number. The initials indicate the tank's ownership, and the tank number identifies the specific tank.

The initials and tank number are generally on the right side of the tank, as one faces it from either side, and on both ends. They may be displayed either on the tank itself or on the frame.

With this information, shippers, carriers, and emergency response personnel can identify the tank's contents, using shipping papers or computer data. They can then determine if the contents are hazardous.

Specification Marking. The design, construction, and use of tank containers must conform to strict standards and regulations of many agencies, both in the United States and abroad. Markings on the tank container indicate the standards to which the tank was built.

In the United States, tank containers must meet the design, construction, and safety standards set forth by the DOT. Tanks meeting these standards have the specification markings or an exemption number displayed on both sides (generally the tank's initials and number). Examples of specification markings are IM 101 (IMO Type 1), IM 102 (IMO Type 2), and Spec. 51 (IMO Type 5 or IMO Type 7).

DOT Special Permit (Previously Called Exemption) Marking. When DOT grants special permits (previously exemptions) from the regulations governing packages and containers, and the preparation and offering of hazardous materials for shipment, the outside of each package must be plainly and durably marked in 2 in. (50.8 mm) letters and numbers—that is, DOT-SP (previously DOT-E) followed by the number assigned, such as DOT-SP 8623 (previously DOT-E8623).

AAR-600 Marking. For interchange purposes in rail transportation, tank containers should conform to the requirements of Section 600, "Specification for Acceptability of Tank Containers" of the AAR *Manual of Standards and Recommended Practices, Section C—Part III, Specification for Tank Cars.* Tanks meeting these requirements display the AAR 600 markings in 2 in. (50.8 mm) letters on both sides, near the tank's initials and number. The AAR-600 marking identifies tanks that can be used for regulated materials, whereas the AAR-600NR marking identifies tanks that cannot be used for regulated materials.

Country and Size Type Markings. In addition to the initials and number and the specification marking, the tank also displays a country code and a size/type code. When displayed, the two- or three-letter country code indicates the tank's country of registry.

The four-character size/type code follows the country code. Its first two characters (digits) jointly indicate the container's length and height. The second pair of characters (T + a digit) is the type code, which indicates the tank's pressure range.

Dataplate. For further technical, approval, and operational data, dataplates are permanently attached to the tank containers' tanks or frames.

Tank and Valve Test Dates. Tanks and pressure-relief devices, if installed, must have a retest interval not greater than 5 years. Retest and test due dates must be marked or stenciled on the tank or on the dataplate.

General Classes of Tank Containers

Tank containers are classed according to the specification of the tank and fittings. The classification of a tank container determines which products it may carry.

Nonpressure Tank Containers. Also called intermodal portable tanks or IM portable tanks, nonpressure tank containers comprise over 90 percent of the total (Figure 21.8.19). They usually transport liquid and solid materials at maximum allowable working pressures (MAWP) of up to 100 psi (690 kPa). Tanks are tested to at least 1.5 times the MAWP. In the United States, the following two groups of nonpressure tank containers are common:

1. *IM 101 portable tanks.* These tanks are built to withstand MAWP of from 25.4 to 100 psi (175 to 690 kPa). They may transport both nonhazardous and hazardous materials, including toxics, corrosives, and flammables, with flashpoints below 32°F (0°C). Internationally, an IM 101 portable tank is called an IMO type 1 tank container.

2. *IM 102 portable tanks.* These tanks are designed to handle lower MAWP—that is, from 14.5 to 25.4 psi (100 to 175 kPa). They transport materials such as liquor, alcohols, some corrosives, pesticides, insecticides, resins, industrial solvents, and flammables with flashpoints between 32 and 140°F (0 and 60°C). More often they transport various nonregulated materials, such as food-grade commodities. Internationally, an IM 102 tank is called an IMO type 2 tank container.

Pressure Tank Containers. Also known as DOT Spec. 51 portable tanks, these containers are less common in transport. Designed to handle internal pressures ranging from 100 to 500

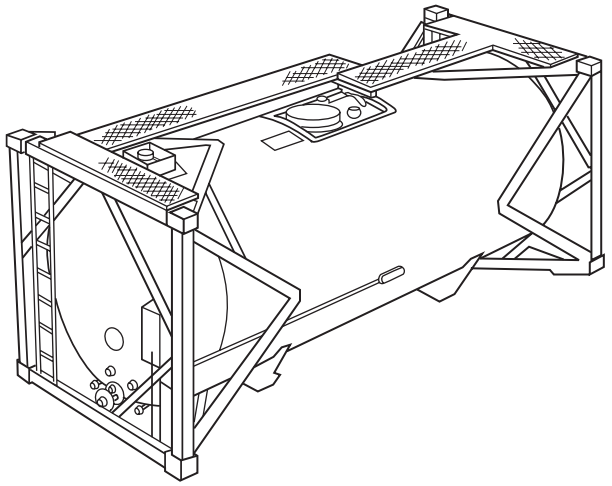


FIGURE 21.8.19 Nonpressure Tank Container

psi (690 to 3450 kPa), they generally transport gases liquefied under pressure, such as LP-gas and anhydrous ammonia. They may also carry liquids, such as motor fuel antiknock compounds or aluminum alkyls. Internationally, they are called IMO type 5 tank containers (Figure 21.8.20).

Specialized Tank Containers. There are several other variations of tank-type containers. Among them are the following:

1. *Cryogenic tank containers.* These containers carry refrigerated liquid gases, such as argon, oxygen, and helium, and are built to DOT Spec. 51 standards. Internationally, they are called IMO type 7 tank containers.
2. *Tube modules.* These containers transport gases in high-pressure 3T cylinders tested to 3000 or 5000 psi (20,700 or 34,500 kPa), permanently mounted within a full or half-height ISO frame (Figure 21.8.21).

Tank Container Fittings

Nonpressure Tank Container Fittings. Various fittings make nonpressure tank containers functional and safe.

Spillbox. On nonpressure tanks, a spillbox encloses the top fittings. It protects the tank's shell from any spillage. Any spilled material, as well as rainwater in the spillbox, drains through an open pipe.

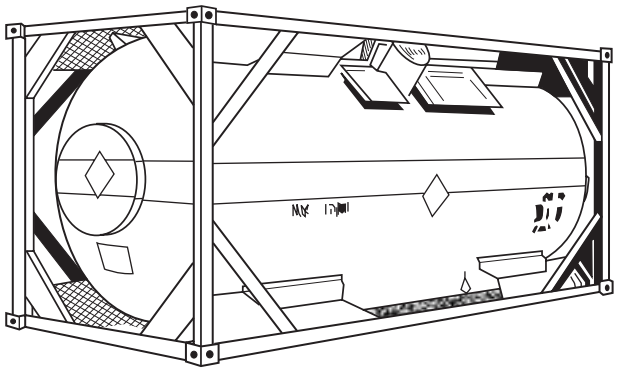


FIGURE 21.8.20 Typical Pressure Tank Container

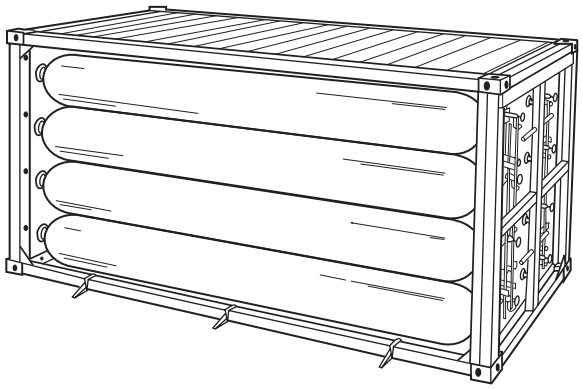


FIGURE 21.8.21 Tube Module

Manhole, Cover, and Dipstick. The manhole, located on the top center of the tank, is secured by six or eight wing nuts on a hinged and bolted lid fitted with a replaceable gasket.

The dipstick may be inside the manhole. Used in conjunction with a calibration chart, known as a strapping chart, it measures the amount of commodity in the tank. For liquids other than compressed gases, a minimum outage of 2 percent of total tank capacity must be provided in rail transportation.

Top-Loading Valves. Top-loading valves attached to a removable eduction pipe—dip leg, dip tube, or siphon tube—run into the tank.

Bottom-Outlet Valves. When tank containers are used for hazardous materials, two externally operated, bottom-outlet valves are required. Connected in series with a replaceable gasket between them, they are located at one end of the tank, the so-called discharge end. A liquidtight closure on the external valve is also required. It may be a blind flange, which is required on international shipments; a screw cap; or a cam-lock cap attached to the external valve. A positive lock is required on the external bottom valve to keep it closed.

In an emergency, the internal valve, or foot valve, can be shut off from a remote location. As one faces the discharge end of the tank, the emergency shutoff is on the right side near the far end.

Air-Line Connection. An air-line connection, located on the tank's top, can be used for pressure unloading, vapor return, and blanketing contents with an inert gas. On occasion, blind flanges may replace the top-loading valve and air-line connection. In this situation, the shipper or supplier of the tank must provide appropriate fittings for loading and unloading.

Pressure/Vacuum Relief Devices. Generally found in pairs on nonpressure tank containers, a combination pressure/vacuum relief device serves dual purposes of protecting the tank from both overpressure and from a vacuum of more than 0.75 psi (5 kPa) negative pressure. In many cases, this relief valve has a rupture, or bursting, disk between the pressure-relief valve spring and the commodity. It protects the spring from the commodity.

Thermometer. Some tanks have a built-in thermometer to measure the temperature of the lading.

Pressure Tank Container Fittings. Like nonpressure tank containers, pressure tank containers are equipped with various fittings to make them functional and safe. A wide variety of fitting arrangements exists for pressure tank containers. Pressure intermodal tanks may have fittings on top, at the end, or on the bottom. Generally, fittings are recessed or enclosed with a cover to protect them from mechanical damage.

Loading/Unloading Valves. Liquid and vapor valves are used to fill and empty the tank. The liquid valve reaches into the lading

by means of an eduction pipe, which may be fitted with an excess-flow check valve. Vapor valves, which also may have an excess-flow check valve, are used to remove vapor from the tank or to pressurize the tank for unloading.

Pressure-Relief Devices. Pressure-relief valves, mounted on top, protect the tank from overpressure under abnormal conditions. In many cases, a rupture disk between the pressure-relief valve spring and the commodity protects the spring from the contents.

Gauging Devices. Gauging devices may be installed to measure how much liquid is in the tank.

Other Fittings. A sample line for sampling the lading and a thermometer well for measuring lading temperature may also be installed.

SUMMARY

Fire hazards in rail transportation systems exist in principally three areas: physical plants, ranging from office buildings to diesel fuel storage and dispensing facilities; trains, involving locomotives, rolling stock, passengers, or cargo; and adjacent, privately owned properties that can be damaged by a train or right-of-way fire. Fire protection for diesel, electrical, and other locomotives and for freight and other types of cars, together with fittings and equipment, includes proper design, preventive maintenance, protective equipment, and safe operations. Identification and proper documentation of the hazardous material are essential. Many rail carriers provide guidelines and training for responding to rail emergencies involving hazardous materials. Fire protection for fueling facilities and other railroad buildings and structures includes noncombustible construction, proper maintenance, fire suppression systems, and adequate water and hydrant systems. Measures that reduce the risk of right-of-way fires include improved railroad equipment, controlled burning, chemical control of vegetation, and installation of fire breaks.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on rail transportation systems discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following document.)*

NFPA 130, *Standard for Fixed Guideway Transit and Passenger Rail Systems*

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Chapter 9

Aviation

Revised by
Brian Boucher

Chapter Contents

Airport Safety Worldwide
Aircraft Fire Safety
Airport Facilities
Aircraft Maintenance and Servicing

Key Terms

aircraft, aircraft cabin, aircraft fire fighting, aircraft fuel, aircraft loading walkway, aircraft power plant, aircraft rescue, airport terminal building, air transport, aviation fuel, dangerous goods, hangar, hazardous materials, restricted articles

Aviation fire hazards develop from the energy of motion, the conversion of fuel to propulsive power, and the machinery necessary for the creation of a life-supporting environment above the surface of the earth. Complex system safety analysis and procedures are conducted to prevent problems from developing and to limit consequences of failures and mishaps that do occur. Most nations have extensive design, builder, and operator criteria for aircrews and maintenance personnel. A cohesive and comprehensive approach to safety during the operational phase of flight servicing must include training of baggage and cargo handlers, cabin clean-up crews, and customer contact personnel about their role in the safety management system and in response to a major accident or occurrence.

Airborne and ground navigational aids, weather monitoring, air traffic control, runways and overruns, taxiway design, the proper maintenance of such equipment including maintenance of clear approach, departure, and taxi paths are beyond the scope of this chapter.

For related topics, see Section 13, Chapter 7, "Aircraft Rescue and Fire Fighting (ARFF)"; and Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems."

AIRPORT SAFETY WORLDWIDE

Commercial aircraft internal fire safety features do not vary greatly worldwide since the choice of metals, composites, fuels, and interior furnishings are led by technical considerations and by major manufacturers throughout the world. Because builders must have their products accepted in worldwide markets, the degree of fire safety is uniformly high.

There are diverse approaches to fire safety goals in aviation ground facilities worldwide. In passenger terminals there may be only spot use of fire sprinklers and large areas of low risk may be unsprinklered. Although terminal buildings are rarely over five stories in height (except for towers), restaurant fires and fires in baggage-handling areas have contributed to serious smoke problems in passenger common areas.

For aircraft hangars, the design and construction materials may differ depending on the owner's and user's view of what is at risk: the aircraft or the building. Air-supported unconventional structures have received some attention. Military considerations, however, have brought about reinforced concrete shelters that provide internal aircraft fueling, maintenance, loading facilities, and electronic system testing. Because of the hazards associated with these activities, the hangars are equipped with ultrafast fire detection and suppression systems.

Aircraft loading walkways have been used that feature glass sidewalls. Although aircraft fires, both internal and external to the aircraft, at the loading walkways are rare, such incidents do occur.

Aircraft rescue and fire-fighting strategy and tactics, equipment, and personnel do not vary much from one major airport to another. The International Civil Aviation Organization (ICAO), NATO, and various pilots' unions tend to drive a high degree of competence. As in the United

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States, however, third-tier airports in other countries may depend on local or regional funding mechanisms and this usually translates into less than ideal personnel, equipment, and training. The most common and effective aircraft rescue and firefighting agent in the United States is an aqueous film-forming foam based on military specifications. In much of Europe, however, other formulas are favored.

AIRCRAFT FIRE SAFETY

Fire safety in aircraft starts on the drawing board, and aeronautical engineers bear the brunt of responsibility for fire prevention and control. Aircraft require large quantities of fuel, lubricating oils, hydraulic fluids, and Class A combustibles, which are in proximity to potential ignition sources such as power plants, auxiliary power units, electrical systems, and heaters. Many aircraft carry oxygen systems (liquefied and gaseous), and some use oxidizers for auxiliary power units or are equipped with small rocket units for additional takeoff thrust. Consequently, aircraft fire safety requires skillful blending of reasonable safeguards that are lightweight and do not interfere unduly with the use and mission of the particular aircraft.

Most nations that have a major aircraft production industry also have extensive regulations governing the use and arrangement of the foregoing items, and it is extremely important that the designer be thoroughly versed in the letter and intent of these regulations.

Installed fire detection and extinguishing equipment are normally required for those aircraft areas that possess inherent fire hazards and ignition potentials. Other fire prevention techniques used are the following:

- Compartmentation of fire hazard areas from critical structural components and flight control systems
- Judicious use of other materials that are fire or heat resistive or of very low flammability
- Separations of systems containing flammable fluids from potential ignition sources. For example, all aircraft have fire protection systems in washrooms because of the high risk of passengers smoking and placing their cigareete butts in the garbage. Also, aircraft that fly with only two engines follow the guidelines of Extended Twin Operations (ETOPS). Such aircraft must have fire protection systems that will suppress a fire for a minimum of 60 minutes (up to 207 minutes).

Because fires inflight pose tragic life hazard potentials, inflight fire prevention and control must receive high priority. Fires following impact accidents can result in the loss of many lives. Fires during maintenance can have consequences that range from the obviously disastrous to high monetary loss from small and simple fires. Even a very short fire exposure can result in delamination of honeycomb structures.

In commercial, light general aviation, and military reciprocating engine aircraft, the lightweight structure needed to allow the aircraft to perform its mission also permits impact energy to be transmitted to the aircraft occupants. Thus, more deaths occur due to impact trauma than due to fire.

In large turbine aircraft that operate in a more demanding flight envelope, heavier gauge metals, advanced composite materials, and computer-assisted design techniques strengthen airframe structures. These aircraft structures absorb a greater amount of impact energy, thereby transmitting less of it to the occupants. Subsequently, in accidents involving this type of aircraft, the postaccident fire is a more significant cause of serious injuries or death to the occupants.

As a result of aircraft accident investigations, there has been ongoing research on methods of minimizing aircraft fatalities. Improved seat belt design, heat-resistant evacuation slides, elimination of injury-causing projections, floor mounted emergency lighting systems, fire blocking seat materials and wall furnishings, stronger seats that withstand up to 16 g's, and overhead storage bins are some developments that improve occupants' chances of survival when an aircraft accident occurs.[1]

Many methods are being studied to reduce the hazard of postimpact fires. They include, but are not limited to, the following:

1. Segregating flammable-fluid containers and systems from ignition sources
2. Improving fueling systems and fuel containment methods
3. Reducing the rate of evaporation and the speed of flame spread over the surface of the spilled fuel
4. Improving the materials used for interior decor, insulation, sound attenuation, and cushioning to reduce ease of ignition, flame spread, and smoke and toxic gas generation
5. Compartmentation with lightweight fire walls in the occupied portions of the cabin, blind spaces, lavatories, and trash containers
6. Onboard cabin fire suppression systems using a variety of extinguishing agents
7. Early warning fire/smoke detection systems in occupied portions of the fuselage
8. Inerting fuel tank vapor space to reduce the possibility of explosion from static electrical discharge and lightning strikes. This can be effective in flight but does little to contain the postimpact fire, because the inert atmosphere would be lost almost immediately on impact, with the disruption of the tank structure

See Berg,[2] Diehl,[3] and Murray[4] for related information.

Aircraft Power Plants

Civil aircraft in the United States are subject to extensive federal regulation through the U.S. Department of Transportation (DOT), Federal Aviation Administration (FAA). The Code of Federal Regulations (CFR) Title 14, "Aeronautics and Space," contains the Federal Air Regulations. Other nations have similar requirements. The following list summarizes the regulations that apply to aircraft power plants:

1. All reciprocating engines, auxiliary power units, fuel-burning heaters, or other combustion devices intended for operation in flight must be separated from other areas of the aircraft by fire walls, shrouds, or equivalent means so that no hazardous quantities of air, fluid, or flame can pass from these compartments to other portions of the aircraft. These regulations also

apply to the combustion, turbine, and tailpipe sections of turbine engines. The fire walls and shrouds must be made of a material that withstands heat at least as well as steel. When applied to power plants, the material must perform under the most severe conditions of fire and duration likely to occur in such zones. All openings in fire walls and shrouds must be sealed with close-fitting fire-resistive grommets, bushings, or fittings. In engine nacelles, a fire seal or bulkhead is used to isolate the engine power section and exhaust system. In addition, a main fire wall segregates the complete engine assembly (power section, exhaust system, and accessory section) from the remainder of the nacelle section and, as applicable, the wheel well. In gas turbines, the fire seal or bulkhead separates the combustion, turbine, and tailpipe section from the compressor and accessory section. An additional main fire wall isolates the engine assembly from the support pylon or remainder of the aircraft, as applicable.

2. The cowling and nacelle skin are designed to prevent fire from circumventing the fire seals and main fire walls.

3. Tanks containing a flammable fluid cannot be located in a fire zone except when it can be proved that construction, connecting lines, controls, and shutoff means provide protection equivalent to segregation. A specified air gap is required between flammable fluid tanks and a fire wall, and materials that can absorb flammable fluids are prohibited from the area of the tank or any other system containing flammable fluids.

4. Emergency fuel shutoffs are required for each engine, auxiliary power unit, or combustion heater. The emergency shutoffs must be fire resistive or located so that a fire in any fire zone does not affect their operation. Operation of the emergency shutoff must not affect other emergency functions or the operation of any other engine.

5. Flammable liquid lines in fire zones must be fire resistive and, where required, flexible. This also applies to drain and vent lines for flammable fluids or vapor.

6. Reciprocating and turbine engine air inlets must be arranged to prevent backfire flames from entering the fire zone and designed so discharge from vents and drains cannot enter the air induction system.

7. Exhaust systems must discharge in a safe manner, not expose any portion of a flammable fluid system, and be provided with heat shields wherever they may impinge on other potions of the aircraft.

8. Drains must be provided for all fire zones, with the discharge arranged so that drained fluids will not be reingested into any portion of the aircraft.

Aviation Fuels

The fire hazard properties of aviation fuels are identified according to ease of ignition, flashpoints, flammability limits, distillation range (initial and end boiling point), and electrostatic susceptibility. (Note: Octane rating has no relation to the degree of fire hazard of a fuel.) Table 21.9.1 summarizes characteristics of more common aviation fuels. NFPA 407, *Standard for Aircraft Fuel Servicing,* requires that the same fire safety precautions apply to all types.

The following factors must be considered when evaluating fuel in an operating aircraft and when fuel stored in a tank at a bulk plant is being evaluated:

- Because an aircraft travels at different altitudes and through varying ambient temperatures, conditions of flammability in the tank vapor space can change rapidly. Thus, a fuel type such as

TABLE 21.9.1 Summary Data on the Fire Hazard Properties of Aviation Fuels

Characteristics	*Gasoline AVGAS*	*Kerosene Grades JET A, JET A-1, JP-5, JP-6, and JP-8*	*Blends of Gasoline and Kerosene JET B and JP-4*
Freeze point[a]	–76°F	–40°F to –58°F	–60°F
Vapor pressure[b] (Reid-ASTM D323-58)	5.5 to 7.0 psi	0.1 psi	2.0 to 3.0 psi
Flashpoint[a] (by closed-cup method at sea level)	–50°F	+95°F to +145°F	–10°F to +30°F
Flashpoint[a] (by air saturation method)	–75°F to –85°F	None	–60°F
Flammability limits			
Lower limit	1.4%	0.74%	1.16%
Upper limit	7.6%	5.32%	7.63%
Temp. range for flam. mixtures[a]	–50°F to +30°F	+95°F to +165°F	–10°F to +100°F
Autoignition temperature[a]	+825°F to +960°F	+440°F to +475°F	+470°F to +480°F
Boiling points[a]			
Initial	110°F	325°F	135°F
End	325°F	450°F	485°F
Pool rate of flame spread[c,d]	700–800 fpm	100 fpm (or less)	700–800 fpm

Note: Figures vary for some of these values.
[a] 5⁄9(°F – 32) = °C.
[b] 1 psi = 6.9 kPa.
[c] 1 fpm = 0.3 m/min.
[d] In mist foam, rate of flame spread in all fuels is very rapid.

Jet A—which is normally too lean in a tank vapor space at sea level with a fuel temperature of 70°F (21°C)—can move into the flammable range as the aircraft gains altitude. Other factors contribute to this change, such as aircraft skin heating from air friction, outgassing of dissolved oxygen, and sloshing of the fuel from air turbulence. Figure 21.9.1 illustrates changes in flammability limits of aircraft fuels in tank vapor space due to altitude and temperature changes.

- After an impact when major structural damage occurs to aircraft fuel tanks, the fuel may be released as a mist due to forward momentum, splashing, and wind shearing. Regardless of the type of fuel involved, this mist can ignite easily from disrupted electrical circuits, hot engine surfaces, or ignition sources on the ground. The resulting fireball then acts as the ignition source for other combustibles in the area, including pools of high flashpoint Jet A fuel. In some aircraft crashes where deceleration forces are low, liquid fuel flowing from ruptured fuel tanks or broken fuel lines can be vaporized and ignited by hot engine surfaces, hot brakes, heavy electrical arcs, and so forth.
- Reciprocating engines present a fire hazard for a short period after shutdown. However, turbine engine tailpipe fires are fairly common and in crash situations turbine engines may be an ignition source for many minutes after a nominal "shutdown."

Relative Safety of Jet Fuels. The kerosene-type turbine fuels offer a safety advantage over other types of aviation fuels especially during fueling operations and aircraft fuel system maintenance. Fires are less likely in impact-survivable accidents when the aircraft involved has class Jet A fuel in the tanks. However, once ignition occurs, all fuels exhibit similar behavior, and control measures must be instituted quickly to prevent injury and fatalities.

In some portions of the world, Jet A (kerosene grade) fuel is not readily available, and Jet B (JP-4) is used. Some nations also have reduced the minimum flashpoint of Jet A to increase yield of aviation fuel per barrel; the minimum flashpoint has been in the 80°F (27°C) range. The actual flashpoint has been above 100°F (38°C).

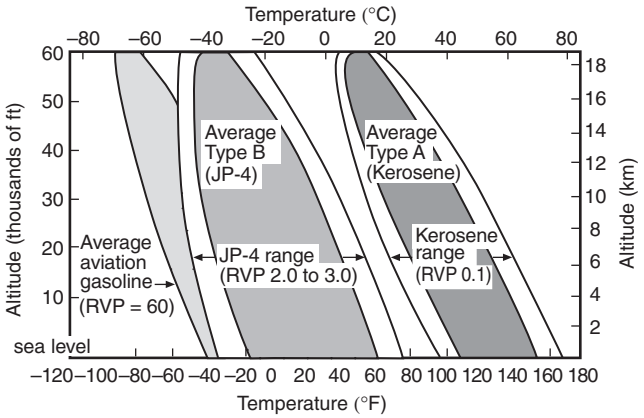


FIGURE 21.9.1 Flammable Ranges of Aviation Gasoline and Jet A (Kerosene) and Jet B (JP-4) Turbine Fuels, Showing Variations with Altitude

Electrostatic Susceptibility and Autoignition. The degree to which a static charge may be acquired by aviation fuels depends on many factors: the amount and type of residual impurities, dissolved water, the linear velocity through piping systems, and the types of filters and water separators used. Jet A and Jet B fuels are better static generators than AVGAS. Although all fuels generate static charges, the electrical conductivity of the fuel directly relates to the speed of charge relaxation (dissipation).

Antistatic additives increase static charge. However, rather than preventing the formation of static charges, they actually increase fuel conductivity, thus considerably shortening relaxation time. The charge generation increases as fuel passes through filter/water separators and other equipment. An unbonded object in the vicinity of the charge generation point before the charge has an opportunity to relax can act as a collector and cause high-energy static discharge.

Although possibly misnamed, antistatic additives have greatly increased the safety of aircraft fueling operations although there are some circumstances that are exceptions (e.g., the unbonded collector in close proximity to the static generation point). Autoignition in fuel cells/tanks can result if the internal fuel pumps run hot and/or dry.

Aircraft Fuel Systems. Most aircraft make extensive use of the internal wing volume to store fuel. In larger aircraft and newer general aviation aircraft, the wing structure is sealed and forms the fuel tank. This is commonly called integral tank, or wet wing, construction. Older and light aircraft may incorporate a flexible bladder to contain the fuel within the wing structure, using the wing structure only for support. Separate metal tanks or fiber-reinforced nonmetallic tanks are not widely used but can be found on aircraft that need extended fuel range when ferrying long distances.

With integral tank construction, and only to a slightly lesser extent with thin-wall bladder tanks, disruption of the wing structure by ground impact or other damage typically results in the release of fuel and potential for ignition. This can occur even though occupied portions of the aircraft may be only slightly damaged. If so, fire becomes a threat to the occupants. Figure 21.9.2 illustrates typical fuel-occupied spaces in a large turbo jet powered aircraft. The reserve tanks and Nos. 1, 2, 3, and 4 are integral tanks in this particular airplane, and the wing center section tank is of the bladder type.

One approach proposed is crash-resistant fuel tank construction with dry break fittings and automatic fuel shutoffs. Although the technology to develop this tank has been highly advanced, it has not been widely adopted due to weight limitations and reduction in volume available for fuel storage in long-range, military, and commercial aircraft. However, certain helicopters operated by the U.S. Army are equipped with such crashworthy fuel systems.

Open-celled plastic foam blocks, cut to fit and placed in the tank, are used on some military aircraft. Although primarily intended for explosion protection after projectile penetration (incendiary bullets, etc.) of the vapor space, they also improve the postcrash fire situation. Tests showed some resulting improvement, but the problems of removal and replacement for tank

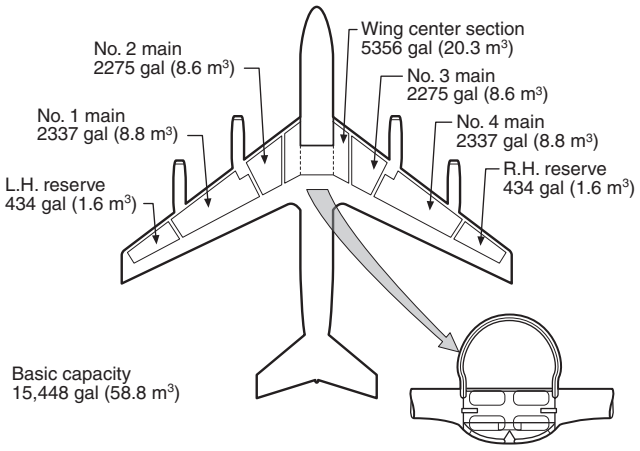


FIGURE 21.9.2 Arrangement of Fuel Tanks in a Typical Turbine-Powered Air Carrier Aircraft

interior maintenance and loss of available fuel volume preclude their use in large, long-range civil and military aircraft.

Aircraft equipped with these foam blocks can have internal fuel tank fires. Foam increases the static charging tendency and/or acts as the unbonded collector. However, the presence of the remaining foam in the tank vapor space prevents further propagation of the fire/explosion.

Many aircraft use the wing center section (where it passes through the fuselage) for additional fuel storage. In some aircraft, such as the Boeing 727 and DC-9, this is an integral tank with a bladder liner. Newer aircraft designs use a double-wall tank of metal with a honeycomb core. Although such tanks are well protected by the center wing section box structure (the heaviest on the aircraft), they directly expose the fuselage interior. To extend normal operating range, some aircraft use fuselage fuel tankage of the double-wall type outside of the wing center section box, and thus are deprived of heavy structural protection. As a reasonable compromise, all fuel tanks (at least those within the fuselage) should be crash-resistant with dry break fittings and automatic shutoff valves.

Certain models of existing aircraft contain fuel tanks well forward or aft in the fuselage. Fuel storage in the horizontal stabilizer and vertical fin is being used on certain aircraft to extend range.

Other Design Considerations

The Federal Air Regulations mention several design principles that affect basic aircraft fire safety and crashworthiness (excluding cabin furnishings and evacuation systems):

1. When the same structure supports fuel tanks and landing gear, shear pins must be incorporated in the landing gear support structure, allowing the gear to be wiped off without applying structural loads to the fuel tanks.
2. The metal aircraft structure must have electrical continuity to prevent accumulation of static electrical charges, particularly in the fuel tank areas. This is extremely important when designing an all-metal aircraft, since the aircraft structure acts as a Faraday Cage, shielding all contents from lightning strikes.
3. Static discharge devices and lightning divertors must be located and installed correctly.
4. Fuel lines supplying rear fuselage-mounted engines must be designed to ensure proper fire resistance and have the flexibility to resist rupture in a crash situation.
5. Fuel lines and main electrical leads must be segregated.
6. Main electrical power cables in the fuselage must be shrouded in fire-resistive flexible conduit.
7. The hydraulic system must be designed properly and use fire-resistive fluids. Such fluids presently in use have autoignition temperatures in excess of 1000°F (538°C) and are only slightly flammable. (Older types of mineral oil-based hydraulic fluids are still widely used, particularly in the military.)

Aircraft Cabin Fires

Cabin fires in flight are infrequent and usually discovered in their incipient stage and rapidly extinguished. The potential life loss, however, is severe if fire progresses beyond the point of control by use of handheld fire extinguishers. The fire reaction of aircraft cabin interior materials, once ignited, is crucial from a life safety viewpoint and can result in severe structural damage or loss of the aircraft, as was the case of Swiss Air 111 over the North Atlantic.

Prior to the mid-1940s, few, if any, regulations concerned the flammability of cabin furnishings. Old aircraft at air shows and in museums show wicker chairs, gauze fabric curtains, and other combustibles. Following World War II, a qualification test was required that involved igniting small horizontally mounted samples by a short exposure to a Bunsen burner flame. If a sample did not continue to burn after removal of the igniting flame, or burned less than a specified distance in the specified time, it was classified as self-extinguishing or slow burning. Although this test procedure was developed for laboratory comparisons, it created a widespread impression in the aviation industry that cabin furnishings were fire resistive. They were not.

In the 1950s and 1960s, research began to improve the fire resistance criteria. Various public and private organizations conducted tests that proved the inadequacies of the existing fire resistance criteria and, further, disclosed the problem of heavy smoke and toxic gas.

In the late 1960s and early 1970s, the fire resistance criteria were upgraded to require a material sample to be self-extinguishing when tested in the vertical position, with exceptions such as floor carpeting. Although flame spread of compliant materials was reduced, there is room for further improvement, and the problem of toxic smoke may need to be addressed directly.

In the late 1970s and early 1980s, researchers developed a method of "fire blocking" aircraft seat cushions. Inserted between the cushion, which is usually made of polyurethane foam and decorative upholstery, this fire-blocking layer is intended to delay or prevent seat cushion involvement in a cabin fire. The FAA now requires all commercial aircraft seat cushions to be fire blocked.

In addition to fire blocking, research is continuing toward the development of an improved, fire-resistant aircraft cabin window material to delay or prevent postimpact fire entry into the fuselage via the windows. These transparencies/windows are complicated design challenges because they must resist heat, cold, vibration, and substantial internal air pressure variations as the aircraft moves from ground level to heights of 40,000 ft (12,500 m) or more.

Many aircraft carry supplemental oxygen for the potential failure of cabin pressurization and in portable cylinders for first-aid purposes. In a crash, localized fire intensification can be expected if the oxygen cylinder fuse plug operates due to fire exposure and releases oxygen in the cabin atmosphere. In addition to potential oxygen release from high-pressure cylinders, some aircraft carry chemical oxygen generators. Improper packaging and transport of such devices in a cargo bay resulted in a disastrous inflight fire over the Florida Everglades.

Possible causes of aircraft cabin fires include the following:

1. Ignition of the cabin interior from a postimpact fuel fire or a fire resulting from a fueling operation malfunction. In such a fire, although the interior materials have a certain fire resistance, heat from the exposing fire overwhelms the materials' resistance.
2. Electrical failure and electrical arcing within concealed spaces, often behind the cabin decorative liner. Such fire can remain undetected for a considerable time period and grow beyond control of handheld fire extinguishers before it is discovered. Flight deck fires (or as often described "smoke in the cockpit") are a threat for several reasons: obscuration of pilot's vision, loss of instrumentation, and incapacitation of the flight deck crew. Radar, radios, life support systems, and motors to operate flight controls require tremendous electrical power. The wiring to serve them is subject to embrittlement, abrasion, vibration, and cracking. Events in the 1990s have resulted in more attention to electrical wiring.
3. Improper use of flammable liquids during cabin cleaning and refurbishing
4. Improper use or disposal of smoking materials (which should decrease due to prevalence of "no smoking" flights). Aircraft lavatories aboard all carriers are now required to be equipped with smoke detectors specifically designed for those areas. In addition to its functional purpose, the requirement deters persons who might wish to smoke in a lavatory. Tampering with or rendering aircraft lavatory smoke detectors inoperational is a serious offense. Figure 21.9.3 shows a UPS DC-8 cargo aircraft that landed successfully in Philadelphia after the pilots reported smoke in the cockpit.

NFPA 424, *Guide for Airport/Community Emergency Planning;* NFPA 415, *Standard on Airport Terminal Buildings, Fueling Ramp Drainage, and Loading Walkways;* and NFPA 402, *Guide for Aircraft Rescue and Fire Fighting Operations,* provide guidance concerning such fires. For more information on aircraft cabin fires and materials for use in aircraft cabins, see Babrauskas[5] and McCaffrey.[6]

FIGURE 21.9.3 Safe Landing of a DC-8 After Report of Cockpit Smoke

Air Transport of Dangerous Goods

Hazardous cargoes (hazardous materials, nuclear materials, and restricted articles) can present a problem to aircraft in flight, on the ground, during ground handling, and in a postcrash situation. This is an international problem, since many shipments cross national boundaries. Many agencies regulate hazardous cargoes, including the U.S. Department of Transportation, the International Air Transport Association, the International Civil Aviation Organization (an agency of the United Nations), and others.

The regulations cover the type of cargo that may be shipped, quantities allowed, packaging method, and aircraft type (passenger or cargo only) in which this material may be carried. Flight crews must be informed of the presence of hazardous cargoes on the manifest and, in some cases, the captain can refuse to carry the material.

If the rules are followed rigidly, there is little hazard to safety of flight or to ground personnel, whether in normal handling or a postcrash situation. Problems arise when the shipper, either in ignorance or in willful contempt of the regulations, misrepresents the contents of the shipment to a carrier or does not package the material adequately to ensure containment during transit.

After several serious crashes in the 1980s and early 1990s, the regulations were revised and further restrictions adopted. Better training is now required for each carrier's receiving agents, standard labels have been adopted, and penalties are assessed against shippers who violate the law. Detailed information regarding the air transport of dangerous goods and a listing of the United Nations warning label system can be found in Appendix B of NFPA 402.

Aircraft Fire Detection and Extinguishing Systems

Fire detection and extinguishing systems are required in certain zones of the aircraft, notably the power plant areas. These systems are defined in design regulations of the nation of aircraft origin.

The systems are similar to those used in ground installations, but there are significant differences. In most aircraft installations, the flight crew manually activates the extinguishing system. The detection system must be very sensitive, very stable (i.e., free of false alarms), and able to withstand extremes of the environment in which it must function—temperature, vibration, high airflows, and structural flexing. The system must also reset automatically to notify the flight crew when the fire has been extinguished, or when the temperature in the protected zone drops below the set point. System response must be within seconds of the beginning of abnormal conditions.

Extinguishing agent hardware must be lightweight, rugged, and, to overcome the high flows of flight, capable of higher rates of agent discharge than would be expected in a similar ground installation.

The most common extinguishing agents used in aircraft are bromotrifluoromethane (Halon 1301) and bromochlorodifluoromethane (Halon 1211). Due to the ozone depletion characteristics of the halogenated hydrocarbons, these chemicals are being phased out in accordance with international treaties. The development of suitable replacement agents is under way. See Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems." Older aircraft still use carbon dioxide, methyl bromide, and chlorobromomethane. All are somewhat effective on flammable liquid and electrical fires.

Cargo Compartment Fire Detection and Extinguishing Systems. Cargo compartments in passenger aircraft often are equipped with fire detection systems. Air starvation is one of the more common techniques used in fire extinguishment in cargo spaces. Upon actuation of fire detection systems, all ventilation to the compartment is sealed off and the fire is allowed to self-extinguish due to lack of oxygen. Fire extinguishing systems traditionally using Halon 1301 or Halon 1211 will need to switch to treaty-compliant halon alternatives.

Recent regulations have been adopted to improve the fire resistance and fire penetration-resisting capabilities of cargo compartment liners. An upper limit has been placed on the volume of a cargo compartment; above this limit, a fire suppression system must be installed regardless of compartment construction. For more information, see Bennett[7] and Grosshandler.[8]

Figure 21.9.4 shows an electric fire that occurred inflight over Canada. The fire was caused by an electrical arcing of a heater ribbon tape. The aircraft landed safely and ARFF crews quickly extinguished the fire.

Aircraft Hand Fire Extinguishers

The FAA requires portable hand fire extinguishers in all air transport category aircraft. In some smaller general aviation aircraft, they are recommended but not required.

NFPA 408, *Standard for Aircraft Hand Portable Fire Extinguishers,* requires portable hand fire extinguishers on all aircraft and describes the type, quantity, minimum capacity, installation, location, and spacing of the extinguishers.

Although the FAA recognizes carbon dioxide, water, dry chemical, Halon 1211, Halon 1301, and halon combinations, at least two extinguishers installed on large transport aircraft must be of the Halon 1211 or combination Halon 1211/1301 type. Due to environmental problems associated with halogenated agents, their use is prohibited except in specific circumstances.

FIGURE 21.9.4 Results of an In-Flight Electrical Fire

NFPA 408 no longer recognizes carbon dioxide and dry chemical as suitable for use on aircraft. Carbon dioxide is not recognized as suitable for the following reasons:

1. Ineffectiveness on Class A materials
2. Chilling effect of solid carbon dioxide (snow) may damage delicate electronic components
3. Weight of container and agent versus similar agent capacities of the halon type
4. Required dwell time and concentration for Class A fires is not compatible with human life

Dry chemical has long been banned from aircraft in NFPA 408 for the following reasons:

1. Obscuration of the operator's vision, particularly in confined spaces
2. Possibility of an insulating chemical layer forming on delicate electrical contacts, which could affect continued safety in flight
3. Dry chemical can irritate the eyes and mucous membranes even though it is not considered toxic
4. If not immediately cleaned up, certain types of dry chemical can be highly corrosive to aircraft metals

Means of Egress from Aircraft

In aircraft, emergency exit facilities are particularly important because postcrash fire exposure can be severe and safe evacuation time for the occupants is limited.

U.S. Federal Air Regulations set the number of exits required in transport category aircraft, depending on passenger capacity. The manufacturer or operator must demonstrate that evacuating a full load of passengers can be accomplished in 90 seconds or less, with half the available exits inoperative. These simulations require that the test subjects represent an

average passenger load, with certain percentages of able-bodied males and females, elderly, children, and disabled. Tests are accomplished without normal cabin lighting; emergency lighting, however, is functional. The exits to be blocked are not preannounced to crew or occupants.

The simulations have some shortcomings:

1. Smoke, which could obscure emergency lights or exit signs, is not used.
2. The test subjects know this is an emergency exit certification test and will seek any usable exit. (In real life, most passengers may pay little attention to preflight announcements and, consequently, tend to attempt leaving the aircraft by the same door through which they entered.)
3. Again, many test subjects have taken part in previous demonstrations and although there is a required minimum time period since last participation, retain a certain knowledge of "what to do in the test."
4. Actual crash experience has shown considerable obstruction of egress because of failure of overhead storage bins, presence of carry-on luggage, and beverage/food service carts.

Escape Systems and Devices. It is acceptable and permissible to use the normal entrance and passenger service doors as part of the emergency exit system. If the door is power assisted in its normal mode of operation and operates relatively slowly, it is equipped with a high-speed power assist for the emergency mode.

Modern passenger aircraft are equipped with inflatable evacuation slides at all emergency exits that have a normal door sill height that exceeds 5 ft (1.5 m). The distance from door sill to ground level, however, can drastically change in the event of a collapse of the main gear or nose gear. (A deployed slide under these conditions would not provide an effective angle for safe descent.) FAA regulations require the slide to deploy and inflate automatically when an exit door opens in emergency mode. In many instances evacuation slides can also serve as life rafts. Figure 21.9.5 shows evacuation slides used in an emergency passenger evacuation in Lajes, Azores, after an AirBus 330 aircraft ran out of fuel and landed successfully without engines. The 300 passengers sustained only minor injuries.

FIGURE 21.9.5 AirBus 330 That Landed Without Engine Power

The openings designated as emergency exits must be operable from the outside and designed to resist jamming due to fuselage distortion. The slides must deploy properly regardless of wind direction or other influences.

The fire resistance of the slide material used to be very low, and even slight exposure to flame caused deflation of the slide. However, slide material has now been developed that incorporates a reflective coating, reducing the possibility of damage and deflation caused by radiant heat. At present, not all aircraft have been upgraded with this new material.

Emergency escape slides that are enabled during flight operations are deactivated when the aircraft reaches the terminal/parking spot. Consequently these systems are not available for food servicing, cleaning, and toilet service personnel.

Obscuration of exit signs and emergency exit lighting by smoke can seriously impede evacuation of the aircraft. All air transport aircraft are required to have exit signs installed at a lower level and the exit access must be visible from a minimum distance of 35 ft (11 m), assuming a smoke level above the seat back height. In addition, illuminated exit path lights installed in aisle seat armrests or in the floor must be provided.

Aircraft Construction Materials

Aircraft from small personal and business reciprocating engine powered to the largest and fastest of commercial and military jet aircraft use an amazing smorgasbord of metals, organic fibers, gases, and fluids. Metals such as aluminum, magnesium, and titanium can and do burn if heated sufficiently. Composites are used for structural components and for body, wing, and control surfaces. The organic binder and fiber matrix of these metal replacements can fracture under crash conditions and release physiologically dangerous materials to nearby occupants and rescue personnel. Protective clothing and personal breathing equipment should be worn at all times until it can be determined that there is no further risk to rescue personnel.

Pressure hazards range from tires inflated to 250 psi or more to pressure vessels both metal and fiber reinforced plastic wrapped that accumulate pressures of 3000 psi or more. These aspects of aircraft rescue and fire fighting are discussed in NFPA 402.

Aircraft Rescue and Fire Fighting

Aviation fire protection is an enterprise of wide challenge for economic, social, and technical reasons. In aircraft, a firewall can be a thin sheet of metal, an egress path can be an aluminized fabric slide, and survival from fire may be measured in seconds. Generally, survival from fire in exposed intact large aircraft can be as little as 3 minutes. Aluminum skin can burn through in 60 seconds, and windows and insulation may burn through in a few additional seconds. Fortunately, major airfield fires are rare, but it is clear that ready and competent rescue and fire-fighting teams are essential (see NFPA 403, *Standard for Aircraft Rescue*

and Fire-Fighting Services at Airports, and NFPA 405, *Standard for the Recurring Proficiency of Airport Fire Fighters*).

Three distinct types of ground incidents can occur within the flight environment of the aircraft (excluding fires from fueling incidents, malfunction of ground servicing equipment, or fires originating during maintenance procedures).

The first type of ground incident is the high-speed and/or high-angle impact with the ground or other object that results in such structural breakup of the aircraft that survival of the occupants is highly unlikely (i.e., all or nearly all fatalities occur due to impact trauma).

The second incident type involves relatively low-speed and/or shallow ground impact angles. In this type of incident, occupant survival rate can be very high, especially if there is no postcrash fire or if the fire is controlled quickly in the area immediately surrounding the occupied portion of the aircraft.

The third incident type occurs when an aircraft in a landing/takeoff/taxiing mode impacts with another aircraft or other object such as a maintenance vehicle or construction equipment.

Fire can be anticipated in almost all abnormal aircraft landings as well as incidental occurrences such as overheated brakes or undetected fuel leaks. It is essential that airports maintain a well-equipped and trained rescue and fire-fighting capability during all hours that flight operations are in progress. At smaller airports, the response team is often made up of persons having other airport duties such as security, fueling operations, maintenance, or baggage handling. However staffed, personnel need to participate in frequent and meaningful training sessions, be equipped with proper protective gear, and be provided with the means to respond immediately to the scene of any emergency on or adjacent to the airport.

The term *rescue* used in the context of aircraft rescue and fire fighting means the control of life-threatening fire in the critical area during the time necessary for all physically able aircraft occupants to self-evacuate. The continuance of fire control is necessary in order to permit the extrication of those who are severely injured or pinned in the wreckage. Assisted rescue of individuals from small aircraft is often routine; however, in aircraft having a large number of occupants, such assistance is usually not possible in the time available. NFPA 403 mandates that responding units have specialized equipment and manpower for interior fire fighting operating within 5 minutes of notice of an accident.

Survivable accidents tend to occur within a certain area related to the runway centerline and threshold lights. This *critical rescue and fire-fighting access area* (CRFFAA) is clearly defined and illustrated in NFPA 402 (Figure 21.9.6).

To be considered effective, the demonstrated response time of the first responding fire-fighting vehicle to reach any point on the operational runway must be 2 minutes or less, and to any point remaining in the CRFFAA, 2.5 minutes or less. These conditions must be met when flight operations are in progress; however, NFPA 402 recognizes that mitigating circumstances can make it impossible to meet these times.

More accidents tend to occur during inclement weather and this can result in longer response times. In recent years the use of global positioning satellites and forward looking infrared optical devices help locate aircraft more speedily when visibility is poor.

Preplanning for declared emergency landings on airports is extremely important. Prepositioning of personnel and vehicles greatly reduces response time and increases the chance of survival of the aircraft occupants should the landing become a major emergency. Figure 21.9.7 illustrates one system of preplanning for this type of emergency.

Specialized vehicles have been developed that have the ability to transport rescue and fire-fighting personnel, equipment, and extinguishing agents to the scene of aircraft accidents within the required response time despite terrain surface or condition. Detailed information regarding such vehicles is contained in NFPA 414, *Standard for Aircraft Rescue and Fire-Fighting Vehicles.* The number and size of response vehicles and the amounts of extinguishing agents required at a given airport depends on the types of aircraft used and the frequency of air carrier operations.

Part 139 of Title 14 of the Code of Federal Regulations (CFR) contains these minimum levels. In addition, the FAA Advisory Circular 150/5210-6B[9] gives recommended levels of

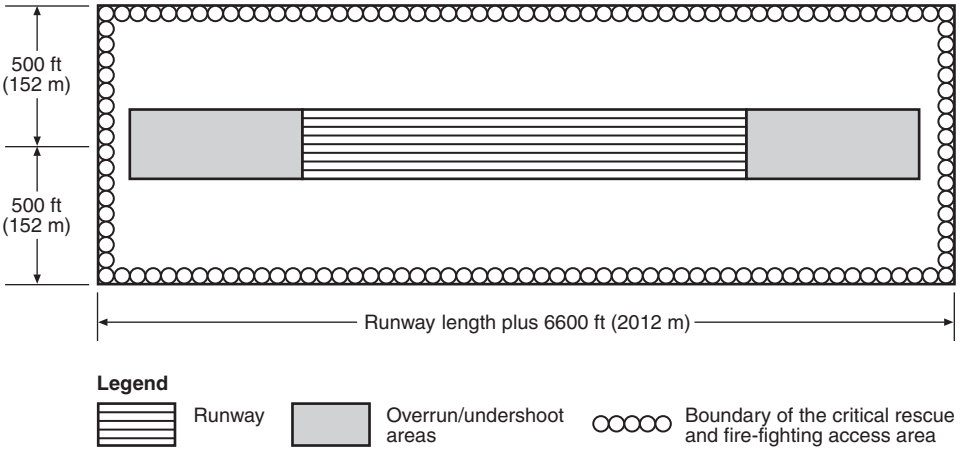


FIGURE 21.9.6 Critical Rescue and Fire-Fighting Access Area (CRFFAA)

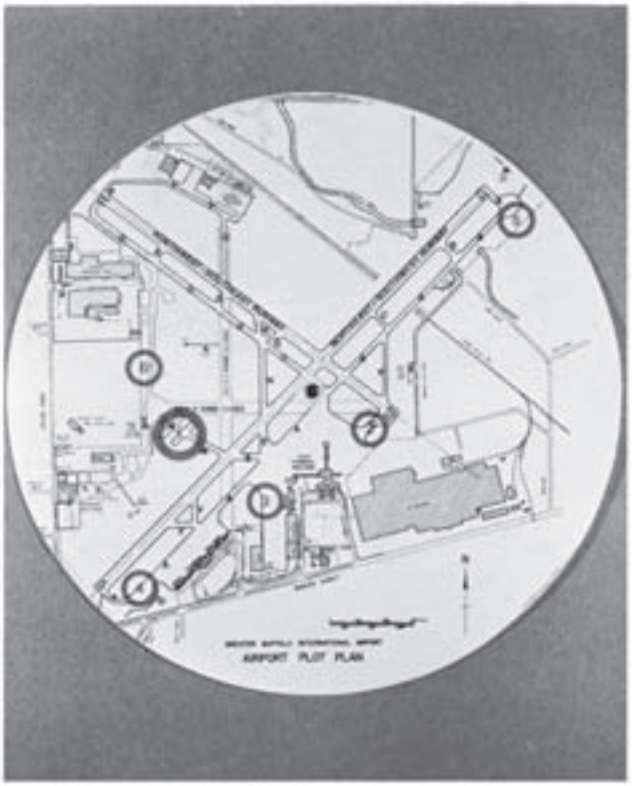


FIGURE 21.9.7 Typical Airport Plot Plan Indicating Preplanned Standby Positions for Rescue and Fire-Fighting (RFF) Vehicle

airport protection that are considerably higher than the minimum levels in Part 139.

Other information on the subject of aircraft rescue and fire-fighting protection is published in NFPA 403 and the International Civil Aviation Organization (ICAO) Annex 14 (Aerodromes) to the Convention on Civil Aviation.

There are interesting similarities of requirements among NFPA, ICAO, and the FAA Advisory Circular 150/5210-6B, as compared to the minimums of CFR Part 139. One major difference among the three is that ICAO and the FAA allow a remission factor so an airport may drop to a lower index if the number of movements (takeoffs and landings) of the largest aircraft to use the airport is below a certain daily or yearly operational level. NFPA does not recognize the remission factor, requiring protection for the largest aircraft that regularly uses the airport, regardless of operational levels.

The term "index" (e.g., l–5, 6, 7–10), as used in the aircraft rescue and fire-fighting context, provides an approximation of the number and size of fire-fighting vehicles required for problems with the larger aircraft using the airport regularly. However, this system (FAA, ICAO, NFPA) does not address the manpower needed to handle the myriad aspects of a rescue/crash response. See NFPA 424 for insight and detail concerning manpower and organizational demands. For a more detailed discussion of aircraft rescue and fire fighting see Section 13, Chapter 7, "Aircraft Rescue and Fire Fighting (ARFF)."

Rescue and Fire-Fighting Personnel, Training, and Safety

After requirements for an airport's rescue and fire-fighting protection have been determined, the next major consideration is the selection of qualified personnel. Airport fire fighters should, at a minimum, meet standards set forth in NFPA 1003, *Standard for Airport Fire Fighter Professional Qualifications.* Candidates should be in top physical condition, and the department should maintain a required physical conditioning program to ensure the best possible performance of its personnel. Physical and mental stresses encountered when dealing with a major aircraft accident can be very demanding, and efficient performance is crucial.

In addition to physical conditioning, frequently scheduled and meaningful training sessions covering all phases of aircraft rescue and fire fighting are extremely important. Such sessions are necessary to maintain a high degree of competence and readiness (see NFPA 405).

Training of attendants proved important in the AirBus 340-300 crash pictured in Figure 21.9.8. Attendants were credited with the successful evacuation of all passengers. The aircraft was consumed by fire.

In addition to the physiological and psychological preparation of responders as individuals, the exercise serves to test communication, command, and control when noise level is high, visibility is poor, and dimensions of the problem may not be fully known.

"Live fire" training using hydrocarbon fuels and other flammable liquids has been suspended at many airports due to local environmental constraints. The FAA, the U.S. military, and private industry are all in the process of developing alternative "live fire" training exercises to duplicate realistic fuel fire atmospheres and at the same time, meet all necessary environmental requirements.

Special aircraft informational charts developed by airframe manufacturers are available to airport fire fighters as well as mutual aid fire departments adjacent to an airport. These charts

FIGURE 21.9.8 Overrun of Toronto, Canada, Runway by AirBus 340-300 in August 2005

indicate locations and operation of emergency exits, areas that normally contain flammable and hazardous materials, oxygen storage, and other pertinent information. Combined with pre-incident planning inspections of aircraft that normally use the airport, periodic review of the charts keeps fire fighters current on pertinent information on various types and models of aircraft. Most airline operators encourage familiarization with their aircraft and schedule tours when flight schedules permit. A variety of aircraft information charts are contained in NFPA 402.

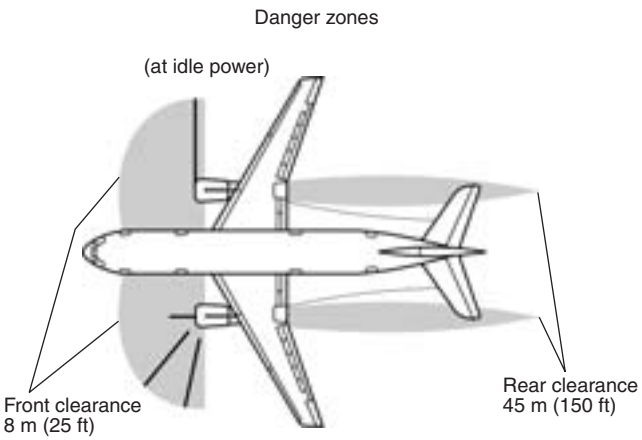
The potential for extreme danger exists anywhere in the vicinity of operating aircraft, especially with regard to rotating propellers and rotors and jet engines. Severe injuries can occur when persons do not remain alert and do not maintain the necessary safe distance. Figure 21.9.9 depicts typical jet engine intake and exhaust danger areas.

Overheated brakes may cause wheel disintegration, control surfaces may deploy unexpectedly, and extremely-high-pressure tanks may rupture under fire conditions. The results of a brake fire and explosion in France can be seen in Figure 21.9.10. The protective fire fighter hoods restrict vision and hearing. NFPA 402 discusses these concerns.

Ground Environment Safety Factors

Serious crashes can occur off the ends of runways due to insufficient clearance from various objects. The problem may be compounded where zoning regulations permit construction in these areas. Dikes, structures supporting navigational aids, and blast fences can be struck by aircraft operating in conditions of poor visibility.

Atmospheric conditions also contribute to serious aircraft incidents. Fog, rain, sleet, and snow all adversely affect runway surfaces, aircraft performance, and visibility from the flight deck. Abnormal wind conditions, particularly the phenomenon called windshear, also can be factors. Normally, unusual atmospheric conditions are handled routinely. When they are involved in combination with other factors, incidents can occur more easily.



Note: Crosswinds will have considerable effect on contours.

FIGURE 21.9.9 Engine Run Dangerous Areas

FIGURE 21.9.10 Brake Fire That Occurred During Certification Testing of an AirBus 340-600

During airport construction and repair, especially on movement areas, presence of construction and resurfacing equipment can be a factor in accidents. Another principal area where incidents can occur is in the overrun portions of runways when aircraft are unable to brake effectively, running off the runway, striking airport boundary fences, or bogging down while traversing unimproved ground surfaces. Unimproved ground surfaces between runways can result in aircraft being inaccessible to fire and rescue equipment, especially equipment not specifically designed for off-highway use.

Heliports present special problems because they are frequently located in congested areas of cities, on roofs of buildings, near hospitals, and on piers adjacent to water. NFPA 418, *Standard for Heliports,* covers landing deck construction, drainage, egress, and fire protection requirements.

Preplanning for Aircraft Incident Emergencies

All commercial airports serving passenger aircraft are required to develop and maintain an emergency plan that can be immediately activated should an aircraft incident occur on or near the airport. The plan needs to be flexible and encompass all aspects of the most difficult anticipated emergencies. All local emergency services, civic organizations, and resources need to be included in the plan. To be effective, a full-scale exercise of the plan should be conducted regularly to test and update its effectiveness.

Both tabletop and full-scale exercises are necessary because of personnel turnover in prime and supporting agencies. Physical changes in and about the airport need to be considered before, during, and after the construction period. Refer to NFPA 424 for further guidance.

Airports located adjacent to large bodies of water must give special consideration to the possibility that an aircraft incident could occur in the water. In these instances, special watercraft equipment dependent on the specific need should be provided. In addition, mutual aid agreements should be established with

all local water rescue resources such as the Coast Guard, Navy, and fireboats.

AIRPORT FACILITIES

Hangars

An aircraft hangar is simply a building built to provide weather protection and shop space during aircraft maintenance and storage. Hangars pose unusual fire protection problems due to their occupancy's special nature. Since removing all fuel from an aircraft before moving it into a hangar is often impractical and economically unsound, potential exists for having large quantities of flammable liquids, mainly aviation fuel, inside the hangar. Quite often, aircraft contained in the hangar, particularly large aircraft, are several times more valuable than the hangar, necessitating some measure of protection for the aircraft as well as the hangar structure.

Aircraft hangars are divided into Types I, II, or III, which roughly correspond to the size and type of aircraft they house and their anticipated fuel loading. NFPA 409, *Standard on Aircraft Hangars,* defines these types and outlines requirements for construction, protection, drainage, fire cutoffs, and other provisions for each type of hangar. Innovative air/steel frame supported tents have been used at a few airfields. Consensus for exact fire protection measures have not been achieved, but it is clear that due to the value of housed aircraft and life hazards, an installed fire protection system will be warranted. Such steel-framed membrane-covered structures are recognized in several building codes.

Fixed hangar fire protection systems of the past provided protection for the hangar structure and consisted mainly of water-type sprinkler systems using the extra-hazard pipe schedule, or hydraulically calculated systems, primarily of the deluge type. In aircraft hangars, these water systems are no longer recognized as viable protection by NFPA 409. With increased size and fuel loading of the aircraft, foam-water deluge sprinkler systems are now common practice. Current designs incorporate foam-producing and oscillating monitor nozzles at (nominal) floor level in conjunction with previously mentioned systems, to provide fire control/extinguishment for the shadow area beneath the wings of large aircraft.

Adequate protection of the hangar structure can be achieved as well as providing increased protection for the aircraft, primarily due to more rapid fire control and/or extinguishment.

In older hangars being modernized, a different technique has more recently been used with the approval of the authority having jurisdiction (AHJ). This technique uses overhead closed-head type sprinkler systems hydraulically designed to deliver a specified minimum water density over a specified area. It is capable of delivering aqueous film-forming foam (AFFF) solution through standard (nonaspirating) sprinklers by using wide-range proportioning devices. Scheffey provides more insight on AFFF in an airport environment.[10]

Primary fire-extinguishing capability affording some degree of aircraft protection is provided by oscillating monitors that completely blanket the floor of the entire hangar with foam within 20 to 30 seconds of actuation.

Whether the foam delivery system is used only for shadow area protection or total floor coverage, foam monitor location, oscillation speed, foam pattern, and nozzle barrel centerline height above the floor are critical. Monitors should be located so that all areas to be covered can be easily reached. Depending on the arc of coverage, no more than 15 seconds should be necessary for a complete cycle. The foam pattern should be dispersed rather than a straight stream. This minimizes turbulence at the point of stream impact with objects or the floor. Figure 21.9.11 shows a typical monitor installation.

Due to hangar sizes or multiple aircraft positions, monitor nozzles can be mounted at the bottom of the roof truss space to provide coverage for these void spaces. Arrangements should be made to exercise and test the oscillating mechanism from the hangar floor or other easily accessible locations (Figure 21.9.12).

The principal means of fire detection for actuation of overhead sprinkler systems in hangars has been rate-of-rise type devices; however, as hangar roof heights have increased to as much as 150 ft (46 m) from the floor to the roof deck, the ability of this type of device to perform within the time required to minimize aircraft damage is limited. In climates with moderate to severe winter conditions, it is difficult to maintain stability of such systems, due to the opening and closing of hangar doors and the installation of high-recovery-rate heating systems, and still maintain the sensitivity necessary for rapid fire detection. Optical-type detectors of ultraviolet/infrared type or dual function can be used for high-speed detection of relatively small fires and actuation of monitor nozzles. Rapid temperature changes do not affect those devices.

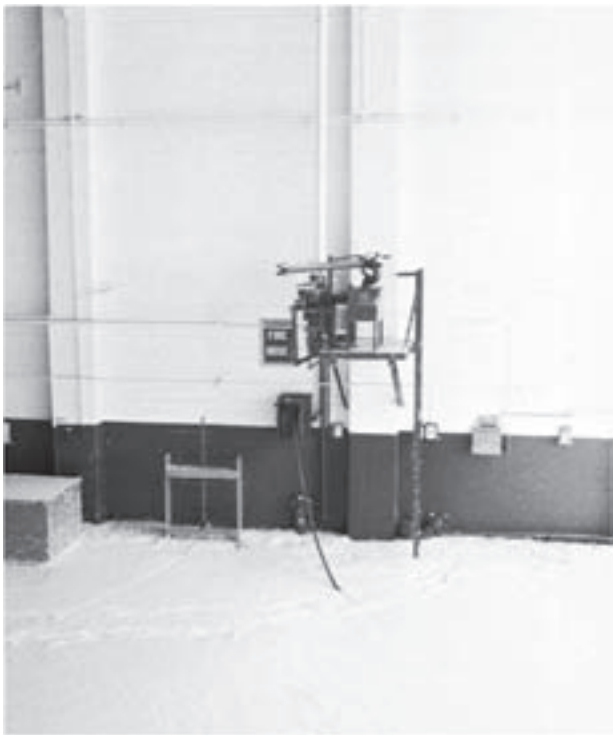


FIGURE 21.9.11 Foam Monitor Nozzle (Source: United Airlines)

FIGURE 21.9.12 Monitor Nozzle Mounted Beneath the Roofwork to Fill Void Areas Unreachable from Monitors Located Near the Walls. Centerline of the barrel is approximately 65 ft (20 m) above the floor. Control valves are located at the floor line along the hangar wall. The small-diameter lines illustrated are for testing and exercising the water-powered oscillating mechanism. (Source: United Airlines)

Care must be taken in selecting the type of detector and control devices for optical detection. They must have demonstrated operational integrity, yet not be overly sensitive and subject to false or unwanted operation. Considerable progress has been made recently in developing optical detection systems that ignore or are insensitive to routine aircraft maintenance procedures involving welding, high-intensity lights, boroscopes, radioisotopes, X-ray inspections, and so on. Whenever an optical system is installed, its sensitivity to fire should be tested. Further, a recording device should be attached to provide a hard-copy record of what detectors "see" during routine aircraft maintenance operations. During the initial period after installation (usually 60 to 90 days), the detection systems should be in the "alarm only" mode and a careful record made of the recording device printout. Aircraft maintenance records can often determine what operation affected the optical detectors.

Floor drainage is another portion of the hangar fire protection system. The drainage system removes excess fire protection water and also removes large quantities of liquid fuel from the fire scene. These systems should be flushed thoroughly with high volumes of water at least annually. Oil/water separators should be meticulously maintained to prevent pollution of lakes and streams and to reduce hazards in the airport drainage system to which the hangar system may be connected.

In recent years environmental concerns have necessitated more restrictions on the disposal of AFFF solution subsequent to discharge. Therefore, new system designs should consider the provision of bypasses and retentional areas for initial and periodic system testing.

Airport Terminal Buildings

Airport terminal buildings include any fully enclosed extensions that function as passenger concourses (sometimes called fingers or piers) and satellite buildings that serve passenger-handling functions. The satellite building may be connected to the main terminal building via tunnels beneath the aircraft operating ramp or via people-mover transit systems operating on a fixed guideway, above or below ground level. Terminals also contain airline-related businesses, such as offices, restaurants, and gift shops. Quaglia and Grubits have discussed the fire safety design of airport terminals.[11]

Special attention is given to airport terminal buildings in NFPA 415. These buildings have a severe fire exposure potential from immediately adjacent aircraft fueling and servicing operations and the high-occupancy (people) load in terminals.

Walls and glass areas of terminal buildings and other airport structures that may be exposed to jet blast or explosion require design for wind loads in excess of that which building codes normally require.

Although NFPA 415 primarily addresses the terminal building interface with the aircraft ramp, a variety of other NFPA codes apply to areas such as restaurants, baggage handling systems, and important electronic and computer installations.

Aircraft Loading Bridges or Walkways

This equipment is frequently installed at the terminal area for passenger convenience and to protect passengers from the weather while they move from the terminal loading gate area to the aircraft. Loading equipment also increases safety by reducing ramp congestion and segregating passengers from the aircraft servicing equipment and personnel.

In the event of fire caused by a fueling malfunction or other reason, a loading bridge or walkway can serve as a means of egress from the aircraft to a safe refuge, for example, the terminal building. Most people naturally tend to exit an area (aircraft or building) the same way they entered. Because the emergency situation requiring evacuation may occur before the preflight safety and evacuation briefing, the loading bridge may be the only means of egress familiar to passengers. For this reason, NFPA 415 requires 5 minutes of safe passage from the aircraft to the terminal. Construction features, special fire protection, or a combination of both may accomplish this. Safe egress must be provided during severe fire exposure to the bridge.

Doors, if any, at the terminal end of the bridge should be equipped with panic hardware and swing in the direction of travel from the aircraft to the terminal. The loading bridge should not be considered part of the terminal egress system, unless a vestibule and stairs conforming to NFPA *101*®, *Life Safety Code*®, are provided at the terminal end, even though auxiliary stairs may be located near the aircraft end. Auxiliary stairs are strictly for the use of aircraft servicing personnel or flight crew.

Training of loading bridge operators in positioning the equipment and obtaining the best possible "seal" with the aircraft in all weather conditions is very important. Unless the bridge and closure curtain are properly positioned and utilized, the integrity of the loading bridge as a means of egress from the aircraft is seriously compromised. The operator must be aware that the closure curtain is a safety item, not merely weather protection.

Since escape slides aboard the aircraft are normally deactivated during the loading, unloading, and maintenance cleanup phases of activity, the loading bridge/walkway is a critical element in the fire safety system. It is essential that this egress path not be blocked by wheelchairs, trash carts, and so on.

Aircraft Fueling Ramp Drainage

The large amounts of combustible/flammable liquids (in the form of fuel) handled on aircraft servicing ramps demand that special attention be paid to the drainage system provided to prevent exposing the terminal or aircraft unnecessarily in the event of unintentional release. NFPA 415 specifies the amount of slope and direction regarding ramp geometry, location of drainage system inlets, water seal traps, and oil/water separators.

AIRCRAFT MAINTENANCE AND SERVICING

Aircraft Maintenance

To keep an aircraft airworthy, every part must be inspected, repaired, or overhauled periodically. The frequency of these procedures varies. Operations may be performed all at once in a single maintenance visit, or as part of a progressive overhaul system where a certain portion of a total overhaul is conducted periodically. In addition, periodic inspections are required between major overhauls to repair minor discrepancies, inspect critical structures, and test various components. Nonroutine maintenance can occur at any time to replace or repair a defective or prematurely failed part.

Many maintenance procedures involve the use of highly flammable solvents, sometimes unstable or toxic chemicals, and personnel entry into integral fuel tanks. When situations such as these occur, special procedures must be developed to ensure the safety of the operation. It is sometimes possible to pressurize equipment housings with shop air, using appropriate power/pressure interlock to prevent penetration of flammable vapors. Localized ventilation and curtailment of operations utilizing flammable or combustible liquids are also helpful. In any event, each potentially hazardous procedure should be developed or reviewed by a person who is thoroughly familiar with the basics of fire safety and aircraft maintenance requirements and procedures. NFPA 410, *Standard on Aircraft Maintenance,* should be used to develop local procedures for the more common hazardous aircraft maintenance operations, such as welding, spray painting, fuel tank ventilation, and so forth.

NFPA 70, *National Electrical Code®*, defines certain areas in hangars and around aircraft as Class I, Group D, Division I or II locations. In this age of sophisticated testing using electronics, eddy currents, X-rays, and so on, it is often impossible to design or obtain equipment listed or approved for these locations. Injuries and fires can occur due to the complexity of aircraft and associated electrical test equipment. Induced current, capacitor-type discharges, errant electromagnetic radiation, and simple poor electrical continuity are some of the electrical fire and safety hazards that can occur during aircraft maintenance. Welding (usually inert gas-shielded arc) is frequently performed on installed engines or aircraft structures.

Testing fuel tanks for system leaks is commonly performed in hangars using high flashpoint Jet A fuel or a special, usually combustible, test fluid. Toward this end, many hangars have a fixed system to load and unload fuel or test fluid. It has also been a practice to park a standard fuel servicing tank truck outside the hangar and run long hoses to the aircraft connection points. This practice is to be discouraged, because the hose is the weak point in any system. Although hoses are necessary for flexible connections, they should be kept as short as possible.

Painting the interior and exterior of aircraft is also accomplished in hangars. Although a few hangars have been constructed specifically for aircraft exterior painting, it is more common to control ignition sources and rely on the sheer volume of the hangar and natural ventilation to dissipate flammable vapors. Latex paints, which contain little, if any, solvent, are being used for aircraft interiors. Interior panel partitions and equipment can be painted in place rather than removed to a standard paint spray booth. Whenever using flammable paints inside an aircraft is necessary, special precautions for ventilation and control of ignition sources must be followed.

Aircraft Fueling

The potential exists for spills and fires each time an aircraft is fueled. Preventing such incidents is aided by reference to NFPA 407, a document accepted worldwide. The standard outlines specific precautions to control the extent of this hazard and gives recommendations on the design of aircraft fueling hose, aircraft fuel servicing tank vehicles, airport fixed fueling systems utilizing fuel hydrants, hydrant vehicles (to connect the fuel hydrant to the aircraft), as well as safety procedures to follow in the event of an accidental spill. A common type of spill is at the aircraft tank vent point, when an aircraft internal shutoff valve fails or closes slowly, allowing an overfill condition to develop.

Aircraft postincident defueling safety is important due to the possibility of injury to technicians, loss of salvage value, and potential environmental impact. Fuel system damage due to impact, inversion, or fire may result in a variety of aircraft balance, wiring, switch, plumbing, pump, tank, or other component irregularities that must be addressed by competent technicians. Only then can restoration of the incident sites be accomplished.

SUMMARY

Civil aircraft in the United States are subject to extensive federal regulation. Aeronautical engineers blend fire prevention and control safeguards with the use and mission of a particular aircraft. Fire detection and extinguishing equipment is normally required for aircraft areas possessing inherent fire hazards and ignition potentials, notably the power plant areas. The extinguishing agents most commonly used in aircraft are Halon 1301 and Halon 1211, although these chemicals are currently being phased out and replacement agents developed. Another key design element is emergency exit facilities, since postcrash fire exposure can be severe and safe evacuation time for the occupants is limited. Aircraft rescue and fire-fighting preplan-

ning for emergency landings is extremely important. Airport facilities, including hangars, terminal buildings, loading bridges, and walkways, all require appropriate safeguards. In addition, special procedures must be developed to ensure the safety of inspection and maintenance operations and aircraft fueling.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on the safeguards for aviation discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 70, *National Electrical Code®*
NFPA 72®, *National Fire Alarm Code®*
NFPA *101®*, *Life Safety Code®*
NFPA 402, *Guide for Aircraft Rescue and Fire Fighting Operations*
NFPA 403, *Standard for Aircraft Rescue and Fire-Fighting Services at Airports*
NFPA 405, *Standard for the Recurring Proficiency of Airport Fire Fighters*
NFPA 407, *Standard for Aircraft Fuel Servicing*
NFPA 408, *Standard for Aircraft Hand Portable Fire Extinguishers*
NFPA 409, *Standard on Aircraft Hangars*
NFPA 410, *Standard on Aircraft Maintenance*
NFPA 412, *Standard for Evaluating Aircraft Rescue and Fire-Fighting Foam Equipment*
NFPA 414, *Standard for Aircraft Rescue and Fire-Fighting Vehicles*
NFPA 415, *Standard on Airport Terminal Buildings, Fueling Ramp Drainage, and Loading Walkways*
NFPA 418, *Standard for Heliports*
NFPA 422, *Guide for Aircraft Accident/Incident Response Assessment*
NFPA 424, *Guide for Airport/Community Emergency Planning*
NFPA 1003, *Standard for Airport Fire Fighter Professional Qualifications*

Chapter 10

Marine Vessels

Randall Eberly

Chapter Contents

Pleasure and Small Commercial Boats
Pleasure and Small Commercial Boat Operations
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Marine Fire Protection Considerations
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Fire Prevention on Ships
Structural Fire Protection
Fire Protection Systems
Fire Detection Systems
Life Safety Considerations
Performance-Based Design
Emergency Response to Ship Fires
NFPA Marine Standards
Other Organizations Contributing to Marine Fire Safety

Key Terms

CNG marine fuel, commercial boat, International Convention for the Safety of Life at Sea (SOLAS), International Maritime Organization (IMO), LNG carrier, LP-gas marine fuel, marine engine, marine vessel, *Morro Castle* fire, performance-based design, pleasure craft, U.S. Coast Guard

According to industry statistics, fires and explosions continue to contribute to the fatalities and injuries experienced in marine vessel casualties. This chapter discusses marine fire hazards on small pleasure craft, small commercial boats, and commercial vessels, as well as the design, construction, and shipboard fire prevention systems normally installed to deal with them. It first covers pleasure and small commercial craft and then devotes the balance of the chapter to large commercial vessels.

Additional information about extinguishing systems suitable for use on vessels is found in the following chapters: Section 16, Chapter 3, "Automatic Sprinkler Systems"; Section 16, Chapter 9, "Water Spray Protection"; Section 17, Chapter 1, "Carbon Dioxide and Application Systems"; Section 17, Chapter 4, "Foam Extinguishing Agents and Systems"; Section 17, Chapter 5, "Fire Extinguisher Use and Maintenance"; and Section 17, Chapter 6, "Halon and Halon Replacement Agents and Systems."

PLEASURE AND SMALL COMMERCIAL BOATS

The latest boating safety statistics from the U.S. Coast Guard (USCG) indicate there are nearly 13 million pleasure and small commercial boats in the United States.[1] Statistics for the 5 year period from 2001 to 2005 show that annually there were approximately 5500 accidents, 700 fatalities, and 3800 injuries involving such boats. The fatality rate for this period is down an average of almost 50 per year (or about 6%) below that for the previous 5 years. The report indicates that approximately 225 fire and explosion accidents caused, on average, about 5 fatalities and 93 injuries per year. These accidents also resulted in a 5 year total property damage of almost $54 million.

The introduction of the 1960 edition of NFPA 302, *Fire Protection Standard for Pleasure and Commercial Motor Craft,* stated, "There are few other uses of petroleum fuels by the public in which the fire and explosion hazards parallel those possible in motor craft." In spite of technical developments since that time, the statement remains true today.

Overview

Boats and vessels of all sizes are constructed to create a form that is closed on the bottom and on all sides. This basic hull form is necessary for the boat to float. In the case of trains, aircraft, and all land vehicles (other than amphibious types), openings can be provided where needed to permit both liquid fuel leakage and heavier-than-air vapors to drain by gravity to the open atmosphere. Gasoline is commonly used for both propulsion engines and for onboard generators, and liquefied petroleum gas (LP-gas) is commonly used for cooking. Any leakage of these fuels and any gas or vapors released as a result of using those fuels is retained inside the hull. The two means of discharging gas and/or vapor "overboard" are (1) the slow process of natural ventilation, which requires airflow over the boat (from boat motion or wind speed), and (2) mechanical ventilation, which is used before starting any engine. Exhaust blowers tend to be effective in only the general area of the exhaust blower pickup. By comparison, automobiles and trucks are normally completely open on the bottom, providing effective ventilation in all areas of the fuel system. Seepage of liquid fuel and vapors can freely drain to the open atmosphere along the road from any point in the system.

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Aircraft, likewise, have drains in their engine nacelles and under their wings, allowing vapors to be dispelled to the atmosphere inflight or on the ground.

Since bottom drains are not possible in a boat, safety on boats depends on a carefully maintained, leak-free fuel system and on ventilation capable of discharging heavier-than-air fuel vapors overboard. When vapors are discharged overboard from lower levels, fresh air is automatically introduced into the hull's upper levels. The fresh air tends to dilute vapors in the upper level. An adequate removal and dilution process keeps the vapor and/or gas mixture below the lower explosive limit.

Consider that 1 oz (0.3 L) of gasoline fuel can create about 11 ft^3 (0.3 m^3) of explosive vapor. Gasoline vapor is approximately four times as heavy as air and tends to sink to the bottom of the bilge. Natural or mechanical ventilation cannot render a boat safe in any reasonable time if any liquid leakage occurs. An operating marine exhaust blower with a pickup duct placed 1 ft (0.3 m) above an open container of gasoline does not materially reduce the time required for the fuel to evaporate. Because an exhaust blower, or any ventilation, does not materially accelerate the fuel's vaporization rate, power ventilation should not be used when liquid fuel is known to be present. Ventilation, in addition to removing some flammable vapors in the duct intake areas, introduces fresh air that can bring an overly rich mixture into the explosive range. Whenever liquid fuel is present, no electrical circuit should be turned on or off. The battery should not be connected or disconnected. An arc can occur when making or breaking a circuit.

Boat Hulls

The hull of a pleasure boat or small commercial vessel must be arranged so that all compartments are as accessible as practicable for inspection and maintenance. Access must always be provided to sea cocks for emergency use. There must be two means of escape from all accommodation spaces in case fire in the engine space or the galley blocks one means of egress. Escape hatches must be unobstructed, readily accessible, and adequately sized and shaped for their designed purposes. Congestion of an engine compartment is unsafe; it may make sea cocks inaccessible and discourages adequate inspection and maintenance of engines and equipment. Adding internal combustion auxiliary machinery increases ventilation requirements.

Engine spaces (for propulsion engines, generators, and other auxiliary engines) must be separated from accommodation spaces by fore, aft, and transverse bulkheads and decks. The separation must serve as an effective fire barrier and minimize the escape of fire-extinguishing media that may be discharged into the space. Unsealed bulkheads with a ¼ in. (6.4 mm) annular space around items penetrating the bulkhead are considered adequate for ignition-protection purposes and for confining fire-extinguishing agents. However, these same bulkheads do not prevent carbon monoxide that may be present in the engine space from passing through the bulkhead to accommodation spaces.

Materials

Boat hulls, bulkheads, and superstructures are constructed of a wide variety of materials, including aluminum, steel, reinforced fiberglass laminates (FRP), and wood. In addition to solid fiberglass laminates, there are fiberglass laminates with balsa wood or plastic honeycomb core materials and wooden structures that have been covered with a fiberglass laminate on both sides, making a sandwich construction. The combustibility, flame spread rate, smoke production, and heat release characteristics of these various flammable materials have not been investigated and classified for use on boats. Thinner outer laminations of cored construction burn through relatively quickly, exposing core materials. Choice of material is determined by boat size, type, intended service, and cost. Horizontal deck surfaces, such as the deck above the engines, are very quickly involved in fire spread because of the low height and small volume of the compartments above which the decks are located. To minimize fire spread, fire-retardant resins and fire-retardant coatings suitable for marine service may be used. Because fire-retardant resins may reduce the structural strength of the laminate in which they are used, changes may be needed to compensate for strength differences. Upholstery and carpeting used in cockpits and accommodation spaces might have high flame spread ratings. The flame spread ratings of all materials and fire-retardant coatings used should be carefully considered. As in engine spaces, ceiling heights in accommodation spaces are low compared to those in buildings, and the height reduction effectively accelerates horizontal flame spread.

Ventilation

Ventilation is defined as the positive changing of air, by natural or mechanical means, within a compartment. Boat ventilation is primarily designed to remove heavier-than-air flammable vapors from the bottom of the compartment. When air is removed from the compartment, fresh air is simultaneously introduced at the upper level. The fresh air dilutes the flammable vapors in the upper levels where the intake ducts terminate.

Natural ventilation's effectiveness depends on outside air velocity and direction. Without wind or boat motion, there is virtually no natural ventilation other than that created by thermal air currents. The most important factors affecting air movement inside a hull are (1) the shape of the boat's superstructure (cabin or, in small open boats, the windshield), (2) the location of the boat cabin or windshield, and (3) the type and location of the ventilation fittings. With a bow wind, a boat cabin's shape makes it function like a ventilating clam shell, reducing pressure under the cabin. In runabouts, pressure is reduced behind the windshield. Reduced pressure results in an airflow to that area. For maximum ventilation efficiency, the engine space airflow that ventilating fittings create should be used to reinforce the airflow the cabin creates. Neither natural nor power ventilation effectively removes the hazard of vapors created by the presence of liquid gasoline because flammable vapors can be generated faster than they can be removed. Airflow created by the ventilating system only slightly affects the time necessary to evaporate liquid gasoline. Therefore, in the presence of liquid gasoline leakage, introducing fresh air by operating blowers may create, rather than eliminate, an explosive mixture. The boat's blowers should not be used.

Ventilation in an engine space plays an important role in controlling heat levels in that space. Ventilation for temperature

control depends on natural airflow into the engine space when the boat is under way and on the efficiency of external ventilating fittings and ducts. These fittings and ducts must be large enough to supply the air required for the engines. The compartment pressure depression must be measured with all engines operating at full power. Exhaust blowers are not used to control temperature or to supply air to the compartment. The engines operate with block temperatures of about 140 to 180°F (60 to 80°C). Because of anticipated high engine room temperatures, electrical conductors are derated in those spaces.

Of all cooking fuels, LP-gas creates the greatest ventilation problem because the gas is approximately 1.6 the density of air. It tends to sink and must be removed with positive ventilation.

Ventilation and Carbon Monoxide

Carbon monoxide (CO) is a flammable, gaseous poison having the same vapor density as that of air. Large quantities of CO are produced as a component of gasoline engine exhausts and, to a lesser degree, from diesel exhausts. Cooking appliances produce smaller quantities. This gas must be kept out of accommodation spaces to the greatest degree possible. Control of CO depends on awareness of the following basic factors:

1. The separation of the engine exhaust system discharge fittings from ventilation system fittings, scuppers, drains, and any other openings into the hull is vital to prevent the gas from reentering the boat. The direction and velocity of airflow over the boat must be considered. It affects the flow of air into and from all the ventilation intakes and exhausts.
2. It is not possible to prevent CO gas from reentering the boat under some operating conditions. One common condition, for instance, would be when a boat is operated at slow speed with a following wind. The operator must recognize and avoid these conditions.
3. Even engine room bulkheads that meet the ignition protection requirements of USCG regulation 33 CFR 183.410 do not effectively prevent CO gas from moving from the engine space into accommodation spaces.
4. A CO detector can help warn the boater of the presence of CO. CO is a flammable gas, but its greatest danger is that it combines with blood hemoglobin in the same manner as oxygen. CO is the leading cause of gas poisoning deaths in the United States.
5. In 2000, the USCG became aware of another dangerous condition involving CO on recreational boats. On boats with gasoline-powered generators and transom exhaust ports, lethal concentrations of CO have been documented and pose a threat to any swimmers using stern swimming platforms. The Coast Guard issued an advisory and the National Marine Manufacturers Association (NMMA) distributed a safety pamphlet on the hazard.

Lightning Protection

Lightning hits many boats every year. USCG statistics consistently show that people killed by lightning on boats are usually in small open motorboats, not sailboats. Even if a sailboat does not have a complete lightning system, its metallic mast inherently serves as the major down conductor. It tends to conduct the lightning past the occupants.

The probability of a lightning strike on a boat varies with geographic location and season. Lightning protection can be provided on a boat that has a conductive mast with a conductivity equal to a No. 4 AWG conductor and enough height that an imaginary line drawn at a 45 degree angle from its tip does not intersect any part of the boat. A pointed lightning rod should be installed at the tip. The mast's base must be connected vertically and as directly as possible to an external grounding plate or grounding strip, located below the lightning mast. An external rectangular (1 ft^2 [0.09 m^2] or larger) grounding plate or an external horizontal grounding strip of the same approximate area may be used, running fore and aft from below the lightning mast to a position aft below the engine(s). Large metallic masses, such as metallic guard rails, engines, and tanks near the lightning ground conductor, should be connected to the grounding strip to prevent side flashes. If the mast being used is stepped on deck, the connection between the mast and the external grounding plate or strip should be made with a No. 4 AWG conductor or two parallel No. 6 conductors routed on both sides of an opening. The normal horizontal electrical system bonding conductor in a boat may be connected to a lightning conductor system, but should not be relied on as a lightning conductor. To be effective, lightning conductors must provide an essentially vertical path to the ground plate or strip.

Figures 21.10.1 through 21.10.4 show normal boat lightning protection systems. Spiral wrapped radio transmitter antennas will not function as lightning masts, but steel antennas may help, provided the antennas' coils are bypassed with a lightning arrester. If an external grounding strip is used, as illustrated in Figure 21.10.2, the sharp edges of the grounding strip should not be rounded. In both sailing auxiliaries and cruising power boats, the external grounding strip most effectively connects items in the boat to the ground without long horizontal conductors inside the boat. The mast and bow rails can be connected to the forward end, and the engine and back stay (sailboats) to the aft end of the strip. In larger boats it is difficult to avoid installing a number of horizontal lightning conductors to connect large metal masses to the system. Instead, an equalization bus may be installed inside the boat parallel to the external lightning grounding strip. The internal equalization bus and external grounding strip are interconnected at the forward and aft ends and must be connected to the lightning ground system. They must never be connected so that they become part of the main down conductor. If a seacock or through-hull fitting carries the full lightning current, any water in the seacock turns to steam instantaneously, breaking the fittings and possibly sinking the boat.

Occasionally, a sailboat's aluminum mast hits an overhead power line, and the question arises whether masts or sections of masts should be made of a nonconductive material to avoid such accidents. The answer is that a boat's lightning system should be maintained.

Engines

Liquid-Cooled Engine. Liquid-cooled marine gasoline and diesel engines may be cooled directly by seawater or with fresh water using a raw water-cooled heat exchanger. Liquid-cooled

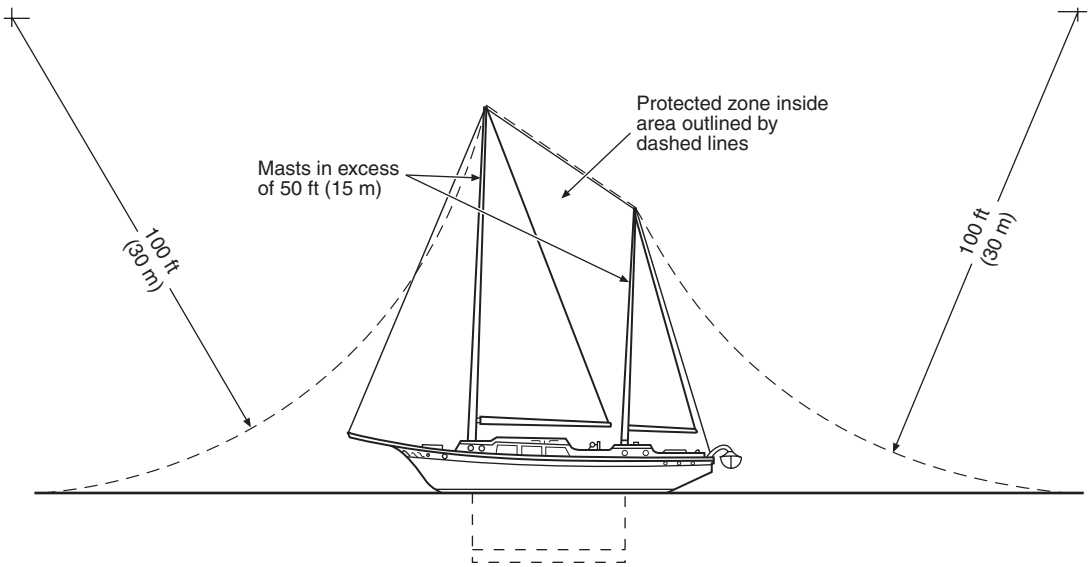


FIGURE 21.10.1 Proper Lightning Protection for a Boat with Masts More Than 50 ft (15 m) Above the Water. Protection is based on a lightning striking distance of 100 ft (30 m).

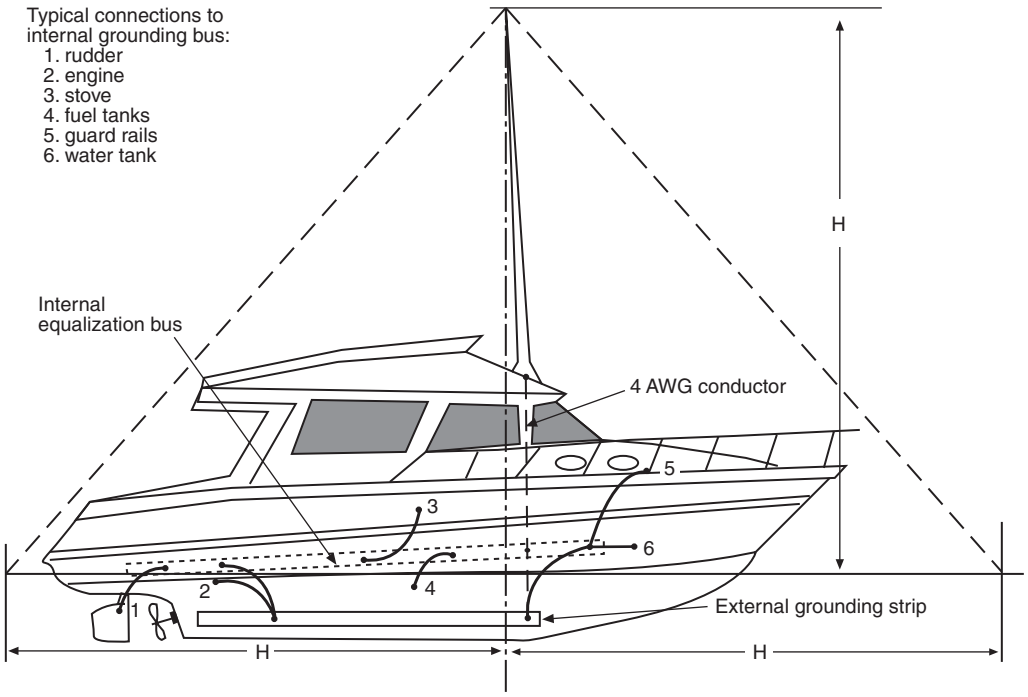


FIGURE 21.10.2 Boat with Mast Not More Than 50 ft (15 m) Connected to External Ground Strip, with Optional Equalization Bus

engines use water-jacketed blocks, heads, and exhaust manifolds. A self-priming, engine-driven pump circulates the cooling water. In a raw water-cooled engine, water circulates through the engine and then discharges into the exhaust pipe to create a raw water-cooled exhaust. The water discharges into the exhaust pipe through a water-jacketed riser at the engine. The riser's design prevents water from backing up into the engine through the exhaust manifold. Fresh water-cooled engines using a heat exchanger require two separate water pumps. One pump recirculates the fresh cooling water through the engine, and the second circulates water through the heat exchanger and provides raw water for the water-cooled exhaust. Fresh water-cooled

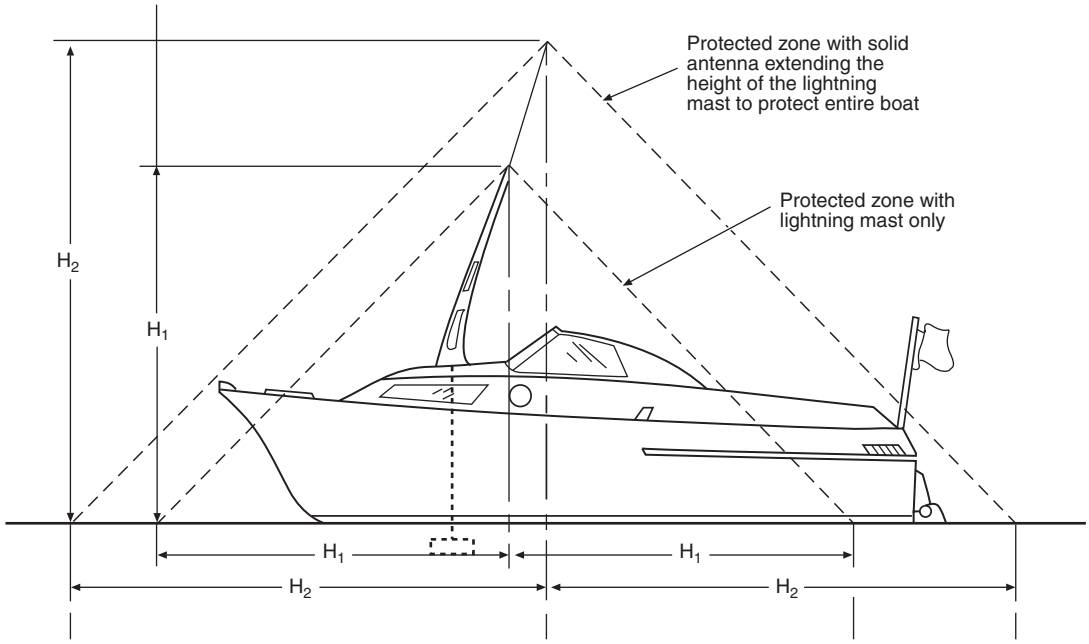


FIGURE 21.10.3 Proper Lightning Protection for a Small Sailboat with a Mast Not More Than 50 ft (15 m) Above the Water

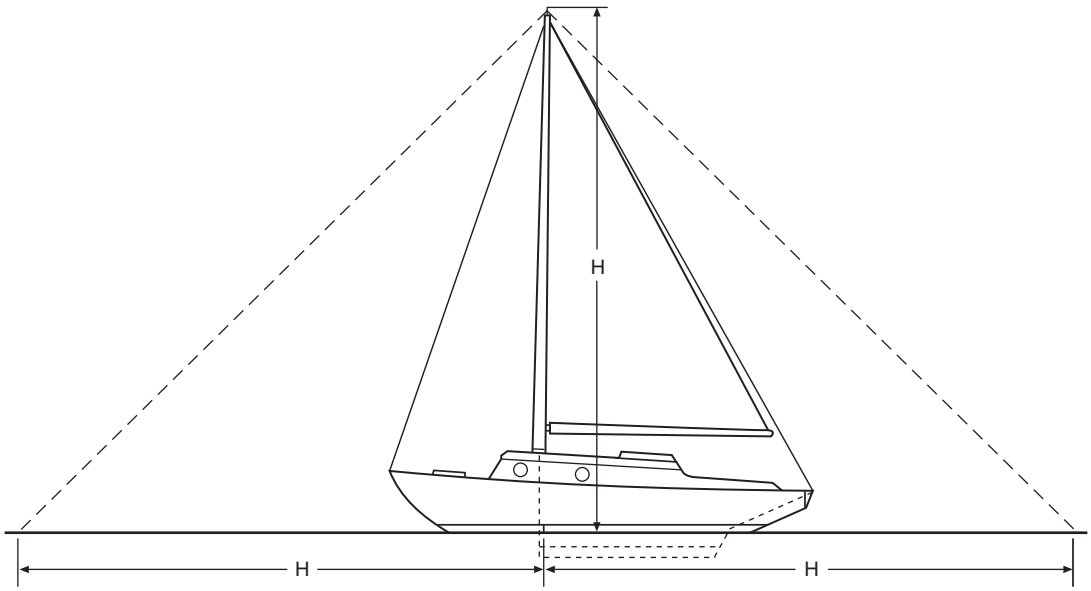


FIGURE 21.10.4 Proper Lightning Protection for a Boat with a Mast Not More Than 50 ft (15 m) Above the Water

engines can operate efficiently at approximately 180°F (82°C), whereas raw water-cooled engines, using seawater, must operate less efficiently at 140°F (60°C). The lower temperature prevents excessive salt precipitation in the block, manifold, and head of the engine. Raw water-cooled engines and engines using a heat exchanger can overheat if the pump fails or the water intake becomes blocked. Means to indicate loss of engine cooling water must be provided at all helm positions for propulsion engines. Nonpropulsion engines must automatically shut down with the loss of lubricating oil pressure, excessive engine temperature, and excess heat in the exhaust system.

Air-cooled engines are not recommended. However, if they are used in an enclosed space, a separate air duct must be provided for effective cooling. Because these ducts are large, they

must be located to minimize the intake of excessive seawater, which could affect boat stability. A device must be provided to warn of excessive temperatures.

Fuel Injection. Technical advancement in automotive and marine engines has caused rapid replacement of carburetion with fuel injection. The more efficient fuel injection systems eliminate boilover and float-leakage problems of carburetors but are still subject to rap or lock. However, injection systems with return fuel lines present a major hazard not encountered in carburetor engines. Fuel injection gasoline engines and diesel engines may use a return fuel line that is warm and under pressure. In comparison, fuel in the distribution line from the fuel tank to the engine operates at reduced pressure, minimizing the hazard. When the engine is not running and the distribution line is at a reduced pressure, a pinhole may not leak any fuel at all. When the engine is running, a pinhole leak in the return line will tend to spray fuel, creating an immediate hazard. Consider that the return line can totally fail and not affect engine operation. The operator may be unaware of fuel spilling into the bilge unless there is an operating vapor detector. The fuel line requirements remain the same for distribution and return lines.

Backfire flame arresters are still required to meet the same requirements, but they no longer require a USCG approval number. Diaphragm fuel pumps must be designed and installed to prevent the release of fuel to the bilge in case of diaphragm failure. All electrical equipment in the engine space must be ignition protected.

Ignition Protection

All ac and dc electrical equipment in a gasoline engine space and any space with fuel line fittings must be ignition protected. Ignition-protected equipment has the same performance objective as hazardous location (explosionproof) equipment on shore and on commercial vessels. However, the requirements for ignition protection are less stringent and do not require hazardous location wiring. Accident statistics indicate that ignition protection has effectively reduced explosions in boats. Unfortunately, investigations of fire and explosion accidents have revealed that ignition-protected equipment is frequently replaced with non-ignition-protected equipment, eliminating the protection originally provided.

To eliminate the need for ignition-protected equipment in accommodation spaces, a bulkhead must separate the engine space from accommodation spaces. The bulkhead must be watertight for 12 in. (30.5 cm) or one-third the bulkhead height, whichever is less. Above that level the annular space around anything passing through the bulkhead (wires, cables, ducts, etc.) must not exceed ¼ in. (6.3 mm).

Fuel Systems

In aircraft and land vehicles, gravity drains liquid leakage, thereby preventing accumulation; this is not possible in a boat. Because both liquid fuel leakage and fuel vapors accumulate in a boat, fuel system components' design must resist vibration and shock failure, corrosion, and chemical deterioration. The system must be designed, installed, and maintained so as to be liquidtight and vaportight to the hull interior at all times. All fuel system parts should be capable of withstanding exposure to free-burning gasoline for 2.5 minutes without fuel leakage. Hose used instead of copper tubing must be USCG Type A1 or A2 fire-resistant hose. (Fire-resistant fuel distribution lines, however, are not required if less than 5 oz [150 mL] of fuel will leak when the distribution line is cut at the lowest point.) When fire resistance is not required, a USCG Type B1 or B2 hose can be used. Metallic fuel fill fittings must be electrically bonded to the engine negative terminal to dissipate static electrical charges. Fill hoses must be double-clamped.

Diesel fuel systems and gasoline fuel injection systems require the installation of efficient fuel filters and water separators to prevent dirt and water from reaching the fuel injector pump. Diesel and some gasoline fuel injector systems have pressurized return lines to the tank that must meet the same requirements as the fuel distribution line to the engine. Heated return fuel will gradually raise the temperature of the fuel in the tank. At normal temperatures, diesel fuel does not vaporize and create an explosive fuel air mixture, but diesel fuel has a greater tendency to accumulate in the bilges and create a fire hazard. Pressurized gasoline lines create an immediate hazard at any leakage level.

Appliances

Open flame appliances must be designed specifically for marine use and be installed to minimize personal and physical hazards. They must also be designed for attended use. The manufacturer must furnish printed instructions for their proper installation, operation, and maintenance. Portable devices and any device that cannot be secured in position when in use or stored are not permitted. A durable and permanently legible instruction sign describing safe operation and maintenance must be provided. The sign should be installed on or adjacent to the appliance where it can be quickly read. Air consumption and exhaust product venting from galley stoves and other appliances must be considered in the design and layout of compartments where they are installed. Lack of permanently open vents to supply air to the appliances can result in oxygen depletion in the compartment. Exposed materials around galley stoves and other heat-producing appliances must have a flame spread index (rating) of less than 75. Fabrics must not be used within 39 in. (1 m) of a galley stove.

Pilot lights and other automatic igniters are prohibited unless they are used in sealed combustion chamber type devices with outside air supply and exhaust discharge. Gas-fueled appliances must be equipped with flame failure devices to prevent gas flow if the flame is extinguished. Unattended devices, such as water heaters, refrigerators, and cabin heaters, cannot have automatic ignition unless they are of the sealed combustion chamber type, with the internal flame completely separated from accommodation spaces. Open flame water heaters and refrigerators are not permitted because they could be left on during fueling and because undetected leaks could occur in the fuel system. Gasoline is not permitted for use as a galley fuel.

Coal, charcoal, and wood-burning stoves must be installed on a hollow tile base or mounted on a noncombustible base with a clearance of 5 in. (13 cm) between the stove bottom and any

deck. The deck must be sheathed with a noncombustible material. The sides and back of a stove must have a clearance of not less than 9 in. (23 cm) and must have a flame spread index of not more than 75.

Liquefied Petroleum Gas and Compressed Natural Gas Systems

The properties of both liquefied petroleum gas (LP-gas) and compressed natural gas (CNG) must be understood to ensure their safe use. Both are frequently used in the galley for cooking and are popular because they do not require priming like pressure alcohol stoves. At ambient temperatures, LP-gas can be liquefied at well under 250 psig (1724 kPa), the rated pressure of an LP-gas cylinder. CNG does not liquefy at ambient temperatures and is stored in cylinders under a pressure of about 2000 psig (13,790 kPa). LP-gas is a two-phase (liquid/vapor) fuel with a higher calorific value than CNG. LP-gas, when released as a gas, has approximately 1.6 times the density of air, and tends to sink to a boat's bilges. CNG is released as a lighter-than-air gas and tends to collect at the top of a compartment if not vented. When confined to a space, the gases will fill that space in a short time through diffusion. Diffusion and convection cause the gases to pass through and over bulkheads in all directions. An odorant added to both gases facilitates detection. A pressure regulator lowers the stored pressure of both gases to a system working pressure. LP-gas, normally stored at a pressure of 150 psig (1034.35 kPa) or less, is delivered to the appliance at approximately 14 in. (36 cm) water column, or about 0.735 psig (5.0 kPa gauge). CNG is reduced to about 6 in. (15 cm) water column, or about 0.22 psig (1.5 kPa gauge) at the appliance.

NFPA 302 permits LP-gas and CNG containers and regulators to be located on an open deck or on a cabin top in a housing, open at the top and bottom so escaping gas does not reenter the hull or accumulate in a cockpit or any enclosed space. The housing must protect the valves and the regulator assembly from mechanical damage. If not located on an upper deck or cabin top, the LP-gas containers and regulator assemblies must be located in a vaportight locker. The locker must be located above the waterline, be vaportight to the hull interior, be provided with a latched gasketed cover, and be vented overboard. It must be located so that when the cover is open, escaping vapor does not flow to the bilges, machinery spaces, accommodation spaces, or other enclosed spaces. Normal locations are along the side of the cabin in a molded-in locker or in an open cockpit in a vaportight locker. LP-gas lockers are vented with a ½ in. (13 mm) line led overboard with traps. The locker vent discharge must be separated from any hull opening and from any exhaust discharge fittings. Because CNG is lighter than air, CNG lockers must be vented with a ½ in. (13 mm) vent to the open atmosphere at a level above the cylinders and regulator assembly. CNG tanks, like LP-gas tanks, may be installed on an open deck, in a vaportight locker with an overboard vent or in a compartment that has no openings to an engine space above the level of the regulator. Engine room bulkheads that meet the ignition-protection requirements are not vaportight and therefore might communicate with other spaces.

Low-pressure distribution lines from the system regulator assembly to an appliance may be either copper tubing or hose. Copper tubing can be used with LP-gas without a problem, but copper tubing used with CNG must be internally tinned. LP-gas hose with permanently attached fittings must meet the requirements of UL Standard 21. CNG hose must meet the requirements of NFPA 52, *Vehicular Fuel Systems Code.* Distribution lines must be installed in continuous lengths from the regulator assembly to the appliance. The only exception is the installation of a flexible hose connection between copper tubing or copper piping and a gimbaled appliance.

Standards prohibit the use of pilot lights or other automatic ignition forms on gas-consuming appliances, but do permit a flame control for an oven in use. The flame control must be off when the oven control is off. All gas-fueled appliances must have a flame failure control to prevent gas flow if the flame is extinguished. Stoves with gas containers having less than 8 oz (0.24 L) of fuel are exempt from this requirement.

LP-gas or CNG systems installed in accordance with NFPA 302 can be simply, quickly, and positively checked for leakage in about 10 minutes. The method, which requires a pressure gauge, should be used frequently. The standard leakage check should be done after the system has been serviced, after the containers have been changed, and after any storm or grounding that might affect the system. NFPA 302 recommends that the check be done at the start of any cruise or voyage during which the system will or may be used. The standard specifies the following procedure:

- With the appliance valves closed and all other valves open, note the pressure on the gauge.
- Close the container valve.
- Observe the pressure to ensure that it remains constant for at least 10 minutes.
- If pressure drops, locate leakage by applying a soapy water solution at all connections.
- Repeat test for each container in multicontainer systems.
- *Never use flame to check for leaks.*
- *Never use soap containing ammonia.*

Electrical Systems Under 50 V

A boat's low-voltage dc system is intended to be a two-wire system with insulated conductors running parallel to each other to and from the power source, to each item of electrical equipment. The two-wire system minimizes the creation of magnetic fields that can affect the compass and other magnetically sensitive equipment and also minimizes the chances for stray dc current flow between metallic underwater components. Negative ground has been adopted as standard for dc systems, and the engine negative terminal is established as the single point for the dc system ground. When stray dc current flows between any two metallic components in contact with an electrolyte, such as seawater, the more positive (anodic) metal suffers accelerated corrosion. The more negative (cathodic) metal tends to be protected. Making the engine's lower unit or propeller and shaft purposely more negative or cathodic protects them and any other metallic objects connected to the same ground from accelerated corrosion due to stray currents. Although a true two-wire system

would best serve the boating industry, most marine engines use converted automotive single-wire components. The automotive industry uses a common chassis ground return system so that all engine-mounted components have a negative conductor grounded to the frame. Because of the engine, the two-wire dc system on a boat is something of a compromise: mostly a two-wire system, it remains a single-wire system at and near the engine. The single-wire system has been extended off the engine by permitting an accessory negative bus for accessories near the engine. Accessories connected to a panelboard may have their negative conductors connected to the accessory bus near the engine, instead of the panelboard negative terminal strip. Whenever the system becomes a single-wire system and the feed and return conductors are not run in a pair, a magnetic loop forms. Standards do permit a completely ungrounded system, provided the engine's electrical components are all ungrounded.

Even though the engine's system is single wire, metal hulls and boat bonding systems must never be used as ground return paths. The boat bonding system—used to connect the non-current-carrying metal housing of dc equipment to the engine negative terminal—serves three functions:

1. Because the non-current-carrying parts of dc electrical equipment are connected to the engine negative terminal, stray current leaking from this equipment returns to the engine negative terminal (and battery negative) on the bonding conductor inside the hull. Electrical flow inside the hull minimizes current flow outside the hull between metallic appendages that would result in stray current corrosion of the equipment. A stray current leak of less than an ampere through a 1 in. (2.5 cm) through-hull fitting can destroy the fitting and sink the boat in 3 days.
2. A boat bonding system may be interconnected with and become part of the lightning protection system. When used in the lightning protection system to interconnect large metallic objects, the conductor size must be at least a No. 6 AWG conductor.
3. The bonding system conductor connects underwater metallic hardware to a galvanic anode (zinc) for galvanic protection.

If a boat has two or more propulsion engines and more than one battery bank, its engine blocks must be interconnected with two conductors capable of carrying the cranking current of the largest engine. The conductors prevent heavy damaging stray current corrosion due to current flow between propellers and shafts or outdrives when cranking one engine from the battery of another. Positive interconnection of all engines also prevents a current path through metallic fuel lines and control cables.

All dc conductors in the boat, except cranking motor conductors, require overcurrent protection at the power source for any circuit, generally within 7 in. (17.8 cm) of the source. USCG regulations and NFPA 302 permit a wire that is directly attached to the battery to be 72 in. (1.8 m) long without overcurrent protection. Using this exception is not recommended. NFPA 302 specifically requires the underground battery charger leads to be protected at the battery point of connection to the dc system. Under the regulations and NFPA 302, it is also possible to extend an unprotected sheathed wire's length from 7 in. (17.8 cm) to 40 in. (101.6 cm). The exception is used between the engine cranking motor solenoid hot terminal and the engine circuit breaker to position the circuit breaker high on the engine.

Boats have a special problem because many dc motors used on boats have no internal thermal protectors and by design cannot have the equivalent impedance protection. Lacking internal protection against overload, branch-circuit breakers or fuses must protect these motor-operated devices (pumps, blowers, etc.) against a "locked-rotor" condition. A locked-rotor condition exists if the pump becomes jammed and cannot turn. The motor manufacturer cannot easily specify the branch-overcurrent protection because it depends on the total wire length in that branch circuit.

Electrical Systems over 50 V

Three different sources may power the 120/240 V ac electrical system on a boat: (1) shore power, (2) an onboard ac generator, or (3) an onboard dc to ac inverter. Using shore power invites a special problem because the ac grounded neutral conductor is grounded to the earth on shore, but must never be grounded on the boat. When powered from shore, ac leakage currents return to the earth ground on shore. In contrast, both the onboard ac generators and the onboard inverters are grounded on the boat so that all leakage current remains on the boat. When two or all three sources of ac power are available, a switching arrangement must be provided to prevent any two sources of power from feeding the same circuit at the same time. This switch must disconnect one ac power source before connecting the circuits to another power source.

As on shore, under NFPA 70, *National Electrical Code®*, a green grounding-wire system keeps the non-current-carrying housings of ac appliances and ac equipment at ground potential to prevent electrical shock. When ac current is from an ac generator or an inverter on the boat, the green grounding-wire connects to the generator or inverter ground on the boat. With shore power, the green ac grounding-wire to the boat engine's negative terminal connects the underwater hardware of the boat (propellers, shaft, outdrivers, etc.) to other boats or any grounded metal on shore. Accordingly, aluminum- and steel-hulled boats and boats with aluminum outboard engines or aluminum stern drives suffer accelerated corrosion when connected to more noble metals (cathodic materials) on other boats or the dock. The interconnection with other boats or the dock can result in severe continuous galvanic corrosion of the anodic metals. This interboat corrosion could be stopped by not connecting the green grounding-wire to the boat engines, but any ac leakage on the boat can charge the surrounding water, electrocuting any swimmer near the boat. The solution requires the installation of a marine "galvanic isolator" or the installation of an isolation transformer in accordance with NFPA 302. The galvanic isolator is a device installed in series with the green grounding-wire on the boat. The device blocks the flow of dc galvanic currents while permitting the flow of ac current in the grounding conductor. The galvanic isolator must be sized to carry the system's full current because if it fails, the green grounding-wire stops working.

Fire Extinguishers

Testing laboratories normally evaluate the fire extinguishment potentials of portable fire extinguishers. The USCG also classifies portable fire extinguishers based on the Underwriters Laboratories Inc. classification of fires, but uses a different method to indicate extinguishment potential. Table 21.10.1 lists these designations.

PLEASURE AND SMALL COMMERCIAL BOAT OPERATIONS

General Maintenance

Operation and maintenance of pleasure and small commercial boats rely on general good housekeeping practices. Safety requires periodic inspection and maintenance of all equipment. When checks are conducted, unprotected electric lights should not be taken into areas of possible vapor accumulation from gasoline or liquids used for cleaning. The following, and other inspections and tests, are needed:

1. *Rags.* Clean rags should be kept in covered metal containers. Dirty waste and rags should be kept in separate covered metal containers. These should be disposed of each time the boat is docked.
2. *Fuel system.* The entire fuel system, from the fuel tank to the engine, must be visually examined periodically. The fuel tank should be checked to determine whether it shows any evidence of corrosion or leakage. Once a year the entire system should be pressure checked at 3 psi (20.7 kPa). The fuel hoses should be checked to determine that the connections (fittings and clamps, etc.) are tight and that hoses show no signs of deteriorating or cracking. The fuel pump should be checked to determine that it is a marine type, with a hose back to the intake manifold or carburetor in case of diaphragm failure. Fuel filters should be checked to determine that they are clean and not leaking. Used gaskets should be replaced with appropriate new ones whenever a fuel filter is cleaned.
3. *Detectors.* All detectors must be checked to determine whether they are working.
4. *Exhaust blowers.* Ventilating ducts should be checked to determine that they are installed without excessive bends and are neither kinked nor torn. Overcurrent protection should be checked to determine that it includes locked-rotor protection.
5. *Ignition protection.* All electrical equipment in the engine space and any space with fuel line fittings should be checked to determine that it is ignition protected. Replacement with automotive parts eliminates such protection.
6. *Painting.* When interior areas are repainted, fire-retardant paints should be used.

Proper maintenance and sensible fuel system operation, used together with ignition-protected electrical equipment, are probably a boat owner's most important fire prevention duties.

Fueling

Utmost care must be exercised during fueling operations. The following are general guidelines to be observed during fueling operations:

1. Fueling should not be undertaken at night, except under well-lighted conditions.
2. Smoking must be forbidden on board the boat and in the area of the fuel pumps and hose.

TABLE 21.10.1 Number and Distribution of Fire Extinguishers

Boat Type	*No. of Extinguishers*	*Minimum ANSI/UL Rating*[a,b]	*Minimum USCG Rating*[c]	*Location*
Open boats under 16 ft (4.8 m) with fiberglass or metal hulls and a light load of flammable Class A materials	1	5 B:C	B-1	Steering position
Open boats under 16 ft (4.8 m)	1	1A: 10B:C	B-1	Steering position
Boats 16 ft (4.8 m) up to, but not including, 26 ft (8 m)	2	1A: 10B:C	B-1	Steering position and galley, when on board, or cockpit
Open boats 16 ft (4.8 m) up to, but not including, 26 ft (8 m)	2	1A: 10B:C	B-1	Steering position and galley or cockpit
Boats 26 ft (8 m) up to, but not including, 40 ft (12 m)	3	1A: 10B:C	B-1	Outside engine compartment, steering position, and near galley or passenger cockpit
Boats 40 ft (12 m) up to, but not including, 65 ft (20 m)	4	1A: 10B:C	B-1	Outside engine compartment, steering position, crew quarters, and galley, when on board, or cockpit

[a]If a discharge port is installed, a USCG Type B-1 portable fire extinguisher might not be adequate.
[b]Extinguishers intended for machinery space protection are not required to have a Class A rating.
[c]Boats under 26 ft (8 m) in length without enclosed accommodation spaces or enclosed galleys shall be permitted to be equipped with a bucket with attached lanyard in lieu of Class A-rated portable fire extinguishers.

3. Before opening fuel tanks,
   a. Shut down all engines, motors, and fans
   b. Extinguish all open flames
   c. Close all ports, windows, doors, and hatches
   d. Determine the quantity of fuel to be taken aboard before fueling operations start
   e. Point out to the fuel attendant the correct deck fuel fitting for each tank
4. The fuel delivery nozzle must be in contact with the fuel fill deck fitting before fuel delivery begins. This contact should be maintained continuously until flow has stopped. Static discharge is a serious hazard if this rule is not followed. The fuel-fill fitting must be of a material that conducts electricity and must be electrically connected to the engine's negative terminal to ground the static charge.
5. Fuel tanks should never be completely filled because fuel expands. A minimum of 5 percent tank space must be allowed for expansion.
6. After fuel flow stops,
   a. Tightly secure the fill fitting cap
   b. Completely wipe up spillage
   c. Ventilate all spaces and check for gasoline vapors before starting any engine or operating any appliance

Storage Between Voyages

Before storing a boat, even for a short time period, several precautionary actions should be taken. The entire vessel should be thoroughly inspected. All combustible trash and rags should be removed, as well as any paint or other flammable liquids. Bilges should be inspected and pumped dry. All underwater hardware, including propellers, outdrives, rudders, through-hull fittings, and the hull should be checked and necessary repairs made. All seacocks should be checked and operated to make sure they can operate in an emergency. Liquid level of batteries and specific gravity of battery cells should be checked. If possible, lockers and bilge hatches should be secured in a partially open position to ventilate the spaces.

COMMERCIAL VESSELS

Code of Federal Regulations (CFR)

Ships and offshore marine structures present a wide range of potential fire risks that could threaten the safety of the public and our environment. The U.S. Congress has assigned the task of developing and instituting marine fire protection regulations to the United States Coast Guard, through the various laws governing marine inspection in the United States Code (USC). These laws delegate the authority to enforce all applicable federal laws on the high seas and on the waters subject to the jurisdiction of the United States for the safety of life and property. They are enforced through the application of detailed technical regulations for fire-fighting equipment and other precautionary measures guarding against fire, including the number, type, size, capacity, details of construction, methods of operation, stowage, maintenance, and drills and exercises necessary to assure proper functioning of the fire protection measures. The fire protection regulations are listed in the *Code of Federal Regulations* (CFR) under Title 46, *Shipping*. The regulations are further broken down into the various parts of Title 46, which address the different types of vessels and the types of fire hazards related to their normal operation. The transportation of hazardous materials on ships, or dangerous goods as they are called internationally, is regulated by the U.S. Department of Transportation (DOT) rules in Title 49 of the CFR Parts 171–180, *Hazardous Materials Regulations,* and by the Coast Guard at Title 46, Parts 147–148, *Dangerous Cargoes,* and Parts 150–154, *Certain Bulk Dangerous Cargoes.*

The regulations covering U.S. flag commercial vessels are contained in the following parts of the *Code of Federal Regulations:*

46 CFR Parts 24–28, *Uninspected Vessels*
46 CFR Parts 30–40, *Tank Vessels*
46 CFR Parts 70–80, *Passenger Vessels*
46 CFR Parts 90–105, *Cargo and Miscellaneous Vessels*
46 CFR Parts 107–109, *Mobile Offshore Drilling Units*
46 CFR Parts 114–122, *Small Passenger Vessels Carrying More Than 150 Passengers or with Overnight Accommodations for More Than 49 Passengers*
46 CFR Parts 125–134, *Offshore Supply Vessels*
46 CFR Parts 166–169, *Nautical Schools*
46 CFR Parts 175–185, *Small Passenger Vessels (under 100 gross tons)*
46 CFR Parts 188–196, *Oceanographic Research Vessels*

International Ship Fire Safety Requirements

The United States is a signatory nation to the International Convention for the Safety of Life at Sea treaty (SOLAS), which establishes regulations for fire protection on vessels that engage in international voyages to countries outside of the United States. The SOLAS convention is maintained by the International Maritime Organization (IMO), a specialized agency of the United Nations headquartered in London, England. IMO is the repository of all treaties dealing with commercial vessel safety, and has developed mandatory requirements as well as recommended codes and standards of practice relating to specialized maritime subjects. Under the terms of the SOLAS convention, all signatory countries are obligated to accept a SOLAS safety certificate, issued by another member country, as evidence of a ship's compliance with the convention. The use of mutually accepted safety certificates ensures a minimum level of safety and permits ships to operate freely between nations. The SOLAS regulations are sometimes written in very general terms to allow the use of equipment that is commonly accepted and approved by one member state, but which may be unfamiliar in other geographic locations. In some cases, SOLAS wording is intentionally vague, resulting from an inability to reach international agreement on more precise terms. As a result, there may be different interpretations between the member states regarding the SOLAS regulations. The convention has provisions permitting the countries where ships call to perform additional inspections, if needed, to ensure compliance with SOLAS. These inspections are called port state inspec-

tions, whereas those conducted by the ship's country of registry are called flag state inspections.

The Coast Guard regulations contained in the CFR are consistent with many of the SOLAS requirements, except that the CFR lifesaving and fire protection equipment and material requirements are much more detailed. Historically, SOLAS did not contain any type approval or testing requirements for the required fire protection measures, relying instead on nationally accepted procedures of the flag states. In 1998, a new Fire Test Procedures (FTP) Code was adopted that lists mandatory testing procedures for structural fire protection measures.

U.S. flag ships that engage only in domestic routes do not need to comply with the SOLAS requirements. Vessels that engage in international trade, however, must comply with SOLAS.

The SOLAS convention currently in effect is SOLAS 1974, as amended. This convention became effective for ships built after May 25, 1980, and has been amended several times since it was accepted. The large number of unrelated amendments and interpretations to SOLAS following its adoption made the convention difficult to apply. The International Maritime Organization, therefore, decided to perform a comprehensive review of the fire protection regulations in SOLAS and to update and reorganize the document to make it more user friendly. This updated version was adopted in the 2000 SOLAS amendments.

The update included several key changes. It incorporated the existing amendments and interpretations directly into the text of the Convention and included a new performance-based option. It was also decided that the fire extinguishing and fire detection system design and installation requirements in SOLAS should be removed from the convention and placed into a new mandatory standard called the International Code for Fire Safety Systems (FSS Code). Finally, new requirements were introduced for the carriage of emergency escape breathing devices (EEBDs), supplemental local application fire-fighting systems for the protection of high-hazard areas within machinery spaces, and a new Part E which contains requirements for the operational readiness of fire protection systems.

The performance-based option required changes to the Chapter II-2 regulations to include defined fire safety objectives and functional requirements within each regulation. In addition, a new regulation II-2/17 was developed to provide a methodology for approving alternate design and arrangements. Thus, owner/operators have the option of specifying ships that comply with either the prescriptive criteria listed in SOLAS, or specifying ships with performance-based designs that are demonstrated to achieve the stated fire safety objectives.

United States Domestic Ship Fire Safety Requirements

The fire safety regulations for vessels in domestic U.S. service are based on the principle of passive fire safety. Noncombustible fire boundaries and limited use of combustible materials are intended to limit fires to their space of origin. The different vessel regulations in the CFR are intended to provide a consistent level of fire protection safety to the many types of vessels common to the maritime industry. Ships may travel on different routes, have more passengers, engage in operations with varying levels of risk, or carry cargoes of varying fire hazard. The regulations, therefore, look at each class of ships separately, considering key fire protection and life safety risk factors. The regulations are based on many years of operating experience, compliance with international requirements, and lessons learned from casualty investigations.

The following service-related factors have been considered in the development of the vessel regulations:

- Relative size of the vessel
- Quantity, stowage arrangement, fire risk, and packaging of the cargoes carried
- Level of protection offered by the vessel's hull in collisions and groundings
- Number of passengers carried
- Length of a typical voyage
- Ship's means of propulsion and fuel type
- Route the ship will follow, as affected by weather issues and day or night operations

The following general vessel descriptions are provided to clarify the application of the regulations.

Uninspected Vessels. Uninspected vessels are generally smaller ships, such as tugboats, charter fishing boats, motorboats, or recreational boats (Figure 21.10.5). The fire risks are limited because the vessels carry limited cargoes, are limited in size, and carry only a small number of passengers. Vessels that are under 100 gross tons and carry less than six passengers for hire fit into this category. 46 CFR 28 contains regulations that specifically apply to commercial fishing, fish processing, and fish tender vessels. These vessels not only catch fish but may also include large refrigerated storage holds and processing facilities to cut, package, and flash-freeze the fish while at sea.

Tank Vessels. Tank vessels are vessels and barges that are designed to carry bulk liquid cargoes, mainly liquid petroleum products, that are usually flammable or combustible in nature. Because of the quantity and hazard of the cargoes carried, this class of vessels is subject to significant fire safety requirements, both in their design and operation. Tank vessels also include ships that carry hazardous chemicals and pressurized

FIGURE 21.10.5 Uninspected Tugboat Towing an Open Hopper Type Barge

or liquefied gases. Liquefied natural gas (LNG) or liquefied propane gas (LP-gas) carriers are included in this category.

Passenger Vessels. Passenger vessels are vessels that carry passengers for hire. Passengers for hire are defined as passengers who have either paid fares or contributed other consideration, as a condition of carriage on the vessel, whether directly or indirectly flowing to the owner, charterer, operator, agent, or any other person having an interest in the vessel. Passenger vessels may be further divided into five distinct classes:

1. *Uninspected passenger vessels less than 100 gross tons carrying 6 or fewer passengers.* Charter sailing vessels, charter fishing boats, and small water taxis are in this category.
2. *Uninspected passenger vessels more than 100 gross tons carrying 12 or fewer passengers.* Large luxury charter yachts are the best-known representatives of this class of vessels.
3. *Small passenger vessels less than 100 gross tons carrying more than 6 passengers.* Examples of this class include inflatable dive boats, passenger submarines, small ferries, dinner and tour boats, charter fishing headboats, and various types of sailing vessels. These vessels are also called "T boats," because their regulations are found in Subchapter T of 46 CFR.
4. *Small passenger vessels less than 100 gross tons carrying more than 150 daytime passengers or more than 49 overnight.* Typical examples include larger dinner cruise boats, casino vessels, and ferries. With their regulations located in Subchapter K of 46 CFR, these vessels are also called "K boats."
5. *Passenger vessels more than 100 gross tons carrying more than 12 passengers.* Examples of these type vessels are very large casino vessels and riverboats, as well as large oceangoing cruise ships. The regulations for these vessels are in Subchapter H of 46 CFR.

The majority of the passenger vessels in U.S. domestic service are Subchapter T and K boats. (Note that Subchapter T and K vessels that engage in international service must also comply with SOLAS.) Large oceangoing cruise ships are Subchapter H vessels if they are U.S. flag vessels. The majority of cruise ships are not U.S. flag vessels. They are foreign flag ships subject to the SOLAS regulations and U.S. port state inspection.

Cargo and Miscellaneous Vessels. Cargo and miscellaneous vessels are ships designed to carry general freight for hire, either in bulk, breakbulk, or containerized form. Breakbulk cargo is a nautical term that refers to cargoes that are baled, palletized, or placed in packaging for shipment and are consigned by various owners for delivery to different purchasers, yet are stowed in a common hold for shipment. Bulk cargoes are those that are loaded in loose condition, such as ores, grains, and coal. Breakbulk cargoes are loaded into the ship's holds by cranes, whereas bulk cargoes are usually loaded into the holds using conveyor belts, blowers, or grab buckets. This vessel category also includes container ships carrying multimodal freight containers that can be loaded directly onto railcars or truck chassis to continue their voyage. Vehicles carried as cargo can be driven on and off specialized cargo ships known as roll-on/roll-off or just ro-ro ships.

Mobile Offshore Drilling Units (MODUs). MODUs are special marine vessels designed for exploratory drilling operations on the ocean subfloor for possible offshore oil and gas well locations. These units must be mobile, because they are moved from site to site to look for new resources. Once a well is drilled and found to be satisfactory, a production platform is constructed at the site. Production platforms routinely pump thousands of barrels of oil daily, whereas MODUs only find productive well sites. The production platforms are thus exposed to greater fire risks. Production platforms are either connected to a pipeline through which oil is pumped to a refinery, or the oil is stored on the platform until it can be loaded onto a tank ship to be taken to the refinery terminal. Among the common types of MODUs are the following:

- *Jackup rigs:* These are mobile drilling rigs that float, so they can be moved or towed into position. A jackup rig has a series of self-elevating legs that are lowered to the seafloor to anchor the unit and lift the drilling platform out of the water. These rigs are generally used where the water depth is less than 400 ft (122 m).
- *Submersible rigs:* These are mobile drilling rigs that can be moved or towed into position. The rig has a hull that allows the unit to float. When the rig is in position, the lower section of the hull is flooded, causing it to settle onto the seabed, but keeping the work platform above the water. Submersibles provide very stable drilling platforms, but can only be used in limited water depths.
- *Semisubmersible rigs:* These are similar to submersible units; however, when the hull is flooded, the rig does not settle on the seabed, but floats beneath the surface of the water, keeping the working platform above the water. These types of rigs can be used in very deep water, as their submerged section assists in stabilizing the rig in heavy seas.
- *Drilling ships and barges:* These rigs are easily moved, as they are designed with similar hull shapes as oceangoing vessels. They are used to drill wells in remote locations. The limitation of these rigs is their lack of stability in very rough weather. They are, therefore, mainly used in locations where calm seas are enjoyed most of the time.

There are several types of production platforms in use, depending primarily on the water depth at the well site and the distance to the refinery:

- *Rigid steel platforms:* These are rigid platforms with a tubular steel foundation or jacket that is supported on piles driven into the seabed. The steel jacket is usually so large that it is towed to the site in a horizontal position and partially flooded to tip it into a vertical position and lower it onto the pilings. The crew quarters, the drilling rig, and all support equipment are then put on a platform positioned at the top of the jacket.
- *Rigid concrete platforms:* These are rigid platforms that resemble steel platforms, except the platform is supported

on large hollow concrete caissons. The entire rig is constructed and towed to the site, and then the caissons are flooded to anchor the unit to the seabed. Because of the tremendous weight of the concrete caissons, the rig does not have to be attached to the bottom with pilings. The hollow caissons are used to store the oil until it can be offloaded into tankers for delivery to the refinery. Because of their weight, these platforms are very stable in rough seas and are common in the North Sea.

- *Tension leg platforms:* Rigid platforms are limited in application to water depths less than roughly 1000 ft (305 m). For deeper water, a type of production rig called a tension leg platform (TLP) is used. Resembling semisubmersible drilling rigs, TLPs are moved into location and are then anchored to the seabed with tensioned steel tubes or cables. The working platform floats on the surface but is stabilized by the steel tensioning apparatus.
- *SPAR platforms:* Designed for very deep waters, SPAR platforms consist of a large cylindrical tube that floats vertically, anchored to the seafloor. Water ballast in the lower end of the tube keeps the SPAR deep in the water for stability in adverse sea conditions. The end of the cylinder above the water supports production and accommodation facilities. Newer SPARs are large enough to also accommodate a drilling rig for drilling new wells. Oil and gas processed on the SPAR are pumped into an underwater pipeline system.
- *Single point buoy mooring system (SPBM):* In locations in which a pipeline from the well to a refinery is neither economical nor practical to construct, a special mooring system can be built to allow oil tankers to load oil directly from the wells or from an underwater pipeline system serving several wells. A piping riser is constructed from the ocean floor to a mooring buoy that floats on the surface of the water. The oil tankers tie up to this buoy using a single line from the bow of the ship, hence the name. Some buoy systems also have a permanently attached tanker that is used for oil storage. These facilities are called floating production, storage, and offloading (FPSO) systems.

Offshore Supply Vessels. Offshore supply vessels are small cargo ships specifically designed to carry equipment, supplies, and workers to and from oil production platforms and drilling rigs. Special regulations were developed because these vessels are part cargo ship, part tanker, and part passenger ship, and they generally travel in limited geographic regions. The regulations were adapted to the specialized service of these vessels.

Nautical School Ships. Nautical school ships are training vessels used by merchant marine academies to provide their students with actual maritime operating experience. Although nautical school ships may be designed as cargo ships, they are provided with additional safety measures because the students carried on board are not licensed mariners, and there are generally more students on board than would be expected on a typical merchant ship.

Oceanographic Research Vessels. Oceanographic research vessels are vessels that are similar to small passenger vessels that have onboard laboratories to conduct research of water quality, marine life, or environmental science. The accommodation areas on these type ships are typically larger than those on board cargo vessels, because they need sufficient berthing capacity for the normal ship's crew plus the scientific complement. The laboratory areas are required to be separated from the accommodation areas by fire-rated bulkhead and decks, since flammable and combustible liquids may be used for the experiments.

MARINE FIRE PROTECTION CONSIDERATIONS

The application of fire protection engineering principles to ships and offshore marine structures is based on much of the technology used for the protection of buildings, warehouses, industrial plants, tank farms, and similar shoreside installations. Because the design and operating environment of ships are quite different from that of buildings, the basic fire protection principles have been adapted to suit the different marine-related circumstances.

Layout and Configuration

The basic layout and configuration of ships must be different from that of buildings because of their movement and the effects of the wind and wave forces they must endure. Ships cannot easily be designed with numerous deck levels without affecting their stability or their natural ability to remain upright. Similar to a building, a resting ship floating in calm water is subject to only the vertical force of the ship's weight acting through its center of gravity in a downward direction and the upward force of the water's buoyancy. Buildings, however, are designed as nonmoving structures, able to resist wind and weather forces without movement. Ships float and are propelled through the water. The directional forces caused by ships' engines and the wind and waves causes them to roll and pitch in the water. If more deck levels are added to a ship, its center of gravity is raised upward. The center of gravity is the chief force that keeps the ship in an upright position, and if the center of gravity is located too high on the vessel relative to its center of buoyancy, its righting ability is limited. Ships must be built in a horizontal rather than a vertical aspect because of this.

Multistory buildings have a similar footprint on each floor, which simplifies the design and layout of sprinkler and detection system devices. This common arrangement also greatly simplifies the arrangement of fire barriers and the means of egress. The main fire subdivisions in buildings are formed by the floor/ceiling assemblies, which prevent vertical fire spread. In contrast, the decks of a ship may vary considerably in shape and configuration on each level. The deck construction prevents vertical fire spread, but additional fire barriers must be provided to limit horizontal fire spread. The decks on some passenger vessels can be over 200 m in length. Horizontal fire barriers are only seen in very large buildings where the floor area exceeds that allowed by the building codes. The regulations for passenger ships require a 1-hour-rated fire barrier every 40 m fore and aft to subdivide them into fire areas called main vertical zones (MVZs).

Construction Materials and Design

The materials and design of fire barriers used in shipboard construction are quite different from those in buildings. The origin of modern shipboard fire barrier design can be traced to 1934, when the U.S. passenger ship *Morro Castle* burned off the coast of New Jersey, taking 124 lives. The combustible wooden construction and open stairways were determined to be the cause of the rapid fire spread throughout the vessel.[2] Outrage over this massive loss of life prompted the U.S. Senate Committee on Commerce to create a special Subcommittee on Fireproofing and Fire Prevention to develop recommendations for enhanced fire protection measures aboard ships.

The subcommittee procured a surplus ship, the *S.S. Nantasket,* from the Maritime Administration's reserve fleet moored on Virginia's James River and used it for a series of full-scale fire tests. Conducted in 1936, these tests showed the superior performance of steel bulkheads insulated with asbestos blanket insulation and joinerwork bulkheads constructed of noncombustible asbestos cement board panels.[2] The testing program also compared the temperatures developed in the full-scale *S.S. Nantasket* fires to those developed in the ASTM Standard E119 laboratory furnace to determine how other construction materials might be accepted.

At the conclusion of the *S.S. Nantasket* test series, the subcommittee report to Congress recommended the use of only noncombustible materials of construction.[2] The nearly exclusive use of noncombustible materials for shipboard fire protection has resulted in the development of methods and materials that are unique to ships. Although there have been many advances in the materials used for shipboard construction, the requirement for noncombustible materials remains the cornerstone of the structural fire protection system.

The majority of modern ships are constructed of steel. The regulations have, therefore, only needed to address one type of construction. Thus, they do not prescribe height and area limitations based on the type of construction, as is customary with the various building codes. Recent trends in construction methods are advancing the use of aluminum and composite materials for shipbuilding; however, the regulations have not fully recognized these materials, except in the development of the IMO High Speed Craft Code. This code was developed for the construction of lightweight high-speed vessels that cannot be constructed of steel without affecting their performance. These ships use lighter weight materials of construction such as aluminum alloys and fiberglass composites.

Fire Extinguishing and Fire Detection Systems Design

The design of fire extinguishing and fire detection systems on board ships also merits special consideration. Fire protection systems installed on board seagoing ships are more susceptible to environmental and operationally induced failures than those installed in buildings because of their continual exposure to salt water, humidity, shock, and vibration.

Because ships are moving structures, the installed equipment is regularly exposed to the vessel's motions and opposing wind and wave forces. Wiring connections may come loose from the constant vibration, so ring type connectors are used instead of spade connectors. Wiring nuts and solid conductor wiring, commonly used in building fire alarm systems, are not acceptable on ships because exposure of these components to vibration may result in circuit failure. Vibration is also a concern for the mounting brackets and equipment used to secure high-pressure cylinders employed in fire-extinguishing systems and portable fire extinguishers. The cylinders must be properly mounted to prevent vibration from causing damage to them or from causing their inadvertent operation.

The quality of the water supply used for fire protection is another matter that affects shipboard systems. Most ships sail in salt water. Those that do not, sail in river water that contains mud, sediment, and debris. Both fresh and salt water may contain biological organisms such as barnacles, Asiatic clams, or Zebra mussels. The fire main and sprinkler system suction arrangements must be designed with positive features to prevent clogging from these contaminants. Moreover, shipboard automatic sprinkler systems must be kept charged with potable fresh water to avoid marine growth in their branch lines. A very limited onboard fresh water supply is provided that automatically switches to a seawater pump during a fire to provide sufficient duration for the sprinkler protection.

The use of common shoreside materials such as anodized aluminum for fire hose couplings and nozzles is not realistic on ships because of corrosion-related failures. Fire-fighting equipment made from brass, bronze, or galvanized steel must be used to prevent corrosion problems. Stainless steel can be used in some applications, except that stainless steel fire extinguisher shells cannot be used on board ships because of their history of stress-corrosion cracking when exposed to saltwater environments.

Oceangoing ships can regularly be miles from the nearest port of refuge. It is essential that the installed fire protection equipment is rugged and reliable. Ships cannot depend on fire-fighting aid from a local fire department, so they must carry their own equipment and trained fire fighters. Fire-fighting tactics on ships are quite different from those used to attack fires in buildings. Ships are compartmentalized by steel bulkheads and decks. The fire brigade cannot ventilate a space before entering it by cutting openings in the overhead. The fire fighters entering confined areas may therefore be exposed to temperature extremes. As previously noted, stability is a significant concern, and the unlimited application of fire-fighting water on the upper decks must be controlled to keep the ship upright. This is compounded by the inability to readily drain water out of fire-affected compartments because floor drains and exterior doorways are not always available. Accumulated water can threaten the stability of the ship, so bilge pumps need to be operating when a significant amount of water has been used in fire-fighting efforts.

Evacuation

The evacuation of passenger ships is much more complex than the evacuation of a building. Ships have emergency evacuation components that are rarely, if ever, used for normal building occupancy. Passengers normally board cruise ships in port via

gangways that connect the dock to the main deck of the ship. The capacity and configuration of the ship's main access corridors and stairways are planned to facilitate passenger movement across the gangways.

If a fire occurs while the vessel is in port, the gangways can be used for emergency evacuation of the ship. If a fire occurs at sea, the paths to the dock are no longer available, and the only means available to evacuate the ship are the survival craft (lifeboats, inflatable life rafts, etc.). The egress paths to the survival craft are through totally different routes from those used to board the ship.

Because passenger ships have multiple types of occupancies, emergency evacuations are further complicated by the possibility of two distinct initial passenger distribution conditions. The daytime condition considers that most of the passengers will be distributed throughout the public assembly spaces such as the restaurants, lounges, and theaters. During the nighttime condition the majority of the passengers are expected to be in their staterooms asleep. This variation is similar to that expected in a large shoreside hotel; however, unlike a hotel, passenger ships do not have direct exits on the ground floor to evacuate the public spaces. Passengers exiting from the public spaces to the open deck may have to reenter the ship to travel to the survival craft. For either the daytime or the nighttime condition, the passengers must assemble and move to the survival craft, which may be located several decks above the public spaces. On many ships, an emergency evacuation requires the passengers to ascend stairways. This action may seem foreign to many passengers, who are accustomed to exiting buildings by descending the exit stairways.

Ships are considered their own best lifeboat and are only evacuated if it appears that sinking is imminent. Evacuation procedures initially move passengers from the fire-affected spaces on the ship to areas of safe refuge called assembly stations. These are usually areas where there is ready access to the survival craft. When the passengers ultimately discharge from the exit system on board the ship, they are not at a safe location. Passenger ship exit systems discharge to the assembly stations, and if necessary, the occupants are put into the survival craft and lowered to the water (Figure 21.10.6). Depending on the weather, time of year, and location, the sea could be a much more hazardous environment than the ship. Thus, evacuation of a ship is only done when the ship is in peril. Shipboard evacuations must be possible in adverse sea states, with ship movements and even the possibility that one side of the ship might be inaccessible (due to listing or rolling to one side, for example).

Regulatory Review

Ships may be subject to regulatory review by different authorities having jurisdiction (AHJ) throughout their lifetime. Owners of vessels on international voyages must have their ship design and operation approved by the maritime authority of the country where the ship is registered (flag state), which is primarily responsible for ensuring that the ship meets international standards. Authorities of the countries to which the ship sails have the right to examine the ship to confirm compliance with international standards (port state control). This sometimes results in difficulty dealing with differing interpretations of the same regulations. Even ships limited to U.S. domestic service come under the jurisdiction of different Coast Guard authorities when they change their home port. Different local conditions and interpretations can mean that some aspect of ship design or operation acceptable in one port will not be acceptable in another. This is not the case for buildings, which are usually within the same jurisdiction for the life of the building.

FIGURE 21.10.6 Enclosed Survival Craft Being Launched

The ship's crew can also include residents of many different countries, who may not all speak or understand the language of the flag state. Some ships may also be built in shipyards located outside of the flag state. For these reasons, there may be significant language issues to overcome in order to ensure that the entire crew understands the emergency procedures to follow in a fire emergency. The crew may also need supplemental training in the operation and maintenance of the installed fire protection equipment to ensure that it is properly serviced and remains operable at all times.

MARINE FIRE HAZARDS

General Fire Hazard Analysis

The general fire hazards on board ships can be analyzed looking at the three major occupancies common to all ships: (1) the engine room, which contains the propulsion machinery and auxiliary equipment; (2) the cargo holds or cargo tanks depending on the service of the vessel; and (3) the accommodation and service areas where the crew and/or passengers are berthed.

The U.S. Coast Guard maintains a database that is used to track casualty information relating to accidents investigated by the Coast Guard.[3] The database has been in use since 1985 and is useful to show trends in fire-related casualties. From an overall fire damage perspective, roughly 60 percent of all shipboard fires occur in the engine room. The remaining 40 percent of the total number of fires are split evenly between the cargo area and the accommodation area.

Engine Rooms. The engine rooms on modern ships usually have one or more large diesel engines and related auxiliary equipment for the propulsion of the ship. Some vessels may also have steam boilers for propulsion or auxiliary purposes. Engineering support systems include electrical generators and

distribution systems, hydraulic systems, ventilation systems, and lubricating oil systems. The diesel engines are supplied with fuel from small capacity day tanks located in the engine room, which are filled by fuel pumps that take suction from large fuel storage tanks located outside the engine room. Casualty data shows that the majority of engine room fires are caused by broken fuel or lube oil lines spraying onto hot surfaces such as exhaust manifolds, turbochargers, or engine casings.[3] The next most likely engine room fire cause is attributable to shipboard electrical systems, usually a short circuit or failure of an electrical component or device. Although not seen as frequently, engine crankcase, clutch, and turbocharger explosions may occur, usually due to wear on the equipment. Human error is also a noted contributor to engine room fires, primarily cutting and welding operations that are not safely performed.[3]

Cargo Holds. The cargo holds on general cargo ships and container ships are nothing more than a series of large separated warehouse spaces. These ships could be used to transport general cargo in packages, multimodal containers, or portable tanks; vehicles; or flammable liquids or gases. Vehicle carrier holds are similar to general cargo holds except that they may have internal elevators or power-operated doors and may run the entire length of the vessel without subdivision. The vehicles carried may have gasoline in their tanks, which requires the cargo hold electrical system to be suitable for use in hazardous atmospheres. Bulk liquid cargo tanks on tank vessels are used to carry a variety of flammable and combustible liquids and are segregated from the accommodations areas aft where sources of ignition could be present. Electrical shorts and sparking are listed as the most frequently identified fire cause of shipboard cargo areas, followed by cutting and welding, contact with hot surfaces, human error/discarded cigarettes, static electricity/lightning, explosions, and chemical reactions.[3]

Accommodation and Service Areas. Shipboard accommodation and service areas include the staterooms and berthing areas, galleys, mess rooms, pantries, ship's offices, laundry facilities, navigating bridge, and radio room. The fire hazards in these areas are typical for light or ordinary hazard occupancies. Casualty statistics[3] show the leading causes of fires in these areas to be electrical in nature, followed by galley and cooking fires, human error/cigarettes, cutting and welding, portable heaters, and contact with hot surfaces.

Detailed Fire Hazard Analysis

Engine Rooms. Shipboard engine rooms or machinery spaces typically occupy the aft (rear) section of the ship up to the main deck, with the machinery space casing extending up through the accommodation area to the top of the vessel. The casing is a narrowing vertical trunk, similar to a pipe chase, which contains the engine exhaust pipes and ventilation equipment. A typical engine room has multiple levels separated only by steel gratings and ladders. The engineer's control room and various workshops could also be included within the engine room boundaries. Engine rooms are separated from the remainder of the ship by steel bulkheads and decks, with all openings and penetrations sealed to prevent the migration of hydrocarbon vapors to adjacent occupied areas.

The primary fire hazard in the engine room is the fuel oil used to supply the engines or boilers. This is usually marine diesel fuel, which is similar to # 2 fuel oil, or it may be a heavy oil called bunker C, which is similar to # 6 fuel oil. If heavy fuel oils are used, they must be heated in order to be transferred. Fuel and lube oil systems are the principal causes of fires in shipboard engine rooms.[3] Failures may occur in the fuel line piping and fittings from the continual exposure to vibration or because components were replaced with substandard parts not qualified for the intended service. Many ships are also fitted with duplex fuel strainers, which have two separate filter chambers that allow the crew to manually switch between them to clear the operating filter without stopping the engines. A significant number of fires occur in these filters because they are normally operated while the fuel system is under pressure.[4] Most ships will also have one or more day tanks that feed fuel to the engine room under a gravity head.

If an engine room fire occurs, the fuel in the tanks could continue to leak into the engine room until the tanks are empty. Because of this, fuel lines have remotely operated shutoff valves to allow the fuel tanks to be isolated from outside the engine room in the event of a fire. Beginning in 2002, the SOLAS convention required additional fuel system safeguards on new vessels. Specifically, all high-pressure fuel piping is required to be double jacketed, and any fuel lines that could spray onto hot surfaces must be suitably shielded or guarded.

Engine crankcase explosions are another recognized fire source in shipboard machinery spaces.[5] These explosions can occur when the engine's piston rings or related components become worn and allow fuel oil to be forced from the combustion chambers into the crankcase. Rigorous maintenance programs to replace worn equipment are the most effective way to prevent crankcase explosions. Pressure-relief vents are also provided on engine blocks to mitigate the effects of explosions. Recent advancements in oil mist detection technology show promise in their use for recognizing component wear before an explosion occurs.[5]

Because of the fire hazards inherent to engine rooms, the Coast Guard regulations require them to be protected by a total flooding carbon dioxide or clean agent fire-extinguishing system. Detection systems are not required except when the engine room is automated and when engineers are not continually present. The extinguishing systems are required to have a manual means of release to guard against unintentional discharges. The inadvertent discharge of an automatic engine room extinguishing system will cause the engines to shut down, leading to the loss of propulsion and steering. This could place a moving vessel in an extremely dangerous situation, depending on its location.

The SOLAS regulations allow the use of water spray or high-expansion foam protection for engine rooms in lieu of a total flooding gaseous system; however, these types of systems are currently not accepted for use aboard U.S. flag vessels. Water mist systems are the only water-based system accepted by the Coast Guard for the total flooding protection of engine rooms. Type approval for total flooding systems is based on IMO MSC/

Circ. 1165, *Revised Guidelines for the Approval of Equivalent Water-Based Fire-Extinguishing Systems for Machinery Spaces and Cargo Pump-Rooms.*

Galleys. Ships' galleys are similar to commercial restaurant kitchens. As a result they are vulnerable to the same fire hazards (Figure 21.10.7). Ship galley fires are often attributable to the buildup of grease in the galley hood and exhaust ducts, or from malfunctions in the cooking appliances themselves. Galley range tops and cooking appliances are designed with battens or guardrails to keep the cookware in place on the burners when the ship is in motion. The restraints prevent personnel injury and also guard against the heated cookware contacting adjacent combustibles. Galleys on domestic passenger vessels are required to have either a dry chemical or wet chemical extinguishing system for the protection of the hood. SOLAS vessels must have a fixed means of extinguishing a fire in the galley exhaust duct. On all vessels, the galley exhaust ducts must be separated from adjacent combustibles; however, fires still occur because crew members improperly store trash and other combustibles in void spaces or in lockers adjacent to the galley exhaust ducts.

Breakbulk General Cargo. Breakbulk cargo consists of general commodities in separate packaging that is stowed in a hold and tracked by separate bills of lading, as opposed to bulk cargoes such as coal or gain. Cargo holds designed for the carriage of breakbulk general cargoes typically comprise three or more levels: a lower hold, a 'tween deck, and an upper 'tween deck. 'Tween deck is a nautical term referring to the mezzanine levels between the bottom and top of a hold. Each cargo hold level has a fixed peripheral area, called the wing area, while the center area of the hold is open and is covered by removable hatch covers to allow vertical loading of the cargo by overhead cranes. The cargo is normally loaded into the center of each level by cranes, and then the stevedores move the cargo into the wing areas with forklifts until the hold is completely filled. The only other access to the holds is through small manholes and ladders. Breakbulk cargo is not loaded with any access aisles or storage racks in order to maximize the ship's carrying capacity. The cargo pile height is usually near the overhead, and may range from 10 to 20 ft (3 to 6 m) in height on each deck. At sea, the cargo holds are rarely accessed.

FIGURE 21.10.7 Typical Galley on Board a Large Passenger Ship

Many ships also have provisions for on-deck stowage, which is generally reserved for hazardous materials or bulky items. The materials carried on cargo ships are as varied as those in any general storage warehouse and routinely include hazardous chemicals, explosives, oxidizers, and flammable liquids and gases. The segregation and stowage of incompatible materials must be carefully controlled to minimize the risks of fire or explosion. The U.S. Department of Transportation (DOT) regulations in Title 49 of the Code of Federal Regulations and the IMO International Maritime Dangerous Goods (IMDG) Code provide highly specific packaging, stowage, ventilation, and segregation requirements for the loading of hazardous materials.

Breakbulk cargo holds are large open warehouse type spaces surrounded by steel bulkheads and decks. For efficiency in loading, and to maximize the quantity of goods that may be loaded, the decks and surrounding bulkheads are made as smooth and regularly shaped as possible. Lighting and ventilation systems are the main support equipment normally found in cargo holds. Some ships may have battery chargers for the forklifts as well as electrical systems that allow the stowage of refrigerated containers. Fires in cargo holds are mainly attributable to electrical sources, although there have been some cases reported of spontaneous combustion occurring in the cargo.[6] The tight stowage of the cargo in the holds limits the air available for combustion; if a fire does occur, it is generally a deep-seated, slowly developing event.

The standard protection for cargo holds consists of smoke detection and total flooding carbon dioxide systems. Because the cargo handling operations in the holds could damage or impair the function of electrical fire detection devices, an air-sampling detection system (called a sample extraction system in SOLAS regulations) is used. There are no smoke detectors in the holds; they are located in the system control cabinet. Cargo hold detection systems are combined with the carbon dioxide system discharge piping. The system control cabinet is located outside the cargo area and arranged to take suction through the carbon dioxide system discharge piping in each hold. The air samples are aspirated from each hold individually and then routed in sequence through an optical smoke detection chamber. If the system goes into alarm, valves are provided to isolate the discharge piping from the detection system prior to the release of the extinguishing gas. The carbon dioxide system is designed to provide a quantity of extinguishing agent intended for fire control until the ship can make it to a port of refuge. Because of the tight stowage arrangements and the likelihood of deep-seated fires, it is not considered realistic to expect the system to extinguish the fire.

Container Holds. Cargo holds designed for the carriage of shipping containers are similar to those on breakbulk ships; thus the same fire protection measures are provided. Unlike general cargo ships, however, container ship cargo holds are designed with very large hatch covers and do not have 'tween decks. This arrangement permits the entire hold to be loaded by the overhead gantry cranes, without movement of the cargo below decks. The containers are lifted into the holds and aligned and restrained by vertical cell guides. The clearances between the rows of containers is only several inches, making access to

the loaded hold impossible. The fire hazards and protection for container holds is the same as for general cargoes. The steel, aluminum, or fiberglass shipping containers further segregate the combustible material and may restrict the spread of fire. However, they can also act as a shield to limit the application of extinguishing agents. The fire risks presented by containerized cargo are considered equivalent to those involved with the breakbulk shipment of commodities.

Bulk Cargo Holds. Bulk cargoes are loose commodities such as grain, ores, minerals, and coal, which are usually loaded and unloaded using conveyor belts, blowers, or grab buckets. The likely fire hazards involving these cargoes are very limited and may involve dust explosions and self-heating of some agricultural commodities. Detection and suppression systems would provide limited benefit and are therefore not required.

Some bulk cargo ships are self-unloaders, with a conveyor belt running beneath the cargo holds. These systems are common on both U.S. and Canadian vessels on the Great Lakes. The holds are hopper-shaped and have doors at the bottom to discharge the cargo onto the belt. At the end of the belt, another set of belts lifts the cargo above the deck and onto a conveyor boom, which can be turned to either side of the vessel to discharge the cargo. These conveyor systems with their numerous rollers, motors, and gearboxes can be the source of fires and should be protected with detection and suppression systems.

Vehicle Holds. Cargo ships designed for the carriage of vehicles can have a variety of different hold arrangements. These ships commonly transport automobiles, trucks, trains, military vehicles, or trailers. There are two basic loading arrangements for these ships. The vehicles may either be lifted on and off the ship by cranes, or they may be driven onto and off of the ship. Lift on/lift off (lo-lo) cargo holds designed for vehicles are similar in configuration to general cargo holds. Cargo holds designed for driving, or roll-on/roll-off (ro-ro) service, have multiple 'tween decks generally with only enough overhead clearance for one level of vehicles, to maximize the load-out of the ship.

If the vehicles are lifted on and off of the ship or if the vehicles are tractor-trailer trucks (briefly driven onto the ship just to deposit the trailer), there is no fuel in the vehicles, in which case the vehicles pose no greater fire hazard than general cargoes. If the vehicles are driven on and off of the ship and contain gasoline and charged batteries, additional fire protection is required. A higher concentration of carbon dioxide is specified by the regulations because the expected fires in the vehicle holds are not slow-developing, deep-seated fires, but flammable liquid fires. Additionally, protected electrical fixtures and mechanical ventilation systems are provided to protect against the ignition of explosive gasoline vapors.

Cargo Tanks. Tank vessels are designed for the carriage of bulk liquids, including crude oil, refined petroleum products, vegetable oils, alcohols, and chemicals. The most common types of tank vessels are designed for the carriage of petroleum products such as crude oil, heating oil, or gasoline. The greatest fire risk on tankships is the chance of flammable cargo vapors coming into contact with an ignition source. To protect against this, the ships are provided with restricted ventilation systems and are often arranged with a cargo pump room located between the engine room and the first row of tanks (in the aft portion of the vessel), to isolate the cargo from the ignition hazards in the engine room. Additionally, all deckhouses and machinery must be located aft of the cargo tank area to minimize contact of flammable vapors with possible ignition sources. Furthermore, the forward-facing portions of the deckhouse that face the cargo area are constructed of fire-rated bulkheads, with closeable steel covers over the windows.

Crude oil carriers are perhaps the most common type of oceangoing tankships. Crude oil carriers are generally designed with a series of large tanks of similar volume. The fire hazards of crude oil vary due to its elemental makeup and the geographic region where it was obtained. Crude oil contains all of the products that are separated during the refining process; thus crude oil includes volatile elements (such as gasoline) that have very low flashpoints. The fire risk of petroleum products is based on the flashpoint and volatility of the liquid. The volatile gases rising from the surface of the petroleum are the fire hazard, and burning gases produce the visible flames. The rate at which the gases are given off is expressed by the product's Reid vapor pressure. In order for the petroleum to burn, it must be mixed with air in the correct ratio. The flammable range for typical petroleum products carried on tankships is between 1 and 10 percent by volume in air. Air spaces in the cargo tanks and piping systems are inerted to further guard against the possibility of a cargo fire. Tankships have inert gas generators or use treated flue gas to provide the oxygen-deficient atmosphere that is needed for this purpose.

The cargo tanks may be connected with the ship's hull, in which case a grounding or collision is likely to result in an explosion and fire involving the cargo, or they may be independent from the hull. The public reaction over the *Exxon Valdez* oil spill in March 1989, where the cargo tanks were connected, resulted in the Oil Pollution Act of 1990. This law requires new tankers built after June 1995 to have independent cargo tanks separated from the hull by a void space. Existing single hull tankers must be retrofitted with double hulls over a 20 year period that began in 1995 and terminates in 2015. The required date of compliance is based on the original build date or date of major conversion of the tankship. The void space between the outer hull and the cargo tank provides added protection against damage in a grounding.

Fire protection of the cargo tank deck area is provided by manually operated deck foam systems that discharge through fixed monitors. The foam system controls, pumps, and concentrate storage tanks are located in a protected room aft in the deckhouse. In the event of a fire, the system can be started from the protected location and aligned to supply foam solution into the mains. The monitors are arranged to allow the crew to fight the fire from aft to forward.

Chemical tankers differ from oil tankers because they carry a variety of different chemical cargoes in varying lot sizes. These ships have numerous smaller tanks, generally of unequal capacity. The deck foam system must be specifically designed to protect against the different chemical and fire hazard properties of the chemicals. In some cases, the chemicals may be water sol-

uble, requiring specialized "polar solvent" foam concentrates. Protection of chemical tankers can be further complicated by the use of cargo heating systems and the use of specialized piping materials. Compatibility of cargo represents an additional factor that complicates chemical tanker protection. Criteria have been established that restrict certain products from being stored in adjacent tanks.[7]

Liquefied natural gas (LNG) carriers are another type of specialized tank vessel seeing expanded service in the United States. Current vessel designs have a capacity sufficient to hold approximately 4.4 million ft^3 (125,000 m^3) of LNG, but tankers with larger capacities are in the design stages. The liquefied natural gas is contained in specially insulated cargo tanks at a temperature of approximately –256°F (–161°C) at atmospheric pressure. By cooling the gas to cryogenic temperatures, the volume of the cargo can be reduced by a factor of 600 for more cost-effective transport. LNG carriers do not have onboard refrigeration capability to keep the liquid cargo cold. Instead, the cargo tanks are heavily insulated; however, a small amount of the liquid will boil off during the voyage. This gas must either be reliquefied or used as fuel in the ship's boilers.

The composition of natural gas depends on the geographic location where it is produced, but consists primarily of methane with small amounts of other hydrocarbons such as ethane, pentane, and butane. When the natural gas is cooled and liquefied, any of the constituent elements that solidify must be removed to prevent damage to the gas compressors and cargo pumps. As a result, the liquefied cargo being carried on the ship is primarily methane. There are two customary LNG cargo tank designs: freestanding spherical tanks and prismatic membrane tanks.

Freestanding spherical tanks are constructed of either aluminum or nickel steel and are mounted inside the steel hull of the ship with the top half of the tank exposed above the main deck. A double hull arrangement is provided with several feet of separation between the tank and the ship's outer hull to protect the tanks from damage in the event of a collision or grounding. The tanks are surrounded by highly efficient insulation, and a metal weather cover is installed over the exposed parts of the sphere.

Membrane tanks conform to the shape of the hull and consist of an inner membrane constructed of a special nickel-iron alloy that has a very low coefficient of thermal expansion at cryogenic temperatures. A second metal or composite outer membrane is provided that is separated from the inner barrier by several layers of insulation. The space between the two barriers is inerted with nitrogen and monitored for leakage. Similar to the spherical tank design, a double hull is provided to protect the tanks in the event of a collision. Membrane tanks are fitted, for the most part, within the hull, allowing such vessels a lower overhead clearance than spherical tank designs.

For both types of LNG tank designs, fixed dry chemical monitors or hand hose lines are required for the protection of the cargo area. The dry chemical system is intended for the protection of the above-deck cargo area, tank domes, exposed cargo piping, and the cargo handling manifolds. In addition, a fixed water spray system is required for cooling the exposed cargo tank domes, the cargo manifolds, and the boundaries of any superstructures facing the cargo area.

Cargo Pumprooms. Tank vessels have cargo pumprooms that are used to convey the cargo onto and off the ship. On some vessels, deep-well pumps are installed in the cargo tanks, eliminating the need for a dedicated pumproom. The electrical equipment located in the pumproom must be electrically safe for hazardous atmospheres. The cargo pumps are usually arranged with electric motors in the engine room and the pump shafts passing through packing glands in the aft pumproom bulkhead. This arrangement eliminates the need for qualified electric motors in the pumproom. The standard protection for cargo pumprooms is a total flooding gaseous agent system. Some tankers may also have a water spray system or a foam system.

Cargo Ship Accommodation Areas. Accommodation areas are the part of the ship where the officers and crew are housed, and may include sleeping, galley, dining, laundry, and recreation areas. The typical crew staffing level on a modern cargo or tankship is about 20 to 30 persons. The officers and higher-ranking crew members have private rooms, whereas the remainder of the crew is assigned to rooms suitable for two to four occupants. U.S. Coast Guard regulations specify that the materials of construction in these areas must be noncombustible. The expected fire risks are limited to furnishings and personal articles placed in the berthing areas. Casualty statistics[6] show that the predominant fire risk in these areas is attributable to electrical sources, followed by failure to observe proper fire prevention practices.

U.S. flag cargo and tank vessels in domestic service are not required to have automatic sprinkler systems or fire detection systems for the protection of the crew accommodation areas. The primary fire protection measure is the use of noncombustible materials of construction. SOLAS allows three options for the design of cargo ship accommodation areas. They may be constructed of noncombustible materials (Method IC); or they may be constructed of limited combustible materials in conjunction with an automatic sprinkler system and a smoke detection system for the protection of all corridors, stairways, and escape routes (Method IIC); or they may be constructed of limited combustible materials in conjunction with an areawide detection system (Method IIIC). Only Method IC is accepted for U.S. flag vessels.

Passenger Ship Accommodation Areas. The fire risks anticipated in the accommodation areas on passenger vessels are the same as those on cargo ships; however, passenger ships have many more passengers who are not familiar with the vessel and there are public spaces such as casinos, restaurants, spas, movie theaters, and lounges in addition to the berthing areas. These larger public spaces present a higher level of risk because of the greater number of occupants that would have to be evacuated in an emergency. The furnishings in many of the public spaces also have the potential for a higher rate of heat release than those found in a berthing area—for example, a theater that has upholstered seating or a sales shop with combustible merchandise. SOLAS requires areawide automatic sprinkler protection and smoke detector coverage of all of the accommodation areas. The U.S. domestic vessel regulations vary depending on the size of the ship and the number of passengers carried. The individual vessel regulations should be consulted for these requirements.

Small domestic passenger vessels (Subchapter T and K vessels) are sometimes used for dinner cruises. The public spaces on these vessels may have a buffet line set up with portable, solid alcohol food warming equipment. Some vessels may also have casino gaming machines that are constructed with combustible materials and are electrically powered. The higher level of potential fire risk on these vessels is addressed by two additional provisions in the regulations. A limit on the allowable combustible load in the public spaces is applied to restrict the fuel load. For general public spaces, the maximum combustible load is limited to 7.5 lb/ft^2 (37.5 kg/m^2), considering the total volume of all construction and outfitting materials, furniture, furnishings, carpets, draperies, interior finish materials, electrical cable insulation, plastic light diffusers, mattresses, and similar materials. In addition, all accommodation, service, and control spaces must be equipped with a smoke detection system.

Passenger vessels may be designed with architectural features such as balconies and atriums (Figure 21.10.8). The domestic passenger vessel regulations permit atriums if they are of sufficient size for the occupants to be able to observe the outbreak of a fire at any location in the atrium. This concept is based on the minimum opening dimensions taken from the NFPA *101*®, *Life Safety Code*®, requirements for buildings. In addition, areawide automatic sprinklers, smoke detection, and a smoke control system are specified. The smoke control system must be designed to clear all of the smoke from the atrium within 10 minutes.

FIRE PREVENTION ON SHIPS

The basic fire protection philosophy applied to ships is to limit the use of combustible materials of construction, thereby restricting the available fire growth rates. This concept is applied to the materials of construction used for the decks, bulkheads, ceilings, interior finish materials, and any items incidental to the construction of the ship. There is still the possibility, however, that the vessel's furnishings, galley supplies, trash, and similar items can add up to a significant fire risk if safe operational practices are not followed. Although the regulations are not specific regarding housekeeping and fire prevention issues, good marine practice dictates that the handling and use of combustible materials, flammable liquids, and ignition sources be controlled. It is essential that the storage of consumable goods and their packaging be controlled to isolate combustible materials from sources of ignition.

FIGURE 21.10.8 Typical Atrium on a Passenger Ship

Important changes to the international regulations were adopted in 1997 that make fire prevention training mandatory for licensed seafarers serving onboard SOLAS vessels. This is intended to make the crew aware of the need to follow safe practices in the day-to-day operation of the ship. The International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers (STCW), 1978, sets qualifications for masters, officers, and watchkeeping personnel on seagoing merchant ships. These requirements became effective on February 1, 1997, and require candidates for licenses and other certificates to establish competence through both subject-area examinations and demonstration of skills in basic safety training.

Controlling Flammable and Combustible Liquids Storage

The control of flammable and combustible liquids used for daily maintenance and repair activities is an important marine fire prevention practice. Steel lockers should be provided for the storage of paint and other flammable liquids. Hazardous liquids should be stored in the approved lockers at the end of each work shift. It is particularly important to store these materials in protected lockers on fiberglass and wooden hull vessels. The preferred location for these lockers is on the open deck, although the engineer's stores (such as lubricants and solvents) are ordinarily kept inside an approved flammable liquids cabinet in the engine room. Stowage of ordinary combustibles in paint and flammable liquid lockers should not be permitted. In the engine room, lube oil and fuel spills should be routinely cleaned up to keep the bilges from accumulating waste oils. Oily wiping rags should be stowed in sealed metal containers to guard against their spontaneous combustion.

Controlling Fuel Oil Transfers

Fuel oil transfers introduce the possibility of flammable or combustible vapors being released at the dock and in the vicinity of the fuel manifolds on board the ship. Precautions also need to be taken prior to and during fueling operations to lessen the chance of a fuel spill, caused by a fuel hose leak or the overfilling of a tank on the ship. All smoking, open lights, and other ignition sources should be prohibited in the vicinity of the fuel manifold, and only authorized personnel should be allowed to remain in the area. All open doors and windows near the manifold should be closed. The mooring lines should be confirmed tight before fueling is begun. An effective means of communication should be available at all times to permit the rapid shutdown of the fuel pumps in case of an emergency. A calibrated means of determining tank levels should be continuously available to prevent overfilling the ship's fuel tanks. If there are language difficulties between the crew and the fuel

terminal, prior agreement should be made on the verbal expressions to be used for the transfer operations. Appropriate lighting should be readily available in the vicinity of the manifold in the event of a fuel spill.

Controlling Flammable and Combustible Cargo Vapors

On tank vessels, there is a significant fire risk from the release of flammable or combustible cargo vapors. To minimize vapor production, tankships have an inert gas system that maintains an inert atmosphere in the cargo tank and piping system vapor spaces, except when the tanks are required to be gas-free. Inert gas systems are designed to inert empty cargo tanks by displacing the atmospheric air in the tanks with inert gas. When the tanks have been inerted, the cargo can be loaded without the fear of an explosion. During the voyage, the inert gas system supplies makeup volume to maintain the oxygen content in the cargo tank air spaces below 8 percent oxygen by volume, at a positive pressure. When the cargo is offloaded, additional inert gas is supplied to the tank to keep the atmosphere out of the flammable range.

If any work is to be done inside of the cargo tanks, they must first be cleaned and gas-freed. This operation poses a particular risk because the inert gas blanket is pumped out of the tank and air is introduced. In the process, the tank atmosphere changes from a fuel-rich condition to a condition that will not support combustion. The danger of this is the intermediate condition when the tank atmosphere is between the upper and lower flammable limits. An ignition source or static discharge while the tank is in the explosive range could have serious results. Ships in port or a shipyard must engage a marine chemist to certify tanks as being safe for workers or safe for hot work as the job requirements dictate.

NFPA 306, *Standard for the Control of Gas Hazards on Vessels,* provides further technical details on the role of marine chemists. Marine chemists are certificated to perform this service through an industry-sponsored certification program that is administered by NFPA. Basically, the marine chemist must verify that the concentration of oxygen is sufficient to support life and that the concentration of flammable or combustible vapors is below their flammable limits. The marine chemist also verifies that toxic vapors or substances that are harmful to humans are not present in significant concentrations. If any tank or void space entry is to be done while the vessel is at sea, the ships' crew must first verify that the tanks are safe for entry following similar confined space safe practices to those of the marine chemist. In all cases, portable gas analyzers are used to verify that oxygen levels are adequate and cargo vapors are below their flammable range.

STRUCTURAL FIRE PROTECTION

Domestic Service Vessels

The origins of shipboard structural fire protection measures can be traced to the 1930s, when the U.S. Department of Commerce first established regulations for vessel construction in the wake of the *Morro Castle* disaster and the U.S. Senate investigation that followed. The regulations mandated the use of noncombustible insulation and bulkhead panels to protect the steel structure of passenger ships. The laboratory fire test method originally used to approve these materials was ASTM E119, which, with minor modifications, is still used today. In the years that have followed, additional laboratory test methods have been developed for noncombustibility of materials, flame spread on interior finishes, and the fire resistance of deck coverings.

Shipboard structural fire protection is based on the use of fire barriers that are rated for either 60 minutes of structural integrity (designated A-class divisions) or 30 minutes of structural integrity (designated B-class divisions). Marine fire barriers are further classified in terms of their ability to limit temperature rise on the unexposed side of the barrier. Alphanumeric fire ratings are assigned to barriers to indicate their tested temperature rise limitation. For example, an A-0 division provides structural integrity for 60 minutes but provides no temperature rise limitation on the unexposed side of the barrier. Such barriers are typically used for exterior bulkheads that separate interior spaces from the weather decks. An A-30 division provides 60 minutes of structural integrity and will also prevent the average temperature rise on the unexposed side of the barrier from exceeding 284°F (140°C) above ambient for at least 30 minutes. The highest fire rating used is A-60. These barriers can be used to form main vertical zones, separate stair towers from adjacent accommodation areas, or to separate engine rooms from accommodation areas.

The present Coast Guard regulations for fire protection materials are contained in 46 CFR 164. These regulations detail the necessary fire tests that must be conducted for a material to be Coast Guard type-approved for use on U.S. flag vessels. The Coast Guard does not perform the actual fire testing of the materials. The manufacturer is required to have their materials tested to the Coast Guard criteria at an independent testing laboratory that has been accepted by the Coast Guard. Materials that successfully pass the required tests are issued a type approval certificate and the product is added to the list of approved materials posted on the Coast Guard's website.

The current list of approved structural fire protection materials is broken down into the following five categories:

- Deck coverings 46 CFR 164.006
- Structural insulation 46 CFR 164.007
- Bulkhead panels 46 CFR 164.008
- Noncombustible materials 46 CFR 164.009
- Interior finishes 46 CFR 164.012

The Coast Guard publishes Navigation and Vessel Inspection Circular (NVIC) 9-97, which explains the use of these materials for ship construction in detail.

The IMO International Code for Application of Fire Test Procedures (FTP Code) became mandatory for all international service vessels constructed after December 2003. Thus, materials type approved under the categories in the previous list are no longer acceptable for use on board U.S. flag vessels in international service. They may only be used on board domestic service vessels.

Deck Coverings. Deck coverings provide A-60 fire resistance for steel decks. As the name implies, these materials are installed on the top of the steel structure. The test method for deck coverings contains three specific test criteria: limited organic (carbon) content, limited smoke generation, and fire resistance and integrity. Although these requirements are not identical to the noncombustibility test, the resulting performance is very close. Therefore, it is assumed that the materials approved under 164.006 are noncombustible when used in their intended purpose as deck coverings. A limited amount of combustible content is permitted for deck coverings to allow the use of materials better suited as flooring surfaces. Deck coverings are typically cementitious materials, such as oxychloride cements, that are troweled in place.

Structural Insulations. Structural insulations form the primary fire boundaries that separate galleys and machinery spaces from accommodation areas. They are also used to form main vertical zone (MVZ) boundaries on passenger ships. Because the major subdivisions on board ships consist of steel bulkheads (walls) and decks (floors), a system has been devised that uses the steel structure as a component of the required fire separations—hence the term *structural insulation.* The fire test method described in 46 CFR 164.007 requires a 40 in. by 60 in. (100 cm by 150 cm) test sample to be attached to a 0.19 in. (5 mm) thick steel plate, which is considered representative of typical shipboard construction practice. The test specimen is then mounted in a vertical furnace with the insulation on the exposed surface of the test specimen. The assembly is then subjected to the standard time-temperature curve described in ASTM E119 for a 60 minute period. During the test, the average temperature rise on the unexposed side of the plate must not exceed 250°F (140°C) at the end of 60 minutes and the temperature at any one point cannot rise more than 325°F (180°C) above ambient.

A steel plate 0.19 in. (5 mm) thick will pass the standard fire test for a 60 minute period, however, without any limit on the unexposed surface temperature. A bare steel bulkhead is designated an A-0 class barrier. If approved structural insulation is applied, the thickness of insulation tested will limit the temperature rise of the steel boundary for 60 minutes. An insulated fire barrier with this amount of protection is designated an A-60 barrier. It has been found that 75 percent of this thickness will provide at least 30 minutes of fire endurance (A-30 barrier), and 50 percent of this thickness provides at least 15 minutes of protection (A-15 barrier). Structural insulations can be field applied to either side of a bulkhead or to the underside of a deck to form A-class boundaries, based on their testing under 46 CFR 164.007. Structural insulations are typically fibrous batts, or blankets, which may be faced with foil or other noncombustible materials. Calcium silicate panels and spray-on mixtures are also typical.

Bulkhead Panels. The secondary fire separations on ships are formed by non-load-bearing bulkhead panels used to enclose individual rooms and corridors. This construction technique is similar to the use of gypsum board panels in buildings, except that the panels are joined together by a system of metal tracks and connector hardware instead of wooden studs, because only noncombustible materials may be used. The connection system is traditionally called a joinerwork system. B-class bulkheads are typically either 0.75 in. (19 mm) thick homogeneous mineral board panels or 2 in. (50 mm) thick steel-faced, mineral wool sandwich panels. B-class bulkheads are intended to be installed in a single thickness, except where they are used as a component of A-60 class barriers. In such a case, there could be multiple layers of the B-class panels combined with structural insulations.

A variety of laminates and decorative covers can be used to conceal the joiner system and cover the panel surfaces. The tape and spackling system used for buildings is not practical on board ships because of vibration-induced cracking. The bulkhead panels used in this system are approved using the fire test method described in 46 CFR 164.008, which is intended to test the panel and its joinerwork as a complete system. This test is conducted in a vertical furnace, similar to that used for structural insulations; however, the sample size is 50 ft^2 (4.65 m^2) with a height of at least 8 ft (2.44 m).

Bulkhead panels are usually installed on ships with penetrations for lights, receptacles, switches, and controls. Because of this, the laboratory tests generally include a specimen with representative electrical fittings. Bulkhead panels that pass the required fire tests for a 30 minute period are designated B-0 bulkheads. Panels that pass the fire integrity tests for 30 minutes and also provide at least 15 minutes of limited temperature rise on the unexposed surface of the barrier are designated B-15 bulkheads. B-15 bulkheads are qualified to be used as a component of steel A-class construction to offer 60 minutes of fire endurance when combined with other insulating materials.

Noncombustible Materials. The materials used in shipboard construction must be qualified as noncombustible materials before they are subjected to the furnace testing used to establish their fire resistance. Materials that are approved as noncombustible materials must either pass the fire test method in 46 CFR 164.009 or be inherently noncombustible. The test requires a 4.88 $in.^3$ (80 cm^3) sample to be lowered into the test apparatus, which has been preheated to 1382°F (750°C). The pass/fail criteria include maximum temperature rise, flaming conditions, and a percent mass loss as follows:

- No more than 122°F (50°C) furnace temperature rise
- No more than 122°F (50°C) specimen surface temperature rise
- No more than 10 seconds total duration of flaming
- No more than 50 percent weight loss

This test is very stringent and thus, low flame spread and fire-resistant materials will not pass the test and do not qualify as noncombustible materials.

The Coast Guard considers the following materials as inherently noncombustible and no fire tests are required:

- Glass, clay, ceramics, or uncoated glass fiber
- All metals except magnesium or magnesium alloys
- Portland cement, gypsum, concrete with aggregates of only sand, gravel, vermiculite, silica, perlite, or pumice
- Woven or knitted glass fabric containing not more than 2.5 percent lubricant by mass

Interior Finishes. Interior finishes are coatings, overlays, or veneers that are used for decorative purposes. Interior finishes are normally applied to the exposed surfaces of bulkheads, ceilings, and decks, including exposed surfaces in concealed spaces. The two types of interior finishes used on domestic service vessels are approved finishes and combustible finishes. An approved interior finish is required to have a limited flame spread and smoke developed rating; a combustible interior finish may be a material with an unlimited flame spread or smoke developed rating.

Approved interior finishes are required in corridors and stairway enclosures as well as in concealed spaces within accommodation, service, and safety areas. They are also required in low-fire-risk accommodation spaces, which are sometimes required on board passenger ships. Combustible finishes may be installed in all other areas subject to thickness and volume restrictions. On all ships, the maximum allowed thickness of a combustible veneer is 0.075 in. (2 mm). On passenger ships, an additional volume limitation is imposed to restrict the volume of the installed veneer plus any moldings, trim, or decorations to a maximum of 0.1 in. (2.5 mm) times the aggregate surface area of the walls and ceilings in the space. This allows the use of decorative trim pieces of irregular shape. If thicker veneers or trim are installed, they must pass the noncombustibility test of 46 CFR 164.009.

Approved interior finishes must comply with 46 CFR 164.012, which requires the materials to be subjected to either ASTM E84 or NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials.* The acceptance criteria for either test method is a flame spread of 20 or less and a smoke developed rating of 10 or less. The interior finish materials must be tested using the same mounting method or adhesives that are intended for use in the shipyard.

In addition to the type-approved material categories for deck coverings, structural insulations, bulkhead panels, noncombustible materials, and interior finishes, the Coast Guard has developed accepted construction specifications for the design of fire doors, fire dampers, and electrical and piping penetrations. These construction specifications are based on standard shipyard practices, and, as a result, the materials are not required to be fire tested. The details of these construction requirements are listed in the various subchapters applicable to each vessel category. Type approvals are not issued for these materials.

International Service Vessels

CFRs historically contained the requirements for Coast Guard approval of structural fire protection materials and assemblies aboard U.S. flag vessels on both domestic and international routes. Coast Guard approved materials were accepted for vessels on international voyages, because SOLAS did not include fire testing procedures. The IMO Subcommittee on Fire Protection recently decided that uniformly applied fire test procedures should be developed and made mandatory to assure that structural fire protection materials do not deviate significantly among the member states. Effective July 1, 1998, the fire test methods in the International Code for the Application of Fire Test Procedures (FTP Code) were made a mandatory part of SOLAS. All U.S. flag ships that require a SOLAS safety certificate must now use structural fire protection materials that have been tested in accordance with the FTP Code instead of the CFR. The fire test procedures in the FTP Code cover more types of materials than the CFR does, and require the completion of complex fire test protocols using test apparatus that is newer than that used for domestic service materials.

The FTP Code is divided into parts, each dealing with a specific set of performance criteria as follows:

- Part 1: Noncombustibility test
- Part 2: Smoke and toxicity test
- Part 3: Test for Class A and Class B divisions
- Part 4: Test for fire door control systems
- Part 5: Test for surface flammability
- Part 6: Test for primary deck coverings
- Part 7: Test for vertically supported textiles and films
- Part 8: Test for upholstered furniture
- Part 9: Test for bedding components

To implement the new FTP Code requirements, the Coast Guard established the following type approval categories:

• Deck assemblies	164.105
• Primary deck coverings	164.106
• Structural insulations	164.107
• Bulkhead panels	164.108
• Noncombustible materials	164.109
• Structural ceilings	164.110
• Draperies, curtains, and suspended textiles	164.111
• Interior finishes	164.112
• Floor coverings	164.117
• Fire doors	164.136
• Windows	164.137
• Penetration seals (firestops)	164.138
• Fire dampers	164.139
• Bedding components	164.142
• Upholstered furniture	164.144
• Fire-restricting materials for high-speed craft	164.201
• Fire-resisting divisions for high-speed craft	164.207

U.S. flag ships that engage only in domestic voyages have the option of using structural fire protection materials that comply with either the CFRs or the FTP Code, because the FTP Code approval tests requirements are deemed to be more stringent. U.S. flag vessels that engage in international service must meet the FTP Code.

There are many differences between the FTP Code tests and the existing Coast Guard regulations. One major variation is between the Coast Guard's deck covering test and the FTP Code's primary deck covering test. The FTP Code defines primary deck covering as the first layer of a floor construction that is applied directly on top of the deck plating and is inclusive of any primary coat, anticorrosive compound, or adhesive that is necessary to provide protection or adhesion to the deck plating. Primary deck coverings may be installed beneath a floor covering such as tile or carpet, in which case they are tested for ignitability. If the primary deck covering will be used as an exposed surface, it must be tested for surface flammability and smoke and toxic gas production. Primary deck coverings are not tested for their fire-resisting ability. This category has no counterpart in the CFR.

The FTP Code requires structural insulations to be tested in the orientation in which the material will be installed, that is, materials to be installed on both bulkheads and decks must be tested in vertical and horizontal orientations. The bulkhead insulation being tested must be installed on the side of the steel bulkhead not facing the fire (i.e., on the cold side), and deck insulation must be installed on the hot side (i.e., below the steel deck). Insulation tested on only one side is issued a restricted approval, limiting the installation to locations where there is no fire hazard from the uninsulated side.

The FTP Code requires a steel core to be part of a B-class bulkhead panel test assembly for panels that are to be used as a component of A-class construction. To receive an unrestricted approval, two separate tests must be conducted: one test with the B-class bulkhead facing the fire and one test with the steel core facing the fire.

Interior finish materials tested to the FTP Code must pass a flame spread test using a radiant panel test apparatus that differs from the apparatus used to test interior finishes for U.S. domestic approval. In addition, they must pass smoke and toxicity testing in accordance with ISO 5659:1994.

The Coast Guard has not previously issued type approval certificates for fire doors, windows, or fire dampers. However, since the FTP Code requires these materials to meet the referenced fire resistance tests, the Coast Guard has established approval categories for these items.

Coast Guard type approval of structural fire protection materials requires the establishment of a follow-up inspection program monitored by an independent testing laboratory or other accepted organization to ensure that the materials shipped from the factory are representative of the test specimens. If production changes occur because of refinements in the base materials or the dimensions of the approved materials, additional fire testing must be conducted to confirm that the fire performance of the material has not been reduced.

High-Speed Craft

In the latter part of the twentieth century, the maritime industry began developing high-speed vessels for applications such as for use as rapid commuter ferries. Unfortunately, the prescriptive fire protection regulations in SOLAS did not allow the freedom to design and build fast ships that were cost effective. The traditional fire protection materials required by SOLAS add too much weight to a high-speed vessel's design. In response, IMO has developed the High Speed Craft Code (HSC Code) as a valid alternative to SOLAS for designers, builders, and operators to use for ships that meet the definition of a high-speed craft (HSC). HSCs are typically vessels 131 to 328 ft (40 to 100 m) in length, used to transport people, automobiles, and cargo at speeds generally in excess of 20 knots and, in some cases, up to 50 knots. Among other differences from SOLAS, the HSC Code allows the use of lighter-weight materials for the ship's structure, compartment divisions, bulkhead and ceiling linings, and furniture components. Materials of construction must be either noncombustible as defined by SOLAS or fire restricting. Fire-restricting materials are defined by the HSC Code as having low flame-spread characteristics, limited rate of heat release, and low smoke and toxic gas production. Fire-restricting materials are qualified using the ISO 9705 room corner test for ship's structures and compartment linings and the ISO 5660 cone calorimeter test for furniture components (not including upholstery).

Coast Guard Type Approval Program

All structural fire protection materials installed on U.S. flag vessels must be Coast Guard type approved. There are two methods for obtaining type approval; the type approval can be issued by the U.S. Coast Guard, or a European Community representative can issue the approval on behalf of the Coast Guard.

For a Coast Guard–issued type approval, the manufacturer is required to submit the product to a Coast Guard accepted independent laboratory for testing. When the laboratory testing is completed, the test report, pertinent component drawings, installation instructions, and the follow-up services agreement are submitted to the Coast Guard for review. If the appropriate acceptance criteria are satisfied, a type approval certificate is issued and the product is added to the list of approved materials on the Coast Guard website.

Coast Guard–issued type approvals are required to be under a production control or follow-up program conducted by the testing laboratory. The laboratory is required to visit the factory to witness the fabrication of the test specimen prior to conducting the approval tests. After the type approval certificate is issued, the laboratory is required to make periodic factory visits to ensure that the raw materials and production methods for the approved materials have not changed and that the materials being produced remain representative of the specimen that was tested.

The other means for obtaining type approval is to have the material tested at a European Community recognized laboratory. On February 27, 2004, the United States entered into a Mutual Recognition Agreement (MRA) with the European Community (EC) that recognizes type approvals issued by either party. Under the terms of the agreement, manufacturers can obtain a Coast Guard type approval directly from a European Community Notified Body.

MRA type approvals are issued by the EC Notified Body without any review or approval by the Coast Guard. The materials are tested at laboratories specified by the Notified Bodies, using test methods that follow the FTP Code. The Coast Guard does not maintain a listing of MRA approved materials.

FIRE PROTECTION SYSTEMS

The Coast Guard's philosophy on shipboard fire protection emphasizes the use of noncombustible materials and limited fire loads to control the magnitude and severity of expected fires. The use of flammable and combustible liquid fuels and cargoes could result in fires that require supplemental fire-extinguishing systems. The CFR, therefore, specifies protection of engine rooms, larger generator rooms, cargo holds and tanks, certain galley areas, and cargo pumprooms with fixed fire-extinguishing systems. Most of these systems are designed for manual activation to prevent an inadvertent discharge from adversely impacting operation of the ship.

Fire Main System

A fire pump and fire main system are required for the general protection of all shipboard areas. The fire main is intended as the primary means of fire protection in the accommodation and service areas. It is considered a supplemental system for the protection of the machinery spaces and the cargo areas, which are provided with other specialized fire-extinguishing systems. The fire pumps can be sized to supply the fire main and other water-based extinguishing systems such as foam systems, sprinkler systems, or water spray systems. The fire main is required to be arranged so that effective hose station coverage is available in all areas of a vessel. In the fire hose station on board a cruise ship shown in Figure 21.10.9, note the preconnected hose and nozzle, gate valve, and spanner wrench.

Each part of 46 CFR lists specific requirements for the number and capacity of fire pumps. The water supply capacity is based on the expected fire-fighting needs for vessels of the size and service regulated by that part of the rules. Typically, the main fire pump is an independently driven electric motor pump located in the main machinery space, although diesel engine and steam-driven pumps may be encountered. If multiple pumps are required, the pumps must be located in separate fire areas to prevent damage from a fire or accident from impacting all of the pumps.

In addition to separation of the pumps, the regulations also specify that the arrangement of sea connections and sources of power shall be such as to ensure that a fire in any one space will not put all of the fire pumps out of operation. Fire pumps take their suction from an opening in the hull of the ship, called a sea connection. It is common for ships to have several sea connections to supply water pumps for cooling of the machinery, as well as the fire pump.

Because of the many different hose coupling dimensions and thread patterns found worldwide, it is likely that the fire hoses on a ship may not easily connect to those in the various ports visited by the ship. To provide a backup means of supplying fire-fighting water to vessels in port, a universal adapter flange, called an international shore connection, was developed. International shore connections are required on all SOLAS vessels; they consist of a flat-bolted flange that can be attached to the ship's fire main.The flange has a flat face on one side and a permanently attached coupling that fits the ship's hydrants and hose connections on the other side. The international shore connection is bolted to a mating flange from the port using a gasket suitable for 150 psi (1034 kPa) service, together with four ⅝ in. (16 mm) bolts, 2 in. (50 mm) long through a predrilled bolt pattern (Figure 21.10.10).

Automatic Sprinkler Systems

Until recently, automatic sprinkler systems were required on large passenger vessels for the protection of only cargo spaces considered accessible during the voyage. In 1993, the domestic commercial vessel industry expressed an interest in constructing casino gambling vessels and dinner cruise vessels, using alternative designs that featured large, open public areas. Some proposed designs also incorporated atriums that connected multiple decks. The structural fire protection regulations require main vertical zone bulkheads every 131 ft (40 m), which effectively prevent the use of this "open space" concept. For design flexibility, the Coast Guard developed a method to permit the use of this new concept without main vertical zones if areawide automatic sprinklers are installed. In 1996, NFPA 13, *Standard for the Installation of Sprinkler Systems,* was modified to include a Coast Guard–sponsored chapter on marine sprinkler systems, which is used for the design of sprinkler systems on board domestic service vessels. NFPA 13 may also be used to design sprinkler systems for SOLAS vessels, provided the SOLAS requirements for automatic sprinklers, which may exceed those in NFPA 13, are also satisfied.

Marine sprinkler systems are arranged differently from those in buildings because of the quality of the water supply. In buildings, potable fresh water from tanks or the public water supply mains is generally available, whereas the water supply on ships is usually taken from salt water, or water which may contain sediment or other foreign materials. Because of this, clogging and corrosion of the sprinkler system piping and components can occur if they are not designed to accommodate

FIGURE 21.10.9 Typical Fire Hose Station on Board a Cruise Ship

FIGURE 21.10.10 Typical International Shore Connection Manifold Arrangement

raw water supplies. Additional components are thus required to maintain wet pipe marine sprinkler systems filled with potable fresh water. A limited capacity tank is also provided to supply the system for a short period, until the seawater pumps can pressurize the system. In the event the system operates, the sprinkler piping is flushed with fresh water before it is put back into service to prevent degradation. The limited exposure to salt water does not adversely affect the system piping.

Manual Sprinkler Systems

Manual sprinkler systems are intended for the protection of partially enclosed vehicle decks where the use of total flooding carbon dioxide is not practical. The systems use open head 3/8 or 0.375 in. (9.5 mm) sprinkler heads, arranged to discharge on the manual activation of a deluge or control valve. The systems are arranged to protect zones of approximately equal size on each deck area. The zones are overlapped so the end sprinklers on adjacent zones protect the same deck area.

Water Mist Systems

Marine water mist extinguishing systems were originally developed as a replacement for total flooding Halon 1301 systems in engine rooms. However, it was learned that they could be used as an alternative to automatic sprinklers for the protection of light-hazard accommodation and service occupancies. Because of their much lower flow rates, water mist system pipe sizes can be reduced, yielding measurable savings in cost and weight. The lesser amounts of water expelled by mist systems also benefit the overall stability of a vessel. Water mist systems require specialized strainers, components, and piping due to the very small orifices in the discharge nozzles.

Design and approval information regarding water mist systems intended for the protection of accommodation and service areas is contained in IMO Resolution A.800 (19), adopted in November 1995. This guide includes component testing information for water mist nozzles that is based on UL standard 199. It also contains four different fire test protocols using stateroom, corridor, public space, and shopping and storage area fuel packages. The tests are conducted in mock-up full-scale rooms that are considered representative of shipboard hazards. The acceptance criteria are based on maximum ceiling temperatures or a combination of maximum temperatures and damage to simulated furniture placed in the test rooms. Additional information about water mist system design is contained in NFPA 750, *Standard on Water Mist Fire Protection Systems.*

Design and approval information for total flooding water mist systems for the protection of machinery spaces and pumprooms is based on IMO MSC/Circ. 1165, *Revised Guidelines for the Approval of Equivalent Water-Based Fire-Extinguishing Systems for Machinery Spaces and Cargo Pump-Rooms.* This test procedure contains three separate elements: component test standards that evaluate the suitability of the water mist nozzles for use in the marine environment, fire-extinguishing tests that confirm the nozzle's ability to extinguish a variety of fuel oil and heptane pan and spray fires, and thermal management tests that determine the nozzle's ability to cool the test enclosure to less than 212°F (100°C) no later than 5 minutes after the activation of the system. Test experience with total flooding water mist systems has shown that it is not currently possible to positively extrapolate design parameters from a tested volume to a larger protected space; however, advances with computer modeling may allow this in the future. As a result, Coast Guard type approvals for total flooding systems are limited to installation in protected shipboard spaces with a volume no larger than that tested.

The 2000 SOLAS amendments require ships with engine rooms larger than 17,650 ft^3 (500 m^3) to have a fixed local application fire-fighting system in addition to a total flooding system. Casualty data has shown that fuel oil leaks and pressurized sprays striking heated surfaces are the leading causes of engine room fires. The requirement for a local application system is intended to provide a system capable of immediate release to cool the machinery space and limit fire damage until the engineering staff can be evacuated and the total flooding system is activated. Design and approval information for fixed local application water mist systems for the protection of high-hazard areas in machinery spaces is based on IMO MSC/Circ. 913, *Guidelines for the Approval of Fixed Water-Based Local Application Fire-Fighting Systems for Use in Category A Machinery Spaces.* Although the local application system is not intended to have the capability of extinguishing typical flammable liquid fires, its early activation can many times lead to extinguishment before the total flooding system is discharged. On ships with a total flooding water mist system, a branch of the total flooding system can be arranged with appropriate section valves to act as the local application system, provided the nozzles have successfully passed the required MSC/Circ. 913 fire testing.

Foam Systems

Foam fire-fighting systems are approved for tank vessel deck protection, machinery space boiler flat protection, and helicopter deck protection on mobile offshore drilling rigs and offshore supply vessels. Foam systems intended for marine use are required to be Coast Guard type approved as a system, because standard industrial foam system products installed on board ships may not provide effective protection. The primary concern is the tankship structure and piping systems that can be heated to temperatures significantly above the breakdown temperature of the foam blanket. The mass of steel components on ships is much greater than that typically involved with shoreside foam system applications. Thus, marine foam concentrates are tested to ensure that they provide superior breakdown resistance when in contact with hot metal surfaces, and that they continue to provide a seal adjacent to heated metal surfaces for an extended cooling period.

Another significant concern with tankship fires is the large quantities of flammable liquids available for combustion. The laboratory testing of marine foam liquid concentrates, therefore, evaluates their capability to extinguish significant, in-depth flammable liquid fires.

A third concern is the use of seawater to supply the foam system. Standard fire-fighting foams used by municipal fire de-

partments are only tested for their fire-extinguishing capability using fresh water. When they are mixed with salt water, these foam concentrates do not have equal fire-extinguishing effectiveness. The Coast Guard approval tests thus require the use of synthetic seawater.

The final concern is a foam concentrate's ability to contain reignited areas of the fuel after sections of the foam blanket have been disturbed. Coast Guard–approved foam liquids are approved by using a small-scale laboratory test derived from Federal Specification O-F-555C, which is no longer in print. The test standard currently appears in Annex F of NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam.* Breakdown of the foam on contact with heated surfaces is judged by the use of a square 10 ft by 10 ft (3 m by 3 m) steel test pan, 3 ft (0.9 m) in height. The fuel in the test pan is ignited and allowed to burn for 60 seconds before foam application is started. The fire-fighting effectiveness of the foam is evaluated by the use of 75 gal (284 L) of gasoline as the test fuel. The sealability of the foam is determined by the use of a square test pan instead of a round one, in conjunction with a torch test. The foam being tested is required to cover the entire fuel surface, including corners, in 2 minutes. It must also extinguish the test fire within 5 minutes. A burning torch is then passed over the foam blanket beginning 10 minutes after the start of foam application. The torch is eventually touched into the blanket to ensure that an effective seal remains present. The burnback resistance is determined at the end of the test by removing a 6 in. by 6 in. (152 mm by 152 mm) square section of the foam blanket and igniting the exposed fuel. The area of the burning fuel cannot increase beyond an opening measuring 20 in. by 20 in. (508 mm by 508 mm) after 5 minutes of burning.

During the laboratory fire testing, the quality of the foam is measured through a determination of its expansion ratio and its ability to retain water. The foam expansion ratio is measured by comparing the weight of a fixed volume of aerated foam to the weight of the same volume of nonaerated foam solution. Most of the foam concentrates approved for shipboard use have an expansion ratio between 6 to 1 and 12 to 1. The foam's ability to retain water is measured by determining the amount of time it takes for one-quarter of the water to drain out of an aerated foam sample. This measurement is called the foam's 25 percent drainage time.

The quality of the foam used to successfully pass the laboratory fire tests is characterized by its expansion ratio and 25 percent drainage time. The system discharge nozzles and monitors are flow tested to ensure that they produce foam that is comparable to that measured in the laboratory fire tests, thereby ensuring that the foam produced on the ship will be of the same quality. The construction of all devices used in an approved foam system must ensure that they will operate under the extreme environmental conditions likely in the marine environment. Foam system components are installed at exposed locations on deck, where they are routinely exposed to salt spray. Because of this, only corrosion-resistant materials, including stainless steel, brass, or bronze, are acceptable.

In addition to the usual petroleum products, some ships may carry chemical cargoes such as polar solvents, ethers, alcohols, and ketones. Protection of the cargo areas on these ships requires a different design approach because these types of cargoes are partially or completely miscible with water. Such cargoes require an alcohol-resistant foam concentrate capable of forming a barrier between the foam and the cargo. Significantly increased foam application rates may be necessary, depending on the fire hazard of the product. As a result, it is essential that the chemical properties and stowage locations of the cargo are known, to allow the design limitations of the system to be established. Systems may be designed either to protect against the "worst-case" product stored in any tank on the vessel or to protect specific chemicals located only in designated tanks. Because of the large amounts of foam required for "worst-case" products, designing for specific products or a group of products with similar fire-extinguishing requirements is a more typical situation. For further technical information regarding marine foam systems, see NFPA 11.

Carbon Dioxide Systems

The regulations in 46 CFR require the installation of total flooding carbon dioxide systems for the protection of machinery spaces and similar enclosed spaces where there is a possibility of a fire involving flammable or combustible liquids. Carbon dioxide extinguishing systems are also required for the protection of cargo holds whenever combustible Class A materials are carried.

For the successful use of shipboard total flooding carbon dioxide systems, it is necessary to discharge the system and then allow a "soak" time for the heated structures surrounding the space to cool below the reignition temperature of the fuel. Shipboard carbon dioxide systems are designed for a single application. After the system is discharged, there is no backup quantity of agent available. It is critical that the protected space be kept sealed until the danger of reignition is past. For machinery space systems, the discharge of carbon dioxide will likely extinguish the combustible liquid fire in a matter of minutes. However, the potential for reignition exists until all of the heated metal surfaces and other materials have cooled below the autoignition temperature of the fuel. This usually requires a waiting period of several hours after complete extinguishment before a machinery space can be reentered.

In contrast, cargo-hold extinguishing systems are designed to contain the fire until the vessel can make it to port. This is a result of the different combustion properties of solid materials versus liquids. With burning solids, the physical properties of the material and configuration of the surface can vary greatly, allowing combustion to penetrate into the core portions of the material and become a "deep-seated fire." The physical structure of the material then shields the active combustion zone from the surrounding air and causes a lower rate of heat loss. Complete extinguishment of burning Class A materials is very difficult using carbon dioxide and requires very high concentrations of agent.

Cargo-hold systems are not intended to completely extinguish a fire but to provide a reasonable degree of control. They are designed for an initial application of agent followed by periodic release of cylinders to maintain the extinguishing concentration. The system should keep the fire under control

until port is reached and extinguishment is completed by the local fire authorities. If the cargo hold is entered after the carbon dioxide is discharged, there is a serious concern that the fire could rekindle from the introduction of fresh air. There is also a significant risk to personnel attempting to enter the space. The hatches should be left secured until the vessel makes port. In cases where it appears that the fire has been extinguished by the system, the hatches should be kept sealed and regular checks of the temperature of the surrounding bulkheads made for at least 24 hours after extinguishment before reentry is attempted. Even in such cases, it is recommended that the hold not be entered until the vessel reaches port.

Marine carbon dioxide systems are designed to be self-contained. No power source on the ship is needed to discharge the system. The pressure to discharge the gas and operate the warning sirens and the interlocked ventilation and fuel shutoff equipment is provided by the internal pressure in the cylinders.

Shipboard fire-extinguishing systems are designed for a minimum concentration of 34 percent carbon dioxide by volume. A carbon dioxide concentration of 6 to 7 percent is considered the maximum level that humans can be exposed to without harmful effects. Because the quantity of carbon dioxide required for fire-extinguishing systems is well above that which can cause serious injury or death to humans, spaces that are protected by such systems must be evacuated before the extinguishing agent is released. Careful attention must also be paid to areas where carbon dioxide could be inadvertently discharged. Specific safety precautions must be followed whenever carbon dioxide systems are being inspected or serviced. The 2005 edition of NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems,* requires that manually operated total flooding systems installed for the protection of normally occupied engine rooms must have a system lockout valve, a pneumatic time delay with pneumatic predischarge warning sirens, and two independent manual release controls.

The Coast Guard approves both high- and low-pressure total flooding carbon dioxide systems. Low-pressure systems are usually specified where a large quantity of extinguishing agent is needed. The decision to install a high-pressure system or a low-pressure system is generally made on an economic basis.

Two types of system releasing arrangements are approved. A manually released configuration is used on the majority of systems and heat detectors are used to automatically release small systems. Coast Guard regulations permit automatically released carbon dioxide systems only for the protection of unoccupied spaces that are less than 6000 ft^3 (170 m^3) and have a suitable means of horizontal escape.

All manually released systems must be located in a protected storage room outside of the protected space. This requirement ensures that the equipment is not damaged by the fire and that if the remote releasing controls are inoperable, crewmembers can still access the carbon dioxide storage room and discharge the system by using the local manual controls. Automatically released systems that protect unoccupied spaces that are less than 6000 ft^3 (170 m^3) may be located inside the protected space. Additional information on the design of carbon dioxide systems can be found in NFPA 12.

Clean Agent Systems

The Coast Guard regulations specify that machinery spaces and pumprooms must be protected by gaseous-type fire-extinguishing systems. Traditionally, total flooding carbon dioxide systems have been used for this purpose. In the 1970s, the use of Halon 1301 systems became common because of concerns with the accidental discharge of carbon dioxide in occupied areas. Later, unease over the global warming potential of fluorocarbons led to the Montreal Protocol of 1987, which placed functional limits on the use of Halon 1301 as a fire-extinguishing agent. Because of the deterioration of the earth's ozone layer, the use of Halon 1301 in total flooding systems was effectively banned. It is specifically prohibited in SOLAS. As a result, new types of environmentally friendly halogenated and inert gas fire-extinguishing agents were developed. Although these agents are considered safe for use in occupied areas, their chemical properties require that they be used within defined safety parameters.

The U.S. Environmental Protection Agency is responsible for regulating the use of substances that are harmful to the environment. In 1994, new regulations were issued to establish the Significant New Alternatives Policy (SNAP) program. This program is intended to identify acceptable alternatives to known ozone-depleting substances that do not have adverse affects on human health or the environment. FM-200, FE-241, NOVEC 1230, and Inergen are SNAP-approved alternatives to Halon 1301 that are used in Coast Guard–approved systems. NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems,* provides detailed information on the design of these systems.

FIRE DETECTION SYSTEMS

Marine fire detection systems are Coast Guard approved to the criteria listed in 46 CFR 161.002. Basically, shipboard detection systems are identical to those used in buildings, except that the circuit boards, wiring, and connectors are designed to handle the corrosion and vibration common to shipboard installations. Fire alarm control panels are tested to typical industry standards such as UL 864, and the panels must undergo supplemental testing for exposure to increased levels of humidity and vibration. The control panels must also be shown to function properly when inclined. Coast Guard approved detection systems have specific circuit testing and power transfer features that differ from those found on standard panels. Coast Guard approval is granted for complete detection systems; the mixing of components between different approved systems is not permitted.

Initiating devices used for detection systems include heat, smoke and flame detectors, and manual pull stations. Notification appliances can be either audible or visual. The Coast Guard has no particular approval tests for these devices and relies instead on independent laboratory approval and listing. The vessel regulations specify which type of device is to be installed for the protection of specific hazards.

Fire detection systems on large passenger vessels are complex due to the large number of detection devices required throughout the ship. Typical systems monitor several thousand

devices. The fire alarm control panels are usually located on the navigating bridge or in a continuously attended fire control station. It is typical for these systems to be designed with a presignal feature that allows the crew to investigate the fire before an evacuation signal is given. This arrangement is preferred because the evacuation procedures on passenger ships require careful coordination of the crew members to channel passengers to the correct embarkation stations and survival craft. The time delay between notification of the crew and sounding of the general evacuation alarm enables the crew to assemble and make necessary preparations. However, a series of casualties in the 1990s revealed that immediately evacuating passengers from the fire-affected area while the crew investigates may be advantageous.[8] Many of the major cruise lines have since voluntarily decided to supplement the required SOLAS fire alarm system with spot-type smoke detectors that give immediate occupant notification in the local area.

LIFE SAFETY CONSIDERATIONS

The following discussion focuses on the means of egress requirements for large passenger ships. The means of egress requirements for smaller passenger ships (Subchapter T and K), cargo ships, and tankers are much less complex. The individual vessel regulations should be consulted for more information on these type ships.

Means of Egress

The means of egress from occupied shipboard spaces is based on many of the fundamental principles inherent in NFPA *101,* with a number of characteristic differences relating to the design and operation of ships. All ships are required to be designed with two means of egress from occupied areas. However, the arrangement of the means of egress, the components of the means of egress, and the evacuation procedures used in an emergency can vary significantly. Cruise ships usually carry passengers with a broader diversity of physical abilities, cognitive skills, and languages than are found in most buildings, which may cause confusion and delays during an evacuation. However, trained crew members are always present to respond to emergencies and assist the occupants. The trained crew has the potential to rapidly suppress the fire, limiting its effect on the passengers. The crew can also assist in speeding the evacuation by taking control of the situation and directing the passengers to the correct exits. The use of a directed evacuation eliminates many of the human behavioral delays associated with the public response to an unanticipated fire emergency.

The exit system on ships is not designed to move passengers to the public way, since the water surrounding the ship is not considered a safe refuge area. The occupants are, instead, directed to refuge areas called *assembly stations.* (These areas are also referred to as muster stations on some ships.) The assembly stations are adjacent to or near the location where the survival craft are boarded. If a fire occurs that requires a general evacuation, the passengers are first moved to the protected assembly stations while the crew fights the fire. The ship is evacuated only if it is likely to sink.

General Life Safety Requirements. The goals and objectives for occupant life safety on ships are similar to those in buildings, namely, the construction features must be arranged to provide two safe escape routes for the passengers and crew, the escape routes must be maintained in a safe condition clear of obstacles, and additional aids must be provided to clearly identify and illuminate the escape paths. Two means of egress must be available from all areas, and they must be separated to the extent necessary that a single fire will not block both paths. On passenger ships, however, there are additional considerations not relevant to building construction. For example, the bulkheads and decks below the waterline must be watertight to limit the possible extent of flooding during an accident. Any openings in these watertight bulkheads are fitted with heavy steel watertight doors, which are either power operated or manually secured by multiple latching dogs. In Figure 21.10.11, which shows a typical watertight sliding door installation, the door is on the left of the doorway and the hydraulic mechanism and its operating lever for closing and opening the door are located on the right side of the doorway. Watertight doors cannot always be opened in a reasonable time period. The regulations thus specify that one of the means of egress must be independent of watertight doors to prevent unnecessary delays in evacuation times.

Means of Egress Components. Shipboard means of egress components are similar to those in buildings. Doors, ramps, and stairs commonly provided are similar to their land-based counterparts. However, because of space limitations on ships, the effective width of the components is usually less than that permitted by NFPA *101*. Another design consideration is the prospect that the ship could list or roll to one side, which would seriously impair the occupants' ability to rapidly traverse corridors and stairways. SOLAS thus requires stairways intended for use by more than 90 occupants to be situated in a fore and aft direction. In this configuration, the stair treads are parallel to the width of the ship. If the ship lists to one side, the angle of inclination of the stair remains fixed. Fire doors are also designed to close against a 3.5 degree opposing angle for the same reason.

Arrangement of Means of Egress. The stairways on ships are not required to be remotely located based on a diagonal dimension criterion, similar to NFPA *101*. This sort of requirement is

FIGURE 21.10.11 Typical Watertight Sliding Door Installation

not practical to implement on ships due to their horizontal arrangement and varying deck areas. Because the decks on a ship are usually not the same length, the stairways may not serve all areas on each deck. It is common to have a vessel design where some of the stairways end before they reach the level of the assembly stations. In such cases, horizontal means of egress are provided to allow the occupants to access an adjacent stairway to continue toward the assembly stations.

Measurement of Travel Distance. SOLAS requires large passenger ships to be divided into fire areas by the installation of 1-hour-rated main vertical zone bulkheads every 131 ft (40 m). Each main vertical zone is required to have two means of egress, which essentially limits the maximum travel distance to an exit. The requirement for main vertical zones is applicable to all areas on the ship, notwithstanding the type of occupancy. The vessel regulations, therefore, do not contain provisions for maximum travel distances.

Discharge from Exits. The exit discharge provisions on passenger ships are significantly different from those required for buildings. Emergency response procedures do not call for an immediate evacuation. Ships operate at sea, where the ship and its survival craft are the only buoyant platforms available for the safe refuge of the occupants. The ship is designed to safely and comfortably transport the passengers and crew in almost any weather or sea state. The survival craft are a last recourse for the occupants, if the sinking of the ship is imminent. Consequently, if a fire occurs, the occupants are initially marshaled to areas of safe refuge on the ship. The assembly stations may be near the survival craft or in large public restaurants or theaters. The direction of travel from the assembly stations to the survival craft could ultimately be different from the direction of travel the passengers originally followed to reach the assembly areas. The structural fire protection features and installed fire detection and suppression systems are designed to allow the crew to control the fire, making evacuation unnecessary except in extreme situations.

Emergency Lighting

Passenger ships are fitted with emergency lighting systems to illuminate the egress paths along the normal corridors and stairways to the assembly stations and survival craft areas. In addition, emergency lighting is provided to illuminate the survival craft boarding areas and the sides of the ship, including the water below. This is different from emergency lighting in typical buildings. Most building codes do not require illumination of the public way, only the egress paths leading to the public way. Additional emergency lighting is needed on ships to coordinate the launching of the survival craft and, if necessary, the rescue of persons who may have fallen or jumped into the water. The regulations also call for a specialized emergency lighting and exit marking system throughout the accommodation areas. Low-location lighting, using either electrical or photoluminescent strips installed no more than 1 ft (0.3 m) above the deck, is provided to help direct the occupants to the assembly stations. This additional level of emergency lighting is intended to supplement the overhead lighting during a power failure and also allows the occupants to more readily recognize the location of the exits if the corridors become smoke-filled.

IMO has recognized a new development in evacuation guidance systems that uses sound signals to identify evacuation routes. Although the low-location lighting is required to be mounted close to the deck, there is the possibility that smoke obscuration could reduce its effectiveness. The directional sound guidance system consists of strategically placed speakers that produce a broadband sound pattern optimized to allow the occupants to distinguish the direction of exit travel despite visibility. Performance standards for such systems have been developed and are listed in IMO MSC/Circ. 1168, *Interim Guidelines for the Testing, Approval and Maintenance of Evacuation Guidance Systems Used as an Alternative to Low-Location Lighting Systems.* Systems that successfully pass the testing criteria may be substituted for the required low-location lighting system.

Evacuation of Large Passenger Ferries

Passenger ferries have particular stability concerns attributable to the design of their vehicle carrying decks. The vehicle decks on ferries are usually large open spaces, without the benefit of main vertical zones or other means of subdivision. Past casualty experience has shown that an accident that causes flooding of the vehicle decks may cause the ship to capsize or sink much more rapidly than is the case in a standard passenger ship.[9] To offset this, SOLAS requires that the evacuation routes of all roll-on/roll-off passenger vessels built on or after July 1, 1999, be evaluated by an evacuation analysis during the design process. Typical ferry-loading operations have the passengers drive their vehicles on board and park in the designated lanes. The passengers then leave their vehicles and proceed to the accommodation or waiting areas of the ship for the duration of the voyage.

Depending on the duration of the trip, the passengers may wait in large public waiting areas, or, if the voyage is overnight, the passengers may be assigned to individual cabins. The evacuation analysis is intended to identify possible areas where congestion could slow the escape process. The analysis is also used to evaluate the flexibility of the egress design by simulating the blockage of one of the two required escape paths. Similar evacuation analysis requirements will be applied to all passenger ships in the future.

PERFORMANCE-BASED DESIGN

CFR and SOLAS fire protection regulations contain prescriptive requirements based on many years of practical operating knowledge, combined with lessons learned from marine casualty investigations. The regulations address typical ship designs and the expected fire risks on standard cargo, passenger, and tankships. The shipbuilding industry is continually developing novel and unique ship designs to carry different cargoes, to carry cargoes more economically, or to provide passengers with more luxury and entertainment options. Unconventional ship designs must be fit into these few basic regulatory categories. Unfortunately, the regulations offer no mechanism to determine

if the prescriptive level of fire protection required is adequate or overly excessive for the particular arrangement.

A positive step in the advancement of alternative ship design and arrangements was taken by IMO in the 2000 revision of SOLAS. A new regulation was included that allows the use of fire safety engineering to show that alternative design and arrangements offer an equivalent level of safety as the prescriptive regulations. This new regulation allows ship designers to use industry-accepted fire safety engineering principles such as the *SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings* and comparable guides for this purpose.

There is one major point in the application of this concept that differs significantly from land-based projects. If a building is approved using a performance-based design approach, it does not need to be reevaluated by the AHJ unless it changes occupancy. The SOLAS Convention permits ships open access to ports around the world, because all signatory countries are obligated to accept a SOLAS safety certificate as evidence of a ship's compliance with the convention. If the port state was not a participant in the review of the alternative design concept for a particular ship, compliance to the prescriptive regulations may be expected and the ship could be denied entry. To remedy this, IMO has issued guidelines that describe the necessary steps that should be followed to approve an alternative design. The guidelines also include suggested levels of documentation to carry on board the ship at all times for the use of port state inspectors.

EMERGENCY RESPONSE TO SHIP FIRES

Fires on board ships present a number of unique circumstances that must be carefully considered before a fire department reacts to a marine emergency. Fire departments in port cities must respond to ship fires, yet they may have limited experience in the differences between building fires and ship fires. Careful preincident planning of the roads and water supplies to the port, the vessels using the port, and the expected cargoes being handled is essential to ensuring an effective response.

Comprehensive training, operational information, and guidance for shoreside responders to shipboard fires are contained in NFPA 1405, *Guide for Land-Based Fire Fighters Who Respond to Marine Vessel Fires.* Despite the information the standard provides, many shoreside fire fighters are ill prepared for the complexity of fighting a shipboard fire, as found in the accident investigation of the tankship *Seal Island,* which occurred in the U.S. Virgin Islands on October 8, 1994.[10] Ships' decks and main bulkheads are steel, retain the heat of combustion for a long period of time, and can make locating the fire more difficult; spaces and access are more restricted than is the case in buildings, thus making fire fighting and retreating confusing; and the accumulation of water on decks can worsen the situation.

Most importantly, the command structure for fighting a shipboard fire is not always understood. At sea, only the crew is available to respond to fire emergencies; in port, shoreside fire fighters are likely to be called by the Coast Guard.

One readily available piece of information critical for fire fighting is located aboard the ship. All U.S. vessels of 1000 gross tons and over and all vessels subject to SOLAS must permanently display a fire-fighting plan or fire control plan of the ship. Although the plan's primary purpose is to guide shipboard personnel, it should contain the following information to assist port fire-fighting groups:

- Fire control stations for each deck
- Sections enclosed by fire-resistive divisions
- Fire alarms, detection systems, and sprinkler systems
- Fire-extinguishing appliances
- Access to different compartments, decks, and so on
- Ventilating systems, including master fan controls, positions of dampers, location of remote controls, and identification numbers of ventilating fans serving each section

Instead of being posted on a plan, the information listed can be described in a fire-fighting booklet. The booklet is required to be aboard ship at all times. Whether posted as a fire-fighting plan or presented in booklet form, information should be available on all watertight compartments, openings therein, and means of closure, controls, and arrangements for correcting any list due to flooding.

SOLAS '74 requires that a duplicate set of fire control plans be permanently stowed in a prominently marked, weathertight enclosure outside the deckhouse to assist shoreside fire-fighting personnel. Figure 21.10.12 illustrates a fire-fighting plan for the aft end of a super tanker.

The international community has also agreed on standard symbols for fire control plans (Figure 21.10.13). Most symbols are to be shown in red on the general arrangement plan to highlight their location for shipboard and shoreside fire fighters.

NFPA MARINE STANDARDS

In 1994, the U.S. Coast Guard and the marine community embarked on an ambitious project to shift development and maintenance of fire protection regulations applicable to U.S. flagged commercial ships to consensus standards-making organizations. The cornerstone of this effort is NFPA 301, *Code for Safety to Life from Fire on Merchant Vessels,* a "life safety code" for ships. Additionally, chapters on marine application have been added to NFPA 11, NFPA 12, NFPA 13, NFPA 750, and NFPA 2001.

Other NFPA standards relating to marine vessels are contained in NFPA 306; see also NFPA 312, *Standard for Fire Protection of Vessels During Construction, Conversion, Repair, and Lay-Up.* NFPA 306 describes the conditions necessary for safety before repairing any vessel carrying or having carried fuel as cargo, combustible or flammable liquids, flammable compressed gases, and bulk chemicals. NFPA 306 is also the basis for confined space safety in the maritime industry and must be followed by the NFPA-certificated marine chemist. It also contains a section on flammable cryogenic liquid carriers. NFPA 312 covers measures for preventing and controlling fires on vessels in the building or repair yard or on vessels that are laid up. Provisions for each circumstance appear separately in the standard.

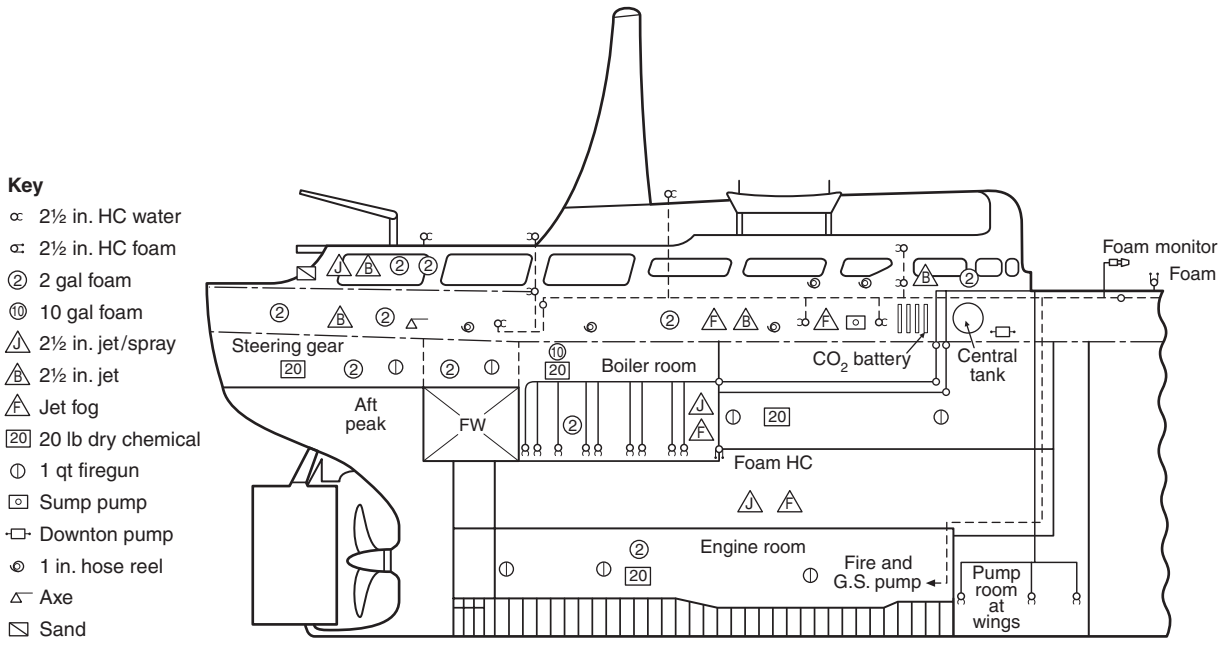


FIGURE 21.10.12 Fire-Fighting Plans for the Aft End of a Super Tanker

OTHER ORGANIZATIONS CONTRIBUTING TO MARINE FIRE SAFETY

American Bureau of Shipping

The American Bureau of Shipping (ABS) is the American classification society whose technical committees develop rules for the dimensions and use of materials in the construction and conversion of marine vessels. After a vessel is completed according to the rules and under the constant supervision of an ABS field inspector, the bureau classes and lists it as having met all design and structural safety requirements.

American Petroleum Institute

In the area of marine fire fighting and fire protection, the American Petroleum Institute (API) is active in developing domestic and international standards, codes, and regulations. Under the policy direction of the API Central Committee on Transportation by Water, most actions are directed by the API Committee on Tank Vessels. Ad hoc groups are sometimes formed for special studies of a nonrepetitive nature.

Marine Chemist Association, Inc.

Established in May 1938 as the Marine Chemists' Subsection of the NFPA Marine Section, the Marine Chemists organized its present association in 1948 after the Marine Section disbanded. This professional organization of chemists is certificated for marine work by NFPA in accordance with provisions of NFPA 306.

National Cargo Bureau, Inc.

The National Cargo Bureau is a nationwide, nonprofit membership organization established in 1952 as a private, nongovernmental agency that formulates recommendations to various governments for regulating the safe stowage of dangerous goods and other cargoes and for regulating related cargo-handling gear.

National Transportation Safety Board

The National Transportation Safety Board (NTSB) is an independent federal agency dedicated to promoting aviation, marine, railroad, highway, pipeline, and hazardous materials safety. Established in 1967, the agency is mandated by Congress through the Independent Safety Board Act of 1974 to investigate transportation accidents, including those involving fire, explosion, and pollution; determine the probable cause of accidents; issue safety recommendations; study transportation safety issues; and evaluate the safety effectiveness of government agencies involved in transportation. The Safety Board makes public its actions and decisions through accident reports, safety studies, special investigation reports, safety recommendations, and statistical reviews.

USCG Advisory Committee on Hazardous Materials

This committee of the National Academy of Sciences, National Research Council, is charged with advising the U.S. Coast Guard on scientific and technical matters relating to safe maritime transportation of hazardous materials.

Fire control plan (red/black)

Push button/switch for fire alarm (red/black)

Horn fire alarm (red/black)

Bell fire alarm (red/black)

Manual-operating position fire alarm (red/black)

Space protected by automatic fire alarm (red/black)

Fire alarm panel (red/black)

Sprinkler installation (red/black)

Space protected by sprinkler (red/black)

Sprinkler horn (red/black)

Sprinkler section valve (red/black)

CO_2 battery (red/black)

Space protected by CO_2 (red/black)

CO_2 horn (red/black)

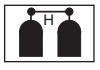
CO_2 release station (red/black)

Halon 1301 battery (red/black)

Space protected by Halon 1301 (red/black)

Halon horn (red/black)

Halon release station (red/black)



Halon 1301 bottles placed in protected area (red/black)

Powder installation (red/black)

Powder monitor (gun) (red/black)

Powder hose and handgun (red/black)

Powder release station (red/black)

Foam installation (red/black)

Foam monitor (gun) (red/black)

Foam nozzle (red/black)

Space protected by foam (red/black)

Foam valve (red/black)

Foam release station (red/black)

Fire main with fire valves (red/black)

Hose box with spray/jet fire nozzle (red)

International shore connection (red/black)

Fire pump (red/black)

Emergency fire pump (red/black)

Remote control fire pumps or emergency switches (red/black)

Bilge pump (black)

Emergency bilge pump (red/black)

Water monitor (gun) (red/black)

Water fog applicator (red/black)

Drenching installation (red/black)

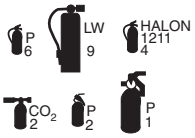
Space protected by drenching system (red/black)

Section valves drenching system (red/black)

(continued)

FIGURE 21.10.13 Symbols for Use in Accordance with Regulation 11-2/20 of the 1974 SOLAS Convention as Amended

Portable fire extinguishers (red/black)



Wheeled fire extinguishers (red/black)

Fire station (red)

Locker with fireman's outfit (red)

Locker with additional breathing apparatus (blue/black)

Locker with additional protective clothing (red/black)

Primary means of escape (green/black)

Secondary means of escape (green/black)

Class A division (red/black)

Class B division (yellow/black)

Fire damper in vent duct (red/black)

Remote control skylights (black)

Remote control fuel/lubricating oil valves (red/black)

Control station (red)

Portable foam applicator (red/black)

Inert gas installation (red)

High-expansion foam supply truck (red/black)

CO_2/Nitrogen bulk inst. (red/black)

Emergency generator (red/black)

Emergency switchboard (red/black)

Class A fire door (red/black)

Class A fire door (red/black)

Class A fire door self-closing (red/black)

Class A fire door self-closing (red/black)

Class B fire door (yellow/black)

Class B fire door (yellow/black)

Class B fire door self-closing (yellow/black)

Class B fire door self-closing (yellow/black)

Closing appliance for exterior ventilation inlet or outlet (red/black)

Remote ventilation shutoff (black)

Main vertical zone (red/black)

Smoke detector (red/black)

Heat detector (red/black)

Gas detector (red/black)

Flame detector (red/black)

Emergency telephone station (red/black)

Fire ax (red/black)

FIGURE 21.10.13 Continued

SUMMARY

Fires and explosions are frequent contributors to marine vessel injuries and fatalities. In pleasure and small commercial boats, gasoline is commonly used for both propulsion engines and onboard generators, and liquefied petroleum gas (LP-gas) is commonly used for cooking. Boats are constructed in such a way that they are closed on the bottom and on all sides, resulting in less effective ventilation than found in other types of vehicles such as trains and aircraft. Means of fire protection include leak-free fuel systems, ventilating systems, unobstructed areas and escape hatches, fire-retardant coatings for flammable materials, lightning protection, proper installation of electrical systems, and fire extinguishers. Safety procedures include thorough maintenance, inspection, and testing, careful fueling operations, and proper storage of the boat when not in use.

Fire protection regulations for commercial ships and offshore marine vessels are covered by the *Code of Federal Regulations* (CFR) and, for international voyages, the International Convention for the Safety of Life at Sea (SOLAS). The regulations are specific to different types of vessels, such as passenger ships, cargo vessels, and supply vessels. Marine fire protection considerations include construction materials and design, fire-extinguishing and fire detection systems, and evacuation. Fire hazards should be analyzed and controlled in the three major occupancies common to all ships: the engine room, the cargo holds or tanks, and the accommodation and service areas. Fire prevention measures include limiting the use of combustible construction materials and the safe handling and use of combustible materials, flammable liquids, and ignition sources.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on marine fire hazards discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of the current edition of the following documents.)*

NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 12, *Standard on Carbon Dioxide Extinguishing Systems*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 30A, *Code for Motor Fuel Dispensing Facilities and Repair Garages*
NFPA 52, *Vehicular Fuel Systems Code*
NFPA *101®*, *Life Safety Code®*
NFPA 301, *Code for Safety to Life from Fire on Merchant Vessels*
NFPA 302, *Fire Protection Standard for Pleasure and Commercial Motor Craft*
NFPA 303, *Fire Protection Standard for Marinas and Boatyards*
NFPA 306, *Standard for the Control of Gas Hazards on Vessels*
NFPA 312, *Standard for Fire Protection of Vessels During Construction, Conversion, Repair, and Lay-Up*
NFPA 750, *Standard on Water Mist Fire Protection Systems*
NFPA 1405, *Guide for Land-Based Fire Fighters Who Respond to Marine Vessel Fires*
NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*

Chapter 11

Road Tunnels and Bridges

Arthur G. Bendelius

Chapter Contents

Road Tunnels
Key Elements of Road Tunnel Fire Protection
Identification, Verification, and Location of Fires
Emergency Communications
Smoke Management
Fire Suppression
Emergency Response Planning
Evacuation and Rescue
Engineering Analysis
Tunnel Fire Tests
Road Bridges

Key Terms

emergency communication, emergency planning, fire model, fire pump, fire test, point of safety, portable fire extinguisher, road bridge, road tunnel, smoke management, standpipe, tenability, ventilation (mechanical), ventilation (natural), ventilation system, water supply

This chapter addresses the unique fire protection and life safety considerations and challenges posed by road tunnels and road bridges. A road tunnel is defined as any enclosed facility through which road vehicles (cars, vans, buses, and trucks) travel. These vehicles are typically powered by internal combustion engines using traditional fuels such as gasoline and diesel. However, in recent years vehicles powered by alternative fuels such as CNG, LP-gas, LNG, or one of the blends of gasoline and feedstock fuel such as ethanol are becoming prevalent in the vehicle fleet.[1]

Road tunnels are usually constructed to overcome an obstacle, such as a mountain or a body of water. However, several new road tunnels result from the developmental benefits of the real estate created by putting roadways below the surface and developing the air rights above. Road tunnels are therefore typically catagorized, based on the obstacle encountered, as follows: mountain tunnel, subaqueous (underwater) tunnel, urban tunnel, or air-rights tunnel.

Fire protection for road tunnels requires a unique application of common fire protection, fire fighting, and fire suppression systems and techniques. The fire load in a tunnel is continuously changing and is basically unpredictable. The potential always exists, however, for fires to occur that are of significant scale in comparison to most commercial structures. Also, unlike commercial or industrial buildings and facilities, road tunnels do not offer any compartmentalization, making evacuation and rescue far more difficult. The entire population to be rescued will most likely be in the same "compartment" as the fire, and because a tunnel is essentially a linear structure, the fire must be fought from a position in the same compartment. This chapter addresses the unique aspects of road tunnel fire protection and explores the application of standard fire protection, fire suppression, and fire-fighting system practices and techniques to road tunnels.

Similar to road tunnels, bridges designed to carry vehicle traffic offer very limited access to emergency responders and can therefore pose unique challenges in the ability to ensure motorist life safety protection in the case of a fire. This chapter addresses the fire protection considerations for bridges built to transport road vehicles over another road, a railroad, a waterway, or a valley.

For related topics, see Section 12, Chapter 15, "Public Emergency Services Alarm, Dispatch, and Communications Systems"; and Section 16, Chapter 8, "Water Mist Fire Suppression Systems."

ROAD TUNNELS

History of Road Tunnel Fires

There are more than 150 road tunnels in the United States and several thousand more throughout the world. Table 21.11.1 lists some of the major operating U.S. road tunnels and their categories, length, and ventilation systems.

There have been over 30 reported serious road tunnel fires since the first one occurred over 60 years ago in New York's Holland Tunnel in 1949.[2] Serious road tunnel fires are those in which there

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TABLE 21.11.1 Selected U.S. Operating Road Tunnels

Tunnel	*Date Opened*	*Category*	*Location*	*Length (ft)*	*Length (m)*	*Bores/ Lanes*	*Ventilation System*
Anton Anderson*	2000	Mountain	Alaska	13,727	4184	1/1	Longitudinal
Brooklyn Battery	1950	Subaqueous	New York	9,210	2807	2/4	Full transverse
Ted Williams	1995	Subaqueous	Massachusetts	8,957	2730	2/4	Full transverse
Holland	1927	Subaqueous	New York-New Jersey	8,530	2600	2/4	Full transverse
Lincoln	1937	Subaqueous	New York-New Jersey	8,216	2504	3/6	Full transverse
	1945			8,005	2440		
	1957			7,484	2281		
Eisenhower	1973	Mountain	Colorado	8,148	2484	1/2	Full transverse
Central Artery-I93	2003	Urban	Massachusetts	8,100	2469	2/6	Full transverse w/ longitudinal on some ramps
Baltimore Harbor	1957	Subaqueous	Maryland	7,710	2350	2/4	Full transverse
Hampton Roads	1958	Subaqueous	Virginia	7,470	2277	2/4	Full transverse
	1975			7,314	2229		
Fort McHenry	1985	Subaqueous	Maryland	7,215	2199	4/8	Full transverse
Queens Midtown	1940	Subaqueous	New York	6,400	1951	2/4	Full transverse
Allegheny	1940	Mountain	Pennsylvania	6,073	1851	2/4	Semitransverse
	1966						
Liberty	1924	Mountain	Pennsylvania	5,905	1800	2/4	Longitudinal
Thimble Shoal	1964	Subaqueous	Virginia	5,740	1750	1/2	Full transverse
East River	1974	Mountain	Virginia-West Virginia	5,661	1726	2/4	Full transverse
Sumner	1934	Subaqueous	Massachusetts	5,657	1724	1/2	Full transverse
Baltimore Channel	1961	Subaqueous	Virginia	5,450	1661	1/2	Full transverse
Bankhead	1941	Subaqueous	Alabama	5,390	1643	1/2	Semitransverse
Tuscarora	1960	Mountain	Pennsylvania	5,328	1624	2/4	Semitransverse
	1968						
Central Artery-I90 Extension	2003	Urban	Massachusetts	5,300	1615	4/7	Full transverse w/ longitudinal on some ramps
Harano	1997	Mountain	Hawaii	5,165	1574	2/4	Full transverse
				4,890	1491		
Detroit Windsor	1930	Subaqueous	Michigan-Ontario	5,125	1562	1/2	Full transverse
Callahan	1961	Subaqueous	Massachusetts	5,085	1550	1/2	Full transverse
Monitor Merrimac	1992	Subaqueous	Virginia	4,783	1458	2/4	Full transverse
Kittatinny	1940	Mountain	Pennsylvania	4,728	1441	2/4	Semitransverse
	1968						
Cumberland Gap	1996	Mountain	Kentucky-Tennessee	4,600	1402	2/4	Longitudinal
Lehigh	1940	Mountain	Pennsylvania	4,462	1360	2/4	Semitransverse
	1991			4,380	1335		Longitudinal
Blue Mountain	1940	Mountain	Pennsylvania	4,340	1323	2/4	Semitransverse
Big Walker	1972	Mountain	Virginia	4,229	1289	2/4	Full transverse
Squirrel Hill	1953	Mountain	Pennsylvania	4,225	1288	2/4	Semitransverse
Elizabeth River-Midtown	1962	Subaqueous	Virginia	4,194	1278	1/2	Full transverse
Fort Pitt	1960	Mountain	Pennsylvania	3,603	1098	2/4	Semitransverse
Posey	1928	Subaqueous	California	3,545	1081	1/2	Full transverse
Mount Baker Ridge	1989	Urban	Washington	3,501	1067	3/8	Full transverse
Mall	1973	Urban	District of Columbia	3,400	1036	2/8	Full transverse
Mobile River	1972	Subaqueous	Alabama	3,380	1030	1/2	Longitudinal
Elizabeth River	1954	Subaqueous	Virginia	3,350	1021	2/4	Full transverse
Downtown	1986			3,814	1163		Semitransverse
Caldecott	1982	Subaqueous	California	3,350	1021	3/6	Full transverse
Webster Street	1963	Urban	California	3,350	1021	1/2	Full transverse
Mercer Island	1999	Urban	Washington	2,999	914	3/8	Full transverse
Wilson	1960	Mountain	Hawaii	2,813	857	2/4	Semitransverse
				2,775	846		
Lowry Hill	1971	Urban	Minnesota	1,496	456	3/6	Semitransverse
Battery Street	1952	Urban	Washington	2,100	671	2/4	Hybrid supply
Pali	1961	Mountain	Hawaii	1,577	481	2/4	Natural
	1957			1,500	457		

*A combined road/rail tunnel.

has been loss of life or significant property damage to either vehicles or tunnel structure. Table 21.11.2 lists selected road tunnel fires involving either loss of life, damage to vehicles, or damage to a significant portion of the tunnel, beginning with the 1949 Holland Tunnel fire.[2] In 1999 and 2001 several extremely serious road tunnel fires occurred. Three of these occurred in long single-bore, bidirectional trafficked, Alpine tunnels. (As illustrated in Figure 21.11.1, a bore is defined as a longitudinal compartment of a tunnel, either in a separate structure or in a single structure divided by a solid wall or rock.) The first of these Alpine tunnel fires occurred in the Mont Blanc Tunnel between France and Italy on March 24, 1999,[3,4] the second occurred in the Austrian Tauern Tunnel on May 29, 1999,[4] and the third occurred in the Swiss St. Gotthard Tunnel in October 2001.[4] Details of these three serious road tunnel fires are shown in Table 21.11.3.

Unknown Fire Loads

One of the major factors to be considered in the fire protection of a road tunnel is the unknown nature of the potential fire load. In other transportation tunnels, such as transit tunnels, the potential fire load can be estimated with reasonable accuracy, since both the vehicles and the passenger load are controlled by the operating agency. Such is not the case for the typical road tunnel, where an innocent-looking truck may be carrying a load that is capable of supporting a fast-growing, potentially lethal fire, but that is not necessarily "classified" as hazardous cargo.

TABLE 21.11.2 Selected Serious Road Tunnel Fires

	Tunnel Length								
Tunnel	*ft*	*m*	*Opening Date*	*Country*	*Fire Date*	*Fatalities*	*Injuries*	*Vehicles*	*Tunnel Damage*
Holland	8,180	2,550	1927	United States	1949	0	66	23	Serious
Moorfleet	797	243	—	Germany	1968	0	0	1	Serious
Guadarrama	10,731	3,345	1972	Spain	1975	0	0	1	Serious
Velser	2,470	770	1957	Netherlands	1978	5	5	6	Serious
Nihonzaka	6,560	2,045	1978	Japan	1979	7	2	173	Serious
Kajiwara	2,374	740	1963	Japan	1980	1	0	2	Serious
Sakai	1,472	459	—	Japan	1980	5	5	NA	Serious
Caldecott	3,298	1,028	1964	United States	1982	7	2	8	Serious
Percoile	2,124	662	1967	Italy	1983	8	22	10	Limited
Frejus	41,367	12,895	1980	France/Italy	1983	0	1	1	Serious
St. Gotthard	54,273	16,918	1980	Switzerland	1984	0	0	1	Serious
Felbertauren	17,015	5,304	1967	Austria	1984	0	0	1	Serious
L'Arme	3,625	1,105	1979	France	1986	3	5	5	Limited
Gumefens	1,100	343	1981	Switzerland	1987	2	5	3	Slight
Tanzenberg	7,847	2,446	1983	Austria	1987	0	1	NA	Serious
Brenner	2,634	803	1971	Italy	1989	2	9	NA	Serious
Serra Ripoli	1,418	442	—	Italy	1993	4	4	15	Limited
Huguenot	12,556	3,914	—	South Africa	1994	1	28	1	Serious
St. Gotthard	54,273	16,918	1980	Switzerland	1994	0	0	2	Serious
Pfänder	21,555	6,719	1980	Austria	1995	3	4	4	Serious
Isola delle Femine	475	148	—	Italy	1996	5	20	20	Serious
Gleinalm	26,691	8,320	1978	Austria	1998	0	0	1	Serious
Mont Blanc	37,213	11,600	1965	France/Italy	1999	39	NA	27	Serious
Tauren	20,534	6,401	1975	Austria	1999	12	49	40	Serious
Seljestad	4,081	1,272	1964	Norway	2000	0	6	NA	Serious
Gleinalm	26,691	8,320	1978	Austria	2001	5	4	2	—
Guldborgsund	1,476	460	1988	Denmark	2001	5	6	NA	—
St. Gotthard	54,273	16,918	1980	Switzerland	2001	11	0	2	Serious
Ostwaldiberg	1,476	460	1988	Austria	2002	1	NA	1	Serious
Baregg	4,459	1,390	1970	Switzerland	2004	1	1	2	Serious
Frejus	41,367	12,895	1980	France/Italy	2005	2	NA	5	Serious

Note: NA = not available.

TABLE 21.11.3 Details of Recent Road Tunnel Fires

Tunnel (Country)	*Opening Date (Fire Date)*	Tunnel Length *ft*	Tunnel Length *m*	*Number of Bores*	*Persons Dead*	*Vehicles Destroyed*	Serious Tunnel Damage *ft*	Serious Tunnel Damage *m*
Mont Blanc (France, Italy)	1965 (March 1999)	38,058	11,600	1	39 27 in own vehicles 2 in other vehicles 2 in refuge shelter 7 outside of vehicles 1 postincident	34 20 tractor-trailers 1 pickup truck 9 passenger cars 1 motorcycle 2 ATMB vehicles	2,953	900
Tauren (Austria)	1974 (May 1999)	20,997	6,400	1	12 8 in accident 1 upon return to his truck 2 in own vehicle 1 fleeing from fire	34 14 trucks 20 passenger cars	1,640	500
St. Gotthard (Switzerland)	1980 (October 2001)	55,512	16,920	1	8 5 in vehicles 3 walking and not finding emergency exits	23 13 trucks 10 passenger cars	2,297	700

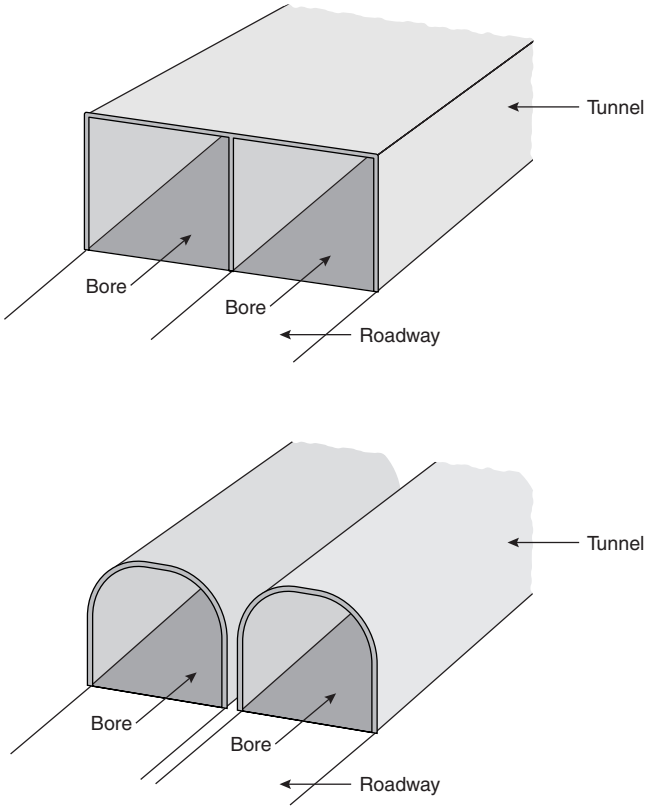


FIGURE 21.11.1 Tunnel with Two Bores

TABLE 21.11.4 Typical Tunnel Fire Incident Vehicle Loads

Tunnel Fire	*Year*	*Vehicle Load*
Holland	1949	Carbon bisulfate
Moorfleet	1968	Polyethylene bags
Guadarrama	1975	Pine resin
B6	1976	Polyester bundles
Kajiwara	1980	Paint in cans
Caldecott	1982	Petrol
Percoile	1983	Fish
Frejus	1983	Plastic materials
St. Gotthard	1984	Rolls of plastic
Mont Blanc	1990	Cotton
Serra Repoli	1993	Rolls of paper
St. Gotthard	1994	Cartons
St. Gotthard	1994	Plastic wrapping
Isola delle Femmine	1996	Liquid gas
Mont Blanc	1999	Margarine
Mont Blanc	1999	Flour
Tauern	1999	Aerosol paint cans
Prapontin	2001	Beets
St. Gotthard	2001	Tires
Frejus	2005	Tires
Frejus	2005	Cheese
Frejus	2005	Glue

A good example is the primary cargo—margarine and flour—in the incident truck involved in the Mont Blanc fire in 1999. Table 21.11.4 contains a list of the materials carried by the incident vehicle for many of the tunnel fires shown in Table 21.11.2.

Global Guidelines and Standards

Guidelines and standards for road tunnel fire protection have been published worldwide by both international organizations and individual countries. Both the National Fire Protection Association (NFPA) and the World Road Association (PIARC) publish standards and guidelines on road tunnel fire protection. Table 21.11.5 provides a sample list of some of the more pertinent global guidelines and standards.

Three NFPA standards address the fire protection requirements for the underground environment: NFPA 130, *Standard for Fixed Guideway Transit and Passenger Rail Systems;* NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways;* and NFPA 520, *Standard on Subterranean Spaces.* The definitive standard for road tunnels is NFPA 502. Although the other two standards contain material that may be applicable to road tunnels, the NFPA Technical Committee on Road Tunnels and Highway Fire Protection has reviewed all of the material contained in these two documents and has applied what was determined to be truly pertinent and included references where appropriate. Elements of several other NFPA codes and standards may be applied to fire protection systems within road tunnels; these codes and standards are appropriately referenced in NFPA 502 and also appear at the end of this chapter. The fire protection requirements prescribed by NFPA Standard 502 are graphically displayed in Table 21.11.6. These prescribed fire protection requirements vary based on tunnel length. PIARC has published a number of documents particularly in the technical area of ventilation and fire and smoke control. The most important document is *Fire and Smoke Control* published in 1999.[5]

KEY ELEMENTS OF ROAD TUNNEL FIRE PROTECTION

The following are the primary objectives of road tunnel fire protection:

- Permit and encourage escape and evacuation of all motorists (i.e., motor vehicle occupants including the driver and passengers) from the tunnel
- Facilitate the entrance of fire-fighting personnel into the tunnel to combat the fire
- Protect the tunnel structure and facilities

TABLE 21.11.5 Road Tunnel Fire Safety Standards and Guidelines

Individual Countries	
Australia	*Road Tunnel Design Guideline, Fire Safety Design,* Parts 1–3, Roads and Traffic Authority (RTA), Australia, 2007
Austria	*Design Guidelines Tunnel Ventilation,* RVS 9261:9262, Austria, 1997
Croatia	*Regulations on Technical Standards and Conditions for Design and Construction of Tunnels on Roads,* Croatia, 1991
Czech Republic	*Design of Road Tunnels,* Standard ČSN 73 7507
	Road Tunnel Equipment—Technical Specifications—Guideline TP 98
France	*Inter-Ministry Circular No. 2000-63—Safety in the Tunnels of the National Highways Network,* Ministry of the Establishment, Transport and Housing, France, 2000
Germany	Forschungsgesellschaft für Strassen- and Verkehrswesen, Richtlinien fuer Ausstattung und Betrieb von Strassentunneln (RABT), Germany, 2006
Japan	*National Safety Standard of Emergency Facilities on Road Tunnels,* Japan Road Association, Japan, 2001
Netherlands	*Recommendations: Ventilation of Road Tunnels,* RWS Bouwdienst, Steunpunt Tunnelveiligheid, 2005
Norway	*Norwegian Design Guide—Road Tunnels,* Public Roads Administration, Norway, 1990
Nordic countries	*Ventilation of Road Tunnels,* Sub-Committee 61, Report No. 6, Nordisk Vejteknisk Forbund (NVF), 1993
Sweden	*Tunnel 2004—General Technical Specification for New Tunnels and Upgrading of Old Tunnels,* Publ. 2004, 124, Swedish National Road Administration, Sweden, 2004
Switzerland	*Ventilation for Road Tunnels,* Swiss Federal Roads Authority (FEDRO), 2004
United Kingdom	*Design Manual for Roads and Bridges,* Part 9, BD 78/99, Design of Road Tunnels, 1999
United States	*Road Tunnel Design Guidelines,* FHWA-IF-05-023, Federal Highway Administration, 2004
International Organizations	
NFPA	NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways,* National Fire Protection Association, Quincy, MA, 2008
PIARC	*Fire and Smoke Control in Road Tunnels,* World Road Association (PIARC), Paris, 1999
	Systems and Equipment for Fire and Smoke Control in Road Tunnels, World Road Association (PIARC), Paris, 2007
European Union	Directive 2004/54/EC of the European Parliament and of the Council on minimum safety requirements for tunnels in the trans-European road network, 29 April 2004
United Nations	Economic Council, Economic Commission for Europe, Inland Transport Committee, Recommendations of the Group of Experts on Safety in Road Tunnels, 10 December 2001

TABLE 21.11.6 Road Tunnel Fire Protection Requirements

Tunnel Categories		X	A	B	C	D	
Fire Protection Systems	*NFPA 502 Sections*	*7.2(1)*	*7.2(2)*	*7.2(3)*	*7.2(4)*	*7.2(5)*	*Notes*
Fire Detection							
Manual fire alarm boxes	7.4.1.2			¤	¤	¤	
CCTV	7.4.1.3 7.4.1.4.6			¤	¤	¤	
Automatic fire detectors	7.4.1.4			¤	¤	¤	
Fire control panel	7.4.2			¤	¤	¤	
Communication							
Radio	7.5			¤	¤	¤	
Telephone	7.5			¤	¤	¤	
Traffic Control							
Stop traffic approaching tunnel portal	7.6.1		¤				
Stop traffic from entering tunnel's direct approaches	7.6.2			¤	¤	¤	
Fire Protection							
Fire apparatus	Annex J		+	+	+	+	Not mandatory to be at tunnel, however, they must be near to minimize response time
Fire standpipe	7.7 9.1		¤	¤	¤	¤	
Water supply	7.7 9.2		¤	¤	¤	¤	
Fire department connections	9.3		¤	¤	¤	¤	
Hose connections	9.4		¤	¤	¤	¤	
Fire pumps	9.5		+	+	+	¤	If required, must follow Section 9.5 in NFPA 502
Portable fire extinguisher	7.8			¤	¤	¤	
Water-based fixed fire fighting system	7.9		+	+	+	+	If installed, must follow Section 7.10 in NFPA 502
Emergency ventilation	7.10			#	#	¤	Section 10.1 in NFPA 502 allows engineering analysis to determine requirements
Drainage system	7.11			¤	¤	¤	
Hydrocarbon detector	7.11.7			¤	¤	¤	
Egress							
Emergency egress	7.14.1.1		¤	¤	¤	¤	
Exit identification	7.14.1.2		¤	¤	¤	¤	
Tenable environment	7.14.2		¤	¤	¤	¤	
Emergency exits	7.14.6		¤	¤	¤	¤	
Cross passageways	7.14.7		¤	¤	¤	¤	
Electrical							
Emergency lighting	11.6		¤	¤	¤	¤	
Emergency power	11.4		¤	¤	¤	¤	
Redundant power	11.5					¤	
Security plan	11.7		¤	¤	¤	¤	
Emergency response plan	12.3		¤	¤	¤	¤	

Legend: ¤ Mandatory requirement + Not mandatory requirement—see Notes # Conditionally mandatory—see Notes

Tunnel Categories. For the purpose of the 2008 edition of NFPA 502, tunnel length shall dictate the minimum fire protection requirements, as follows:

X—Where tunnel length is less than 300 ft (90 m), the provisions of this standard shall not apply.

A—Where tunnel length is 300 ft (90 m) or greater, standpipe systems and traffic control systems shall be installed in accordance with the requirements of Chapter 9 and Section 7.6, respectively, in NFPA 502.

B—Where tunnel length equals or exceeds 800 ft (240 m) and where the maximum distance from any point within the tunnel to a point of safety exceeds 400 ft (120 m), all provisions of this standard shall apply.

C—Where the tunnel length equals or exceeds 1000 ft (300 m), all provisions of this standard shall apply unless noted otherwise in this document.

D—Where the tunnel length equals or exceeds 3280 ft (1000 m), all provisions of this standard shall apply.

Source: Adapted from NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways,* 2008 edition, Table 7.2, p. 502-10.

An effective road tunnel fire protection system program must contain the following elements:

- Fire identification, verification, and detection
- Emergency communications
- Smoke management
- Fire suppression
- Emergency response planning
- Evacuation and rescue

Traffic control, which is another element in an effective road tunnel fire protection system program, is not addressed in this chapter.

A road tunnel's fire protection system must be able to readily identify, verify, and locate a fire anywhere within the tunnel. Determining the location of the fire is critical to safe evacuation, since the success of many companion fire and life safety systems such as smoke control (ventilation) depend on knowing where the fire is within the tunnel to permit the appropriate operational response.

The mission during the initial phase of a tunnel fire-based emergency is to establish safe evacuation and rescue options for those persons within the tunnel. Safe evacuation and rescue requires the establishment of a tenable environment for the entire evacuation path. If the fire incident occurs relatively near one of the tunnel portals, the path to the portal may be the shortest route to a safe area. When the fire incident occurs deeper into the tunnel, the evacuation path will be through an emergency stairway to the surface or a cross passage to a parallel bore (Figure 21.11.2). The entrance to a typical cross passage to a parallel tunnel bore is shown in Figure 21.11.3. The tenable environment in the evacuation path is typically created by the operation of a smoke control or ventilation system. When all of the motorists in the tunnel have been either evacuated or rescued, the responding fire department must proceed with the necessary efforts to extinguish the fire.

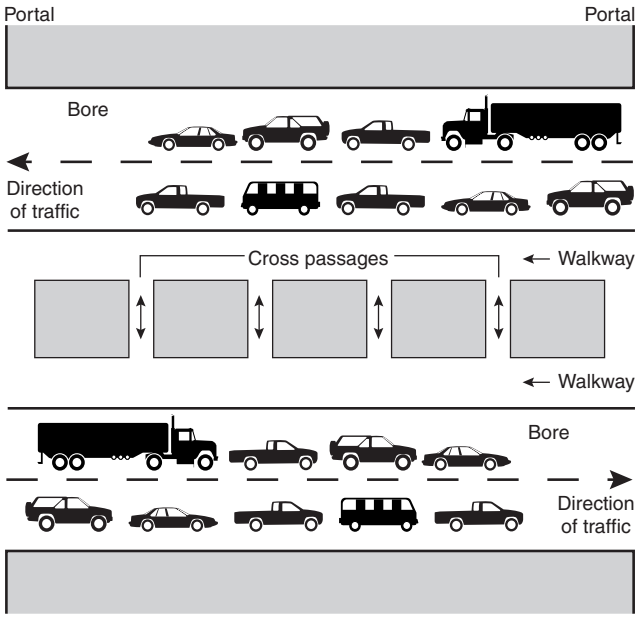


FIGURE 21.11.2 Cross Passages Leading to a Parallel Tunnel Bore

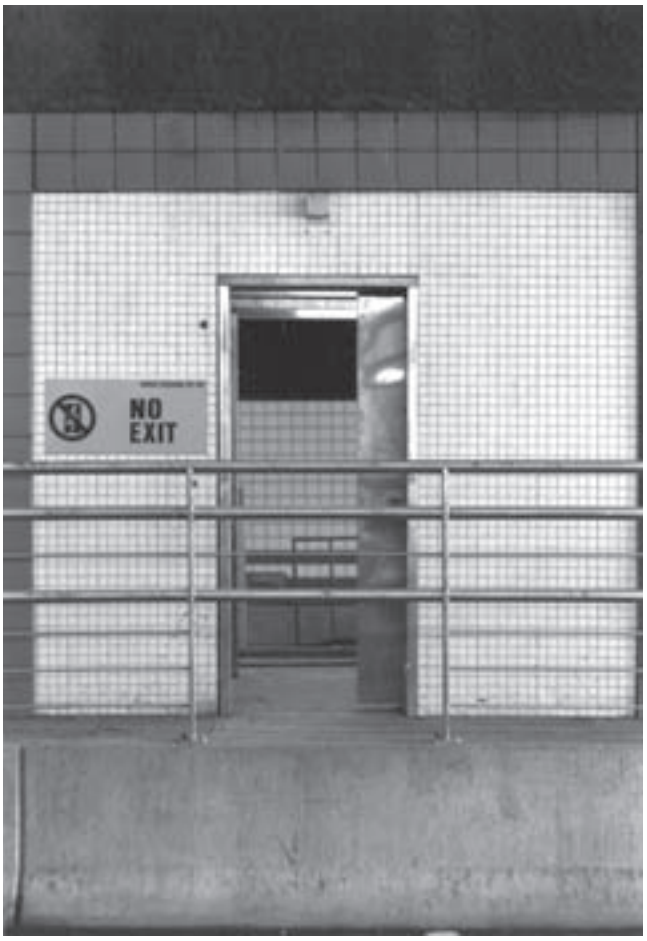


FIGURE 21.11.3 Typical Cross Passage Entrance

IDENTIFICATION, VERIFICATION, AND LOCATION OF FIRES

As previously stated, quick response is critical to the effective management of a fire emergency in a road tunnel. Once a fire has been detected and its location verified, it may take several minutes to fully initiate all necessary emergency response systems and procedures. Therefore, a reliable means to identify, verify, and locate a fire incident is required by NFPA 502 in all road tunnels over 1000 ft (300 m). There are several practical methods considered acceptable within NFPA 502 as a reliable means to identify, verify, and locate a fire within a road tunnel.

Visual Identification

Closed circuit television (CCTV), although not a listed fire detection device, has proven to be one of the most effective means for identifying and verifying a fire within a road tunnel. NFPA

502 considers CCTV monitoring an acceptable means of fire detection if the tunnel is fully monitored by dedicated staff on a 24 hour basis.

Manual Detection

Pull Box. The manual pull-box alarm is a common device used in most building fire protection systems. In a road tunnel, the installation of a pull box provides an opportunity for motorists within the tunnel to send a manual alarm in the event of an emergency, without relying on voice communication. NFPA 502 requires manual pull-box alarms (Figure 21.11.4) to be spaced at 300 ft (90 m) intervals within a road tunnel.

Emergency Telephone. Emergency telephones, generally located adjacent to where the main pull-box alarms are installed (they are at 300 ft [90 m] spacing), provide another means for sending an alarm manually, although the noise level within the tunnel roadway may prohibit clear voice communications. A number of European road tunnel owners have installed telephone booths to combat the problem of high ambient noise. However, the concept is not universally accepted because many believe that motorists might view the enclosure as a point of safety, which is not the case, unless the booths are designed specifically as a refuge with an appropriate fire-rated enclosure and environmental control system.

FIGURE 21.11.4 Fire Alarm Pull Box

Mobile Telephone. It is becoming more and more common for road tunnels to provide capability for signal reception for the use of mobile telephones. As such, the universal popularity of mobile phones provides another manual means for motorists to report an emergency within the tunnel.

Automatic Detection

Heat detectors, flame detectors, and digital imaging systems (using CCTV) are the most applicable forms of automatic fire detection systems for road tunnels. The most prevalent type of detector used in road tunnels worldwide is the heat detector—more specifically the linear heat detector. Flame detectors are found predominantly in Japanese road tunnels. CCTVs using digital imaging are a relatively new technology compared to linear heat detectors.

Linear Heat Detectors. Linear heat detectors are designed to sense an increase in temperature anywhere along the detector's length, to send a signal to a control center, and with this signal to identify the specific location of the alarm site within the tunnel. They are usually installed in zones (generally correlated with the ventilation zones) along the entire length of the road tunnel. The types of linear heat detectors that have been utilized in a road tunnel include the following:

- Electrical cable
- Fiber optic cable
- Thermocouple cable
- Gas-filled cable

Linear heat detectors have not yet received universal approval for application in road tunnels primarily due to their ensuing maintenance needs and their tendency to provide false and late alarms. To be effective, linear heat detectors must be installed directly above the travel lanes. Maintenance of any device mounted over the traveled roadway is always a more costly process, due to the need to close one or two lanes of traffic and use a unique maintenance vehicle with an elevating overhead platform.

Spot Heat Detectors. Spot heat detectors have been installed in a number of tunnels worldwide. However, one of the major drawbacks of spot heat detectors is the number of individual detectors necessary to locate the fire site as quickly and as precisely as possible. This required precision creates the need for a system with a number of spot detectors that may become unmanageable.

Other Detection Systems

Flame Detectors. Flame detectors were installed in over 60 tunnels in Japan beginning in the early 1960s. The early installed versions of the flame detector suffered from false alarm problems. As the products evolved in the ensuing years, flame

detectors were developed to a point where the false alarms were limited. Some of the design modifications were believed to result in more sensitive detectors and the need for fewer detectors per length of tunnel. The most recent designs allow addressing individual detectors in order to identify the fire location within 75 ft (25 m).

Digital Imaging. A recent development is the ability of CCTV systems to automatically detect a fire through digital image analysis. CCTV surveillance systems are typically installed in road tunnels; therefore, the ability of this system to automatically detect and locate a fire in a road tunnel is extremely attractive. This capability, coupled with the existing capability of the CCTV systems to automatically monitor traffic, would enhance the ability of the tunnel operator to respond to a fire in a timely fashion. However, this technology has not yet been proven in the road tunnel environment, although it continues to be tested in trial tunnel installations.

Gas Detectors. Gas detectors, primarily for detection of carbon monoxide (CO), are used in almost all road tunnels to monitor vehicle emission levels during normal tunnel operations. They have not been used for fire detection in road tunnels primarily due to the difficulty in differentiating between concentrated vehicle exhaust and the hot gases from a fire.

Smoke Alarms. Smoke alarms are designed to sense the presence of particles of combustion, either by photoelectric or by ionization sensors. These systems are not designed for outdoor application and would not perform well in a tunnel environment due to a tendency for false alarms caused by heavy diesel engine exhaust.

Visibility Detectors. Visibility measurements are conducted in some road tunnels to monitor for safe operating conditions and in a limited number of tunnels to control the ventilation system during normal operation. These units can also be utilized for detection of a fire. An alarm is triggered once the preset limit value is attained. These detectors are based on either diffused light or illumination.

Research

A study to investigate the performance of fire detection systems in road tunnels was initiated by the Fire Protection Research Foundation (FPRF) in 1999. For Phase II the FPRF has teamed with the National Research Council of Canada (NRCC) and with the Port Authority of New York and New Jersey (PANYNJ). A Technical Advisory Group consisting of fire and transportation officials, engineering firms, researchers, and system manufacturers was formed to oversee the project.

The following are the goals of this research:

- Investigate the performance attributes of current fire detection technologies for road tunnel protection
- Develop performance criteria for fire and smoke detection systems in road tunnel applications
- Optimize technical specifications and installation requirements for this application

The first phase of this project, literature review of past and current research and application of fire detection systems for road tunnels, has been completed.[6] The second phase of the research program will include the following tasks performed at the following locations:

- Laboratory tests—NRCC Fire Research Facilities
- Laboratory tunnel tests—Carleton University–NRCC Test Facility
- Computation modeling—NRCC
- Field fire tests—operating tunnel in Montreal (Viger Tunnel)
- Environmental monitoring – PANYNJ operating tunnel (Lincoln Tunnel)
- Simulated fire tests—PANYNJ operating tunnel (Lincoln Tunnel)

The benefits of this research will be a better understanding of the reliability of various types of fire detection systems and how the operational and environmental factors within a road tunnel influence their performance.

EMERGENCY COMMUNICATIONS

Emergency communications permit the operator to communicate with the motorists within the tunnels and permit emergency responders to communicate with each other during an emergency in the tunnel. Emergency communication devices should have the following features:

- Conspicuous by means of indicating lights or other suitable markers
- Identified by a readily visible number plate or other appropriate device
- Posted with suitable instructions for use by motorists

Loudspeakers

Loudspeakers are prevalent in many European road tunnels. These systems are used to alert the motorists of an emergency situation and to provide directions and guidance. The use of loudspeakers in road tunnels is not a universally accepted safety concept. There are several problems with their application to the tunnel environment, including the following:

- Hard surfaces within the tunnel roadway that make it extremely difficult to understand most announcements
- Motorists' vehicles moving
- Vehicle windows closed (due to air conditioning)
- Potential language barriers

Therefore, the use of loudspeakers within a road tunnel is not a recommended means of reliable communication for emergencies.

Radio

Radio communication systems, such as highway advisory radio (HAR) and AM/FM commercial station overrides can be an effective means to communicate an emergency to motorists and to provide them with direction.

Regardless of type, all communications and messaging systems used within road tunnels should be capable of real-time composition and selection by the emergency response authority, and should not be of the recorded type. All areas planned for use of emergency refuge or assembly should be equipped with reliable two-way voice communication with the emergency response authority.

SMOKE MANAGEMENT

In a road tunnel, smoke management requires either direct extraction at the fire site or the generation of a longitudinal velocity in the tunnel capable of transporting the smoke and heated gases in the desired direction to a point of extraction or discharge from the tunnel. Without a smoke management system, the direction and rate of movement of the smoke and heated gases will be determined by fire size, tunnel grade, prefire tunnel conditions, and external meteorological conditions.

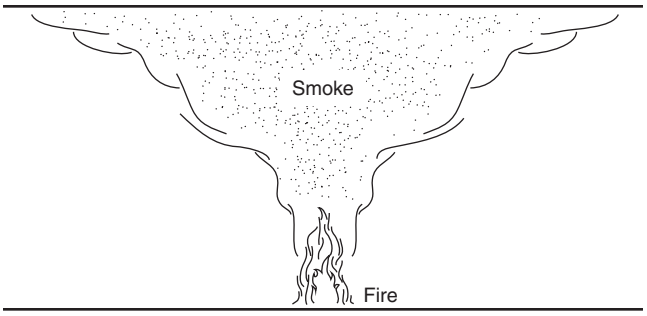
The primary purpose for controlling smoke in a tunnel is to protect life and to permit safe evacuation of the tunnel. This involves creating a safe path of egress for both motorists and any operating personnel located within the tunnel when the fire starts. The secondary purpose of smoke control ventilation is to assist fire fighters in accessing the fire site, by again providing a clear path to the fire site if possible.

The tunnel ventilation system is not specifically designed to protect property, although the effect of ventilation in diluting smoke and heated gases, thus removing some of the heat, results in reduced damage to the facilities and vehicles. The primary method of smoke management is the tunnel ventilation system, which provides the means for controlling smoke movement in the event of a fire incident. The approach used for smoke management varies depending on the type of ventilation system being used and whether the tunnel is serving unidirectional or bidirectional traffic.

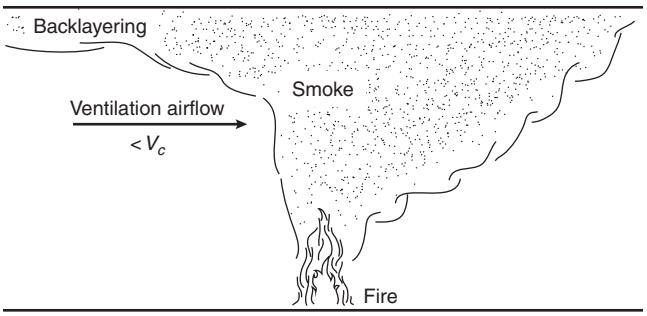
Road Tunnel Ventilation System Types

The primary purpose of tunnel ventilation systems in a tunnel fire emergency is to control and/or remove the heated gases and smoke from the egress path. In essentially all emergency cases, protection of motorists and employees is enhanced by prompt activation of emergency ventilation procedures as planned in advance. The effectiveness of an emergency ventilation system in providing a sufficient quantity of uncontaminated air and in minimizing the hazard of smoke backlayering (i.e., the movement of smoke and hot gases contrary to the direction of the ventilation airflow) in an evacuation pathway is a function of the fire load (Figure 21.11.5).

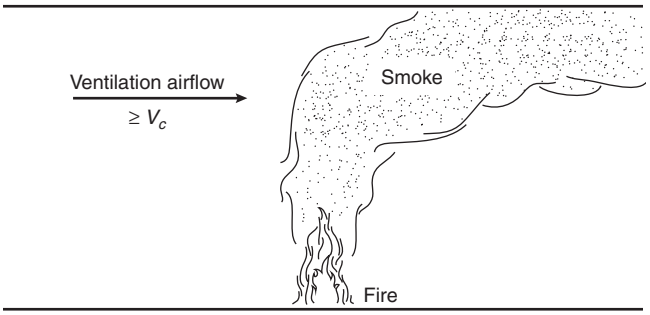
Ventilation is required in many road tunnels to limit the concentrations of vehicle-emitted contaminants to acceptable levels during normal traffic operations. The ventilation systems can also be used to control smoke and heated gases generated during a fire emergency in the tunnel. There are many short tunnels that are ventilated naturally (without fans); such tunnels, however, may still require mechanical ventilation to assist in a fire emergency.



(a) Tunnel fire. No ventilation and 0% grade



(b) Tunnel fire. Underventilated tunnel with backlayering



(c) Tunnel fire. Sufficiently ventilated tunnel to prevent backlayering

FIGURE 21.11.5 Backlayering of Smoke and Hot Gases

Natural Ventilation

Tunnels with natural ventilation only (no fans) rely chiefly on both the ambient meteorological conditions and on the piston effect generated by the moving traffic to maintain a satisfactory environment within the tunnel during normal operations (Figure 21.11.6). However, to handle a fire-based emergency within the naturally ventilated tunnel, an emergency ventilation system may be needed. NFPA 502 requires the consideration of emergency ventilation for all road tunnels over 1000 ft (300 m) in length. Given the lack of a mechanical ventilation system, the smoke and heated gases will, in the case of a tunnel without a grade (level) and without external wind, flow out of both portals. If the tunnel has a grade, the smoke will most likely flow toward the higher portal unless

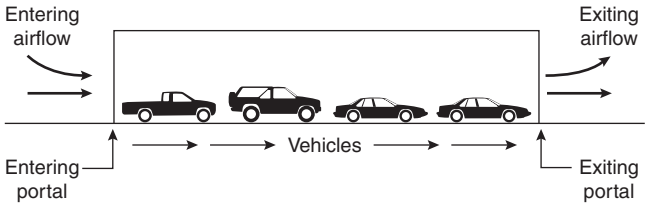


FIGURE 21.11.6 Natural Ventilation

there are abnormal meteorological conditions at the time of the incident.

Mechanical Ventilation

The systems used for mechanical, or fan-driven, ventilation can be classified as longitudinal or transverse. The longitudinal ventilation system achieves its objectives through the longitudinal flow of air within the roadway; the transverse system achieves its objectives by the uniform distribution and/or collection of air continuously throughout the length of the tunnel. The transverse ventilation system also experiences some longitudinal airflow, with the quantity dependent on the type of system.

Longitudinal Ventilation. Longitudinal ventilation is a system in which the air is introduced into or removed from the tunnel roadway at a limited number of points (such as at a portal or a shaft), thus creating a longitudinal flow of air within the roadway discharging at the exiting portal. Longitudinal ventilation systems can be further classified into those using central fans and those using local, or jet, fans.

Central fan longitudinal ventilation systems employ centrally located fans to inject air into the roadway usually through a high-velocity, or Saccardo, nozzle (Figure 21.11.7). The injection of air can take place at the entering portal or in midtunnel. Both concepts can provide the required longitudinal ventilation within the tunnel. An exhaust shaft may be combined with the injection nozzle to increase the quantity of air introduced into the tunnel. Jet fan–based longitudinal ventilation employs a series of axial fans mounted at the ceiling level of the tunnel roadway. These fans, through the effects of the high-velocity discharge thrust, induce a total longitudinal airflow through the length of the tunnel (Figure 21.11.8).

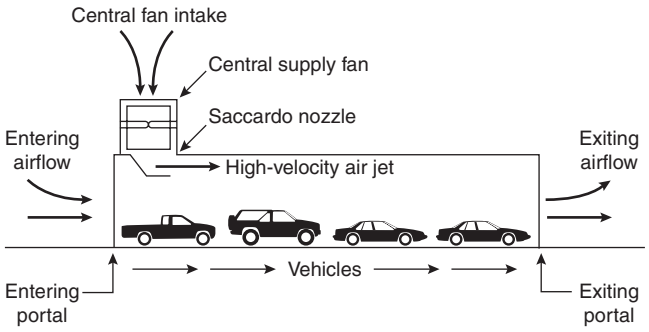


FIGURE 21.11.7 Longitudinal Ventilation with Saccardo Nozzle

Longitudinal ventilation can only be used in a unidirectional tunnel. In all longitudinal systems the smoke and heated gases (or pollutants during normal operations) will discharge from the exit portal. To achieve the required longitudinal movement of smoke, the longitudinal velocity must be sufficient to prevent backlayering of smoke over the stopped vehicles. The critical velocity must be achieved with the tunnel cross section (discussed later in the section "Engineering Analysis"). Longitudinal ventilation systems do not require a longitudinal duct with the tunnel, and systems employing jet fans do not require a ventilation building.

Transverse Ventilation. Transverse ventilation systems, which can be used in either bidirectional or unidirectional trafficked tunnels, are those that feature the uniform collection and/or distribution of air throughout the length of the tunnel. There are full transverse and semitransverse systems. In addition, there are both supply and exhaust versions of semitransverse systems.

Full transverse ventilation systems have both supply and exhaust systems throughout the length of the tunnel (Figure 21.11.9). When a full transverse system is employed, the majority of the smoke and heated gases (or pollutants during normal operations) will be discharged through a stack with a portion

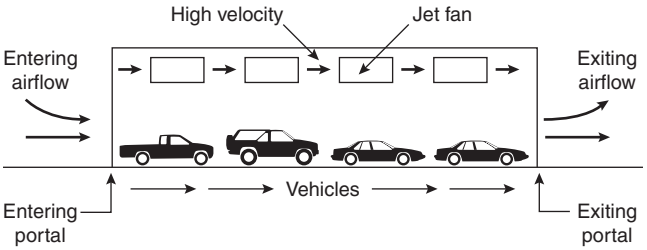


FIGURE 21.11.8 Longitudinal Ventilation with Jet Fans

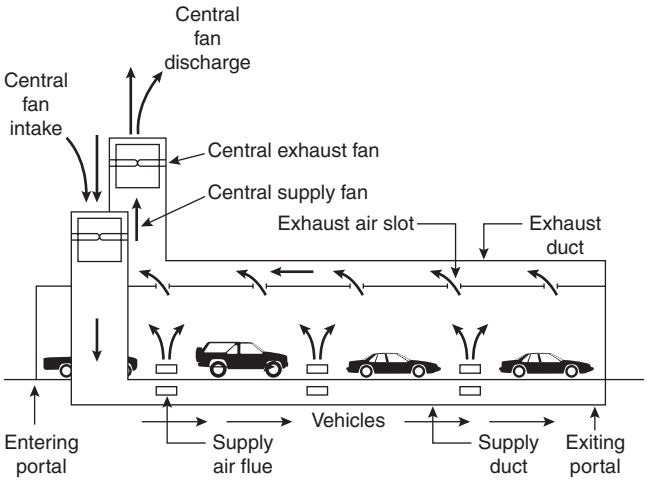


FIGURE 21.11.9 Full Transverse Ventilation

of the smoke exiting through the portals. A full transverse ventilation system can be either balanced (exhaust equals supply) or unbalanced (exhaust is greater than supply). Semitransverse systems are those that have only supply (Figure 21.11.10) or exhaust elements (Figure 21.11.11). The effluent exhaust from the tunnel is discharged at either the portals (supply system) or through ventilation stacks (exhaust system).

Smoke and heated gases from a tunnel fire can be mitigated in a tunnel outfitted with transverse ventilation in one of the following methods:

- Dilution
- Longitudinal airflow
- Extraction

Dilution was shown to be effective only up to a 20 MW fire and not effective beyond that.[7] Longitudinal airflow is an extremely effective method of controlling smoke and heated gases during a tunnel fire. Longitudinal airflow can be achieved in a multizone full transverse system by varying the operation mode between supply and exhaust for different zones.

Extraction is also an excellent method to control the smoke and heated gases within a tunnel. This concept will work with a transverse system with an overhead exhaust duct by outfitting the exhaust duct with a limited number of operable dampered openings. When a fire is identified and located, the control system can open the damper or dampers nearest the fire and extract the smoke and heated gases as close to the fire site as possible, thus removing most of the smoke. The capacity of the emergency ventilation system must be based on the design fire size selected for each specific tunnel.

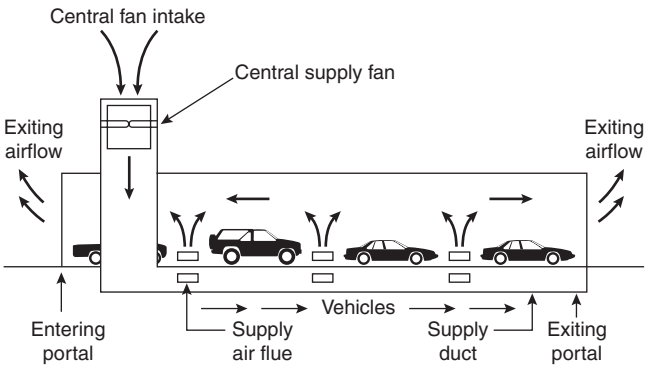


FIGURE 21.11.10 Semitransverse Supply Ventilation

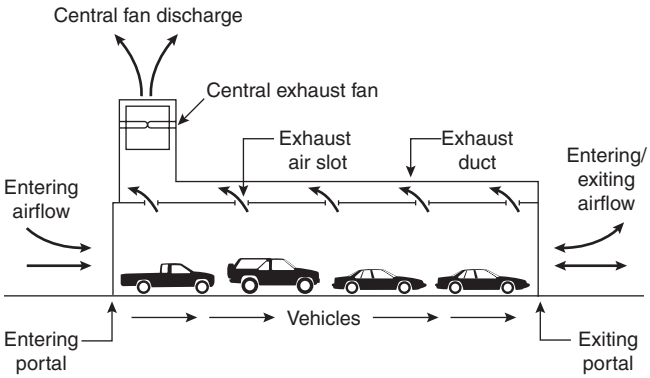


FIGURE 21.11.11 Semitransverse Exhaust Ventilation

FIRE SUPPRESSION

Portable Fire Extinguishers

NFPA 502 requires portable fire extinguishers to be located in the tunnel roadway in wall cabinets at 300 ft (90 m) spacing (Figure 21.11.12). The size and type of portable extinguishers are defined as 2-A:20-B:C and 20 lb (9 kg) as defined in NFPA 10, *Standard for Portable Fire Extinguishers.* It is prudent to install a device to provide the operator with an alarm indication that a fire extinguisher has been removed from its station. This signal could be an indication either of a fire within the tunnel or of the theft of an extinguisher (a common occurrence in some locations).

Standpipe

According to NFPA 502, a Class 1 standpipe system is required in all road tunnels over 300 ft (90 m) in length. The system should be of the wet type. However, if a wet-type system is not possible due to climatic conditions, a dry system is acceptable, provided that the system fill time is less than 10 minutes.

As specified in NFPA 502, the road tunnel standpipe system must be designed to provide support to a minimum of two fire hose streams delivering 250 gpm (16 L/sec) each. The standpipe system must be installed in accordance with NFPA 14, *Standard for the Installation of Standpipe and Hose Systems.*

Water Supply

The water supply system, whether municipal or private, should have adequate waterflow and pressure along with the required system integrity. The water supply system considered should have a minimum supply capacity of 1 hour of fire fighting as

FIGURE 21.11.12 Portable Fire Extinguisher in Cabinet

prescribed by NFPA 502 and should be configured in accordance with NFPA 14. If a storage tank is required to meet the water supply capacity, it should be installed in accordance with NFPA 22, *Standard for Water Tanks for Private Fire Protection.*

Hose Connections

According to NFPA 502, standpipe hose connections or hose valves should be installed in the road tunnel, so that no point on the protected tunnel roadway is more than 150 ft (45 m) from an active hose valve. The spacing of the standpipe hose valves should not be greater than 275 ft (85 m), and the hose connection should be equipped with 2½ in. (65 mm) external threads (see NFPA 1963, *Standard for Fire Hose Connections*). Figure 21.11.13 illustrates a diagram of a typical hose valve installation in a cabinet with a portable fire extinguisher. Figure 21.11.14 shows an actual installation of hose valves in a road tunnel. A fire cabinet with hose valves is shown in Figure 21.11.15.

Fire Hose

Some tunnels outside the United States provide a fire hose within the tunnel at each hose valve location. In many circumstances, this is a small diameter first aid hose. However, in the United States, fire departments are reluctant to use hose that they have not maintained. Consequently, in the United States, fire hose is not placed or stored in the tunnel but carried on the responding fire apparatus.

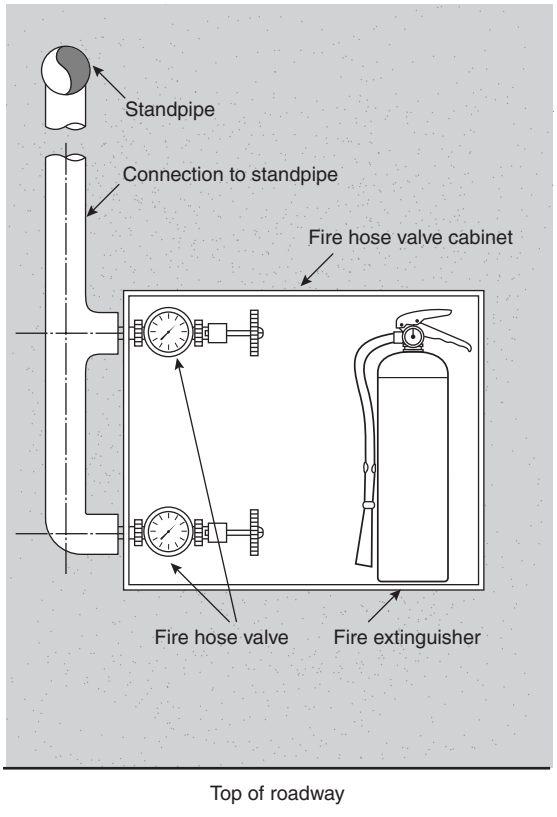


FIGURE 21.11.13 Typical Hose Valve Cabinet

Fire Pumps

When fire pumps are required to provide the necessary flow capacity and pressure in the road tunnel standpipe system, they should be installed in accordance with NFPA 20, *Standard for*

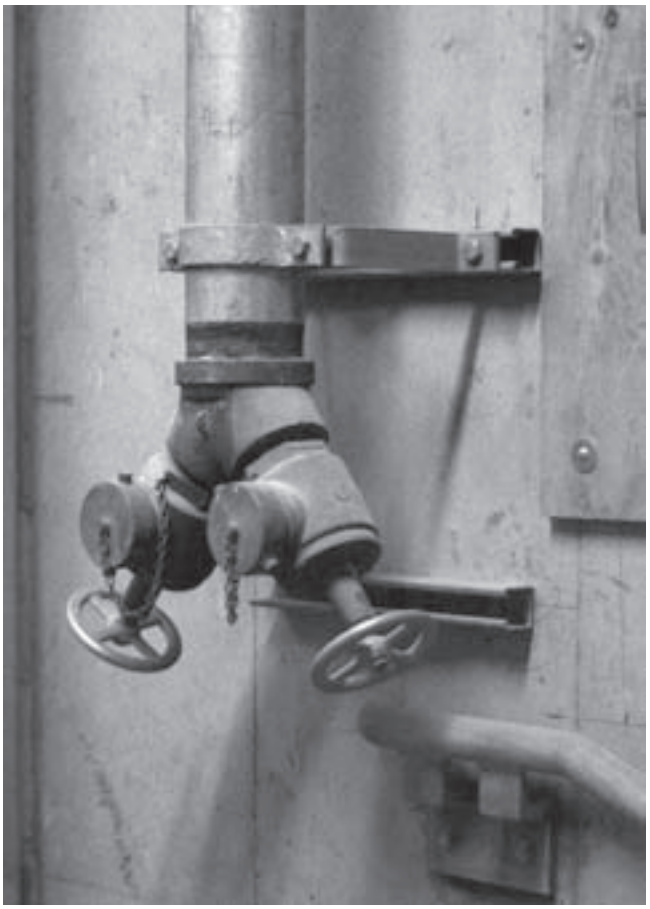


FIGURE 21.11.14 Hose Valves

FIGURE 21.11.15 Hose Valves in Fire Cabinet

the Installation of Stationary Pumps for Fire Protection. Figures 21.11.16 and 21.11.17 show typical installations of fire pumps and controls in a road tunnel application.

Fire Department Connection

Fire department connections are required to allow the fire department to charge the standpipe line. Two connections should be provided for every standpipe system and installed in accordance with NFPA 14. Each fire department connection should be installed within 100 ft (30.5 m) of an active hydrant that is tied into an approved water supply. A typical road tunnel fire department connection (FDC) and its active hydrant are shown in Figure 21.11.18.

Fixed Fire-Fighting Systems (FFFSs)

In road tunnels, fixed fire-fighting systems are defined as consisting of fire-fighting equipment, permanently attached to the tunnel, consisting of a piping system with a fixed supply of water or extinguishing agent which, when operated, has the intended effect of reducing the heat release and fire growth rates by discharging the water or extinguishing agent directly on the fire. Examples of fixed fire-fighting systems include sprinkler and deluge systems.

FIGURE 21.11.16 Fire Pump

FIGURE 21.11.17 Fire Pump Control Cabinet

FIGURE 21.11.18 Fire Department Connection (FDC) with Hydrant

Sprinkler Systems. These are fixed fire-fighting systems consisting of an integrated system of piping designed in accordance with fire protection engineering standards. The system is designed for each sprinkler head to be activated individually by heat from a fire itself so as to dispense water in the areas where it is needed to ensure rapid suppression of the fire.

Deluge Systems. These are fixed fire-fighting systems employing open nozzles that are attached to a zoned piping system that is connected to a water supply through a valve that is opened either manually or automatically. When this valve opens, water flows into the piping system and discharges from all nozzles in the designated zone.

Water Mist Systems. Water mist systems are pressurized fixed fire-fighting systems that operate by propelling very small droplets of water with high momentum which absorbs the fire's energy, cools the surrounding hot air and gases, and prevents oxygen from entering the combustion area.

Additives. Additives such as AFFF (aqueous film-forming foam) are being considered for in-tunnel fixed fire-fighting systems in lieu of water-only systems. The use of water only poses several concerns when applied to roadway tunnels. The high water demand rate needs to be available from the local supply, and this demand requires that in-tunnel drainage piping, storage, and pumping systems all become much larger.

History

The use and effectiveness of fixed fire-fighting systems in road tunnels has not been universally accepted; however, the recent severe fires in road tunnels in Europe have focused attention on the issue of fixed fire-fighting systems in road tunnels. NFPA

502 states that "the use of sprinklers (FFFS) in road tunnels generally is not recommended" (2004), and the World Road Association (PIARC) states that "sprinklers (FFFS) are generally not considered as cost effective and are not recommended in usual road tunnels"[4] (1999). Australia and Japan routinely install FFFS in their road tunnels. In addition, Austria, the Netherlands, Spain, and the United States have installed such systems in tunnels or are planning to do so in the near future. There are currently five U.S. road tunnels that have been equipped with fixed fire-fighting systems as shown in Table 21.11.7. Full-scale tests of fixed fire-fighting systems are or have been conducted by France, the Netherlands, Norway, and Spain.

Design and Control

System Design. When a fixed fire-fighting system is designed and installed in a road tunnel, the system should be designed as a manually activated deluge system to help ensure against accidental discharge of a sprinkler system. The system piping should be arranged using interval zoning so that the discharge can be focused in the zone or zones of incident without necessitating discharge for the entire length of the tunnel. Each zone should be equipped with its own proportioning valve set to control the appropriate water/foam mixture percentage if a water additive is being employed. Discharge heads should provide an open deluge and be spaced so that coverage extends to roadway shoulders and, if applicable, maintenance/patrol walkways. The system should be designed with enough water (and/or foam) capacity to allow operation of at least two zones adjacent to the incident zone. Zone length should be based on activation time as determined by the authority having jurisdiction (AHJ). Piping should be designed to allow drainage of the fixed fire-fighting systems after flow is stopped.

System Control. A full-time attended control room should be available for any road tunnel facility in which safe passage necessitates fixed fire-fighting system protection. Therefore, consideration should be given to human interaction in the system control and activation design to minimize false alarms and accidental discharges. Any automatic mode of operation should include a discharge delay to allow incident verification and assessment of in-tunnel conditions by trained operators. An integrated graphic display of the sprinkler system zones, fire detection system zones, tunnel ventilation system limits, and emergency access and egress locations should be provided at the control room to allow tunnel operators and responding emergency personnel to make appropriate initial response decisions.

Standards and Guidelines

NFPA 502 currently addresses road tunnel–based fixed fire-fighting systems as follows:

> Where sprinklers (fixed fire-fighting systems) are installed in road tunnels, the sprinkler systems (fixed fire-fighting systems) shall be installed, inspected and maintained in accordance with NFPA 13.

The catastrophic tunnel fires experienced in Europe during the last several years have prompted industry experts to revisit the potential benefit of fixed fire-fighting system applications in road tunnels. Research and test initiatives have been, and continue to be, performed by various organizations in both Europe and Japan that have provided new insight on the effectiveness of various FFFS technologies and their advantages and disadvantages under varying in-tunnel fire scenarios.

The technical committee for NFPA 502 has continued to monitor these programs and has acknowledged that when properly designed and maintained, FFFS can offer a potential life safety benefit in some road tunnel applications. As such the 2008 edition of NFPA 502 will reflect the latest technical considerations on the benefits of FFFS in road tunnels and will permit the installation of an FFFS where it can be shown by engineering analysis that the current level of safety can be equaled or exceeded by the use of fixed fire-fighting systems. As part of an integrated approach to the management of safety, such systems will be permitted in accordance with an engineering installation, inspection, and maintenance schedule using the design parameters for a particular tunnel which demonstrate that the level of performance provided by the fire-fighting systems will be maintained.

TABLE 21.11.7 Fixed Fire-Fighting Systems in U.S. Road Tunnels

Tunnel	*Location*	*Route*	*Opened to Traffic*	Length		*Bores/Lanes*	*Fixed Fire-Fighting System Type*	*System Zones*
				ft	*m*			
CANA Northbound	Boston, Massachusetts	US 1	1990	1540	470	1/3	Deluge foam	15
CANA Southbound	Boston, Massachusetts	US 1	1990	900	275	1/3	Deluge foam	9
Mercer Island	Seattle, Washington	I-90	1989	2800	853	3/8	Deluge foam	37
Mt. Baker Ridge	Seattle, Washington	I-90	1989	3500	1067	3/8	Deluge foam	50
Battery Street	Seattle, Washington	Battery Street	1952	2140	652	2/4	Deluge water	14
I-5 Convention Center	Seattle, Washington	I-5	1988	547	167	1/12	Deluge foam	9

Source: Adapted from NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways,* 2008 edition, Table E.3, p. 502-28.

In addition where fixed fire-fighting systems are installed in road tunnels, the fixed fire-fighting system should be installed, inspected, and maintained in accordance with other NFPA standards such as the following:

- NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
- NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
- NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems*
- NFPA 18, *Standard on Wetting Agents*
- NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
- NFPA 750, *Standard on Water Mist Fire Protection Systems*

The reader is referred to Annex D of NFPA 502 for an extensive discussion on the use of fixed fire-fighting systems (sprinklers) in road tunnels. In addition, the subject of fixed fire-fighting systems is addressed by the World Road Association (PIARC) in their technical reports titled *Fire and Smoke Control in Road Tunnels,*[5] *Systems and Equipment for Fire and Smoke Control in Road Tunnels,*[8] and *Road Tunnels: An Assessment of Fixed Fire Fighting Systems.*[9]

Tunnel Drainage

A tunnel drainage system of sufficient capacity must be provided in any road tunnel to collect and discharge the water from seepage, rain, and fire-fighting activities, including the deployment of fixed fire-fighting systems. This system can be either gravity or pumped and should be designed, installed, and maintained in accordance with NFPA 502.

EMERGENCY RESPONSE PLANNING

The operation of any road tunnel includes many operation elements, but one of the most important from a safety viewpoint is the operation of the tunnel facility during a fire emergency. Key components necessary to be prepared for an emergency incident are the development of an integrated emergency response plan, the training of all participants, and the conducting of regularly scheduled exercises.

Emergency Response Plan Participants

An effective emergency response plan includes the interaction of not only the operators of the tunnel but of all outside agencies that might become active in an emergency response to a tunnel incident. Some or all of the following external agencies could be included:

- Police department
- Fire department (brigade)
- Civil defense
- Emergency medical services
- U.S. Department of Transportation (USDOT)
- Local private firms (equipment)
- Department of Public Works
- Water company
- U.S. Coast Guard
- U.S. Federal Emergency Management Agency (FEMA)
- Power company
- Telephone company

NFPA 502 contains a sample outline of a typical emergency response plan in Annex F.

Training and Exercises

A regular training program, which must be included as a part of an emergency response plan, should be scheduled for and should involve all operating personnel and all anticipated responders from external agencies. Because staff assignments within the responding agencies can change frequently, training should be continuous. Retraining of personnel should also be considered because the opportunity to participate in an actual response in a specific road tunnel may be infrequent.

Full-scale exercises should be conducted at least once a year and preferably twice a year. All potential responding external agencies should participate in these exercises so that all external agency representatives become familiar with the unique aspects of a road tunnel emergency response. Tabletop exercises, although extremely beneficial, do not replace the need for full-scale exercises.

Mutual-Aid Response

Arrangements for the response of nearby fire companies and emergency squads should be made a part of the emergency response planning process. Means of access that allows the entrance of outside aid companies to the facility should be provided, and procedures for utilizing such access need to be included in the emergency response plan. Appropriate precautions should be taken at the points of entry to alert and control traffic to allow safe entrance by emergency equipment.

Fire Apparatus

Fire apparatus suitable for fighting fires within road tunnels should be available within the general facility area, thus permitting a rapid response to a fire emergency. This apparatus should be equipped to deal effectively with flammable liquid and hazardous material fires. The responding fire apparatus should be appropriately equipped to fight fire within the road tunnel for a minimum of 30 minutes. If water supply is not available, suitable arrangements are needed to transport water so that the required apparatus delivery rate at the fire can be maintained for an additional 45 minutes. These fire-fighting units should carry multipurpose dry chemical extinguishers and an extinguishing agent for Class D metal fires.

Where the road tunnel is a high-capacity facility in a congested urban area, it may be appropriate to house such apparatus at the tunnel portal or portals. It may also be appropriate at these urban tunnels to combine the fire apparatus with the apparatus provided to effect retrieval and removal of disabled vehicles from the tunnel. Provisions should be taken to permit operation of vehicles and fire fighters in a potentially hazardous smoke and high-temperature gas-laden environment that may also have insufficient oxygen.

EVACUATION AND RESCUE

Point of Safety

A *point of safety* is defined by NFPA 502 as a location outside the incident structure that affords adequate protection for the motorist. Thus in the case of a road tunnel, the potential points of safety are the outside, the parallel nonincident bore (if it is a multibore facility), and a safety refuge (if one is provided). The potential egress paths would include the roadway, the cross passages, the emergency exits, and the safety refuge as shown in Figure 21.11.19. The egress path must be provided with a tenable environment for a sufficient period of time to permit motorist evacuation from the incident bore.

Tenable Environment Criteria

To a large extent, the quantitative aspect of the criteria for emergency situations is arbitrary because there are no universally accepted tolerance limits pertaining to air temperature and velocity. In fact, tolerance limits vary with age, health, weight, sex, and acclimatization.

Air Temperature Criteria. Motorists should not be exposed to maximum air temperatures exceeding 140°F (60°C) during emergencies. It is anticipated that the 140°F (60°C) air temperature will place a physiological burden on a few motorists, but the exposure also is anticipated to be brief and to produce no lasting harmful effects.

Air Velocity Criteria. When ventilation air is needed in evacuation routes to control smoke and heated gases, it might be necessary to expose motorists to high air velocities. The only upper limit to the ventilation rate occurs when the air velocity becomes great enough to create a hazard to persons walking in that airstream. According to the descriptions of the effects of various air velocities given in the Beaufort scale, motorists

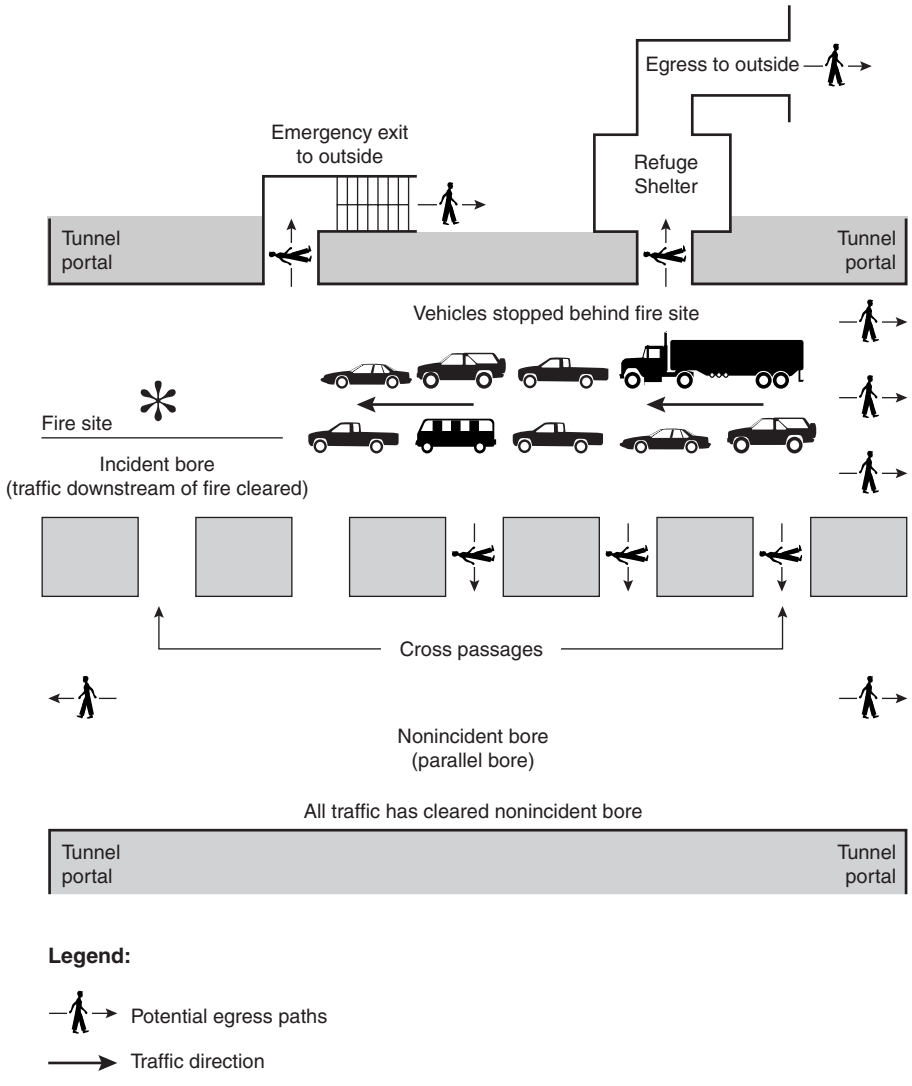


FIGURE 21.11.19 Typical Tunnel Means of Egress

under emergency conditions can tolerate as much as 2200 ft/min (11 m/sec).

ENGINEERING ANALYSIS

Engineering analysis is one of the key elements of the evaluation, development, and approval of any tunnel fire protection system. Many of the design concepts developed must be evaluated and their applicability and capacity demonstrated to the AHJ prior to approval. These analyses may be performed manually or by use of a computer program.

Calculations

Fire Heat Release Rate—Design Fire. The first design issue to be resolved is the selection of the design fire or fires—that is, the value of heat released that will provide the basis for the design of the emergency ventilation system. In a road tunnel, the vehicle fire load is either unknown or inconsistent. As a result, the review of data, such as those contained in Table 21.11.8, is extremely useful in the establishment of the design fire or fires.

Critical Velocity. The minimum air velocity within the tunnel section experiencing the fire emergency should be sufficient to mitigate backlayering of the smoke. The simultaneous solution of Equation 1 and Equation 2, by iteration, determines the critical velocity. The grade in these equations is taken in the direction of the airflow as shown in Figure 21.11.20.

The critical velocity (Figure 21.11.21) is the minimum steady-state velocity of the ventilation air moving toward the fire that is necessary to prevent backlayering:

TABLE 21.11.8 Typical Design Fire Size Data

Cause of Fire	*Peak Fire Heat Release Rate (MW)*
Passenger car	5–10
Multiple passenger cars (2–4 vehicles)	10–20
Bus	20–30
Heavy goods truck	70–200
Tanker*	200–300

Notes:
1. The designer should consider the rate of fire development (peak heat release rates may be reached within 10 minutes), the number of vehicles that could be involved in the fire, and the potential for the fire to spread from one vehicle to another.
2. Temperatures directly above the fire can be expected to be as high as 1832 to 2552°F (1000 to 1400°C).

*Flammable and combustible liquids for the tanker fire design should include adequate drainage to limit the area of the pool fire and its duration. The heat release rate may be greater than in the table if more than one vehicle is involved.

Source: Adapted from NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways,* 2008 edition, Table A.10.5.1, p. 502-23.

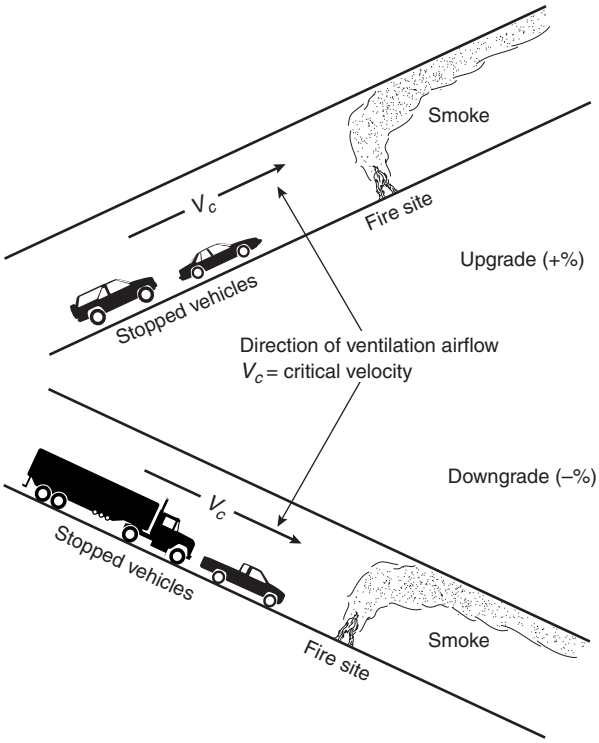


FIGURE 21.11.20 Grade Determination

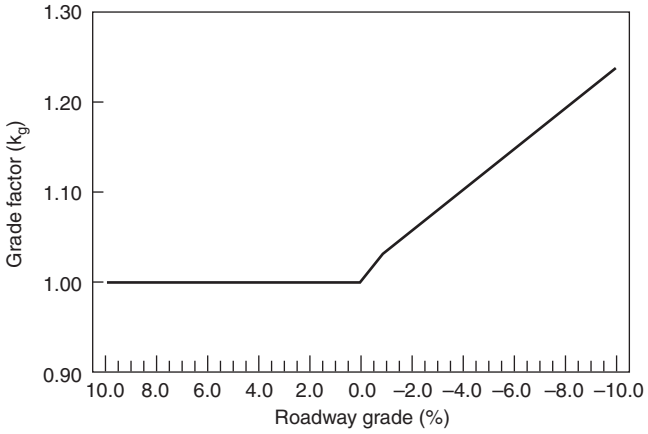


FIGURE 21.11.21 Critical Velocity Grade Factor

$$V_c = K_1 K_g \left(\frac{gHQ}{\rho C_p A T_f} \right)^{1/3} \quad (1)$$

$$T_f = \left(\frac{Q}{\rho C_p A V_c} \right) + T \quad (2)$$

where

A = Area perpendicular to the flow (ft^2 [m^2])
C_p = Specific heat of air (Btu/lb R [kJ/kg K])

g = Acceleration caused by gravity (ft/sec^2 [m/sec^2])
H = Height of the tunnel at the fire site (ft [m])
K_1 = 0.606
K_g = Grade factor (Figure 21.11.21)
Q = Heat the fire is adding directly to the air at the fire site (Btu/sec [MW])
T = Temperature of the approach air (degrees R [K])
T_f = Average temperature of the fire site gases (degrees R [K])
V_c = Critical velocity (ft/min [m/sec])
ρ = Average density of the approach (upstream) air (lb/ft^3 [kg/m^3])

Fire Models as Analytical Tools

The three following types of fire models can be applied to the road tunnel environment:

- One-dimensional models
- Zone models
- Field models

One-dimensional models are extremely useful and effective if the bulk results (i.e., the average values for results like airflow and temperature) are satisfactory. The zone models developed for use in buildings, which utilize room configurations, do not lend themselves to a linear configuration such as a road tunnel. Field models or computational fluid dynamics (CFD) will provide detailed results, including temperature and smoke profiles, and are therefore ideally suited to perform analyses for road tunnels. However, CFD simulation can be expensive to conduct.

A number of computer-based analytical tools have been developed that are applicable to road tunnels. Models are available to evaluate smoke control and ventilation requirements as well as emergency egress. Ventilation analyses have moved from the one-dimensional models developed 20 to 30 years ago to the three-dimensional aspects of computational fluid dynamics. CFD has been in use in other industries for many years, but only in the last 10 years has it begun to be used in tunnel fire protection applications.

SES. An excellent example of a one-dimensional model used in the analysis of road tunnel emergency ventilation requirements is the Subway Environment Simulation (SES) program. The SES is a one-dimensional network model that is extremely effective in the evaluation of tunnel/shaft configurations.

The SES program, which is essentially a one-dimensional, incompressible, turbulent, slug-flow model, comprises a series of interdependent computation subprograms to address vehicle performance, aerodynamics, temperature/humidity, heat sink, environmental control, and fire. The SES computer model provides a dynamic simulation of bidirectional traffic in a road tunnel and permits continuous reading of the average air velocity, temperature, and humidity throughout any arrangement of tunnels, ventilation buildings, and shafts.

The SES fire model, which has the ability to model the aerodynamic and thermodynamic effects of a tunnel fire, was designed to simulate the overall effects of a tunnel fire on the ventilation system. This level of detail is considered sufficient for evaluating the adequacy of an emergency ventilation system. The input/information required by the program and the outputs produced are tailored for use by design engineers concerned with practical environmental problems. The SES model[10] is available from the Volpe Transportation Center in Cambridge, Massachusetts.

TUNVEN. The TUNVEN computer program[11] solves the coupled one-dimensional steady-state road tunnel aerodynamics and advection equations to obtain the longitudinal air velocities and pollutant concentrations for a given road tunnel design, traffic load, and ventilation rate. The effect of ambient conditions external to the tunnel, such as portal winds and local pollutant levels, can also be included. This program can be used to determine ventilation requirements for natural, longitudinal, semi-transverse, and full transverse ventilation systems.

A road tunnel is modeled in the TUNVEN computer program as a one-dimensional longitudinal air duct with inflow and outflow at each end and along its length. Airflow through the tunnel is caused by a pressure differential between the ends, by the piston action of the vehicles, and by addition or removal of air through the ventilation system. The forces generated by these effects are balanced in the steady-state case by opposing friction forces along the tunnel walls and flow entrance and exit losses.

Vehicles traveling through the tunnel also emit pollutants, which are diluted by the tunnel air to a concentration that depends on the pollutant sources in the upstream sections of the tunnel and on the local airflow velocity. The dependence on pollutant sources couples the aerodynamic and advection (or concentration) equations, making it necessary to compute the flow field before the concentrations can be determined. The TUNVEN model is available from National Technical Information Services (NTIS).

SOLVENT. SOLVENT[12] is a computational fluid dynamics model developed as a part of the Memorial Tunnel Fire Ventilation Test Program, for the simulation of fluid flow, heat transfer, and smoke transport in road tunnels. SOLVENT can be applied to all of the ventilation systems deployed in road tunnels, including longitudinal ventilation using jet fans, transverse ventilation, and natural ventilation.

The primary objective for the model is the ability to simulate the interactive effects of a tunnel fire and the ventilation system to determine the unsafe regions of the tunnel, where the hazardous effects of the fire (smoke and high temperature) are confined, and how these regions are affected by the ventilation system configuration, capacity, and operation.

For transverse ventilation systems, a flow network model is used to predict the flow rates, temperatures, and pressures in the ducts. The ventilation ducts and the tunnel (which uses the CFD model) are coupled via boundary conditions. SOLVENT is being applied to develop the emergency ventilation operating mode matrix for the many operating road tunnels. The matrix identifies how each ventilation zone is to be operated as a function of fire incident location and traffic direction. Figure 21.11.22 is a copy of the animation of the SOLVENT output

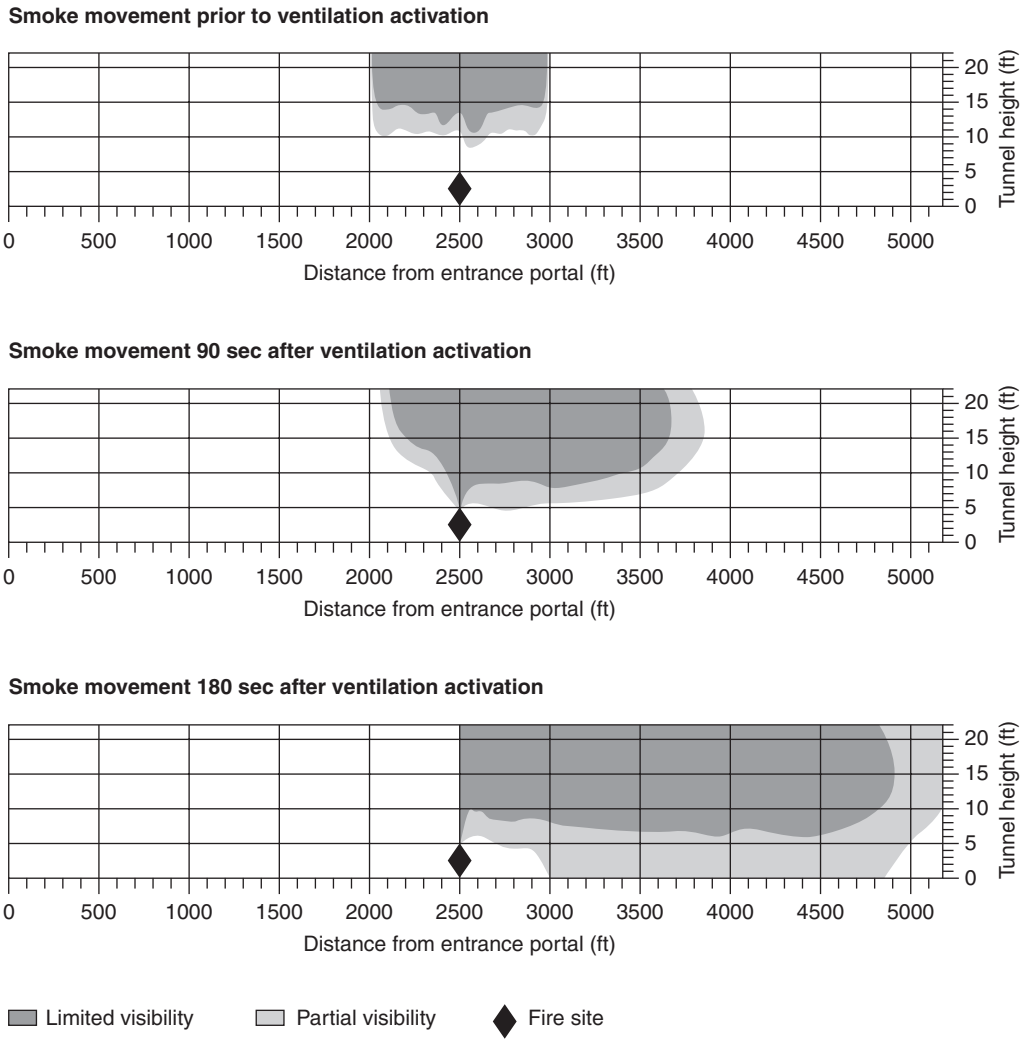


FIGURE 21.11.22 Smoke Movement Simulation

from simulations for a road tunnel with a longitudinal ventilation system. These graphics show the movement of the smoke before and after ventilation activation. They clearly show the progressive movement of the smoke and the ultimate elimination of any backlayering.

The SOLVENT model has been validated against the data compiled from the Memorial Tunnel Fire Ventilation Test Program.[12] The SOLVENT model is available, under license, from Parsons Brinckerhoff Quade & Douglas, Inc., in New York and Innovative Research, Inc., in Minneapolis.

Emergency Egress Models

Evacuation modeling software, such as SIMULEX, can be employed to simulate the escape movement of people to a point of safety during incidents within road tunnels. The algorithms for the movement of individuals are based on real-life data. The program shows the evacuation process graphically on the screen, with the plan view of passengers moving toward emergency exits or cross passages, and predicts where the exiting choke points occur within the tunnel. The egress times computed by this program can be used to evaluate alternative distances between emergency exits and can allow comparisons among alternative sizes of cross-passageways, exit stairways, and walkways. The program has been upgraded to simulate walkways in road tunnels and people walking at the 200 fpm (1 m/sec) exiting speed (the design speed for exiting passengers) specified in NFPA 130.

Current applicable standards for road tunnels require emergency exits and cross-passageways be provided throughout the tunnels and spaced so that the distance between exits is not greater than the limit specified in the standard. There is an ongoing interest to determine the most appropriate distance between emergency exits, minimum size of exit stairways, and widths of walkways in road and rail tunnels, which will ultimately lead to the development of more performance-based codes. The output in Figure 21.11.23 is a printout of an emergency egress simulation for a road tunnel employing SIMULEX. This figure shows the motorists in the process of leaving their vehicles and subsequently entering an emergency exit enclosure leading to an emergency exit stairway. The SIMULEX model is available, under license, from Integrated Environmental Solutions

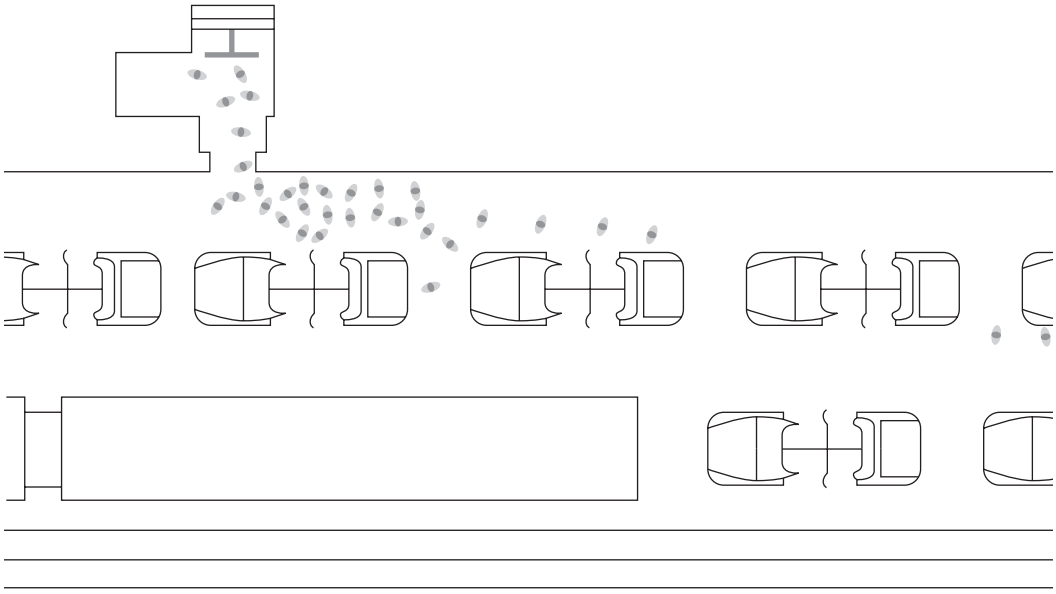


FIGURE 21.11.23 Emergency Egress Model Output

(IES) of Glasgow, Scotland.[13] There are other egress models currently being applied to tunnel egress such as STEPS, Exodus, and Legion.

TUNNEL FIRE TESTS

Over the past 40 years, a series of full-scale tunnel fire tests have been conducted to permit fire protection and ventilation engineers to better understand the phenomenon of fire and smoke within a tunnel. These tests were conducted in Switzerland, Austria, Japan, Norway, and the United States, as shown in Table 21.11.9. The most recent of these were the Eureka Project 499 FIRETUN, conducted in an abandoned mining tunnel in northern Norway by nine European countries;[14] the Memorial Tunnel Fire Ventilation Test Program (MTFVTP),[7] conducted in the United States; and the Runehamer tests,[15] conducted in Norway in 2003.

The most significant to the tunnel industry in the United States were the tests conducted at the Memorial Tunnel, an

TABLE 21.11.9 Full-Scale Tunnel Fire Tests

Fire Test Program	*Country*	*Year(s)*	*Test Tunnel Type*	*Number of Tests*	Test Tunnel Length		*Fire Type*	*Pan Fuel*
					(ft)	*(m)*		
Ofenegg	Switzerland	1965	Railway	11	623	190	Pan	Gasoline
Zwenberg	Austria	1975	—	30	—	—	Pan	Diesel
PWRI[a]	Japan	1980	Road	8	9843	3000	Pan and vehicle	—
PWRI	Japan	1980	Test facility[b]	16	2297	700	Pan and vehicle	Heptane
Eureka[c] Project 499 FIRETUN	Norway[d]	1990–1992	Mining	21	7218	2200	Pan and vehicle	Wood cribs
Memorial Tunnel	United States	1993–1995	Road	98	2800	854	Pan	Diesel
Runehamar	Norway	2003	Road	4	5413	1650	Vehicle[e]	—

[a]Public Works Research Institute.
[b]A tunnel test facility built by PWRI.
[c]Eureka tests were conducted in the Repparfjord Tunnel in Norway.
[d]Although the Eureka tests were conducted in Norway, nine European countries conducted the specific tests.
[e]The fuel used was as follows for each of the four tests:

- Wood and plastic pallets
- Wood pallets and mattresses
- Furniture and tires
- Plastic cups in cardboard cartons

abandoned road tunnel in West Virginia. This comprehensive test program, which began with the initial fire tests in September 1993 and concluded with the final tests in March 1995, produced data that were acquired in a full-size facility, under controlled conditions, and over a wide range of system parameters.

Hot-Smoke Testing in Tunnels

Hot-smoke tests were initially conducted as a means of verifying smoke modeling predictions. More recently it has become common practice to use a hot-smoke test to actually test the smoke management systems of a completed tunnel. These tests have become valuable as a commissioning tool, allowing testing of the integrational functioning of all systems related to the fire life safety of the tunnel, including the detection, ventilation, smoke exhaust, dampers, fire-fighting systems, and fire control panels.[16]

Memorial Tunnel Fire Ventilation Test Program

The Memorial Tunnel Fire Ventilation Test Program[7] represented a unique opportunity to evaluate and develop design methods and operational strategies leading to safe road tunnels. The purpose of this test program was to develop a database that provides tunnel design engineers and operators with an experimentally proven means to determine the ventilation rates and ventilation system configurations that provide effective smoke control management during a tunnel fire emergency. It was even more important to establish specific operational strategies to permit effective reconfiguration of ventilation operational parameters for existing tunnel facilities.

The Memorial Tunnel, a two-lane, 2800 ft (854 m) road tunnel located near Charleston, West Virginia, was built in 1953 as part of the West Virginia Turnpike and abandoned in 1987 when it was bypassed by an open-cut section of a new six-lane interstate highway. The tunnel has a 3.2 percent uphill grade from the south to the north tunnel portal. The existing ventilation equipment was replaced with new variable speed, reversible, axial flow central ventilation fans. Fires were produced in roadway-level steel pans, with average fire heat release rates as shown in Table 21.11.10.

The ventilation systems, tested under varying flow rates and varying heat release rates with one or two zones of ventilation, included the following:

- Natural ventilation
- Longitudinal ventilation with jet fans
- Longitudinal ventilation with central fans and Saccardo nozzles
- Transverse ventilation
- Transverse ventilation with point extraction and oversized exhaust ports

TABLE 21.11.10 MTFVTP Test Fire Sizes

Nominal Fire Heat Release Rate (MW)	*Vehicle Incident Equivalent*
10	Two passenger cars
20	Bus or truck
50	Large truck
100	Petrol tanker

Source: "Memorial Tunnel Fire Ventilation Test Report."[7]

Suppression System. A fire suppression system employing a 3 percent aqueous film-forming foam (AFFF) solution was installed in the Memorial Tunnel primarily to suppress the test fire in an emergency; however, it was also used during several tests to evaluate the impact of horizontal roadway ventilation airflow on the operation of a foam suppression system.

The effectiveness of the foam suppression system tested was not diminished by operation in high-velocity longitudinal airflow (825 fpm [4.2 m/sec]). The time for the suppression system to extinguish the open pan fire with the nozzles located at the ceiling, 14 ft (4.3 m) above the roadway, ranged from 5 to 25 seconds for a 50 MW fire. This was the configuration for the transverse tests.

When the longitudinal ventilation tests with jet fans were conducted, the nozzles were located on the west wall, 7 ft (2.1 m) above the roadway. In this configuration the time to extinguishment was 102 seconds (50 MW) and 11 seconds (100 MW). The results of these suppression tests are shown in Table 21.11.11.

Video Recording System. The CCTV system included seven video cameras, two located within the tunnel with water-cooled enclosures, one roadway-level camera north of the fire to secure added video footage of smoke movement, two located at the tunnel portals, and two located on the north and south meteorological towers. This system provided essential video footage of smoke behavior during the fires.

Findings and Conclusions of the Memorial Tunnel Fire Ventilation Test Program. *Natural ventilation* resulted in extensive spread of smoke and heated gases upgrade of the fire but relatively clear conditions downgrade of the fire. Other conclusions related to natural ventilation included the following:

TABLE 21.11.11 Foam Suppression Tests

Ventilation System	*Fire Size (MW)*	Air Velocity Across Fire *(fpm)*	Air Velocity Across Fire *(m/sec)*	*Time to Extinguish (sec)*
Full transverse	50	115	0.6	5
Semitransverse—exhaust	50	210	1.1	8
Exhaust—single port	50	825	4.2	25
Longitudinal—jet fans	50	500	2.5	102
Longitudinal—jet fans	100	400	2.0	111

Source: "Memorial Tunnel Fire Ventilation Test Report."[7]

- The spread of smoke and heated gases during a 50 MW fire was considerably greater than during a 20 MW fire. The depth of the smoke layer increased with fire size.
- The time for the smoke layer to descend to a point where it posed an immediate life safety threat was dependent on the fire size and tunnel geometry, specifically the tunnel height.
- In the Memorial Tunnel, smoke traveled between 950 and 1200 ft (290 and 365 m) along the arched tunnel roof before cooling and descending into the roadway.
- The restriction to visibility caused by the movement of smoke occurred more quickly than did a temperature high enough to be debilitating.
- Exposure to high levels of carbon monoxide was never more critical than smoke or temperature for any test.

Longitudinal Ventilation System. A longitudinal ventilation system employing jet fans was highly effective in managing the direction of the spread of smoke for fires sizes tested up to 100 MW in a 3.2 percent grade tunnel. Jet fans located downgrade from the fire site were subjected to the temperatures shown in Table 21.11.12.

Transverse Ventilation. It was demonstrated in the MTFVTP that dilution as a sole means for temperature and smoke control was not very effective. Some means of extraction should be incorporated. Extraction and longitudinal airflow when combined can significantly increase the effectiveness of a road tunnel ventilation system to manage and control the movement of smoke.

Single-zone balanced full transverse ventilation systems operated at 100 cubic feet per minute per lane foot (cfm/lf) (0.155 cubic meters per second per lane meter [m^3/sec/lm]) were ineffective in the management of smoke and heated gases for fire sizes 20 MW and larger. Single-zone unbalanced full transverse ventilation systems generate some longitudinal airflow in the roadway. The result of this longitudinal airflow was to offset some of the effects of buoyancy for a 20 MW fire. The effectiveness of unbalanced full transverse ventilation systems is sensitive to the fire location, since there is no control over the airflow direction.

The tested two-zone transverse ventilation system provided control over the direction and magnitude of the longitudinal airflow. Airflow rates of 100 cfm/lf (0.155 m^3/sec/lm) contained high temperatures from a 20 MW fire within 100 ft (31 m) of the fire in the lower elevations of the roadway and smoke within 200 ft (61 m). The maximum temperatures experienced at the inlet to the central fans closest to the fire are shown in Table 21.11.13.

Smoke and Heated Gas Movement. The time for the smoke layer to descend to a point where it poses an immediate life safety threat is dependent on the fire size and tunnel geometry, specifically the tunnel height. As noted under the section on natural ventilation, smoke traveled between 950 and 1200 ft (290 and 365 m) along the arched tunnel roof before cooling and descending into the roadway. Selected smoke movement data for a naturally ventilated tunnel with a 3.2 percent grade is shown in Table 21.11.14.

Fan Operation Delays. The spread of hot gases and smoke was significantly greater with a longer fan response time. Hot smoke

TABLE 21.11.12 Temperatures at Jet Fans

Nominal Fire Size (MW)	Maximum Temperature *(°F)*	*(°C)*
20	400	204
50	630	332
100	1250	677

Note: The jet fans subjected to these maximum temperatures during the Memorial Tunnel Fire Ventilation Test Program were located 170 ft (51.8 m) downgrade of the fire site.

Source: "Memorial Tunnel Fire Ventilation Test Report."[7]

TABLE 21.11.13 Temperatures at Central Fan Inlet

Nominal Fire Size (MW)	Maximum Temperature *(°F)*	*(°C)*
20	225	107
50	255	124
100	325	163

Note: The central fans exposed (subjected) to these maximum temperatures during the Memorial Tunnel Fire Ventilation Test Program were located approximately 700 ft (213 m) from the fire site.

Source: "Memorial Tunnel Fire Ventilation Test Report."[7]

TABLE 21.11.14 Smoke Movement in a Naturally Ventilated Tunnel

Test Number	Fire Heat Release Rate: Nominal *10^6 Btu/hr*	Nominal *MW*	Peak *10^6 Btu/hr*	Peak *MW*	*Smoke Layer Begins Descent (min)*	*Smoke Fills Tunnel Roadway (min)*	Peak Smoke Velocity *fpm*	*m/sec*
501	68	20	99	29	3+	5	1200	6.1
502	171	50	195	57	1+	3	1600	8.1

Source: "Memorial Tunnel Fire Ventilation Test Report."[7]

layers were observed to spread very quickly—1600 to 1900 ft (490 to 580 m) in the initial 2 minutes of a fire.

Ventilation System Enhancements. The ability to extract smoke quickly and as close as possible to the fire location can significantly reduce smoke and heat migration in undesired directions and facilitate two-way traffic operations. This localized extraction is possible with the application of single-point extraction openings (SPE) to a transverse ventilation system. SPE systems are applicable to two-way traffic flow with a dependency on the location, size, and spacing of the SPE openings. Smoke and heat drawn from the fire to the SPE could pass over or possibly around stalled traffic and vehicle occupants. An SPE located upgrade of the fire is very effective in temperature and smoke management. With the SPE located downgrade of the fire, only minimal improvement in temperature and smoke conditions over a single-zone partial transverse exhaust system was achieved. A single-point opening of 300 ft^2 (27.9 m^2) was most effective in temperature and smoke management of the SPE sizes tested. Significantly greater smoke and heat spread was observed with a 100 ft^2 (9.3 m^2) opening compared to the 300 ft^2 (27.9 m^2) opening.

For 20 MW fires, partial transverse ventilation exhaust ventilation operated with 100 cfm/lf (0.155 m^3/sec/lm) and supplemented with a large (300 ft^2 [27.9 m^2]) single-point opening limited smoke and heated gases migration to 200 ft (61 m) from the fire. A partial transverse exhaust system supplemented with oversized exhaust ports and operated with 85 cfm/lf (0.132 m^3/sec/lm) limited high temperatures to an area extending 100 ft (31 m) from the fire and sustained the stratified smoke layer above the occupied zone. For 50 MW fires, partial transverse ventilation exhaust ventilation operated with 110 cfm/lf (0.170 m^3/sec/lm) and supplemented with a large (300 ft^2 [27.9 m^2]) single-point opening limited smoke and heated gases migration to 280 ft (85 m) from the fire.

ROAD BRIDGES

The 2004 version of NFPA 502 provides the fire protection requirements for road bridges spanning more than 400 ft (122 m). A fire occurring on a bridge is a much less serious situation than that posed by the same fire size in a tunnel for the very basic reason that the resulting heat and smoke is not contained within the same confined space as the motorists. However, depending on the severity and location (on or under the bridge) of the fire, the risk to structure may threaten the life safety of motorists traveling both on and below the bridge. Similar to a tunnel, most bridges afford only limited access for emergency responders; therefore, emergency response planning for longer span bridges is recommended. Further, the fact that cargo restrictions are far less stringent on bridges (and likely nonexistent beneath bridges) than in tunnels suggests that the potential for a large-scale fire is far greater on such structures. This issue of structure fire resistance and methods for fire protection on bridges is likely to become an increasingly important consideration as more lightweight and double-decked bridges are built.

Recent Road Bridge Fires

Fires on or under road bridges can be devastating to the integrity of the bridge support structure. Examples of several such fires that have occurred on Interstate 95 (I-95) are briefly described as follows:

- A fire broke out under the elevated section of I-95 in Pennsylvania, near Philadelphia, in 1996, between Westmoreland Street and Tioga Street and caused three spans of the 26-span, 1707 ft (520 m) Westmoreland Viaduct to buckle. The cause of the fire was a stack of discarded tires in an illegal dump underneath the viaduct.
- A tanker truck loaded with 8700 gal (33,000 L) of gasoline was traveling on I-95 in Pennsylvania in 1998. While swerving to avoid a passing car, the tanker truck jumped the Jersey barrier and exploded after striking a pickup truck in the southbound lanes. Both drivers died at the scene. Nine steel support girders, each 6 ft (2 m) long and 8 in. (20 cm) tall, and between 65 and 80 ft (20 and 24 m) of the bridge crossing the Chester Creek, were damaged.[17]
- In 2004 a tanker truck carrying 12,000 gal (45,500 L) of fuel oil collided with another vehicle and caught fire on Interstate 95 near Bridgeport, Connecticut. The resulting blaze was hot enough to melt steel support beams on the southbound side of the bridge over Howard Avenue. I-95 was closed in both directions.

Recommendations for Road Bridge Fire Protection

Currently, NFPA 502 provides that the following fire protection system elements be considered for application on long span road bridges:

- Emergency communications
- Signage
- Traffic control
- Fire suppression
- Drainage
- Control of hazardous materials
- Emergency response planning

Emergency Communications. Emergency communications, where required by the AHJ, will be provided by the installation of outdoor-type telephone boxes, coded alarm telegraph stations, radio transmitters, or other approved devices. These devices should have all of the following features:

- Made conspicuous by means of indicating lights or other approved markers
- Identified by a readily visible number plate or other approved device
- Posted with instructions for use by motorists
- Located in approved locations so that motorists can park vehicles clear of the travel lanes

Signage. Signs, mile markers, or other approved location reference markers will be installed along the highway to allow mo-

torists to provide authorities with accurate locations for accident or emergency areas.

Traffic Control. A traffic control procedure will be established so that vehicles either stop or proceed with caution. Traffic will not be permitted to block or otherwise interfere with the response of emergency and fire apparatus.

Fire Suppression System. Where the distance from an acceptable water supply source to any point on the bridge exceeds 400 ft (120 m), the bridge will be provided with a Class I standpipe system in accordance with NFPA 14. The maximum flow of the standpipe system will be 500 gpm (1920 L/min) for one hour. Standard hose connections will be provided so that no location on the roadway is more than 150 ft (45 m) from the hose connection; however, the spacing will not exceed 275 ft (85 m). Two standard fire department connections (FDC) will be provided for each independent standpipe system.

Drainage. Drainage systems on bridges will be designed to channel and collect spilled hazardous or flammable liquids to drain areas that cannot cause additional hazards. Expansion joints will be designed to prevent spillage to the area below the bridge.

Control of Hazardous Materials. Control of hazardous materials will be in accordance with the requirements of Chapter 13 of NFPA 502.

Emergency Response Plan. The designated agency (operating) will carry out a complete and coordinated program of fire protection that will include written preplanned emergency response procedures and standard operating procedures. Emergency response procedures and the development of an emergency response plan will comply with the requirements of Chapter 12 of NFPA 502.

SUMMARY

Road tunnels, which include mountain tunnels, underwater tunnels, urban tunnels, and air-rights tunnels, represent a unique challenge in fire protection. The linear shape, limited accessibility, and lack of compartmentalization of road tunnels make fire fighting and evacuation difficult. For most road tunnels, the potential fire load is unknown because of the variety of vehicles and cargoes that pass through. The primary objectives of a road tunnel fire protection system are to permit evacuation, facilitate the entrance of fire fighters, and protect the tunnel structure and facilities. The key elements of road tunnel fire protection are fire identification, verification, and location; emergency communications; smoke management; fire suppression; emergency response planning; and evacuation and rescue.

Means of fire identification, verification, and detection include closed circuit television, pull boxes, emergency telephones, and detection systems such as heat, flame, and smoke detectors. Emergency communications can be transmitted by radio, whereas the use of loudspeakers is not recommended. Smoke management can be achieved by a variety of ventilation systems. Fire suppression systems include portable fire extinguishers, standpipes, hoses, fire pumps, and sprinklers. The emergency response plan should include the interaction of all potential responders such as nearby fire companies and emergency squads. For evacuation and rescue, potential egress paths are the roadway, the cross passages, the emergency exits, and the safety refuge. When developing an effective fire protection system for a road tunnel, an engineering analysis, performed manually or by use of a computer program, is essential.

Road bridges, providing long span crossings of waterways, railroads, and other roadways, would appear to pose minimum life safety risk since they are not enclosed as is a tunnel. However, there are significant motorist life safety risks created by the potential for much larger-scale fires due to the less restrictive regulation of cargo and the failure of the bridge supporting structure from a fire located either on or under the bridge. Double-decked bridges create the additional risk of a fire developing on the lower level and ultimately impacting the integrity of the support structure of the upper level. In addition to proper methods for fire resistance protection of the bridge structure and the provision of minimal fire protection systems as required by NFPA 502, bridge operators and emergency responders must also develop an emergency response plan similar to that recommended for road tunnels.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on road tunnels and bridges discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA 10, *Standard for Portable Fire Extinguishers*
NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam*
NFPA 13, *Standard for the Installation of Sprinkler Systems*
NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*
NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection*
NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems*
NFPA 18, *Standard on Wetting Agents*
NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 22, *Standard for Water Tanks for Private Fire Protection*
NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*
NFPA 30, *Flammable and Combustible Liquids Code*
NFPA 70, *National Electrical Code®*
NFPA 72®, National Fire Alarm Code®
NFPA *101®, Life Safety Code®*
NFPA 130, *Standard for Fixed Guideway Transit and Passenger Rail Systems*
NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations*
NFPA 259, *Standard Test Method for Potential Heat of Building Materials*
NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways*
NFPA 520, *Standard on Subterranean Spaces*
NFPA 750, *Standard on Water Mist Fire Protection Systems*
NFPA 1963, *Standard for Fire Hose Connections*

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